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Manufacturing Control of Textile Materials

Operational Computerized Non-contact
Methods

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Preface

One of the most important tasks relevant for light industry enterprises is to ensure the production process for the manufacture of textile materials by using systems for the operational control of their technological parameters to ensure the quality characteristics of competitive products. Textile materials have a wide range of applications. They are used for the manufacture of various items of clothing, household textiles, fabrics and knitwear for technical purposes. Modern devices and control systems do not allow the use of continuous monitoring of technological parameters in the production process, and laboratory control of textile material samples is mainly used. This does not allow for a prompt response to a change in the value of a technological parameter, which may go beyond the regulated limits in the process of production of a controlled material, which reduces the quality of the finished product, increases the amount of defects and used energy resources. For the practical implementation of operational and continuous monitoring of the quality of textile materials, it is necessary to develop a methodology for constructing modern computerized systems for monitoring their technological parameters using non-contact ultrasonic methods for material with a complex structure. To solve this problem, it is necessary to obtain analytical dependences that connect the technological parameters of textile materials with the informative parameters of ultrasonic waves, which will allow to develop non-contact control methods. Based on the obtained methods, it is possible to develop different computerized systems depending on the technological parameter that needs to be controlled. Computerized systems for the control of technological parameters in the manufacturing process must simultaneously process several informative parameters of ultrasonic waves arriving at the receiving transducers to take into account the complex structure of the textile material. Such systems are necessary to ensure the possibility of strict observance of the main technological parameters during the manufacturing processes of products that affect both the consumer properties of textile materials and their physical and mechanical characteristics within the established limits. And this is an actual task.

One of these parameters is the surface density and porosity of the textile material. Changes in these parameters are also influenced by the regulation of the tension of the

threads of the textile material on the technological equipment during the production process.

To control the main technological parameters of textile materials using modern computerized systems, it is necessary to use technical complexes with the ability to quickly determine the required values in real time. For the manufacturing process, it is important to control the given surface density and ensure the uniformity of the structure of the textile material, taking into account the actual value of the controlled parameter. In order to meet the required porosity value with a certain tolerance of its values, appropriate performance characteristics for various textile materials are ensured. By determining the actual value of porosity for finished textile fabrics, it is possible to ensure the optimal consumption of special substances for their manufacturing and coloration.

The control of the surface density and porosity of the textile fabric, taking into account the tension of the threads, must be carried out using computerized systems, using non-contact methods, since only they allow to quickly respond to changes in the value of these parameters directly in the manufacturing process.

Thus, by constantly monitoring the surface density and porosity of textile materials, taking into account their tension, using modern computerized systems, it is possible to obtain high-quality finished products with minimal raw material costs. Such operational control will ensure the specified shape stability, rigidity, heat-shielding properties of various fabrics, as well as important and relevant for the production of such textile materials. This, in turn, will increase the economic efficiency of textile products on the market.

Kyiv, Ukraine
December 2021

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Abbreviations

ADC	Analog-to-digital converter
BBA	Block of basic adjustment
CNC	Computer numerical control
CTM	Composite textile material
ECU	Engine control unit
GUTC	General unit of information transmission and control
MC	Microcontroller
MCU	Motor control unit
PC	Personal computer
UCIP	Unit of conversion and information processing
UUS	Unit with ultrasonic sensors

Symbols

$T_{b, w}$	Linear density, tex (mg/m)
$m_{b, w}$	Weight, threads, mg
R_{sur}	Surface porosity, %
m_s	Basis weight, g/m ²
Z_1	Acoustic impedance air, kg m ⁻² s ⁻¹
Z_2	Acoustic impedance of the first layer of material, kg m ⁻² s ⁻¹
Z_3	Acoustic impedance of the second layer of material, kg m ⁻² s ⁻¹
h_1	Thickness of the first layer of material, mm
h_2	Thickness of the second layer of material, mm
α_3	Attenuation coefficient of ultrasonic waves, m ⁻¹
$W(\omega)$	Complex coefficient of ultrasonic waves transmission through a material
c_{23}	Is the average propagation speed of the ultrasonic wave in the material, m/s
N	Is the number of wave reflections that equals to 0, 1, 2, 3, . . . , ∞
t	Is the current time, s
τ_0	Pulse duration, s
ω_0	Angular frequency of the pulse signal filling, rad/s
ω	Angular frequency, rad/s
t'	Is the time considering the partial delay of the ultrasonic signal, s
$V(\omega)$	Complex coefficient of ultrasonic waves reflection from the material
$ W $	Module of complex coefficient of transmission of waves from the material
$ V $	Module of complex coefficient of reflection of waves from the material
$ W_p $	Module of complex coefficient of transmission of waves from the polymeric material with pores
$ V_p $	Module of complex coefficient of reflection of waves from the polymeric material with pores
$ W_{\alpha\beta} $	Module of complex coefficient of transmission of waves from the fabric
$ V_{\alpha\beta} $	Module of complex coefficient of reflection of waves from the fabric
A_0	Unit amplitude of the incident ultrasonic wave on the surface of the material
A_w	Amplitude of waves that passed through the material
A_v	Amplitude of reflected waves from the material

A_{wp}	Amplitude of waves that passed through the material with pores
A_{vp}	Amplitude of reflected waves from the material with pores
f	Oscillation frequency, kHz
$\delta_{ w }$	Change in the magnitude of the module of the complex coefficient of transmission, %
$\delta_{ v }$	Change in the magnitude of the module of the complex reflection coefficient, %
$\Delta W $	Difference for the waves that have passed the composite material
$\Delta V $	Difference between the ratios of the reflected waves from the composite material
$ W_{def.} $	Module of complex coefficient of transmission of waves from the composite material with defect
$ V_{def.} $	Module of complex coefficient of reflection of waves from the composite material with defect
$\Delta\phi_w$	Phase shift of waves that passed through the composite material, °
$\Delta\phi_v$	Phase shift of reflected waves from the composite material, °
Q_T	Fabric tension, cN
Q_o	Tension of the warp in the area of fabric formation, cN
P	Force of the weft thread battening, cN
d_o	Warp thread diameter, mm
d_y	Weft thread diameter, mm
α_0	Half the bite angle in battening, °
α	Angle of circumference of the weft thread surface with the warp thread, °
β	Weft angle in the fabric, °
D_{wt}	Number of weft threads per 1 dm, threads/dm
D_{wp}	Number of warp threads per 1 dm, threads/dm
T_o	Linear density of warp threads, tex (mg/m)
T_y	Linear density of weft threads, tex (mg/m)
$ W_o $	Module of complex coefficient of transmission of waves from the material of warp threads
$ V_o $	Module of complex coefficient of reflection of waves from the material of warp threads
K_ρ	Coefficient characterizing the receipt of the reflected ultrasonic signal to the receiver of oscillations from the structural parameters of the fabric threads and their position relative to the receiver
B_0	Stiffness coefficient of the thread when bending, cN/mm ²
E_1	Modulus of the thread elasticity during compression, cN/mm ²
P_I	Tension of the leading branches of the yarn, cN
P_0	Tension of the trailing branches of the yarn, cN
R	Curvature radius of the cylindrical guide, mm
$ W_{lp} $	Module of the complex coefficient of longitudinal transmission of ultrasonic waves that have passed the textile material
P_n	Initial tension of the textile material, N
P_k	Final tension of the textile material, N
T_m	Linear density of material, tex (mg/m)

δ_{P_k}	Deviation of the fabric tension, %
Q_{0p}	Porosity of the reference sample, mm ³
Q_p	Porosity of the samples of different fabrics, mm ³
δ_{Q_p}	Deviation of the fabric porosity, %
δ_{m_s}	Deviation of the fabric basis weight, %
P^*	Thread tension, cN
δ_{P^*}	Deviation of the thread tension, %
$ W_1 $	Module of the complex transmission coefficient of ultrasonic wave of smaller pk of amplitude
$ W_2 $	Module of the complex transmission coefficient of wave of bigger peak

Chapter 1

Analysis of the Current State of Methods and Means for Monitoring the Technological Parameters of Textile Materials



1.1 Review of Existing Destructive Methods and Means for Monitoring the Technological Parameters of Textile Materials

In light industry, the method of sampling is used [1] to measure the linear dimensions, linear density of threads, yarn and basis weight of textile fabrics. To control the quality of the fabric from the roll, point samples are taken, from each of which, in turn, take basic samples for specific tests. Point sampling causes inconvenience, leads to a violation of the canvas integrity, its damage, thus causing material damage to the enterprise.

The number of point samples taken for the fabric depends on the batch size in production. If the total length of the fabric in the batch does not exceed 5000 m, then three pieces are selected; at a length of more than 5000 m, one additional piece is additionally taken from each subsequent 5000 m. Each point sample is cut off from the piece selected from the batch from any place except the ends.

For laboratory determination of the structure and properties of the material from the point sample elementary samples are cut out. The shape, size and number of elementary samples are determined according to the relevant standards for the types of tests or according to the proposed methods.

The following rules are observed when placing elementary samples on a point sample:

- elementary samples are placed, departing from the edge or longitudinal bend of the canvas by 50 mm; elementary samples in the form of rectangles or strips, as a rule, should be located strictly in the specified direction (on warp or weft threads, along looped columns or rows, along or across a cloth, at a certain angle to the longitudinal direction);
- in elementary samples of the same type, designed to determine the mechanical (tensile, bending, friction) and physical (capillarity, electrification, etc.) properties, the same threads, columns, rows should not be located in the direction of the

test, in other words, samples in the direction of the test should not be a continuation of each other;

- in elementary samples of the same type, which are used to assess shrinkage, abrasion, physical properties (absorption capacity, permeability, thermophysical, optical) must not pass the same threads, columns or rows;
- in canvases with a large weave report, elementary samples are placed separately on each section of the report, which are characterized by their density, type of weave, type of thread and thickness.

The geometric parameters include the thickness, width and length of the fabric. Tissue thickness, b_{tk} , mm is the distance between the areas of tissue that protrude the most from the front and back. The thickness of the fabrics varies from 0.1 to 7 mm and determines the purpose of the materials, the height of the flooring when cutting, the consumption of sewing threads, the class of the machine and processing methods.

The length of the fabric, L_{tk} , mm is the distance between the ends of a piece of fabric. The length of the fabric in the piece depends on the type of fabric and its basis weight. The length of a piece of coat fabric, drape and batting is 25–30 m, woolen fabric for dresses 40–60 m, silk 60–80 m, cotton 70–100 m, knitted fabric 25–40 m. The greater the length of the piece, the easier it is to calculate it for flooring with a minimum amount of finite irrational residues.

Width, V_{tk} , mm is the distance between the two edges of the fabric. The width of the fabrics varies from 60 to 250 cm. When cutting parts of garments of different types, not all widths provide minimal inter-treatment waste. Not all widths are rational. Recommendations have been developed for the production of fabrics of nominal width, and the deviation of the average actual width from the designed and approved standard should not exceed the following values, cm: for fabric width up to 70 ± 1 ; up to 100 ± 1.5 ; up to 150 ± 2 ; 170 ± 2.5 ; more than 170 ± 3 ; for all fabrics, except fabrics from synthetic and crepe threads and fabrics with the maintenance in a weft of a shaped yarn, the admissible deviation of 2.5 cm.

The characteristics of the fabric structure include density at the base and weft, filling (linear, surface, volume) and fabric filling, filling by weight, total porosity, coefficient of connectivity and the nature of the support surface.

The density of the fabric at the base of the P_b and the weft P_w is the absolute number of threads per 100 mm of fabric in the direction of the base or weft.

Each fabric in accordance with the requirements of the standard must have a set number of main and weft threads at a length (width) of 100 mm. Failure to comply with the regulated density changes the weight, strength, wear resistance of the fabric, which leads to a decrease in its grade and shortage. Therefore, it is very important that each fabric has a standard density set for it. For example, the deviations on density (GOST 5012-66) regulated for woolen and semi-woolen fabrics should not exceed: on a basis—2%, on a weft—3%.

The thickness of the fabric threads is characterized by the linear density, $T_{b,w}$, tex, and the calculated diameter, mm

$$T_{b,w} = \frac{m_{b,w}}{L_m}, \quad (1.1)$$

where $m_{b,w}$ is weight, mg, threads (yarns) of the base or weft of fabric with length $L_m = 1$ m.

The linear fabric filling on the basis of E_b and on the weft E_w , %, shows what part of the fabric length along the base or weft is occupied by the diameters of parallel threads, without taking into account their interweaving with threads of the perpendicular system.

Linear filling is defined as the ratio of the actual number of base threads P_b or weft P_w , located on the length L , to the maximum possible number of threads $P_{\max}$ of the same diameter d , which can theoretically be located without gaps, shifts and wrinkles on the same length, by the formulas:

$$E_b = A_n \sqrt{T} P_b / 31.6, \quad E_w = A_n \sqrt{T} P_w / 31.6, \quad (1.2)$$

where A_n is the coefficient depends on the nature of the fiber.

Depending on the purpose of the fabric, its linear filling can vary from 25 to 150%. If the linear filling of the fabric is greater than the maximum density, i.e. more than 100%, the threads are either flattened, taking an elliptical shape, or arranged with a shift at different heights.

Surface filling, E_{sur} , %, shows what part of the fabric is filled with threads of both systems, taking into account their interweaving and overlapping, and is characterized by the ratio of the area of fabric filled with projections of base and weft threads to the total fabric area.

Since, interweaving with each other, the base and weft threads are superimposed on each other, the area of their projections is less than the area occupied by each of the components separately. Surface filling is calculated by the formula:

$$E_{sur} = E_b + E_w - 0.01 \cdot E_b E_w. \quad (1.3)$$

Knowing the surface filling of the fabric, you can determine its surface porosity R_{sur} , %, which shows the ratio of the area of the through pores to the area of the entire fabric:

$$R_{sur} = 100 - E_{sur}. \quad (1.4)$$

The volume filling E_v , % shows what part of the volume of the fabric is the volume of the base and weft threads. The volume filling can be expressed as the ratio of the volumetric mass of the fabric to the volumetric mass of the threads:

$$E_v = 100 \delta_f / \delta_t, \quad (1.5)$$

where δ_f and δ_t are the volumetric mass of threads and fabric, mg/mm³.

$$\delta_f = (m_s \cdot 10^{-3})/b_f, \quad (1.6)$$

where b_f is the thickness of the fabric, mm; m_s —basis weight of fabric, g/m².

The volumetric mass of the thread δ_f is determined from tabular data depending on the nature of the fibers.

Filling by weight of fabric E_f , %, is determined by the ratio of the mass of the threads to the mass that the material could have in the complete absence of pores both between the threads and inside the threads between the fibers and macromolecules and is calculated by the formula:

$$E_f = 100\delta_f/\gamma, \quad (1.7)$$

where γ is the density of the substance of the fibers, mg/mm³, it is chosen by tabular values. The total porosity of the fabric, P_{bf} , %, characterizes the proportion of all gaps between the threads, inside the threads and fibers:

$$P_{bf} = 100(1 - \delta_f/\gamma) = 100 - E_f. \quad (1.8)$$

The total tissue porosity ranges from 50 to 95%.

The linear density of the fabric m_L , g/m, is the mass of 1 m of the fabric length at its actual width, can be determined by calculating the mass of the spot sample m_{ss} , g, length L_f , mm, by the formula:

$$m_L = m_{ss} \cdot 10^3/L_f. \quad (1.9)$$

The basis weight of the fabric m_s , g/m² is the mass per unit area of the fabric, i.e. one square meter of fabric.

The basis weight of the fabric is determined by converting the mass of the spot sample length L_f , mm, and width B_f , mm, to an area of 1 m² by the formula:

$$m_s = m_{ss} \cdot 10^6/(L_f \cdot B_f). \quad (1.10)$$

Basis weight is also calculated from the structural parameters of the fabric:

$$m_{sp} = 0.01 \cdot (P_b P_b + P_w P_w) \eta, \quad (1.11)$$

where η is a coefficient that takes into account the change in fabric mass in the process of its production and processing.

According to prof. N.A. Arkhangelsky, the coefficient η depends on the type of tissue and can be determined by tabular data.

The deviation $\delta_{m_{sp}}$ of the basis weight values obtained by experimental m_s and calculation m_{sp} methods should not exceed 2%. This deviation can be submitted as following:

$$\delta_{m_{sp}} = \frac{(m_s - m_{sp})}{m_{sp}} \cdot 100\%, \quad (1.12)$$

Due to the hygroscopicity of textile fibers and threads, the basis weight of the fabric actual and calculated may differ, so the basis weight of the fabric is determined at normalized humidity.

For knitted fabrics, the expression (1.12) is also valid, only for the calculated parameter the dependence will be its own, which will take into account the weave of the directly controlled material.

The means used in measuring the geometric linear dimensions and indicators of the fabric structure with the subsequent determination of its basis weight are as following:

- thickness gauges of the indicator type TR-10 with an error of 0.01 mm;
- ruler with an error of up to 1 mm;
- measuring table;
- scales with an error of up to 0.001 g for weighing fabric samples;
- optical microscope IPT-1 facilitates the counting of the number of filaments;
- scales with an error of 0.1 mg for weighing thread samples;
- PM-4 optical device for determining the degree of uniform filling of the material surface with threads and fibers.

The means used in measuring the geometric linear dimensions and indicators of the structure of knitted fabrics with the subsequent determination of their basis weight are as following:

- thickness gauges with an error of 0.01 mm at a measuring pressure of not more than 10 PA;
- measuring the angle of skew of the loop rows with an error of not more than 10°;
- ruler with an error of up to 1 mm;
- measuring table;
- scales with an error of up to 0.001 g for weighing fabric samples;
- rack and load for straightening threads when measuring their length;
- scales with an error of 0.1 mg for weighing samples of threads.

Based on the above, it can be concluded that it is currently impossible to carry out operational control of the main technological parameters of textile fabrics using contact destructive methods and tools.

Methods including manual labor are used, the shortage can be missed for controlled canvases, which does not allow to obtain quality products at the exit. Most of the existing methods of control of technological parameters of textile materials allow the selection of samples for testing at the final stage of production, while the shortcomings of the defect can no longer be corrected. Sampling for testing is destructive, which can reduce the grade of the canvas from which the samples are taken. At the same time, textile enterprises are forced to constantly update and improve their technological base. The speed of production is constantly increasing, the range is changing. Therefore, there is a need for [2–7] operational quality control of raw

materials and finished products. It is for such control that non-destructive methods of determining the technological parameters of textile materials in production are used.

1.2 Review of Non-destructive Methods for Control and Analysis of the Possibility of Their Application for Technological Parameters of Textile Materials

Non-destructive testing methods do not require cutting samples, destruction of finished products, thus reducing material costs. The following non-destructive methods can be used to control the technological parameters of textile materials: capacitive, radioisotope, optical, radio wave, pneumatic, photoelectric and ultrasonic. Classification of the main non-destructive methods of control, which can be used both non-contact and contact for textile materials, is shown in Fig. 1.1 [8–13].

We will consider the description of the specified methods further in work, and then we will carry out the short analysis of scientists' works which are connected with development of modern methods for control of various technological parameters of textile materials [14–17].

The radio wave method is based on the dependence of the reflection coefficient of the high-frequency electromagnetic field on the diameters of the controlled special fibers (with electrically conductive components) with a known electrical conductivity of the latter to the receiver with subsequent signal processing. Devices based on this method can have a very high sensitivity. This fact allows them to be used to control the diameter of thin (10 ... 200 μm) and ultra-thin (less than 10 μm) electrically conductive fibers.

The pneumatic method is based on measuring the variable pressure of the gas flowing around the controlled fiber. The advantages of this method include insensitivity to the physical and mechanical properties of the controlled fiber, the effects of strong electromagnetic fields, as well as the ability to control fibers with a cross section of any shape. The disadvantages of this method include the error in changing environmental conditions and low speed.

The capacitive method refers to electrical control methods. Currently, it is one of the most promising methods of controlling the diameter of thin, but only conductive special fibers. Often in the control of this method transducers are used that are made in the form of a round hollow cylinder, which forms a measuring capacitor with a coaxially controlled fiber.

The radioisotope method of controlling the diameter of the fibers or determining the linear density of the textile tape is based on the interaction of radioisotope radiation with the controlled material. The linear density of the tape is determined by the scattering or absorption of radiation by the controlled material. The method has advantages: the independence of the error from environmental conditions and the ability to control the fiber mass of considerable thickness. However, this method is

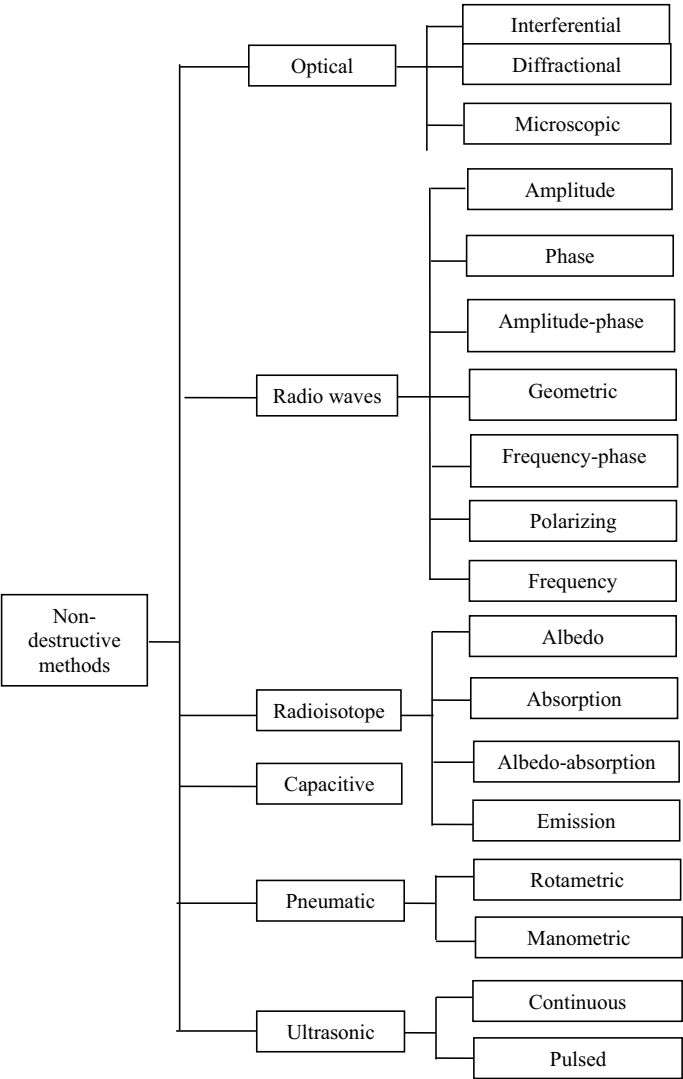


Fig. 1.1 Classification of the main methods of non-destructive testing that can be used for textile materials

not used to control the failure to comply with all safety measures for staff, and the source of radioisotope radiation may lose its activity over time.

The most effective are *optical non-contact methods*, which are characterized by a significant variety. The general trend of their development is due to the requirement of a significant increase in accuracy—a decrease in the wavelength of the radiation probing the measured object or material and the transition to visible waves.

Radiowave and ultrasonic methods, which operate with radio and acoustic waves of longer length than optical ones, are characterized by lower accuracy of measurements.

Recently, a large number of non-contact optical methods based on various optical phenomena have been developed. These include interference and diffraction of a plane wave incident on a homogeneous or inhomogeneous dielectric cylinder, refraction of a narrow probe beam, radiation when the beam passes through a dielectric cylinder, its reflection from the end face, and others. Control methods are implemented in various ways, using both integral transformations (Fourier, Radon, Abel) and solutions of differential equations of the theory of diffraction on a dielectric cylinder.

All optical methods, in turn, can be divided into two groups: destructive and non-destructive testing.

In the schemes implemented on the basis of non-destructive testing methods, probing radiation is directed perpendicular to the optical axis of the fiber or at a certain angle.

These methods are applied to the control of fiber blanks, fibers of complex non-circular cross-sections, both smoothly inhomogeneous and stepwise inhomogeneous (multilayer) [18–23].

Non-destructive testing methods are used mainly to estimate the diameters of the core and shell of the fiber, the degree of ellipticity of its cross section, the roughness of the outer surface, as well as to determine the law of change of refractive index of the fiber material [24–27].

The optical properties of the fibers are controlled by the results of the analysis:

- diagrams of plane wave scattering in the anterior and posterior hemispheres of the fiber;
- the degree of focusing of the incident wave by the cylindrical core of the fiber;
- field pictures with an interference microscope;
- holographic image of the fiber field;
- pictures of wave diffraction on a fiber.

The large number of optical methods makes it difficult to choose the best of them for specific measurement conditions and controlled material. Optical control methods are compared and classified to establish the limits of their application and to be able to select the optimal method for different conditions of use. All methods are classified by the type of irradiation signal and the area of registration of the information signal.

The process of non-destructive measurement of geometric-optical characteristics of the object consists of three stages: the formation of the irradiating signal, its interaction with the object of measurement and the formation of the registration area of the information signal. According to the type of irradiating beam, the methods can be divided into two classes: those that use a narrow beam (compared to the geometric dimensions of the cross section of the object) and a wide beam whose size is an order of magnitude larger than the diameter of the object. The information signal can be registered in two areas—the near or far zone of the image plane. Modern measuring instruments are based on various methods of measuring the characteristics of fibers.

One of the promising methods of controlling the shape of the cross section of the canvas is the diffraction method. Its advantages include high accuracy, short action time, locality of measurements (possibility to control fibers even on small sites), absence of need of fixing in space and possibility of reception from the control sensor of the feedback signal intended for influence on technological process of fiber stretching.

The diffraction method of measurements is also suitable for measuring the cross-sectional shape and refractive index of non-round fibers, capillaries and their blanks (rods), as well as the degree of eccentricity of the shell and core in the process of manufacturing a two-layer fiber.

The implementation of the diffraction method in practice is quite weak. This can be explained by higher in comparison with interference and holographic methods the complexity of solving diffraction problems. Derived exact formulas for the rapid production of scattering patterns in the far zone have significantly increased the accuracy of diffraction measurements by moving to balance schemes for comparison with reference or calibration graphs.

The ultrasonic method consists in probing the controlled material by a continuous or pulsed signal and by changing its parameters of amplitude, phase, delay time in the thickness of the material to determine its various technological parameters. Ultrasound methods can be contact or non-contact. For textile materials of small thickness it is expedient to apply contactless ultrasonic transducers.

The comparison of automated methods of fabric control shows that the most necessary and most profitable is to use inexpensive methods suitable for controlling several technological parameters of textile materials [28–31].

In work [32], to control violations of the textile materials structure, there has been developed a number of control devices by optical methods, each of which includes an interface that allows to digitize and input information from optical sensors to a PC. The authors investigated the relationship between the optical characteristics of tissues and their structural parameters, resulting in mathematical models. The authors use methods of reflection and transmission of a world stream by the investigated material.

Komarov [33] continued the development and improvement of the theory of computer recognition of tissue structure parameters. He proposed an automated method for determining the parameters of the structure and defects of fabrics using a flatbed scanner and specially designed software that can reproduce images of fabrics on a graphical model and model images of fabrics of different weaves.

Professor Shlyakhtenko [34–36] developed non-destructive methods for controlling structural parameters of textile materials. His proposed method is based on the analysis of Fraunhofer diffraction patterns constructed on a computer using two-dimensional Fourier transform programs monochromatic light. After passing through the fabric of a parallel beam of light with a wavelength λ perpendicular to the surface, the symmetry and relative position of the main maxima in the diffraction pattern are analyzed. According to the results of the analysis the width and length of the report, the amount of linear filling on the base, the appearance of local thickenings of the warp and weft, the violation of weaves are determined. Low versatility and high complexity are the main disadvantages of this method.

A method of computer photogrammetry for tissue studies has been developed [37–40]. To obtain the characteristics of the fabric, the same part of it is photographed at different angles. The image of the fabric is processed on a computer using an algorithm that allows to determine the reference points of the thread elements in two planes, and then, using formulas, calculate their characteristics. The disadvantages of this method include high requirements for image clarity of the study area, the informativeness of which is also affected by the fabric reflectivity, which, in turn, depends on the nature of the fiber tissues, their dyeing, method of production. Also, using the photogrammetric method of control, it is necessary to take into account the unevenness of the yarn in linear density.

There is a known non-contact method of fabric structure analysis to determine the basis weight of the fabric, its phase structure, coefficients of linear and surface filling, yarn warp and weft threads, it has been proposed to improve the existing photogrammetric non-destructive method of control. The method essence is to use a video image of the tissue obtained with two video cameras. The images obtained this way are reproduced on a computer monitor, where they are processed. This method makes it possible to study the tissue structure during its movement.

Ternova's work [41] is devoted to the development and application of methods of analysis and quality control of textile materials, where the mathematical model of fabric is specified, which takes into account the technology of its production and hardware features of automatic control systems. Based on a refined mathematical model, the authors use an elastic standard that allows you to take into account and control such variables as tension, compression and skew. The method of information compensation flows from the standard and the controlled fabric is also improved in the work that allows to minimize time expenses of system of automatic recognition of defects. The authors proposed a method for finding tissue defects using a modified Radon transformation. The raster scan signal received from the monitored object by optical sensors has a low "signal-to-noise" ratio, making it difficult to distinguish the defect signal against the background of the signal from the fabric structure. The proposed method allows to increase the value of the "signal-to-noise" ratio several times, which minimizes the probability of passing the defect by automated systems.

An attempt to develop technology and methods for detecting external defects of textile materials using local binary templates and wavelet analysis was made by Yakunin [42]. The algorithm for searching defective area by means of local binary templates is shown in the work, and also, on the basis of achievements of applied mathematics, the method of classification of fabric defects by means of Gabor's wavelet function has been developed.

Thus, an algorithm based on local binary templates was chosen for filtering fabric images, and mathematical statistics—chi-square distribution—were used to analyze the obtained binary code. Local binary templates are a description of the image (environment) around the pixel in binary form. The pixel values are compared to the center pixel. The result is an eight-bit binary code that describes the pixel environment. The use of Gabor's wavelet function, which is the basis of the method for determining fabric defects, is necessary to clear up the image from noise. Anything that is not a defect is considered to be noise. Gabor functions are in the spatial and frequency

domain and have the form of a plane wave with a wave vector. The result of the transformation depends on forty sets of wavelet coefficients, which are obtained for the image of a defect-free piece of tissue (sample) and for a defective area.

The defect search is reduced to finding differences in brightness values in the digital image matrix, where forty is a defect-free zone, and any value other than forty is a defect zone.

Each defect is an area with a known brightness of the defective pixels. The coordinates of these pixels allow to set the defect size, the orientation of the grid fabric threads of the defect area in space.

The disadvantages of this method are the difficulty of correct interpretation of the data. In order to solve this problem, methods of analysis of wavelet schedule coefficients have been developed.

Thus, these days, control devices are widely used, which are based on optical methods and work on the basis of control of light that passes through the fabric and is reflected from it.

The principle of optical scanning of the fabric surface, laid down in them, is the basis for all modern methods of digital image processing of fabric. However, the disadvantages of optoelectric control devices include the inaccuracy of measurements, that is associated with the devices sensitivity to the color and complexity of the fabric structure.

Despite the fact that the development of contactless methods for automated controlling technological parameters of textile materials and their defects has been going on for a long time, in practice the assessment of these parameters is carried out by imperfect technical means that cannot control several indicators of textile quality.

For example, the control of the fabric covering is carried out mostly by a human operator. The results of such control are subjective, as well as inaccurate due to the rapid fatigue of the operator and due to the performance of monotonous work.

Therefore, there is a need to create reliable, simple, affordable, fast, effective methods and means for automated control of technological parameters of textile materials that do not require increased safety measures.

Nowadays each method is aimed at controlling a single technological parameter of the fabric, resulting in the problem of simultaneous application of a large number of complex methods for controlling several indicators of textile quality.

1.3 Review of Non-destructive Testing of Textile Materials for Light Industry

Many measuring instruments that can be used to determine the various parameters of textile materials are based on schemes for measuring the geometric and optical characteristics of inhomogeneous optical fibers. *The balanced fiber comparison scheme* is one that is measured with an orthogonally located reference. Consider the principle of operation of such a system [43–48].

The mutually perpendicular position of the controlled and reference optical fibers is more promising and provides two diffraction patterns (reference and controlled fibers) that do not interact with each other. The reference and controlled optical fiber are irradiated with the same section of the laser beam. The two images obtained in the anterior hemisphere are compared by combining their diffraction minima of the same order. The diameter of the controlled optical fiber is estimated by comparing the distances from the center of the resulting cross-shaped pattern in the far zone to the corresponding minima of its two partial partial linear patterns—the reference and controlled.

Diffraction marks (minimums) are used as a reference scale in the control. They are obtained from a reference optical fiber of the same type as the batch of controlled fibers. The distance between the labels is related to the diameter of the fiber.

The scheme of the device [49] with photodetectors for registration of minimums position of a diffraction picture is presented in Fig. 1.2a. The radiation from the coherent source 1 is formed by the collimation system 2 in a flat beam with a uniform amplitude-phase distribution, the cross section of which (4 mm) significantly exceeds the diameter of the controlled optical fiber (50 ... 250 μm). The collimation optical system consists of microobjects 3, 5. A point diaphragm 4 located in the common focal plane of the microlens is used as a spatial frequency filter. The aperture 6 forms a rectangular distribution of the X and Y axes in the control area, where two optical fibers (reference 7 and fiber that is controlled 8) are located mutually perpendicularly. The controlled optical fiber is located vertically, and the reference one—horizontally so that the projection of their intersection to be in the center of the registration unit 10. With the help of the projection optical system 9, two mutually perpendicular diffraction patterns (from the reference and controlled optical fiber) are formed, which do not overshadow each other. The accuracy of the measurement significantly depends on the registration method of the diffraction distribution, which informs about the measured diameter. Two registration options are evaluated: the intensity of the diffraction field at several selected fixed points, as well as the distance between the minima of one order of the diffraction pattern. For diameters of 50 ... 250 μm , the optimal way is to register the dimensions of the diffraction pattern in its central zone; they change when the diameter of the controlled optical fiber changes.

In the process of research in the areas of zero and first diffraction minimums of the reference fiber photodetectors 11 are installed according to the scheme shown in Fig. 1.2b. At a given level of intensity, which is 0.01 of the maximum intensity I_{max}/I_0 of the central petal of the diffraction pattern for the reference optical fiber, concentric circles are formed in the regions $\Delta 1$, $\Delta 2$, $\Delta 3$ of the first, second and third minimus of the reference pattern. They determine the range of changes in the diameters of the controlled optical fibers. The positions of the minima of the pictures from the controlled and reference fibers are compared with each other.

The inconsistency signal from the photodetectors 11 characterizes the degree of deviation of the position of the minimus of the horizontal picture (controlled fiber) relative to the vertical one.

The inconsistency signal is fed to the information processing unit 12 for recalculation and output of measurement results. Therefore, the diameter of the controlled

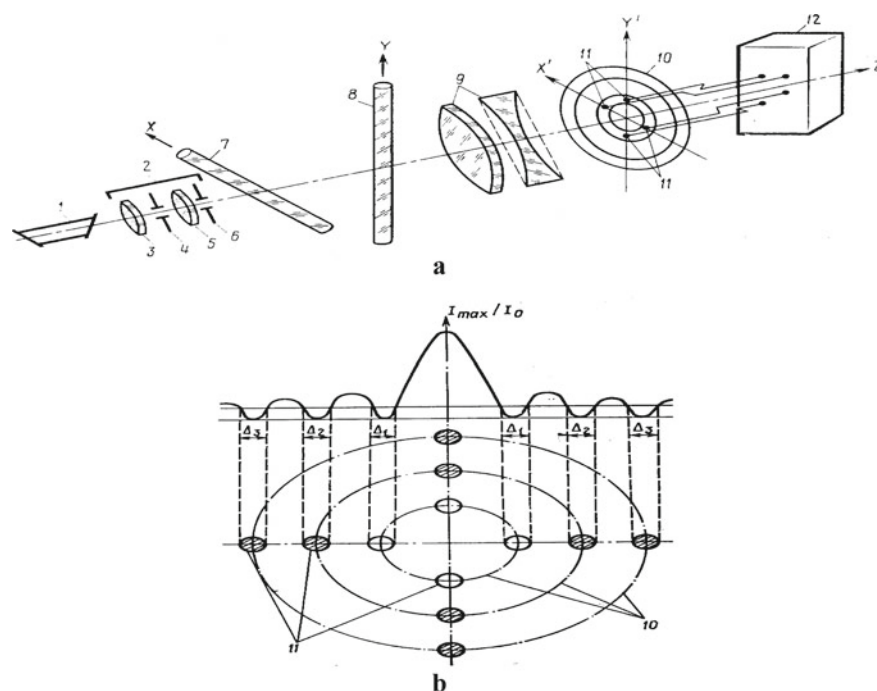


Fig. 1.2 Fiber diameter estimation according to two diffraction patterns: **a** the scheme of an orthogonal arrangement of the reference and controlled optical fiber; **b** layout of photodetectors

fiber is estimated by the distance between the first and second minimums of its horizontal diffraction pattern. Shifting the position of the minimum towards the center (to the maximum of zero order of the vertical picture) for the reference fiber indicates that the diameter of the controlled optical fiber exceeds the diameter of the reference, the deviation of the minimum from the center of the vertical picture—indicates its reduction compared to the reference.

The accuracy of the measurements depends on two factors: the error in determining the diameter of the reference optical fiber (of the same type as the controlled one) by some other independent method; accuracy of comparison of distances between the corresponding minimums of a picture from the controlled and reference optical fiber.

Let us consider a tool with a *diffraction control scheme* to maintain the stability of the stretched fiber diameter.

As a reference fiber in the modified scheme, it has been proposed to use a canvas of the same batch as the controlled one, which has been rewound and corresponds to the orthogonally measured area of the stretched fiber. This scheme provides support for the stability of the diameter of the optical fiber during the technological process of its stretching from the spinneret of the stretching mechanism, as well as improving the accuracy and reliability of control.

The deviation of the diameter value on the controlled section of the fiber from its reference section is determined in this scheme by the deviation of the minimums position of the diffraction pattern of the controlled section of the fiber made of the reference one. The scheme of the device for monitoring the outer diameter of the optical fiber in industrial tensile conditions is presented in Fig. 1.3a.

The radiation from the laser 1 is formed by the optical system 2 into a converging conical beam. Behind it the optical transmission system 4 is located, which provides the same scale of diffraction patterns from the reference 3 and the controlled 5 sections of the stretched optical fiber. The rewinding unit 12 changes the direction of fiber winding so that the reference section of the optical fiber is located horizontally, and the controlled—vertically. The receiving optical system 6 forms two orthogonally located diffraction patterns from the reference and controlled areas of the optical fiber, which do not overshadow each other. The minimums positions of the pictures are registered by the registration unit 7. The inconsistency signal from the photodetectors of the registration unit characterizes the deviation degree of the minimums position of the picture of the optical fiber controlled area relative to the reference. To recalculate

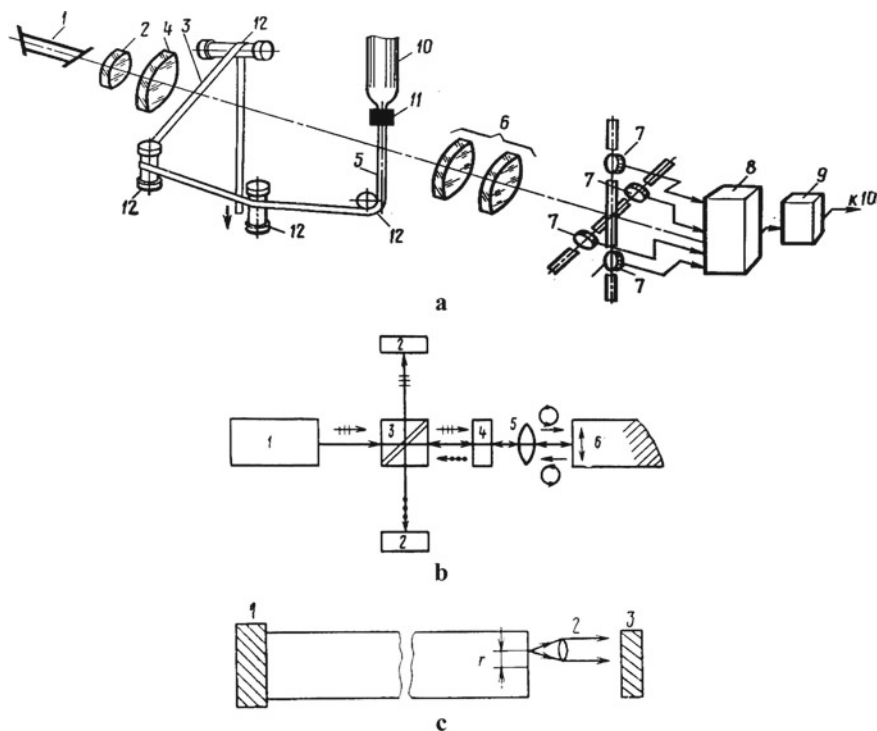


Fig. 1.3 Optical means for measuring the parameters of the material fibers: **a** a diagram of a measuring device maintaining the stability of the stretched fiber; **b** a diagram for measuring the parameters of the optical fiber by the method of reflecting the light flux in the balance scheme; **c** a diagram for measuring the parameters of an optical fiber by a method of the near zone

and output data on the results of measurements of the controlled optical fiber, the inconsistency signal is fed to the signal processing unit 8, and then to the feedback unit 9 and the control unit of the die 10, which changes the size of the die 11 of the stretching mechanism.

Therefore, the diameter of the controlled optical fiber is estimated by the distance between the minimums of the same order in the horizontal pattern. The deviation of the position of the minimums of the corresponding orders towards the center (to the minimums of the zero order of the diffraction pattern from the reference part of the fiber) indicates that the diameter of the controlled area of the optical fiber is larger than the reference, and the deviation of the minimums from the center of the reference. The obtained results in the form of an analog signal are used to control the technological mode of stretching. The device for monitoring and maintaining the stability of the diameter of the stretched optical fiber has high vibration resistance and control accuracy, as well as stability.

A means and *method of reflecting the light flux* [49] can also be used to control textile fibers. The tool works on the intensity of the light flux reflected by the end of the fiber or the workpiece when falling on the collimated light beam, parallel to the optical axis of the fiber (Fig. 1.3b). The end of the measured fiber 6 is moved relative to the focal spot, and the probing and reflecting radiation is registered by two fixed receivers 2.

The prism 3 and the quarter-wave plate 4 serve to collect the radiation reflected by the front end of the fiber and to exclude the radiation reflected by other surfaces. To eliminate the reflection from the far end, it is placed in the immersion fluid, which reduces the measurement error by an order of magnitude. The measurement of the reflected flow power relative to the incident flow power, which characterizes the distribution of the reflection coefficient, is measured by a differential amplifier. The laser beam 1 is focused on the end face of the fiber by a lens 5, which creates an irradiation beam with a diameter not exceeding $0.5 \mu\text{m}$, i.e. it is on the verge of diffraction expansion.

The reflection coefficient when illuminating the reflecting surface at a right angle is determined by the ratio of the power of the reflected light to the power of the incident light as follows:

$$\frac{P_r}{P_{ri}} = \left(\frac{(n_q(r) - 1)}{(n_q(r) + 1)} \right)^2, \quad (1.13)$$

where $n_q(r)$ is the refractive index at a distance r from the optical axis.

Also from optical means we will consider those which are based on a *near field method*.

The near field method uses the following light feature: the power transmitted by all modes of optical fiber through a given point of cross section is proportional to the difference between the refractive indices of the core at this point and the shell provided a uniform distribution of radiation power within the optical fiber aperture. The use of an incoherent light source, such as a light emitting diode, pressed close

to the end of the fiber, provides the same excitation of all modes. By the method of geometric optics, taking into account the cutoff condition of the directional modes, it is possible to derive the relationship between the distribution of light intensity in the near zone and the profile of the refractive index.

In one of the fiber ends light from an incoherent source is introduced, such as a light emitting diode 1 and using a well-focused microscope 2 the flux density in the near area at the other end is determined (3—radiation receiver in the diagram). The light source must have a constant radiation intensity across the fiber, which satisfies Lambert's law.

The operation of the canvas scanning system has been described [50] and noted about the *capacitive sensors* that can be used to monitor the basis weight m_s of the fabric. Such a sensor is shown in Fig. 1.4a.

This is a parallel-plate capacitor. The capacitance of the capacitor of the parallel plate is determined from the known expression as follows:

$$C = 0.089 \cdot \frac{S_{sq.} \cdot \varepsilon_0}{d}, \quad (1.14)$$

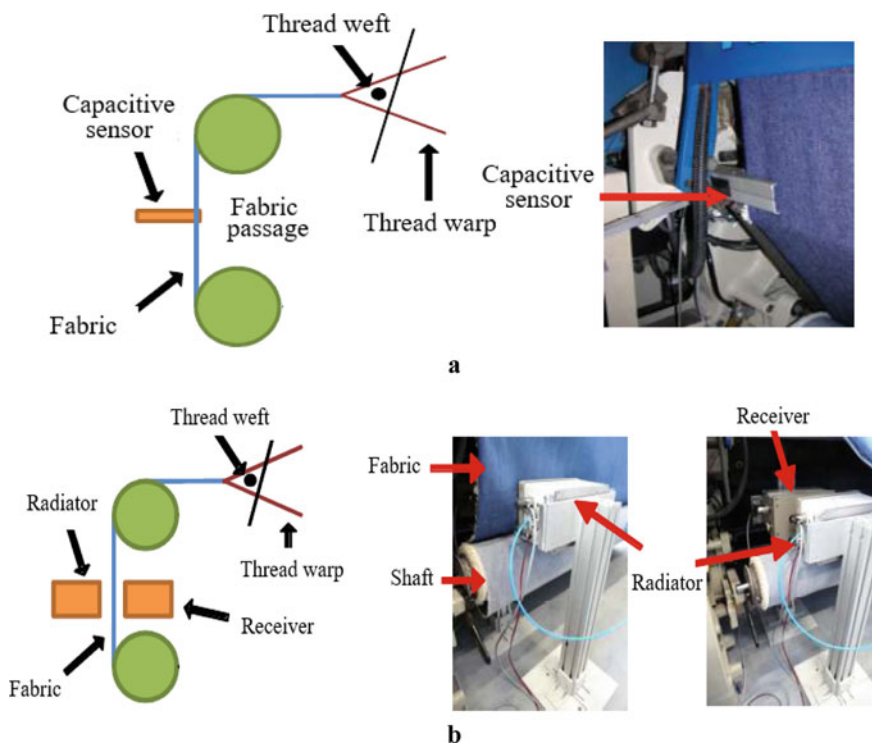


Fig. 1.4 Non-destructive means of controlling the fabric basis weight m_s : **a** measurement of the fabric basis weight m_s with a capacitive sensor; **b** measurement of the fabric basis weight m_s with a radiometric sensor

where C is the flat capacitor capacitance; S_{sq} is the area of the capacitor plates; ε_0 dielectric constant of air; d the distance between the plates.

The authors describe that passing the fabric between the plates of the capacitor (Fig. 1.4a), the values in the dielectric constant of the air will change, and the capacity, in turn, will also change accordingly. In doing so, the relationship between capacity C and basis weight m_s is established.

If you use *the means to absorb the radiation energy*, then using the degree of attenuation γ of the energy flux density, which is proportional to the fabric basis weight m_s , you can determine the required technological parameter for the canvas as follows:

$$m_s = \gamma = \frac{\Delta m_k}{\Delta S}, \quad (1.15)$$

where Δm_k is the mass of the controlled fabric in the control area; ΔS area of the control zone.

The company BST ProControl GmbH offers such a radiometric absorption system [50] with a set voltage of less than 5 kV, such systems do not require a permit for use in Germany. The sensor is suitable for measuring from 50 to 1000 g/m² with a resolution of 0.1 g/m² and an accuracy of 0.3 g/m². The installation of the sensor on the loom is shown (Fig. 1.4b).

The sensor functionality was tested on twill cotton fabric 3/1. The weaving machine worked at a speed of 700 rpm while measuring the basis weight of the sensor.

It is also necessary to consider the current state of *control and regulation of yarn tension* when feeding it to the textile machine in the process of fabric production. Figure 5a shows the movement of the yarn when feeding it to the circular knitting machine with the adjustment of its tension by means of a contact thread tensioner without the possibility of determining its value. Modern available means of determining the tension of textile materials are mainly contact (Fig. 1.5b), which are based on strain-resistant elements of the transformation of measuring information. The problem with such means is that when the textile material is fed to the area where such a sensor is, through the feeder with rollers, friction against which at a significant speed of the thread can lead to its breakage. It should also be noted that the contact of the sensor with the surface of the thread or yarn of the textile material can have a very significant effect on the readings of the measured values of tension.

Studies are conducted with simulation of cyclic loads on different types of yarn, thread with the help of special stands using microprocessor technology [51] as shown in Fig. 1.5b. You can see that such test benches include a contact tension meter, a device for feeding material to the sensor, the control unit of the stepper motor, which reproduces the change of tension depending on the algorithm of the control program on the PC.

Such experiments show that it is quite a difficult task to quickly measure the tension of a textile material at high speeds with the help of contact sensors.

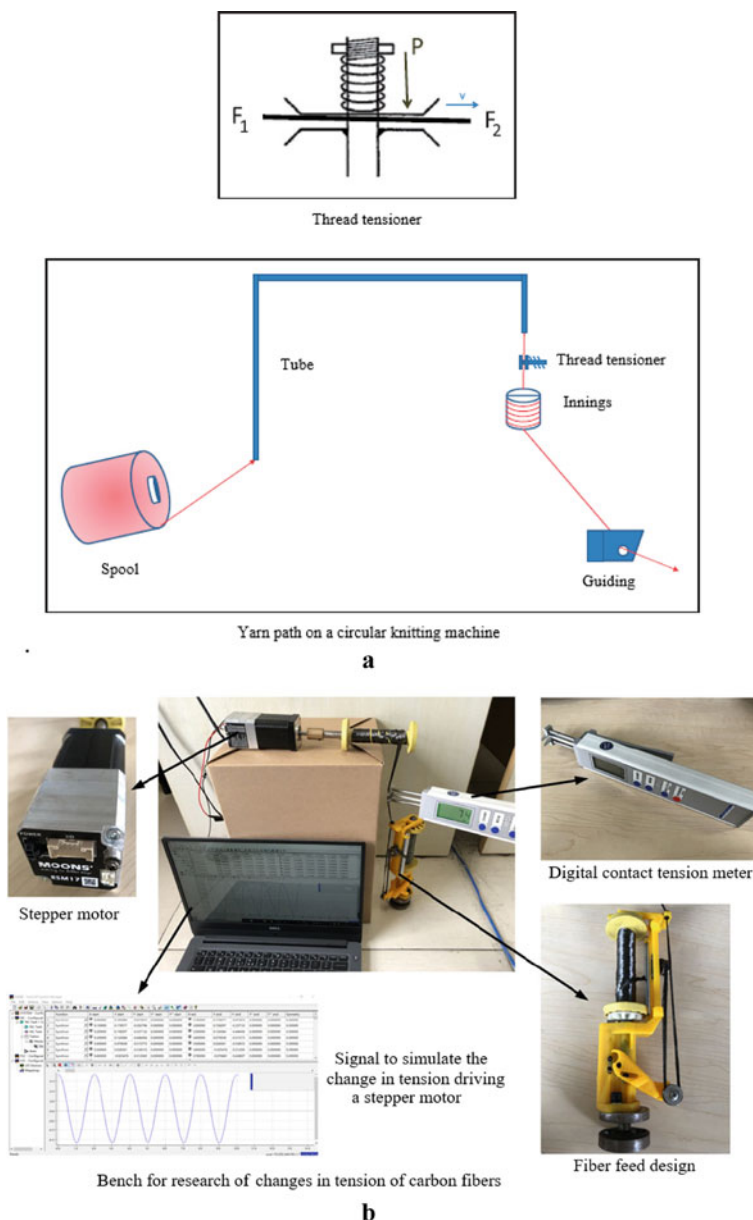


Fig. 1.5 Control and regulation of yarn tension by existing means in production: **a** the way of feeding the yarn to the circular knitting machine and adjusting its tension; **b** studies to determine the change in tension of carbon fibers by digital contact means

Therefore, the use of non-contact measuring sensors, the radiation source of which does not need to be adjusted over time, as well as which are safe for human life and health, will allow rapid measurement of yarn or thread tension values at high speeds when applied to process equipment. The best for non-contact control of thread tension is the ultrasonic method, which is reliable and easy to implement.

After analyzing all methods and tools to control the various technological parameters of textile materials, we can finally conclude that it is advisable to use ultrasonic measuring devices.

Such tools are quite accurate, easy to implement and operate, cost little compared to analogues and are safe for humans, so we will consider them further.

1.4 Review of Methods and Means for Ultrasonic Control of Textile Materials in Light Industry

The most mobile, efficient and safe for humans and, thus, the most promising is the ultrasonic method of automated control of technological parameters of textile materials.

In the middle of XX century, the basic models were developed, which today constitute the traditional theory of ultrasonic control. Kolganov [52] developed an ultrasonic non-contact method as well as software and hardware for automated control of the integrity of products made of polymer composite materials. However, even now these methods are not common.

Classification of parameters of textile materials that can be controlled by non-contact ultrasonic methods is shown in Fig. 1.6a, and the scientific and technical problem to be solved for the possibility of using such methods in production using modern computerized systems is shown in Fig. 1.6b.

Kostyukov's works [53–56] study the amplitude method of parameters control of textile fiber mass and show the coefficient of passage of an ultrasonic signal through a multilayer ordered fiber system which is expressed by the following equation:

$$\begin{aligned}
 B_{SH} = & \prod_{i=1}^{M_H} \left(1 + \frac{P_{i \text{ pacc}}}{P_0 + \sum_{j=i-1}^{M_H-1} P_{j \text{ pacc}}} \right) \\
 & + \sum_{i=1}^{M_H} \prod_{l=1}^{M_H} \left[1 + \frac{P'_{l \text{ pacc}}}{P_{j \text{ omp}} + \sum_{j=l-1}^{M_H-1} P_{j \text{ pacc}}} \right], \quad (1.16)
 \end{aligned}$$

$$P_{\text{pacc}} = \sqrt{\frac{2}{\pi k R_0}} \cdot e^{ikR_0 - \frac{i\pi}{4}} \cdot (2N_B + 1) \cdot \sum_{m=-\infty}^{\infty} C_m \cdot e^{im\theta};$$

$$P_{\text{omp}} = -\frac{k S_L}{2} \cdot \cos \theta \cdot e^{ikR_0 - i\frac{\pi}{4}},$$

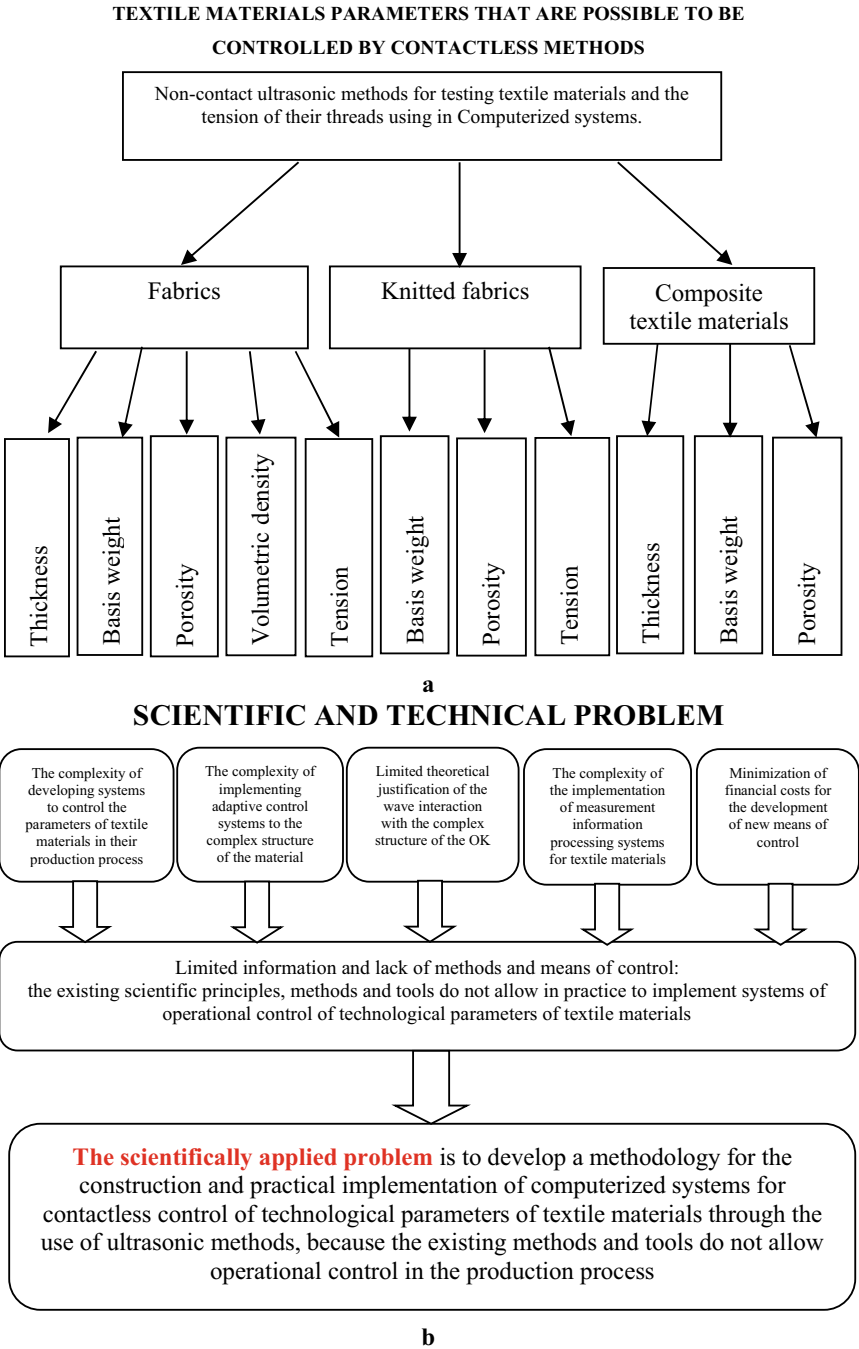


Fig. 1.6 Textile materials parameters for which non-contact ultrasonic control methods can be applied and scientific and technical problem that needs to be solved: **a** material parameters for which ultrasonic control can be applied; **b** scientific and technical problem that needs to be solved

where B_{SH} is the probabilistic coefficient of passage; M_H mathematical expectation of the mass of a single fiber; k is the wave coefficient; $2N_\theta + 1$ is the number of fibers in the layer; m is the integer number of the reflecting fiber; l is the integer number of the fiber layer; $S_L = 2dN_\theta$ is the area of the irradiated surface of the lattice fibers; R_o is the distance from the plane of the lattice to the point of observation (reception); C_m is coefficients that take into account possible interactions between fibers as a result of multiple mappings; θ is the angle to the normal to the plane of the lattice, under which the acoustic wave falls; P_0 , P_{pacc} , P'_{pacc} and P_{omp} —respectively, the amplitude of the pressure of the incident, scattered, back pressure generated by the scattered and reflected waves.

From expressions (1.16) it follows that the amplitude of the signal that passed through the sample is in a pronounced nonlinear (exponential) dependence on the number of fibers in the path of propagation of the ultrasonic (US) wave.

Figure 1.7 shows the proposed models of ultrasonic signal propagation in the textile fiber mass in the process of acoustic control.

Another means of controlling textile material was proposed in the work [57]. It is known that ultrasonic vibrations pass with some speed in different environments. Therefore, control and measuring devices, which are based on the speed of propagation of ultrasonic vibrations, are used to control the parameters of technological processes in production. The speed of ultrasound in fibrous media depends on the volumetric density of the material. The dependence of velocity on the density of the material can be determined if the number of fibers in a given volume is known. In the sensor, the volume stability was provided by a constant cross section of the channel shape and a constant long sounding area. But, controlling the tape in the forming channel, it is impossible to establish exactly the area of the product corresponding to any specific indications. It is also impossible to ensure the repetition of measurements, as the product can be deformed, elongated and at the same time change the location of the fibers in the cross section of the product.

To perform multiple measurements, to confirm the repeatability of the results, a control sample was made, which is a piece of tape of a certain length and known mass. In order to preserve the structure and mass of the fiber in repeated tests, the sample was placed in a template. The pattern has the shape of a parallelepiped with side walls, part of which is made of thin mesh and steel plates, respectively. One of the grids can be discarded to replace the test specimens. The choice of wall sizes can be arbitrary. But since the speed of propagation of ultrasound depends on the volumetric density of the material, and the characteristic of the product is the linear density, the cross section of the tape in the template, it is advisable to set so that it was easiest to translate some parameters into others. Therefore, the cross section of the template is chosen equal to 1 cm^2 , and the dimensions of the sides, maintaining the normal ratio of the dimensions of the diameter of the products 2: 1, set at 14.14 mm and 7.07 mm. That is, the height of the sound layer h is 7.07 mm.

For the convenience of input and output of the sample from the control area, the structure is mounted on a rod with transverse dimensions equal to the transverse dimensions of the template. The exact orientation of the sample relative to the axis

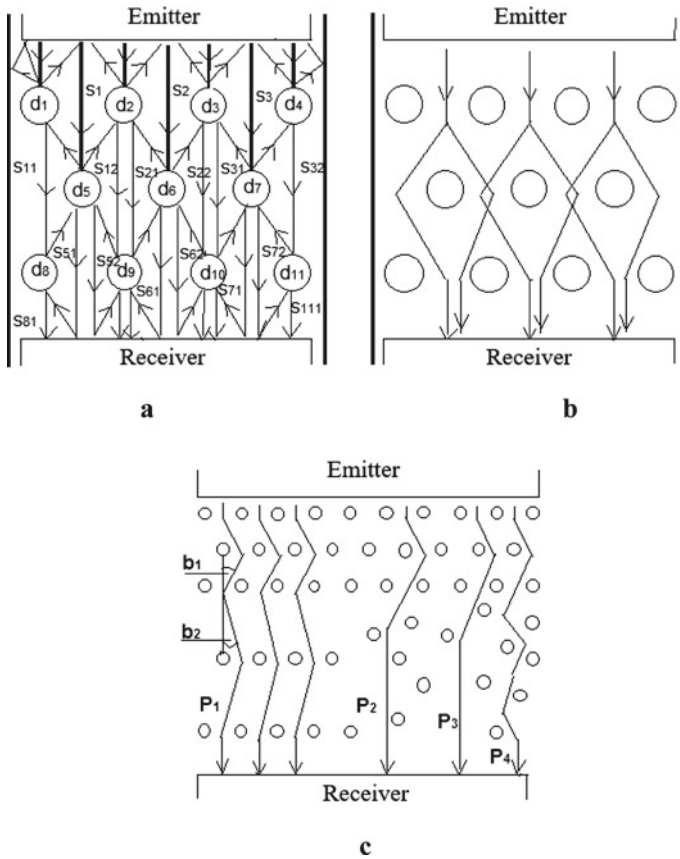


Fig. 1.7 Models of the ultrasonic signal propagation in the textile fiber mass in the process of acoustic control, which are proposed by Kostyukov A.F.: **a** scheme of reflection and superimposition of ultrasonic signal in the fiber mass; **b** scheme of ultrasonic signal passage through the fiber mass; **c** influence model of basis weight and volumetric density of fiber mass on amplitude and phase of ultrasonic signal

of the ultrasonic beam is achieved by the fact that a slightly curved shape is added to the side walls.

The ultrasound speed in a fibrous medium is easiest to measure by the phase method. Knowing the sound speed in the air under normal conditions, you can record the phase value of the receiver signal in the absence of ultrasound beam of material, and then, placing in the field a sample with known parameters, note the phase shift relative to this fixed value.

The dependence of the sound speed on the material density is presented in the form of graphs shown in Fig. 1.8a. The abscissa axis is shown in the scales of linear density and volumetric density.

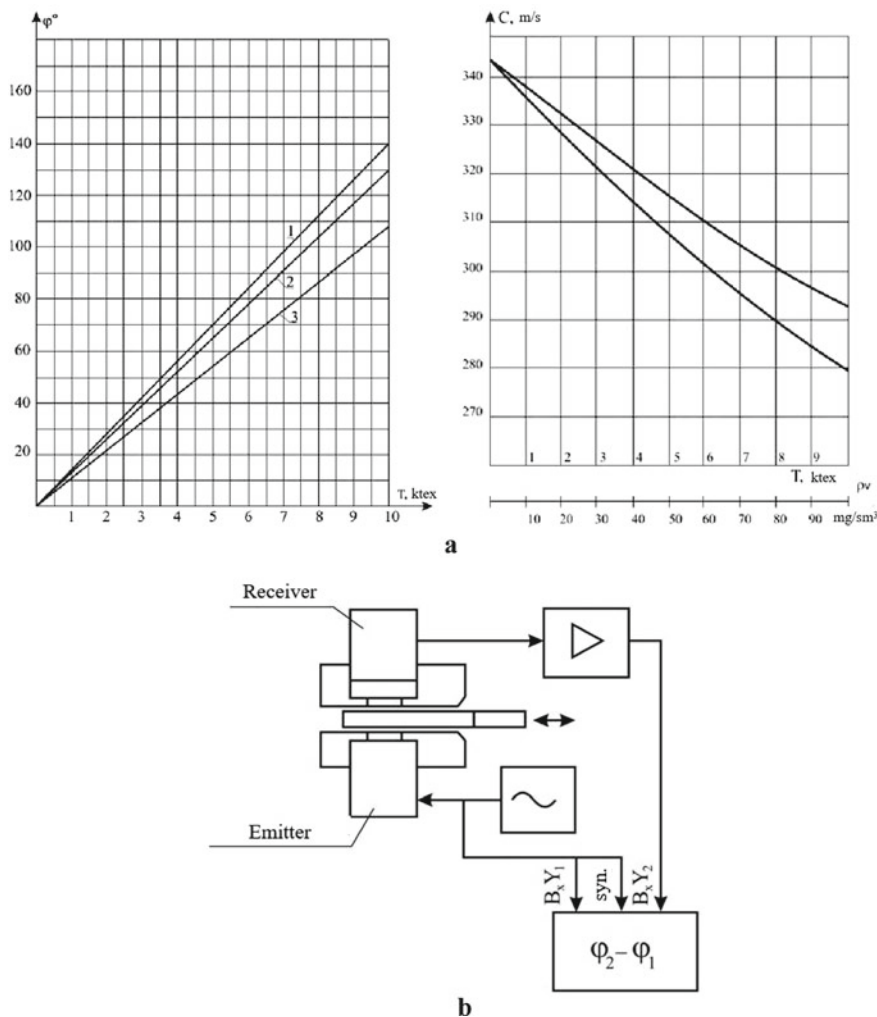


Fig. 1.8 Ultrasonic control of fiber tapes: **a** the dependence of the receiver signal phase on the linear density of the fiber tape (line 1—cotton tape, line 2—cotton comb tape, line 3—mylar) and the dependence of the sound speed on the material density (1—for pure cotton tapes, 2—for pure mylar of numerical tapes); **b** the block diagram of an installation for determining the sound speed in the fiber mass

As a result of experimental researches it has also been established that at compression of a control sample in the direction of sounding the phase of the received signal remains constant, i.e. in the conditions of constant weight of a sample the passed phase depends only on quantity of fiber in a column of the sounded material.. Therefore, the accuracy of measurement (Fig. 1.8b) of the phase of ultrasonic oscillations

does not depend on the deformation of the product in the direction of wave propagation, as well as on the nature of the distribution of the fiber structure along this direction.

Since the phase decreases with decreasing volume occupied by the fiber, and the length of the path that passes the sound in the environment decreases, then, accordingly, the sound speed decreases. The irregularity of the fiber structure can be considered in terms of uneven compression of the material in the amount it occupies and, consequently, it is advisable to enter into the calculation of the ratio for the sound speed parameter characterizing the degree of fiber compression.

The analysis showed that today there is a need for ultrasonic control of textile materials, and for such measurements it is necessary to calculate the various parameters of the sensors, which will be described below.

1.5 Main Dependences of Pulsed Ultrasonic Transducers for Probing Textile Materials

In order to describe the operation of non-contact ultrasonic wave transducers that can be used to probe various textile materials, it is necessary to consider the operation of crystals, which depends on the change in the amount of free energy of such transducers.

The change in the value of free energy during isothermal compression of the crystal is a quadratic function of the strain tensor. This function has not two but more independent coefficients.

The general form of the value of the free energy of the deformed crystal can be represented as follows:

$$F = \frac{1}{2} \lambda_{iklm} u_{ik} u_{lm}, \quad (1.17)$$

where λ_{iklm} is the tensor of elasticity modulus; u_{ik} , u_{lm} deformation tensors.

According to expression (1.17) for the value F the dependence of the stress tensor σ_{ik} on the strain tensor u_{ik} has the form in crystals:

$$\sigma_{ik} = \frac{\partial F}{\partial u_{ik}} = \lambda_{iklm} u_{lm}. \quad (1.18)$$

The presence of one or another symmetry of the crystal leads to relationships between different components of the tensor λ_{iklm} .

Let us consider these relations [58] for some types of piezoelectric crystals.

Piezoelectrics include crystals, rhombic class system D_2 , tetragonal class system D_{2d} , D_4 , rhombohedral class system D_3 . For a rhombic class system D_2 the expression for the value F with free energy has the form:

$$F = \frac{1}{2}\lambda_{xxxx}u_{xx}^2 + \frac{1}{2}\lambda_{yyyy}u_{yy}^2 + \frac{1}{2}\lambda_{zzzz}u_{zz}^2 + \lambda_{xxyy}u_{xx}u_{yy} + \lambda_{xxzz}u_{xx}u_{zz} + \lambda_{yyzz}u_{yy}u_{zz} + 2\lambda_{xyxy}u_{xy}^2 + 2\lambda_{xzxz}u_{xz}^2 + 2\lambda_{yzyz}u_{yz}^2, \quad (1.19)$$

where λ_{xxxx} , λ_{yyyy} , λ_{zzzz} , λ_{xxyy} , λ_{xxzz} , λ_{yyzz} , λ_{xyxy} , λ_{xzxz} , λ_{yzyz} are components of the elasticity modulus tensor; u_{xx} , u_{yy} , u_{zz} , u_{xy} , u_{xz} , u_{yz} are components of deformation tensors.

For a tetragonal class systems D_{2d} , D_4 the expression for the value F with free energy has the form:

$$F = \frac{1}{2}\lambda_{xxxx}(u_{xx}^2 + u_{yy}^2) + \frac{1}{2}\lambda_{zzzz}u_{zz}^2 + \lambda_{xxzz}(u_{xx}u_{zz} + u_{yy}u_{zz}) + \lambda_{xxyy}u_{xx}u_{yy} + 2\lambda_{xyxy}u_{xy}^2 + 2\lambda_{xzxz}(u_{xz}^2 + u_{yz}^2). \quad (1.20)$$

For a rhombohedral class system D_3 , the expression for the value F with free energy has the form:

$$F = \frac{1}{2}\lambda_{zzzz}u_{zz}^2 + 2\lambda_{\xi\eta\xi\eta}(u_{xx} + u_{yy})^2 + \lambda_{\xi\xi\eta\eta}((u_{xx} - u_{yy})^2 + 4u_{xy}^2) + 2\lambda_{\xi\eta\eta z}(u_{xx} + u_{yy})u_{zz} + 4\lambda_{\xi z\eta z}(u_{xz}^2 + u_{yz}^2) + 4\lambda_{\xi\xi\xi z}((u_{xx} - u_{yy})u_{xz} - 2u_{xy}u_{yz}). \quad (1.21)$$

where $\lambda_{\xi\eta\xi\eta}$, $\lambda_{\xi\xi\eta\eta}$, $\lambda_{\xi\eta\eta z}$, $\lambda_{\xi z\eta z}$, $\lambda_{\xi\xi\xi z}$ are components of the elasticity modulus tensor.

These dependences (1.17–1.21) make it possible to refine the field model that can be created by pulse piezoelectric transducers from certain types of crystals.

Mathematical conversion factors and field characteristics are completely determined by solving the wave equations of the piezoelectric plate and the delay line of the media. It is also necessary to take into account the equations of electrostatics. The complete solution of the problem is from a system of equations with initial and boundary conditions [59]:

$$\frac{\partial \sigma_{ik}}{\partial x_k} = \rho \frac{\partial^2 \xi_i}{\partial t^2}, \quad (1.22)$$

$$\sigma_{ik} = \lambda_{iklm}u_{lm} - e_{lik}E_l, \quad (1.23)$$

$$\frac{\partial D_i}{\partial x_i} = 0, \quad \frac{\partial \varphi_e}{\partial x_i} = -E_i, \quad (1.24)$$

$$D_i = \varepsilon_0 \varepsilon_{ik}E_k + e_{ikl}u_{lm}. \quad (1.25)$$

where ξ_i , E_i , D_i are components of the vectors of mechanical displacement in the elastic wave, electric field strength and electric induction, respectively; x_k are

Cartesian coordinates; ρ is environment density; ϕ_e is electric field potential; $\varepsilon_0 \varepsilon_{ik}$ is dielectric constant; e_{ikl} are piezoelectric constant tensors.

The type of piezoelectric conversion factors can be found taking into account the electrical loads and taking into account the elastic modulus and polarization in the direction of one of the coordinates, as well as the symmetry of the piezoceramics:

$$C_{11} \frac{\partial^2 \xi_1}{\partial x^2} + \frac{C_{66}}{2} \frac{\partial^2 \xi_1}{\partial y^2} + \frac{C_{55}}{2} \frac{\partial^2 \xi_1}{\partial z^2} + C_{12} \frac{\partial^2 \xi_2}{\partial x \partial y} + \frac{C_{66}}{2} \frac{\partial^2 \xi_2}{\partial x \partial y} + C_{13} \frac{\partial^2 \xi_3}{\partial x \partial z} + \frac{C_{55}}{2} \frac{\partial^2 \xi_3}{\partial x \partial z} - \rho \frac{\partial^2 \xi_1}{\partial t^2} = e_{31} \frac{\partial E_3}{\partial x} + e_{15} \frac{\partial E_1}{\partial z}, \quad (1.26)$$

$$\frac{C_{66}}{2} \frac{\partial^2 \xi_2}{\partial x^2} + C_{11} \frac{\partial^2 \xi_2}{\partial y^2} + \frac{C_{44}}{2} \frac{\partial^2 \xi_2}{\partial z^2} + \frac{C_{66}}{2} \frac{\partial^2 \xi_1}{\partial x \partial y} + C_{12} \frac{\partial^2 \xi_1}{\partial x \partial y} + \frac{C_{44}}{2} \frac{\partial^2 \xi_3}{\partial y \partial z} + C_{13} \frac{\partial^2 \xi_3}{\partial y \partial z} - \rho \frac{\partial^2 \xi_2}{\partial t^2} = e_{31} \frac{\partial E_3}{\partial y} + e_{15} \frac{\partial E_2}{\partial z}, \quad (1.27)$$

$$\frac{C_{55}}{2} \frac{\partial^2 \xi_3}{\partial x^2} + \frac{C_{44}}{2} \frac{\partial^2 \xi_3}{\partial y^2} + C_{33} \frac{\partial^2 \xi_3}{\partial z^2} + C_{13} \frac{\partial^2 \xi_1}{\partial x \partial z} + \frac{C_{55}}{2} \frac{\partial^2 \xi_1}{\partial x \partial z} + \frac{C_{44}}{2} \frac{\partial^2 \xi_2}{\partial y \partial z} + C_{13} \frac{\partial^2 \xi_2}{\partial y \partial z} - \rho \frac{\partial^2 \xi_3}{\partial t^2} = e_{15} \frac{\partial E_1}{\partial x} + e_{15} \frac{\partial E_2}{\partial y} + e_{33} \frac{\partial E_3}{\partial z}, \quad (1.28)$$

$$\varepsilon_0 \varepsilon \left(\frac{\partial^2 \varphi_e}{\partial x^2} + \frac{\partial^2 \varphi_e}{\partial y^2} + \frac{\partial^2 \varphi_e}{\partial z^2} \right) = e_{15} \left(\frac{\partial u_5}{\partial x} + \frac{\partial u_4}{\partial y} \right) + e_{31} \left(\frac{\partial u_1}{\partial z} + \frac{\partial u_2}{\partial z} \right) + e_{33} \frac{\partial u_3}{\partial z}, \quad (1.29)$$

where C_{11} , C_{12} , C_{13} , C_{33} , C_{44} , C_{55} , C_{66} are elastic constants; e_{15} , e_{31} , e_{33} are piezoelectric coefficients.

When using the one-dimensional approximation in the case of uniform polarization, you can use the following expressions:

$$\rho c^2 = C_{11} + \frac{e_{33}^2}{\varepsilon_0 \varepsilon}, \quad (1.30)$$

$$Dl = e_{33}(\xi_l - \xi_0) + \varepsilon_0 \varepsilon U_n, \quad (1.31)$$

where c is the speed of wave propagation in the medium; l is thickness of the piezoelectric plate; ξ_0 is initial displacement of the piezoelectric plate; ξ_l is final displacement of the piezoelectric plate.

From the last dependence, it is possible to determine the voltage on the piezoelectric transducer in general:

$$U_n = \frac{Dl - e_{33}(\xi_l - \xi_0)}{\varepsilon_0 \varepsilon}. \quad (1.32)$$

The current I_g of electrical pulses generated and then emitted by the piezoelectric plate can then be shown as follows:

$$I_g = \frac{e_{33} S_n}{l} \cdot \frac{\partial(\xi_l - \xi_0)}{\partial t} - \frac{\varepsilon_0 \varepsilon S_n}{l} \cdot \frac{\partial U_n}{\partial t} + (Y_3 + Y_g) U_n, \quad (1.33)$$

where S_n is the area of the radiating surface of the piezoelectric plate; Y_3 , Y_g are conductivities of the common electrical circuit of the piezoelectric transducer and the generator, respectively.

In the mode of receiving oscillations by the transducer, if we take a flat incident wave that propagates perpendicular to the surface of the piezoelectric plate, the following parameters for it and the voltage generated by the transducer can be given as follows:

$$\Delta_0 = 1 - V_{pd} V_{pl} \cdot e^{-2j \frac{\omega l}{c_n}}, \quad (1.34)$$

$$\Delta_1 = \frac{\beta_k c_n}{\omega l} \cdot \left(1 - e^{-j \frac{\omega l}{c_n}}\right) \left(2 + V_{pd} V_{pl} - (V_{pd} + V_{pl} + 2 V_{pd} V_{pl}) \cdot e^{-j \frac{\omega l}{c_n}}\right), \quad (1.35)$$

$$U_n(\omega) = \sigma(\omega) \frac{e_{33} S_n}{l} \cdot \frac{1 + V_{pl}}{Z} \cdot \frac{\left(1 - e^{-j \frac{\omega l}{c_n}}\right) \left(1 - V_{pd} \cdot e^{-j \frac{\omega l}{c_n}}\right)}{(\Delta_0 - \Delta_1)(Y_3 + Y_n)}, \quad (1.36)$$

where β_k is transmission ratio; V_{pd} is reflection coefficient at the piezoelectric plate-damper boundary; V_{pl} is reflection coefficient at the piezoelectric plate boundary—acoustic load; c_n is speed of wave propagation in the plate; ω is circular frequency of waves; Z_n is acoustic resistance of the piezoelectric plate; Y_n is electrical conductivity of the piezoelectric plate; $\sigma(\omega)$ is dependence of mechanical stress on circuit frequency.

These equations can be used to calculate the electric field for ultrasonic pulse signal converters, which can be used to irradiate various textile materials. Also, the obtained dependences can be used to obtain a model of the sound field of oscillations in the process of passing the textile material or reflecting waves from it, which will implement in practice operational probing of textile fabrics to determine various technological parameters during their production.

The given review of existing and promising methods and means of controlling the technological parameters of textile materials showed that of all the methods most suitable for their characteristics and capabilities are ultrasound methods. This is due to many factors, but mainly to those that make it possible in large volumes and at relatively low cost to establish mass production of ultrasound equipment and systems with the required accuracy of measurement of technological parameters. This is necessary to ensure the modernization of existing equipment in textile industries using computerized systems, where necessary. This will improve the quality

characteristics of finished products through the use of operational control and appropriate adjustments to the production process. Such devices and systems are quite accurate, easy to implement and operate compared to more expensive counterparts.

For most industries, the processes of monitoring and measuring the required parameters of products that have a relatively simple structure have long been automated and performed with a fairly high accuracy and efficiency. The processes of responsible control and measurement of various technological parameters in various textile industries are carried out using manual labor with high labor costs. This is due to a number of problems that arise in the development of more effective means of controlling the parameters of textile fabrics. Since only non-contact ultrasonic devices in combination with computerized systems can be used for operational control, it is necessary to expand the theory of the interaction of ultrasonic radiation with the complex structure of textile fabrics. This is mainly due to the difficulties that have been associated with the underdevelopment of the theory and practice of such systems.

Therefore, to create high-tech non-contact means and computerized control systems for the parameters of various textile fabrics, taking into account the above, it is necessary to perform the following generalized tasks:

- to analyze the physical basis of the interaction of ultrasonic radiation with various textile materials with a continuous and porous structure;
- to develop a non-contact amplitude method for determining the threads tension using specialized waveguides with a rectangular cross section;
- to develop a non-contact amplitude method for determining the basis weight and porosity of textile fabrics, taking into account their tension;
- to develop other non-contact methods and samples of computerized systems for controlling technological parameters of textile canvas taking into account their difficult spatial structure;
- to carry out experimental non-contact measurements and comparative analysis between the measured values of technological parameters of textile fabrics, obtained with the help of ultrasonic samples of computerized systems and with the values of parameters when using existing contact methods.

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Chapter 2

Development of a Computerized Control System Structure and Study of Ultrasonic Wave Propagation in Various Textile Materials



2.1 Development of the Overall Computerized System Structure for Non-contact Ultrasonic Control Over Technological Parameters of Textile Materials

In order to be able to use ultrasonic waves in non-contact control over technological parameters of textile materials, it is necessary to develop a universal structure for a computerized system that will process information about informative parameters of ultrasonic waves interacting with the material. For realization of the original task, it is also necessary to carry out a deep analysis of the influence of technological parameters of various materials on informative parameters of ultrasonic waves [1–3].

Proceeding from this task, we consider the generalized structure of the computerized system that can be used to control various technological parameters of textile materials [4–6]. This structure of the generalized system for operational control is shown in Fig. 2.1.

As it can be seen from Fig. 2.1, the generalized structure diagram of the computerized system of operational control over technological parameters of textile materials consists of the main structural parts. Such components include: ultrasonic sounding signal generator, which can be adjusted both by an external control signal and manually adjusting the oscillation frequency; power amplification unit for electric oscillations with a given frequency range; emitting piezoelectric transducers of electric oscillations into ultrasonic waves; receiving piezoelectric transducers of ultrasonic waves into electric oscillations; unit of adjustable amplification of the received electric oscillations; unit of amplitude and phase detectors of received oscillations, which are used depending on the method of parameter control; microprocessor system for processing received signals and controlling engines for moving scanning platforms according to a given algorithm along the material; power part of engine control for moving scanning platforms with non-contact ultrasonic sensors; logic signal level converter; personal computer with various software units for processing measurement information and setting the control algorithm for scanning textile fabrics.

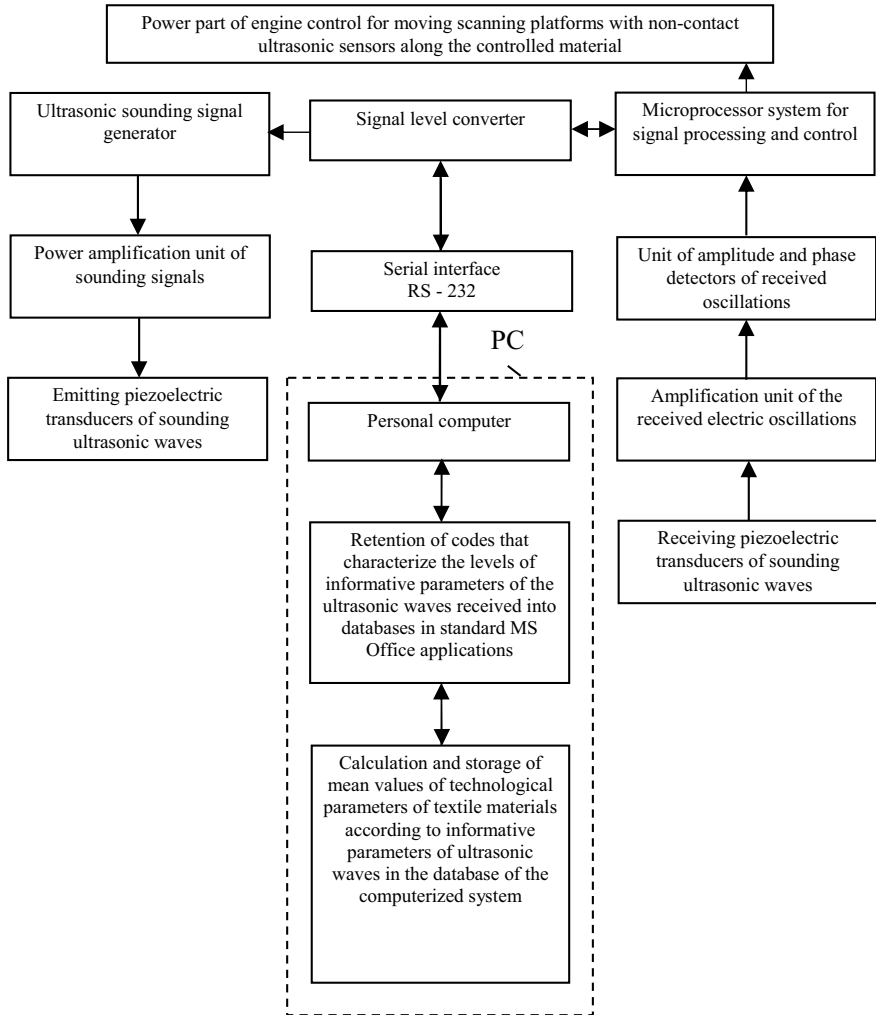


Fig. 2.1 Overall structure diagram of a computerized system for operational control over technological parameters of textile materials

The developed structure of the computerized system is universal for the implementation of non-contact control over many technological parameters of textile materials with existing through pores [7–11].

Its operating principle can be described as follows. Ultrasonic oscillations made by the generator, the frequency of which can be adjusted from a personal computer provided that there is a special microprocessor coupling unit in the generator, are fed to the power amplification unit. There, they are amplified for better performance of radiating piezoelectric transducers, which emit ultrasonic waves with a certain given frequency to the controlled textile material.

After the corresponding interaction of ultrasonic waves with the material, their informative parameters (amplitude, phase shift, propagation velocity) undergo certain changes, which are further determined by the system, and by which the technological parameters for different materials are calculated according to certain analytical dependences. To describe this process in more detail, the ultrasonic waves, after interacting with the controlled textile material, enter the receiving piezoelectric transducers that convert them into electrical oscillations. Next, the electric oscillations are amplified by a unit of adjustable amplification and get into the unit of amplitude and phase oscillation detectors, which are used depending on the method of determining the technological parameter of the material.

The converted signal from the system detectors is then sent to a microprocessor data processing system, where it is converted into digital code that goes to a personal computer via a logic level converter. There, by means of developed software units, codes that characterize the levels of informative parameters of the received ultrasonic waves and their change are stored in databases in standard MS Office applications. From these stored databases, another software unit retrieves data on the obtained various informative parameters of ultrasonic waves, which belong to the same time of interrogation of sensors by a non-contact system, and calculates the value of the technological parameter according to a certain analytical dependence. Next, the mean value of the technological parameter for a certain point of the controlled textile fabric, scanned by movable platforms with ultrasonic sensors, is calculated. The platforms can be placed on special structures mechanically moved by appropriate motors. Such drives can, in turn, be controlled by the power part of the circuit, started by the microprocessor system according to an autonomous material scanning algorithm or a modified scanning algorithm, which is set directly by the operator from a personal computer of the general system.

Separately, to increase the sensitivity of ultrasonic sensors to the textile material, it is possible to use certain devices for introducing ultrasonic waves, as well as various concentrating surfaces of the general ultrasonic signal.

For the effective operation of the proposed computerized control system, it is necessary to obtain refined models of the interaction of ultrasonic waves with different materials with the existing through pores and with a complex spatial structure. It is also necessary to analyze how they differ from the models that describe the interaction of waves with single-layer solid materials. Only by conducting an in-depth analysis of this interaction and understanding the mechanism of influence of different technological parameters of materials on the informative parameters of ultrasonic waves, it is possible to simplify the task of non-contact control over textile fabrics in the process of their production [12–16].

Therefore, we will further consider the pulse ultrasonic signal propagation in different materials both with pores of a complex spatial structure and in solid materials simple in their structure [17–20].

2.2 Study of a Pulse Ultrasonic Signal Transmission Through Two-Layer Composite, Single-Layer Textile Materials with Through Pores and Without Them

The simplest case of a composite material is a two-layer one. This composition of different constituent materials in terms of density and speed of wave propagation in their medium represents different limits for the transmission of ultrasonic vibrations [21–30].

Let us consider the transmission of a plane ultrasonic wave through a controlled two-layer material (Fig. 2.2a) during its normal fall from the medium (air) with acoustic impedance Z_1 ($Z_1 = \rho_1 c_1$, where $\rho_1 c_1$ is bulk density of the medium and the propagation speed of the ultrasonic wave in it). The material itself is solid without pores with the thickness of the first layer h_1 , which has acoustic impedance Z_2 ($Z_2 = \rho_2 c_2$, where $\rho_2 c_2$ is bulk density of the component of the first layer of material and the propagation speed of the ultrasonic wave in its medium, respectively), the second layer of material with a layer thickness h_2 , which has acoustic impedance Z_3 ($Z_3 = \rho_3 c_3$, where $\rho_3 c_3$ is bulk density of the component of the second layer of material and the propagation speed of the ultrasonic wave in its medium, respectively), the last layer rests on a medium with acoustic impedance Z_4 .

The ultrasonic pulse signal as a function of pressure change in the wave $P_{1w.}(t')$, which passed the controlled two-layer solid material, taking into account the propagation time t' of the wave, can be shown as follows:

$$P_{1w.}(t') = \frac{1}{2\pi} \int_{-\infty}^{\infty} W(\omega) S(\omega) \cdot e^{j\omega t'} d\omega, \quad (2.1)$$

where $S(\omega)$ is the spectral density of the incident ultrasonic signal; $W(\omega)$ —the complex coefficient of ultrasonic waves passing in the material, taking into account the attenuation.

The complex coefficient of ultrasonic waves transmission through a two-layer material at $Z_2 > Z_1$, $Z_3 > Z_1$, $Z_2 > Z_4$, $Z_3 > Z_4$ can be presented as follows:

$$W(\omega) = \frac{W_{12} W_{23} W_{34} \cdot e^{j \left(\left(\frac{\omega b}{c_2} + j \alpha_{23} \right) \cdot h_1 + \left(\frac{\omega b}{c_3} + j \alpha_{33} \right) \cdot h_2 \right)}}{1 - (1 - (1 - V_{21} V_{34})(1 + V_{23})(1 + V_{32})) \cdot e^{2j \left(\left(\frac{\omega b}{c_2} + j \alpha_{23} \right) \cdot h_1 + \left(\frac{\omega b}{c_3} + j \alpha_{33} \right) \cdot h_2 \right)}}, \quad (2.2)$$

where W and V are the corresponding coefficients of wave transmission and reflection at the boundaries of the respective media (the first index indicates the medium from which the wave falls, and the second—the medium into which it passes, or from which the wave is reflected); $b = \omega/\omega_0$ is the ratio of the carrier angular frequency and the angular frequency of the pulse signal filling; α_{23} , α_{33} is the attenuation coefficient of ultrasonic waves in the first and second layers of the material, respectively.

Taking the material, in which $h_1 = h_2$ or $h_1 \approx h_2$ (cases that often occur in practice), the expression (2.2) can be shown as follows:

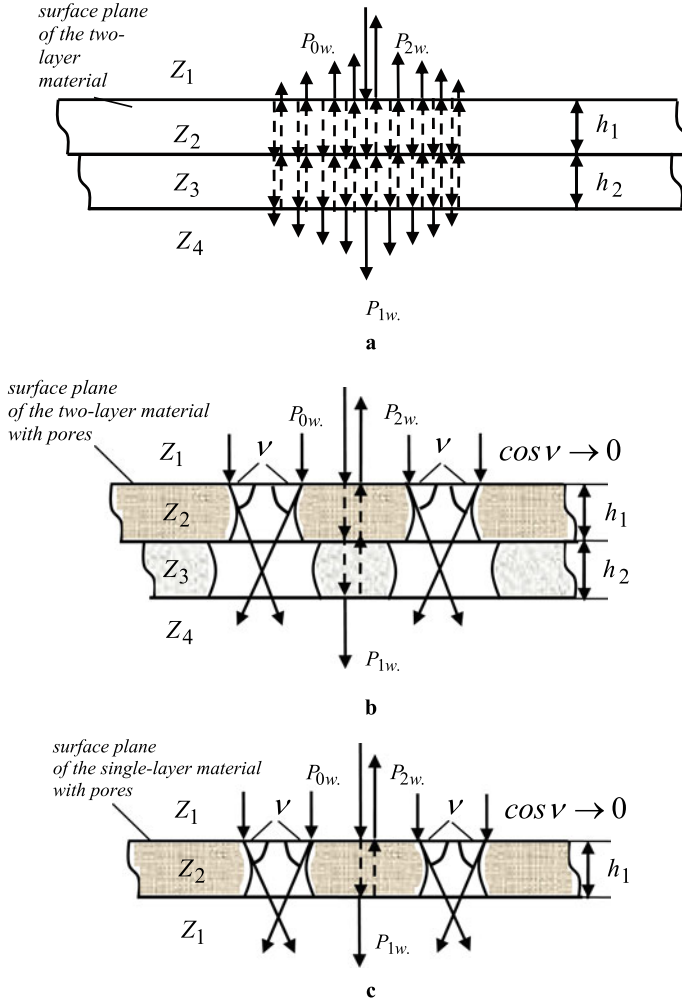


Fig. 2.2 The transmission of ultrasonic waves through various materials: **a** two-layer material without pores; **b** two-layer material with through pores; **c** single-layer material with through pores

$$W(\omega) = \frac{W_{12} W_{23} W_{34} \cdot e^{j \left(\frac{\omega b}{c_{23}} + j \alpha_3 \right) \cdot (h_1 + h_2)}}{1 - (1 - (1 - V_{21} V_{34})(1 + V_{23})(1 + V_{32})) \cdot e^{2j \left(\frac{\omega b}{c_{23}} + j \alpha_3 \right) \cdot (h_1 + h_2)}}, \quad (2.3)$$

where α_3 is the overall attenuation coefficient of ultrasonic waves in the material; $c_{23} = (c_2 + c_3)/2$ is the average propagation speed of the ultrasonic wave in the material.

The expression (2.3) can be written as the sum of the geometric progression as follows:

$$W(\omega) = W_{12} W_{23} W_{34} \sum_{N=0}^{\infty} (1 - (1 - V_{21} V_{34})(1 + V_{23})(1 + V_{32}))^N \times e^{-(2N+1) \left(-j \frac{\omega b}{c_{23}} + \alpha_3 \right) \cdot (h_1 + h_2)}, \quad (2.4)$$

where N is the number of wave reflections that equals to 0, 1, 2, 3, ..., ∞ .

The corresponding values for W and V can be written as:

$$\begin{aligned} W_{12} &= \frac{2Z_1}{Z_1 + Z_2}, & V_{12} &= \frac{Z_1 - Z_2}{Z_1 + Z_2}, \\ W_{21} &= \frac{2Z_2}{Z_1 + Z_2}, & V_{21} &= \frac{Z_2 - Z_1}{Z_1 + Z_2}, \\ W_{23} &= \frac{2Z_2}{Z_2 + Z_3}, & V_{23} &= \frac{Z_2 - Z_3}{Z_2 + Z_3}, \\ W_{32} &= \frac{2Z_3}{Z_2 + Z_3}, & V_{32} &= \frac{Z_3 - Z_2}{Z_2 + Z_3}, \\ W_{34} &= \frac{2Z_3}{Z_3 + Z_4}, & V_{34} &= \frac{Z_3 - Z_4}{Z_3 + Z_4}, \end{aligned} \quad (2.5)$$

then, by substituting the dependence (2.5) for (2.4), the complex transmission coefficient can be shown as:

$$\begin{aligned} W(\omega) &= \frac{2Z_1}{Z_1 + Z_2} \cdot \frac{2Z_2}{Z_2 + Z_3} \cdot \frac{2Z_3}{Z_3 + Z_4} \\ &\times \sum_{N=0}^{\infty} \left(1 - \left(1 - \frac{Z_2 - Z_1}{Z_2 + Z_1} \cdot \frac{Z_3 - Z_4}{Z_3 + Z_4} \right) \left(1 + \frac{Z_2 - Z_3}{Z_2 + Z_3} \right) \left(1 + \frac{Z_3 - Z_2}{Z_3 + Z_2} \right) \right)^N \\ &\times e^{-(2N+1) \left(-j \frac{\omega b}{c_{23}} + \alpha_3 \right) \cdot (h_1 + h_2)}, \end{aligned} \quad (2.6)$$

after some transformations, the expression (2.6) can be presented as:

$$\begin{aligned} W(\omega) &= \frac{4}{1 + \frac{Z_1}{2Z_2} + \frac{Z_1}{2Z_3} + \frac{Z_2}{2Z_1} + \frac{Z_2}{2Z_3} + \frac{Z_3}{2Z_1} + \frac{Z_3}{2Z_2}} \\ &\times \sum_{N=0}^{\infty} \left(1 - \left(1 - \frac{Z_2 Z_3 - Z_2 Z_1 - Z_1 Z_3 + Z_1^2}{Z_2 Z_3 + Z_2 Z_1 + Z_1 Z_3 + Z_1^2} \right) \left(1 + \frac{Z_2 - Z_3}{Z_2 + Z_3} \right) \left(1 + \frac{Z_3 - Z_2}{Z_3 + Z_2} \right) \right)^N \\ &\times e^{-(2N+1) \left(-j \frac{\omega b}{c_{23}} + \alpha_3 \right) \cdot (h_1 + h_2)}, \end{aligned} \quad (2.7)$$

taking into account the significant inequality of acoustic impedance $Z_1 \ll Z_2$ and $Z_1 \ll Z_3$, the expression (2.7) can be reduced to the following:

$$\begin{aligned} W(\omega) &= \frac{4}{1 + \frac{Z_2}{2Z_3} + \frac{Z_3}{2Z_2} + \frac{Z_2}{2Z_1} + \frac{Z_3}{2Z_1}} \\ &\times \sum_{N=0}^{\infty} \left(1 - \left(1 - \frac{Z_2(Z_3 - Z_1) + Z_1(Z_1 - Z_3)}{Z_2(Z_3 + Z_1) + Z_1(Z_1 + Z_3)} \right) \left(1 + \frac{Z_2 - Z_3}{Z_2 + Z_3} \right) \left(1 + \frac{Z_3 - Z_2}{Z_3 + Z_2} \right) \right)^N \\ &\times e^{-(2N+1) \left(-j \frac{\omega b}{c_{23}} + \alpha_3 \right) \cdot (h_1 + h_2)}, \end{aligned} \quad (2.8)$$

then, by substituting the dependence (2.8) for (2.1), the ultrasonic pulse signal can be shown as:

$$\begin{aligned}
 P_{1w.}(t') &= \frac{4}{1 + \frac{Z_2}{2Z_3} + \frac{Z_3}{2Z_2} + \frac{Z_2}{2Z_1} + \frac{Z_3}{2Z_1}} \\
 &\times \sum_{N=0}^{\infty} \left(1 - \left(1 - \frac{Z_2(Z_3 - Z_1) + Z_1(Z_1 - Z_3)}{Z_2(Z_3 + Z_1) + Z_1(Z_1 + Z_3)} \right) \left(1 + \frac{Z_2 - Z_3}{Z_2 + Z_3} \right) \left(1 + \frac{Z_3 - Z_2}{Z_3 + Z_2} \right) \right)^N \\
 &\times \frac{1}{2\pi} \int_{-\infty}^{\infty} S(\omega) \cdot e^{-(2N+1) \left(-j \frac{\omega b}{c_{23}} + \alpha_3 \right) \cdot (h_1 + h_2)} \cdot e^{-j\omega t} d\omega, \tag{2.9}
 \end{aligned}$$

where t is the current time.

The spectral density of this signal can be presented as:

$$S(\omega) = \frac{P_{0w.} \tau_0 \sqrt{\pi}}{2 \ln \sqrt{2}} \cdot e^{-\left(\frac{(\omega - \omega_0) \tau_0}{4 \ln \sqrt{2}} \right)^2}, \tag{2.10}$$

where $P_{0w.}$ is pressure in the incident ultrasonic wave on the surface of the material; τ_0 —pulse duration; ω_0 —angular frequency of the pulse signal filling.

Putting the expression (2.10) in (2.9), we will write the pulse signal as follows:

$$\begin{aligned}
 P_{1w.}(t') &= \frac{4}{1 + \frac{Z_2}{2Z_3} + \frac{Z_3}{2Z_2} + \frac{Z_2}{2Z_1} + \frac{Z_3}{2Z_1}} \\
 &\times \sum_{N=0}^{\infty} \left(1 - \left(1 - \frac{Z_2(Z_3 - Z_1) + Z_1(Z_1 - Z_3)}{Z_2(Z_3 + Z_1) + Z_1(Z_1 + Z_3)} \right) \left(1 + \frac{Z_2 - Z_3}{Z_2 + Z_3} \right) \left(1 + \frac{Z_3 - Z_2}{Z_3 + Z_2} \right) \right)^N \\
 &\times \frac{P_{0w.} \tau_0}{4 \sqrt{\pi \ln \sqrt{2}}} \int_{-\infty}^{\infty} e^{-\left(\frac{(\omega - \omega_0) \tau_0}{4 \ln \sqrt{2}} \right)^2 - (2N+1) \left(-j \frac{\omega b}{c_{23}} + \alpha_3 \right) \cdot (h_1 + h_2) - j\omega t} d\omega. \tag{2.11}
 \end{aligned}$$

Let us transform the expression (2.11) in the exponent, which can be presented as:

$$\begin{aligned}
 &-\left(\frac{(\omega - \omega_0) \tau_0}{4 \ln \sqrt{2}} \right)^2 - (2N + 1) \left(-j \frac{\omega b}{c_{23}} + \alpha_3 \right) \cdot (h_1 + h_2) - j\omega t \\
 &= -\left(\frac{(\omega - \omega_0) \tau_0}{4 \ln \sqrt{2}} \right)^2 + j(2N + 1) \frac{\omega b (h_1 + h_2)}{c_{23}} \\
 &\quad - \alpha_3 (2N + 1) (h_1 + h_2) - j\omega t \\
 &= \frac{-\tau_0^2 \omega^2 + 2\omega_0 \omega \tau_0^2 - \omega_0^2 \tau_0^2}{(4 \ln \sqrt{2})^2} + j \frac{\omega b (2N + 1) (h_1 + h_2)}{c_{23}} \\
 &\quad - \alpha_3 (2N + 1) (h_1 + h_2) - j\omega t = -\left(\frac{\tau_0}{4 \ln \sqrt{2}} \right)^2 \omega^2
 \end{aligned}$$

$$\begin{aligned}
& + \left(j \left(\frac{b(2N+1)(h_1+h_2)}{c_{23}} - t \right) + \frac{2\omega_0\tau_0^2}{(4 \ln \sqrt{2})^2} \right) \omega - \left(\frac{\omega_0\tau_0}{4 \ln \sqrt{2}} \right)^2 \\
& - \alpha_3(2N+1)(h_1+h_2).
\end{aligned} \tag{2.12}$$

After performing the transformation and putting the expression (2.12) in (2.11), the ultrasonic pulse signal after passing through the two-layer material can be shown as:

$$\begin{aligned}
P_{1w.}(t') &= \frac{4}{1 + \frac{Z_2}{2Z_3} + \frac{Z_3}{2Z_2} + \frac{Z_2}{2Z_1} + \frac{Z_3}{2Z_1}} \\
&\times \sum_{N=0}^{\infty} \left(1 - \left(1 - \frac{Z_2(Z_3 - Z_1) + Z_1(Z_1 - Z_3)}{Z_2(Z_3 + Z_1) + Z_1(Z_1 + Z_3)} \right) \left(1 + \frac{Z_2 - Z_3}{Z_2 + Z_3} \right) \left(1 + \frac{Z_3 - Z_2}{Z_3 + Z_2} \right) \right)^N \\
&\times \frac{P_{0w.}\tau_0}{4\sqrt{\pi} \ln \sqrt{2}} \cdot e^{-\left(\frac{\omega_0\tau_0}{4 \ln \sqrt{2}} \right)^2} - \alpha_3(2N+1)(h_1+h_2) \\
&\times \int_{-\infty}^{\infty} e^{-\left(\frac{\tau_0}{4 \ln \sqrt{2}} \right)^2 \omega^2 + \left(j \left(\frac{b(2N+1)(h_1+h_2)}{c_{23}} - t \right) + \frac{2\omega_0\tau_0^2}{(4 \ln \sqrt{2})^2} \right) \omega} d\omega.
\end{aligned} \tag{2.13}$$

Having defined the integral in (2.13), let us write down this expression as real $\text{Re } P_{1w.}(t')$ and imaginary $\text{Im } P_{1w.}(t')$ components of the pulse ultrasonic signal that has passed through the controlled two-layer material, in the following way:

$$\begin{aligned}
P_{1w.}(t') &= \text{Re } P_{1w.}(t') + j \text{Im } P_{1w.}(t') \\
&= P_{0w.} \cdot \frac{4}{1 + \frac{1}{2} \left(\frac{Z_2}{Z_3} + \frac{Z_3}{Z_2} + \frac{Z_2+Z_3}{Z_1} \right)} \\
&\times \sum_{N=0}^{\infty} \left(1 - \left(1 - \frac{Z_2(Z_3 - Z_1) + Z_1(Z_1 - Z_3)}{Z_2(Z_3 + Z_1) + Z_1(Z_1 + Z_3)} \right) \left(1 + \frac{Z_2 - Z_3}{Z_2 + Z_3} \right) \left(1 + \frac{Z_3 - Z_2}{Z_3 + Z_2} \right) \right)^N \\
&\times \left(\cos \left(\omega_0 \left(\frac{(h_1+h_2)}{c_{23}} b(2N+1) - t \right) \right) \right. \\
&+ j \sin \left(\omega_0 \left(\frac{(h_1+h_2)}{c_{23}} b(2N+1) - t \right) \right) \Bigg) \\
&\times \exp \left(- \frac{\left(\frac{(h_1+h_2)}{c_{23}} b(2N+1) - t \right)^2}{\left(\frac{\tau_0}{\ln 2} \right)^2} \right) \\
&- \alpha_3(2N+1)(h_1+h_2).
\end{aligned} \tag{2.14}$$

We will select the real part $\text{Re } P_{1w.}(t')$ from the dependence (2.14) and present it as the pressure value in the wave that has passed through the two-layer material:

$$\text{Re } P_{1w.}(t') = P_{0w.} \cdot \frac{4}{1 + \frac{1}{2} \left(\frac{Z_2}{Z_3} + \frac{Z_3}{Z_2} + \frac{Z_2+Z_3}{Z_1} \right)}$$

$$\begin{aligned}
& \times \sum_{N=0}^{\infty} \left(1 - \left(1 - \frac{Z_2(Z_3 - Z_1) + Z_1(Z_1 - Z_3)}{Z_2(Z_3 + Z_1) + Z_1(Z_1 + Z_3)} \right) \right. \\
& \left. \left(1 + \frac{Z_2 - Z_3}{Z_2 + Z_3} \right) \left(1 + \frac{Z_3 - Z_2}{Z_3 + Z_2} \right) \right)^N \\
& \times \cos \left(\omega_0 \left(\frac{(h_1 + h_2)}{c_{23}} b(2N + 1) - t \right) \right) \\
& \times \exp \left(- \frac{\left(\frac{(h_1 + h_2)}{c_{23}} b(2N + 1) - t \right)^2}{\left(\frac{\tau_0}{\ln 2} \right)^2} \right) \\
& - \alpha_3 \cdot (2N + 1)(h_1 + h_2)).
\end{aligned} \tag{2.15}$$

It is possible to obtain the imaginary part $\text{Im } P_{1w.}(t')$ of the pulse ultrasonic signal from the dependence (2.14) and present it as:

$$\begin{aligned}
\text{Im } P_{1w.}(t') &= P_{0w.} \cdot \frac{4}{1 + \frac{1}{2} \left(\frac{Z_2}{Z_3} + \frac{Z_3}{Z_2} + \frac{Z_2 + Z_3}{Z_1} \right)} \\
& \times \sum_{N=0}^{\infty} \left(1 - \left(1 - \frac{Z_2(Z_3 - Z_1) + Z_1(Z_1 - Z_3)}{Z_2(Z_3 + Z_1) + Z_1(Z_1 + Z_3)} \right) \right. \\
& \left. \left(1 + \frac{Z_2 - Z_3}{Z_2 + Z_3} \right) \left(1 + \frac{Z_3 - Z_2}{Z_3 + Z_2} \right) \right)^N \\
& \times \sin \left(\omega_0 \left(\frac{(h_1 + h_2)}{c_{23}} b(2N + 1) - t \right) \right) \\
& \times \exp \left(- \frac{\left(\frac{(h_1 + h_2)}{c_{23}} b(2N + 1) - t \right)^2}{\left(\frac{\tau_0}{\ln 2} \right)^2} \right) \\
& - \alpha_3 \cdot (2N + 1)(h_1 + h_2)).
\end{aligned} \tag{2.16}$$

The unit amplitude of the incident ultrasonic wave on the surface of the two-layer material can be presented as:

$$A_0(t) = e^{-\left(\frac{t \ln 2}{\tau_0} \right)^2} \cdot \cos(\omega_0 t). \tag{2.17}$$

We are considering a bell-shaped ultrasonic pulse signal that is often used in the sounding of different materials, the change of phase shift of which can affect the detection of the peak value of wave amplitudes associated with changes in time delays required to adjust selectors of information signals from measuring channels. The wave amplitude of the pulse signal that has passed through two layers of the material in relative units according to the dependence (2.17) and (2.15) considering

the time delay of waves in the media of the material components (the delay in the medium of the material in the process of signal transmission and reflection from the controlled sample is now taken into account in the expressions of the most complex coefficients of the wave transmission and reflection) can be given as:

$$\begin{aligned}
 A_W(t') = & 2 \left(\frac{Z_1}{Z_1 + Z_2} \cdot \frac{Z_2}{Z_2 + Z_3} \cdot \frac{Z_3}{Z_3 + Z_4} \right) \\
 & \times \sum_{N=0}^{\infty} \left(1 - \left(1 - \frac{Z_2 - Z_1}{Z_2 + Z_1} \cdot \frac{Z_3 - Z_4}{Z_3 + Z_4} \right) \left(1 + \frac{Z_2 - Z_3}{Z_2 + Z_3} \right) \left(1 + \frac{Z_3 - Z_2}{Z_3 + Z_2} \right) \right)^N \\
 & \times \cos \left(\omega_0 \left(\frac{(h_1 + h_2)}{c_{23}} b(2N + 1) - t \right) \right) \\
 & \times \exp \left(- \frac{\left(\frac{(h_1 + h_2)}{c_{23}} b(2N + 1) - t \right)^2}{\left(\frac{\tau_0}{\ln 2} \right)^2} \right) \\
 & - \alpha_3 \cdot (2N + 1)(h_1 + h_2).
 \end{aligned} \tag{2.18}$$

The phase shift of the ultrasonic pulse signal, which has passed through the controlled two-layer material without pores, can be presented as:

$$\varphi_W = \arctg \frac{\sum_{N=0}^{\infty} V_L^N \cdot \exp(Y) \sin \left(\omega_0 \left(\frac{(h_1 + h_2)}{c_{23}} b(2N + 1) - t \right) \right)}{\sum_{N=0}^{\infty} V_L^N \cdot \exp(Y) \cos \left(\omega_0 \left(\frac{(h_1 + h_2)}{c_{23}} b(2N + 1) - t \right) \right)}, \tag{2.19}$$

where

$$\begin{aligned}
 V_L = & 1 - \left(1 - \frac{Z_2 - Z_1}{Z_2 + Z_1} \cdot \frac{Z_3 - Z_4}{Z_3 + Z_4} \right) \left(1 + \frac{Z_2 - Z_3}{Z_2 + Z_3} \right) \left(1 + \frac{Z_3 - Z_2}{Z_3 + Z_2} \right), \\
 Y = & - \frac{\left(\frac{(h_1 + h_2)}{c_{23}} b(2N + 1) - t \right)^2}{\left(\frac{\tau_0}{\ln 2} \right)^2} - \alpha_3 \cdot (2N + 1)(h_1 + h_2).
 \end{aligned}$$

If in the two-layer material (Fig. 2.2b) there are pores (the value $\cos \nu$ is responsible for their total volume and shape, where ν is the angle between the direction of propagation of ultrasonic waves passing through pores and surface of the two-layer material), the expression (2.18) can be presented as follows:

$$\begin{aligned}
 A_{WP}(t') = & 2 \left(\frac{Z_1}{Z_1 + Z_2} \cdot \frac{Z_2}{Z_2 + Z_3} \cdot \frac{Z_3}{Z_3 + Z_4} \right) \\
 & \times \sum_{N=0}^{\infty} V_L^N \cdot \cos \left(\omega_0 \left(\frac{(h_1 + h_2) \cos \nu}{c_{23}} b(2N + 1) - t \right) \right) \\
 & \times \exp \left(- \frac{\left(\frac{(h_1 + h_2) \cos \nu}{c_{23}} b(2N + 1) - t \right)^2}{\left(\frac{\tau_0}{\ln 2} \right)^2} \right)
 \end{aligned}$$

$$-\alpha_3.(2N + 1)(h_1 + h_2) \cos \nu). \quad (2.20)$$

The phase shift of this ultrasonic pulse signal, which has passed through the controlled two-layer material with pores, can be shown as:

$$\varphi_{Wp} = \arctg \frac{\sum_{N=0}^{\infty} V_L^N \cdot \exp(Y_\nu) \sin\left(\omega_0 \left(\frac{(h_1+h_2) \cos \nu}{c_{23}} b(2N+1) - t\right)\right)}{\sum_{N=0}^{\infty} V_L^N \cdot \exp(Y_\nu) \cos\left(\omega_0 \left(\frac{(h_1+h_2) \cos \nu}{c_{23}} b(2N+1) - t\right)\right)}, \quad (2.21)$$

where

$$Y_\nu = -\frac{\left(\frac{(h_1+h_2) \cos \nu}{c_{23}} b(2N+1) - t\right)^2}{\left(\frac{\tau_0}{\ln 2}\right)^2} - \alpha_3.(2N + 1)(h_1 + h_2) \cos \nu.$$

Let us consider the transmission of a pulse ultrasonic signal through a single-layer material with a thickness h_1 and acoustic impedance Z_2 in the presence of through pores in it (Fig. 2.2c). In addition, the material was placed in the air medium $Z_1 = Z_4$, and for the amplitude of the pulse ultrasonic signal, having carried out similar expression transformations for this case, the following dependence can be obtained:

$$\begin{aligned} A_{Wp}(t') &= \frac{4 Z_1 Z_2}{(Z_1 + Z_2)^2} \sum_{N=0}^{\infty} \left(\frac{Z_2 - Z_1}{Z_1 + Z_2}\right)^{2N} \\ &\times \cos\left(\omega_0 \left(\frac{h_1 b(2N+1) \cos \nu}{c_2} - t\right)\right) \cdot \exp\left(-\frac{\left(\frac{h_1 b(2N+1) \cos \nu}{c_2} - t\right)^2}{\left(\frac{\tau_0}{\ln 2}\right)^2}\right) \\ &- \alpha_3.(2N + 1) h_1 \cos \nu). \end{aligned} \quad (2.22)$$

Let us consider an ultrasonic pulse signal that has passed through a controlled single-layer fabric (Figs. 2.3a, b, 2.4a) with an average thickness of two–three average nominal diameters of warp and weft threads with the parameter $\cos \nu$ within $\frac{3}{4} > \cos \nu > 0$. The dependence for this signal can be given as follows:

$$P_{1w.}(t') = P_{1w.}\left(\frac{\pi d_{oy}}{4c_2} - t\right) = \frac{1}{2\pi} \int_{-\infty}^{\infty} W_{\alpha\beta}(\omega) S(\omega) \cdot e^{j\omega\left(\frac{\pi d_{oy}}{4c_2} - t\right)} d\omega, \quad (2.23)$$

where $t' = \frac{\pi d_{oy}}{4c_2} - t$ is the time that takes into account the partial delay of the ultrasonic signal in the structure of this material for the given case, which is connected with the phase structure of the fabric.

The time t' is ignored in the expression of the complex coefficient of transmission through the woven fabrics (as for the flat layer material), where the equivalent thickness of a single-layer fabric is set, which is numerically equal to the cross sections of

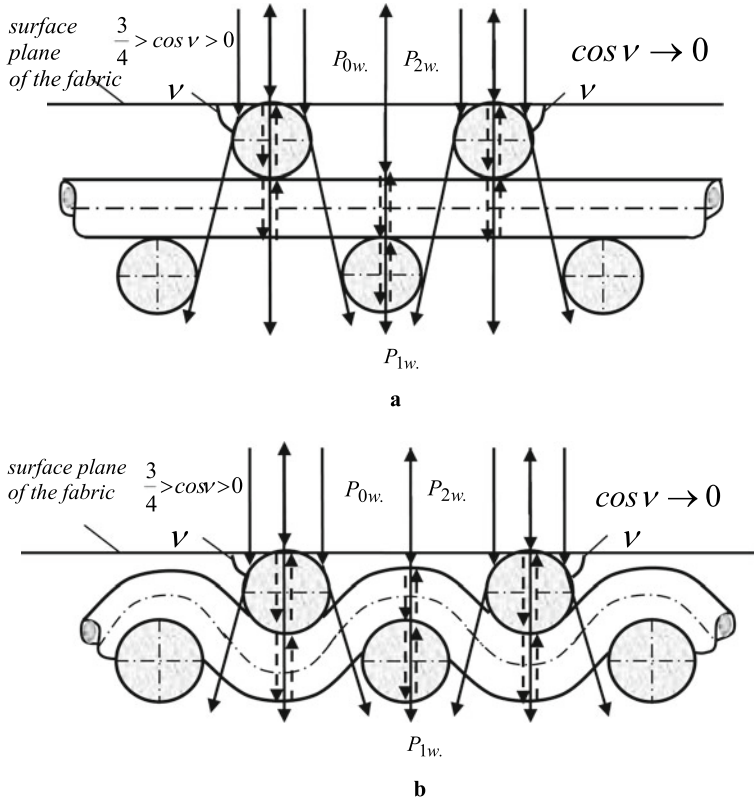


Fig. 2.3 The transmission of ultrasonic waves through the fabric with a different phase structure at the parameter $\cos \nu$ within $\frac{3}{4} > \cos \nu > 0$: **a** single-layer fabric with a thickness of three mean diameters of warp and weft threads; **b** single-layer fabric with a thickness of two mean diameters of warp and weft threads

the warp thread and weft thread when they are creased. This thickness indicates the delay time in the thread fibers where the signal is attenuated. So, in the dependence (2.23), $\frac{\pi d_{oy}}{4c_2} - t$ related to the phase structure of the fabric is considered.

The expression (2.23) can be roughly used for nonwoven fabrics. The complex coefficient of transmission through these materials can be then presented as follows:

$$W_{\alpha\beta}(\omega) = \frac{W_{12}W_{21} \cdot e^{j\left(\frac{\omega b}{c_2} + j\alpha_3\right) \cdot d_{oy} \frac{\pi}{4} \cos \nu}}{1 - V_{21}V_{21} \cdot e^{2j\left(\frac{\omega b}{c_2} + j\alpha_3\right) \cdot d_{oy} \frac{\pi}{4} \cos \nu}}, \quad (2.24)$$

or

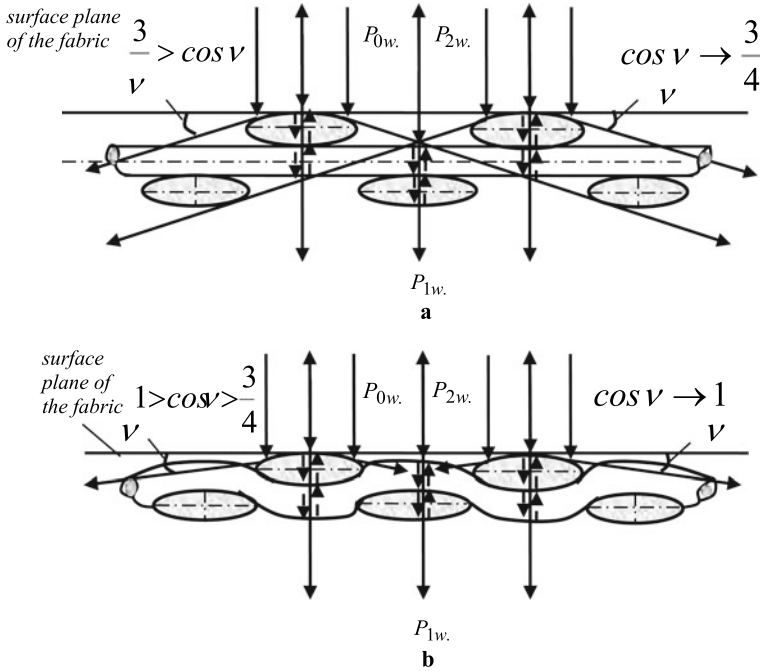


Fig. 2.4 The transmission of ultrasonic waves through a dense single-layer fabric almost without pores with different phase structure: **a** single-layer fabric with a thickness of three nominal mean diameters of the warp and weft thread (thread wrinkling is present) with the parameter $\cos \nu$ within $\frac{3}{4} > \cos \nu > 0$; **b** single-layer fabric with an average thickness approaching two nominal mean diameters of warp and weft threads (thread wrinkling is present) with the parameter $\cos \nu$ within $1 > \cos \nu > \frac{3}{4}$

$$W_{\alpha\beta}(\omega) = \frac{\frac{4Z_1 Z_2}{(Z_1 + Z_2)^2} \cdot e^{\left(j\frac{\omega b}{c_2} - \alpha_3\right) \cdot d_{oy} \frac{\pi}{4} \cos \nu}}{1 - \left(\frac{Z_2 - Z_1}{Z_1 + Z_2}\right)^2 \cdot e^{2\left(j\frac{\omega b}{c_2} - \alpha_3\right) \cdot d_{oy} \frac{\pi}{4} \cos \nu}}. \quad (2.25)$$

Taking into account the dependences (2.23) and (2.25), similarly to the previously considered cases, it is possible to obtain a dependence for the amplitude of a pulse ultrasonic signal in the time, which has passed through a single-layer fabric with the parameter $\cos \nu$ within $\frac{3}{4} > \cos \nu > 0$. This signal, associated with the thickness through the nominal diameters of warp and weft threads of the material, can be presented as follows:

$$A_{W\alpha}(t') = \frac{4Z_1 Z_2}{(Z_1 + Z_2)^2} \sum_{N=0}^{\infty} \left(\frac{Z_2 - Z_1}{Z_1 + Z_2}\right)^{2N} \cdot \cos\left(\omega_0 \left(\frac{\pi d_{oy} (b(2N+1) \cos \nu + 1)}{4c_2} - t\right)\right) \times \exp\left(-\frac{\left(\frac{\pi d_{oy} (b(2N+1) \cos \nu + 1)}{4c_2} - t\right)^2}{\left(\frac{\tau_0}{\ln 2}\right)^2} - \frac{\alpha_3 (2N+1) \pi d_{oy} \cos \nu}{4}\right). \quad (2.26)$$

If we consider the transmission of the ultrasonic pulse signal through the controlled very dense single-layer fabric almost without pores (Fig. 2.4b) with an average thickness approaching two mean nominal diameters of the warp and weft thread (thread wrinkling is present) with the parameter $\cos \nu$ within $1 > \cos \nu > \frac{3}{4}$, the amplitude of this pulse ultrasound signal can be given as:

$$A_{W\beta}(t') = \frac{4 Z_1 Z_2}{(Z_1 + Z_2)^2} \sum_{N=0}^{\infty} \left(\frac{Z_2 - Z_1}{Z_1 + Z_2} \right)^{2N} \cdot \cos \left(\omega_0 \left(\frac{\pi d_{oy} b (2N + 1) \cos \nu}{4c_2} - t \right) \right) \\ \times \exp \left(- \frac{\left(\frac{\pi d_{oy} b (2N+1) \cos \nu}{4c_2} - t \right)^2}{\left(\frac{\tau_0}{\ln 2} \right)^2} - \frac{\alpha_3 \cdot (2N + 1) \pi d_{oy} \cos \nu}{4} \right). \quad (2.27)$$

If we write down the expression (2.23), with a thickness ranging from two to three mean diameters of the warp and weft thread with the parameter $\cos \nu$ within $\frac{3}{4} > \cos \nu > 0$, by associating it with the basis weight m_s of the controlled fabric and coefficient K of changes in pore size relative to the reference sample, this dependence will look like:

$$P_{1w.}(t') = P_{1w.} \left(\frac{K m_s}{\pi Z_2} - t \right) = \frac{1}{2\pi} \int_{-\infty}^{\infty} W_{\alpha\beta}(\omega) S(\omega) \cdot e^{j\omega \left(\frac{K m_s}{\pi Z_2} - t \right)} d\omega, \quad (2.28)$$

where $t' = \frac{K m_s}{\pi Z_2} - t$ is the time considering the partial delay of the ultrasonic signal in the structure of this material for the given case, which is due to the phase structure of the fabric expressed in terms of the basis weight m_s .

By associating the expression (2.25) with the basis weight m_s of the controlled fabric, the complex transmission coefficient can be presented as:

$$W_{\alpha\beta}(\omega) = \frac{\frac{4Z_1 Z_2}{(Z_1 + Z_2)^2} \cdot e^{\left(j \frac{\omega b}{c_2} - \alpha_3 \right) \cdot \frac{K m_s \cos \nu}{\pi \rho_2}}}{1 - \left(\frac{Z_2 - Z_1}{Z_1 + Z_2} \right)^2 \cdot e^{2 \left(j \frac{\omega b}{c_2} - \alpha_3 \right) \cdot \frac{K m_s \cos \nu}{\pi \rho_2}}}, \quad (2.29)$$

then the amplitude of the ultrasonic pulse signal, which is represented by the expression (2.26), can be applied through the basis weight m_s as:

$$A_{W\alpha}(t') = \frac{4 Z_1 Z_2}{(Z_1 + Z_2)^2} \sum_{N=0}^{\infty} \left(\frac{Z_2 - Z_1}{Z_1 + Z_2} \right)^{2N} \cdot \cos \left(\omega_0 \left(\frac{K m_s (b (2N + 1) \cos \nu + 1)}{\pi Z_2} - t \right) \right) \\ \times \exp \left(- \frac{\left(\frac{K m_s (b (2N+1) \cos \nu + 1)}{\pi Z_2} - t \right)^2}{\left(\frac{\tau_0}{\ln 2} \right)^2} - \frac{\alpha_3 \cdot (2N + 1) K m_s \cos \nu}{\pi \rho_2} \right). \quad (2.30)$$

If we consider the transmission of the ultrasonic pulse signal through a controlled dense fabric with an average thickness approaching two mean diameters of the warp

and weft tread with the parameter $\cos \nu$ within $1 > \cos \nu > \frac{3}{4}$, the expression (2.27), taking into account the basis weight m_s , can be presented as:

$$A_{W\beta}(t') = \frac{4 Z_1 Z_2}{(Z_1 + Z_2)^2} \sum_{N=0}^{\infty} \left(\frac{Z_2 - Z_1}{Z_1 + Z_2} \right)^{2N} \cdot \cos \left(\omega_0 \left(\frac{K m_s b (2N+1) \cos \nu}{\pi Z_2} - t \right) \right) \times \exp \left(- \frac{\left(\frac{K m_s b (2N+1) \cos \nu}{\pi Z_2} - t \right)^2}{\left(\frac{\tau_0}{\ln 2} \right)^2} - \frac{\alpha_{3, (2N+1) K m_s \cos \nu}}{\pi \rho_2} \right). \quad (2.31)$$

Thus, after studying the pulse ultrasonic signal that passes through different constituent layers of materials with different structure, it is possible to conclude that the resulting amplitude of such waves mainly depends on the density, thickness and structure of the controlled material.

The difference in the magnitude of the amplitude ratios of ultrasonic waves that interact between different materials with different structures also depends on the properties of materials, which are due to their microstructure. This parameter can affect the attenuation coefficient that can vary significantly. If, for example, there are small air bubbles in the material, the transmission coefficient can be significantly reduced compared to the solid material. This is due to the fact that part of the ultrasonic energy is dissipated and heats the material from the inside. The microstructure of the material can increase the internal reflection of ultrasonic waves.

Comparing two-layer and single-layer solid materials and materials with existing through pores, we can make a conclusion that part of the ultrasonic waves that pass through the pores significantly affects the resulting signal compared to part of the waves that pass through the material itself.

Due to ultrasonic waves passing through a composite or textile material, it is possible to control its basis weight if the structure of the material itself is homogeneous and continuous. The thickness of the material should be such that the ultrasonic waves can pass through it with an amplitude that will enable to capture the measuring signal by the detector. Therefore, it is advisable to control single-layer and double-layer materials with a small thickness. If through pores appear in the material and its thickness increases, most of the ultrasonic waves pass through the air in the through pores. Therefore, the resulting signal of the amplitude of the waves on the detector is affected by the pores. As the number of layers in the material with pores through which ultrasonic waves pass increases, the phenomenon of internal dissipation of oscillation energy can occur (depending on the thickness of the material package and the pore size of each layer). Considering the above, it is necessary to choose single-layer or double-layer materials with a small thickness to monitor their technological parameters using non-contact ultrasonic sensors. It is also necessary to further determine the pore size of the material and take it into account when calculating the technological parameters of various textile materials.

To determine the change in pore size in the material it is necessary to use the amplitude of ultrasonic waves reflected from its surface. Measurement of an additional information parameter will make it possible to carry out adaptive ultrasonic control in a real-time mode.

Having analyzed the above, it can be concluded that it is necessary to get the dependence for the signal reflected from the controlled material as well. This will make it possible to conduct operational control over various materials at the place of production using waves reflected from their surface to determine the presence and size of through pores in their structures, and waves that pass through the pores and the materials themselves can be used, taking into account the pore size while determining the basis weight. Therefore, it is advisable to further study the reflection of the pulse ultrasonic signal from different materials with different structure and porosity.

2.3 Study of the Pulse Ultrasonic Signal Reflection from Two-Layer Composite, Single-Layer Textile Materials with Through Pores and Without Them

In order to conduct a careful study of the interaction of the pulse ultrasonic signal with different textile and composite materials, it is necessary to consider the reflection of the signal package waves from different materials and their constituent layers.

The pressure in the pulse ultrasonic signal reflected from the two-layer material can be shown, in general terms, as follows:

$$P_{2w.}(t') = \frac{1}{2\pi} \int_{-\infty}^{\infty} V(\omega) S(\omega) \cdot e^{j\omega t'} d\omega, \quad (2.32)$$

where $V(\omega)$ is the complex coefficient of ultrasonic waves reflection from the material, taking into account the attenuation.

The complex coefficient of ultrasonic waves reflection from a two-layer material, in which $h_1 = h_2$ or $h_1 \approx h_2$, can be presented as:

$$V(\omega) = \frac{\sqrt{V_L} - \sqrt{V_L} \cdot e^{2j\left(\frac{\omega b}{c_{23}} + j\alpha_3\right) \cdot (h_1 + h_2)}}{1 - V_L \cdot e^{2j\left(\frac{\omega b}{c_{23}} + j\alpha_3\right) \cdot (h_1 + h_2)}}, \quad (2.33)$$

or this expression can be written down as the sum of the geometric progression of the wave components that fall and reflect from the surface of the controlled material consisting of two different layers as follows:

$$V(\omega) = \left(\sqrt{V_L} - \sqrt{V_L} \cdot e^{-2\left(-j\frac{\omega b}{c_{23}} + \alpha_3\right) \cdot (h_1 + h_2)} \right) \times \sum_{N=0}^{\infty} V_L^N \cdot e^{-2N\left(-j\frac{\omega b}{c_{23}} + \alpha_3\right) \cdot (h_1 + h_2)}. \quad (2.34)$$

For convenience, the dependence (2.34) in subsequent transformations will be shown as:

$$V(\omega) = \sqrt{V_L} \cdot \sum_{N=0}^{\infty} V_L^N \cdot e^{-2N \left(-j \frac{\omega b}{c_{23}} + \alpha_3 \right) \cdot (h_1 + h_2)} - \sqrt{V_L} \cdot \sum_{N=0}^{\infty} V_L^N \cdot e^{-(2N+2) \left(-j \frac{\omega b}{c_{23}} + \alpha_3 \right) \cdot (h_1 + h_2)}. \quad (2.35)$$

By substituting the expression (2.35) in (2.32), the ultrasonic pulse signal reflected from the two-layer material can be presented as:

$$P_{2w.}(t') = \sqrt{V_L} \cdot \sum_{N=0}^{\infty} V_L^N \cdot \frac{1}{2\pi} \int_{-\infty}^{\infty} S(\omega) \cdot e^{-2N \left(-j \frac{\omega b}{c_{23}} + \alpha_3 \right) \cdot (h_1 + h_2)} \cdot e^{-j\omega t} d\omega - \sqrt{V_L} \cdot \sum_{N=0}^{\infty} V_L^N \cdot \frac{1}{2\pi} \int_{-\infty}^{\infty} S(\omega) \cdot e^{-(2N+2) \left(-j \frac{\omega b}{c_{23}} + \alpha_3 \right) \cdot (h_1 + h_2)} \cdot e^{-j\omega t} d\omega, \quad (2.36)$$

then substituting the dependence for the spectral density (2.10) in (2.36) for the pulse ultrasonic signal, the complex pressure in the waves reflected from the two layers of material can be presented as follows:

$$P_{2w.}(t') = \sqrt{V_L} \cdot \sum_{N=0}^{\infty} V_L^N \cdot \frac{P_{0w.}\tau_0}{4\sqrt{\pi} \ln \sqrt{2}} \times \int_{-\infty}^{\infty} e^{-\left(\frac{(\omega - \omega_0)\tau_0}{4 \ln \sqrt{2}} \right)^2 - 2N \left(-j \frac{\omega b}{c_{23}} + \alpha_3 \right) \cdot (h_1 + h_2) - j\omega t} d\omega - \sqrt{V_L} \cdot \sum_{N=0}^{\infty} V_L^N \times \frac{P_{0w.}\tau_0}{4\sqrt{\pi} \ln \sqrt{2}} \cdot \int_{-\infty}^{\infty} e^{-\left(\frac{(\omega - \omega_0)\tau_0}{4 \ln \sqrt{2}} \right)^2 - (2N+2) \left(-j \frac{\omega b}{c_{23}} + \alpha_3 \right) \cdot (h_1 + h_2) - j\omega t} d\omega, \quad (2.37)$$

having carried out transformations in the first and in the second indicators of the expression exponent (2.37), the result of transformations can be shown as follows:

$$- \left(\frac{\tau_0}{4 \ln \sqrt{2}} \right)^2 \omega^2 + \left(j \left(\frac{2Nb(h_1 + h_2)}{c_{23}} - t \right) + \frac{2\omega_0\tau_0^2}{(4 \ln \sqrt{2})^2} \right) \omega - \left(\frac{\omega_0\tau_0}{4 \ln \sqrt{2}} \right)^2 - \alpha_3 \cdot 2N(h_1 + h_2), \quad (2.38)$$

$$\begin{aligned}
& - \left(\frac{\tau_0}{4 \ln \sqrt{2}} \right)^2 \omega^2 + \left(j \left(\frac{b(2N+2)(h_1+h_2)}{c_{23}} - t \right) + \frac{2\omega_0 \tau_0^2}{(4 \ln \sqrt{2})^2} \right) \omega \\
& - \left(\frac{\omega_0 \tau_0}{4 \ln \sqrt{2}} \right)^2 - \alpha_{3, (2N+2)(h_1+h_2)}, \tag{2.39}
\end{aligned}$$

taking into account the waves that can be shown by subintegral expressions, one of which characterizes the complex reflection from the boundary of the two-layer material, and the other characterizes the reflection of the wave with its double transmission of its thickness, due to (2.38) and (2.39), the dependence (2.37) can be also presented as:

$$\begin{aligned}
P_{2w.}(t') &= \sqrt{V_L} \cdot \sum_{N=0}^{\infty} V_L^N \cdot \frac{P_{0w.}\tau_0}{4\sqrt{\pi} \ln \sqrt{2}} \cdot \left(e^{-\left(\frac{\omega_0 \tau_0}{4 \ln \sqrt{2}}\right)^2 - \alpha_{3, 2N(h_1+h_2)}} \right. \\
&\quad \times \int_{-\infty}^{\infty} e^{-\left(\frac{\tau_0}{4 \ln \sqrt{2}}\right)^2 \omega^2 + \left(j \left(\frac{2Nb(h_1+h_2)}{c_{23}} - t \right) + \frac{2\omega_0 \tau_0^2}{(4 \ln \sqrt{2})^2} \right) \omega} d\omega \\
&\quad - e^{-\left(\frac{\omega_0 \tau_0}{4 \ln \sqrt{2}}\right)^2 - \alpha_{3, (2N+2)(h_1+h_2)}} \\
&\quad \times \left. \int_{-\infty}^{\infty} e^{-\left(\frac{\tau_0}{4 \ln \sqrt{2}}\right)^2 \omega^2 + \left(j \left(\frac{b(2N+2)(h_1+h_2)}{c_{23}} - t \right) + \frac{2\omega_0 \tau_0^2}{(4 \ln \sqrt{2})^2} \right) \omega} d\omega \right). \tag{2.40}
\end{aligned}$$

Taking the integrals in (2.40), we will present this expression as:

$$\begin{aligned}
P_{2w.}(t') &= \sqrt{V_L} \cdot \sum_{N=0}^{\infty} V_L^N \cdot \frac{P_{0w.}\tau_0}{4\sqrt{\pi} \ln \sqrt{2}} \\
&\quad \times \left(\exp \left(- \left(\frac{\omega_0 \tau_0}{4 \ln \sqrt{2}} \right)^2 - \alpha_{3, 2N(h_1+h_2)} \right) \cdot \frac{4\sqrt{\pi} \ln \sqrt{2}}{\tau_0} \right. \\
&\quad \times \exp \left(\frac{\left(j \left(\frac{2Nb(h_1+h_2)}{c_{23}} - t \right) + \frac{2\omega_0 \tau_0^2}{(4 \ln \sqrt{2})^2} \right)^2}{\left(\frac{\tau_0}{\ln 2} \right)^2} \right) \\
&\quad - \exp \left(- \left(\frac{\omega_0 \tau_0}{4 \ln \sqrt{2}} \right)^2 - \alpha_{3, (2N+2)(h_1+h_2)} \right) \cdot \frac{4\sqrt{\pi} \ln \sqrt{2}}{\tau_0} \\
&\quad \times \left. \exp \left(\frac{\left(j \left(\frac{b(2N+2)(h_1+h_2)}{c_{23}} - t \right) + \frac{2\omega_0 \tau_0^2}{(4 \ln \sqrt{2})^2} \right)^2}{\left(\frac{\tau_0}{\ln 2} \right)^2} \right) \right), \tag{2.41}
\end{aligned}$$

after making the transformation, for the convenience of selecting the real and imaginary component, the pulse ultrasonic signal reflected from this material can be shown as:

$$\begin{aligned}
 P_{2w.}(t') &= \text{Re } P_{2w.}(t') + j \text{Im } P_{2w.}(t') = P_{0w.} \cdot \sqrt{V_L} \cdot \sum_{N=0}^{\infty} V_L^N \\
 &\times \left(\left(\cos \left(\omega_0 \left(\frac{2Nb(h_1 + h_2)}{c_{23}} - t \right) \right) \right. \right. \\
 &\left. \left. + j \sin \left(\omega_0 \left(\frac{2Nb(h_1 + h_2)}{c_{23}} - t \right) \right) \right) \right) \\
 &\times \exp \left(- \frac{\left(\frac{2Nb(h_1 + h_2)}{c_{23}} - t \right)^2}{\left(\frac{\tau_0}{\ln 2} \right)^2} - \alpha_3 \cdot 2N(h_1 + h_2) \right) \\
 &- \left(\cos \left(\omega_0 \left(\frac{b(2N + 2)(h_1 + h_2)}{c_{23}} - t \right) \right) \right. \\
 &\left. + j \sin \left(\omega_0 \left(\frac{b(2N + 2)(h_1 + h_2)}{c_{23}} - t \right) \right) \right) \\
 &\times \exp \left(- \frac{\left(\frac{b(2N + 2)(h_1 + h_2)}{c_{23}} - t \right)^2}{\left(\frac{\tau_0}{\ln 2} \right)^2} \right) \\
 &- \alpha_3 \cdot (2N + 2)(h_1 + h_2) \Big). \tag{2.42}
 \end{aligned}$$

From the obtained expression (2.42) for a complex presentation of pressure in the waves of the pulse ultrasonic signal reflected from the two-layer material, it is possible to receive separately the real part $\text{Re } P_{2w.}(t')$ and the imaginary component $\text{Im } P_{2w.}(t')$. As only the real component of pressure in the wave is measured $\text{Re } P_{2w.}(t')$ and the imaginary component $\text{Im } P_{2w.}(t')$ is used to determine the phase shift φ_V of the signal, they will be presented by separate expressions. The real component $\text{Re } P_{2w.}(t')$ will be shown in the pressure values as:

$$\begin{aligned}
 \text{Re } P_{2w.}(t') &= P_{0w.} \cdot \sqrt{V_L} \cdot \sum_{N=0}^{\infty} V_L^N \cdot \left(\cos \left(\omega_0 \left(\frac{2Nb(h_1 + h_2)}{c_{23}} - t \right) \right) \right. \\
 &\times \exp \left(- \frac{\left(\frac{2Nb(h_1 + h_2)}{c_{23}} - t \right)^2}{\left(\frac{\tau_0}{\ln 2} \right)^2} - \alpha_3 \cdot 2N(h_1 + h_2) \right) \\
 &\left. - \cos \left(\omega_0 \left(\frac{b(2N + 2)(h_1 + h_2)}{c_{23}} - t \right) \right) \right)
 \end{aligned}$$

$$\begin{aligned}
& \times \exp \left(- \frac{\left(\frac{b(2N+2)(h_1+h_2)}{c_{23}} - t \right)^2}{\left(\frac{\tau_0}{\ln 2} \right)^2} \right) \\
& - \alpha_{3, (2N+2)(h_1+h_2)})).
\end{aligned} \tag{2.43}$$

The imaginary component $\text{Im } P_{2w.}(t')$ of the pulse ultrasound signal is then given as follows:

$$\begin{aligned}
\text{Im } P_{2w.}(t') &= P_{0w.} \cdot \sqrt{V_L} \cdot \sum_{N=0}^{\infty} V_L^N \cdot \left(\sin \left(\omega_0 \left(\frac{2Nb(h_1+h_2)}{c_{23}} - t \right) \right) \right. \\
& \times \exp \left(- \frac{\left(\frac{2Nb(h_1+h_2)}{c_{23}} - t \right)^2}{\left(\frac{\tau_0}{\ln 2} \right)^2} - \alpha_{3, 2N(h_1+h_2)} \right) \\
& - \sin \left(\omega_0 \left(\frac{b(2N+2)(h_1+h_2)}{c_{23}} - t \right) \right) \\
& \times \exp \left(- \frac{\left(\frac{b(2N+2)(h_1+h_2)}{c_{23}} - t \right)^2}{\left(\frac{\tau_0}{\ln 2} \right)^2} \right) \\
& \left. - \alpha_{3, (2N+2)(h_1+h_2)} \right)).
\end{aligned} \tag{2.44}$$

The amplitude of the wave of this pulse signal reflected from the material in relative units in accordance with the dependences (2.17) and (2.43), taking into account the time delay of the waves in the media of the components of the material, will be shown as follows:

$$\begin{aligned}
A_V(t') &= \sqrt{V_L} \cdot \sum_{N=0}^{\infty} V_L^N \cdot \left(\cos \left(\omega_0 \left(\frac{2Nb(h_1+h_2)}{c_{23}} - t \right) \right) \right. \\
& \times \exp \left(- \frac{\left(\frac{2Nb(h_1+h_2)}{c_{23}} - t \right)^2}{\left(\frac{\tau_0}{\ln 2} \right)^2} - \alpha_{3, 2N(h_1+h_2)} \right) \\
& - \cos \left(\omega_0 \left(\frac{b(2N+2)(h_1+h_2)}{c_{23}} - t \right) \right) \\
& \times \exp \left(- \frac{\left(\frac{b(2N+2)(h_1+h_2)}{c_{23}} - t \right)^2}{\left(\frac{\tau_0}{\ln 2} \right)^2} \right) \\
& \left. - \alpha_{3, (2N+2)(h_1+h_2)} \right)).
\end{aligned} \tag{2.45}$$

The phase shift of the ultrasonic pulse signal reflected from such a composition of layers of the material without pores, can be presented as:

$$\varphi_V = \arctg \frac{\sum_{N=0}^{\infty} V_L^N \cdot (\exp(Y_1) \sin(\omega_0 Y_3) - \exp(Y_2) \sin(\omega_0 Y_4))}{\sum_{N=0}^{\infty} V_L^N \cdot (\exp(Y_1) \cos(\omega_0 Y_3) - \exp(Y_2) \cos(\omega_0 Y_4))}, \quad (2.46)$$

where

$$\begin{aligned} Y_1 &= -\frac{\left(\frac{2Nb(h_1+h_2)}{c_{23}} - t\right)^2}{\left(\frac{\tau_0}{\ln 2}\right)^2} - \alpha_3 \cdot 2N(h_1 + h_2), \\ Y_2 &= -\frac{\left(\frac{b(2N+2)(h_1+h_2)}{c_{23}} - t\right)^2}{\left(\frac{\tau_0}{\ln 2}\right)^2} - \alpha_3 \cdot (2N + 2)(h_1 + h_2), \\ Y_3 &= \frac{2Nb(h_1 + h_2)}{c_{23}} - t, \quad Y_4 = \frac{b(2N + 2)(h_1 + h_2)}{c_{23}} - t. \end{aligned}$$

The wave amplitude of the pulse signal reflected from the two layers of the material, in relative units, taking into account the through pores in the media of the components of the material (Fig. 2.5) will be shown as follows:

$$\begin{aligned} A_{V_p}(t') &= \sqrt{V_L} \cdot \sum_{N=0}^{\infty} V_L^N \cdot \left(\cos\left(\omega_0 \left(\frac{2Nb(h_1 + h_2) \cos v}{c_{23}} - t\right)\right) \right. \\ &\quad \times \exp\left(-\frac{\left(\frac{2Nb(h_1+h_2) \cos v}{c_{23}} - t\right)^2}{\left(\frac{\tau_0}{\ln 2}\right)^2} - \alpha_3 \cdot 2N(h_1 + h_2) \cos v\right) \\ &\quad \left. - \cos\left(\omega_0 \left(\frac{b(2N + 2)(h_1 + h_2) \cos v}{c_{23}} - t\right)\right) \right. \\ &\quad \times \exp\left(-\frac{\left(\frac{b(2N+2)(h_1+h_2) \cos v}{c_{23}} - t\right)^2}{\left(\frac{\tau_0}{\ln 2}\right)^2} - \alpha_3 \cdot (2N + 2)(h_1 + h_2) \cos v\right) \Big). \end{aligned} \quad (2.47)$$

The phase shift φ_{V_p} for this ultrasonic signal, reflected from the porous two-layer material, can be represented by dependence (2.46), but the values included in the expression itself, will be given for this case as:

$$Y_1 = -\frac{\left(\frac{2Nb(h_1+h_2) \cos v}{c_{23}} - t\right)^2}{\left(\frac{\tau_0}{\ln 2}\right)^2} - \alpha_3 \cdot 2N(h_1 + h_2) \cos v,$$

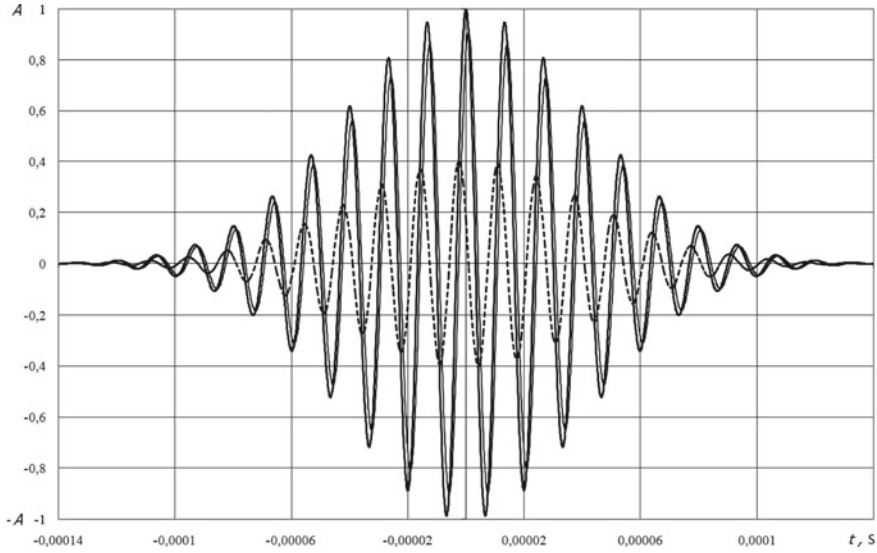


Fig. 2.5 Change of amplitudes A_0 , A_{Wp} , A_{Vp} of ultrasonic wave packages in relative units over time t , c for two-layer porous material with a total $h = 20 \mu\text{m}$. — amplitude A_0 of ultrasonic waves that fall on the material; — amplitude A_{Wp} of ultrasonic waves that pass through the material; ---- amplitude A_{Vp} of ultrasonic waves that are reflected from the material

$$Y_2 = -\frac{\left(\frac{b(2N+2)(h_1+h_2)\cos v}{c_{23}} - t\right)^2}{\left(\frac{\tau_0}{\ln 2}\right)^2} - \alpha_3(2N+2)(h_1+h_2)\cos v,$$

$$Y_3 = \frac{2Nb(h_1+h_2)\cos v}{c_{23}} - t, \quad Y_4 = \frac{b(2N+2)(h_1+h_2)\cos v}{c_{23}} - t.$$

Let us also consider the reflection of the pulse ultrasonic signal from a single-layer material with a thickness h_1 and acoustic impedance Z_2 , as described above for the waves that have passed through two layers of the material (Fig. 2.6a, b). In addition, we believe that the material was placed in the air medium $Z_1 = Z_4$, then for the amplitude of the pulse ultrasonic signal, by carrying out similar transformations of expressions for this case, it is possible to obtain the following dependence:

$$V(\omega) = \frac{V_{21} - V_{21} \cdot e^{2j\left(\frac{\omega b}{c_2} + j\alpha_3\right) \cdot h_1}}{1 - V_{21}V_{21} \cdot e^{2j\left(\frac{\omega b}{c_2} + j\alpha_3\right) \cdot h_1}}, \quad (2.48)$$

or

$$V(\omega) = \frac{\frac{Z_2-Z_1}{Z_1+Z_2} - \frac{Z_2-Z_1}{Z_1+Z_2} \cdot e^{-2\left(-j\frac{\omega b}{c_2} + \alpha_3\right) \cdot h_1}}{1 - \left(\frac{Z_2-Z_1}{Z_1+Z_2}\right)^2 \cdot e^{-2\left(-j\frac{\omega b}{c_2} + \alpha_3\right) \cdot h_1}}, \quad (2.49)$$

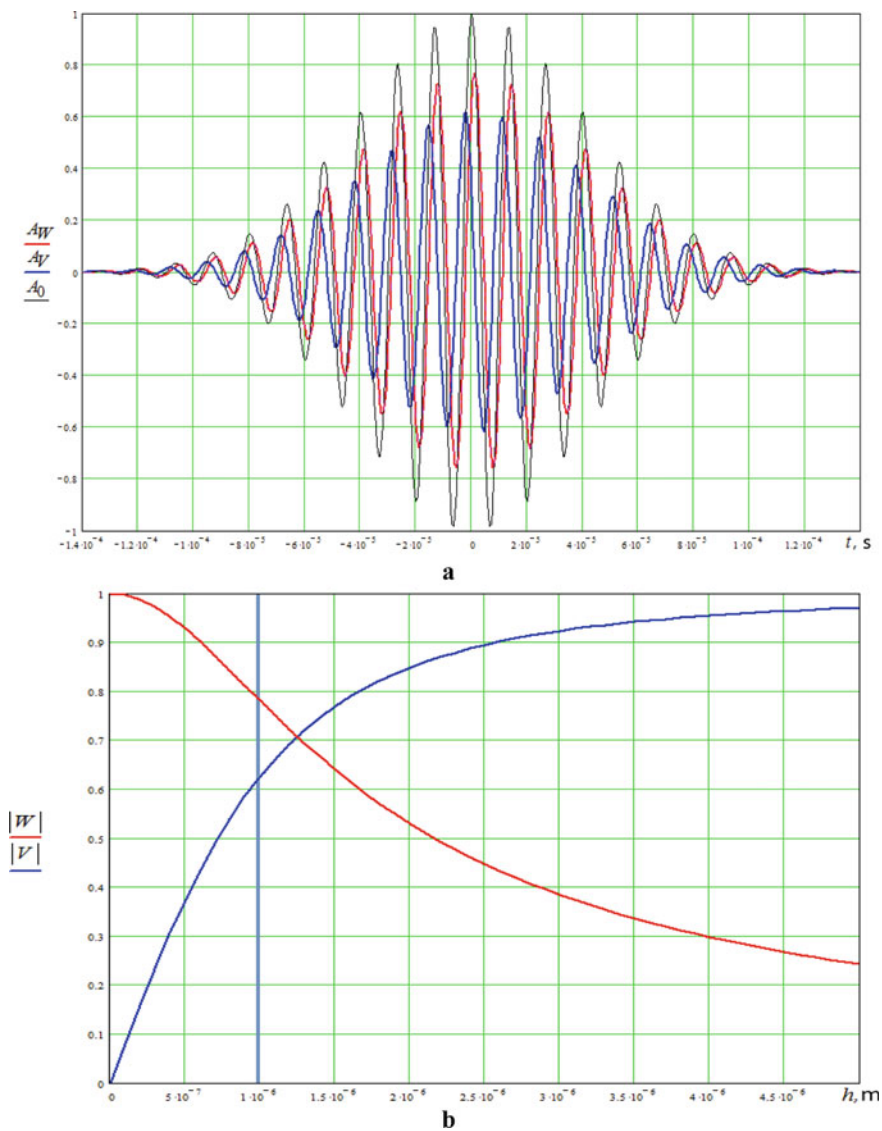


Fig. 2.6 Change in amplitudes A_0 , A_W , A_V for a thin film of $1 \mu\text{m}$ and modules $|W|$, $|V|$: **a** change in amplitudes A_0 , A_W , A_V of sounding waves for a thin film with $h = 1 \mu\text{m}$; **b** dependences of module changes $|W|$, $|V|$ of waves on the film thickness h (cross-section of $1 \mu\text{m}$)

for the convenience of further transformations, the expression (2.49) is shown as:

$$V(\omega) = \frac{Z_2 - Z_1}{Z_1 + Z_2} \cdot \sum_{N=0}^{\infty} \left(\frac{Z_2 - Z_1}{Z_1 + Z_2} \right)^{2N} \cdot e^{-2N \left(-j \frac{\omega b}{c_2} + \alpha_3 \right) \cdot h_1} - \frac{Z_2 - Z_1}{Z_1 + Z_2} \cdot \sum_{N=0}^{\infty} \left(\frac{Z_2 - Z_1}{Z_1 + Z_2} \right)^{2N} \cdot e^{-(2N+2) \left(-j \frac{\omega b}{c_2} + \alpha_3 \right) \cdot h_1}, \quad (2.50)$$

then having performed similar transformations for this case, but immediately taking into account through pores in the material (Figs. 2.7, 2.8 and 2.9), we will obtain the following expression for the amplitude of the reflected wave of the pulse signal:

$$A_{Vp}(t') = \frac{Z_2 - Z_1}{Z_1 + Z_2} \sum_{N=0}^{\infty} \left(\frac{Z_2 - Z_1}{Z_1 + Z_2} \right)^{2N} \cdot \left(\cos \left(\omega_0 \left(\frac{2Nb h_1 \cos \nu}{c_2} - t \right) \right) \times \exp \left(- \frac{\left(\frac{2Nb h_1 \cos \nu}{c_2} - t \right)^2}{\left(\frac{\tau_0}{\ln 2} \right)^2} - \alpha_3 \cdot 2N h_1 \cos \nu \right) - \cos \left(\omega_0 \left(\frac{b(2N+2) h_1 \cos \nu}{c_2} - t \right) \right) \times \exp \left(- \frac{\left(\frac{b(2N+2) h_1 \cos \nu}{c_2} - t \right)^2}{\left(\frac{\tau_0}{\ln 2} \right)^2} - \alpha_3 \cdot (2N+2) h_1 \cos \nu \right) \right). \quad (2.51)$$

As for the dependence (2.23) we will obtain the expression for the pulse signal reflected from the controlled single-layer fabric (Fig. 2.10) with an average thickness ranging from two to three mean diameters of the warp and weft threads with the parameter $\cos \nu$ within $\frac{3}{4} > \cos \nu > 0$. The dependence for this signal can be given as follows:

$$P_{2w.}(t') = P_{2w.} \left(\frac{\pi d_{oy}}{4c_2} - t \right) = \frac{1}{2\pi} \int_{-\infty}^{\infty} V_{\alpha\beta}(\omega) S(\omega) \cdot e^{j\omega \left(\frac{\pi d_{oy}}{4c_2} - t \right)} d\omega. \quad (2.52)$$

The complex reflection coefficient from this fabric can then be presented as:

$$V_{\alpha\beta}(\omega) = \frac{\frac{Z_2 - Z_1}{Z_1 + Z_2} - \frac{Z_2 - Z_1}{Z_1 + Z_2} \cdot e^{2 \left(j \frac{\omega b}{c_2} - \alpha_3 \right) \cdot d_{oy} \frac{\pi}{4} \cos \nu}}{1 - \left(\frac{Z_2 - Z_1}{Z_1 + Z_2} \right)^2 \cdot e^{2 \left(j \frac{\omega b}{c_2} - \alpha_3 \right) \cdot d_{oy} \frac{\pi}{4} \cos \nu}}. \quad (2.53)$$

Taking into account the dependences (2.52) and (2.53), similarly to the previously considered cases, it is possible to obtain an expression for the amplitude of the pulse

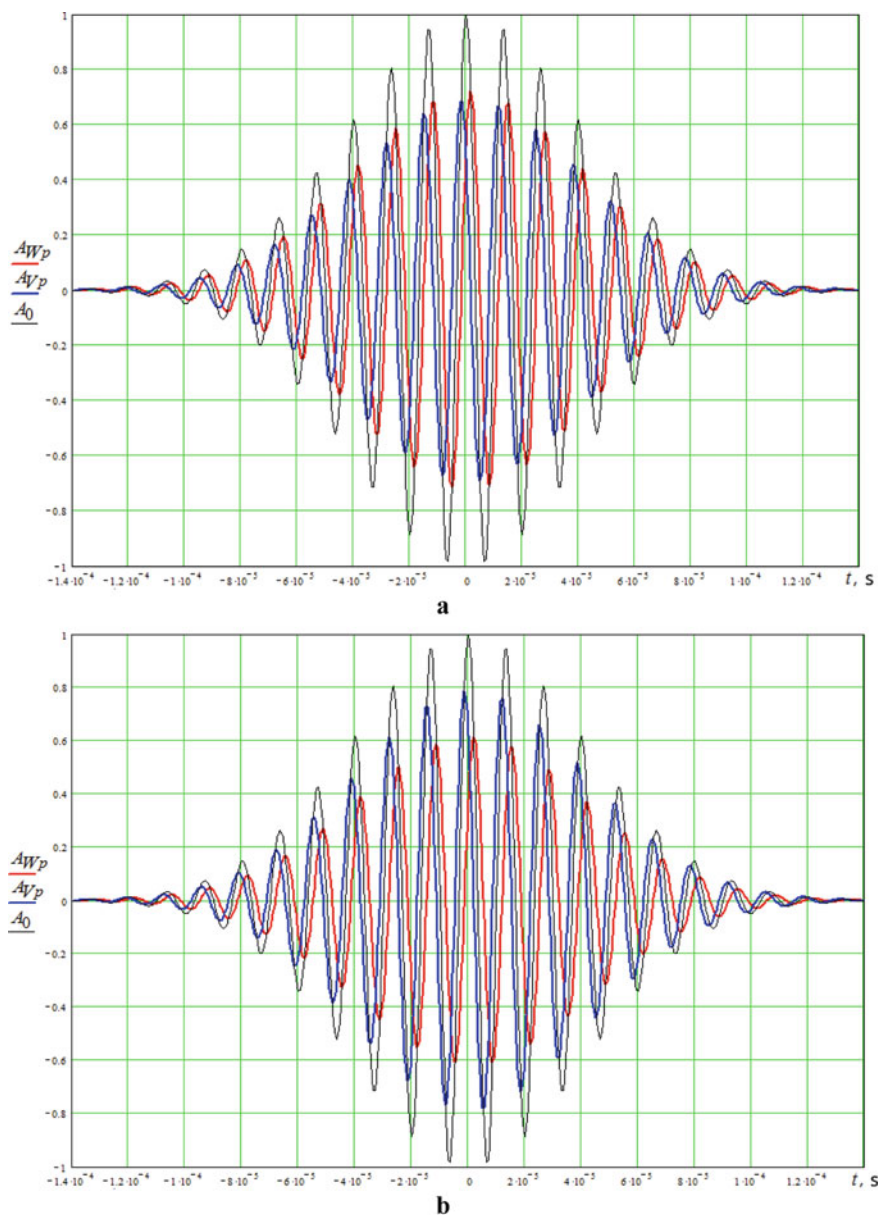


Fig. 2.7 Change in amplitudes A_0 , A_{Wp} , A_{Vp} for the materials with pores at $\cos \nu = 0.002$: **a** change in amplitudes of sounding waves for the polymeric material with $h = 0.6$ mm; **b** change in amplitudes of sounding waves for the polymeric material with $h = 0.8$ mm

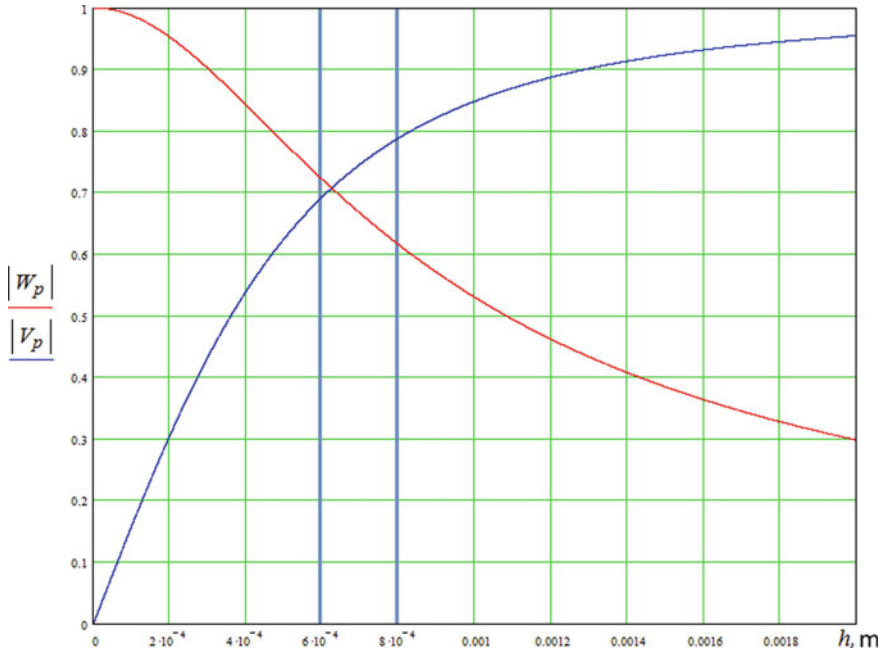


Fig. 2.8 Dependences of the module change $|W_p|$, $|V_p|$ of complex coefficients of transmission and reflection of waves from the thickness h of the polymeric material with pores at $\cos \nu = 0.002$ (cross-section with $h = 0.6$ mm and $h = 0.8$ mm)

ultrasonic signal reflected from the fabric, associating it with the thickness through the diameters of warp and weft treads of the material. It should be also noted that for this case, the phase structure of the fabric is considered, which has an additional effect on the parameter $\cos \nu$ at the same parameters of the ultrasonic incident signal waves. This results in an additional time delay of the ultrasonic pulse compared to the delay in the single-layer material. This pulse signal propagates in a nonuniform (presence of through pores and porosity inside between the fibers of the fabric treads is possible) textile material, so when it is reflected from the threads, the expression for the amplitude can be shown in relative units as follows:

$$\begin{aligned}
 A_{V\alpha}(t') = & \frac{Z_2 - Z_1}{Z_1 + Z_2} \sum_{N=0}^{\infty} \left(\frac{Z_2 - Z_1}{Z_1 + Z_2} \right)^{2N} \cdot \left(\cos \left(\omega_0 \left(\frac{\pi d_{oy}(2Nb \cos \nu + 1)}{4c_2} - t \right) \right) \right) \\
 & \times \exp \left(- \frac{\left(\frac{\pi d_{oy}(2Nb \cos \nu + 1)}{4c_2} - t \right)^2}{\left(\frac{\tau_0}{\ln 2} \right)^2} - \frac{\alpha_3, 2N \pi d_{oy} \cos \nu}{4} \right) \\
 & - \cos \left(\omega_0 \left(\frac{\pi d_{oy}(b(2N + 2) \cos \nu + 1)}{4c_2} - t \right) \right)
 \end{aligned}$$

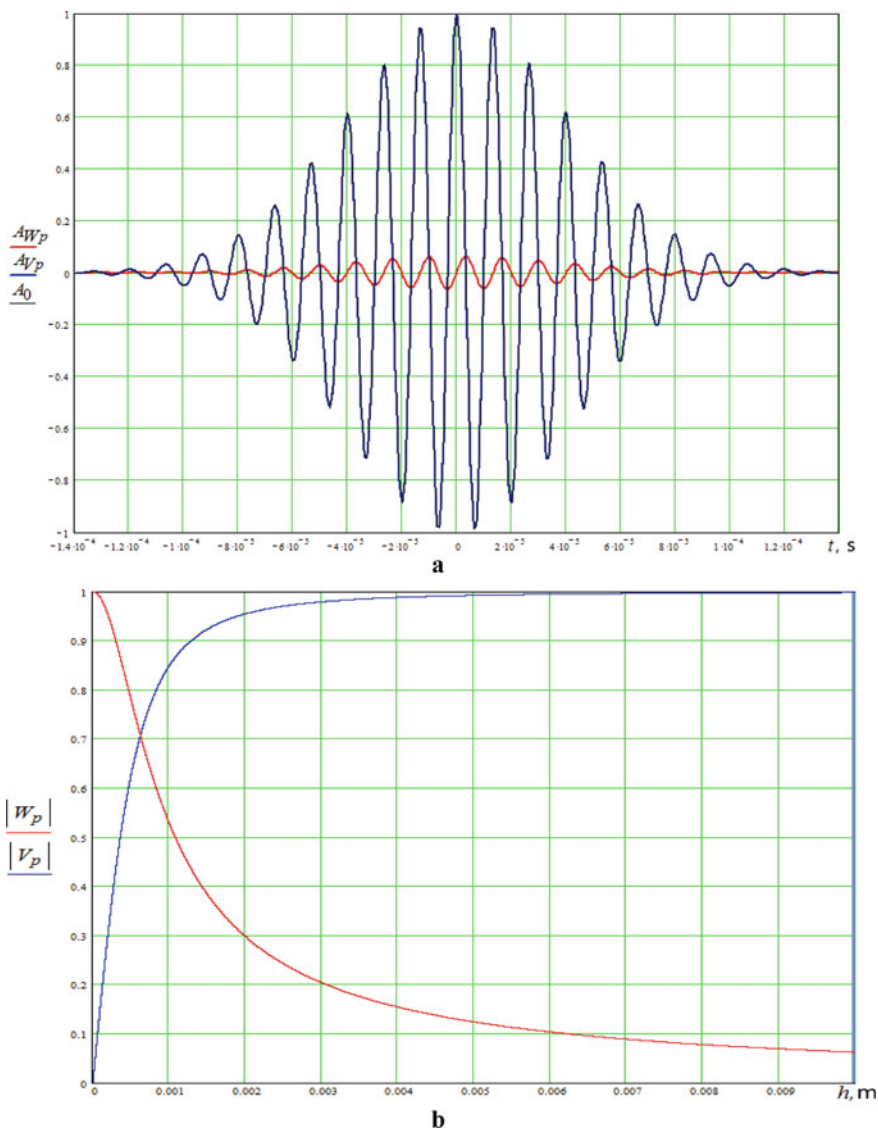


Fig. 2.9 Change in amplitudes A_0 , A_{Wp} , A_{Vp} for the material of 1 cm and modules $|W_p|$, $|V_p|$: **a** change in amplitudes A_0 , A_{Wp} , A_{Vp} of sounding waves for the material with $h = 1$ cm, with pores at $\cos \nu = 0.002$; **b** dependences of a wave module change $|W_p|$, $|V_p|$ on the thickness h of the material with pores at $\cos \nu = 0.002$ (cross-section of $h = 1$ cm)

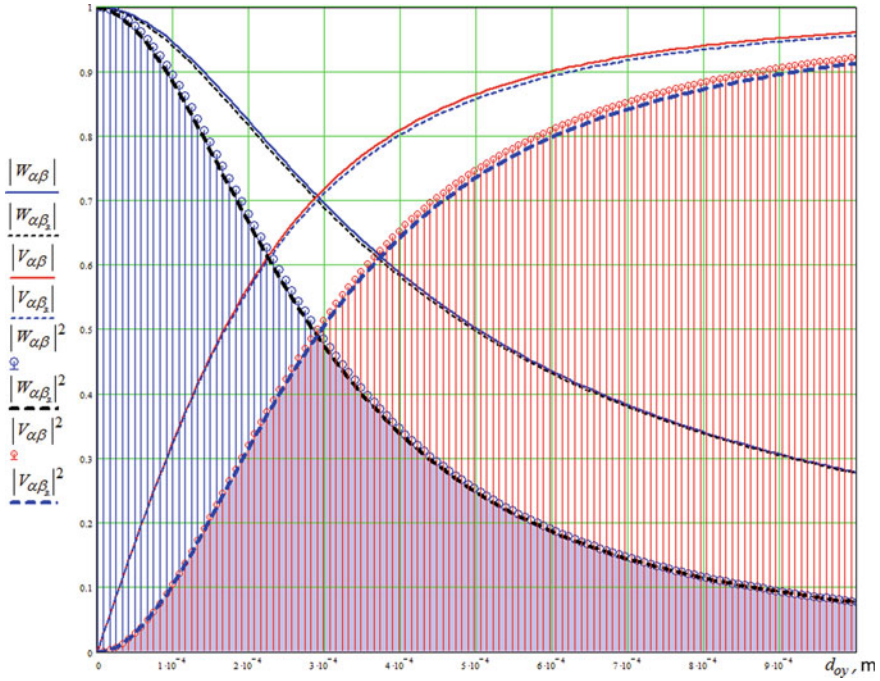


Fig. 2.10 Dependence of modules without attenuation $|W_{\alpha\beta}|$, $|V_{\alpha\beta}|$ ($\alpha_3 = 0$), with attenuation $|W_{\alpha\beta_3}|$, $|V_{\alpha\beta_3}|$ ($\alpha_3 = 15 \text{ m}^{-1}$) and their coefficients by energy without attenuation $|W_{\alpha\beta}|^2$, $|V_{\alpha\beta}|^2$ ($\alpha_3 = 0$), with attenuation $|W_{\alpha\beta_3}|^2$, $|V_{\alpha\beta_3}|^2$ ($\alpha_3 = 15 \text{ m}^{-1}$) on the sum of warp and weft thread diameters d_{oy} of the fabric at $\cos \nu = 0.0147$

$$\times \exp \left(- \frac{\left(\frac{\pi d_{oy}(b(2N+2) \cos \nu + 1)}{4c_2} - t \right)^2}{\left(\frac{\tau_0}{\ln 2} \right)^2} - \frac{\alpha_3 (2N+2) \pi d_{oy} \cos \nu}{4} \right). \quad (2.54)$$

For the controlled fabric with the parameter $\cos \nu$ within $1 > \cos \nu > \frac{3}{4}$ the amplitude of the reflected pulse signal can be given as:

$$A_{V\beta}(t') = \frac{Z_2 - Z_1}{Z_1 + Z_2} \sum_{N=0}^{\infty} \left(\frac{Z_2 - Z_1}{Z_1 + Z_2} \right)^{2N} \cdot \left(\cos \left(\omega_0 \left(\frac{\pi d_{oy} 2Nb \cos \nu}{4c_2} - t \right) \right) \right. \\ \left. \times \exp \left(- \frac{\left(\frac{\pi d_{oy} 2Nb \cos \nu}{4c_2} - t \right)^2}{\left(\frac{\tau_0}{\ln 2} \right)^2} - \frac{\alpha_3 2N \pi d_{oy} \cos \nu}{4} \right) \right)$$

$$\begin{aligned}
& - \cos \left(\omega_0 \left(\frac{\pi d_{oy} b(2N+2) \cos \nu}{4c_2} - t \right) \right) \\
& \times \exp \left(- \frac{\left(\frac{\pi d_{oy} b(2N+2) \cos \nu}{4c_2} - t \right)^2}{\left(\frac{\tau_0}{\ln 2} \right)^2} \right) \\
& - \frac{\alpha_3 \cdot (2N+2) \pi d_{oy} \cos \nu}{4} \left. \right) \Bigg). \quad (2.55)
\end{aligned}$$

If we write down the expression (2.52) for the reflected pulse signal, with a thickness in the range from two to three mean diameters of the warp and weft thread with the parameter $\cos \nu$ within $\frac{3}{4} > \cos \nu > 0$, associating it with the basis weight m_s of the controlled fabric (Figs. 2.11 and 2.12), this dependence can be shown as follows:

$$P_{2w.}(t') = P_{2w.} \left(\frac{K m_s}{\pi Z_2} - t \right) = \frac{1}{2\pi} \int_{-\infty}^{\infty} V_{\alpha\beta}(\omega) S(\omega) \cdot e^{j\omega \left(\frac{K m_s}{\pi Z_2} - t \right)} d\omega. \quad (2.56)$$

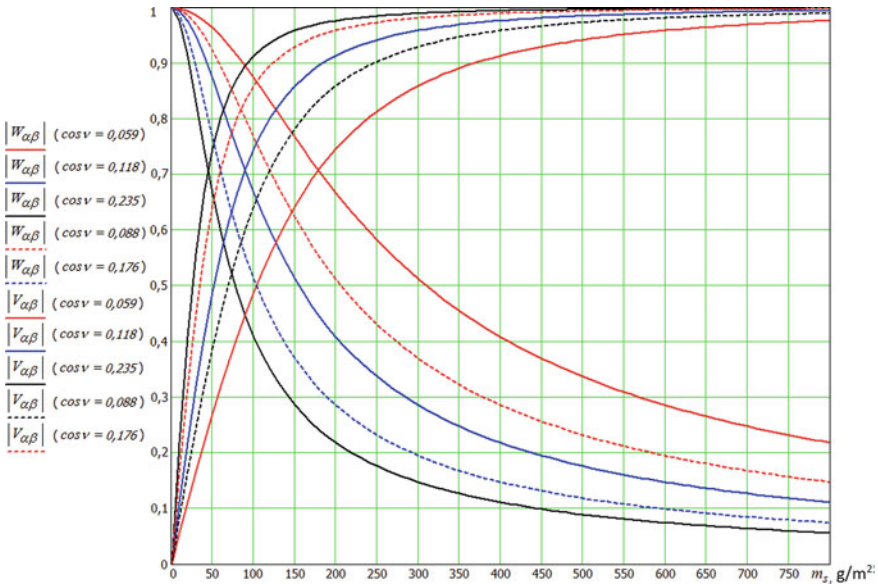


Fig. 2.11 Dependence of modules of complex transmission coefficient $|W_{\alpha\beta}|$ and reflection $|V_{\alpha\beta}|$ of ultrasonic waves from the fabric basis weight m_s , g/m² at various values of $\cos \nu$

A complex coefficient of reflection from this fabric, taking into account the dependence (2.53) and relating it to the basis weight m_s of the controlled fabric, can be presented as:

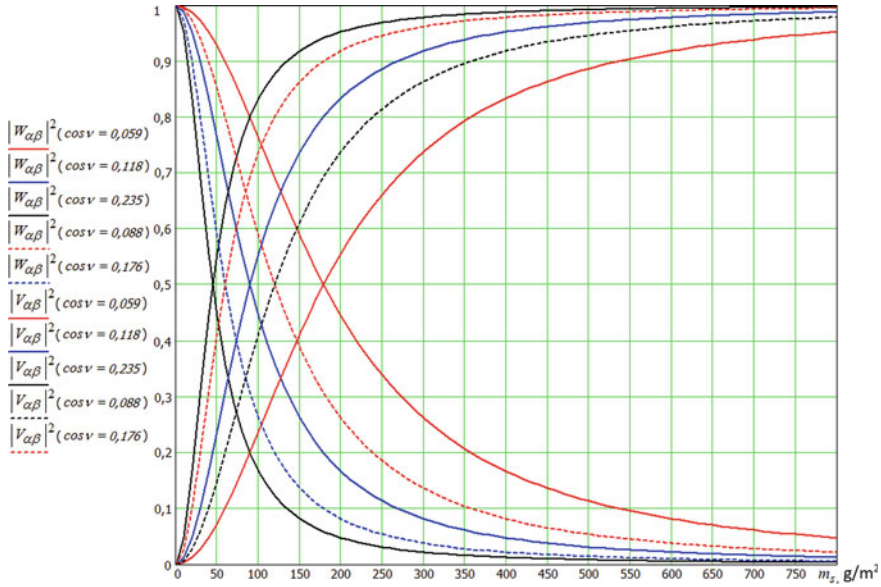


Fig. 2.12 Dependence of transmission $|W_{\alpha\beta}|^2$ and reflection $|V_{\alpha\beta}|^2$ coefficients by energy for ultrasonic waves from the fabric basis weight m_s , g/m^2 of fabrics at various values of $\cos \nu$

$$V_{\alpha\beta}(\omega) = \frac{\frac{Z_2 - Z_1}{Z_1 + Z_2} - \frac{Z_2 - Z_1}{Z_1 + Z_2} \cdot e^{2\left(j\frac{\omega b}{c_2} - \alpha_3\right) \cdot \frac{K m_s \cos \nu}{\pi \rho_2}}}{1 - \left(\frac{Z_2 - Z_1}{Z_1 + Z_2}\right)^2 \cdot e^{2\left(j\frac{\omega b}{c_2} - \alpha_3\right) \cdot \frac{K m_s \cos \nu}{\pi \rho_2}}} \quad (2.57)$$

Considering the dependences (2.54), (2.56) and (2.57), it is possible to obtain the expression for the amplitude of the pulse ultrasonic signal reflected from the material, associating it with the basis weight m_s of the controlled fabric.

The reflected pulse ultrasonic signal should be used to determine the total porosity of the textile fabric, the structure of which may provide additional ultrasonic signal propagation, which may affect the overall reception and processing of the resulting signal; therefore, it is necessary to keep this in mind when using relative measurements of the amplitudes of ultrasonic waves that interact with the fabric. The expression for the amplitude of the reflected pulse ultrasonic signal can be shown in relative units as:

$$A_{V\alpha}(t') = \frac{Z_2 - Z_1}{Z_1 + Z_2} \sum_{N=0}^{\infty} \left(\frac{Z_2 - Z_1}{Z_1 + Z_2}\right)^{2N} \cdot \left(\cos\left(\omega_0 \left(\frac{K m_s (2Nb \cos \nu + 1)}{\pi Z_2} - t\right)\right)\right) \times \exp\left(-\frac{\left(\frac{K m_s (2Nb \cos \nu + 1)}{\pi Z_2} - t\right)^2}{\left(\frac{\tau_0}{\ln 2}\right)^2} - \frac{\alpha_3 \cdot 2N K m_s \cos \nu}{\pi \rho_2}\right)$$

$$\begin{aligned}
& - \cos \left(\omega_0 \left(\frac{K m_s (b(2N+2) \cos \nu + 1)}{\pi Z_2} - t \right) \right) \\
& \times \exp \left(- \frac{\left(\frac{K m_s (b(2N+2) \cos \nu + 1)}{\pi Z_2} - t \right)^2}{\left(\frac{\tau_0}{\ln 2} \right)^2} \right. \\
& \left. - \frac{\alpha_3 (2N+2) K m_s \cos \nu}{\pi \rho_2} \right) \Bigg). \tag{2.58}
\end{aligned}$$

For the controlled fabric with the parameter $\cos \nu$ within $1 > \cos \nu > \frac{3}{4}$ the expression (2.55), by associating the amplitude of the reflected pulse signal with the basis weight m_s , can be given as:

$$\begin{aligned}
A_{V\beta}(t') &= \frac{Z_2 - Z_1}{Z_1 + Z_2} \sum_{N=0}^{\infty} \left(\frac{Z_2 - Z_1}{Z_1 + Z_2} \right)^{2N} \cdot \left(\cos \left(\omega_0 \left(\frac{K m_s 2Nb \cos \nu}{\pi Z_2} - t \right) \right) \right. \\
& \times \exp \left(- \frac{\left(\frac{K m_s 2Nb \cos \nu}{\pi Z_2} - t \right)^2}{\left(\frac{\tau_0}{\ln 2} \right)^2} - \frac{\alpha_3 2N K m_s \cos \nu}{\pi \rho_2} \right) \\
& - \cos \left(\omega_0 \left(\frac{K m_s b(2N+2) \cos \nu}{\pi Z_2} - t \right) \right) \\
& \times \exp \left(- \frac{\left(\frac{K m_s b(2N+2) \cos \nu}{\pi Z_2} - t \right)^2}{\left(\frac{\tau_0}{\ln 2} \right)^2} \right. \\
& \left. \left. - \frac{\alpha_3 (2N+2) K m_s \cos \nu}{\pi \rho_2} \right) \right) \Bigg). \tag{2.59}
\end{aligned}$$

Having obtained analytical dependences for ultrasonic waves, it is possible to study various single-layer and double-layer composite and textile materials on the interaction with them. Due to the change in the amplitude ratios of ultrasonic waves (units of complex wave coefficients) and due to the phase shift or time delay of the signal, it is possible to show this interaction of oscillations with the material itself, which may have a different structure.

The dependence for changing the amplitudes of ultrasonic waves in the pulse signal package over time at a total thickness of two layers up to 2 mm, if the acoustic supports of the two layers are close to each other, can be represented by an expression for a single-layer material to simplify calculations when building a mathematical model. The possibility of using the expressions of single-layer materials for two layers of the composite can often be used in practice for different textile materials. This can be explained by the structure of different textile materials, which can affect the transmission of ultrasonic waves more than the material itself. The thread fibers of the textile material, as well as the position of the threads themselves in its structure,

can make additional dispersion of ultrasonic waves. Therefore, in a small range of ultrasonic oscillation frequencies, in which non-contact control can be performed for different materials with a complex structure, it is necessary to select the ratio of the ultrasonic wavelength to the distance of the thread diameter and pores of the textile fabric together. The greater this ratio is, the more the structure of the textile material will approach the flat layer. If we consider a solid material in which only through pores are made, additional dispersion (both from the fibers of the textile material and from its structure) may not occur. This case is considered below for a two-layer material with through pores. Using the obtained expressions in Fig. 2.5, there was shown the change in amplitudes A_0 , A_{Wp} , A_{Vp} of ultrasonic wave packages in relative units over time t taking into account the phase shift for a two-layer porous material with a $10 \mu\text{m}$ thickness of each layer.

It can be seen from Fig. 2.5 that for the total thickness of the material in $20 \mu\text{m}$, the amplitude of the waves passing through it is significant due to through pores. When sounding a solid single-layer material much smaller in thickness, the amplitude of ultrasonic waves passing through it will be smaller compared to the material with pores. Figure 2.6a shows the change in amplitudes A_0 , A_W , A_V of ultrasonic wave packages in relative units over time t considering the phase shift for a single-layer thin continuous film of $1 \mu\text{m}$, the acoustic impedance of the film is $Z_2 = 1893728 \text{ kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$. Figure 2.6b shows amplitude relations (modules of complex coefficients $|W|$ and $|V|$) of waves, of one that has passed or been reflected from the film material, to the other that falls on the material surface depending on its thickness h . Also Fig. 2.6b shows a cross-section of the values of the amplitude relations corresponding to the peak values of the amplitudes A_W , A_V of ultrasonic wave packages in relative units in Fig. 2.6a.

The demonstrated example allows us to see how a solid material can differ from a porous one in its ability to transmit ultrasonic vibrations. Therefore, according to the expressions obtained in the work, Fig. 2.7a, b shows the change of amplitudes A_0 , A_{Wp} , A_{Vp} with the phase shift of ultrasonic waves that have passed or been reflected from different materials with pores at which $\cos \nu = 0.002$. Figure 2.7a shows the wave that has passed through the porous material. It is slightly larger than the wave reflected from the material, and Fig. 2.7b, on the contrary, shows the same wave, but with a smaller amplitude, which interacted with another material. Figure 2.8 shows the dependences of the modules $|W_p|$, $|V_p|$ of complex coefficients of transmission and reflection of waves on the thickness h of the polymeric material with pores at $\cos \nu = 0.002$, as well as cross-sections of the values of the amplitude ratios that correspond to the peak values of the amplitudes A_{Wp} , A_{Vp} of ultrasonic wave packages in relative units in Fig. 2.7a, b.

The same parameters of ultrasonic waves and cross-section of the values of the amplitude ratios, but for a thicker material $h = 1 \text{ cm}$ at $\cos \nu = 0.002$ are shown in Fig. 2.9a, b.

Using expressions that allow to represent the dependence of amplitude ratios $|W_{\alpha\beta_3}|$, $|V_{\alpha\beta_3}|$ of ultrasonic waves and their transmission $|W_{\alpha\beta_3}|^2$ and reflection $|V_{\alpha\beta_3}|^2$ coefficients by energy directly on the sum of warp and weft thread diameters

d_{oy} , it is possible to analyze the influence of thread thickness and structure of different fabrics on the transmission and reflection of waves from textile fabrics taking into account attenuation of the signal itself.

Fig. 2.10 shows the dependences of the modules without attenuation $|W_{\alpha\beta}|$, $|V_{\alpha\beta}|$ ($\alpha_3 = 0$), with attenuation $|W_{\alpha\beta_3}|$, $|V_{\alpha\beta_3}|$ ($\alpha_3 = 15 \text{ m}^{-1}$) and their coefficients by energy without attenuation $|W_{\alpha\beta}|^2$, $|V_{\alpha\beta}|^2$ ($\alpha_3 = 0$), with attenuation $|W_{\alpha\beta_3}|^2$, $|V_{\alpha\beta_3}|^2$ ($\alpha_3 = 15 \text{ m}^{-1}$) on the sum of warp and weft thread diameters d_{oy} of the fabric at $\cos \nu = 0.0147$.

It can be seen from Fig. 2.10 that the attenuation introduces an error of less than 2% to the amplitude ratios $|W_{\alpha\beta_3}|$ and $|V_{\alpha\beta_3}|$ of ultrasonic waves. The energy distribution over the points shows that the energy in the course of passing and reflecting waves for this case will be the same at the point with the value $d_{oy} = 2,9 \cdot 10^{-4} \text{ m}$. This can be used to simplify the construction of special devices for non-contact control of fabric thickness with different structure.

Since the main technological parameter for the textile industry is the basis weight m_s of materials, it is obvious to use in practice the expressions for the amplitude ratios associated with, taking into account the parameter $\cos \nu$, which has a large impact depending on the structure of the material shown in Figs. 2.11 and 2.12.

The analysis showed that the obtained expressions for pulse ultrasonic signals, which can interact with materials with different structure, can be used to create new methods and means of non-destructive non-contact control over technological parameters of textile materials.

The dependences of the amplitude ratios of ultrasonic waves on the thickness of single-layer, two-layer materials with and without pores can be used to create new methods and means of controlling this parameter for various composite materials of a wide application. The dependences of the amplitude ratios of ultrasonic waves, where the thickness of the textile material is expressed by the sum of nominal diameters of the fabric warp and weft thread, will determine the fabric thickness taking into account the deformation of threads, porosity and phase structure. The basis weight of textile materials can be determined using the expressions obtained in the work, which also consider the structure of the fabric, which can be monitored continuously during production by ultrasonic waves that passed through the material and waves that reflected from it.

This leaves the question of how much the attenuation of ultrasonic waves affects their amplitude ratios during their transmission and reflection from the previously mentioned materials. This can affect the accuracy of devices, the construction of which will be based on the dependences of the interaction of ultrasonic waves with the complex structure of different composite and textile materials. Therefore, it is necessary to consider separately the attenuation of ultrasonic waves in their frequency range, which is suitable for non-contact control, in comparison with the thicknesses or surface densities of the previously considered materials with different structure.

This will allow to create complex and universal devices for non-contact control over various technological parameters for consumer goods in the textile industry.

2.4 Attenuation of the Pulse Ultrasonic Signal During the Wave Transmission and Reflection from Two-Layer Composite, Single-Layer Textile Materials with Through Pores and Without Them

The study of the pulse ultrasonic signal attenuation in the course of transmission and reflection of waves during their interaction with various controlled materials is an important task, the solution of which will improve the methods and accuracy of non-contact devices used to determine the basic technological parameters of composite and textile materials.

In order to conduct a detailed analysis of the effect of attenuation on the amplitude ratios of ultrasonic waves that have passed through the two-layer material to the waves that just fall on it, it is necessary to decompose the complex coefficient of oscillation $W(\omega)$ into real and imaginary components as follows:

$$W(\omega) = \operatorname{Re} W(\omega) + j \operatorname{Im} W(\omega), \quad (2.60)$$

where

$$\begin{aligned} \operatorname{Re} W(\omega) = & \frac{Z_1}{Z_1 + Z_2} \cdot \frac{Z_2}{Z_2 + Z_3} \cdot \frac{Z_3}{Z_3 + Z_4} \cdot \sum_{N=0}^{\infty} V_L^N \cdot \cos\left((2N+1) \frac{\omega b (h_1 + h_2)}{c_{23}}\right) \\ & \times e^{-\alpha_3 \cdot (2N+1) (h_1 + h_2)}, \end{aligned} \quad (2.61)$$

$$\begin{aligned} \operatorname{Im} W(\omega) = & \frac{Z_1}{Z_1 + Z_2} \cdot \frac{Z_2}{Z_2 + Z_3} \cdot \frac{Z_3}{Z_3 + Z_4} \cdot \sum_{N=0}^{\infty} V_L^N \cdot \sin\left((2N+1) \frac{\omega b (h_1 + h_2)}{c_{23}}\right) \\ & \times e^{-\alpha_3 \cdot (2N+1) (h_1 + h_2)}, \end{aligned} \quad (2.62)$$

then the module itself $|W(\omega)|$ or the amplitude ratio of ultrasonic waves with $h_1 \approx h_2$ will be shown as:

$$|W(\omega)| = \sqrt{\operatorname{Re} W(\omega)^2 + \operatorname{Im} W(\omega)^2}, \quad (2.63)$$

or

$$\begin{aligned} |W(\omega)| = & \left(\left(\frac{Z_1}{Z_1 + Z_2} \cdot \frac{Z_2}{Z_2 + Z_3} \cdot \frac{Z_3}{Z_3 + Z_4} \right)^2 \cdot \left(\sum_{N=0}^{\infty} V_L^N \cdot \cos\left((2N+1) \frac{\omega b (h_1 + h_2)}{c_{23}}\right) \right. \right. \\ & \times e^{-\alpha_3 \cdot (2N+1) (h_1 + h_2)} \Big)^2 + \left(\sum_{N=0}^{\infty} V_L^N \cdot \sin\left((2N+1) \frac{\omega b (h_1 + h_2)}{c_{23}}\right) \right. \\ & \times e^{-\alpha_3 \cdot (2N+1) (h_1 + h_2)} \Big)^2 \Big)^{\frac{1}{2}}. \end{aligned} \quad (2.64)$$

If this material is considered with through pores, then the dependence (2.64) is written as follows:

$$|W_p(\omega)| = \left(\left(\frac{Z_1}{Z_1 + Z_2} \cdot \frac{Z_2}{Z_2 + Z_3} \cdot \frac{Z_3}{Z_3 + Z_4} \right)^2 \times \left(\sum_{N=0}^{\infty} V_L^N \cdot \cos \left((2N+1) \frac{\omega b (h_1 + h_2) \cos \nu}{c_{23}} \right) \cdot e^{-\alpha_3 \cdot (2N+1) (h_1 + h_2) \cos \nu} \right)^2 + \left(\sum_{N=0}^{\infty} V_L^N \cdot \sin \left((2N+1) \frac{\omega b (h_1 + h_2) \cos \nu}{c_{23}} \right) \cdot e^{-\alpha_3 \cdot (2N+1) (h_1 + h_2) \cos \nu} \right)^2 \right)^{\frac{1}{2}}. \quad (2.65)$$

To find this dependence of wave amplitude ratios on the circular frequency ω taking into account attenuation α_3 , for a single-layer material with through pores, which can be characterized by the parameter $\cos \nu$ reflecting transmission of a part of sound energy through pores, it is necessary to write the following equations $\text{Re } W_p(\omega)$ and $\text{Im } W_p(\omega)$ and for this case as:

$$\text{Re } W_p(\omega) = \frac{4 Z_1 Z_2}{(Z_1 + Z_2)^2} \cdot \sum_{N=0}^{\infty} \left(\frac{Z_2 - Z_1}{Z_1 + Z_2} \right)^{2N} \cdot \cos \left((2N+1) \frac{\omega b h_1 \cos \nu}{c_2} \right) \times e^{-\alpha_3 \cdot (2N+1) h_1 \cos \nu}, \quad (2.66)$$

$$\text{Im } W_p(\omega) = \frac{4 Z_1 Z_2}{(Z_1 + Z_2)^2} \cdot \sum_{N=0}^{\infty} \left(\frac{Z_2 - Z_1}{Z_1 + Z_2} \right)^{2N} \cdot \sin \left((2N+1) \frac{\omega b h_1 \cos \nu}{c_2} \right) \times e^{-\alpha_3 \cdot (2N+1) h_1 \cos \nu}, \quad (2.67)$$

then the module $|W_p(\omega)|$ for a single-layer material with pores is obtained as follows:

$$|W_p(\omega)| = \left(\left(\frac{4 Z_1 Z_2}{(Z_1 + Z_2)^2} \right)^2 \cdot \left(\left(\sum_{N=0}^{\infty} \left(\frac{Z_2 - Z_1}{Z_1 + Z_2} \right)^{2N} \cdot \cos \left((2N+1) \frac{\omega b h_1 \cos \nu}{c_2} \right) \times e^{-\alpha_3 \cdot (2N+1) h_1 \cos \nu} \right)^2 + \left(\sum_{N=0}^{\infty} \left(\frac{Z_2 - Z_1}{Z_1 + Z_2} \right)^{2N} \cdot \sin \left((2N+1) \frac{\omega b h_1 \cos \nu}{c_2} \right) \times e^{-\alpha_3 \cdot (2N+1) h_1 \cos \nu} \right)^2 \right) \right)^{\frac{1}{2}}. \quad (2.68)$$

If writing the module of a complex transmission coefficient $|W_{\alpha\beta}(\omega)|$ for a fabric with different deformation of threads and with a phase structure with a nominal thickness, which can be represented by the sum of the warp and weft thread diameter d_{oy} , it can be shown as follows:

$$|W_{\alpha\beta}(\omega)| = \left(\left(\frac{4 Z_1 Z_2}{(Z_1 + Z_2)^2} \right)^2 \cdot \left(\left(\sum_{N=0}^{\infty} \left(\frac{Z_2 - Z_1}{Z_1 + Z_2} \right)^{2N} \cdot \cos \left((2N+1) \frac{\omega b \pi d_{oy} \cos \nu}{4 c_2} \right) \right)^2 + \left(\sum_{N=0}^{\infty} \left(\frac{Z_2 - Z_1}{Z_1 + Z_2} \right)^{2N} \cdot \sin \left((2N+1) \frac{\omega b \pi d_{oy} \cos \nu}{4 c_2} \right) \right)^2 \right) \right)^{\frac{1}{2}}$$

$$\begin{aligned} & \times e^{-\alpha_3 \cdot (2N+1) \frac{\pi d_{oy} \cos v}{4}} \Bigg)^2 + \left(\sum_{N=0}^{\infty} \left(\frac{Z_2 - Z_1}{Z_1 + Z_2} \right)^{2N} \cdot \sin \left((2N+1) \frac{\omega b \pi d_{oy} \cos v}{4 c_2} \right) \right. \\ & \left. \times e^{-\alpha_3 \cdot (2N+1) \frac{\pi d_{oy} \cos v}{4}} \right)^2 \Bigg)^{\frac{1}{2}}. \end{aligned} \quad (2.69)$$

The expression (2.69), by associating it with the basis weight m_s of the textile fabric itself, can be represented as:

$$\begin{aligned} |W_{\alpha\beta}(\omega)| &= \left(\left(\frac{4 Z_1 Z_2}{(Z_1 + Z_2)^2} \right)^2 \cdot \left(\left(\sum_{N=0}^{\infty} \left(\frac{Z_2 - Z_1}{Z_1 + Z_2} \right)^{2N} \cdot \cos \left((2N+1) \frac{K m_s \omega b \cos v}{\pi Z_2} \right) \right. \right. \right. \\ & \times e^{-\alpha_3 \cdot (2N+1) \frac{K m_s \cos v}{\pi \rho_2}} \Bigg)^2 + \left(\sum_{N=0}^{\infty} \left(\frac{Z_2 - Z_1}{Z_1 + Z_2} \right)^{2N} \cdot \sin \left((2N+1) \frac{K m_s \omega b \cos v}{\pi Z_2} \right) \right. \\ & \left. \left. \left. \times e^{-\alpha_3 \cdot (2N+1) \frac{K m_s \cos v}{\pi \rho_2}} \right)^2 \right) \right)^{\frac{1}{2}}. \end{aligned} \quad (2.70)$$

In order to conduct a detailed analysis of the effect of attenuation on the amplitude ratio of ultrasonic waves reflected from a two-layer material to the waves that just fall on it, it is first necessary to decompose the complex reflection coefficient $V(\omega)$ into the real and imaginary components, according to the given expressions (2.60), (2.61), (2.62) for the transmission coefficient $W(\omega)$, and show these dependences as follows:

$$V(\omega) = \text{Re } V(\omega) + j \text{Im } V(\omega), \quad (2.71)$$

where

$$\begin{aligned} \text{Re } V(\omega) &= \sqrt{V_L} \cdot \left(\sum_{N=0}^{\infty} V_L^N \cdot \cos \left(2N \frac{\omega b (h_1 + h_2)}{c_{23}} \right) \cdot e^{-\alpha_3 \cdot 2N (h_1 + h_2)} \right. \\ & \left. - \sum_{N=0}^{\infty} V_L^N \cdot \cos \left((2N+2) \frac{\omega b (h_1 + h_2)}{c_{23}} \right) \cdot e^{-\alpha_3 \cdot (2N+2) (h_1 + h_2)} \right), \end{aligned} \quad (2.72)$$

$$\begin{aligned} \text{Im } V(\omega) &= \sqrt{V_L} \cdot \left(\sum_{N=0}^{\infty} V_L^N \cdot \sin \left(2N \frac{\omega b (h_1 + h_2)}{c_{23}} \right) \cdot e^{-\alpha_3 \cdot 2N (h_1 + h_2)} \right. \\ & \left. - \sum_{N=0}^{\infty} V_L^N \cdot \sin \left((2N+2) \frac{\omega b (h_1 + h_2)}{c_{23}} \right) \cdot e^{-\alpha_3 \cdot (2N+2) (h_1 + h_2)} \right), \end{aligned} \quad (2.73)$$

then the module of the complex reflection coefficient $|V(\omega)|$ for a two-layer material with $h_1 \approx h_2$ is written down as:

$$|V(\omega)| = \sqrt{\operatorname{Re} V(\omega)^2 + \operatorname{Im} V(\omega)^2}, \quad (2.74)$$

or

$$\begin{aligned} |V(\omega)| = & \left(V_L \cdot \left(\left(\sum_{N=0}^{\infty} V_L^N \cdot \left(\cos \left(2N \frac{\omega b (h_1 + h_2)}{c_{23}} \right) \cdot e^{-\alpha_3 \cdot 2N (h_1 + h_2)} \right. \right. \right. \right. \\ & \left. \left. \left. - \cos \left((2N + 2) \frac{\omega b (h_1 + h_2)}{c_{23}} \right) \cdot e^{-\alpha_3 \cdot (2N + 2) (h_1 + h_2)} \right) \right)^2 \right. \\ & \left. + \left(\sum_{N=0}^{\infty} V_L^N \cdot \left(\sin \left(2N \frac{\omega b (h_1 + h_2)}{c_{23}} \right) \cdot e^{-\alpha_3 \cdot 2N (h_1 + h_2)} \right. \right. \right. \right. \\ & \left. \left. \left. - \sin \left((2N + 2) \frac{\omega b (h_1 + h_2)}{c_{23}} \right) \cdot e^{-\alpha_3 \cdot (2N + 2) (h_1 + h_2)} \right) \right)^2 \right) \right)^{\frac{1}{2}}. \quad (2.75) \end{aligned}$$

If there are pores in this material, then given the change in the parameter $\cos \nu$, which depends on the magnitude of the wave transmission through the pores, it is possible to present the module of reflection $|V_p(\omega)|$ of ultrasonic waves from this material as follows:

$$\begin{aligned} |V_p(\omega)| = & \left(V_L \cdot \left(\left(\sum_{N=0}^{\infty} V_L^N \cdot \left(\cos \left(2N \frac{\omega b (h_1 + h_2) \cos \nu}{c_{23}} \right) \cdot e^{-\alpha_3 \cdot 2N (h_1 + h_2) \cos \nu} \right. \right. \right. \right. \\ & \left. \left. \left. - \cos \left((2N + 2) \frac{\omega b (h_1 + h_2) \cos \nu}{c_{23}} \right) \cdot e^{-\alpha_3 \cdot (2N + 2) (h_1 + h_2) \cos \nu} \right) \right)^2 \right. \\ & \left. + \left(\sum_{N=0}^{\infty} V_L^N \cdot \left(\sin \left(2N \frac{\omega b (h_1 + h_2) \cos \nu}{c_{23}} \right) \cdot e^{-\alpha_3 \cdot 2N (h_1 + h_2) \cos \nu} \right. \right. \right. \right. \\ & \left. \left. \left. - \sin \left((2N + 2) \frac{\omega b (h_1 + h_2) \cos \nu}{c_{23}} \right) \cdot e^{-\alpha_3 \cdot (2N + 2) (h_1 + h_2) \cos \nu} \right) \right)^2 \right) \right)^{\frac{1}{2}}. \quad (2.76) \end{aligned}$$

We will show the dependences of the amplitude ratios of the waves on their circular frequency ω , taking into account the attenuation α_3 , for a single-layer material with through pores and the components of equality $\operatorname{Re} V_p(\omega)$ and $\operatorname{Im} V_p(\omega)$ for this case as:

$$\begin{aligned} \operatorname{Re} V_p(\omega) = & \frac{Z_2 - Z_1}{Z_1 + Z_2} \cdot \left(\sum_{N=0}^{\infty} \left(\frac{Z_2 - Z_1}{Z_1 + Z_2} \right)^{2N} \cdot \cos \left(2N \frac{\omega b h_1 \cos \nu}{c_2} \right) \cdot e^{-\alpha_3 \cdot 2N h_1 \cos \nu} \right. \\ & \left. - \sum_{N=0}^{\infty} \left(\frac{Z_2 - Z_1}{Z_1 + Z_2} \right)^{2N} \cdot \cos \left((2N + 2) \frac{\omega b h_1 \cos \nu}{c_2} \right) \cdot e^{-\alpha_3 \cdot (2N + 2) h_1 \cos \nu} \right), \quad (2.77) \end{aligned}$$

$$\begin{aligned} \text{Im } V_p(\omega) = & \frac{Z_2 - Z_1}{Z_1 + Z_2} \cdot \left(\sum_{N=0}^{\infty} \left(\frac{Z_2 - Z_1}{Z_1 + Z_2} \right)^{2N} \cdot \sin \left(2N \frac{\omega b h_1 \cos \nu}{c_2} \right) \cdot e^{-\alpha_3 \cdot 2N h_1 \cos \nu} \right. \\ & \left. - \sum_{N=0}^{\infty} \left(\frac{Z_2 - Z_1}{Z_1 + Z_2} \right)^{2N} \cdot \sin \left((2N + 2) \frac{\omega b h_1 \cos \nu}{c_2} \right) \cdot e^{-\alpha_3 \cdot (2N+2) h_1 \cos \nu} \right), \end{aligned} \quad (2.78)$$

then

$$\begin{aligned} |V_p(\omega)| = & \left(\left(\frac{Z_2 - Z_1}{Z_1 + Z_2} \right)^2 \cdot \left(\left(\sum_{N=0}^{\infty} \left(\frac{Z_2 - Z_1}{Z_1 + Z_2} \right)^{2N} \cdot \left(\cos \left(2N \frac{\omega b h_1 \cos \nu}{c_2} \right) \right. \right. \right. \right. \\ & \times e^{-\alpha_3 \cdot 2N h_1 \cos \nu} - \cos \left((2N + 2) \frac{\omega b h_1 \cos \nu}{c_2} \right) \\ & \times e^{-\alpha_3 \cdot (2N+2) h_1 \cos \nu} \Bigg)^2 \\ & + \left(\sum_{N=0}^{\infty} \left(\frac{Z_2 - Z_1}{Z_1 + Z_2} \right)^{2N} \cdot \left(\sin \left(2N \frac{\omega b h_1 \cos \nu}{c_2} \right) \cdot e^{-\alpha_3 \cdot 2N h_1 \cos \nu} \right. \right. \\ & \left. \left. - \sin \left((2N + 2) \frac{\omega b h_1 \cos \nu}{c_2} \right) \cdot e^{-\alpha_3 \cdot (2N+2) h_1 \cos \nu} \right) \right)^2 \Bigg)^{\frac{1}{2}}. \end{aligned} \quad (2.79)$$

Connecting the module of the complex reflection coefficient $|V_{\alpha\beta}(\omega)|$ for the fabric with the nominal thickness d_{oy} , it can be shown as follows:

$$\begin{aligned} |V_{\alpha\beta}(\omega)| = & \left(\left(\frac{Z_2 - Z_1}{Z_1 + Z_2} \right)^2 \cdot \left(\left(\sum_{N=0}^{\infty} \left(\frac{Z_2 - Z_1}{Z_1 + Z_2} \right)^{2N} \cdot \left(\cos \left(2N \frac{\omega b \pi d_{oy} \cos \nu}{4 c_2} \right) \right. \right. \right. \right. \\ & \times e^{-\alpha_3 \cdot 2N \frac{\pi d_{oy} \cos \nu}{4}} - \cos \left((2N + 2) \frac{\omega b \pi d_{oy} \cos \nu}{4 c_2} \right) \\ & \times e^{-\alpha_3 \cdot (2N+2) \frac{\pi d_{oy} \cos \nu}{4}} \Bigg)^2 \\ & + \left(\sum_{N=0}^{\infty} \left(\frac{Z_2 - Z_1}{Z_1 + Z_2} \right)^{2N} \cdot \left(\sin \left(2N \frac{\omega b \pi d_{oy} \cos \nu}{4 c_2} \right) \cdot e^{-\alpha_3 \cdot 2N \frac{\pi d_{oy} \cos \nu}{4}} \right. \right. \\ & \left. \left. - \sin \left((2N + 2) \frac{\omega b \pi d_{oy} \cos \nu}{4 c_2} \right) \cdot e^{-\alpha_3 \cdot (2N+2) \frac{\pi d_{oy} \cos \nu}{4}} \right) \right)^2 \Bigg)^{\frac{1}{2}}. \end{aligned} \quad (2.80)$$

The expression (2.80) can be related to the basis weight m_s of the textile fabric and given as:

$$|V_{\alpha\beta}(\omega)| = \left(\left(\frac{Z_2 - Z_1}{Z_1 + Z_2} \right)^2 \cdot \left(\left(\sum_{N=0}^{\infty} \left(\frac{Z_2 - Z_1}{Z_1 + Z_2} \right)^{2N} \cdot \left(\cos \left(2N \frac{K m_s \omega b \cos \nu}{\pi Z_2} \right) \right. \right. \right. \right.$$

$$\begin{aligned}
& \times e^{-\alpha_3 \cdot 2N \frac{K m_s \cos v}{\pi \rho_2}} - \cos\left((2N + 2) \frac{K m_s \omega b \cos v}{\pi Z_2}\right) \\
& \times e^{-\alpha_3 \cdot (2N+2) \frac{K m_s \cos v}{\pi \rho_2}} \Big)^2 \\
& + \left(\sum_{N=0}^{\infty} \left(\frac{Z_2 - Z_1}{Z_1 + Z_2} \right)^{2N} \cdot \left(\sin\left(2N \frac{K m_s \omega b \cos v}{\pi Z_2}\right) \cdot e^{-\alpha_3 \cdot 2N \frac{K m_s \cos v}{\pi \rho_2}} \right. \right. \\
& \left. \left. - \sin\left((2N + 2) \frac{K m_s \omega b \cos v}{\pi Z_2}\right) \cdot e^{-\alpha_3 \cdot (2N+2) \frac{K m_s \cos v}{\pi \rho_2}} \right) \right)^2 \Big)^{\frac{1}{2}}.
\end{aligned} \tag{2.81}$$

Having obtained the basic expressions for the amplitude ratios taking into account the attenuation for ultrasonic waves that have passed through the material and reflected from it to the waves just incident on its surface, we can analyze the effect of this attenuation on the amplitude error (relative change of their amplitudes) caused by it.

In general, these relative changes for the amplitudes of the waves that have passed and reflected from the material can be represented as follows:

$$\delta_{|W(\omega)|} = \frac{|W(\omega)| - |W(\omega)|_0}{|W(\omega)|_0} \cdot 100\%, \tag{2.82}$$

and

$$\delta_{|V(\omega)|} = \frac{|V(\omega)| - |V(\omega)|_0}{|V(\omega)|_0} \cdot 100\%, \tag{2.83}$$

where $\delta_{|W(\omega)|}$ is the relative change in the module of the complex transmission coefficient of ultrasonic waves caused by attenuation; $\delta_{|V(\omega)|}$ —the relative change in the module of the complex reflection coefficient of ultrasonic waves caused by attenuation; $|W(\omega)|_0$, $|V(\omega)|_0$ —modules of complex coefficients of transmission and reflection without taking into account the attenuation of waves in the material ($\alpha_3 = 0$).

We will give two cases (for materials different in structure) of relative changes in wave amplitudes, using the obtained expressions for the modules of complex coefficients of transmission and reflection of oscillations, substituting them for the general formulas (2.82) and (2.83). The notation of the modules $|W(\omega)|$ and $|V(\omega)|$ of the corresponding coefficients with the transition of the circular frequency record ω to f will be shown simply as $|W|$ and $|V|$, and the values $\delta_{|W(\omega)|}$, $\delta_{|V(\omega)|}$ will be given as $\delta_{|W|}$ and $\delta_{|V|}$.

The relative changes in the amplitudes of waves caused by the attenuation of signals for single-layer materials with pores after simplification of the composite expressions with a transition from circular frequency ω to f can be represented as follows:

$$\delta_{|W|} = \left(|W| \sqrt{1 + \left(\frac{\pi f \rho_2 h_1 \cos v}{Z_1} \right)^2} - 1 \right) \cdot 100\%, \quad (2.84)$$

$$\delta_{|V|} = \left(|V| \sqrt{1 + \left(\frac{Z_1}{\pi f \rho_2 h_1 \cos v} \right)^2} - 1 \right) \cdot 100\%. \quad (2.85)$$

The relative changes in the wave amplitudes caused by the signal attenuation for fabrics that are associated with the nominal thickness d_{oy} , after simplification of the component expressions with a transition from the circular frequency ω to f can be presented as follows:

$$\delta_{|W|} = \left(|W| \sqrt{1 + \left(\frac{\pi^2 f \rho_2 d_{oy} \cos v}{4 Z_1} \right)^2} - 1 \right) \cdot 100\%, \quad (2.86)$$

$$\delta_{|V|} = \left(|V| \sqrt{1 + \left(\frac{4 Z_1}{\pi^2 f \rho_2 d_{oy} \cos v} \right)^2} - 1 \right) \cdot 100\%. \quad (2.87)$$

The relative changes in the wave amplitudes caused by the signal attenuation for textile fabrics, taking into account the dependences (2.86) and (2.87), associating them with the basis weight m_s , after simplifying the components of expressions with a transition from the circular frequency ω to f , can be presented as follows:

$$\delta_{|W|} = \left(|W| \sqrt{1 + \left(\frac{K m_s f \cos v}{Z_1} \right)^2} - 1 \right) \cdot 100\%, \quad (2.88)$$

and

$$\delta_{|V|} = \left(|V| \sqrt{1 + \left(\frac{Z_1}{K m_s f \cos v} \right)^2} - 1 \right) \cdot 100\%, \quad (2.89)$$

Fig. 2.13 shows how the attenuation parameter α_3 , (with the peaks of the curves at $\alpha_3 = 0$ and $\alpha_3 = 15 \text{ m}^{-1}$) of ultrasonic waves affects their amplitude ratios $|W|$, $|V|$ depending on changes in oscillation frequency f in the controlled material (on the change of the wave length λ_2 in the material with pores). The change in the amplitude attenuation from the wave frequency is best determined by the parameter of the ratio of material thickness to the wavelength h_1/λ_2 for materials with a flat layer and by parameter $m_s/(\rho_2 \lambda_2)$ for textile materials. Figures 2.13, 2.14, 2.15 and 2.16 show how the attenuation of the wave amplitude changes when changing their frequency in the material of the flat polymer layer with small pores, which can be used in composites, and Figs. 2.17, 2.18, 2.19 and 2.20 show how the attenuation changes in the textile material with through pores.

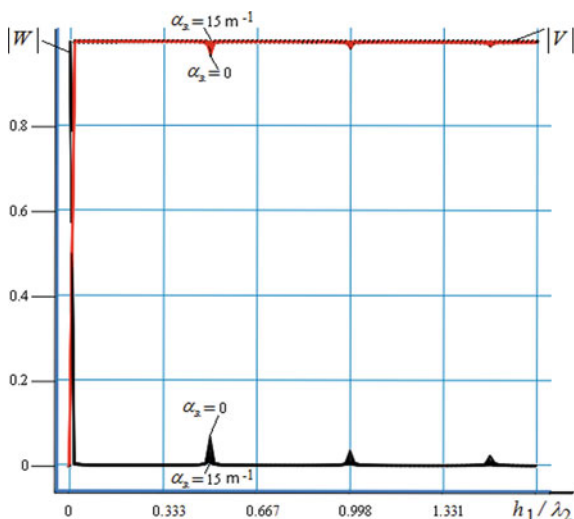


Fig. 2.13 Dependences of modules $|W|$, $|V|$ for a polymeric material with small pores on the parameter h_1/λ_2 (at $\alpha_3 = 0$ and $\alpha_3 = 15 \text{ m}^{-1}$)

As it can be seen from the above dependences (Figs. 2.13, 2.14, 2.15 and 2.16), with the presence of small pores in the polymeric material, the transmission of ultrasonic waves is close to the transmission of oscillations in a solid material. This occurs because the waves that travel through small pores have less of an effect on the resulting signal than those that travel through pores in a textile material (at a certain ratio of the size of through pores to the length of ultrasonic waves). The part of ultrasonic waves that travels through the polymeric material undergoes significant attenuation (compared to the textile fabric) because it does not have interfiber porosity in its structure, as textile fabrics do. It should be also noted that the nominal thickness of the textile layer can significantly exceed the thickness of the polymeric material in the composite, through which ultrasonic waves can travel in the process of non-contact control. This is due to less attenuation of ultrasonic oscillations in the textile layer.

The attenuation of the reflected ultrasonic waves has a much smaller effect on the change in the magnitude of the module of the complex reflection coefficient $\delta_{|V|}$ than on the change in the magnitude of the module of the complex coefficient of transmission $\delta_{|W|}$ of waves through the polymeric material (Figs. 2.15, 2.16). If we compare these indicators of relative changes of modules of complex coefficients of ultrasonic waves with the similar ones for textile fabrics, the difference between $\delta_{|W|}$ and $\delta_{|V|}$ for such single-layer materials will be insignificant, and their value will be much smaller than these indicators for polymeric materials. Therefore, it is possible to make a conclusion that attenuation of ultrasonic waves, at cross sounding of textile fabrics can be neglected (Figs. 2.17, 2.18). The average speed of propagation of ultrasonic waves, with this sounding of a textile single-layer material, will be close

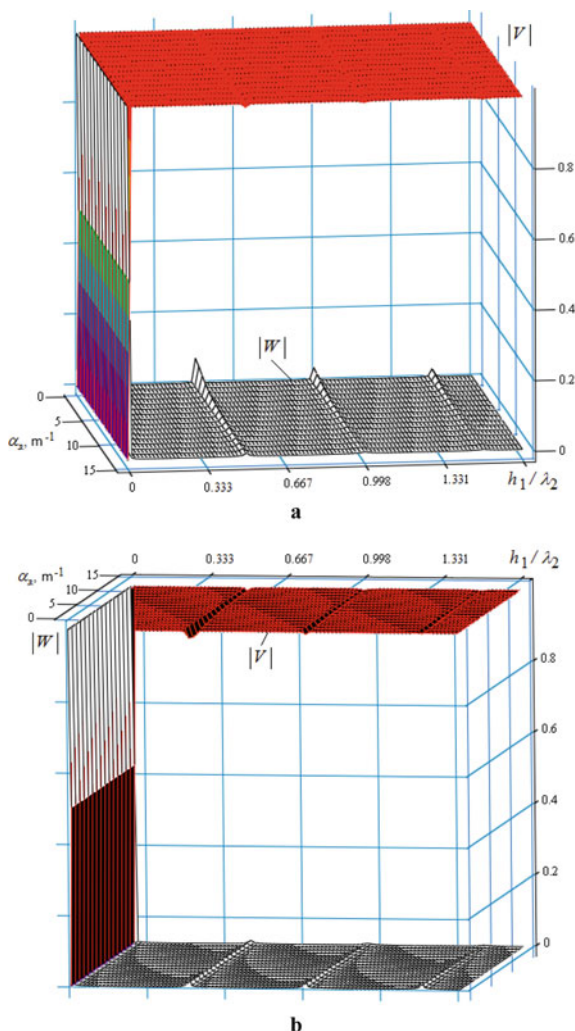


Fig. 2.14 Dependences of modules $|W|$, $|V|$ for the polymeric material with small pores on the parameters h_1/λ_2 and attenuation α_3 : **a** module change $|W|$ depending on the parameters h_1/λ_2 and α_3 ; **b** module change $|V|$ depending on the parameters h_1/λ_2 and α_3 .

to the speed of propagation of sound waves in the air, because most of the oscillations pass through it, bypassing threads of the material. For the materials with different internal structure, the speed of wave propagation may vary.

As it can be seen from Figs. 2.19 and 2.20 for fabrics, which are mainly produced by domestic textile enterprises, the attenuation of ultrasonic waves, used for transverse sounding of such textiles, will be insignificant and can be neglected. This can be explained by the fact that although the wave attenuation in the fibers of textile materials can be $\alpha_3 = 15 \text{ m}^{-1}$, due to the fact that most of the oscillations go around

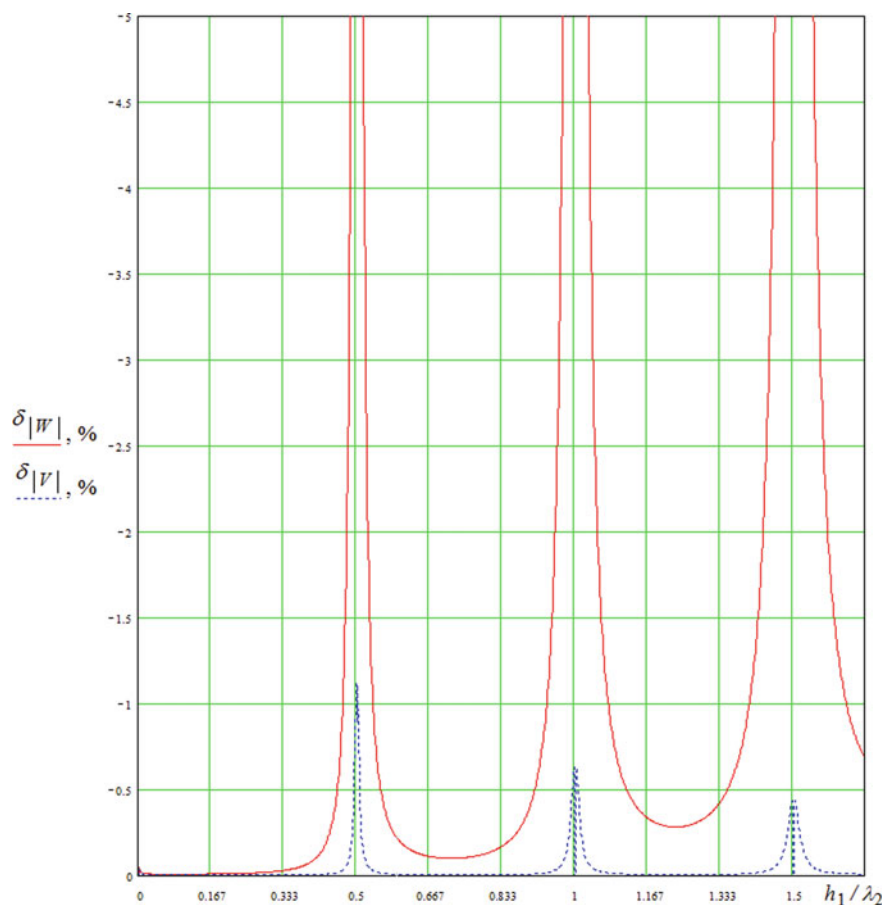


Fig. 2.15 Dependences of relative changes of modules of complex coefficients of transmission $\delta|W|$ and reflection $\delta|V|$ for the polymeric material with small pores on the parameter h_1/λ_2

the threads with the fibers of the textile material and pass through the pores, this attenuation for the resulting ultrasonic signal can be neglected. Therefore, the attenuation peak of the amplitude of ultrasonic waves interacting with textile materials falls on the sloping part of the dependences of the modules $|W|$, $|V|$ for textile materials on the parameters $m_s/(\rho_2\lambda_2)$ and attenuation α_3 , in the control range of the fabrics (Figs. 2.18, 2.19 and 2.20). It is shown that such attenuation has little effect on the change in wave amplitudes, which does not exceed 1% by the module for textile fabrics, while attenuation for single-layer polymeric materials with small pores can significantly affect the change in wave amplitudes, which can exceed 60% by the module.

After analyzing the attenuation of ultrasonic waves in different materials, it can be concluded that the frequency range of these oscillations and the range of basis weight

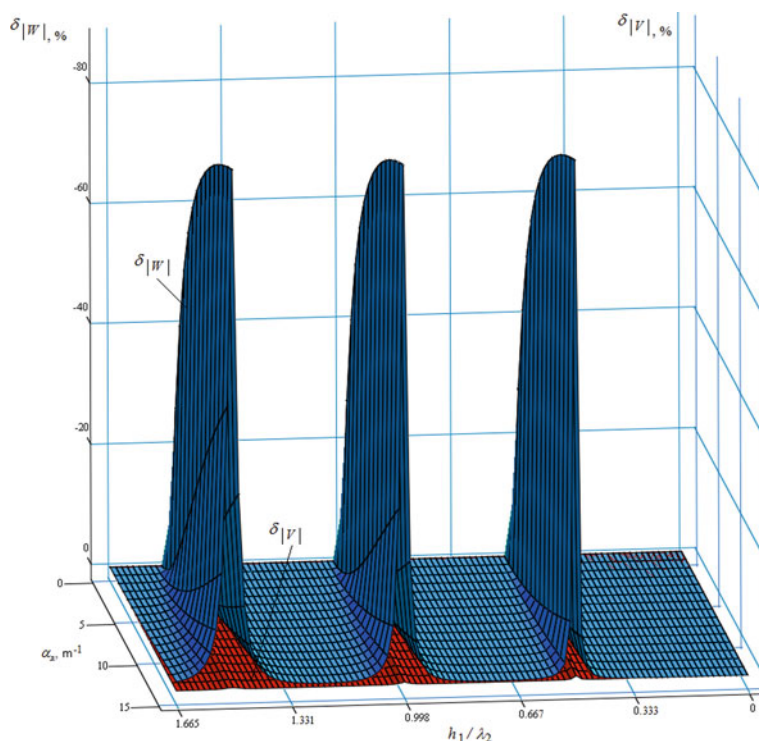


Fig. 2.16 Dependences of relative changes of modules of complex coefficients of transmission $\delta|W|$ and reflection $\delta|V|$ for the polymeric material with small pores on the parameters h_1/λ_2 and α_3 .

of the fabrics used for non-contact control over different parameters may be greater than such ranges for thin single-layer materials used for composites. This difference between the materials is explained by the internal structure of the materials, which can affect the ability of some waves to go round the material itself, if the ratio of wavelength and through pore is not clearly expressed.

The studies have shown that low-power sensors can be used to determine various technological parameters of textile materials without taking into account the attenuation itself, because most of the ultrasonic waves pass through the pores of the fabric. To increase the sensitivity of the measuring channel, it is advisable to use waveguides for individual threads and tapes.

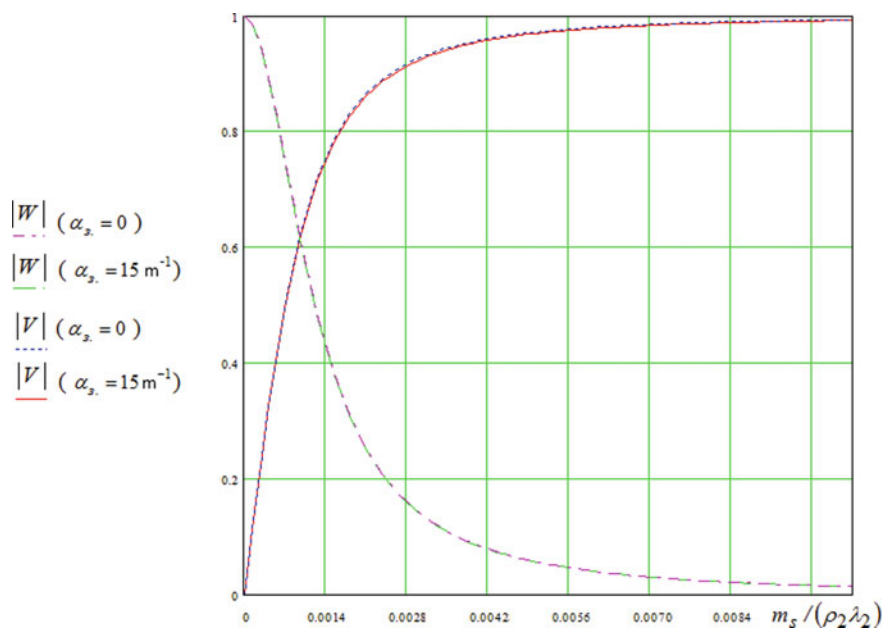


Fig. 2.17 Dependences of modules $|W|$, $|V|$ for textile materials on the parameter $m_s / (\rho_2 \lambda_2)$ with attenuation ($\alpha_3 = 15 \text{ m}^{-1}$) and without it ($\alpha_3 = 0$) in the range of fabric control

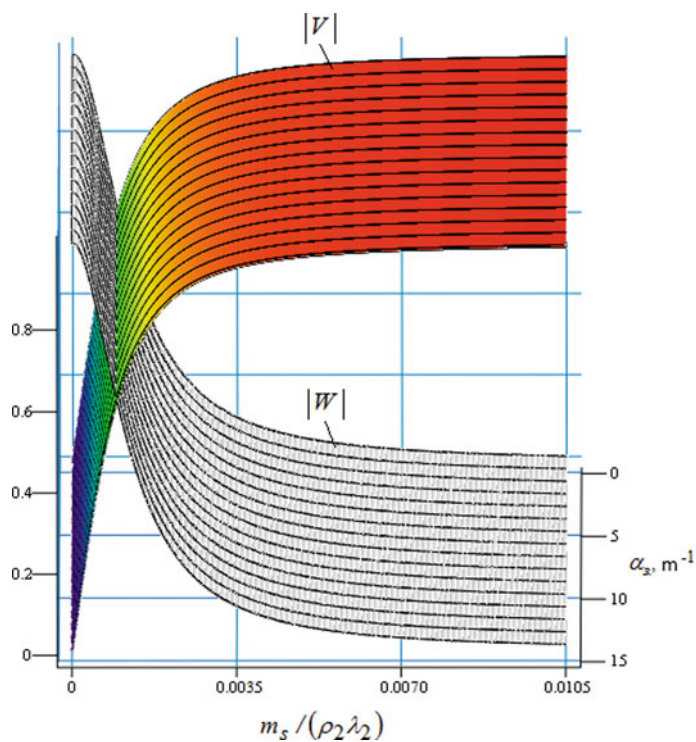


Fig. 2.18 Dependences of modules $|W|$, $|V|$ for textile materials on the parameters $m_s / (\rho_2 \lambda_2)$ and attenuation α_3 , in the range of fabric control

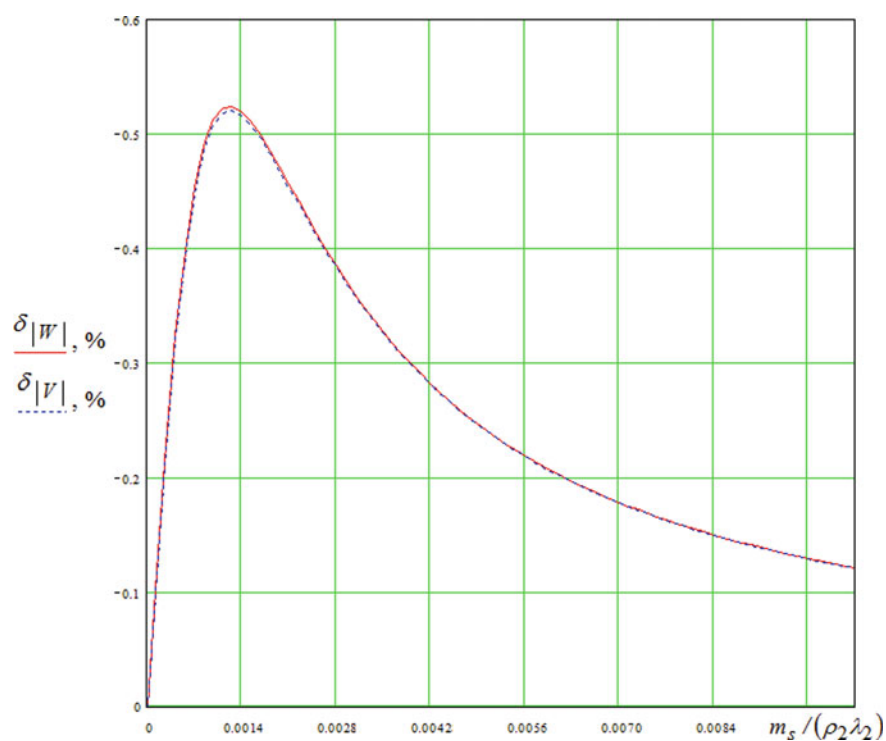


Fig. 2.19 Dependences of relative changes of modules of complex coefficients of transmission $\delta|W|$ and reflection $\delta|V|$ for textile materials on the parameter $m_s / (\rho_2 \lambda_2)$ in the range of fabric control

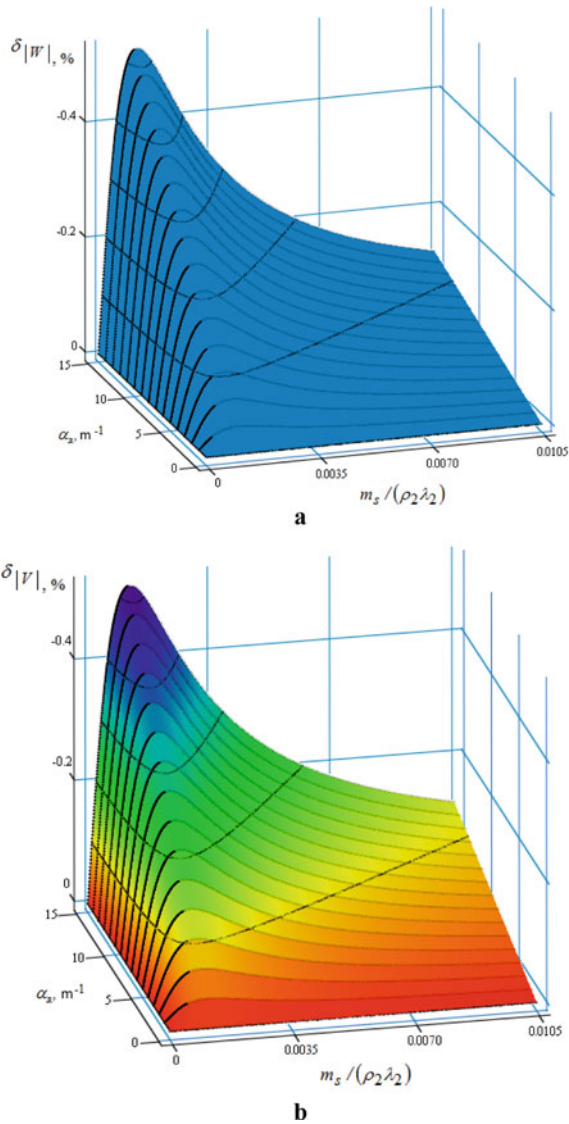


Fig. 2.20 Dependences of relative changes of modules of complex coefficients of transmission $\delta|W|$ and reflection $\delta|V|$ for textile materials on the parameters $m_s / (\rho_2 \lambda_2)$ and α_3 : **a** dependence of the relative change $\delta|W|$ on the parameters $m_s / (\rho_2 \lambda_2)$ and α_3 ; **b** dependence of the relative change $\delta|V|$ on the parameters $m_s / (\rho_2 \lambda_2)$ and α_3 .

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Chapter 3

Research on the Interaction of Ultrasonic Waves with Various Textile Materials in the Process of Non-contact Control



3.1 Reflection of Ultrasonic Waves from a Composite of Small Thickness at Their Normal Incidence with the Detection of Defects in the Material Structure

To detect stratification or other defects in materials using the non-contact method, it is necessary to consider in detail the reflection of ultrasonic waves from the adjoining media [1–8] that interact with them.

The process of ultra sound reflection will be first considered taking into account the normal incidence of waves relative to the item under control. In order to describe the reflection of waves from a material in which defects are present, a similar description must be first made for a material in which they are absent. It is also necessary to take into account the attenuation of waves in the layers of the CTM, resulting from the analysis described in this paper.

The amplitude of ultrasonic waves, included in the packages of pulse signals, is less affected by their reflection and overlap comparing with the case of continuous radiation of oscillations that can have influence on the resulting signal. Therefore, the pulse ultrasonic signal should be used for non-contact ultrasonic control of various materials. The amplitude of the ultrasonic wave reflected from the material in which there are no defects can be shown through the module of the complex reflection coefficient. The coefficient itself can be presented as follows:

$$\begin{aligned} V_e &= \text{Re}V_e + j\text{Im}V_e, \\ V_e &= \left(\left(\left(ch \alpha_3 h + \left(\frac{Z_2}{2Z_1} + \frac{Z_1}{2Z_2} \right) \cdot sh \alpha_3 h \right) \cdot \cos \frac{\omega h}{c_2} \right)^2 \right. \\ &\quad + \left(\left(sh \alpha_3 h + \left(\frac{Z_2}{2Z_1} + \frac{Z_1}{2Z_2} \right) \cdot ch \alpha_3 h \right) \cdot \sin \frac{\omega h}{c_2} \right)^2 \\ &\quad \left. - \left(ch \alpha_3 h + \left(\frac{Z_2}{2Z_1} + \frac{Z_1}{2Z_2} \right) \cdot sh \alpha_3 h \right) \cdot \cos \frac{\omega h}{c_2} \right) \end{aligned}$$

$$\begin{aligned}
& \times \left(\left(\left(ch \alpha_3 h + \left(\frac{Z_2}{2 Z_1} + \frac{Z_1}{2 Z_2} \right) \cdot sh \alpha_3 h \right) \cdot \cos \frac{\omega h}{c_2} \right)^2 \right. \\
& + \left. \left(\left(sh \alpha_3 h + \left(\frac{Z_2}{2 Z_1} + \frac{Z_1}{2 Z_2} \right) \cdot ch \alpha_3 h \right) \cdot \sin \frac{\omega h}{c_2} \right)^2 \right)^{-1} \\
& - j \left(\left(sh \alpha_3 h + \left(\frac{Z_2}{2 Z_1} + \frac{Z_1}{2 Z_2} \right) \cdot ch \alpha_3 h \right) \right. \\
& \times \sin \frac{\omega h}{c_2} \cdot \left(\left(\left(ch \alpha_3 h + \left(\frac{Z_2}{2 Z_1} + \frac{Z_1}{2 Z_2} \right) \cdot sh \alpha_3 h \right) \cdot \cos \frac{\omega h}{c_2} \right)^2 \right. \\
& \left. \left. + \left(\left(sh \alpha_3 h + \left(\frac{Z_2}{2 Z_1} + \frac{Z_1}{2 Z_2} \right) \cdot ch \alpha_3 h \right) \cdot \sin \frac{\omega h}{c_2} \right)^2 \right)^{-1} \right), \quad (3.1)
\end{aligned}$$

where $\text{Re}V_e$, $\text{Im}V_e$ is the real and imaginary components of the complex reflection coefficient V_e for the defect-free (standard) material. The module of the complex reflection coefficient can be generally written as follows:

$$\begin{aligned}
|V_e| &= \sqrt{\text{Re}V_e^2 + \text{Im}V_e^2}, \\
|V_e| &= \left(1 + \left(1 - \left(ch \alpha_3 h + \left(\frac{Z_2}{2 Z_1} + \frac{Z_1}{2 Z_2} \right) \cdot sh \alpha_3 h \right) \cdot 2 \cos \frac{\omega h}{c_2} \right) \right. \\
& \times \left(\left(\left(ch \alpha_3 h + \left(\frac{Z_2}{2 Z_1} + \frac{Z_1}{2 Z_2} \right) \cdot sh \alpha_3 h \right) \cdot \cos \frac{\omega h}{c_2} \right)^2 \right. \\
& \left. \left. + \left(\left(sh \alpha_3 h + \left(\frac{Z_2}{2 Z_1} + \frac{Z_1}{2 Z_2} \right) \cdot ch \alpha_3 h \right) \cdot \sin \frac{\omega h}{c_2} \right)^2 \right)^{-1} \right)^{\frac{1}{2}}, \quad (3.2)
\end{aligned}$$

at $\alpha_3 = 0$ and $Z_1/Z_2 \ll 1$ expression (3.2) can be simplified to the following:

$$|V_e| = \sqrt{1 + \frac{1 - 2 \cdot \cos \frac{\omega h}{c_2}}{\left(\cos \frac{\omega h}{c_2} \right)^2 + \left(\frac{Z_2}{2 Z_1} \cdot \sin \frac{\omega h}{c_2} \right)^2}}. \quad (3.3)$$

Then for most materials $\omega h/c_2 \ll 1$ the expression (3.3) can be written as:

$$|V_e| = \frac{1}{\sqrt{1 + \left(\frac{2 Z_1 c_2}{Z_2 \omega h} \right)^2}}, \quad (3.4)$$

where for this case: h is the total thickness of the composite material; Z_1 —acoustic impedance of the environment; Z_2 —acoustic impedance of the composite material; c_2 —the speed of ultrasonic wave propagation in the material.

From the expression (3.4) it is also possible to determine the thickness of the reference material (for thin materials) if necessary. The reflection of waves from the CTM, which may have a defect representing a thin layer of air, can be described by the input acoustic impedance $Z_{in.}^{(4)}$ for the four media.

$$\begin{aligned}
 Z_{in.}^{(4)} = & (Z_1 Z_2 Z_3 - Z_1 Z_3^2 t g K_2 h_1 t g K_3 h_2 \\
 & - Z_1 Z_3 Z_4 t g K_2 h_1 t g K_4 h_3 - Z_1 Z_2 Z_4 t g K_3 h_2 t g K_4 h_3 \\
 & - j(Z_2^2 Z_3 t g K_2 h_1 + Z_2 Z_3^2 t g K_3 h_2 + Z_2 Z_3 Z_4 \\
 & \times t g K_4 h_3 - Z_2^2 Z_4 t g K_2 h_1 t g K_3 h_2 t g K_4 h_3)) \cdot (Z_2 Z_3 Z_4 \\
 & - Z_2^2 Z_4 t g K_2 h_1 t g K_3 h_2 - Z_2^2 Z_3 t g K_2 h_1 t g K_4 h_3 \\
 & - Z_2 Z_3^2 t g K_3 h_2 t g K_4 h_3 - j(Z_1 Z_3 Z_4 t g K_2 h_1 + Z_1 Z_2 \\
 & \times Z_4 t g K_3 h_2 + Z_1 Z_2 Z_3 t g K_4 h_3 \\
 & - Z_1 Z_3^2 t g K_2 h_1 t g K_3 h_2 t g K_4 h_3))^{-1} \cdot Z_4,
 \end{aligned} \tag{3.5}$$

where for this case: h_1 is the thickness of the material under the defect; h_2 —the thickness of the defect in the material; h_3 —the thickness of the material layer over the defect; Z_2 —acoustic resistance of the material under the defect; Z_3 —acoustic resistance of the defect layer; Z_4 —acoustic resistance of the material layer over the defect; K_2 —wave number for the material layer under the defect; K_3 —wave number for the defect layer; K_4 —wave number for the material layer that is over the defect. Then the complex reflection coefficient can be shown as follows:

$$V_{def.} = \frac{Z_{in.}^{(4)} - Z_1}{Z_{in.}^{(4)} + Z_1}. \tag{3.6}$$

By changing the amplitude of the ultrasonic waves reflected from the CTM with the existing defect (often delamination in the form of an air gap), relative to the reference CTM without defects, it is possible to determine the presence of undesirable inhomogeneities in the composite material.

To determine the peak amplitude and phase of the pulse ultrasound signal reflected from the defective CTM relative to the amplitude and phase of the ultrasonic pulse signal reflected from the reference sample CTM, it is necessary to distinguish from the expression (3.6) real $\text{Re}V_{def.}$ and imaginary $\text{Im}V_{def.}$ components. By the amplitude ratios (modules $|V_e|$, $|V_{def.}|$ which are associated with the peak amplitudes of the waves) and the phase of ultrasonic vibrations that interact with the controlled materials, it is possible to increase the sensitivity of the measuring system to the presence of a defect in the CTM. The corresponding transformations for further decomposition of the expression (3.6) into real $\text{Re}V_{def.}$ and imaginary $\text{Im}V_{def.}$ components will be shown below:

$$\begin{aligned}
V_{def.} = & (Z_4 \cdot (Z_2^2 Z_3 \operatorname{tg} K_2 h_1 + Z_2 Z_3^2 \operatorname{tg} K_3 h_2 \\
& + Z_2 Z_3 Z_4 \operatorname{tg} K_4 h_3 - Z_2^2 Z_4 \times \operatorname{tg} K_2 h_1 \operatorname{tg} K_3 h_2 \operatorname{tg} K_4 h_3) \\
& + j(Z_4 \cdot (Z_1 Z_2 Z_3 - Z_1 Z_3^2 \operatorname{tg} K_2 h_1 \operatorname{tg} K_3 h_2 \\
& - Z_1 Z_3 Z_4 \operatorname{tg} K_2 h_1 \operatorname{tg} K_4 h_3 - Z_1 Z_2 Z_4 \operatorname{tg} K_3 h_2 \operatorname{tg} K_4 h_3) \\
& - Z_1 \cdot (Z_2 Z_3 Z_4 - Z_2^2 Z_4 \operatorname{tg} K_2 h_1 \operatorname{tg} K_3 h_2 \\
& - Z_2^2 Z_3 \operatorname{tg} K_2 h_1 \operatorname{tg} K_4 h_3 - Z_2 Z_3^2 \operatorname{tg} K_3 h_2 \operatorname{tg} K_4 h_3)) \\
& - Z_1 \cdot (Z_1 Z_3 Z_4 \operatorname{tg} K_2 h_1 + Z_1 Z_2 Z_4 \operatorname{tg} K_3 h_2 + Z_1 Z_2 Z_3 \operatorname{tg} K_4 h_3 \\
& - Z_1 Z_3^2 \operatorname{tg} K_2 h_1 \operatorname{tg} K_3 h_2 \operatorname{tg} K_4 h_3)) \cdot (Z_4 \cdot (Z_2^2 Z_3 \operatorname{tg} K_2 h_1 \\
& + Z_2 Z_3^2 \operatorname{tg} K_3 h_2 + Z_2 Z_3 Z_4 \operatorname{tg} K_4 h_3 \\
& - Z_2^2 Z_4 \operatorname{tg} K_2 h_1 \operatorname{tg} K_3 h_2 \operatorname{tg} K_4 h_3) + j(Z_4 \cdot (Z_1 Z_2 Z_3 \\
& - Z_1 Z_3^2 \operatorname{tg} K_2 h_1 \operatorname{tg} K_3 h_2 - Z_1 Z_3 Z_4 \operatorname{tg} K_2 h_1 \operatorname{tg} K_4 h_3 \\
& - Z_1 Z_2 Z_4 \operatorname{tg} K_3 h_2 \operatorname{tg} K_4 h_3) + Z_1 \cdot (Z_2 Z_3 Z_4 \\
& - Z_2^2 Z_4 \operatorname{tg} K_2 h_1 \operatorname{tg} K_3 h_2 - Z_2^2 Z_3 \operatorname{tg} K_2 h_1 \operatorname{tg} K_4 h_3 \\
& - Z_2 Z_3^2 \operatorname{tg} K_3 h_2 \operatorname{tg} K_4 h_3)) + Z_1 \cdot (Z_1 Z_3 Z_4 \operatorname{tg} K_2 h_1 \\
& + Z_1 Z_2 Z_4 \operatorname{tg} K_3 h_2 + Z_1 Z_2 Z_3 \operatorname{tg} K_4 h_3 \\
& - Z_1 Z_3^2 \operatorname{tg} K_2 h_1 \operatorname{tg} K_3 h_2 \operatorname{tg} K_4 h_3))^{-1}, \tag{3.7}
\end{aligned}$$

and making a substitution and some mathematical transformations:

$$\begin{aligned}
A = & Z_4 \cdot (Z_2^2 Z_3 \operatorname{tg} K_2 h_1 + Z_2 Z_3^2 \operatorname{tg} K_3 h_2 + Z_2 Z_3 Z_4 \operatorname{tg} K_4 h_3 \\
& - Z_2^2 Z_4 \times \operatorname{tg} K_2 h_1 \operatorname{tg} K_3 h_2 \operatorname{tg} K_4 h_3) \\
& - Z_1 \cdot (Z_1 Z_3 Z_4 \operatorname{tg} K_2 h_1 + Z_1 Z_2 Z_4 \operatorname{tg} K_3 h_2 \\
& + Z_1 Z_2 Z_3 \operatorname{tg} K_4 h_3 - Z_1 Z_3^2 \operatorname{tg} K_2 h_1 \operatorname{tg} K_3 h_2 \operatorname{tg} K_4 h_3); \\
B = & Z_4 \cdot (Z_2^2 Z_3 \operatorname{tg} K_2 h_1 + Z_2 Z_3^2 \operatorname{tg} K_3 h_2 + Z_2 Z_3 Z_4 \operatorname{tg} K_4 h_3 \\
& - Z_2^2 Z_4 \times \operatorname{tg} K_2 h_1 \operatorname{tg} K_3 h_2 \operatorname{tg} K_4 h_3) + Z_1 \cdot (Z_1 Z_3 Z_4 \operatorname{tg} K_2 h_1 \\
& + Z_1 Z_2 Z_4 \operatorname{tg} K_3 h_2 + Z_1 Z_2 Z_3 \operatorname{tg} K_4 h_3 \\
& - Z_1 Z_3^2 \operatorname{tg} K_2 h_1 \operatorname{tg} K_3 h_2 \operatorname{tg} K_4 h_3); \\
C = & Z_4 \cdot (Z_1 Z_2 Z_3 - Z_1 Z_3^2 \operatorname{tg} K_2 h_1 \operatorname{tg} K_3 h_2 \\
& - Z_1 Z_3 Z_4 \operatorname{tg} K_2 h_1 \operatorname{tg} K_4 h_3 - Z_1 Z_2 Z_4 \operatorname{tg} K_3 h_2 \operatorname{tg} K_4 h_3) \\
& - Z_1 \cdot (Z_2 Z_3 Z_4 - Z_2^2 Z_4 \operatorname{tg} K_2 h_1 \operatorname{tg} K_3 h_2 \\
& - Z_2^2 Z_3 \operatorname{tg} K_2 h_1 \operatorname{tg} K_4 h_3 - Z_2 Z_3^2 \operatorname{tg} K_3 h_2 \operatorname{tg} K_4 h_3); \\
D = & Z_4 \cdot (Z_1 Z_2 Z_3 - Z_1 Z_3^2 \operatorname{tg} K_2 h_1 \operatorname{tg} K_3 h_2 \\
& - Z_1 Z_3 Z_4 \operatorname{tg} K_2 h_1 \operatorname{tg} K_4 h_3 - Z_1 Z_2 Z_4 \operatorname{tg} K_3 h_2 \operatorname{tg} K_4 h_3) \\
& + Z_1 \cdot (Z_2 Z_3 Z_4 - Z_2^2 Z_4 \operatorname{tg} K_2 h_1 \operatorname{tg} K_3 h_2
\end{aligned}$$

$$-Z_2^2 Z_3 t g K_2 h_1 t g K_4 h_3 - Z_2 Z_3^2 t g K_3 h_2 t g K_4 h_3), \quad (3.8)$$

from which

$$V_{def.} = \frac{A \cdot B + C \cdot D + j(B \cdot C - A \cdot D)}{B^2 + D^2} = \frac{A \cdot B + C \cdot D}{B^2 + D^2} + j \frac{B \cdot C - A \cdot D}{B^2 + D^2}, \quad (3.9)$$

and the module itself can then be presented as follows:

$$|V_{def.}| = \sqrt{\frac{(A \cdot B + C \cdot D)^2 + (B \cdot C - A \cdot D)^2}{(B^2 + D^2)^2}}. \quad (3.10)$$

Now when the expressions (3.1), (3.4) for the coefficients V_e , $V_{def.}$ and (3.9), (3.10) for the values $|V_e|$, $|V_{def.}|$ have been obtained, we can determine the difference in peak amplitudes through the relative module indicators and the phase shift of the sounding waves in the controlled CTM relative to the signal in reference CTM by modules and phases φ_e , $\varphi_{def.}$ of these signals. These values can be given as follows:

$$\Delta|V| = |V_{def.}| - |V_e|, \quad (3.11)$$

$$\Delta\varphi = \varphi_{def.} - \varphi_e, \quad (3.12)$$

where (taking into account the attenuation α_3 in the material)

$$\begin{aligned} \varphi_e = & \arctg \left(- \left(sh \alpha_3 h + \left(\frac{Z_2}{2 Z_1} + \frac{Z_1}{2 Z_2} \right) \cdot ch \alpha_3 h \right) \cdot \sin \frac{\omega h}{c_2} \right. \\ & \times \left(\left(\left(ch \alpha_3 h + \left(\frac{Z_2}{2 Z_1} + \frac{Z_1}{2 Z_2} \right) \cdot sh \alpha_3 h \right) \cdot \cos \frac{\omega h}{c_2} \right)^2 \right. \\ & + \left(\left(sh \alpha_3 h + \left(\frac{Z_2}{2 Z_1} + \frac{Z_1}{2 Z_2} \right) \cdot ch \alpha_3 h \right) \cdot \sin \frac{\omega h}{c_2} \right)^2 \\ & \left. \left. - \left(ch \alpha_3 h + \left(\frac{Z_2}{2 Z_1} + \frac{Z_1}{2 Z_2} \right) \cdot sh \alpha_3 h \right) \cdot \cos \frac{\omega h}{c_2} \right)^{-1} \right), \end{aligned} \quad (3.13)$$

with $\alpha_3 = 0$ and $Z_1/Z_2 \ll 1$ the expression (3.13) can be simplified to the following:

$$\varphi_e = \arctg \left(\frac{-\frac{Z_2}{2 Z_1} \cdot \sin \frac{\omega h}{c_2}}{\left(\cos \frac{\omega h}{c_2} \right)^2 + \left(\frac{Z_2}{2 Z_1} \cdot \sin \frac{\omega h}{c_2} \right)^2 - \cos \frac{\omega h}{c_2}} \right), \quad (3.14)$$

and the expression for the defective material can be presented as:

$$\varphi_{def.} = \arctg\left(\frac{B \cdot C - A \cdot D}{A \cdot B + C \cdot D}\right). \quad (3.15)$$

In order to detect the presence of a defect in the CTM, it is necessary to control the various textile layers of the composite, using two parameters of ultrasonic waves: amplitude and phase shift. This will increase the sensitivity of the measuring system using reference and measuring signals. An increase in the difference between the amplitudes of these signals and their phase shift will indicate an increase in the size of the defect in the structure of the controlled CTM. This means that delamination of the material can occur in its thickness, which can be recorded by comparing the information parameters of the reference and measuring signals of ultrasonic waves.

On the basis of the conducted research it is possible to implement a method of control over the CTM with textile layers of the material, which are its component parts. For this purpose it is necessary to use separately-combined transducers of ultrasonic waves for the detection of oscillations with a certain delay in time at their normal subsidence and reflection.

This complicates the practical implementation of this method, so it is necessary to further investigate the interaction of ultrasonic waves with the CTM, when they propagate at an angle to its surface during production.

3.2 Transmission and Reflection of Ultrasonic Waves from the Composition of the Layers of Liquid Polymer Melts, Their Solutions and from the Textile Layers with the Detection of Inhomogeneities in the Structure of the Composite of Small Thickness

As discussed earlier, the practical implementation of the control method over the CTM in the process of its production (the process of applying liquid polymer melts or its solutions on the textile layers of the composite) for the presence of inhomogeneities in its structure can be complicated from a technical point of view. This is due to the normal incidence of the ultrasonic wave. Therefore, we will show the possibility of non-contact ultrasonic control of the CTM in the process of its production, given that this is the case when the wave falls at an angle to the surface of the material. During the subsidence, the wave is reflected from the material or passes mainly through the media of liquid solutions or melts of various polymers and other constituent substances. This occurs during the operational control over the CTM itself. The wave also propagates in the air gaps of the pores in the textile layers, as most of the waves go round the threads of the textile material. Therefore, we will consider this process as the interaction of ultrasonic oscillations with liquid and gaseous media [9–15]. Thus we will accept textile layers of a composite for which the insignificant ratio of a sounding wave length to the sizes of pores between their threads or between their interfiber distances is carried out.

First, we will show the expressions of the complex transmission of the waves of the material and its module, with their normal incidence. This is necessary for further comparison and to obtain finite dependences for ultrasonic oscillations that fall at an angle to the material. The expressions for the transmission of the wave during its normal incidence on the reference material are written as follows:

$$W = \text{Re}W + j\text{Im}W = \frac{W_{12}W_{21} \cdot e^{jK_2h}}{1 - V_{21}V_{21} \cdot e^{2jK_2h}}, \quad (3.16)$$

$$|W| = \sqrt{\text{Re}W^2 + \text{Im}W^2}. \quad (3.17)$$

The dependences (3.16), (3.17) for the complex transmission coefficient and its module, taking into account the incident wave at an angle can be presented as:

$$W_\theta = \text{Re}W_\theta + j\text{Im}W_\theta = \frac{W_{\theta 12}W_{\theta 21} \cdot e^{jK_2h}}{1 - V_{\theta 21}V_{\theta 21} \cdot e^{2jK_2h}}, \quad (3.18)$$

$$|W_\theta| = \sqrt{\text{Re}W_\theta^2 + \text{Im}W_\theta^2}, \quad (3.19)$$

where $\text{Re}W_\theta$, $j\text{Im}W_\theta$ is the real and imaginary components of the complex coefficient of wave propagation at a certain angle of incidence θ .

The obtained expression (3.19) can be also written down using the dependence for the transmission coefficient module (3.17) and by the angle of the wave transmission through the material θ_2 as follows:

$$|W_\theta| = \sqrt{\text{Re}W^2 + \text{Im}W^2} \cdot \cos \theta_2, \quad (3.20)$$

For the dependence (3.18), the corresponding partial coefficients of transmission $W_{\theta 12}$, $W_{\theta 21}$ and reflection $V_{\theta 12}$, $V_{\theta 21}$ at the corresponding boundaries of the media and the complex wave transmission coefficient at the angle W_θ can be also presented as:

$$\begin{aligned} W_{\theta 12} &= \frac{2Z_1 \cdot \cos \theta_2}{Z_1 \cdot \cos \theta_2 + Z_2 \cdot \cos \theta_1}, & V_{\theta 12} &= \frac{Z_1 \cdot \cos \theta_2 - Z_2 \cdot \cos \theta_1}{Z_1 \cdot \cos \theta_2 + Z_2 \cdot \cos \theta_1}, \\ W_{\theta 21} &= \frac{2Z_2 \cdot \cos \theta_1}{Z_1 \cdot \cos \theta_2 + Z_2 \cdot \cos \theta_1}, & V_{\theta 21} &= \frac{Z_2 \cdot \cos \theta_1 - Z_1 \cdot \cos \theta_2}{Z_1 \cdot \cos \theta_2 + Z_2 \cdot \cos \theta_1}, \end{aligned} \quad (3.21)$$

$$W_\theta = \frac{W_{12}W_{21} \cdot e^{jK_2 \frac{h}{\cos \theta_2}}}{1 - V_{21}V_{21} \cdot e^{2jK_2 \frac{h}{\cos \theta_2}}}, \quad (3.22)$$

from where

$$K_2 = \frac{2\pi f}{c_2} + j\alpha_3, \quad (3.23)$$

where θ_1 is the angle of the ultrasonic wave incidence on the composite material.

After substituting the dependences (3.5) and (3.23) in the expression (3.22) and simple mathematical transformations, the complex coefficient of ultrasonic wave transmission at the angle to the material W_θ can be represented as:

$$W_\theta = 2 \cdot \left(\left(e^{\frac{h(-\alpha+j\frac{2\pi f}{c_2})}{\cos \theta_2}} + e^{\frac{h(\alpha-j\frac{2\pi f}{c_2})}{\cos \theta_2}} \right) - \left(\frac{Z_2}{2Z_1} + \frac{Z_1}{2Z_2} \right) \left(e^{\frac{h(-\alpha+j\frac{2\pi f}{c_2})}{\cos \theta_2}} - e^{\frac{h(\alpha-j\frac{2\pi f}{c_2})}{\cos \theta_2}} \right) \right)^{-1}, \quad (3.24)$$

or

$$W_\theta = \left(\cos \left(\frac{h}{\cos \theta_2} \frac{2\pi f}{c_2} + j \frac{h}{\cos \theta_2} \alpha_3 \right) - j \left(\frac{Z_2}{2Z_1} + \frac{Z_1}{2Z_2} \right) \cdot \sin \left(\frac{h}{\cos \theta_2} \frac{2\pi f}{c_2} + j \frac{h}{\cos \theta_2} \alpha_3 \right) \right)^{-1}. \quad (3.25)$$

If the expression (3.25) is decomposed into real and imaginary components, it can be shown as follows:

$$W_\theta = \frac{1 + \alpha_3 \cdot \left(\frac{Z_2}{2Z_1} + \frac{Z_1}{2Z_2} \right) \frac{h}{\cos \theta_2}}{\left(1 + \alpha_3 \cdot \left(\frac{Z_2}{2Z_1} + \frac{Z_1}{2Z_2} \right) \frac{h}{\cos \theta_2} \right)^2 + \left(\frac{2\pi f}{c_2} \left(\frac{Z_2}{2Z_1} + \frac{Z_1}{2Z_2} \right) \frac{h}{\cos \theta_2} \right)^2} + j \frac{\frac{2\pi f}{c_2} \left(\frac{Z_2}{2Z_1} + \frac{Z_1}{2Z_2} \right) \frac{h}{\cos \theta_2}}{\left(1 + \alpha_3 \cdot \left(\frac{Z_2}{2Z_1} + \frac{Z_1}{2Z_2} \right) \frac{h}{\cos \theta_2} \right)^2 + \left(\frac{2\pi f}{c_2} \left(\frac{Z_2}{2Z_1} + \frac{Z_1}{2Z_2} \right) \frac{h}{\cos \theta_2} \right)^2}, \quad (3.26)$$

where the dependence (3.26) for the complex transmission coefficient can be also presented by values A_θ , B_θ such as:

$$A_\theta = 1 + \alpha_3 \cdot \left(\frac{Z_2}{2Z_1} + \frac{Z_1}{2Z_2} \right) \frac{h}{\cos \theta_2}, B_\theta = \frac{2\pi f}{c_2} \left(\frac{Z_2}{2Z_1} + \frac{Z_1}{2Z_2} \right) \frac{h}{\cos \theta_2}, \quad (3.27)$$

$$W_\theta = \text{Re}W_\theta + j\text{Im}W_\theta = \frac{A_\theta}{A_\theta^2 + B_\theta^2} + j \frac{B_\theta}{A_\theta^2 + B_\theta^2}, \quad (3.28)$$

where taking into account the expression (3.28), it is possible to show the dependence for the complex reflection coefficient V_θ of ultrasonic waves from this material as:

$$V_\theta = 1 - W_\theta = \text{Re}V_\theta + j\text{Im}V_\theta = \frac{A_\theta^2 + B_\theta^2 - A_\theta}{A_\theta^2 + B_\theta^2} - j \frac{B_\theta}{A_\theta^2 + B_\theta^2}. \quad (3.29)$$

With $\alpha_3 = 0$ the expression (3.28) can be rewritten as follows:

$$W_\theta = \frac{1}{1 + \left(\frac{2\pi f}{c_2} \left(\frac{Z_2}{2Z_1} + \frac{Z_1}{2Z_2} \right) \frac{h}{\cos \theta_2} \right)^2} + j \frac{\frac{2\pi f}{c_2} \left(\frac{Z_2}{2Z_1} + \frac{Z_1}{2Z_2} \right) \frac{h}{\cos \theta_2}}{1 + \left(\frac{2\pi f}{c_2} \left(\frac{Z_2}{2Z_1} + \frac{Z_1}{2Z_2} \right) \frac{h}{\cos \theta_2} \right)^2}, \quad (3.30)$$

and the dependence (3.29) can be written as:

$$V_\theta = \frac{\left(\frac{2\pi f}{c_2} \left(\frac{Z_2}{2Z_1} + \frac{Z_1}{2Z_2} \right) \frac{h}{\cos \theta_2} \right)^2}{1 + \left(\frac{2\pi f}{c_2} \left(\frac{Z_2}{2Z_1} + \frac{Z_1}{2Z_2} \right) \frac{h}{\cos \theta_2} \right)^2} - j \frac{\frac{2\pi f}{c_2} \left(\frac{Z_2}{2Z_1} + \frac{Z_1}{2Z_2} \right) \frac{h}{\cos \theta_2}}{1 + \left(\frac{2\pi f}{c_2} \left(\frac{Z_2}{2Z_1} + \frac{Z_1}{2Z_2} \right) \frac{h}{\cos \theta_2} \right)^2}, \quad (3.31)$$

when $Z_1/Z_2 \ll 1$ and there are small pores in the textile layers of the composite material, the expressions (3.30) and (3.31) can be presented as follows:

$$W_\theta = \frac{1}{1 + \left(\frac{\pi f \rho_2}{Z_1} \frac{h \cdot \cos v}{\cos \theta_2} \right)^2} + j \frac{\frac{\pi f \rho_2}{Z_1} \frac{h \cdot \cos v}{\cos \theta_2}}{1 + \left(\frac{\pi f \rho_2}{Z_1} \frac{h \cdot \cos v}{\cos \theta_2} \right)^2}, \quad (3.32)$$

or

$$\begin{aligned} W_\theta &= \frac{1}{1 + \left(\frac{\pi f \rho_2}{Z_1} \frac{h \cdot \cos v}{\cos \theta_2} \right)^2} + j \frac{1}{\frac{Z_1}{\pi f \rho_2} \frac{\cos \theta_2}{h \cdot \cos v} + \frac{\pi f \rho_2}{Z_1} \frac{h \cdot \cos v}{\cos \theta_2}}, \\ V_\theta &= \frac{\left(\frac{\pi f \rho_2}{Z_1} \frac{h \cdot \cos v}{\cos \theta_2} \right)^2}{1 + \left(\frac{\pi f \rho_2}{Z_1} \frac{h \cdot \cos v}{\cos \theta_2} \right)^2} - j \frac{\frac{\pi f \rho_2}{Z_1} \frac{h \cdot \cos v}{\cos \theta_2}}{1 + \left(\frac{\pi f \rho_2}{Z_1} \frac{h \cdot \cos v}{\cos \theta_2} \right)^2}, \end{aligned} \quad (3.33)$$

or

$$V_\theta = \frac{1}{1 + \left(\frac{Z_1}{\pi f \rho_2} \frac{\cos \theta_2}{h \cdot \cos v} \right)^2} - j \frac{1}{\frac{Z_1}{\pi f \rho_2} \frac{\cos \theta_2}{h \cdot \cos v} + \frac{\pi f \rho_2}{Z_1} \frac{h \cdot \cos v}{\cos \theta_2}}.$$

Then the modules for the corresponding coefficients of transmission W_θ and reflection V_θ of the ultrasonic wave incident at an angle to the surface of the material (taking into account (3.32) and (3.33)) can be shown as:

$$|W_\theta| = \frac{1}{\sqrt{1 + \left(\frac{\pi f \rho_2}{Z_1} \frac{h \cdot \cos v}{\cos \theta_2} \right)^2}}, \quad (3.34)$$

$$|V_\theta| = \frac{1}{\sqrt{1 + \left(\frac{Z_1}{\pi f \rho_2} \frac{\cos \theta_2}{h \cdot \cos v} \right)^2}}, \quad (3.35)$$

The dependences for the phase of the waves passing through this material and the waves reflected from it can then be given as follows:

$$\varphi_{W\theta} = \arctg\left(\frac{\pi f \rho_2 h \cdot \cos v}{Z_1 \cos \theta_2}\right), \quad (3.36)$$

$$\varphi_{V\theta} = \arctg\left(-\frac{Z_1}{\pi f \rho_2 h \cdot \cos v} \frac{\cos \theta_2}{\cos \theta_2}\right), \quad (3.37)$$

The obtained expressions (3.19), (3.34), (3.35), (3.36), (3.37) can be used when it comes to the reference two-layer CTM [16–22] without an air gap or other defect between its components with similar acoustic impedance, where ρ_2 is the average bulk density for it.

It is possible to describe the wave reflection at an angle to this reference two-layer CTM using the acoustic impedance for the two media $Z_{\theta in.}^{(2)}$ and the complex reflection coefficient V_θ with the help of the dependences, respectively, as:

$$Z_{\theta in.}^{(2)} = \frac{\frac{Z_1}{\cos \theta_1} - j \frac{Z_2}{\cos \theta_2} \operatorname{tg}(K_2 h)}{\frac{Z_2}{\cos \theta_2} - j \frac{Z_1}{\cos \theta_1} \operatorname{tg}(K_2 h)} \cdot \frac{Z_2}{\cos \theta_2}, \quad (3.38)$$

then

$$V_\theta = \frac{Z_{\theta in.}^{(2)} \cos \theta_1 - Z_1}{Z_{\theta in.}^{(2)} \cos \theta_1 + Z_1}. \quad (3.39)$$

To simplify the record, the formula (3.38) and (3.39) can be approximately presented as follows:

$$Z_{\theta in.}^{(2)} = \frac{Z_1 - j Z_2 \operatorname{tg}\left(\frac{K_2 h}{\cos \theta_2}\right)}{Z_2 - j Z_1 \operatorname{tg}\left(\frac{K_2 h}{\cos \theta_2}\right)} \cdot Z_2, \quad (3.40)$$

then

$$V_\theta = \frac{Z_{\theta in.}^{(2)} - Z_1}{Z_{\theta in.}^{(2)} + Z_1}. \quad (3.41)$$

Basically, the obtained expressions can be used to determine the change in the total thickness of the constituent materials included in the composite, as well as the change in the total bulk density of the material.

Based on the above, it is possible to present similar dependences for the reference composite material, consisting of two layers with acoustic impedances, which are very different from each other ($Z_2 \neq Z_3$). For this case, the acoustic impedance $Z_{\theta in.}^{(3)}$ and the complex reflection coefficient V_θ for the three media will be presented

and given in the following way:

$$\begin{aligned}
 Z_{\theta in.}^{(3)} = & \left(\frac{Z_1 Z_2}{\cos \theta_1 \cdot \cos \theta_2} - \frac{Z_1 Z_3}{\cos \theta_1 \cdot \cos \theta_3} \operatorname{tg}(K_2 h_1) \operatorname{tg}(K_3 h_2) \right. \\
 & \left. - j \left(\left(\frac{Z_2}{\cos \theta_2} \right)^2 \operatorname{tg}(K_2 h_1) + \frac{Z_2 Z_3}{\cos \theta_2 \cdot \cos \theta_3} \operatorname{tg}(K_3 h_2) \right) \right) \cdot \frac{Z_3}{\cos \theta_3} \\
 & \times \left(\frac{Z_2 Z_3}{\cos \theta_2 \cdot \cos \theta_3} - \left(\frac{Z_2}{\cos \theta_2} \right)^2 \operatorname{tg}(K_2 h_1) \operatorname{tg}(K_3 h_2) \right. \\
 & \left. - j \left(\frac{Z_1 Z_3}{\cos \theta_1 \cdot \cos \theta_3} \operatorname{tg}(K_2 h_1) + \frac{Z_1 Z_2}{\cos \theta_1 \cdot \cos \theta_2} \operatorname{tg}(K_3 h_2) \right) \right)^{-1}, \quad (3.42)
 \end{aligned}$$

then

$$V_{\theta} = \frac{Z_{\theta in.}^{(3)} - \frac{Z_1}{\cos \theta_1}}{Z_{\theta in.}^{(3)} + \frac{Z_1}{\cos \theta_1}}. \quad (3.43)$$

Given the obtained expression (3.43) for the reference CTM with acoustic impedances of layers that are very different from each other, we can show the reflection of waves from the CTM that may have a defect. Such defects can be delaminating with poor adhesion of the layers to each other, their deformation, as well as the temperature of the composite during its production. Since the textile layers of the composite material may contain pores, the delamination must be much larger in thickness or area of the defect compared to the pores to be able to detect it by means of ultrasonic waves.

Let us consider the CTM with small pore sizes in its structure, which can be neglected. The delamination, which is a thin layer of air in the material or its inhomogeneity, can be described by the input acoustic impedance $Z_{\theta in.}^{(4)}$ for the four media as:

$$\begin{aligned}
 Z_{\theta in.}^{(4)} = & \left(\frac{Z_1 Z_2 Z_3}{\cos \theta_1 \cdot \cos \theta_2 \cdot \cos \theta_3} - \frac{Z_1}{\cos \theta_1} \cdot \left(\frac{Z_3}{\cos \theta_3} \right)^2 \cdot \operatorname{tg}(K_2 h_1) \operatorname{tg}(K_3 h_2) \right. \\
 & - \frac{Z_1 Z_3 Z_4}{\cos \theta_1 \cdot \cos \theta_3 \cdot \cos \theta_4} \operatorname{tg}(K_2 h_1) \operatorname{tg}(K_4 h_3) \\
 & - \frac{Z_1 Z_2 Z_4}{\cos \theta_1 \cdot \cos \theta_2 \cdot \cos \theta_4} \times \operatorname{tg}(K_3 h_2) \operatorname{tg}(K_4 h_3) - \\
 & j \left(\left(\frac{Z_2}{\cos \theta_2} \right)^2 \cdot \frac{Z_3}{\cos \theta_3} \cdot \operatorname{tg}(K_2 h_1) + \frac{Z_2}{\cos \theta_2} \cdot \left(\frac{Z_3}{\cos \theta_3} \right)^2 \times \operatorname{tg}(K_3 h_2) \right. \\
 & \left. + \frac{Z_2 Z_3 Z_4}{\cos \theta_2 \cdot \cos \theta_3 \cdot \cos \theta_4} \operatorname{tg}(K_4 h_3) - \left(\frac{Z_2}{\cos \theta_2} \right)^2 \cdot \frac{Z_4}{\cos \theta_4} \cdot \operatorname{tg}(K_2 h_1) \right)
 \end{aligned}$$

$$\begin{aligned}
& \times tg(K_3 h_2)tg(K_4 h_3)) \cdot \left(\frac{Z_2 Z_3 Z_4}{\cos \theta_2 \cdot \cos \theta_3 \cdot \cos \theta_4} - \left(\frac{Z_2}{\cos \theta_2} \right)^2 \cdot \frac{Z_4}{\cos \theta_4} \right. \\
& \times tg(K_2 h_1)tg(K_3 h_2) - \left(\frac{Z_2}{\cos \theta_2} \right)^2 \frac{Z_3}{\cos \theta_3} \cdot tg(K_2 h_1)tg(K_4 h_3) \\
& - \frac{Z_2}{\cos \theta_2} \cdot \left(\frac{Z_3}{\cos \theta_3} \right)^2 \times tg(K_3 h_2)tg(K_4 h_3) \\
& - j \left(\frac{Z_1 Z_3 Z_4}{\cos \theta_1 \cdot \cos \theta_3 \cdot \cos \theta_4} \cdot tg(K_2 h_1) + \frac{Z_1 Z_2 Z_4}{\cos \theta_1 \cdot \cos \theta_2 \cdot \cos \theta_4} \right. \\
& \times tg(K_3 h_2) + \frac{Z_1 Z_2 Z_3}{\cos \theta_1 \cdot \cos \theta_2 \cdot \cos \theta_3} \cdot tg(K_4 h_3) \\
& \left. \left. - \frac{Z_1}{\cos \theta_1} \cdot \left(\frac{Z_3}{\cos \theta_3} \right)^2 tg(K_2 h_1) \times tg(K_3 h_2)tg(K_4 h_3) \right) \right)^{-1} \cdot Z_4, \quad (3.44)
\end{aligned}$$

where for this case (similar to the previously considered one with a normal wave subsidence): h_1 is the thickness of the material under the defect; h_2 —the thickness of the defect in the material; h_3 —the thickness of the material layer over the defect; Z_2 —acoustic impedance of the material under the defect; Z_3 —acoustic impedance of the defect layer; Z_4 —acoustic impedance of the material layer over the defect; K_2 —wave number for the material layer under the defect; K_3 —wave number for the defect layer; K_4 —wave number for the material layer that is over the defect; θ_3 —the angle of the wave transmission through the defect layer; θ_4 —the angle of the wave transmission through the material layer over the defect.

Taking into account the expression (3.44), the complex reflection coefficient V_θ can be shown as follows:

$$V_\theta = \frac{Z_{\theta in.}^{(4)} - \frac{Z_1}{\cos \theta_1}}{Z_{\theta in.}^{(4)} + \frac{Z_1}{\cos \theta_1}}. \quad (3.45)$$

In order to obtain the expression for the reflection module $|V_\theta|$, it is necessary to select the real $Re V_\theta$ and imaginary $Im V_\theta$ components from the expression (3.45) but, first of all, make the appropriate transformations, which will be shown below:

$$\begin{aligned}
C_\theta &= \frac{Z_4}{\cos \theta_4} \cdot \left(\left(\frac{Z_2}{\cos \theta_2} \right)^2 \cdot \frac{Z_3}{\cos \theta_3} \cdot tg(K_2 h_1) + \frac{Z_2}{\cos \theta_2} \cdot \left(\frac{Z_3}{\cos \theta_3} \right)^2 \right. \\
& \times tg(K_3 h_2) + \frac{Z_2 Z_3 Z_4}{\cos \theta_2 \cdot \cos \theta_3 \cdot \cos \theta_4} \cdot tg(K_4 h_3) - \left(\frac{Z_2}{\cos \theta_2} \right)^2 \cdot \frac{Z_4}{\cos \theta_4} \cdot tg(K_2 h_1) \\
& \times tg(K_3 h_2)tg(K_4 h_3)) - \frac{Z_1}{\cos \theta_1} \cdot \left(\frac{Z_1 Z_3 Z_4}{\cos \theta_1 \cdot \cos \theta_3 \cdot \cos \theta_4} \cdot tg(K_2 h_1) \right. \\
& + \frac{Z_1 Z_2 Z_4}{\cos \theta_1 \cdot \cos \theta_2 \cdot \cos \theta_4} \cdot tg(K_3 h_2) + \frac{Z_1 Z_2 Z_3}{\cos \theta_1 \cdot \cos \theta_2 \cdot \cos \theta_3} \cdot tg(K_4 h_3) \\
& \left. \left. - \frac{Z_1}{\cos \theta_1} \cdot \left(\frac{Z_3}{\cos \theta_3} \right)^2 \cdot tg(K_2 h_1)tg(K_3 h_2)tg(K_4 h_3) \right) \right);
\end{aligned}$$

$$\begin{aligned}
D_\theta &= \frac{Z_4}{\cos \theta_4} \cdot \left(\left(\frac{Z_2}{\cos \theta_2} \right)^2 \cdot \frac{Z_3}{\cos \theta_3} \cdot \text{tg}(K_2 h_1) + \frac{Z_2}{\cos \theta_2} \cdot \left(\frac{Z_3}{\cos \theta_3} \right)^2 \right. \\
&\quad \times \text{tg}(K_3 h_2) + \frac{Z_2 Z_3 Z_4}{\cos \theta_2 \cdot \cos \theta_3 \cdot \cos \theta_4} \cdot \text{tg}(K_4 h_3) - \left(\frac{Z_2}{\cos \theta_2} \right)^2 \cdot \frac{Z_4}{\cos \theta_4} \cdot \text{tg}(K_2 h_1) \\
&\quad \times \text{tg}(K_3 h_2) \text{tg}(K_4 h_3) + \frac{Z_1}{\cos \theta_1} \cdot \left(\frac{Z_1 Z_3 Z_4}{\cos \theta_1 \cdot \cos \theta_3 \cdot \cos \theta_4} \cdot \text{tg}(K_2 h_1) \right. \\
&\quad + \frac{Z_1 Z_2 Z_4}{\cos \theta_1 \cdot \cos \theta_2 \cdot \cos \theta_4} \cdot \text{tg}(K_3 h_2) + \frac{Z_1 Z_2 Z_3}{\cos \theta_1 \cdot \cos \theta_2 \cdot \cos \theta_3} \cdot \text{tg}(K_4 h_3) \\
&\quad \left. - \frac{Z_1}{\cos \theta_1} \cdot \left(\frac{Z_3}{\cos \theta_3} \right)^2 \cdot \text{tg}(K_2 h_1) \text{tg}(K_3 h_2) \text{tg}(K_4 h_3) \right); \\
E_\theta &= \frac{Z_4}{\cos \theta_4} \cdot \left(\frac{Z_1 Z_2 Z_3}{\cos \theta_1 \cdot \cos \theta_2 \cdot \cos \theta_3} - \frac{Z_1}{\cos \theta_1} \cdot \left(\frac{Z_3}{\cos \theta_3} \right)^2 \cdot \text{tg}(K_2 h_1) \text{tg}(K_3 h_2) \right. \\
&\quad - \frac{Z_1 Z_3 Z_4}{\cos \theta_1 \cdot \cos \theta_3 \cdot \cos \theta_4} \cdot \text{tg}(K_2 h_1) \text{tg}(K_4 h_3) - \frac{Z_1 Z_2 Z_4}{\cos \theta_1 \cdot \cos \theta_2 \cdot \cos \theta_4} \cdot \text{tg}(K_3 h_2) \\
&\quad \times \text{tg}(K_4 h_3) - \frac{Z_1}{\cos \theta_1} \cdot \left(\frac{Z_2 Z_3 Z_4}{\cos \theta_2 \cdot \cos \theta_3 \cdot \cos \theta_4} - \left(\frac{Z_2}{\cos \theta_2} \right)^2 \cdot \frac{Z_4}{\cos \theta_4} \right. \\
&\quad \times \text{tg}(K_2 h_1) \text{tg}(K_3 h_2) - \left(\frac{Z_2}{\cos \theta_2} \right)^2 \cdot \frac{Z_3}{\cos \theta_3} \cdot \text{tg}(K_2 h_1) \text{tg}(K_4 h_3) - \frac{Z_2}{\cos \theta_2} \\
&\quad \left. \times \left(\frac{Z_3}{\cos \theta_3} \right)^2 \cdot \text{tg}(K_3 h_2) \text{tg}(K_4 h_3) \right); \\
F_\theta &= \frac{Z_4}{\cos \theta_4} \cdot \left(\frac{Z_1 Z_2 Z_3}{\cos \theta_1 \cdot \cos \theta_2 \cdot \cos \theta_3} - \frac{Z_1}{\cos \theta_1} \cdot \left(\frac{Z_3}{\cos \theta_3} \right)^2 \cdot \text{tg}(K_2 h_1) \text{tg}(K_3 h_2) \right. \\
&\quad - \frac{Z_1 Z_3 Z_4}{\cos \theta_1 \cdot \cos \theta_3 \cdot \cos \theta_4} \cdot \text{tg}(K_2 h_1) \text{tg}(K_4 h_3) - \frac{Z_1 Z_2 Z_4}{\cos \theta_1 \cdot \cos \theta_2 \cdot \cos \theta_4} \cdot \text{tg}(K_3 h_2) \\
&\quad \times \text{tg}(K_4 h_3) + \frac{Z_1}{\cos \theta_1} \cdot \left(\frac{Z_2 Z_3 Z_4}{\cos \theta_2 \cdot \cos \theta_3 \cdot \cos \theta_4} - \left(\frac{Z_2}{\cos \theta_2} \right)^2 \cdot \frac{Z_4}{\cos \theta_4} \right. \\
&\quad \times \text{tg}(K_2 h_1) \text{tg}(K_3 h_2) - \left(\frac{Z_2}{\cos \theta_2} \right)^2 \cdot \frac{Z_3}{\cos \theta_3} \cdot \text{tg}(K_2 h_1) \text{tg}(K_4 h_3) - \frac{Z_2}{\cos \theta_2} \\
&\quad \left. \times \left(\frac{Z_3}{\cos \theta_3} \right)^2 \cdot \text{tg}(K_3 h_2) \text{tg}(K_4 h_3) \right). \tag{3.46}
\end{aligned}$$

In the case where parts of the constituent layers have a common boundary and are porous materials, the ultrasonic wave may not be refracted when falling at an angle, passing this boundary. This is because most of the ultrasonic signal can bypass the threads of the material. Therefore, such component layers of the composite with significant pores can be considered as approaching gaseous media. To calculate such CTMs and component layers of liquid solutions or composite polymer melts (Fig. 3.1), taking into account (3.46), making a certain replacement and some mathematical transformations, the dependence (3.45) can be shown as follows:

$$V_\theta = \frac{C_\theta \cdot D_\theta + E_\theta \cdot F_\theta + j(D_\theta \cdot E_\theta - C_\theta \cdot F_\theta)}{D_\theta^2 + F_\theta^2}, \tag{3.47}$$

or

$$V_\theta = \frac{C_\theta \cdot D_\theta + E_\theta \cdot F_\theta}{D_\theta^2 + F_\theta^2} + j \frac{D_\theta \cdot E_\theta - C_\theta \cdot F_\theta}{D_\theta^2 + F_\theta^2}, \tag{3.48}$$

from where you can get the following expression for the complex transmission coefficient W_θ of the wave at an angle to the defective material as follows:

$$W_\theta = \frac{D_\theta(D_\theta - C_\theta) + F_\theta(F_\theta - E_\theta)}{D_\theta^2 + F_\theta^2} - j \frac{D_\theta \cdot E_\theta - C_\theta \cdot F_\theta}{D_\theta^2 + F_\theta^2}, \quad (3.50)$$

and the module itself can be presented as:

$$|W_\theta| = \sqrt{\frac{(D_\theta(D_\theta - C_\theta) + F_\theta(F_\theta - E_\theta))^2 + (D_\theta \cdot E_\theta - C_\theta \cdot F_\theta)^2}{(D_\theta^2 + F_\theta^2)^2}}. \quad (3.51)$$

when $Z_1 = Z_3$, $Z_2 = Z_4$, $h_1 = h_3$, the presented dependences (3.46), (3.49) and (3.51) can be shown as follows:

$$\begin{aligned} C_\theta &= 2 \left(\frac{Z_1}{\cos \theta_1} \cdot \left(\frac{Z_2}{\cos \theta_2} \right)^3 - \left(\frac{Z_1}{\cos \theta_1} \right)^3 \frac{Z_2}{\cos \theta_2} \right) \operatorname{tg}(K_2 h_1) \\ &\quad + \left(\left(\frac{Z_1}{\cos \theta_1} \right)^4 - \left(\frac{Z_2}{\cos \theta_2} \right)^4 \right) \operatorname{tg}(K_1 h_2) \cdot (\operatorname{tg}(K_2 h_1))^2; \\ D_\theta &= 2 \left(\frac{Z_1}{\cos \theta_1} \cdot \left(\frac{Z_2}{\cos \theta_2} \right)^3 + \left(\frac{Z_1}{\cos \theta_1} \right)^3 \frac{Z_2}{\cos \theta_2} \right) \operatorname{tg}(K_2 h_1) \\ &\quad + \left(2 \left(\frac{Z_1}{\cos \theta_1} \right)^2 \left(\frac{Z_2}{\cos \theta_2} \right)^2 - \left(\left(\frac{Z_1}{\cos \theta_1} \right)^4 \right. \right. \\ &\quad \left. \left. + \left(\frac{Z_2}{\cos \theta_2} \right)^4 \right) \cdot (\operatorname{tg}(K_2 h_1))^2 \right) \operatorname{tg}(K_1 h_2); \\ E_\theta &= 0; \\ F_\theta &= 2 \left(\left(\frac{Z_1}{\cos \theta_1} \right)^2 \left(\frac{Z_2}{\cos \theta_2} \right)^2 (1 - (\operatorname{tg}(K_2 h_1))^2) \right. \\ &\quad \left. - \left(\frac{Z_1}{\cos \theta_1} \cdot \left(\frac{Z_2}{\cos \theta_2} \right)^3 \right. \right. \\ &\quad \left. \left. + \left(\frac{Z_1}{\cos \theta_1} \right)^3 \frac{Z_2}{\cos \theta_2} \right) \cdot \operatorname{tg}(K_1 h_2) \cdot \operatorname{tg}(K_2 h_1) \right), \end{aligned} \quad (3.52)$$

$$|V_\theta| = \sqrt{\frac{(C_\theta \cdot D_\theta)^2 + (C_\theta \cdot F_\theta)^2}{(D_\theta^2 + F_\theta^2)^2}}. \quad (3.53)$$

$$|W_\theta| = \sqrt{\frac{(D_\theta(D_\theta - C_\theta) + F_\theta^2)^2 + (C_\theta \cdot F_\theta)^2}{(D_\theta^2 + F_\theta^2)^2}}. \quad (3.54)$$

Based on the obtained expressions (3.43), (3.48), (3.49), (3.50) and (3.51), it is possible to obtain the difference between the amplitudes of the waves from the reference channel (waves that interacted with the reference CTM during its production) and waves from the controlled channel (waves interacting with the CTM with a possible defect in its structure during production), as well as calculate the phase shift between these waves. The following dependences of these values, when $Z_1 \neq Z_3$, $Z_2 \neq Z_4$, $h_1 \neq h_3$, and neglecting the pore sizes in the textile layers of the composite material, are then given as follows:

$$\Delta|V| = \sqrt{\frac{(C_\theta \cdot D_\theta + E_\theta \cdot F_\theta)^2 + (D_\theta \cdot E_\theta - C_\theta \cdot F_\theta)^2}{(D_\theta^2 + F_\theta^2)^2}} - \left| \frac{Z_{\theta in.}^{(3)} - Z_1}{Z_{\theta in.}^{(3)} + Z_1} \right|, \quad (3.55)$$

$$\Delta|W| = \sqrt{\frac{(D_\theta(D_\theta - C_\theta) + F_\theta(F_\theta - E_\theta))^2 + (D_\theta \cdot E_\theta - C_\theta \cdot F_\theta)^2}{(D_\theta^2 + F_\theta^2)^2}} - \left| 1 - \frac{Z_{\theta in.}^{(3)} - Z_1}{Z_{\theta in.}^{(3)} + Z_1} \right|, \quad (3.56)$$

$$\begin{aligned} \Delta\varphi_V &= \arctg\left(\frac{D_\theta \cdot E_\theta - C_\theta \cdot F_\theta}{C_\theta \cdot D_\theta + E_\theta \cdot F_\theta}\right) \\ &\quad - \arctg\left(\frac{D_{\theta e} \cdot E_{\theta e} - C_{\theta e} \cdot F_{\theta e}}{C_{\theta e} \cdot D_{\theta e} + E_{\theta e} \cdot F_{\theta e}}\right), \\ \Delta\varphi_W &= \arctg\left(\frac{D_\theta \cdot E_\theta - C_\theta \cdot F_\theta}{D_\theta(D_\theta - C_\theta) + F_\theta(F_\theta - E_\theta)}\right) \\ &\quad - \arctg\left(\frac{D_{\theta e} \cdot E_{\theta e} - C_{\theta e} \cdot F_{\theta e}}{D_{\theta e}(D_{\theta e} - C_{\theta e}) + F_{\theta e}(F_{\theta e} - E_{\theta e})}\right). \end{aligned} \quad (3.57)$$

where

$$\begin{aligned} C_{\theta e} &= \frac{Z_4}{\cos \theta_4} \cdot \left(\left(\frac{Z_2}{\cos \theta_2} \right)^2 \cdot \frac{Z_3}{\cos \theta_3} \cdot \operatorname{tg}(K_2 h_1) \right. \\ &\quad \left. + \frac{Z_2 Z_3 Z_4}{\cos \theta_2 \cdot \cos \theta_3 \cdot \cos \theta_4} \times g(K_4 h_3) \right) \\ &\quad - \frac{Z_1}{\cos \theta_1} \cdot \left(\frac{Z_1 Z_3 Z_4}{\cos \theta_1 \cdot \cos \theta_3 \cdot \cos \theta_4} \operatorname{tg}(K_2 h_1) \right) \end{aligned}$$

$$\begin{aligned}
& + \frac{Z_1 Z_2 Z_3}{\cos \theta_1 \cdot \cos \theta_2 \cdot \cos \theta_3} \operatorname{tg}(K_4 h_3) \Big); \\
D_{\theta e} = & \frac{Z_4}{\cos \theta_4} \cdot \left(\left(\frac{Z_2}{\cos \theta_2} \right)^2 \cdot \frac{Z_3}{\cos \theta_3} \cdot \operatorname{tg}(K_2 h_1) \right. \\
& + \frac{Z_2 Z_3 Z_4}{\cos \theta_2 \cdot \cos \theta_3 \cdot \cos \theta_4} \times \operatorname{tg}(K_4 h_3) \Big) \\
& + \frac{Z_1}{\cos \theta_1} \cdot \left(\frac{Z_1 Z_3 Z_4}{\cos \theta_1 \cdot \cos \theta_3 \cdot \cos \theta_4} \operatorname{tg}(K_2 h_1) \right. \\
& + \frac{Z_1 Z_2 Z_3}{\cos \theta_1 \cdot \cos \theta_2 \cdot \cos \theta_3} \operatorname{tg}(K_4 h_3) \Big); \\
E_{\theta e} = & \frac{Z_4}{\cos \theta_4} \cdot \left(\frac{Z_1 Z_2 Z_3}{\cos \theta_1 \cdot \cos \theta_2 \cdot \cos \theta_3} - \right. \\
& \frac{Z_1 Z_3 Z_4}{\cos \theta_1 \cdot \cos \theta_3 \cdot \cos \theta_4} \times \operatorname{tg}(K_2 h_1) \cdot \operatorname{tg}(K_4 h_3) \Big) \\
& - Z_1 \cdot \left(\frac{Z_2 Z_3 Z_4}{\cos \theta_2 \cdot \cos \theta_3 \cdot \cos \theta_4} - \left(\frac{Z_2}{\cos \theta_2} \right)^2 \cdot \frac{Z_3}{\cos \theta_3} \right. \\
& \times \operatorname{tg}(K_2 h_1) \cdot \operatorname{tg}(K_4 h_3) \Big); \\
F_{\theta e} = & \frac{Z_4}{\cos \theta_4} \cdot \left(\frac{Z_1 Z_2 Z_3}{\cos \theta_1 \cdot \cos \theta_2 \cdot \cos \theta_3} \right. \\
& - \frac{Z_1 Z_3 Z_4}{\cos \theta_1 \cdot \cos \theta_3 \cdot \cos \theta_4} \times \operatorname{tg}(K_2 h_1) \cdot \operatorname{tg}(K_4 h_3) \Big) \\
& + Z_1 \cdot \left(\frac{Z_2 Z_3 Z_4}{\cos \theta_2 \cdot \cos \theta_3 \cdot \cos \theta_4} - \left(\frac{Z_2}{\cos \theta_2} \right)^2 \cdot \frac{Z_3}{\cos \theta_3} \right. \\
& \times \operatorname{tg}(K_2 h_1) \cdot \operatorname{tg}(K_4 h_3) \Big), \tag{3.58}
\end{aligned}$$

If the pore sizes in the textile layers of the composite must be taken into account, then in the expressions (3.55), (3.56), (3.57) and (3.58), when substituting the values $K_2 h_1$ and $K_4 h_3$, it is necessary to replace them with $K_2 h_1 \cdot \cos \nu_1$ and $K_4 h_3 \cdot \cos \nu_3$, respectively. The values $\cos \nu_1$ and $\cos \nu_3$ characterize the influence of the pore sizes of the first and second layers of textile materials on the transmission of the resulting ultrasonic signal through their structures and the reflection of the signal from them, respectively.

In the case when $Z_1 = Z_3$, $Z_2 = Z_4$, $h_1 = h_3$, neglecting the pore sizes in the textile layers of the composite material, we will use the expressions (3.34), (3.35), (3.36), (3.37), (3.41), (3.53) and (3.54), and give the following dependencies in the following way:

$$\Delta|V| = \sqrt{\frac{(C_\theta \cdot D_\theta)^2 + (C_\theta \cdot F_\theta)^2}{(D_\theta^2 + F_\theta^2)^2}} - \left| \frac{Z_{\theta in.}^{(2)} - Z_1}{Z_{\theta in.}^{(2)} + Z_1} \right|, \quad (3.59)$$

or

$$\begin{aligned} \Delta|V| &\approx \sqrt{\frac{(C_\theta \cdot D_\theta)^2 + (C_\theta \cdot F_\theta)^2}{(D_\theta^2 + F_\theta^2)^2}} - \frac{1}{\sqrt{1 + \left(\frac{Z_1}{\pi f \rho_2} \frac{\cos \theta_2}{2h_1}\right)^2}}, \\ \Delta|W| &= \sqrt{\frac{(D_\theta(D_\theta - C_\theta) + F_\theta^2)^2 + (C_\theta \cdot F_\theta)^2}{(D_\theta^2 + F_\theta^2)^2}} - \left| 1 - \frac{Z_{\theta in.}^{(2)} - Z_1}{Z_{\theta in.}^{(2)} + Z_1} \right|, \end{aligned} \quad (3.60)$$

or

$$\begin{aligned} \Delta|W| &\approx \sqrt{\frac{(D_\theta(D_\theta - C_\theta) + F_\theta^2)^2 + (C_\theta \cdot F_\theta)^2}{(D_\theta^2 + F_\theta^2)^2}} \\ &\quad - \frac{1}{\sqrt{1 + \left(\frac{\pi f \rho_2}{Z_1} \frac{2h_1}{\cos \theta_2}\right)^2}}, \\ \Delta\varphi_V &= \arctg\left(-\frac{C_\theta \cdot F_\theta}{C_\theta \cdot D_\theta}\right) - \arctg\left(-\frac{C_{\theta e} \cdot F_{\theta e}}{C_{\theta e} \cdot D_{\theta e}}\right), \end{aligned} \quad (3.61)$$

or

$$\Delta\varphi_V \approx \arctg\left(-\frac{C_\theta \cdot F_\theta}{C_\theta \cdot D_\theta}\right) - \arctg\left(-\frac{Z_1 \cos \theta_2}{\pi f \rho_2 2h_1}\right),$$

where

$$\begin{aligned} C_{\theta e} &= 2 \left(\frac{Z_1}{\cos \theta_1} \cdot \left(\frac{Z_2}{\cos \theta_2} \right)^3 - \left(\frac{Z_1}{\cos \theta_1} \right)^3 \frac{Z_2}{\cos \theta_2} \right) \operatorname{tg}(K_2 h_1); \\ D_{\theta e} &= 2 \left(\frac{Z_1}{\cos \theta_1} \cdot \left(\frac{Z_2}{\cos \theta_2} \right)^3 + \left(\frac{Z_1}{\cos \theta_1} \right)^3 \frac{Z_2}{\cos \theta_2} \right) \operatorname{tg}(K_2 h_1); \\ F_{\theta e} &= 2 \left(\frac{Z_1 Z_2}{\cos \theta_1 \cdot \cos \theta_2} \right)^2 \cdot (1 - (\operatorname{tg}(K_2 h_1))^2), \\ \Delta\varphi_W &= \arctg\left(\frac{C_\theta \cdot F_\theta}{D_\theta(D_\theta - C_\theta) + F_\theta^2}\right) \\ &\quad - \arctg\left(\frac{C_{\theta e} \cdot F_{\theta e}}{D_{\theta e}(D_{\theta e} - C_{\theta e}) + F_{\theta e}^2}\right), \end{aligned} \quad (3.62)$$

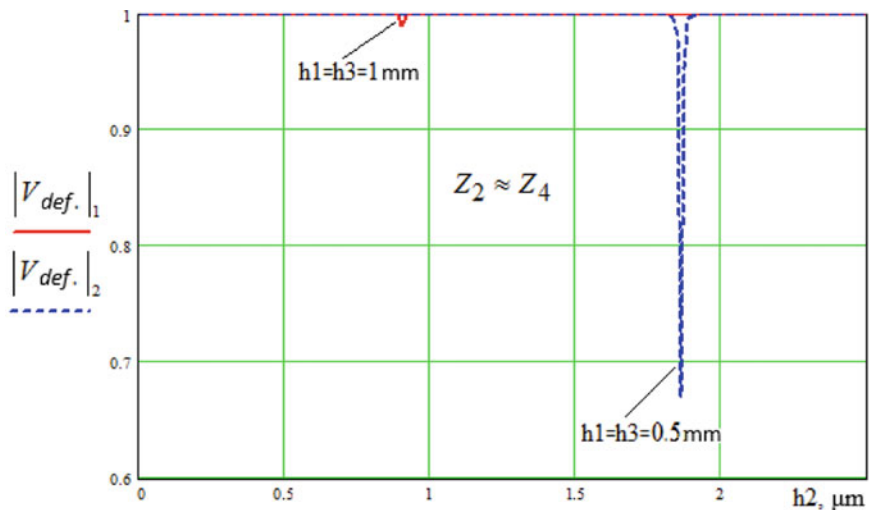
or

$$\Delta\varphi_W \approx \arctg\left(\frac{C_\theta \cdot F_\theta}{D_\theta(D_\theta - C_\theta) + F_\theta^2}\right) - \arctg\left(\frac{\pi f \rho_2 2h_1}{Z_1 \cos \theta_2}\right),$$

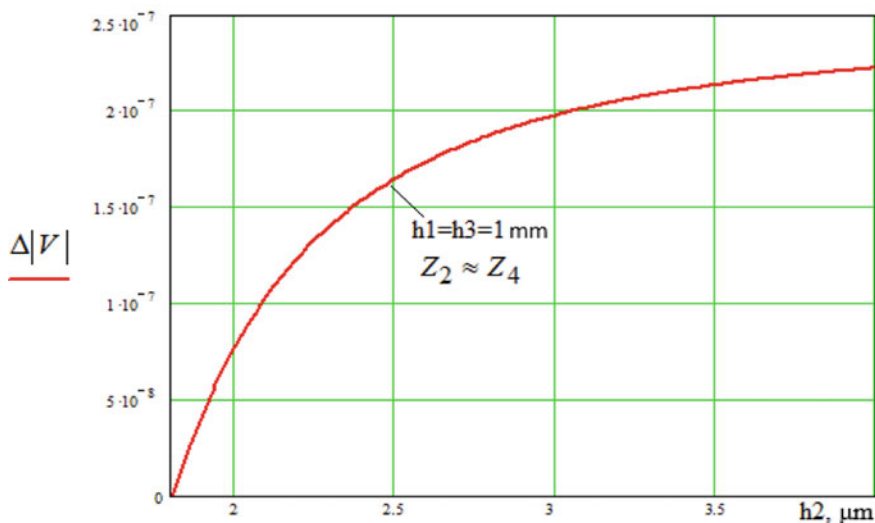
If we take into account the pores that will be the same size for the two layers of textile material, then in the expressions (3.59), (3.60), (3.61) and (3.62) the values $K_2 h_1$ and $\pi f \rho_2 2h_1$ should be replaced with $K_2 h_1 \cdot \cos \nu$ and $\pi f \rho_2 2h_1 \cdot \cos \nu$, respectively. The value $\cos \nu$ characterizes the influence of the pore sizes of the first and second layers of textile materials on the transmission of the resulting ultrasonic signal through their structures and the reflection of the signal from them.

After analyzing the obtained expressions and taking the angle of incidence $\theta_1 = 0$ for waves with the frequency $f = 75$ kHz, interacting with the composite material, which consists of two flat layers without pores with similar acoustic impedance $Z_2 \approx Z_4 = 1893728 \text{ kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ (selected to simplify the construction of models), the dependences of the modules of complex coefficients of reflection $|V_{def.}|$ and transmission $|W_{def.}|$ of ultrasonic waves on the thickness h_2 of the air layer at various thicknesses h_1, h_3 of the composite components are shown in Fig. 3.2a and in Fig. 3.4a. Figures 3.2b and 3.4b show the dependences of the values of the difference $\Delta|V|$ between the ratios of the reflected waves and the difference $\Delta|W|$ for the waves that have passed the composite material, on the thickness of the defect layer h_2 at $h_1 = h_3 = 1$ mm. There have been constructed the surfaces that show the dependences $\Delta|V|$ and $\Delta|W|$ on the thickness h_2 of the defect layer and on the same change in the thicknesses h_1, h_3 , presented in Figs. 3.3, 3.5 and 3.6.

It can be seen from the given figures that to control the presence of defects in composite materials of small thickness, consisting of two solid flat polymer layers, or to control the individual components of the multilayer composite, it is necessary to use ultrasonic devices with switching and modulation conversion of measuring signals. This is explained by the need to determine small values of the change in the amplitudes of the ultrasonic waves interacting with the controlled composite material relative to the amplitude of the waves that interacted with the reference material. It can be seen from Figs. 3.2 and 3.4 that to control composite two-layer materials without pores with a small thickness for the presence of delamination between the components of the composite, it is advisable to use ultrasonic waves that pass through the material. Figures 3.3 and 3.5 show that the parameters $\Delta|V|$ and $\Delta|W|$ can differ significantly in size. Therefore, in practice, it is advisable to use ultrasonic waves that have passed through the material to control composite materials without pores with a small thickness, because their amplitude changes more with the defect size than the amplitude of reflected waves, which can increase the sensitivity of the measuring system. It is necessary to adjust a certain frequency of ultrasonic waves, depending on the thickness of the component layers of the composite and the thickness of the possible delamination for the sensitivity increase or control of the measuring system.



a



b

Fig. 3.2 Dependences of wave amplitude ratios $|V_{def.}|_1$, $|V_{def.}|_2$ and the difference $\Delta|V|$ of the ratios of the reflected waves on the thickness of the defect layer h_2 , μm : **a** dependences $|V_{def.}|_1$, $|V_{def.}|_2$ on the thickness of the defect layer h_2 , μm ; **b** dependence $\Delta|V|$ on the thickness of the defect layer h_2 , μm with $h_1 = h_3 = 1\text{ mm}$

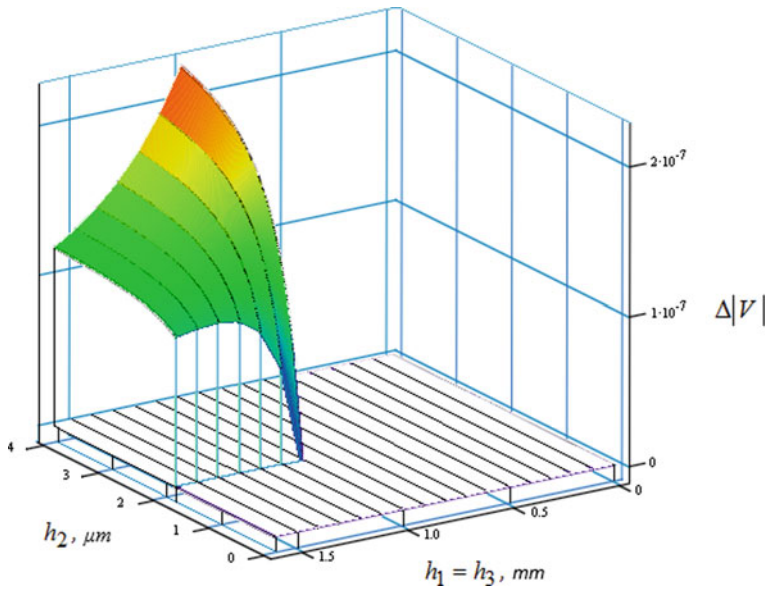


Fig. 3.3 Dependence of the difference $\Delta|V|$ of amplitude ratios of waves reflected from the controlled and reference composite materials to incident oscillations on the thickness of the defect layer h_2 , μm and on the thicknesses of the layers of the composite components, which vary equally in magnitude $h_1 = h_3$, mm (the range is shown for $h_1 = h_3$ from 1 mm to 1.6 mm)

This will make it possible to create devices that will be able to effectively monitor multilayer products without through pores in the process of their production. Let us consider another extreme case for composite materials, when there is a layer of air between two porous textile layers, which is significant in area or thickness compared to the size of the most through pores of the material. The pore size is the same throughout the composite. Figure 3.7 shows how the phase shifts $\Delta\varphi_W$ and $\Delta\varphi_V$ (at $\theta_1 = 0$) for the composite without pores are changing, as well as how these parameters are changing in magnitude for porous composites.

The change in phase shifts $\Delta\varphi_W$ and $\Delta\varphi_V$ for sounding waves in the porous material is explained by the increase in the transmission of part of the ultrasonic waves through the air pores and the defect layer with the bypass of the threads of the material.

The dependences of the values that characterize the change in the transmission $\Delta|W|$ and reflection $\Delta|V|$ of ultrasonic waves from two porous layers of a composite with a layer of air relative to the same material without defect (at the angle of incidence $\theta_1 = 10^\circ$) on the parameters h_2 and $\cos \nu$, are shown in Figs. 3.8 and 3.9. It can be seen from these figures that even with decreasing pore size ($\cos \nu$ varies in the range from 0 to 0.002, which characterizes the change in pore size) in the layers of composite material, but increasing the air layer thickness (h_2 varies from 0 to 4 μm) the amplitude of reflected ultrasonic waves from the composite will still decrease. For the waves passing through this composite, their amplitude also decreases relative

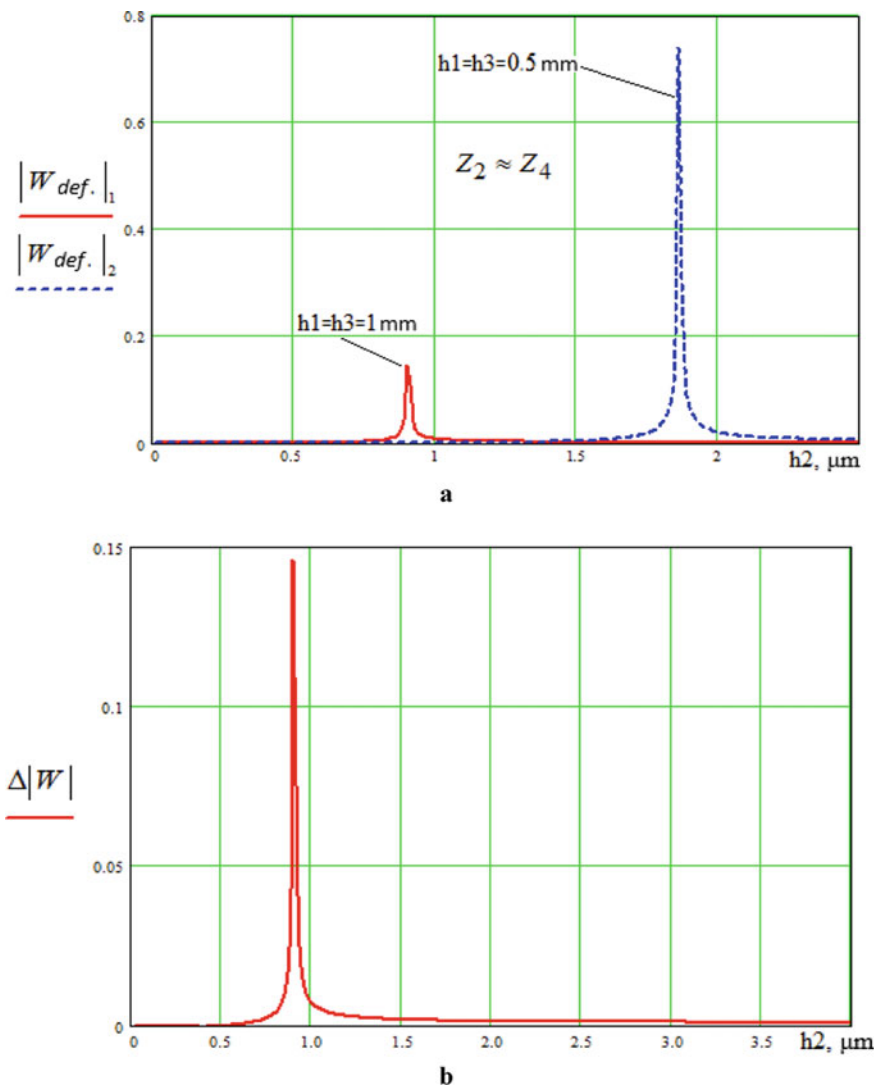


Fig. 3.4 Dependences of amplitude ratios of ultrasonic waves $|W_{def.}|_1$, $|W_{def.}|_2$ and difference $\Delta|W|$ of ratios of the waves which have passed through the material, on the thickness of a defect layer h_2 , μm : **a** dependences $|W_{def.}|_1$, $|W_{def.}|_2$ on the thickness of a defect layer h_2 , μm ; **b** dependence $\Delta|W|$ on the thickness of a defect layer h_2 , μm with $h_1 = h_3 = 1 \text{ mm}$

to the amplitude of oscillations passing through the reference material. This can be explained by the dispersion of part of the waves between the fibers of the composite and their attenuation in the air gaps through the pores and the defect. The difference $\Delta|W|$ is bigger than $\Delta|V|$, which indicates the feasibility of using ultrasonic waves that pass through the material to probe and control the porous layers of the composite.

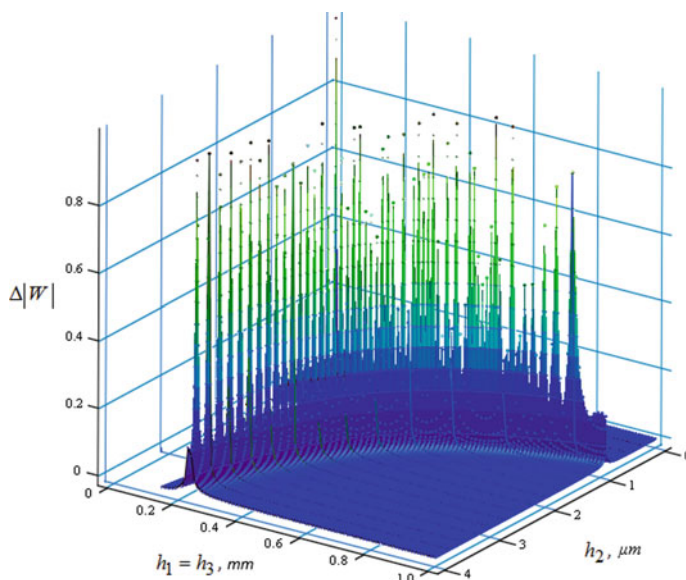


Fig. 3.5 Dependence of the difference $\Delta|W|$ of amplitude ratios of the waves, which passed the controlled and reference composite materials, to incident oscillations, on the thickness of the defect layer $h_2, \mu m$ and on the thicknesses of the layers of the composite components, which vary equally in magnitude $h_1 = h_3, mm$ (the range is shown for $h_1 = h_3$ from 0.1 mm to 1.0 mm)

The transmission of ultrasonic waves for the above materials increases relative to the continuous layers of the composite components with the same total thickness of 2 mm and with the same defect. This case is shown in Fig. 3.10 (at the angle of incidence $\theta_1 = 10^\circ$), then the module difference $\Delta|W|$ will be smaller, respectively. Figure 3.10 also shows the tendency to change the transmission of ultrasonic waves, even with very small gaps of delamination between the composite components, comparing the porous material and the material with a solid component layer. This will make it possible to determine the thickness of the layers between the solid and porous layers for one composite in the process of its production and to ensure the operational control over the finished products.

The conducted research can help to create new means and methods of control over the CTM and their components in the course of production. It is important to be able to comply with the established regulations on key technological parameters. Most materials need to be controlled in the process of their production. As the material with a different composition of the constituent layers, when it leaves the production line, can only be rejected in the presence of defects in its structure. Therefore, the control of the CTM or its constituent layers at a certain stage of production will increase the quality of finished products and its economic efficiency.

Installation of ultrasonic sensors must be provided at a certain distance from the surface of the controlled material. This distance should not be large so as not to significantly attenuate the ultrasonic waves in the air, but at the same time it should

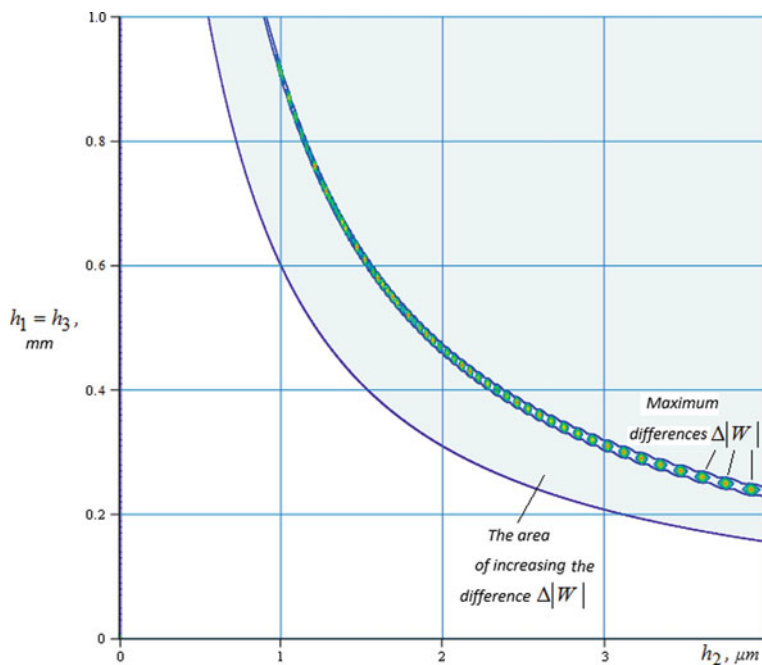


Fig. 3.6 Top view of the dependence of the difference $\Delta|W|$ on the thickness of the defect layer $h_2, \mu\text{m}$ and on the thicknesses of the layers of the composite components, which vary equally in magnitude $h_1 = h_3, \text{ mm}$ (the difference maximums $\Delta|W|$ and their location are shown)

not lead to reflections of oscillations from the surfaces of the transducers and the material at small angles of incidence of the waves with their subsequent superposition. It should be also noted that for the porous layers of textile materials, the sensitivity of ultrasonic sensors may be low, so it is possible to use oscillations with their reflection at an angle to the material surface in special waveguides, through which the controlled material will pass. This can help solve the problem of sensitivity of the amplitude of sounding waves to the presence of a defect, but it is also necessary to adjust the parameters of frequency, power and even the shape of the radiated oscillations.

Special waveguides with non-contact ultrasonic transducers can be used as sensors of breakage of threads with high linear density on textile machines in the process of production of fabrics for various purposes. This is also an urgent task because thread breakage sensors are mainly contact and mechanical, and may not always work, which can lead to a defect in the textile fabric itself.

Therefore, later in the paper we will show research on the propagation of ultrasonic waves in a waveguide with their interaction with a textile material.

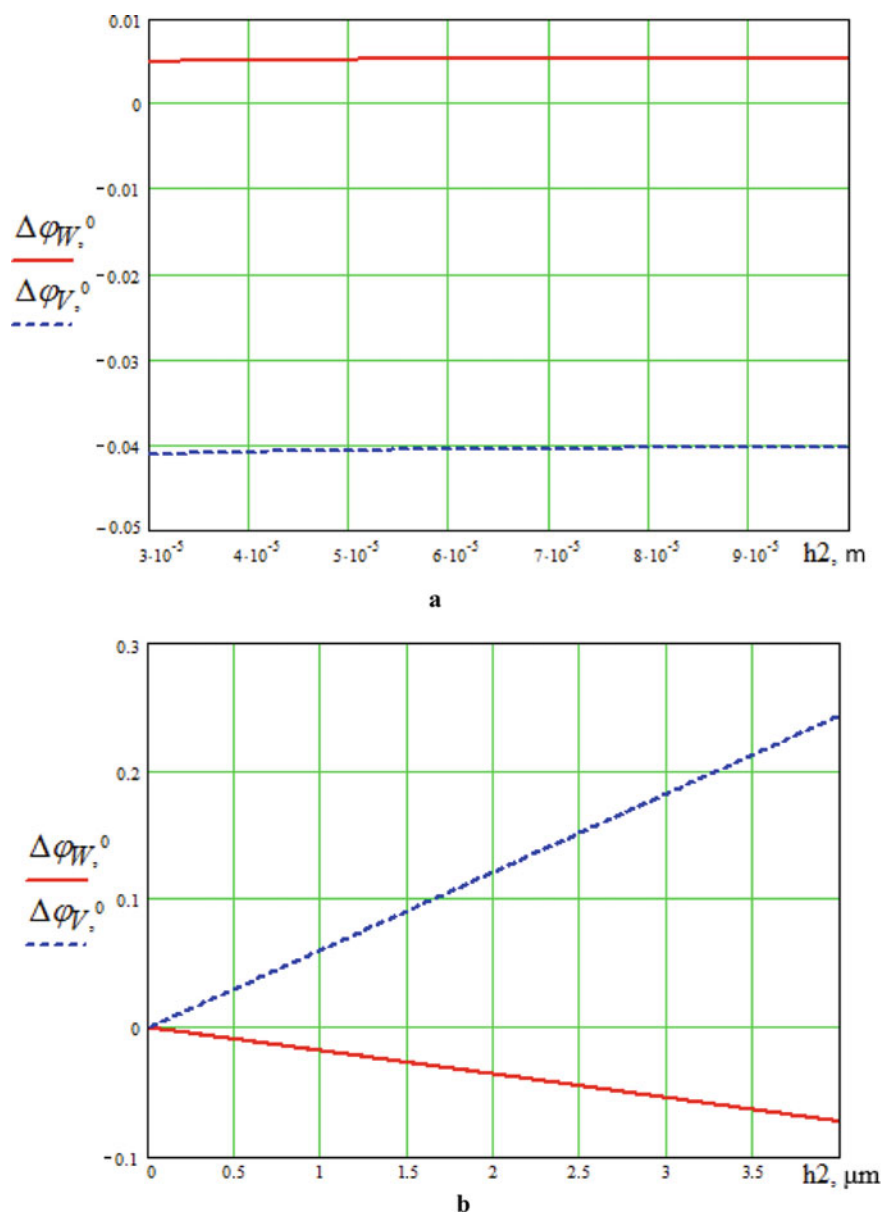


Fig. 3.7 Dependences of phase shifts $\Delta\varphi_{W,0}$ and $\Delta\varphi_{V,0}$ of sounding waves in the controlled material, relative to oscillations in the reference material, on the thickness of the defect layer h_2 , μm (the angle of wave incidence is $\theta_1 = 0$): **a** dependences $\Delta\varphi_{W,0}$, $\Delta\varphi_{V,0}$ on the thickness of a defect layer h_2 , μm ($h_1 = h_3 = 1 \text{ mm}$ for flat layers of the composite components without pores); **b** dependences $\Delta\varphi_{W,0}$, $\Delta\varphi_{V,0}$ on the thickness of a defect layer h_2 , μm ($h_1 = h_3 = 1 \text{ mm}$ for textile layers of the composite with pores at $\cos \nu = 0.002$)

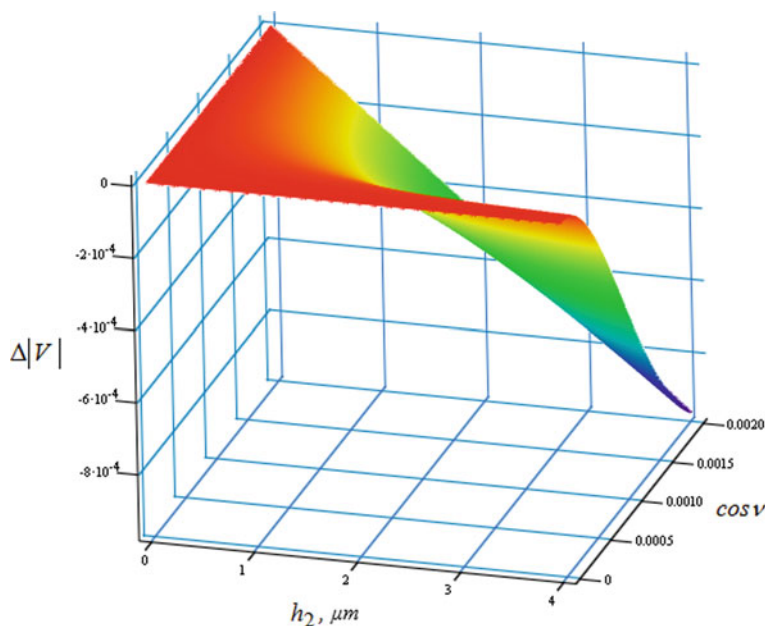


Fig. 3.8 Dependence of the difference $\Delta|V|$ of amplitude ratios of waves reflected from the controlled and reference composite materials with the same pores in their textile layers, to incident oscillations on the thickness of the defect layer h_2 , μm and on the parameter $\cos \nu$ (the angle of wave incidence is $\theta_1 = 10^0$)

3.3 Study on the Reflection of Ultrasonic Waves from the Composition of Textile Layers Moving Along the Guide Support, and the Interaction of Oscillations in the Waveguide with the Textile Material

As discussed earlier, to control the CTM with pores or just textiles with significant interfiber distances in their structure, it is necessary to analyze the interaction of ultrasonic waves with this material [23–30] (See Fig. 3.11a). Its movement on a rigid support or in a special waveguide during production is taken into account. The speed of movement of the material on the guide is much less than the speed of sound propagation in the air, so its effect on the reflection of waves in the structure of the moving composite can be neglected. This case, which is the reflection of waves from the material during its motion, can be described by the interaction of subsequent waves (See Fig. 3.11b, for complete internal attenuation of reflected waves in the first dense layer of the material) and the change in their pressures, respectively:

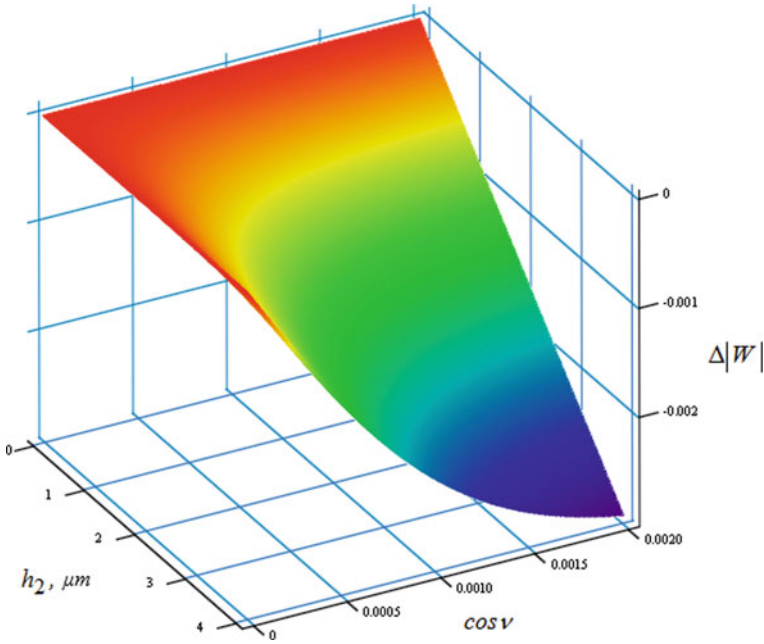


Fig. 3.9 Dependence of the difference of amplitude ratios $\Delta|W|$ of the waves that have passed through the controlled and reference composite materials with the same pores in their textile layers, to incident oscillations on the thickness of a defect layer h_2 , μm and on the parameter $\cos \nu$ (the angle of wave incidence is $\theta_1 = 10^\circ$)

$$\begin{aligned}
 P_{1w.} &= P_{0w.}(-V_{\theta 12}); \\
 P_{2w.} &= P_{0w.}(-W_{\theta 12} V_{\theta 23} W_{\theta 21} \cdot e^{2j K_2 h_2}); \\
 P_{3w.} &= P_{0w.}(-W_{\theta 12} W_{\theta 23} V_{\theta 34} W_{\theta 32} W_{\theta 21} \cdot e^{2j(K_2 h_2 + K_3 h_3)}); \\
 P_{4w.} &= P_{0w.}(-W_{\theta 12} W_{\theta 23} V_{\theta 34} V_{\theta 32} V_{\theta 34} W_{\theta 32} W_{\theta 21} \cdot e^{2j(K_2 h_2 + 2K_3 h_3)}); \\
 P_{5w.} &= P_{0w.}(-W_{\theta 12} W_{\theta 23} V_{\theta 34} V_{\theta 32} V_{\theta 34} V_{\theta 32} V_{\theta 34} W_{\theta 32} W_{\theta 21} \cdot e^{2j(K_2 h_2 + 3K_3 h_3)}); \\
 &\quad \dots; \\
 P_{w.} &= \sum_{i=1}^m P_{i w.},
 \end{aligned} \tag{3.63}$$

$$\begin{aligned}
 V_{\theta 1} &= \frac{P_{w.}}{P_{0w.}} = -V_{\theta 12} - W_{\theta 12} V_{\theta 23} W_{\theta 21} \cdot e^{2j K_2 h_2} - W_{\theta 12} W_{\theta 23} V_{\theta 34} W_{\theta 32} W_{\theta 21} \\
 &\quad \times e^{2j(K_2 h_2 + K_3 h_3)} - W_{\theta 12} W_{\theta 23} V_{\theta 34} V_{\theta 32} V_{\theta 34} W_{\theta 32} W_{\theta 21} \cdot e^{2j(K_2 h_2 + 2K_3 h_3)} \\
 &\quad - W_{\theta 12} W_{\theta 23} V_{\theta 34} V_{\theta 32} V_{\theta 34} V_{\theta 32} V_{\theta 34} W_{\theta 32} W_{\theta 21} \cdot e^{2j(K_2 h_2 + 3K_3 h_3)} - \dots
 \end{aligned} \tag{3.64}$$

where $V_{\theta 1}$ is the complex coefficient of ultrasonic wave reflection from the composite textile material with two component layers and the support medium on which the composite moves; $P_{0w.}$ —the pressure in the incident wave on the surface of

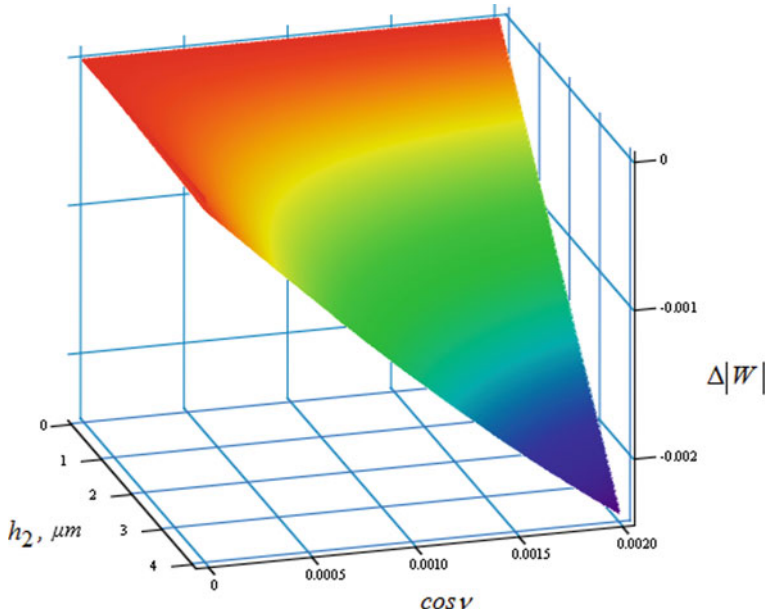


Fig. 3.10 Dependence of the difference between the amplitude ratios $\Delta|W|$ of the waves that passed through the controlled and reference composite materials with the same pores in their textile layers, with solid flat components of the composite, to the incident oscillations on the thickness of the defect layer h_2 , μm and on the parameter $\cos \nu$ (the angle of wave incidence is $\theta_1 = 10^\circ$)

the controlled material; P_w —the total pressure in the reflected wave from the controlled material; m —the number of multi-path waves of the wave components; K_2, K_3 —the wave numbers of the first and second components of the composite layers for this case; h_2, h_3 —nominal thicknesses of the first and second components of the composite layers for this case; $P_{1w}, P_{2w}, P_{3w}, P_{4w}, \dots, P_{mw}$ —pressures in waves that interact with the textile material and with a rigid support; $W_{\theta 12}, W_{\theta 21}, W_{\theta 23}, W_{\theta 32}, V_{\theta 12}, V_{\theta 23}, V_{\theta 32}, V_{\theta 34}$ —the coefficients of partial transmission and reflection of waves from the corresponding media, which are calculated similarly to the expressions (3.21).

Presenting the dependence (3.64) through a geometric progression, it can be shown as follows:

$$\begin{aligned}
 V_{\theta 1} = & -V_{\theta 12} - W_{\theta 12} V_{\theta 23} W_{\theta 21} \cdot e^{2j K_2 h_2} - W_{\theta 12} W_{\theta 23} V_{\theta 34} W_{\theta 32} W_{\theta 21} \\
 & \times e^{2j(K_2 h_2 + K_3 h_3)} \cdot \sum_{N=0}^{m-3} (V_{\theta 32} V_{\theta 34} \cdot e^{2j K_3 h_3})^N.
 \end{aligned} \quad (3.65)$$

Given that $-V_{\theta 12} = V_{\theta 21}$ and taking the structure of the fabric with pores, the expression (3.65) can be shown as:

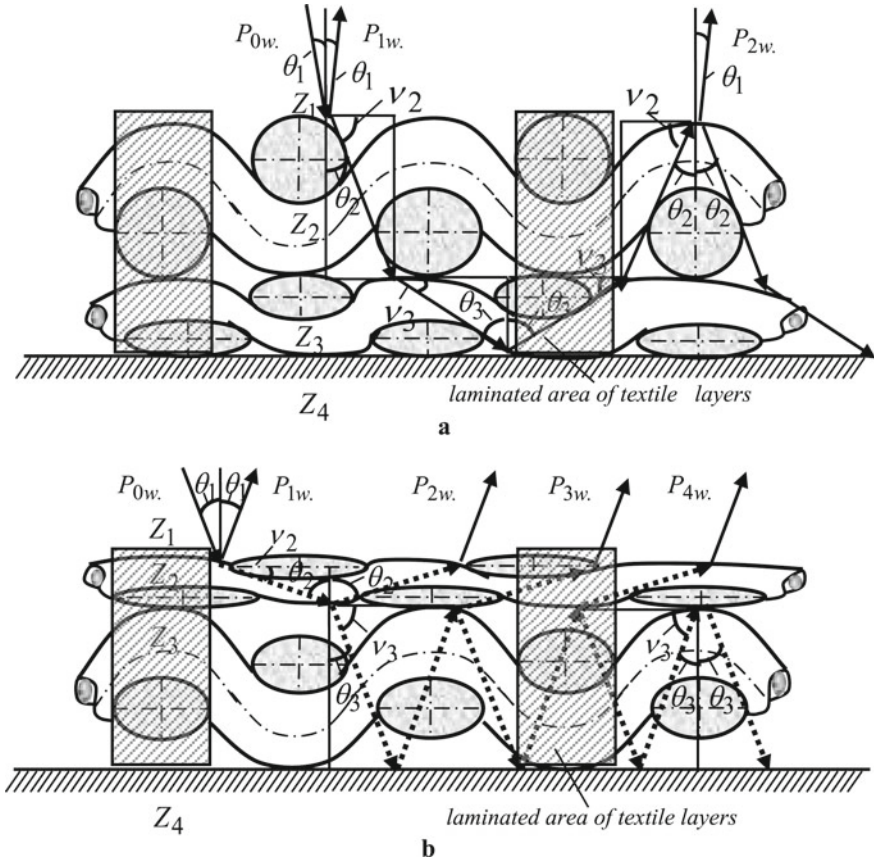


Fig. 3.11 Transmission and reflection of ultrasonic waves from the CTM, which moves along the guide: **a** transmission and reflection of ultrasonic waves from the composite components with medium pore sizes (the first layer with larger pores than the second one); **b** transmission and reflection of ultrasonic waves from the composite with small and large pore sizes in its constituent layers (the first layer with small pores, and the second layer with large ones)

$$V_{\theta 1} = V_{\theta 21} - W_{\theta 12} V_{\theta 23} W_{\theta 21} \cdot e^{2j K_2 d_{oy2} \frac{\pi}{4} \cos v_2} - W_{\theta 12} W_{\theta 23} V_{\theta 34} W_{\theta 32} W_{\theta 21} \\ \times e^{2j (K_2 d_{oy2} \frac{\pi}{4} \cos v_2 + K_3 d_{oy3} \frac{\pi}{4} \cos v_3)} \cdot \sum_{N=0}^{m-3} (V_{\theta 32} V_{\theta 34} \cdot e^{2j K_3 d_{oy3} \frac{\pi}{4} \cos v_3})^N, \quad (3.66)$$

the following geometric progression can be presented for further transformations as follows:

$$V_{\theta 1} = V_{\theta 21} - W_{\theta 12} V_{\theta 23} W_{\theta 21} \cdot e^{2j K_2 d_{oy2} \frac{\pi}{4} \cos v_2} \\ - \frac{W_{\theta 12} W_{\theta 23} V_{\theta 34} W_{\theta 32} W_{\theta 21} \cdot e^{2j (K_2 d_{oy2} \frac{\pi}{4} \cos v_2 + K_3 d_{oy3} \frac{\pi}{4} \cos v_3)}}{1 - V_{\theta 32} V_{\theta 34} \cdot e^{2j K_3 d_{oy3} \frac{\pi}{4} \cos v_3}}, \quad (3.67)$$

or

$$V_{\theta 1} = V_{\theta 21} - W_{\theta 12} V_{\theta 23} W_{\theta 21} \cdot e^{2j K_2 d_{oy2} \frac{\pi}{4} \cos v_2} - \left(\frac{1}{W_{\theta 12} W_{\theta 23} V_{\theta 34} W_{\theta 32} W_{\theta 21}} \right. \\ \left. \times e^{-2j (K_2 d_{oy2} \frac{\pi}{4} \cos v_2 + K_3 d_{oy3} \frac{\pi}{4} \cos v_3)} - \frac{V_{\theta 32}}{W_{\theta 12} W_{\theta 23} W_{\theta 32} W_{\theta 21}} \times e^{-2j K_2 d_{oy2} \frac{\pi}{4} \cos v_2} \right)^{-1}.$$

To determine the real $\text{Re}V_{\theta 1}$ and imaginary components of the expression (3.66), we will rewrite the dependence (3.67) as follows:

$$V_{\theta 1} = (V_{\theta 21} - V_{\theta 21} V_{\theta 32} V_{\theta 34} \cdot e^{2j K_3 d_{oy3} \frac{\pi}{4} \cos v_3} - W_{\theta 12} V_{\theta 23} W_{\theta 21} \\ \times e^{2j K_2 d_{oy2} \frac{\pi}{4} \cos v_2} + W_{\theta 12} W_{\theta 21} V_{\theta 34} (V_{\theta 23} V_{\theta 32} - W_{\theta 23} W_{\theta 32}) \\ \times e^{2j (K_2 d_{oy2} \frac{\pi}{4} \cos v_2 + K_3 d_{oy3} \frac{\pi}{4} \cos v_3)}) \cdot (1 - V_{\theta 32} V_{\theta 34} \cdot e^{2j K_3 d_{oy3} \frac{\pi}{4} \cos v_3})^{-1}, \quad (3.68)$$

then, taking into account (3.66) and (3.68), $\text{Re}V_{\theta 1}$ and $\text{Im}V_{\theta 1}$ can be shown as:

$$\text{Re}V_{\theta 1} = V_{\theta 21} \sum_{N=0}^{m-3} (V_{\theta 32} V_{\theta 34})^N \cdot \cos\left(2N K_3 d_{oy3} \frac{\pi}{4} \cos v_3\right) - V_{\theta 21} V_{\theta 32} V_{\theta 34} \\ \times \sum_{N=0}^{m-3} (V_{\theta 32} V_{\theta 34})^N \cdot \cos\left((2N + 2) K_3 d_{oy3} \frac{\pi}{4} \cos v_3\right) - W_{\theta 12} V_{\theta 23} W_{\theta 21} \\ \times \sum_{N=0}^{m-3} (V_{\theta 32} V_{\theta 34})^N \cdot \cos\left(2 K_2 d_{oy2} \frac{\pi}{4} \cos v_2 + 2N K_3 d_{oy3} \frac{\pi}{4} \cos v_3\right) \\ + W_{\theta 12} W_{\theta 21} V_{\theta 34} (V_{\theta 23} V_{\theta 32} - W_{\theta 23} W_{\theta 32}) \cdot \sum_{N=0}^{m-3} (V_{\theta 32} V_{\theta 34})^N \\ \times \cos\left(2 K_2 d_{oy2} \frac{\pi}{4} \cos v_2 + (2N + 2) K_3 d_{oy3} \frac{\pi}{4} \cos v_3\right), \quad (3.69)$$

$$\text{Im}V_{\theta 1} = V_{\theta 21} \sum_{N=0}^{m-3} (V_{\theta 32} V_{\theta 34})^N \cdot \sin\left(2N K_3 d_{oy3} \frac{\pi}{4} \cos v_3\right) - V_{\theta 21} V_{\theta 32} V_{\theta 34} \\ \times \sum_{N=0}^{m-3} (V_{\theta 32} V_{\theta 34})^N \cdot \sin\left((2N + 2) K_3 d_{oy3} \frac{\pi}{4} \cos v_3\right) - W_{\theta 12} V_{\theta 23} W_{\theta 21} \\ \times \sum_{N=0}^{m-3} (V_{\theta 32} V_{\theta 34})^N \cdot \sin\left(2 K_2 d_{oy2} \frac{\pi}{4} \cos v_2 + 2N K_3 d_{oy3} \frac{\pi}{4} \cos v_3\right) \\ + W_{\theta 12} W_{\theta 21} V_{\theta 34} (V_{\theta 23} V_{\theta 32} - W_{\theta 23} W_{\theta 32}) \cdot \sum_{N=0}^{m-3} (V_{\theta 32} V_{\theta 34})^N$$

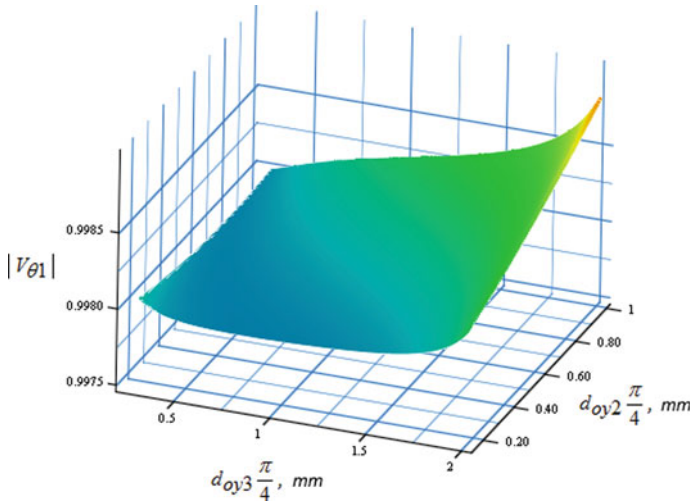


Fig. 3.12 Surface showing the change in the module $|V_{\theta 1}|$, proportional to the amplitude of the reflected ultrasonic waves, depending on the index $d_{oy2} \frac{\pi}{4}$ of the first dense layer of the material and on the index $d_{oy3} \frac{\pi}{4}$ of its second layer

$$\times \sin\left(2 K_2 d_{oy2} \frac{\pi}{4} \cos v_2 + (2N + 2) K_3 d_{oy3} \frac{\pi}{4} \cos v_3\right), \quad (3.70)$$

and the module itself (Fig. 3.12) can be shown as:

$$|V_{\theta 1}| = \sqrt{\operatorname{Re} V_{\theta 1}^2 + \operatorname{Im} V_{\theta 1}^2}. \quad (3.71)$$

To be able to control textile tapes or threads with high linear density by the non-contact method, it is necessary to solve the problem of increasing the sensitivity of the change in the amplitude of sounding waves to the parameters of textile materials. One of the solutions to this problem may be the use of waveguides of rectangular cross section to increase the distance of the ultrasonic wave through the textile material structure. This can be realized by selecting a certain number of reflections of ultrasonic waves in the waveguide, adjusting the desired frequency of the waves, their power, as well as the shape of the signal, which was discussed earlier in the work.

Let us consider an example of the interaction of ultrasonic waves with a textile tape in a waveguide. The waveguide itself in length and with mounting for ultrasonic transducers allows the wave emitted and passing through the structure of the textile tape at an angle with a certain number of its main reflections, to be received by the oscillation receiver with a larger change in its amplitude. In order to present the interaction of waves with the material and with the waveguide itself, it is necessary to first show the complex transmission coefficient W_{cm}^* through the walls of the waveguide and the complex reflection coefficient V_{cm}^* from them for sounding oscillations

falling from the air, in the following way:

$$\begin{aligned}
 W_{cm}^* = & 2 \cdot \left(\frac{Z_2 \cdot \cos^2(2\gamma_2) \cos \theta_1}{Z_1 \sin(K_2(h_1 + h_1^*) \cos \theta_2) \cos \theta_2} \right. \\
 & + \frac{\rho_2 b_2 \sin^2(2\gamma_2) \cos \theta_1}{Z_1 \sin(\chi_2(h_1 + h_1^*) \cos \gamma_2) \cos \gamma_2} \Bigg) \\
 & \times \left(2 \cdot \left(\frac{Z_2 \cdot \cos^2(2\gamma_2) \cdot \operatorname{ctg}(K_2(h_1 + h_1^*) \cos \theta_2) \cdot \cos \theta_1}{Z_1 \cos \theta_2} \right. \right. \\
 & + \frac{\rho_2 b_2 \cdot \sin^2(2\gamma_2) \cdot \operatorname{ctg}(\chi_2(h_1 + h_1^*) \cos \gamma_2) \cdot \cos \theta_1}{Z_1 \cos \gamma_2} \Bigg) \\
 & - j \left(\left(\frac{Z_2 \cdot \cos^2(2\gamma_2) \cos \theta_1}{Z_1 \sin(K_2(h_1 + h_1^*) \cos \theta_2) \cos \theta_2} \right. \right. \\
 & + \frac{\rho_2 b_2 \sin^2(2\gamma_2) \cos \theta_1}{Z_1 \sin(\chi_2(h_1 + h_1^*) \cos \gamma_2) \cos \gamma_2} \Bigg)^2 \\
 & - \left(\frac{Z_2 \cdot \cos^2(2\gamma_2) \cdot \operatorname{ctg}(K_2(h_1 + h_1^*) \cos \theta_2) \cdot \cos \theta_1}{Z_1 \cos \theta_2} \right. \\
 & + \left. \left. \frac{\rho_2 b_2 \cdot \sin^2(2\gamma_2) \cdot \operatorname{ctg}(\chi_2(h_1 + h_1^*) \cos \gamma_2) \cdot \cos \theta_1}{Z_1 \cos \gamma_2} \right)^2 + 1 \right) \Bigg)^{-1}, \quad (3.72)
 \end{aligned}$$

$$\begin{aligned}
 V_{cm}^* = & j \left(\left(\frac{Z_2 \cdot \cos^2(2\gamma_2) \cdot \operatorname{ctg}(K_2(h_1 + h_1^*) \cos \theta_2) \cdot \cos \theta_1}{Z_1 \cos \theta_2} \right. \right. \\
 & + \frac{\rho_2 b_2 \cdot \sin^2(2\gamma_2) \cdot \operatorname{ctg}(\chi_2(h_1 + h_1^*) \cos \gamma_2) \cdot \cos \theta_1}{Z_1 \cos \gamma_2} \Bigg)^2 \\
 & - \left(\frac{Z_2 \cdot \cos^2(2\gamma_2) \cos \theta_1}{Z_1 \sin(K_2(h_1 + h_1^*) \cos \theta_2) \cos \theta_2} \right. \\
 & + \frac{\rho_2 b_2 \sin^2(2\gamma_2) \cos \theta_1}{Z_1 \sin(\chi_2(h_1 + h_1^*) \cos \gamma_2) \cos \gamma_2} \Bigg)^2 + 1 \Bigg) \\
 & \times \left(2 \cdot \left(\frac{Z_2 \cdot \cos^2(2\gamma_2) \cdot \operatorname{ctg}(K_2(h_1 + h_1^*) \cos \theta_2) \cdot \cos \theta_1}{Z_1 \cos \theta_2} \right. \right. \\
 & + \frac{\rho_2 b_2 \cdot \sin^2(2\gamma_2) \cdot \operatorname{ctg}(\chi_2(h_1 + h_1^*) \cos \gamma_2) \cdot \cos \theta_1}{Z_1 \cos \gamma_2} \Bigg)
 \end{aligned}$$

$$\begin{aligned}
& -j \left(\left(\frac{Z_2 \cdot \cos^2(2\gamma_2) \cos \theta_1}{Z_1 \sin(K_2(h_1 + h_1^*) \cos \theta_2) \cos \theta_2} \right. \right. \\
& + \left. \left. \frac{\rho_2 b_2 \sin^2(2\gamma_2) \cos \theta_1}{Z_1 \sin(\chi_2(h_1 + h_1^*) \cos \gamma_2) \cos \gamma_2} \right)^2 \right. \\
& - \left(\frac{Z_2 \cdot \cos^2(2\gamma_2) \cdot \operatorname{ctg}(K_2(h_1 + h_1^*) \cos \theta_2) \cdot \cos \theta_1}{Z_1 \cos \theta_2} \right. \\
& + \left. \left. \frac{\rho_2 b_2 \cdot \sin^2(2\gamma_2) \cdot \operatorname{ctg}(\chi_2(h_1 + h_1^*) \cos \gamma_2) \cdot \cos \theta_1}{Z_1 \cos \gamma_2} \right)^2 + 1 \right) \Big)^{-1}, \quad (3.73)
\end{aligned}$$

where for this case: Z_1 is acoustic air resistance; Z_2 —acoustic impedance of waveguide walls for longitudinal waves; ρ_2 —bulk density of the waveguide wall material; b_2 —the propagation speed of transverse waves in the material of the waveguide walls; K_2 —the wave number of the material of the walls of the waveguide for longitudinal waves; χ_2 —the wave number of the material of the walls of the waveguide for transverse waves; $h_1 + h_1^*$ —the thickness of the waveguide walls in the thickest place (h_1^* —the thickness of the waveguide walls in the thinnest place); θ_1 —the incidence angle of the wave on the waveguide wall material from the air medium (h_1 —the thickness of the air layer in the waveguide in its thinnest place); θ_2 —the angle of the longitudinal wave transmission through the material of the waveguide wall after its refraction in it; γ_2 —the angle of the transverse wave transmission through the material of the waveguide wall after its refraction in it.

When $c_1/b_2 > \sin \theta_1 > c_1/c_2$, where c_1/b_2 is the ratio of wave velocities in the air and transverse waves in the waveguide material; c_1/c_2 —the ratio of wave velocities in the air and longitudinal waves in the waveguide material, the angle θ_2 will be complex, and the longitudinal waves in the wall material will be ‘sliding’ along the boundary of the media. This will make possible the transmission of only transverse oscillations through the walls of the waveguide. Next, we will consider cases for the incidence of an ultrasonic wave in a waveguide on a textile material, when only a transverse wave passes through its walls, and when transverse and longitudinal waves propagate in the material of the waveguide walls along the interface (Fig. 3.13).

First, we will consider the transmission of only a transverse wave through the waveguide walls to obtain general equations at the corresponding angles of the wave incidence. To describe the interaction of ultrasonic waves with the porous medium of a textile material, we will first approximate the expressions (3.72) and (3.73) with the transmission of a transverse wave through the waveguide walls as follows:

$$W_{cm}^* = \frac{W_{\theta 12}^* W_{\theta 21}^* \cdot e^{j \frac{(K_2 + \chi_2)}{2} (h_1 + h_1^*)}}{1 - V_{\theta 21}^{*2} \cdot e^{j(K_2 + \chi_2)(h_1 + h_1^*)}}, \quad (3.74)$$

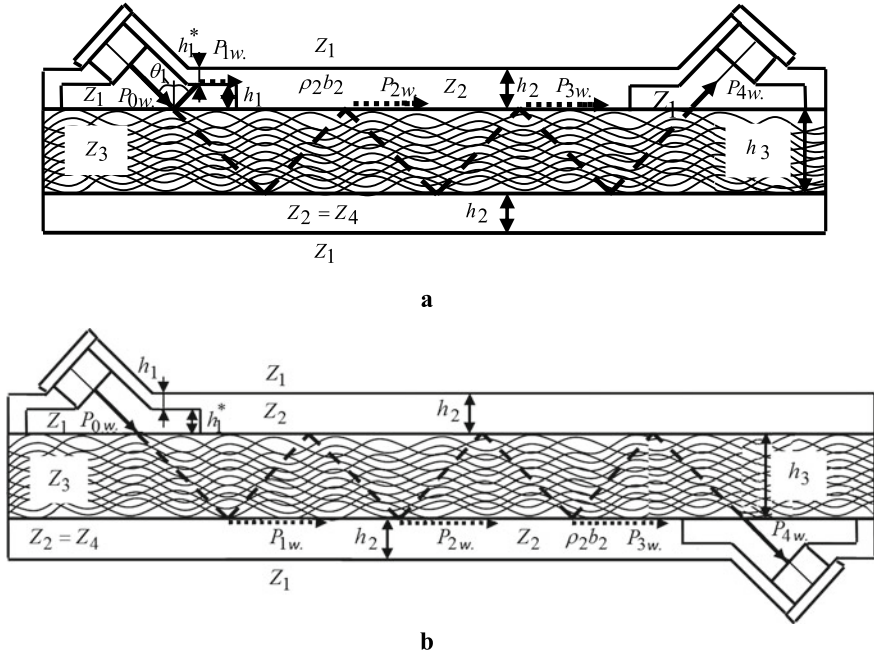


Fig. 3.13 Transmission and reflection of ultrasonic waves from the textile material in the waveguide: **a** the interaction of ultrasonic waves with the textile material in the waveguide with the location of sensors on its one side; **b** the interaction of ultrasonic waves with the textile material in the waveguide with the location of sensors on its different sides

$$V_{cm.}^* = \frac{V_{\theta 21}^* - V_{\theta 21}^* \cdot e^{j(K_2 + \chi_2)(h_1 + h_1^*)}}{1 - V_{\theta 21}^{*2} \cdot e^{j(K_2 + \chi_2)(h_1 + h_1^*)}}. \quad (3.75)$$

Partial coefficients of transmission $W_{\theta 12}^*$, $W_{\theta 21}^*$ and reflection $V_{\theta 21}^*$ of waves from the air boundary with solid waveguide walls can be written as:

$$\begin{aligned} W_{\theta 12}^* &= \frac{2 \rho_2 Z_1}{\rho_1 (\rho_2 b_2 \sin^2(2\gamma_2) + Z_1)}, \\ W_{\theta 21}^* &= \frac{2 \rho_1 \rho_2 b_2 \sin(2\gamma_2)}{\rho_2 (\rho_2 b_2 \sin^2(2\gamma_2) + Z_1)}, \\ V_{\theta 21}^* &= \frac{(\rho_2 b_2 \sin^2(2\gamma_2) - Z_1)}{(\rho_2 b_2 \sin^2(2\gamma_2) + Z_1)}. \end{aligned} \quad (3.76)$$

Based on the obtained expressions (3.74), (3.75) and (3.76), to analyze the transmission of waves at an angle and their reflection from the solid walls of the waveguide in air, we can now describe their interaction with the textile material passing through the waveguide.

For a waveguide with sensor mounting on one side to the textile material, it is necessary to compose equations that describe the superposition of the waves that have passed through or reflected from it. The pressures in the waves coming from one side of the sensors relative to the controlled material, for this case with their five main reflections in the waveguide, which interact with the textile tape, passing through it six times, taking into account the expressions (3.63), (3.64) and (3.76) can be represented as follows:

$$\begin{aligned}
 P_{1w.} &= P_{0w.} \left(-V_{\theta 13} W_{\theta 12}^* W_{\theta 21}^* \cdot e^{j \left(h_1 K_1 + h_1^* \cdot \left(\frac{K_2 + \chi_2}{2} \right) \right)} \right); \\
 P_{2w.} &= P_{0w.} \left(-W_{\theta 13} V_{\theta 32}^* W_{\theta 32}^* W_{\theta 21}^* \cdot e^{2j K_3 h_3 \cos v_3 + j \left(h_1 + h_1^* \right) \cdot \left(\frac{K_2 + \chi_2}{2} \right)} \right); \\
 P_{3w.} &= P_{0w.} \left(-W_{\theta 13} V_{\theta 32}^* W_{\theta 32}^* W_{\theta 21}^* \cdot e^{4j K_3 h_3 \cos v_3 + j \left(h_1 + h_1^* \right) \cdot \left(\frac{K_2 + \chi_2}{2} \right)} \right); \\
 P_{4w.} &= P_{0w.} \left(-W_{\theta 13} V_{\theta 32}^* W_{\theta 31} \cdot e^{6j K_3 h_3 \cos v_3} \right), \tag{3.77}
 \end{aligned}$$

where K_1 is wave number for the air medium.

The partial transmission $W_{\theta 32}^*$ and reflection $V_{\theta 32}^*$ coefficients of oscillations interacting with a solid medium can be determined similarly to the expressions (3.76). Taking into account the critical angles of wave incidence on the walls of the waveguide (after their transmission through the porous textile material), which causes the propagation of transverse and longitudinal waves in the material of the waveguide along its walls and almost complete reflection of sound energy from them, the pressures $P_{1w.}$, $P_{2w.}$, $P_{3w.}$ can be neglected. Then, remembering that the total pressure on one side of the tape will be $P_{w.} \approx P_{4w.}$, we can write the equation of the complex reflection coefficient $V_{\theta 2}$ for the given waveguide (Fig. 3.13a) as:

$$V_{\theta 2} = \frac{P_{w.}}{P_{0w.}} = -W_{\theta 13} V_{\theta 32}^* W_{\theta 31} \cdot e^{2j K_3 h_3 \cos v_3} \cdot \left(V_{\theta 32}^* \cdot e^{2j K_3 h_3 \cos v_3} \right)^2, \tag{3.78}$$

or taking into account the possible arbitrary number of main reflections of the waves, which depends on the wavelength (the next wave transmission of the material is a multiple of two), then in this case (3.78) it will be presented as follows:

$$V_{\theta 2} = \frac{P_{w.}}{P_{0w.}} = -W_{\theta 13} V_{\theta 32}^* W_{\theta 31} \cdot e^{2j K_3 h_3 \cos v_3} \cdot \left(V_{\theta 32}^* \cdot e^{2j K_3 h_3 \cos v_3} \right)^{m-2}. \tag{3.79}$$

Then the module $|V_{\theta 2}|$ of the complex reflection coefficient of sounding oscillations in the system waveguide—textile material can be shown as:

$$\begin{aligned}
 |V_{\theta 2}| &= \sqrt{\operatorname{Re} V_{\theta 2}^2 + \operatorname{Im} V_{\theta 2}^2} \\
 &= \left(\left(W_{\theta 13} V_{\theta 32}^* W_{\theta 31} V_{\theta 32}^{*2(m-2)} \cdot \cos((2(m-2) + 2) K_3 h_3 \cos v_3) \right)^2 \right)
 \end{aligned}$$

$$+ \left(W_{\theta 13} V_{\theta 32}^* W_{\theta 31} V_{\theta 32}^{*2(m-2)} \cdot \sin((2(m-2)+2)K_3 h_3 \cos v_3) \right)^2 \Big)^{\frac{1}{2}}. \quad (3.80)$$

When the transducers attached to the waveguide are on different sides of the textile material (Fig. 3.13b), the complex transmission coefficient $W_{\theta 3}$ for the waveguide can be presented as follows:

$$W_{\theta 3} = W_{\theta 13} W_{\theta 31} \cdot e^{jK_3 h_3 \cos v_3} \cdot (V_{\theta 32}^{*2} \cdot e^{2jK_3 h_3 \cos v_3})^{m-1}, \quad (3.81)$$

then the module of the complex transmission coefficient $|W_{\theta 3}|$ can be shown as:

$$\begin{aligned} |W_{\theta 3}| &= \sqrt{\operatorname{Re} W_{\theta 3}^2 + \operatorname{Im} W_{\theta 3}^2} \\ &= \left(\left(W_{\theta 13} W_{\theta 31} V_{\theta 32}^{*2(m-1)} \cdot \cos((2(m-1)+1)K_3 h_3 \cos v_3) \right)^2 \right. \\ &\quad \left. + \left(W_{\theta 13} W_{\theta 31} V_{\theta 32}^{*2(m-1)} \cdot \sin((2(m-1)+1)K_3 h_3 \cos v_3) \right)^2 \right)^{\frac{1}{2}}. \quad (3.82) \end{aligned}$$

With the help of the obtained dependences, it is possible to analyze the interaction of ultrasonic waves with textile materials of small thickness (textile tape, threads with high linear density, different fiber mass, etc.) to determine their technological parameters in the production process. It is necessary to control the power of ultrasonic waves that interact with the textile fiber material. This is necessary to be able to control the textile by the transmission of waves with their bypassing the material, taking into account its external structure, and for such control of the fibers, considering their internal structure. It is possible, in addition to changing the power of the emitting waves, to adjust their frequency to a different structure of the textile material, which affects the change of its pores. Figures 3.14, 3.15, 3.16 and 3.17 show the dependences associated with the waveguides considered in the work, as well as the surface change of the modules $|V_{\theta 2}|$ and $|W_{\theta 3}|$ on the basis weight m_s (determined by the bulk density ρ_3 , which varies, and the constant thickness of the textile tape h_3) and on the parameter m of the waveguide.

For waveguides with a significant cross-sectional height h_3 or with its significant change, through which different fiber mass with a large thickness (or basis weight m_s) and porosity can pass, we can approximate the modules $|V_{\theta 2}|$ and $|W_{\theta 3}|$ using the dependences (3.80), (3.82). In this case, the acoustic impedance Z_3 changes as many times as the height of the waveguide, filled with the fiber mass, changes in comparison with the thickness of an ordinary textile tape, and the value h_3 then remains constant in the expressions. Also, the obtained dependences (3.79), (3.80), (3.81) and (3.82) can be approximated by the expressions (3.18) and (3.19), multiplying the thickness of the material presented in them by a certain number of wave transmissions through the textile itself.

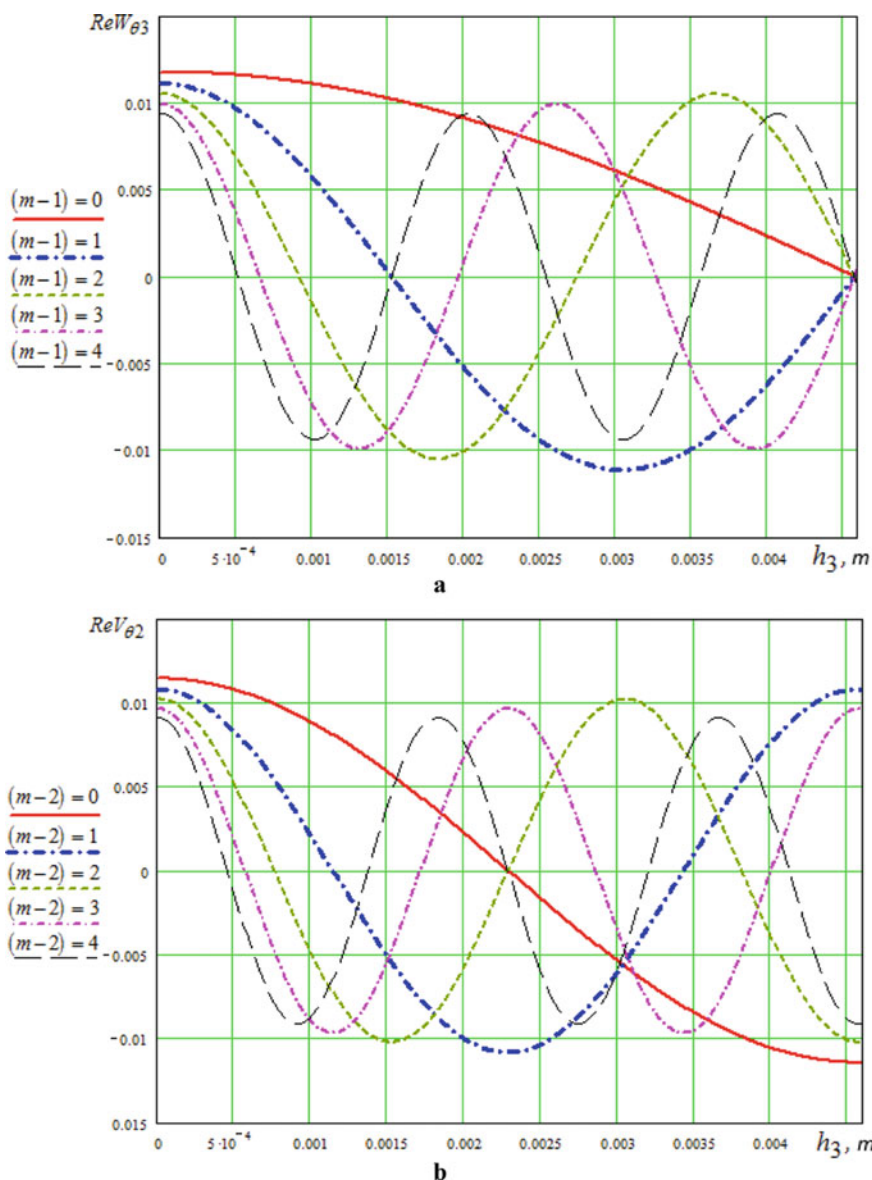


Fig. 3.14 Distribution of coefficients ReW_{θ_3} , ReV_{θ_2} of sound pressure by the thickness h_3 of the textile tape depending on the parameter m of different waveguides: **a** for a waveguide with sensors on different sides of a textile tape; **b** for a waveguide with sensors on one side of a textile tape

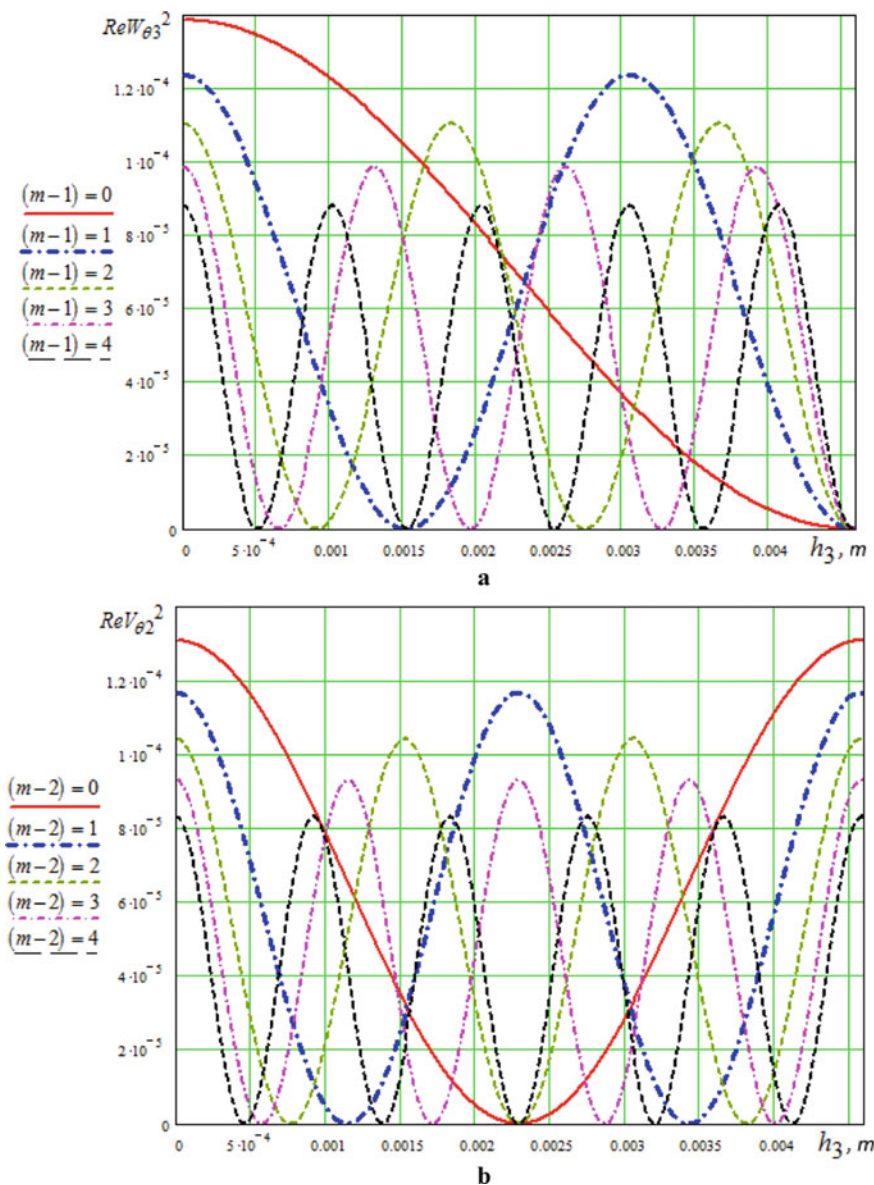


Fig. 3.15 Distribution of energy coefficients $ReW_{\theta_3}^2$, $ReV_{\theta_2}^2$ of waves by the tape thickness h_3 depending on the parameter m of different waveguides: **a** for a waveguide with sensors on different sides of a textile tape; **b** for a waveguide with sensors on one side of a textile tape

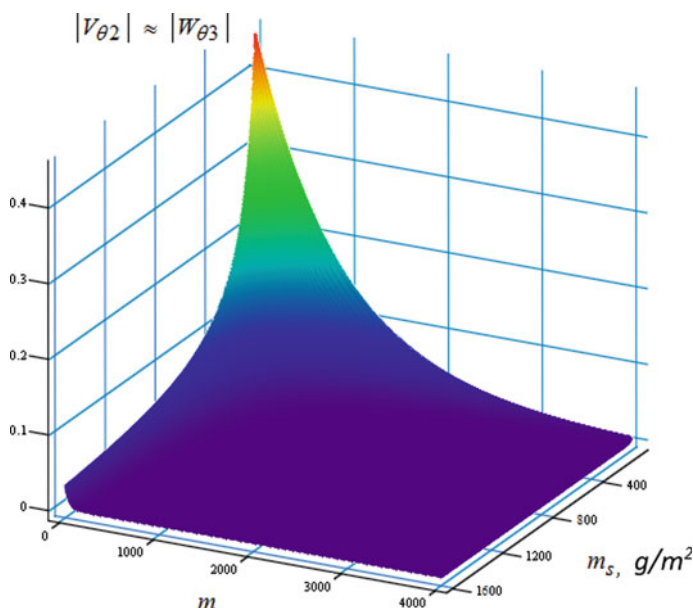


Fig. 3.16 General dependence of a gradual decrease in the amplitudes of waves $|W_{\theta 3}| \approx |V_{\theta 2}|$ interacting with the fiber textile mass in the waveguides on its basis weight m_s and on the multipaths of oscillations, which is characterized by the parameter m

The analysis showed that the propagation of ultrasonic oscillations in the waveguide during their constant transmission through the porous textile material, exponentially increases the change in wave amplitude and can increase the sensitivity of non-contact sensors to the material textile fiber. By this nature, the amplitude of the waves decreases due to the increase in the thickness or basis weight m_s of the textile material that are often limited in size technologically, which, in turn, makes it quite difficult to detect changes in sounding oscillations in working conditions. Therefore, the use of waveguides will help solve the problem of non-contact determination of basic technological parameters for materials such as textile tape, threads with high linear density, fiber mass and many other porous materials with complex internal structure.

In general, the use of guiding surfaces that reflect and concentrate ultrasonic waves for non-contact control of textile materials will help to improve the technological equipment that will be used in light industry. The improvement of the technical means for the production of textile materials can be done by integrating non-contact control systems of technological parameters of fabrics and threads into the structure of textile machines.

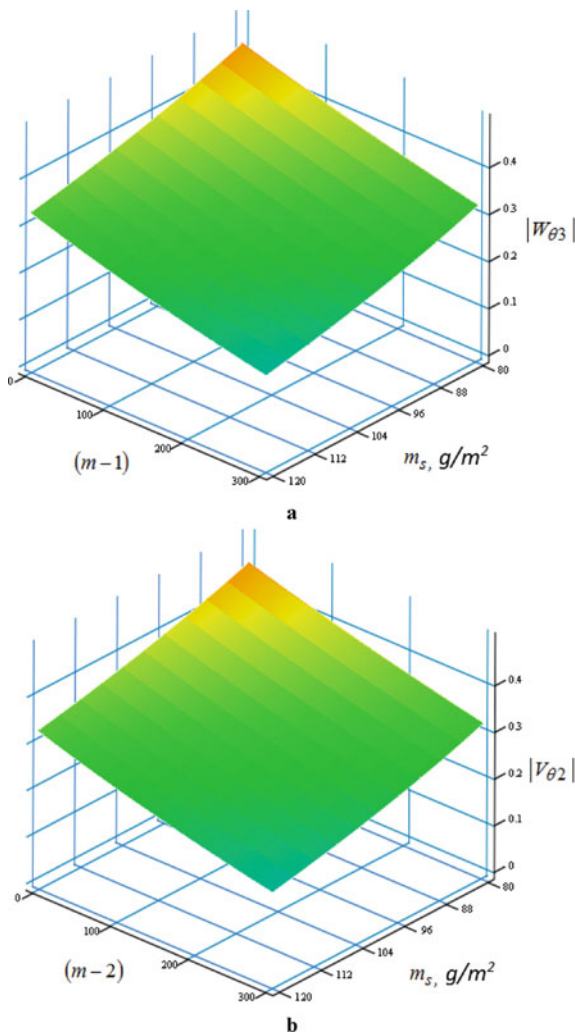


Fig. 3.17 Dependences of wave amplitudes $|W_{\theta 3}|, |V_{\theta 2}|$ on the basis weight m_s of textile fiber mass and on the parameter m of different waveguides: **a** for a waveguide with sensors on different sides of the textile fiber mass; **b** for a waveguide with sensors on one side of the textile fiber mass

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Chapter 4

Application of Non-contact Methods to Control the Technological Parameters of Textile Materials in the Production Process



4.1 Development and Application of Ultrasonic Amplitude Method to Determine the Tension of Warp Threads and the Battening Force in the Process of Weaving Fabrics

As shown by the analysis, which was presented earlier in the paper, the most promising method for non-contact determination of technological parameters of textile materials is ultrasonic. The textile material is irradiated with ultrasonic waves, and the value of the technological parameter is determined by the amplitude ratio of the ultrasonic wave that passed through the textile material or reflected from it to the incident wave.

In addition to determining the technological parameters of textile materials, after their production, it is possible to use the ultrasonic method of control to correct their deviation from the norm directly in the process of weaving. Also, using the amplitude ultrasonic method will optimize the parameters of technological processes of textile production. This can be done by determining the warp threads' tension or the weft threads battening force, which depends on the actual value of one of the main technological parameters—the basis weight of textile fabrics. This can also affect the consumption of raw materials in manufacturing fabrics on weaver's looms, which is essential for large production volumes [1–4].

The creation of mathematical models that will link the tension of textile threads on technological equipment with the amplitude characteristics of reflected and absorbed ultrasonic waves, will analyze, predict and improve the quality characteristics of fabrics, directly in the process of their production using contactless control.

For non-contact control of textile materials, it is necessary to consider one or more informative parameters of the ultrasonic signal. This allows the appropriate processing of the obtained data from the controlled and reference channel to exclude the influence of changes in the physical and mechanical parameters of the material and the environment on the measurement result. It is also necessary to take into account

the errors that may be caused by different transmission rates of these channels and their non-identity with each other [5–11].

By changing the amplitude of the reflected ultrasonic wave from the textile material relative to the amplitude of the incident wave on the material, it is possible to determine the tension or battening force of weft threads in weaving (by changing the diameters of threads, distances between them and between their fibers corresponding to a certain amplitude of reflected wave).

The paper presents the results of research to determine the tension of the warp threads, the battening force of the weft thread in the weaving process using the ultrasonic non-contact method, which, in turn, can also help to reduce the thread breakage and equipment downtime.

Research is crucial for the modern production of woven fabrics and in the future will improve the looms using non-contact technologies to determine the actual threads tension in the weaving process [12–19].

In order to describe the process of ultrasonic waves interaction with the threads in the weaving process, it is necessary to consider the main dependences (expressions (4.1), (4.2), (4.3), (4.4) and studies described in [7, 15]), which are related with one of the main technological operations on the loom, which provides the process of forming the fabric of a given structure. This operation is the weft thread battening, during which the tension of the warp in the area of fabric formation can be represented by the following dependence:

$$Q_o = Q_T \cdot \frac{\left(1 + k \frac{d_o}{d_y} \cdot (\sin \alpha_0 + \sin \alpha)\right) \cdot \left(1 + 2k \frac{d_o}{d_y} \cdot \sin \alpha\right)^{n-1}}{(1 - \delta) \cdot \cos \alpha} \times e^{\frac{\mu r_y \beta \varphi}{(r_o + r_y) \sin \beta}}, \quad (4.1)$$

where Q_T is fabric tension; d_o is the warp thread diameter; d_y is the weft thread diameter; r_o the warp thread radius; r_y is the weft thread radius; n is the number of weft threads in the fabric formation zone; α_0 is half the bite angle in battening; α is the angle of circumference of the weft thread surface with the warp thread; β is the weft angle in the fabric; φ is the sum angle of weft threads circumference in the area of fabric formation; μ is the friction ratio between the thread and the guideway; δ is the tension ratio of the main threads in the absence of fabric tension; k is the complex ratio.

The force of the weft thread battening can be written as follows:

$$P = Q_T \cdot \left(\frac{\left(1 + k \frac{d_o}{d_y} \cdot (\sin \alpha_0 + \sin \alpha)\right) \cdot \left(1 + 2k \frac{d_o}{d_y} \cdot \sin \alpha\right)^{n-1} \cdot \cos \alpha_0}{(1 - \delta) \cdot \cos \alpha} \times \exp\left(\frac{\mu r_y \beta \varphi}{(r_o + r_y) \cdot \sin \beta}\right) - 1 \right). \quad (4.2)$$

The sum angle of the wefts circumference in the area of fabric formation can be shown as:

$$\varphi = \left(\frac{2\alpha \cdot (r_o + r_y) \cdot \sin \beta}{2\alpha \mu r_y \beta + (r_o + r_y) \cdot \sin \beta \cdot \ln \left(1 + 2k \frac{d_o}{d_y} \cdot \sin \alpha \right)} \right) \times \ln \left(\frac{Q_o(1 - \delta) \cdot \left(1 + 2k \frac{d_o}{d_y} \cdot \sin \alpha \right)^{\frac{\alpha_0 + \alpha}{2\alpha}} \cdot \cos \alpha}{Q_T \cdot \left(1 + k \frac{d_o}{d_y} \cdot (\sin \alpha_0 + \sin \alpha) \right)} \right). \quad (4.3)$$

Dependence (4.3) can also be represented as follows:

$$\varphi = \alpha_0 + \alpha + 2\alpha \cdot (n - 1). \quad (4.4)$$

From the expression (4.4) it is possible to determine the number of weft threads of the fabric formation zone and present it as follows:

$$n = 1 + \frac{\varphi - (\alpha_0 + \alpha)}{2\alpha}. \quad (4.5)$$

For the linen weave fabric, Fig. 4.1 shows graphs of the dependence of the weft thread battening force P and the warp tension Q_o on the parameter D_{wt} (number of weft threads per 1 dm) and with the basis weight m_s of the woven fabric. The following parameters have been used: $D_{wp} = 246 \text{ t/dm}$ (number of warp threads per 1 dm); $T_o = 25 \text{ tex}$ (linear density of warp threads); $T_y = 29.4 \text{ tex}$ (linear density of weft threads); $r_o = 0.099 \text{ mm}$; $r_y = 0.107 \text{ mm}$; $Q_T = 4 \text{ cN}$; $k = 0.75$; $\mu = 0.5$; $n = 4.25$. Figure 4.2a shows the change in basis weight m_s from the parameter D_{wt} for the above case, and Fig. 4.2b, c shows the dependence of the change in the circumference angle α of weft thread on the warp from the parameter D_{wt} and the surface m_s density in the forming the fabric on a loom.

Since the warp tension and the weft thread battening force in the weaving process can be determined contactlessly by changing the diameters of the threads and the distances between them, the expression for the amplitude of the ultrasonic wave passing through the warp can be given as follows:

$$|W_o| = \frac{1}{\sqrt{1 + \left(\frac{2\pi f}{c_2} \left(\frac{Z_2}{2Z_1} + \frac{Z_1}{2Z_2} \right) d_o \frac{\pi}{4} \cos v_o \right)^2}}, \quad (4.6)$$

where for this case: $|W_o|$ —the module of the complex coefficient of ultrasonic signal transmission through the warp threads; f —ultrasonic frequency; Z_1 —acoustic air resistance; Z_2 —acoustic resistance of textile material; c_2 —speed of the ultrasonic signal in the textile material; v_o —the angle between the vector of the wave reflected from the warp threads towards the signal, and the threads themselves.

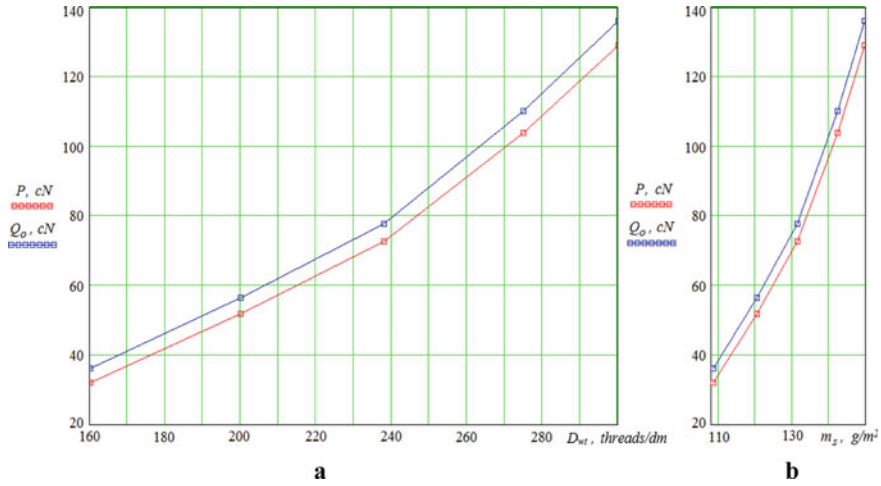


Fig. 4.1 Dependence of the warp threads tension Q_o , cN and the battening force P , cN on the weft threads density D_{wt} , t/dm and the basis weight of the fabric: m_s , g/m²: **a** the dependence of the warp threads tension Q_o and the battening force P on the weft threads density in the fabric D_{wt} ; **b** the dependence of the warp threads tension Q_o and the battening force P on the basis weight of the fabric m_s

From the dependence (b) it is possible to express the warp threads diameter as follows:

$$d_o = \frac{\sqrt{\frac{1}{|W_o|^2} - 1}}{\frac{\pi^2 f}{2c_2} \left(\frac{Z_2}{2Z_1} + \frac{Z_1}{2Z_2} \right) \cos v_o}. \quad (4.7)$$

The modulus of the complex coefficient of ultrasonic wave reflection from the fabric in its formation area in the weaving process can be shown as:

$$|V| = \sqrt{1 - \frac{1}{1 + \left(\frac{K m_s f \cos v}{Z_1} \right)^2}} = \frac{1}{\sqrt{1 + \left(\frac{Z_1}{K m_s f \cos v} \right)^2}}. \quad (4.8)$$

If you determine the diameter of the warp threads by the non-contact method using a reflected ultrasonic wave, knowing the relationship between the reflected waves and the waves passing through the textile material, you can from expression (4.7) give the diameter of the warp threads as follows:

$$d_o = \frac{2|V_o|K_\rho}{\sqrt{1 - |V_o|^2} \cos v_o \frac{\pi^2 f}{c_2} \left(\frac{Z_2}{2Z_1} + \frac{Z_1}{2Z_2} \right)}, \quad (4.9)$$

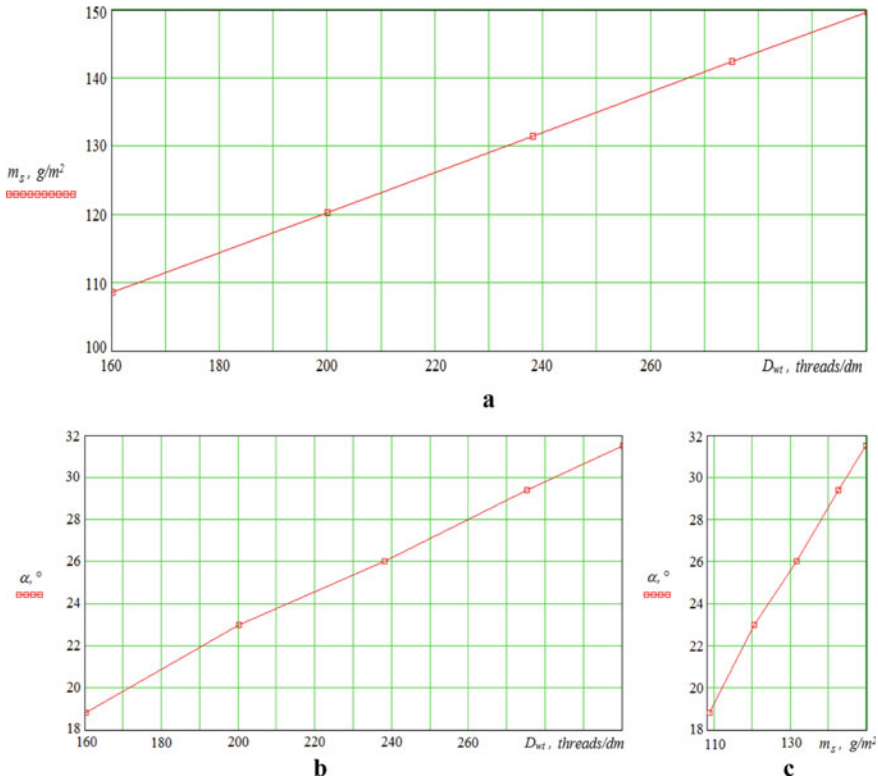


Fig. 4.2 Dependence of the fabric basis weight m_s , g/m^2 on parameter D_{wt} , t/dm and the dependence of the circumference angle α , $^\circ$ of the weft thread surface by warp on the parameter D_{wt} , t/dm and on the basis weight m_s , g/m^2 : **a** dependence of the fabric basis weight m_s on the parameter D_{wt} ; **b** dependence of the circumference angle change α of the weft thread surface on the parameter D_{wt} ; **c** dependence of the circumference angle change α of the weft thread surface by warp on the basis weight of fabric m_s

where $|V_o|$ —the module of the complex coefficient of the ultrasonic signal reflection from the warp threads; K_ρ —coefficient characterizing the receipt of the reflected ultrasonic signal to the receiver of oscillations from the structural parameters of the fabric threads and their position relative to the receiver.

The double average diameter of the fabric threads can be determined as:

$$2d_c = \frac{2|V|K_\rho}{\sqrt{1 - |V|^2} \cos v \frac{\pi^2 f}{c_2} \left(\frac{Z_2}{2Z_1} + \frac{Z_1}{2Z_2} \right)}. \quad (4.10)$$

The dependences discussed above, using the reflected ultrasonic signal from the warp threads and the reflected waves from the fabric, make it possible to determine the diameter of the weft threads. The weft threads diameter with the help of two

reflected signals can be given as follows:

$$d_y = \frac{2 \left(\frac{|V|}{\sqrt{1-|V|^2} \cos v} - \frac{|V_o|}{\sqrt{1-|V_o|^2} \cos v_o} \right) K_\rho}{\frac{\pi^2 f}{c_2} \left(\frac{Z_2}{2Z_1} + \frac{Z_1}{2Z_2} \right)}, \quad (4.11)$$

then the ratio of the warp and weft threads diameters of the fabric through the amplitude dependences of the ultrasonic waves from the two signals can be shown as:

$$\frac{d_o}{d_y} = \frac{|V_o|}{\sqrt{1-|V_o|^2} \cos v_o \left(\frac{|V|}{\sqrt{1-|V|^2} \cos v} - \frac{|V_o|}{\sqrt{1-|V_o|^2} \cos v_o} \right)}, \quad (4.12)$$

or

$$\frac{d_o}{d_y} = \frac{1}{\frac{|V| \sqrt{1-|V_o|^2} \cos v_o}{|V_o| \sqrt{1-|V|^2} \cos v} - 1}.$$

By changing the amplitudes of the reflected ultrasonic waves, the change in fabric diameters can be determined non-contact, but it is necessary to ensure the correct location of the sensors relative to the warp and weft threads together in their weave so that ultrasonic waves can be detected by the receiving part. The radiating and receiving sensors themselves should be positioned so that the phenomenon of wave reflection is not observed with their superimposition on the resulting information signal. All these measures in the complex make it possible to determine the following ratio using ultrasonic waves that interact with the threads of the woven fabric.

$$\begin{aligned} \frac{r_y}{r_o + r_y} &= \frac{|V| - \frac{|V_o| \sqrt{1-|V|^2} \cos v}{\sqrt{1-|V_o|^2} \cos v_o}}{|V|}, \\ \frac{r_y}{r_o + r_y} &= 1 - \frac{|V_o| \sqrt{1 + \left(\frac{Z_1}{K m_s f \cos v} \right)^2} \cdot \sqrt{1 - \frac{1}{1 + \left(\frac{Z_1}{K m_s f \cos v} \right)^2}} \cos v}{\sqrt{1-|V_o|^2} \cos v_o}. \end{aligned} \quad (4.13)$$

If the above dependences (4.12) and (4.13) are substituted in (4.1) and (4.2), then we can obtain expressions for the tension of the warp thread Q_o in the area of fabric formation and for the weft thread battening force P in the weaving process, which can be determined by the amplitudes of the two reflected ultrasonic signals.

$$Q_o = \frac{Q_T \left(1 + k \frac{\sin \alpha_0 + \sin \alpha}{\frac{|V|\sqrt{1-|V_o|^2} \cos v_o}{|V_o|\sqrt{1-|V|^2} \cos v} - 1} \right) \cdot \left(1 + 2k \frac{\sin \alpha}{\frac{|V|\sqrt{1-|V_o|^2} \cos v_o}{|V_o|\sqrt{1-|V|^2} \cos v} - 1} \right)^{n-1}}{(1 - \delta) \cdot \cos \alpha} \times \exp \left(\frac{\mu \beta \varphi \cdot \left(|V| - \frac{|V_o|\sqrt{1-|V|^2} \cos v}{\sqrt{1-|V_o|^2} \cos v_o} \right)}{|V| \cdot \sin \beta} \right), \quad (4.14)$$

$$P = Q_T \cdot \left(\left(1 + k \frac{\sin \alpha_0 + \sin \alpha}{\frac{|V|\sqrt{1-|V_o|^2} \cos v_o}{|V_o|\sqrt{1-|V|^2} \cos v} - 1} \right) \cdot ((1 - \delta) \cdot \cos \alpha)^{-1} \times \left(1 + 2k \frac{\sin \alpha}{\frac{|V|\sqrt{1-|V_o|^2} \cos v_o}{|V_o|\sqrt{1-|V|^2} \cos v} - 1} \right)^{n-1} \cdot \cos \alpha_0 \times \exp \left(\frac{\mu \beta \varphi \cdot \left(|V| - \frac{|V_o|\sqrt{1-|V|^2} \cos v}{\sqrt{1-|V_o|^2} \cos v_o} \right)}{|V| \cdot \sin \beta} \right) - 1 \right). \quad (4.15)$$

Taking into account the dependences (4.14) and (4.15), the number of weft threads in the area of fabric formation can then be represented as follows:

$$n = 1 + \frac{1}{2\alpha} \cdot \left(\left(\frac{2\alpha |V| \cdot \sin \beta}{\sqrt{1-|V|^2} \cos v \frac{\pi^2 f}{c_2} \left(\frac{Z_2}{2Z_1} + \frac{Z_1}{2Z_2} \right)} \right) \times \left(\frac{2\alpha \mu \beta \cdot \left(\frac{|V|}{\sqrt{1-|V|^2} \cos v} - \frac{|V_o|}{\sqrt{1-|V_o|^2} \cos v_o} \right)}{\frac{\pi^2 f}{c_2} \left(\frac{Z_2}{2Z_1} + \frac{Z_1}{2Z_2} \right)} \right) + \frac{|V| \cdot \sin \beta}{\sqrt{1-|V|^2} \cos v \frac{\pi^2 f}{c_2} \left(\frac{Z_2}{2Z_1} + \frac{Z_1}{2Z_2} \right)} \times \ln \left(1 + 2k \frac{\sin \alpha}{\frac{|V|\sqrt{1-|V_o|^2} \cos v_o}{|V_o|\sqrt{1-|V|^2} \cos v} - 1} \right) \right)^{-1}$$

$$\times \ln \left(\frac{Q_o(1-\delta) \cdot \left(1 + 2k \frac{\sin \alpha}{\frac{|V|\sqrt{1-|V_o|^2 \cos v_o}}{|V_o|\sqrt{1-|V|^2 \cos v}} - 1} \right)^{\frac{\alpha_0 + \alpha}{2\alpha}} \cdot \cos \alpha}{Q_T \cdot \left(1 + k \frac{\sin \alpha_0 + \sin \alpha}{\frac{|V|\sqrt{1-|V_o|^2 \cos v_o}}{|V_o|\sqrt{1-|V|^2 \cos v}} - 1} \right)} \right) - (\alpha_0 + \alpha). \quad (4.16)$$

According to the research, the curves were obtained showing the nature of the two ratios change reflected from the interweaving of the warp and weft threads of ultrasonic signals to the amplitude of the incident wave depending on the change in battening force (the diagram in Fig. 4.3 BBB). depending on the change in the thread tension (diagram in Fig. 4.3 BBB). Curves were also obtained showing the nature of the change in the two ratios of the ultrasonic signals reflected from the warp threads to the amplitude of the wave incident on the threads depending on the change in battening force (the diagram in Fig. 4.3 BBB), depending on the change in warp threads tension (the diagram in Fig. 4.3).

From Fig. 4.3 it is seen that the reflected ultrasonic signal from the warp threads is much smaller in amplitude than the signal reflected from the fabric netting. Also from Fig. 4.3 it can be seen that with increasing the warp threads tension and the weft thread battening force the amplitude of the ultrasonic waves reflected from the material also increases at a constant frequency of ultrasonic vibrations.

Additionally, Fig. 4.4 shows the dependences of the change in the amplitude ratios of the reflected ultrasonic waves on the interweaving of the threads (the diagram shown in Fig. 4.4a BBB) and on the warp threads (the diagram shown in Fig. 4.4a BBB)

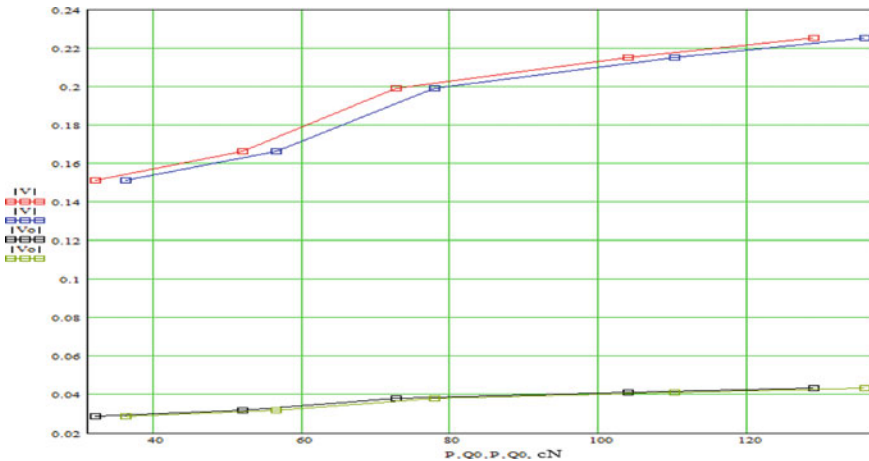


Fig. 4.3 Dependences of amplitude ratios of reflected ultrasonic waves, proportional to modules $|V|$ and $|V_o|$, on the warp threads tension Q_o , cN and on weft threads battening P , cN in the weaving process

depending on the change in the angle of the circumference of the weft thread surface with the warp thread. Also, Fig. 4.4b, c shows the dependences of the ratio change nature of the reflected ultrasonic signal from the threads interweaving to the amplitude of the wave incident on the fabric from the change in the weft threads number D_{wt} and from the change in basis weight m_s (diagrams in Fig. 4.4b, c ~~BBE~~), as well as showing the ratio change nature of the reflected ultrasonic signal from the warp threads to the amplitude of the wave incident on the threads from changes in the weft threads number D_{wt} and from changes in basis weight m_s (diagrams in Fig. 4.4b, c ~~BBE~~).

The general dependences of the amplitude ratios of the reflected ultrasonic waves, proportional to the modulus $|V|$ and $|V_o|$, and, from the weft thread battening force P in the weaving process and from its basis weight m_s are shown in Figs. 4.5 and 4.6, respectively. The presented diagrams and surfaces for the dependences of the amplitude ratios of the ultrasonic probes in Figs. 4.3, 4.4, 4.5 and 4.6 are the further study of this case in operation for which the technological parameters of linen weave fabric were calculated during its weaving.

With the help of ultrasonic sensors installed above the fabric formation area and above the warp, the actual tension of the warp threads and the weft thread battening

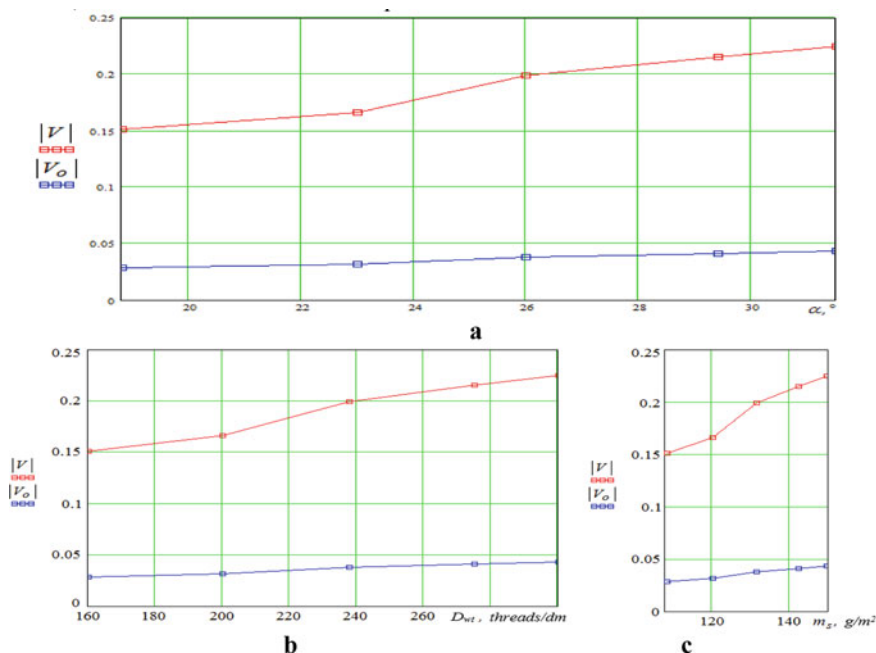


Fig. 4.4 Dependences of amplitude ratios of reflected ultrasonic waves, proportional to modules $|V|$ and $|V_o|$, on the angle of the circumference of the weft thread surface with the warp thread, on the weft thread density D_{wt} , t/dm and on m_s , g/m^2 of the fabric: **a** dependences $|V|$ and $|V_o|$ on the angle of the circumference α ; **b** dependences $|V|$ and $|V_o|$ on the weft thread density in the fabric D_{wt} ; **c** dependences $|V|$ and $|V_o|$ on the basis weight of the fabric m_s

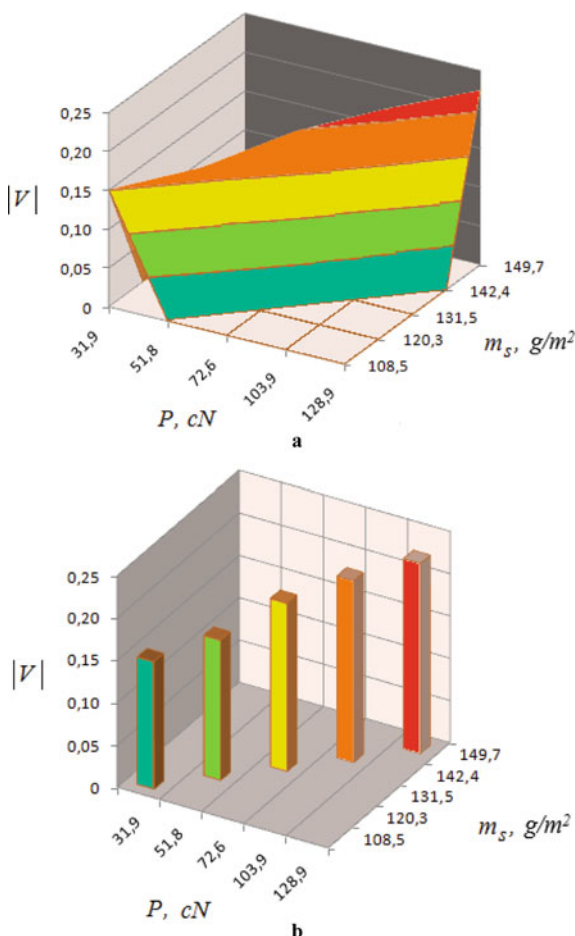


Fig. 4.5 Dependence of amplitude ratios of reflected ultrasonic waves, proportional to module $|V|$, on the weft threads battening force P , cN, fabric in the weaving process and its basis weight m_s , g/m²: **a** dependence shown as a surface for the module $|V|$; **b** dependence shown as discrete values for the module $|V|$

force can be determined, which affects both the change in basis weight of the fabric and the breakage of the threads and textile equipment downtime. A measuring system with a running platform for scanning the fabric formation area will give the best result in determining the actual tension of the threads on the loom, but from a technical point of view, it will be more difficult to implement.

As can be seen from the dependences of Figs. 4.3, 4.4, 4.5 and 4.6, to implement the method of contactless control of the weft thread battening force P or to control the tension of the warp threads Q_o , it is necessary to ensure high sensitivity of the measuring channel of the reflected ultrasonic signal from the warp threads. This is due to the much lower level of amplitude of ultrasonic waves, which are reflected

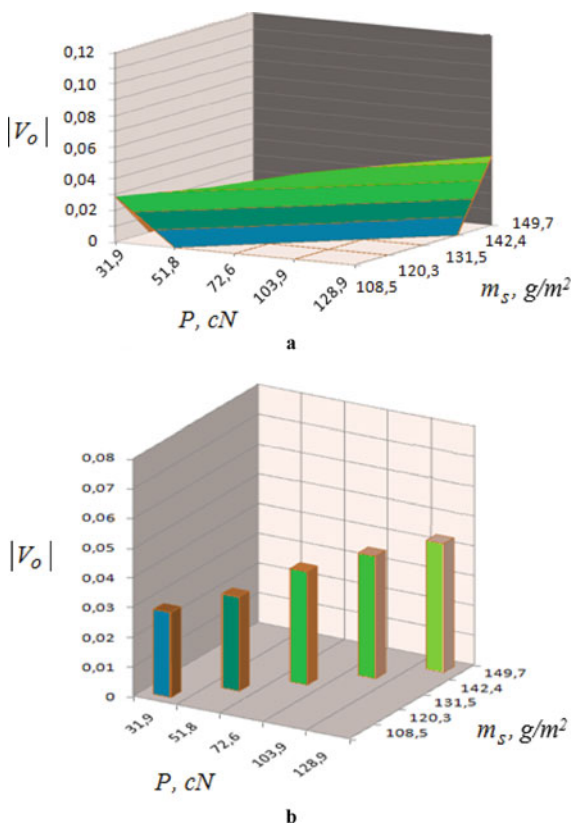


Fig. 4.6 Dependence of amplitude ratios of reflected ultrasonic waves, proportional to module $|V_o|$, on the weft threads battening force P , cN the fabric in the weaving process and on its basis weight m_s , g/m²: **a** dependence shown as a surface for the module $|V_o|$; **b** dependence shown as discrete values for the module $|V_o|$

only from the warp threads in comparison with the reflected waves from the surface of the fabric itself.

To increase the sensitivity of the measuring signal, the guides and concentrating surfaces for transmitted waves can be used, which will allow to additionally determine the parameters of change of interfiber materials porosity if necessary.

Systems using contactless sensors can include platforms for scanning textile fabric and scanning a number of threads at a certain point in time in the weaving process, which enable operational control of technological parameters of different fabrics.

Summarizing the research in this direction, they showed that by changing the amplitude ratios of the reflected ultrasonic waves from the fabric and the warp threads relative to the amplitude of the incident wave on the surface of the material, we can determine their tension and the weft thread battening force in the weaving process.

The results of research on the non-contact determination of the warp threads tension for the process of textile fabrics making will make it possible to reduce their breakage. It will also be possible, knowing the tension of the threads, to determine the actual value of the basis weight in textile fabric manufacturing.

The research is crucial for the modern production of woven fabrics and in the future will improve looms using non-contact technologies to determine the actual tension of the threads in the weaving process. This will enable us to quickly determine both the change in the actual tension of the warp threads and its value to determine the basis weight of the fabric and its deviation from the norm in the weaving process.

4.2 Design and Application of Ultrasonic Amplitude Method for Determining the Tension of Threads on Textile Knitting Machines in the Process of a Knitted Fabric Manufacturing

The quality of various knitted fabrics depends on the main technological parameters, the provision of which makes it possible to obtain its proper level. One of the main such parameters is the basis weight, which was mentioned earlier in the paper. Adherence to the proper basis weight depends on the tension of the threads on the textile machines used to produce knitted fabrics, in accordance with the same as for the fabrics on the looms. Excessive threads tension can cause their breakage on the technological equipment, which leads to a lack of fabric, downtime of textile machines, and loss of money and time to restart them. Since today the systems of thread tension adjustment on various textile machines are mainly mechanical, it is not possible to determine the actual value of this parameter in the process of such systems and accordingly make the right adjustments with the required accuracy, which can significantly affect the quality of finished products.

The development of ultrasonic non-contact methods and means of determining the thread tension on various textile machines will provide operational technological control of this parameter and provide feedback to the systems of thread tension control, which will be adjusted to the actual value of this parameter [20–23].

The movement of threads with a certain tension on the working bodies of knitting machines is a movement on the guides of different shapes. If we consider such interaction of the thread with a cylindrical guide with a curvature radius, then to determine the tension at point A (tension P_A) of the thread on the guide and point B (tension P_B) of its ascent, we can use the expressions described in the paper. These dependencies can be shown as follows:

$$P_A = P_0 \cdot \left(1 - \frac{B_0}{2P_0(R + r(1 - \delta_{T0}))^2}\right), P_B = P_1 \cdot \left(1 - \frac{B_0}{2P_1(R + r(1 - \delta_T))^2}\right), \quad (4.17)$$

then the expression describing the tension of the trailing and leading branches of the yarn, which interacts with the cylindrical guide, can be shown as follows:

$$P_1 = P_0 \cdot \left(1 + \frac{(R+r)(e^{\mu_T \varphi_T} - 1)}{R+r(1-\delta_{T0})} \right) + \frac{B_0}{2(R+r(1-\delta_T))^2} - \frac{B_0}{2(R+r(1-\delta_T))^2} \cdot \left(1 + \frac{(R+r)(e^{\mu_T \varphi_T} - 1)}{R+r(1-\delta_{T0})} \right), \quad (4.18)$$

then

$$\delta_{T0} = \frac{P_0(R+r)}{rP_0 + E_1 b_k (R+r)^2}, \delta_T = \delta_{T0} \cdot e^{\mu_T \varphi_P}, \mu_T = \frac{a_T}{\left(\frac{P_0}{R}\right)^{b_T}}, \quad (4.19)$$

where P_0 , P_1 —tension of the trailing and leading branches of the yarn; r —conventional radius of the thread; R —curvature radius of the cylindrical guide; μ_T —thread friction coefficient; φ_T —the thread wrapping angle of the guide's surface; E_1 —the modulus of the thread elasticity during compression; δ_{T0} , δ_T —the relative deformation of the cross section at the point of entry into the guide and the exit of the thread from it to the beginning of the previous shifting; B_0 —the stiffness coefficient of the thread when bending; b_k —the width of the contact mark of the thread on the guide; a_T , b_T —the corresponding research coefficients (particular values for for each thread); φ_P —the value of the thread wrapping angle of the guide surface before previous shifting.

The value of the thread wrapping angle of the guide surface before can be represented as:

$$\varphi_T = \varphi_P + \arccos\left(1 - \delta_{T0} \left(\frac{2r}{R}\right)^2\right) + \arccos\left(1 - \delta_T \left(\frac{2r}{R}\right)^2\right) - \arccos\left(1 - \frac{B_0}{2P_0(R+r)^2}\right) - \arccos\left(1 - \frac{B_0}{2P_1(R+r)^2}\right). \quad (4.20)$$

To determine the tension of the leading branch of the thread on the cylindrical guide with the help of informative parameters of ultrasonic waves it should be first considered the change of this parameter for different threads and yarns, which are widely used in the knitted fabrics manufacturing.

Let us consider cotton textile material, viscose and capron threads, as well as a woolen textile material, the main initial parameters of which are described in [17, 19, 21–27]. The parameters for these threads and yarns were determined experimentally. The main of these parameters for cotton yarn 27.6 tex include the following values: $2r = 0.22$ mm; $B_0 = 0.7$ cN · mm²; $E_1 = 712.2$ cN/mm²; $a_T = 0.1656$; $b_T = 0.0590$; $b_k = 0.012$ mm; specific breaking load 28.9 cN/tex; relative breaking elongation 9%. The parameters for the viscose thread 16.7 tex include the following values: $2r = 0.17$ mm; $B_0 = 0.2$ cN · mm²; $E_1 = 474.9$ cN/mm²; $a_T = 0.1580$; $b_T = 0.1160$; $b_k = 0.014$ mm; specific breaking load 14.9 cN/tex; relative breaking elongation 24%. The parameters for the capron thread 28 tex include the following values: $2r = 0.2$ mm; $B_0 = 0.22$ cN · mm²; $E_1 = 584.4$ cN/mm²; $a_T = 0.1765$; $b_T = 0.1186$; $b_k = 0.012$ mm; specific breaking load 51.1 cN/tex;

relative breaking elongation 23%. The parameters for wool yarn 29.9 tex include the following values: $2r = 0.23$ mm; $B_0 = 0.1$ cN · mm²; $E_1 = 599$ cN/mm²; $a_T = 0.1330$; $b_T = 0.0910$; $b_k = 0.015$ mm; specific breaking load 10.7 cN/tex; relative breaking elongation 18%. The change in tension P_1 , cN for the leading branch of different threads and yarns depending on different influencing factors in the knitwear production is shown in Figs. 4.7, 4.8, 4.9, 4.10, 4.11 and 4.12.

From Figs. 4.7, 4.8, 4.9 and 4.10 you can see how the tension P_1 changes for different threads and yarns at $P_0 = 10$ cN depending on the change in the radius of the cylindrical guide and depending on the conventional radius.

For cotton textile material, the change in tension P_1 at low linear yarn density is smaller than for viscose and capron yarns, and in comparison with wool, its value is greater, although the absolute change of this parameter with a change in radius is close to wool. It should be noted that for capron and viscose yarns given in the paper (linear density 28 tex and 16.7 tex, respectively), the absolute change in tension P_1 with change is also almost the same, although the value for this parameter is greater for capron.

The highest value of tension P_1 at $P_0 = 10$ cN for the given threads and yarns for both low linear density and high refer to capron threads. The lowest tension P_1 will be for woolen material, approximately similar in magnitude of this parameter will be its values for cotton and viscose for both the low linear density of the material and high.

From the above surfaces it can be seen that at a high linear density of threads and yarns, when the radius of the cylindrical guide is in the range from 1 to 4 mm, the tension P_1 will have its maximum value at $P_0 = 10$ cN. Therefore, it is advisable to take into account the results of this study when choosing threads for the primary non-contact control of increased tension P_1 if necessary, which can cause a break of the textile material. Such control should be performed using ultrasonic sensors.

Additionally, let us study the change in tension P_1 with a change in the conventional radius and with a change in the tension P_0 of the trailing branch of the thread or yarn to determine the range of the controlled parameter. From Figs. 4.11 and 4.12 it can be seen that with increasing parameter P_0 and conventional radius, the tension P_1 also increases significantly. If we pay attention to the value of tension P_1 for different textile threads and yarns, which were considered in the work, then for cotton, viscose and capron its value is similar and is much smaller only for wool.

By changing the diameter of the thread and its density (can vary by reducing the interfiber porosity of the material), using the amplitude ratios of ultrasonic waves interacting with the thread, it is possible to determine its tension in the knitted fabric production.

The radius of the thread can be determined using the amplitude of the reflected wave from it as:

$$r = \frac{|V_{T0}|K_{\rho 2}}{\sqrt{1 - |V_{T0}|^2} \cos \nu_1 \frac{\pi^2 f}{c_2} \left(\frac{Z_2}{2Z_1} + \frac{Z_1}{2Z_2} \right)}. \quad (4.21)$$

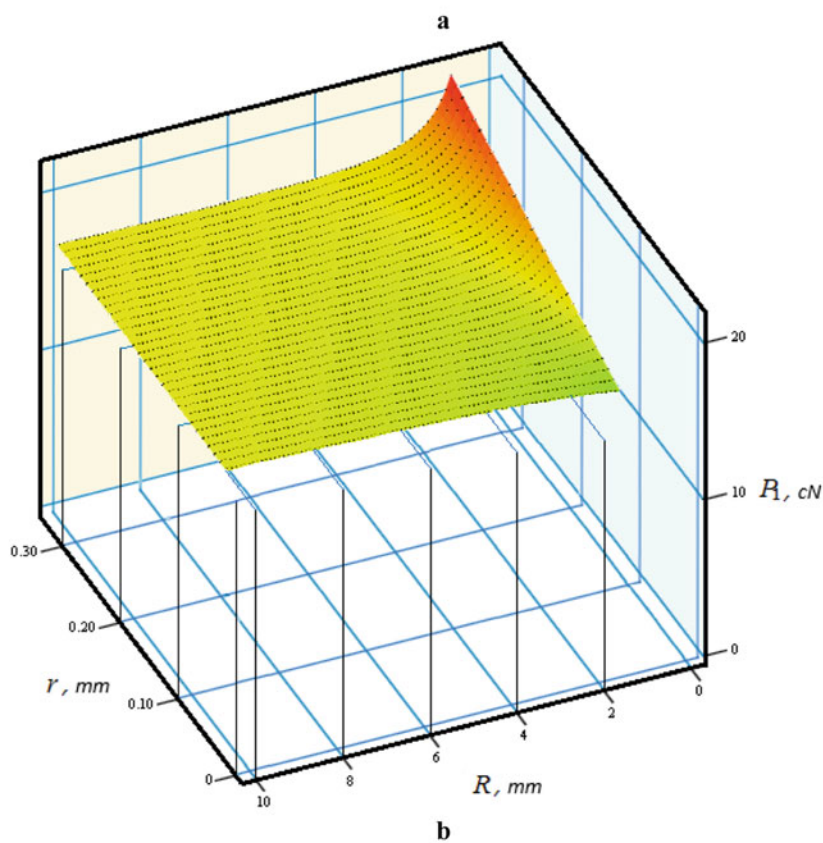
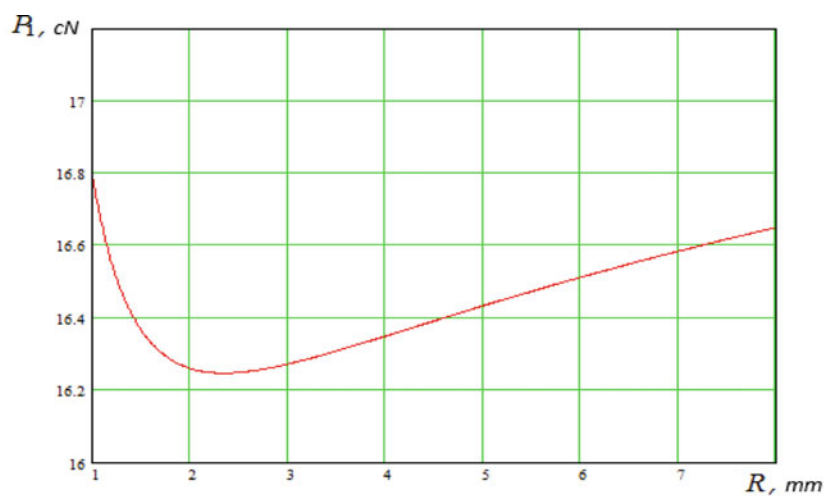


Fig. 4.7 Change of tension P_1 , cN of the leading branch of cotton yarn at $P_0 = 10$ cN: **a** change of tension P_1 , cN of the leading branch of cotton yarn 27.6 tex from R , mm; **b** tension change surface P_1 , cN from r , mm and R , mm for cotton material

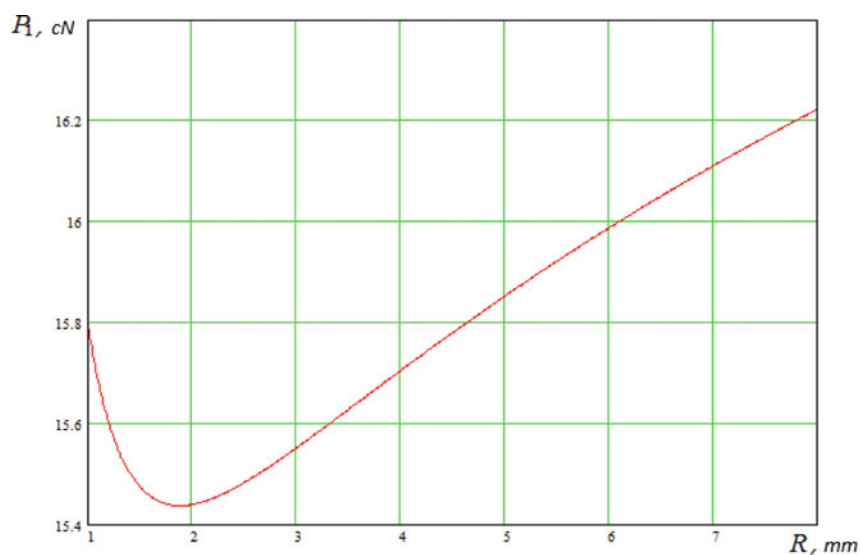
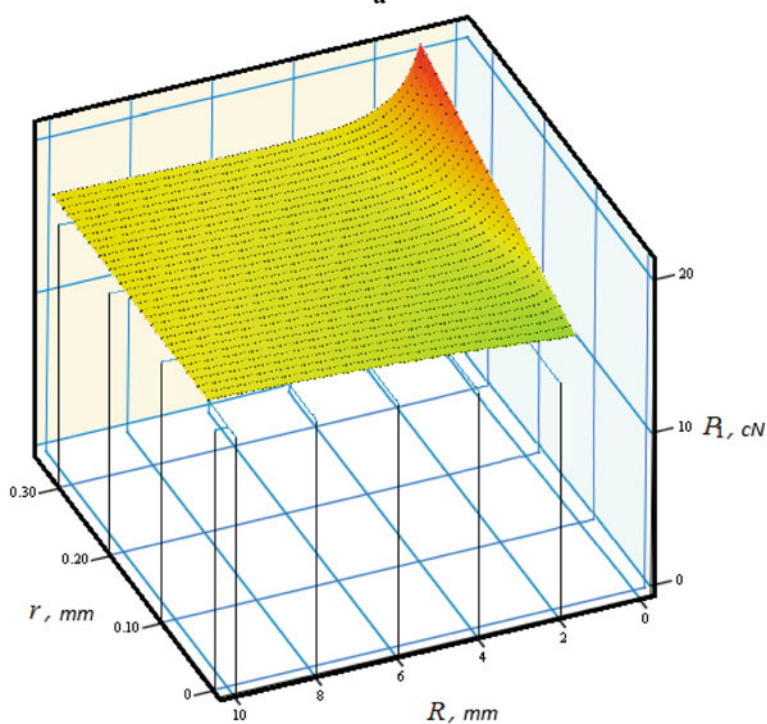
**a****b**

Fig. 4.8 Change of tension P_1 , cN of the leading branch of viscose thread at $P_0 = 10$ cN: **a** change of tension P_1 , cN of the leading branch of viscose thread 16.7 tex from R , mm; **b** tension change surface P_1 , cN from r , mm and R , mm from viscose yarn

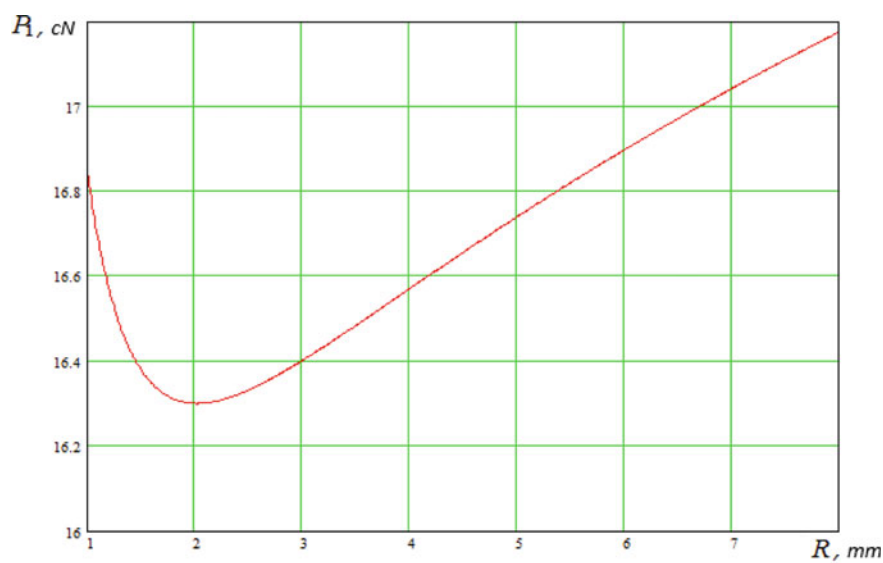
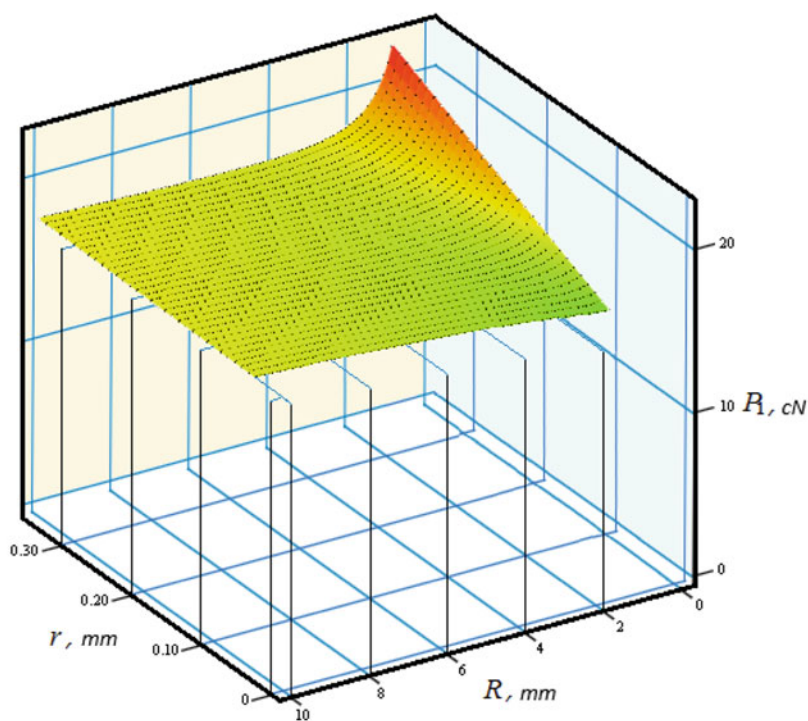
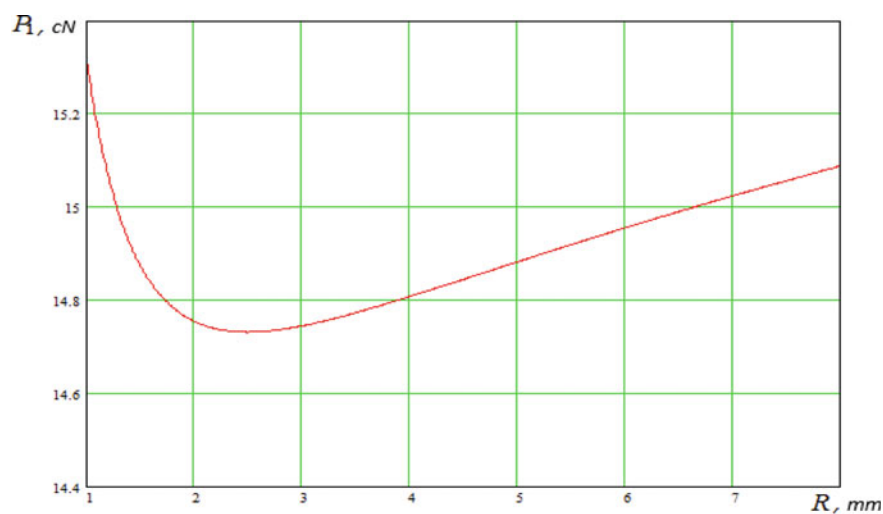
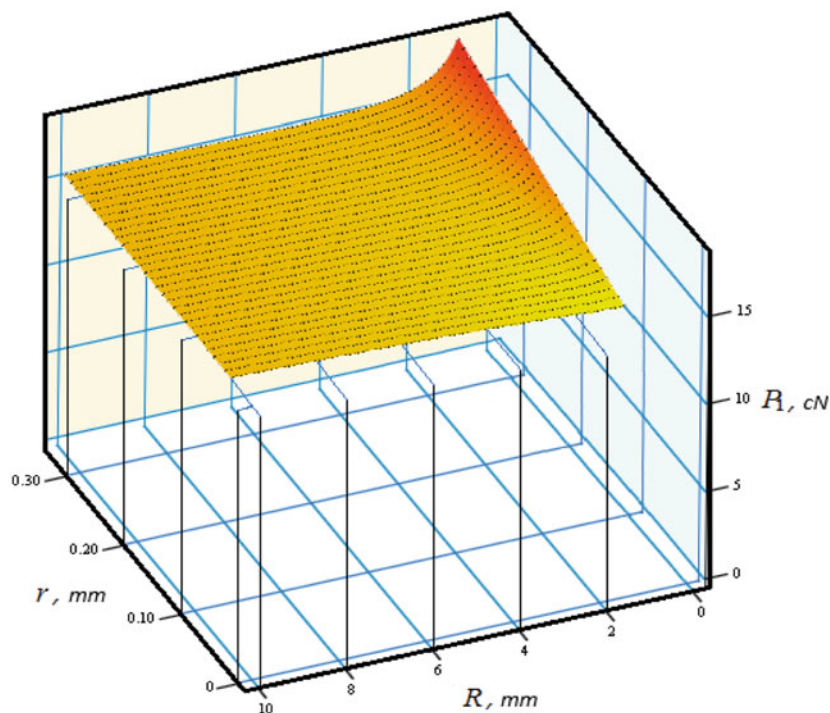
**a****b**

Fig. 4.9 Change of tension P_1 , cN of the leading branch of capron thread at $P_0 = 10$ cN: **a** change of tension P_1 , cN of the leading branch of capron thread 28 tex from R , mm; **b** tension change surface P_1 , cN from r , mm and R , mm for capron yarn



a



b

Fig. 4.10 Change of tension P_1 , cN of the leading branch of a woolen thread where $P_0 = 10$ cN: **a** change of tension P_1 , cN of the leading branch of a woolen thread 29.9 tex from R , mm; **b** tension change surface P_1 , cN from r , mm and R , mm for woolen material

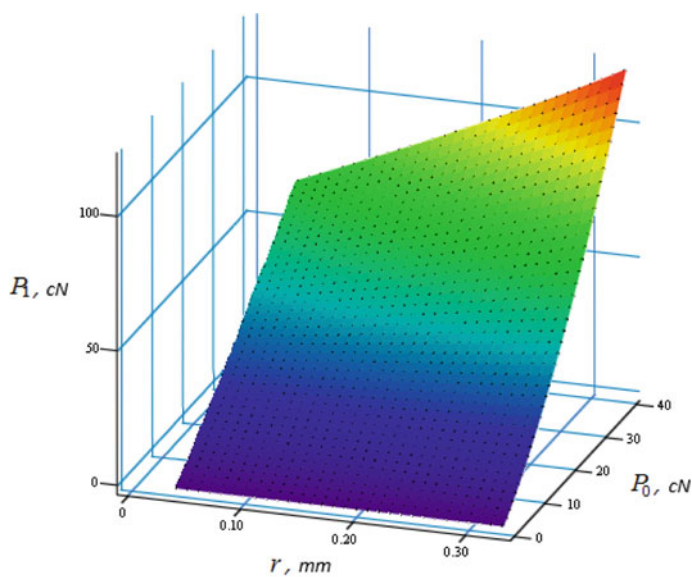
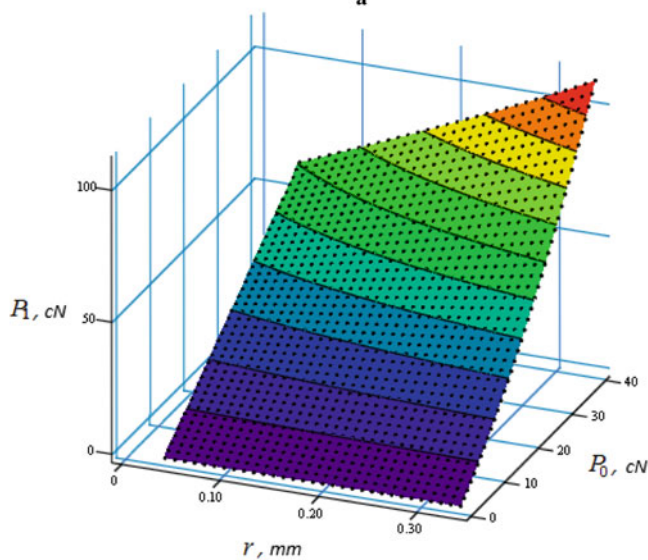
**a****b**

Fig. 4.11 Tension dependence P_1 of leading branch of threads from P_0 and r at $R = 1.1$ mm: **a** tension change P_1 , cN from P_0 , cN and r , mm for cotton material; **b** tension change P_1 , cN from P_0 , cN and r , mm for viscose yarn

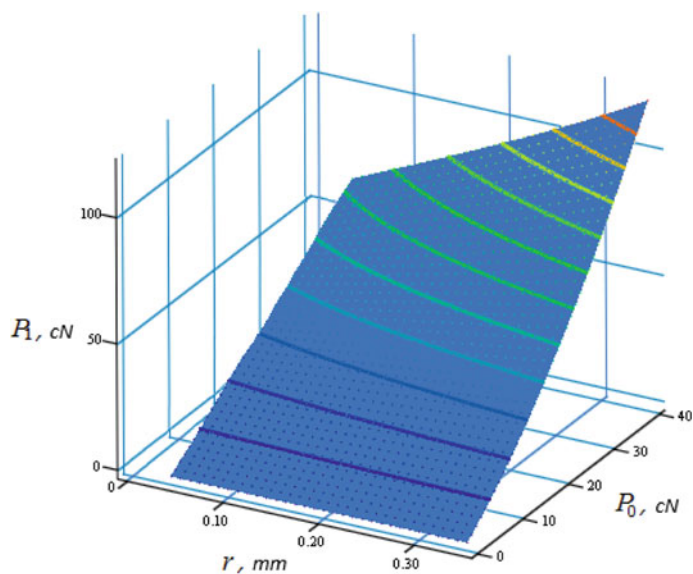
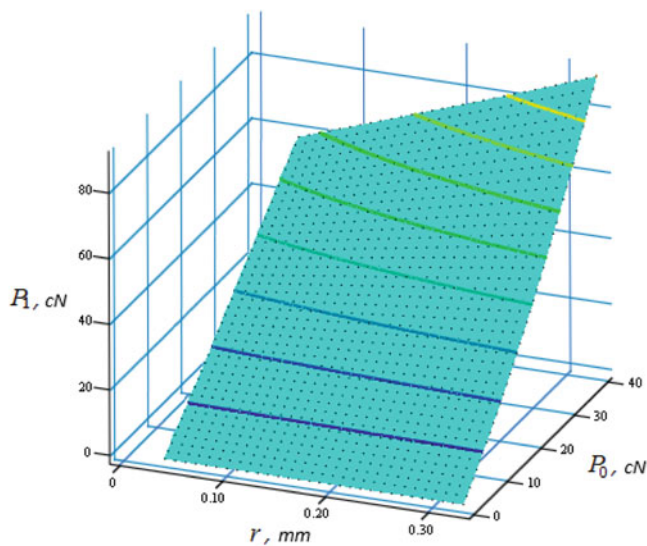
**a****b**

Fig. 4.12 Tension dependence P_1 of the leading branch of threads from P_0 and r at $R = 1.1$ mm: **a** tension change P_1 , cN from P_0 , cN and r , mm for capron threads; **b** tension change P_1 , cN from P_0 , cN and r , mm for woolen textile material

Tension P_1 can be applied as follows:

$$P_1 = P_0 \cdot \left(1 + \frac{\left(R + \frac{|V_{T0}|K_{\rho 2}}{\sqrt{1-|V_{T0}|^2} \cos v_1 \frac{\pi^2 f}{c_2} \left(\frac{Z_2}{2Z_1} + \frac{Z_1}{2Z_2} \right)} \right) (e^{\mu_T \varphi_T} - 1)}{R + \frac{|V_{T0}|K_{\rho 2}(1-\delta_{T0})}{\sqrt{1-|V_{T0}|^2} \cos v_1 \frac{\pi^2 f}{c_2} \left(\frac{Z_2}{2Z_1} + \frac{Z_1}{2Z_2} \right)}} \right) - \frac{B_0}{2 \cdot \left(R + \frac{|V_{T0}|K_{\rho 2}(1-\delta_{T0})}{\sqrt{1-|V_{T0}|^2} \cos v_1 \frac{\pi^2 f}{c_2} \left(\frac{Z_2}{2Z_1} + \frac{Z_1}{2Z_2} \right)} \right)^2} \times \frac{\left(R + \frac{|V_{T0}|K_{\rho 2}}{\sqrt{1-|V_{T0}|^2} \cos v_1 \frac{\pi^2 f}{c_2} \left(\frac{Z_2}{2Z_1} + \frac{Z_1}{2Z_2} \right)} \right) (e^{\mu_T \varphi_T} - 1)}{R + \frac{|V_{T0}|K_{\rho 2}(1-\delta_{T0})}{\sqrt{1-|V_{T0}|^2} \cos v_1 \frac{\pi^2 f}{c_2} \left(\frac{Z_2}{2Z_1} + \frac{Z_1}{2Z_2} \right)}}, \quad (4.22)$$

where for this case: Z_1 —acoustic air resistance; f —frequency of ultrasonic oscillations; ρ_2 —volume density of the thread; $|V_{T0}|$ —the modulus of the complex reflection coefficient, which is proportional to the amplitude ratio of the reflected ultrasonic waves to the incident ones received by the first sensor; v_1 —the angle between the direction of the waves bypassing the thread, without hitting the first sensor, and its surface; $K_{\rho 2}$ —the coefficient of the thread material, characterizing the income of the reflected ultrasonic signal to the first receiving sensor, depending on the internal (interfiber) structure of the thread.

If we take into account that for air and the material of the thread the following inequation is true $Z_1 \ll Z_2$, then expression (4.21) can be shown as:

$$r = \frac{2Z_1 K_{\rho 2}}{\pi^2 f \rho_2 \cdot \sqrt{\frac{1}{|V_{T0}|^2} - 1} \cdot \cos v_1}, \quad (4.23)$$

dependence (4.19) taking into account the amplitude of ultrasonic waves reflected from the textile and coming to the second sensor, can be represented as follows:

$$\delta_{T0} = P_0 \cdot \left(R + \frac{2Z_1 K_{\rho 4}}{\pi^2 f \rho_2 \cdot \sqrt{\frac{1}{|V_T|^2} - 1} \cdot \cos v_2} \right) \times \left(\frac{P_0 2Z_1 K_{\rho 4}}{\pi^2 f \rho_2 \cdot \sqrt{\frac{1}{|V_T|^2} - 1} \cdot \cos v_2} + E_1 b_k \left(R + \frac{2Z_1 K_{\rho 4}}{\pi^2 f \rho_2 \cdot \sqrt{\frac{1}{|V_T|^2} - 1} \cdot \cos v_2} \right)^2 \right)^{-1}, \quad (4.24)$$

where $|V_T|$ —the modulus of the complex reflection coefficient, which is proportional to the amplitude ratio of the reflected ultrasonic waves to the incident ones received by the second sensor; v_2 —the angle between the direction of the waves bypassing

the thread without hitting the second sensor and its surface; $K_{\rho 4}$ —the coefficient of the thread material, characterizing the income of the reflected ultrasonic signal to the second receiving sensor, depending on the internal (interfiber) structure of the thread.

Tension P_1 considering (4.23) can be shown as:

$$P_1 = P_0 + \frac{\left(R + \frac{2Z_1 K_{\rho 2}}{\pi^2 f \rho_2 \cdot \sqrt{\frac{1}{|V_{T0}|^2} - 1 \cdot \cos v_1}} \right) (e^{\mu_T \varphi_T} - 1)}{R + \frac{2Z_1 K_{\rho 2} (1 - \delta_{T0})}{\pi^2 f \rho_2 \cdot \sqrt{\frac{1}{|V_{T0}|^2} - 1 \cdot \cos v_1}}} \times \left(P_0 - B_0 \cdot \left(2 \cdot \left(R + \frac{2Z_1 K_{\rho 2} (1 - \delta_{T0})}{\pi^2 f \rho_2 \cdot \sqrt{\frac{1}{|V_{T0}|^2} - 1 \cdot \cos v_1}} \right)^2 \right)^{-1} \right). \quad (4.25)$$

Given (4.24), (4.25) and $K_{\rho 1}$, $K_{\rho 3}$ —the coefficients of the thread material and its position, characterizing the income of the reflected ultrasonic signal to the first and second receiving sensors in accordance with the external structure of the thread, it is possible to write the dependency that will link the thread tension with the amplitude of waves reflected from the textile material. In general, this expression determines the tension of the leading branch of the yarn by the amplitude ratios of ultrasonic waves reflected from the fibers of the material to the waves that only fall on it when interacting with the working bodies of knitting machines, can be presented as follows:

$$P_1 = P_0 + \left(R + \frac{2Z_1 K_{\rho 2}}{\pi^2 f \rho_2 \cdot \sqrt{\left(\frac{K_{\rho 1}}{|V_{T0}|} \right)^2 - 1 \cdot \cos v_1}} \right) (e^{\mu_T \varphi_T} - 1) \times \left(R + 2Z_1 K_{\rho 2} \left(1 - P_0 \cdot \left(R + \frac{2Z_1 K_{\rho 4}}{\pi^2 f \rho_2 \cdot \sqrt{\left(\frac{K_{\rho 3}}{|V_T|} \right)^2 - 1 \cdot \cos v_2}} \right) \right) \times \left(\frac{P_0 2Z_1 K_{\rho 4}}{\pi^2 f \rho_2 \cdot \sqrt{\left(\frac{K_{\rho 3}}{|V_T|} \right)^2 - 1 \cdot \cos v_2}} + E_1 b_k \right) \times \left(R + \frac{2Z_1 K_{\rho 4}}{\pi^2 f \rho_2 \cdot \sqrt{\left(\frac{K_{\rho 3}}{|V_T|} \right)^2 - 1 \cdot \cos v_2}} \right)^2 \right)^{-1} \times \left(\frac{1}{\pi^2 f \rho_2 \cdot \sqrt{\left(\frac{K_{\rho 1}}{|V_{T0}|} \right)^2 - 1 \cdot \cos v_1}} \right)^{-1} \cdot (P_0 - B_0 \cdot 2^{-1})$$

$$\begin{aligned}
& \times \left(R + 2Z_1 K_{\rho 2} \left(1 - P_0 \cdot \left(R + \frac{2Z_1 K_{\rho 4}}{\pi^2 f \rho_2 \cdot \sqrt{\left(\frac{K_{\rho 3}}{|V_T|} \right)^2 - 1} \cdot \cos v_2} \right) \right. \right. \\
& \times \left(\frac{P_0 2Z_1 K_{\rho 4}}{\pi^2 f \rho_2 \cdot \sqrt{\left(\frac{K_{\rho 3}}{|V_T|} \right)^2 - 1} \cdot \cos v_2} + E_1 b_k \right. \\
& \times \left. \left. \left(R + \frac{2Z_1 K_{\rho 4}}{\pi^2 f \rho_2 \cdot \sqrt{\left(\frac{K_{\rho 3}}{|V_T|} \right)^2 - 1} \cdot \cos v_2} \right)^2 \right)^{-1} \right) \cdot \frac{1}{\pi^2 f \rho_2 \cdot \sqrt{\left(\frac{K_{\rho 1}}{|V_{T0}|} \right)^2 - 1} \cdot \cos v_1} \right)^{-2} \Bigg) \quad (4.26)
\end{aligned}$$

In practice, the sensor delicacy to the reflected ultrasonic waves from the material's thread will be low. The coefficients $K_{\rho 1}$, $K_{\rho 3}$ (ultrasonic wave scattering coefficients depending on the external thread structure and its position), $K_{\rho 2}$, $K_{\rho 4}$ (ultrasonic wave scattering coefficients depending on the interfiber thread structure and its position) affect the resulting reflected signal. It is clear that for such cases it is necessary to use ultrasonic waves that pass through the fibers of the material, as well as those that bypass the thread itself. To increase the sensitivity of the sensors, it is advisable to use waveguides to determine the threads' tension on different knitting machines. Therefore, for operational technological control of thread tension, the amplitude method can be used, which allows changing the amplitude of ultrasonic waves in the waveguide to determine the tension of threads with high linear density in textile fabrics production.

The dependence for determining the tension of the leading branch of the thread by the amplitude ratios of the ultrasonic waves passing the material to the waves that just fall on it, taking into account the scattering of waves reflected by the change in the modulus $|W_{T3}|$, can be presented similarly to expression (4.25) as:

$$\begin{aligned}
P_1 = P_0 + & \frac{\left(R + \frac{2Z_1 \cdot \sqrt{\frac{1}{|W_{T3}|^2} - 1}}{\pi^2 f \rho_2 \cdot \cos v_3} \right) \cdot (e^{\mu_T \varphi_T} - 1)}{R + \frac{2Z_1 \cdot \sqrt{\frac{1}{|W_{T3}|^2} - 1} \cdot (1 - \delta_{T0})}{\pi^2 f \rho_2 \cdot \cos v_3}} \\
& \times \left(P_0 - B_0 \cdot \left(2 \cdot \left(R + \frac{2Z_1 \cdot \sqrt{\frac{1}{|W_{T3}|^2} - 1} \cdot (1 - \delta_{T0})}{\pi^2 f \rho_2 \cdot \cos v_3} \right)^2 \right)^{-1} \right), \quad (4.27)
\end{aligned}$$

where $|W_{T3}|$ —the modulus of the complex transmittance, which is proportional to the amplitude ratio of the ultrasonic waves passing through the fibers of the thread material to the waves that only fall on it, taking into account the attenuation and scattering of the waves; v_3 —the angle between the direction of the waves bypassing the thread and its surface.

To determine the diameter of the thread d or its radius r using ultrasonic waves that have passed through the material, and waves that bypass the thread itself, you can use the following expressions:

$$d = \frac{4Z_1 \cdot \sqrt{\frac{1}{|W_{T3}|^2} - 1}}{\pi^2 f \rho_2 \cdot \cos v_3}, \text{ or } r = \frac{2Z_1 \cdot \sqrt{\frac{1}{|W_{T3}|^2} - 1}}{\pi^2 f \rho_2 \cdot \cos v_3}. \quad (4.28)$$

In general, considering expressions (4.19), (4.27) and (4.28), we can represent the dependence for the tension P_1 of the leading branch of the thread as follows:

$$\begin{aligned} P_1 = & P_0 + \left(R + \frac{2Z_1 \cdot \sqrt{\frac{1}{|W_{T3}|^2} - 1}}{\pi^2 f \rho_2 \cdot \cos v_3} \right) (e^{\mu_T \varphi_T} - 1) \\ & \times \left(R + 2Z_1 \left(1 - P_0 \cdot \left(R + \frac{2Z_1 \cdot \sqrt{\frac{1}{|W_{T3}|^2} - 1}}{\pi^2 f \rho_2 \cdot \cos v_3} \right) \right. \right. \\ & \times \left(\frac{P_0 2Z_1 \cdot \sqrt{\frac{1}{|W_{T3}|^2} - 1}}{\pi^2 f \rho_2 \cdot \cos v_3} + E_1 b_k \right. \\ & \times \left. \left. \left(R + \frac{2Z_1 \cdot \sqrt{\frac{1}{|W_{T3}|^2} - 1}}{\pi^2 f \rho_2 \cdot \cos v_3} \right)^2 \right)^{-1} \right) \cdot \frac{\sqrt{\frac{1}{|W_{T3}|^2} - 1}}{\pi^2 f \rho_2 \cdot \cos v_3} \Bigg)^{-1} \\ & \times \left(P_0 - \frac{B_0}{2} \cdot \left(R + 2Z_1 \left(1 - P_0 \cdot \left(R + \frac{2Z_1 \cdot \sqrt{\frac{1}{|W_{T3}|^2} - 1}}{\pi^2 f \rho_2 \cdot \cos v_3} \right) \right. \right. \right. \\ & \times \left(\left(P_0 2Z_1 \cdot \sqrt{\frac{1}{|W_{T3}|^2} - 1} \right) \cdot (\pi^2 f \rho_2 \cdot \cos v_3)^{-1} + E_1 b_k \right. \\ & \times \left. \left. \left(R + \frac{2Z_1 \cdot \sqrt{\frac{1}{|W_{T3}|^2} - 1}}{\pi^2 f \rho_2 \cdot \cos v_3} \right)^2 \right)^{-1} \right) \cdot \frac{\sqrt{\frac{1}{|W_{T3}|^2} - 1}}{\pi^2 f \rho_2 \cdot \cos v_3} \Bigg)^{-2}. \end{aligned} \quad (4.29)$$

In practice, to increase the sensitivity of ultrasonic waves to changes in the diameter of the thread, it is advisable to use low-power sensors and corresponding waveguides. Waveguides with a rectangular cross section are quite effective.

Figures 4.13, 4.14, 4.15, 4.16, 4.17, 4.18, 4.19, 4.20, 4.21 and 4.22 shows graphs and surfaces that reflect the dependence of the amplitude ratios of ultrasonic waves $|W_{T3}|$ on the tension of the trailing P_0 and leading P_1 branches of the thread for cotton materials (Figs. 4.13, 4.14), viscose threads (Figs. 4.15, 4.16), capron threads (Figs. 4.17, 4.18), wool (Figs. 4.19, 4.20). Figure 4.21 shows a comparison of surfaces

for different materials, considered separately in Figs. 4.13b; 4.15b; 4.17b; 4.19b, reflecting the dependence of the amplitude ratios of ultrasonic waves $|W_{T3}|$ on the conventional radius of the thread r and the parameter $\cos \nu_3$, that shows the effect of some waves bypassing the thread and its fibers (if there is a large interfiber porosity). Figure 4.22 shows a comparison of the surfaces of the dependences $|W_{T3}|$ on the tension of the P_0 trailing and P_1 leading branches of the thread for different materials, considered separately in Figs. 4.14; 4.16; 4.18; 4.20. It should be noted that Figs. 4.21 and 4.22 show surfaces for different materials (cotton, viscose threads, capron threads, wool), which reflect the dependence of those ultrasonic waves amplitudes that mainly bypass the thread (because it is the biggest part of the ultrasonic signal, at which the amplitude detector of determining the thread tension detects a voltage that is proportional to the amplitude of the waves received by the sensor). The part of the ultrasonic signal that passes directly through the structure of the thread itself can also be used to determine changes in the interfiber threads' porosity. This effect of determining the change in interfiber porosity in the process of thread tension is also considered in the work and experimentally recorded using ultrasonic pulse signals of complex shape. Ultrasonic wave packets with two different amplitude peaks must be used to determine changes in interfiber porosity and thread tension.

From Figs. 4.13, 4.14, 4.15 and 4.16, you can see how the modulus of the complex transmittance $|W_{T3}|$ changes, which is proportional to the amplitude ratio of ultrasonic waves (the ratio of waves passing and bypassing the fibers of the thread to the waves that just fall on it), from the tension of the P_0 trailing and P_1 leading branch of the threads for cotton and viscose, as well as from the parameters $\cos \nu_3$, and conventional radius r of these textile materials.

Figures 4.13a and 4.15a show how the modulus of the complex coefficient of transmission $|W_{T3}|$ changes depending on the change in interfiber porosity and increase in volume density ρ_2 of cotton and viscose textile materials, which affects the change in tension of the P_1 leading branch of the thread at $P_0 = 10$ cN.

The diagrams show that at almost the same amplitude of ultrasonic waves, the tension P_1 for cotton yarn will be bigger than the value of this parameter for viscose yarn with different interfiber porosity, which affects the volume density ρ_2 of the material. The dependences of the module $|W_{T3}|$ on the parameters $\cos \nu_3$, that take into account most of the ultrasonic waves that bypass the thread and the conventional radius of these textile materials are shown in Figs. 4.13b and 4.15b. From these surfaces, it can be seen that as the parameter $\cos \nu_3$ decreases, the part of the waves that bypass the thread increases together with the module $|W_{T3}|$, while the amplitude of the waves is simultaneously affected by the change in interfiber porosity, which can change from thread twisting and its tension in the production of the knitted fabric.

In the course of research it has also been determined that when changing the conventional diameters of threads for the considered materials (diameters: $d = 0.22$ mm for cotton yarn with a linear density of 27.6 tex; $d = 0.17$ mm for viscose thread with a linear density of 16.7 tex), the amplitude of the waves can change in a certain range (Figs. 4.14 and 4.16). From the dependence surfaces of the module $|W_{T3}|$, it is seen that the amplitude of the waves changes more at the same tension P_1 for viscose.

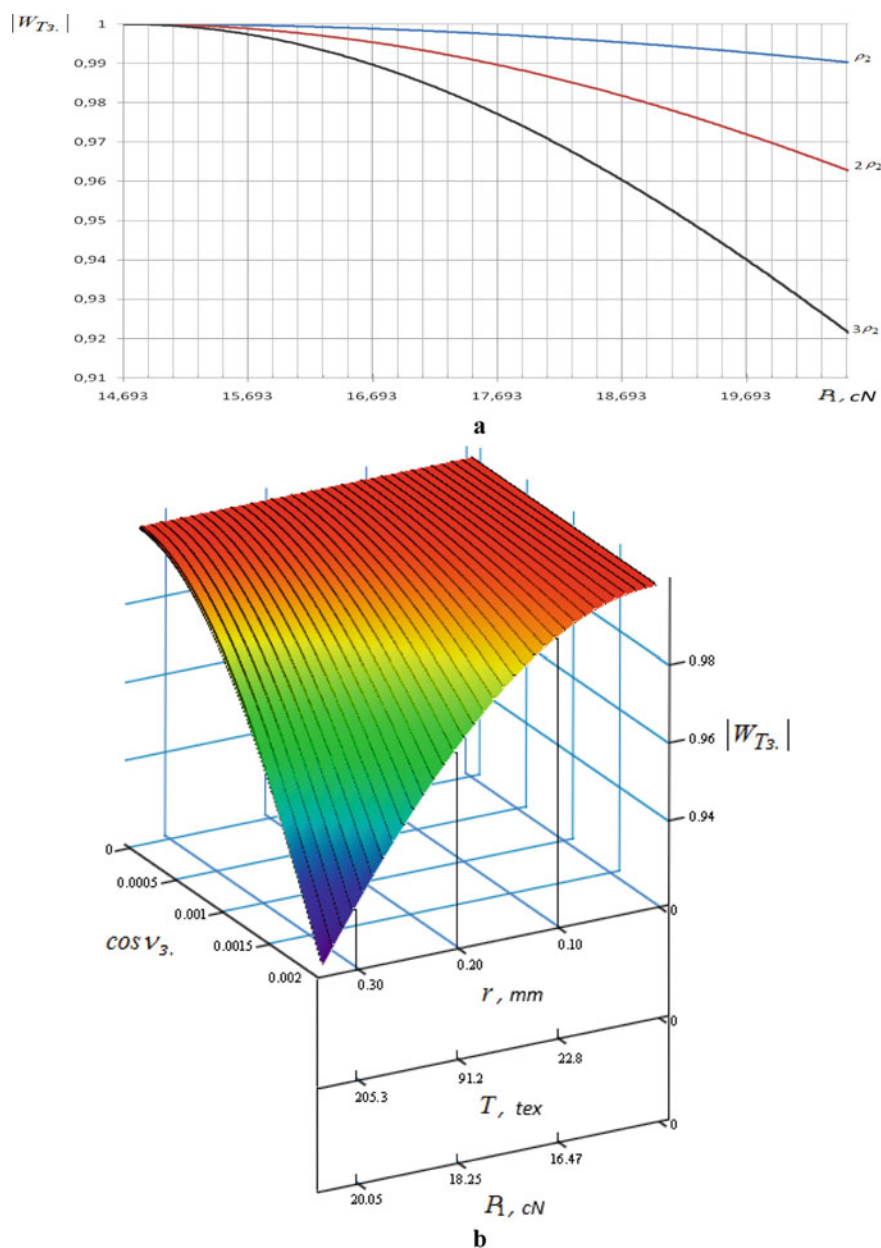


Fig. 4.13 Dependences $|W_{T3}|$ from tension P_1 , cN of cotton yarn at $P_0 = 10$ cN: **a** change $|W_{T3}|$ from tension P_1 , cN of the leading branch of cotton yarn at different ρ_2 ; **b** change surface $|W_{T3}|$ from r , mm and parameter $\cos v_3$ for cotton

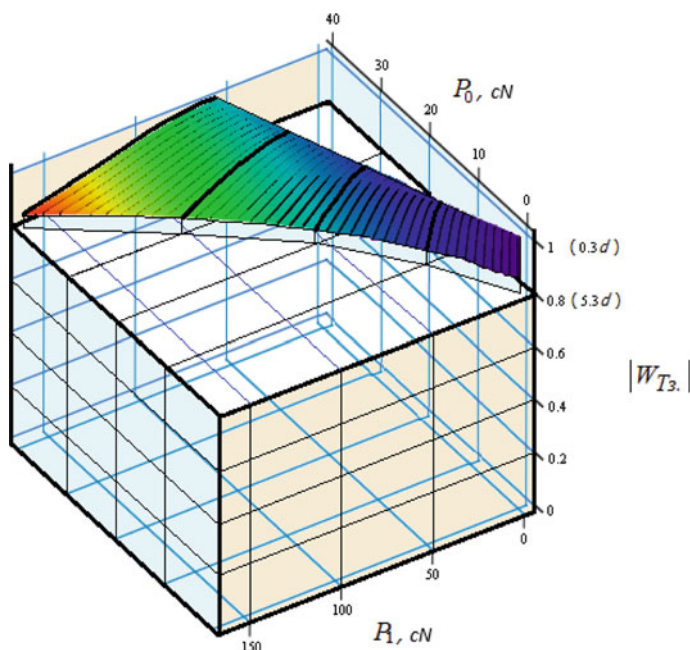


Fig. 4.14 Module change surface $|W_{T3}|$, proportional to the amplitude of the ultrasonic waves passing through the space with textile fibers, from the tension P_1 , cN and from tension P_0 , cN for cotton material when changing its considered conventional diameter from $0.3d$ to $5.3d$

From Figs. 4.17, 4.18, 4.19 and 4.20 it can be seen how the modulus of the complex coefficient of transmittance $|W_{T3}|$ changes from the tension of the P_0 trailing and P_1 leading branches of the thread for capron and wool, as well as from the parameters $\cos \nu_3$ and conventional radius r of these textile materials.

Figures 4.17a and 4.19a show how the modulus of the complex transmittance $|W_{T3}|$ changes depending on the change in interfiber porosity and increase in volume density ρ_2 of capron and wool textile materials, which affects the change in tension of the P_1 leading branch of the thread at $P_0 = 10$ cN. It can be seen from the diagrams that at almost the same amplitude of ultrasonic waves, the tension P_1 for the capron yarn will be much higher than the value of this parameter for woolen yarn with different interfiber porosity, which affects the volume density ρ_2 of the material.

The dependences of the module $|W_{T3}|$ on the parameters $\cos \nu_3$, that consider most of the ultrasonic waves that bypass the thread and the conventional radius r of these textile materials are shown in Figs. 4.17b and 4.19b. From these surfaces, it can be seen that at the same conventional radii r of the capron thread and woolen yarn, the amplitude of the waves that have passed through the space with the fibers will be lower for the first textile material.

It has been determined that when changing the conventional diameters of threads for the considered materials (diameters: $d = 0.2$ mm for capron thread with a linear

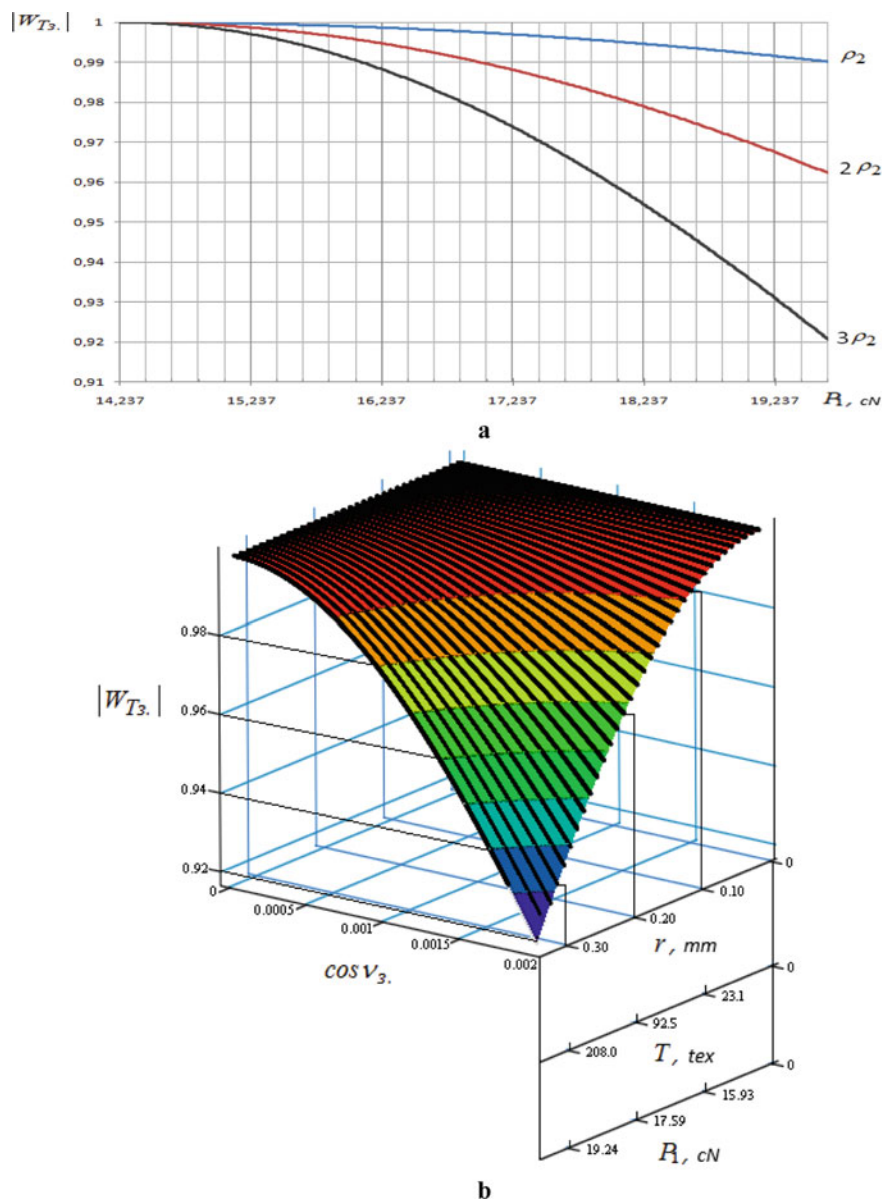


Fig. 4.15 Dependences $|W_{T3}|$ from tension P_1, cN of viscose threads at $P_0 = 10 cN$: **a** change $|W_{T3}|$ from tension P_1, cN of the leading branch of viscose threads at different ρ_2 ; **b** surface change $|W_{T3}|$ from r, mm and parameter $\cos v_3$ for viscose threads

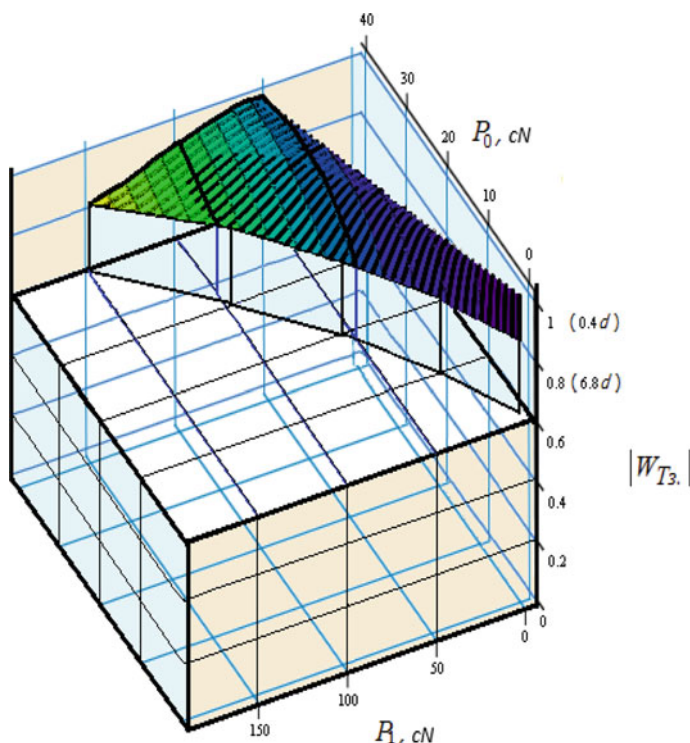


Fig. 4.16 Module change surface $|W_{T3}|$, proportional to the amplitude of the ultrasonic waves passing through the space with textile fibers, from the tension P_1 , cN and from tension P_0 , cN for viscose material when changing its considered conventional diameter from $0.4d$ to $6.8d$

density of 28 tex; $d = 0.23$ mm for wool yarn with a linear density of 29.9 tex), the amplitude of the waves can change in a certain range with tension P_1 in the range from 0 to 130 cN and from 0 to 110 cN (Figs. 4.18 and 4.20).

From the surfaces of the module $|W_{T3}|$ dependence, it is seen that the amplitude of the waves changes more at the same tension P_1 for wool.

In Fig. 4.21. shows a comparison of modulus $|W_{T3}|$ change surfaces from r , mm and $\cos v_3$, and Fig. 4.22 shows a comparison of change $|W_{T3}|$ from tension P_1 , cN and from tension P_0 , cN for textile materials of cotton, viscose, capron, and wool.

Figure 4.21 from the comparison of surfaces shows that the change of modulus $|W_{T3}|$ from r and $\cos v_3$ differs considerably for capron threads in comparison with cotton, viscose, woolen textile materials, which are similar in the parameter value. If we compare the surfaces shown in Fig. 4.22, the highest amplitude of the waves interacting with the thread decreases for wool and has a greater sensitivity to small changes in the tension P_1 of the thread and the smallest range for its determination. The lowest sensitivity of waves to changes in their amplitude to a small change in the tension P_1 of the thread can be attributed to the cotton material and the largest range for its determination, due to both technological and useful measurement information

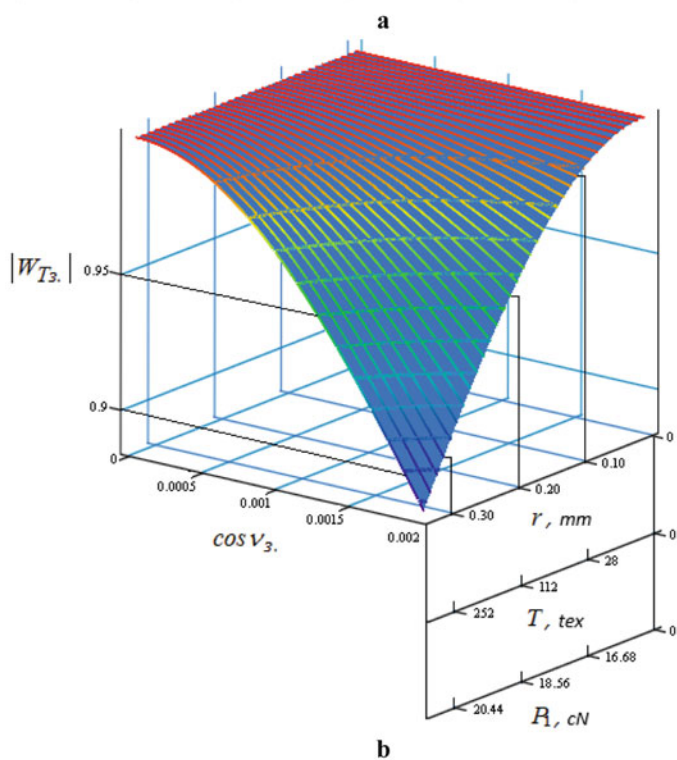
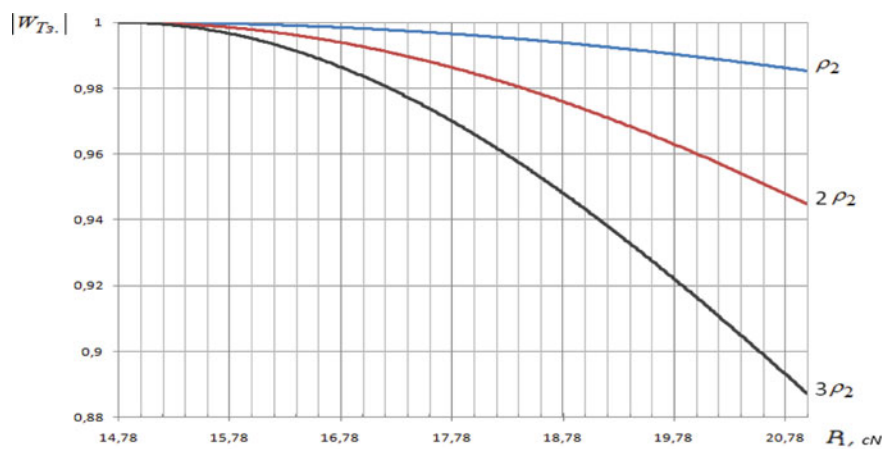


Fig. 4.17 Dependences $|W_{T3}|$ from tension P_1 , cN of capron threads at $P_0 = 10$ cN: **a** change $|W_{T3}|$ from tension P_1 , cN of the leading branch of capron threads at different ρ_2 ; **b** surface change $|W_{T3}|$ from r , mm and parameter $\cos v_3$ for capron threads

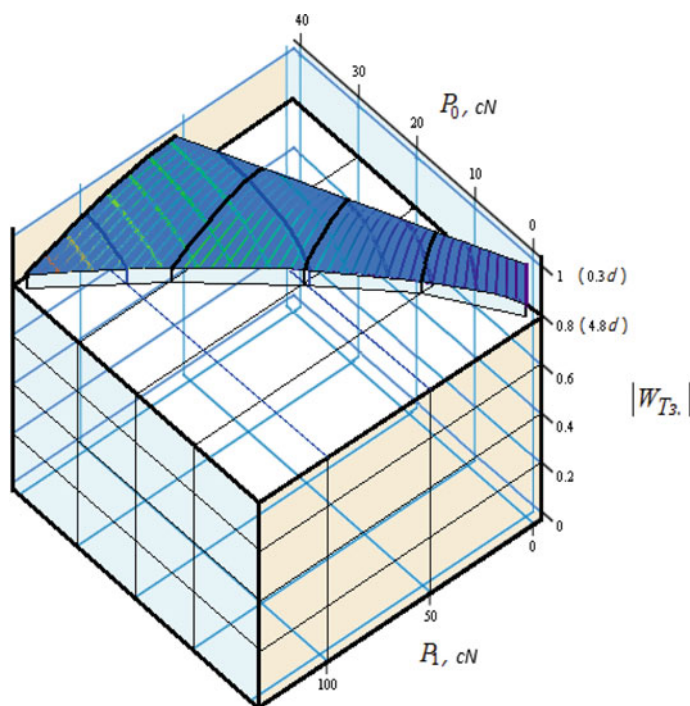


Fig. 4.18 Module change surface $|W_{T3}|$, proportional to the amplitude of the ultrasonic waves passing through the space with textile fibers, from the tension P_1 , cN and from tension P_0 , cN for capron material when changing its considered conventional diameter from $0.3 d$ to $4.8 d$

using non-contact ultrasonic sensors (refers to extensions of the determination range of tension P_1 using the amplitude method). These surfaces will simplify the obtained expressions describing the correlation of ultrasonic waves with textile material during its sounding. This will simplify the task of practical implementation of non-contact means of thread tension control using special waveguides.

The research has shown that with the help of pulsed ultrasonic signals it is possible to determine not only the tension of threads with high linear density but also the degree of complex threads twisting by changing their interfiber porosity. Simultaneously, the interfiber porosity and the change in threads' tension can be determined using ultrasonic wave packets with different peak amplitudes. With increasing the first peak amplitude of the ultrasonic signal of complex shape it is possible to make a conclusion about the increase in tension and decrease the conventional diameter of the thread according to the surfaces shown in Fig. 4.21, and with decreasing the second peak of the ultrasonic signal—about decreasing interfiber porosity.

To implement such non-contact control methods of tension of different textile threads it is necessary to use switching and modulation means.

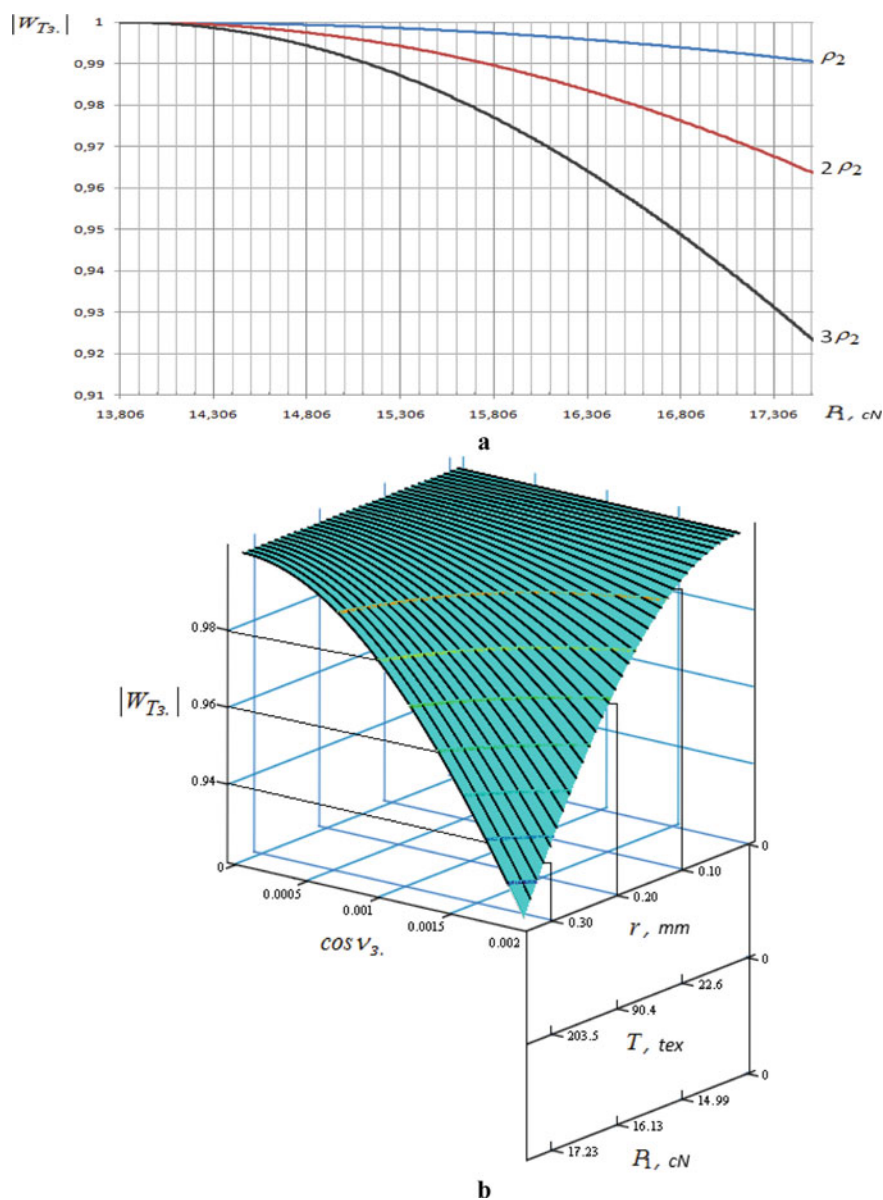


Fig. 4.19 Dependences $|W_{T3}|$ from tension P_1 , cN of woolen yarn at $P_0 = 10$ cN: **a** change $|W_{T3}|$ from tension P_1 , cN of the leading branch of woolen yarn at different ρ_2 ; **b** surface change $|W_{T3}|$ from r , mm and parameter $\cos v_3$ for wool

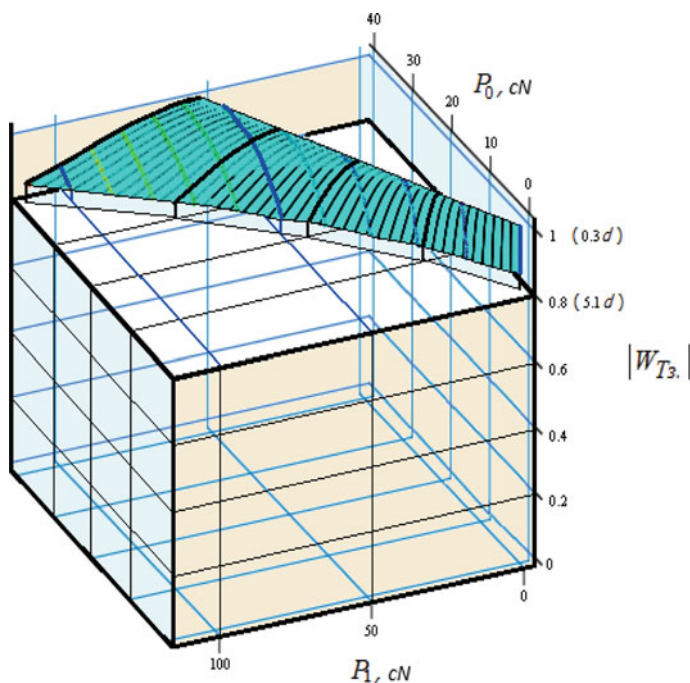


Fig. 4.20 Module change surface $|W_{T3}|$, proportional to the amplitude of the ultrasonic waves passing through the space with textile fibers, from the tension P_1 , cN and from tension P_0 , cN for woolen material when changing its considered conventional diameter from $0.3d$ to $5.1d$

4.3 Development of a Reference Amplitude Method for Determining the Tension of Threads with High Linear Density, Textile Ribbons and Fabrics

To be able to control the tension of high-density threads, textile ribbons, and fabrics by changing the tension of their fibers, you can also use the amplitude of ultrasonic waves that pass them in the longitudinal direction. At the same time, it is necessary to realize contact of converters with textile material for the best transfer of an ultrasonic signal. In this case, there will be the scattering of ultrasonic waves and their attenuation in the fiber material and the environment of interfiber pores with the conversion of part of the sound energy into heat. As the tension of the textile material increases, the elementary fibers in it begin to be uniformly arranged in the structure of the ribbon or threads, gradually straightening. This leads to an increase in the propagation speed of ultrasonic waves in the structure of the fibers themselves and in increased amplitudes of oscillations, which begin to propagate longitudinally along the fibers of the material as waveguides. The amplitude of ultrasonic waves is affected by the coefficient of their attenuation in the structure of the material (the coefficient

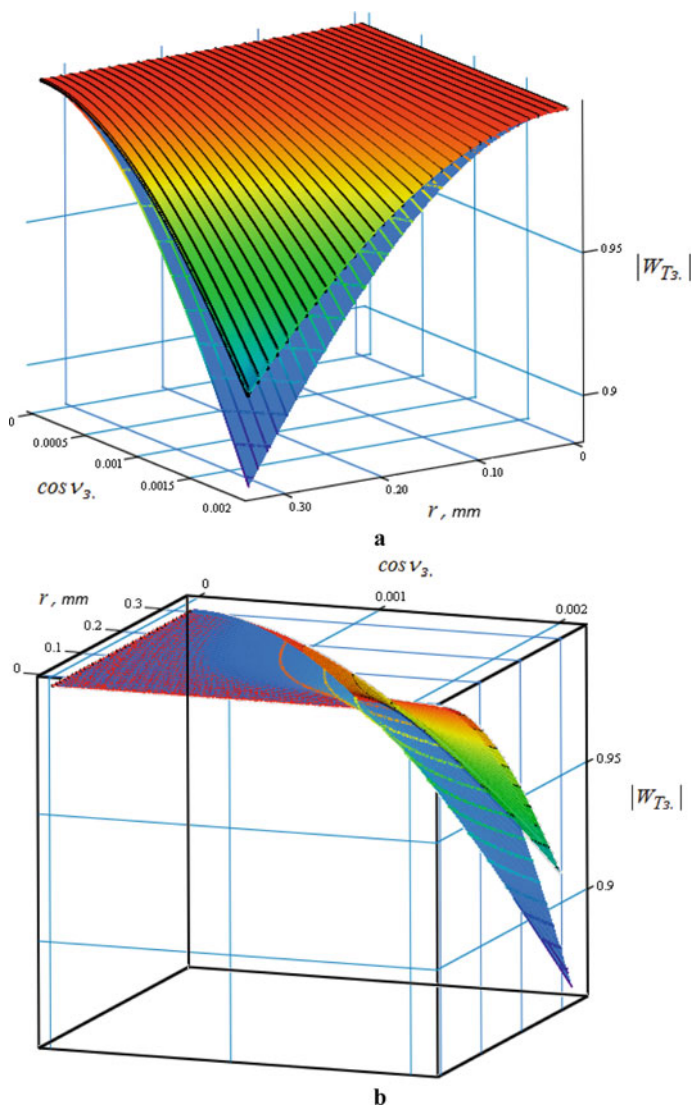


Fig. 4.21 Comparison of changes $|W_{T3}|$ for r , mm and $\cos v_3$. for different materials: **a** dependences $|W_{T3}|$ from r , mm and $\cos v_3$, for the considered materials, top view; **b** dependences $|W_{T3}|$ for r , mm and $\cos v_3$, for the considered materials, bottom view:

depends on the order of the fibers when the textile is stretched), which decreases with the amplitude increase.

This, with regard to the longitudinal sounding of textile materials (threads of fabrics, textile ribbons, and single threads with a high linear density) by the contact method, can be used for the reference definition of the material's tension. This will

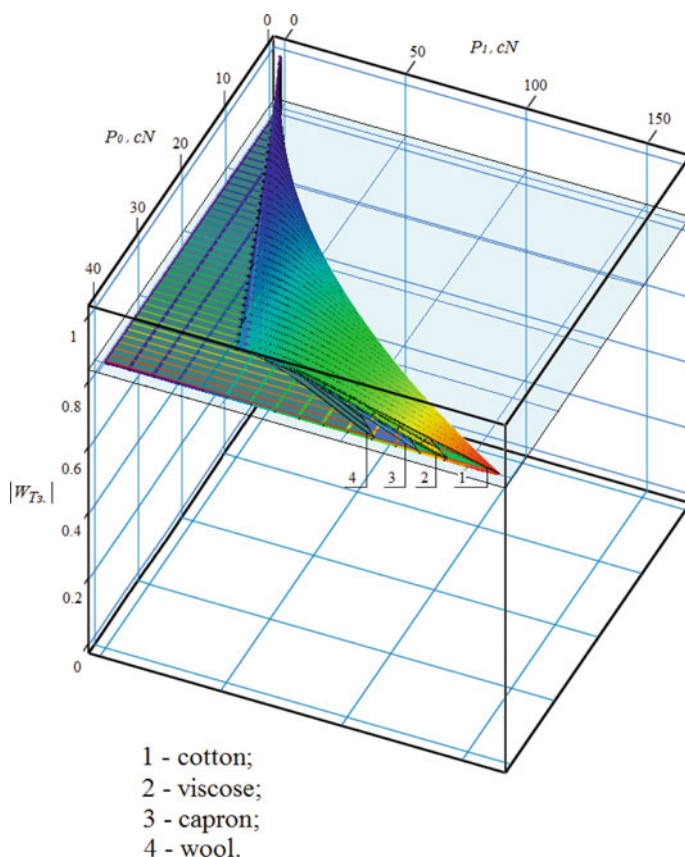


Fig. 4.22 Comparison of module changes $|W_{T3}|$, proportional to the amplitude of the ultrasonic waves passing through the space with textile fibers, from the tension P_1 , cN and from tension P_0 , cN for the considered materials

then make it possible to compare the obtained tension values with the determined values by a non-contact control system of textile materials with transverse textile sounding. Since the ultrasonic wave interacts with more material during the longitudinal sounding of the textile fibers than during its transverse sounding, the sensitivity of the change in amplitude to the change in the tension of the fibers also increases. Therefore, to adjust the ultrasonic sensor with a converter, which will be included in such a reference channel of the contactless tension control system of textile material, it is advisable to use the values of the amplitudes of the waves obtained by the longitudinal sounding of textiles. The difference in the transverse sounding of the material from the longitudinal is that in the second case, the value $\cos \nu_3 \approx 1$ when straightening the textile fibers, increasing the tension and decreasing the interfiber porosity. As the textile tension decreases, the value of the attenuation coefficient α_3 of the wave amplitude in the material increases, and $\cos \nu_3 < 1$ and it will decrease

within certain limits in the presence of significant interfiber distances. A similar effect can be observed in the transverse sounding of a multilayer textile material with a significant thickness and small pores in its structure [24–30].

Let us show the expression of the modulus of the complex transmission coefficient $|W_{lp}|$ of probing ultrasonic waves that have passed the textile material, taking into account the values $\alpha_{3.}$, $\cos \nu_{3.}$ and basis weight of the fiber mass m_s , as follows:

$$|W_{lp}| = \frac{1}{\sqrt{\left(1 + \alpha_{3.} \frac{c_2}{\rho_1 c_1} \cdot \frac{K m_s \cos \nu_{3.}}{2\pi}\right)^2 + \left(\frac{K m_s f \cos \nu_{3.}}{\rho_1 c_1}\right)^2}}. \quad (4.30)$$

If the interfiber distances in the textile material are small enough, then by associating expression (4.30) with the width $B_{m.}$ and linear density $T_{m.}$ of the material, we can show the modulus of the complex coefficient of longitudinal transmission of waves as follows:

$$|W_{lp}| = \frac{1}{\sqrt{\left(1 + \alpha_{3.} \frac{c_2 T_{m.}}{2\pi \rho_1 c_1 B_{m.}}\right)^2 + \left(\frac{T_{m.} f}{B_{m.} \rho_1 c_1}\right)^2}}. \quad (4.31)$$

Due to the fact that the attenuation coefficient of waves $\alpha_{3.}$ varies depending on the tension of the textile controlled material (from the change of elementary fibers orientation in its structure), let us write it approximately as the product of the initial attenuation coefficient $\alpha_{03.}$ of waves and the ratio of initial tension to its final $P_{n.}/P_{\kappa.}$ value:

$$\alpha_{3.} \approx \alpha_{03.} \frac{P_{n.}}{P_{\kappa.}}. \quad (4.32)$$

Substituting the dependence (4.32) in (4.31) let us show the modulus of the complex coefficient of ultrasonic waves transmission as:

$$|W_{lp}| = \frac{1}{\sqrt{\left(1 + \alpha_{03.} \frac{P_{n.} c_2 T_{m.}}{2\pi P_{\kappa.} \rho_1 c_1 B_{m.}}\right)^2 + \left(\frac{T_{m.} f}{B_{m.} \rho_1 c_1}\right)^2}}. \quad (4.33)$$

From the last expression, it is possible to determine the speed of ultrasonic waves in a textile material, which can vary depending on the change in the fibers straightening and their approximation to the elementary waveguide by the propagation of oscillations along with them. The value of this wave speed can be given as follows:

$$c_2 = \frac{2\pi P_{\kappa.} \rho_1 c_1 B_{m.} \cdot \left(\sqrt{\frac{1}{|W_{lp}|^2} - \left(\frac{T_{m.} f}{B_{m.} \rho_1 c_1}\right)^2} - 1\right)}{\alpha_{03.} P_{n.} T_{m.}}, \quad (4.34)$$

and the current final tension of the textile material can then be defined as:

$$P_{\kappa.} = \frac{\alpha_{03.} P_n. c_2 T_m.}{2 \pi \rho_1 c_1 B_m. \cdot \left(\sqrt{\frac{1}{|W_{lp}|^2}} - \left(\frac{T_m. f}{B_m. \rho_1 c_1} \right)^2 - 1 \right)}. \quad (4.35)$$

Figure 4.23 shows the dependence of the change in wave velocity c_2 on the tension $P_{\kappa.}$ of materials and their linear density $T_m.$, and Fig. 4.24 shows the dependence surface of the change in modulus $|W_{lp}|$ on the change in tension $P_{\kappa.}$ and linear density $T_m.$ of the material.

Figure 4.23, a shows that with rising the textile material tension $P_{\kappa.}$ the speed c_2 of ultrasonic waves propagation in the middle of the structure of such textiles increases respectively. In textiles with a higher linear density $T_m.$, the speed of ultrasonic waves propagation c_2 will be lower than the value of this parameter in the material with a lower linear density at the same tension $P_{\kappa.}$ Figure 4.23b shows that the speed of ultrasonic waves in the structure of the textile decreases with increasing linear density $T_m.$ of the material and with less tension $P_{\kappa.}$ Also, a comparison of the diagrams with Figs. 4.23a and 4.23, b shows that greater interfiber porosity can reduce the wave speed c_2 in the textile material during its longitudinal sounding.

Figure 4.24 shows the dependence surface of the change in the modulus $|W_{lp}|$ of longitudinal passing of ultrasonic waves through the textile material on the change in tension $P_{\kappa.}$ and linear density $T_m.$ of the material. It is shown that with an increasing linear density $T_m.$ of textile material the amplitude of probing waves, which is proportional to the modulus $|W_{lp}|$, will decrease, and with increasing textile tension $P_{\kappa.}$, on the contrary, the amplitude will increase.

The analysis shows that the longitudinal sounding makes it possible to further use such a parameter of ultrasonic waves as changing the speed c_2 of probing oscillations in the structure of the textile. According to this parameter and the amplitude of the ultrasonic waves, it is possible to determine the additional tension $P_{\kappa.}$ of the textile material within certain limits.

In general, longitudinal sounding should be used in the reference comparison of a certain value of the textile fabrics tension with the values obtained by the non-contact transverse sounding of the controlled material.

If we consider the non-contact determination of the change in the textile fabric tension during its transverse sounding, the average change of this parameter in a certain area of the material can be determined from the change in the size of the interfiber pores. This change in porosity is caused by a change in the diameters of the threads in the structure of the textile under its tension. In turn, the change in the size of the threads' diameters can be determined by changing the amplitude of the ultrasonic waves reflected from the fabric surface.

When using the range of controlled tension values, within the limits where the dependence of the change in the amplitude of the reflected ultrasonic waves on the threads tension of the fabric itself is characterized by an average value, this dependence can be simplified and shown as follows:

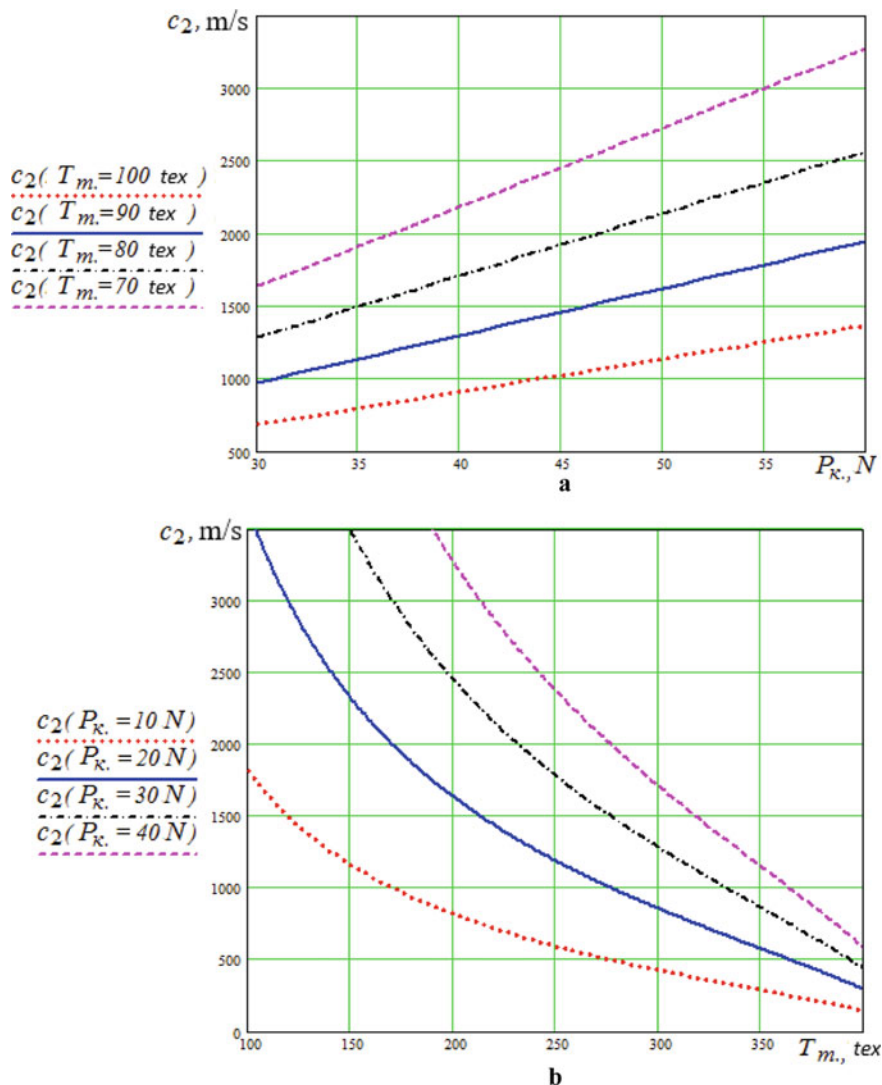


Fig. 4.23 Dependencies of velocity change c_2 ultrasonic waves from tension P_{κ} , different textile materials and their linear density T_m : **a** dependencies c_2 of waves on tension P_{κ} , textile materials with significant interfiber porosity; **b** dependencies c_2 of waves on linear density T_m , textile materials with low interfiber porosity

$$P_{\kappa} = P_n \cdot \left(\frac{|V_{ref.}|}{|V_{0ref.}|} \right)^3. \quad (4.36)$$

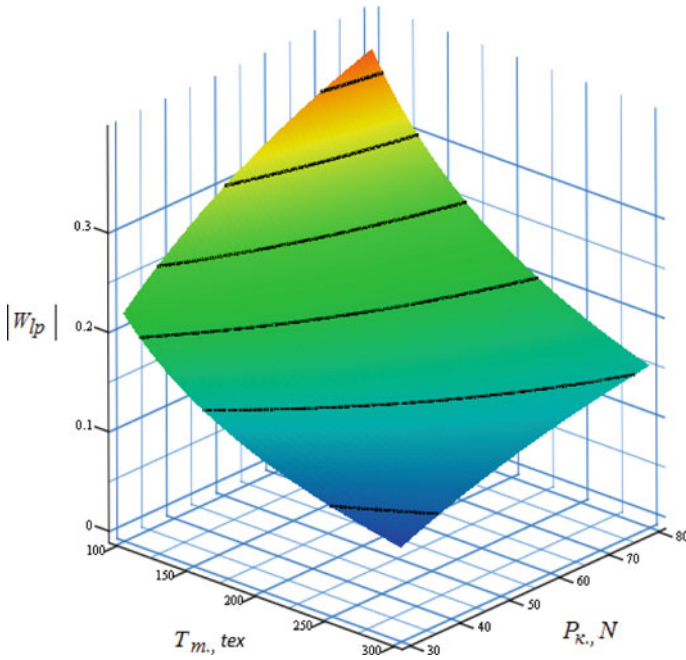


Fig. 4.24 The dependence surface of the module change $|W_{lp}|$ of longitudinal passing of ultrasonic waves through the textile material on the tension change P_k , and linear density T_m , of the material

where $|V_{0ref.}|$ —complex reflection coefficient from a textile single-layer cloth with its initial tension P_n ; $|V_{ref.}|$ —complex reflection coefficient from a textile single-layer cloth at its final tension P_k .

Determining the possible deviation δ_{P_k} of the fabric tension value, which is determined by the transverse sounding of the textile fabric, in comparison with the reference value obtained by longitudinal sounding, can be presented as:

$$\delta_{P_k} = \left(\frac{2 \pi \rho_1 c_1 |V_{ref.}|^3 \cdot \left(\sqrt{\frac{1}{|W_{lp}|^2} - \left(\frac{m_s f}{\rho_1 c_1} \right)^2} - 1 \right)}{\alpha_{03} \cdot c_2 m_s |V_{0ref.}|^3} - 1 \right) \cdot 100\%. \quad (4.37)$$

Considering expression (4.37), it is possible to adjust the non-contact ultrasonic system for determining the tension of a textile single-layer fabric with through pores. This will, in turn, increase the accuracy of non-contact determination of the basis weight of the most controlled fabric, taking into account its tension on different textile machines.

To control textile single-layer cloths with through pores, longitudinal sounding must be realized with the help of a certain number of radiating and receiving converters. Such devices must be specially fixed, so that, if possible, the ultrasonic

waves propagate along the threads of the fabric (for fabrics along the warp and weft threads). Some of the waves will propagate through the threads at a slower speed, which can introduce an error in determining the tension. Therefore, the measurement of the tension of the fabric is influenced by their structure, which makes it difficult to create a universal system for determining this parameter with the longitudinal sounding of threads for different textile fabrics.

Using the dependence (4.35), it is possible to measure the tension for textiles with threads of high linear density and textile ribbons. The difference for transverse sounding is the use of additional waveguides, which will increase the sensitivity of changes in the amplitude of ultrasonic waves to changes in the diameter of the textile material and its tension.

If we control the tension of single threads by non-contact method with the help of special waveguides, it is possible to use the obtained expressions (4.36) and (4.37), which will allow us to change the amplitude of ultrasonic waves interacting with the material, to determine the change in the fiber tension.

For such non-contact control of some threads, it is necessary to apply special concentrating surfaces of sound waves pressure. They will help to determine the average tension of these threads on textile machines in the process of fabric production. It is expedient to adjust such control systems through reference longitudinal sounding of these threads and finding the calibrated values of tension for them.

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Chapter 5

Design of the Models and Methods of Constructing Computerized Control Systems of Technological Parameters of Textile Materials



5.1 Design of the Computerized System of Contactless Control of Technological Parameters of Fabrics in the Production Process

In order to quickly control and maintain the basis weight of textile fabrics within the necessary regulated limits, it is essential to control the tension of the warp threads on the machines where they are produced. When using ultrasonic non-contact methods, to implement this task, an additional reference method of measuring the tension of the threads and the fabric must be used. This reference method enables the determination of the thread tension values at each point of the reference textile fabric and to compare the obtained values with the values that will be determined by non-contact means when scanning the reference and controlled fabrics. Also, the reference method must provide a greater range of thread tension measurement than the non-contact means of measuring this value. This will make it possible to determine the operating range of non-contact means of measuring the tension of textile fabrics and adjust them with a tolerable error. This is done by comparing the measured values obtained by scanning the reference and controlled tissues with the same structure and porosity. When solving the set tasks and taking into account that the porosity of the fabric can affect the ultrasonic waves passing through the canvas and their reflection from the surface of the material, it is necessary to ensure the appropriate constant adjustment of the system. When changing the controlled material, the system must be adjusted, which is associated with a change in the fabric structure, which often affects the change in its porosity [1–7].

The obtained deviations between the readings of the longitudinal (reference) and transverse sounding of the material will first determine the operating range of tension values, which can be used for non-contact control of the fabrics in its production process. This is because the transverse sounding of the material gives less sensitivity to changes in the amplitude of ultrasonic waves to changes in the tension of textile fibers, compared with longitudinal sound. Since only transverse material sounding can be realized by non-contact control, the obtained deviation allows to

further specify the working range of tension, for which non-contact determination of the parameter is possible related to warp threads and textile fabric with the help of ultrasonic waves. The correction of the deviation in temperature and humidity is made to the measured value of the textile material tension in the form of a digital code. The extreme values of the range of measured tension values, which are determined by reference sounding by ultrasonic waves, are compared with the readings of the load weight acting on the reference fabric in the process of tensile test.

Let us present a computerized system for scanning a textile fabric in the process of its weaving with a block of its basic adjustment according to the reference fabric (BBA). This unit implements a reference method of correction of the measured values of textile materials tension obtained using non-contact sensors of the scanning platform of the computerized system. Let us consider the block diagram of a computerized system for scanning textile fabric (Fig. 5.1) in its production process in more detail.

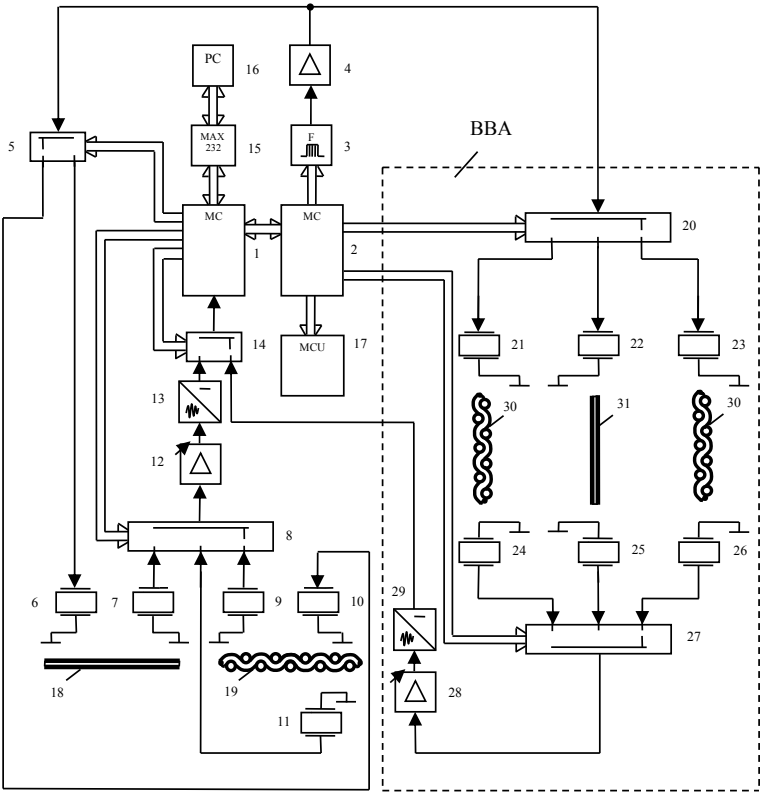


Fig. 5.1 Block diagram of a computerized scanning system for control of technological parameters of fabrics in the production process

Computerized system for scanning textile fabrics consists of: microcontroller 1 (MC 1), microcontroller 2 (MC 2), pulse signal generator 3, amplifier 4, switching unit 5, piezoelectric transducers 6, 7, switching unit 8, piezoelectric transducers 9, 10, 11, adjustable amplifier 12, amplitude detector 13, switching unit 14, logic level conversion chips 15, personal computer 16 (PC 16), motor control unit 17 (MCU 17) for scanning platforms, switching unit 20, piezoelectric transducers 21, 22, 23, 24, 25, 26, switching unit 27, adjustable amplifier 28, amplitude detector 29, controlled warp threads 18, controlled fabric 19, reference fabric 30, reference warp threads 31.

The operation of a computerized system can be described as follows. The pulses of the ultrasonic frequency are sent from MC 2 to the pulse signal generator 3, from its output the voltage pulse packets are sent to the amplifier 4. After amplification, the pulse signal alternately comes through the switching unit 20, then to the piezoelectric transducer 21, or the piezoelectric transducer 22, or to the piezoelectric transducer 23, where it is converted into ultrasonic waves. Switching of the switching unit 20 is controlled by MC 2 according to a certain algorithm. These ultrasonic wave emitters 21, 22, 23 and oscillation receivers 24, 25, 26 belong to the BBA, where the contactless converters of the system are set, through the reference sound of the reference fabric and a number of warp threads comparing the results with data obtained using piezoelectric transducers 6, 7, 9, 10, 11.

The ultrasonic oscillations of the piezoelectric transducer 22 pass longitudinally through a series of reference warp threads, which are stretched by a special device or load, after which they fall on the piezoelectric transducer 25, where they are converted into electrical oscillations. Then they pass through the switching unit 27, which switches MC 2 synchronously with unit 20 to different channels of the material sounding. Next, the electrical oscillations are amplified by the power of the amplifier 28 and detected with conversion into DC voltage U_1 by an amplitude detector 29. This voltage U_1 enters, through the switching unit 14, to MC 1, which controls the switching of the switching unit 14. In MC 1 the converting to digital code N_1 by a ten-bit internal analog-to-digital converter (ADC) of the detected voltage U_1 is performed, which is proportional to the amplitude of the ultrasonic waves passing longitudinally through the reference series of warp threads 31. Taking into account the unit of the smallest least digit r_u ADC MC 1, this code N_1 can be represented as follows:

$$N_1 = \frac{U_1}{r_u} = \frac{K_1 K_2 K_3 K_4 K_5 K_6 K_7}{\sqrt{\left(1 + \alpha_{13} \cdot \frac{P_{noc} C_{oc} T_{oc}}{2\pi P_{koc} Z_1 B_{oc}}\right) + \left(\frac{T_{oc} f}{B_{oc} Z_1}\right)^2}} \frac{U_m}{r_u}, \quad (5.1)$$

where U_m —the amplitude of the electric oscillations voltage at the output of the pulse signal generator 3; r_u —least significant digit of the ADC MC 1 by voltage; U_1 —the voltage amplitude generated at the output of the detector 29, after the ultrasonic waves pass through the reference series of warp threads 31, followed by conversion into electrical oscillations by means of a piezoelectric transducer 25 and sending them to the detector 29; α_{13} —the initial damping coefficient of the oscillation amplitude

in the material of the warp threads 31 at the initial tension P_{noc} and in the longitudinal passing of ultrasonic waves through the threads; T_{oc} —linear density of the reference warp threads 31; B_{oc} —the width of a number of reference warp threads 31, that are sounded; c_{oc} —the speed of ultrasonic waves propagation in the reference warp threads 31; f —frequency of ultrasonic waves; P_{noc} —the initial tension of the reference warp threads 31; P_{koc} —the final tension of the reference warp threads 31; Z_1 —acoustic air resistance; K_1 —the amplifier gain 4; K_2 —the signal transmission factor of the switching unit 20; K_3 —the conversion factor of the radiating piezoelectric transducer 22 and the receiving piezoelectric transducer 25; K_4 —the signal transmission factor of the switching unit 27; K_5 —the adjustable amplifier gain 28; K_6 —the voltage conversion factor of the amplitude detector 29; K_7 —the signal transmission factor of the switching unit 14.

Based on expression (5.1), the unit voltage of the least significant digit of the ten-bit ADC MC 1 can be expressed as follows:

$$r_{u1} = \frac{U_{\max}}{N_{\max}} = \frac{5B}{2^0 + 2^1 + 2^2 + 2^3 + 2^4 + 2^5 + 2^6 + 2^7 + 2^8 + 2^9} = \frac{5B}{1023}, \quad (5.2)$$

where $U_{\max}$ —the maximum voltage amplitude that can be received and digitized using the internal ADC MC 1; $N_{\max}$ —code that proportionally corresponds to the maximum voltage amplitude $U_{\max}$.

Another package of emitted ultrasonic vibrations by the piezoelectric transducer 21, which pass longitudinally through a series of warp threads, but already in the structure of the reference fabric 30, which is stretched by a special device or load, and then fall on the piezoelectric transducer 24, where they are converted into electrical oscillations.. Then they pass through the switching unit 27, which switches MC 2 synchronously with the unit 20 on different channels of probing the material similar to the first case. Next, the electrical oscillations are amplified by the power of the amplifier 28 and detected with conversion into DC voltage U_2 by an amplitude detector 29. This voltage U_2 enters MC 1 through the switching unit 14 which controls the switching of the switching unit 14. It is converted to digital code N_2 by ten-bit internal ADC of the detected voltage U_2 in MC 1, which is proportional to the amplitude of the ultrasonic waves passing longitudinally through a series of warp threads in the structure of the reference fabric 30. This code N_2 is involved in the calculation of the tension parameter, considering the least significant digit of the ADC MC 1 can be represented as:

$$N_2 = \frac{U_2}{r_u} = \frac{K_1 K_2 K_4 K_5 K_6 K_7 K_8}{\sqrt{\left(1 + \alpha_{23} \cdot \frac{P_{no} c_{om} T_{oc}}{2\pi P_{ko} Z_1 B_{om}}\right)^2 + \left(\frac{T_{oc} f}{B_{om} Z_1}\right)^2}} \frac{U_m}{r_u}, \quad (5.3)$$

where α_{23} —the initial attenuation coefficient of the oscillation amplitude in the material of the warp threads in the structure of the reference fabric 30 at the initial tension P_{no} and in the longitudinal passing of ultrasonic waves through the threads; B_{om} —the width of a number of warp threads in the structure of the reference fabric

30, which is sounded; c_{om} —the speed of the ultrasonic waves propagation in the warp threads in the structure of the reference fabric 30; P_{no} —the initial tension of the warp threads in the structure of the reference fabric 30; P_{ko} —the final tension of the warp threads in the structure of the reference fabric 30; K_8 —the oscillation conversion factor of the radiating piezoelectric transducer 21 and the receiving piezoelectric transducer 24.

The package of emitted ultrasonic vibrations by the piezoelectric transducer 23, which pass longitudinally through a series of weft threads in the structure of the reference fabric 30, which is stretched, then falls on the piezoelectric transducer 26, where they are converted into electrical oscillations. Then they pass through the switching unit 27, which switches MC 2 synchronously with unit 20 on different channels of probing the material similar to the first and second cases. Next, the electrical oscillations are amplified by the power of the amplifier 28 and detected with the conversion into a constant voltage U_3 by an amplitude detector 29. This voltage U_3 enters MC 1 through the switching unit 14. In MC 1 itself, the detected voltage is converted into a digital code N_3 by means of an internal ADC U_3 , which is proportional to the amplitude of ultrasonic waves that passed longitudinally through a series of weft threads in the structure of the reference fabric 30. This code N_3 can be represented as follows:

$$N_3 = \frac{U_3}{r_u} = \frac{K_1 K_2 K_4 K_5 K_6 K_7 K_9}{\sqrt{\left(1 + \alpha_{33} \frac{P_{ny} c_{ym} T_{ym}}{2\pi P_{ky} Z_1 B_{ym}}\right)^2 + \left(\frac{T_{ym} f}{B_{ym} Z_1}\right)^2}} \frac{U_m}{r_y}, \quad (5.4)$$

where α_{33} —the initial damping coefficient of the amplitude of oscillations in the material of the weft threads in the structure of the reference fabric 30 at the initial tension P_{ny} and in the longitudinal ultrasonic waves passing; T_{ym} —the linear density of weft threads in the structure of the reference fabric 30; B_{ym} —the width of a number of weft threads in the structure of the reference fabric 30, which is sounded; c_{ym} —the speed of ultrasonic waves propagation in the weft threads in the reference fabric structure 30; P_{ny} —the initial tension of the weft threads in the structure of the reference fabric 30; P_{ky} —the final tension of the weft threads in the structure of the reference fabric 30; K_9 —the conversion factor of the radiating piezoelectric transducer 23 and the receiving piezoelectric transducer 26.

After the further transverse sounding of the reference warp threads 31 and the reference fabric 30 at different tensions of the material, the operating range is determined as well as deviation of the readings of the contactless transducers in comparison with the values obtained with the reference method. Then, considering the settings, the contactless computerized system begins to scan the cfabric 19 already on the loom.

The electric oscillations that are produced and then go to the output of the pulse signal generator 3, through the switching unit 5, which is switched by MC 1, then come to the input of the piezoelectric transducer 10, where they are converted into ultrasonic waves. These oscillations normally fall on the controlled fabric 19 and

pass through it, and then fall on the piezoelectric transducer 11, where they are again converted into electrical oscillations. Then they come through the switching unit 8, which is switched by MC 1, to the adjustable amplifier 12 and amplified by power. The generated electrical oscillations are detected by an amplitude detector 13 with DC U_4 conversion, related to the basis weight m_s of the controlled fabric 19. Then the voltage U_4 flows through the switching unit 14, which also switches the measuring channels with MC 1 to the internal ADC MC 1. In the process of digitizing the voltage value U_4 , a code $N4$ is created, which can be shown as:

$$N4 = \frac{U_4}{r_u} = K_1 K_7 K_{10} K_{11} K_{12} K_{13} K_{14} \frac{1}{\sqrt{1 + \left(\frac{K m_s f \cos v}{Z_1} \right)^2}} \frac{U_m}{r_u}, \quad (5.5)$$

where K_{11} —the conversion factor of the radiating piezoelectric transducer 10 and the receiving piezoelectric transducer 11; K —the coefficient of pore size change in comparison with the reference fabric 30 with a certain tension; v —the angle between the direction of the ultrasonic waves propagation that pass through the pores of the controlled fabric 19, and its surface.

The reflected ultrasonic waves from the surface of the controlled fabric 19 fall on the piezoelectric transducer 9, then are converted into electrical oscillations and fall on the adjustable power amplifier 12. Next, these oscillations are detected by an amplitude detector 13 with conversion to DC voltage U_5 , which is associated with the change in the coefficient K of the controlled fabric 19. Then the voltage U_5 is supplied through the switching unit 14 during the time-shared measurement to the internal ADC MC 1. In the processing of the measured voltage values U_5 , a code N_5 is created, which can be shown as follows:

$$N_5 = \frac{U_5}{r_u} = K_1 K_7 K_{10} K_{12} K_{13} K_{14} K_{15} \frac{K_\rho}{\sqrt{1 + \left(\frac{Z_1}{K m_s f \cos v} \right)^2}} \frac{U_m}{r_u}, \quad (5.6)$$

where K_{15} —the conversion factor of the radiating piezoelectric transducer 10 and the receiving piezoelectric transducer 9; K_ρ —the coefficient of partial impact of the ultrasonic waves reflected from the controlled fabric 19 on the receiving piezoelectric transducer 9.

Separately, the electric oscillations, which are produced and go to the output of the pulse signal generator 3, through the switching unit 5, which is switched with MC 1, then fall to the input of the piezoelectric transducer 6, where they are converted into ultrasonic waves. These oscillations normally fall on the controlled set of warp threads 18 at a certain point in time, which is synchronized with the operation of the loom, and the part of which is reflected from this set of threads, and then falls on the piezoelectric transducer 7, where ultrasonic waves are converted into electric oscillations. Then they come through the switching unit 8, which is switched with MC 1, to the adjustable amplifier 12 and amplified by power. The generated electrical oscillations are detected by an amplitude detector 13 with DC U_6 conversion, related

to the linear density T_{oc} of a set of warp threads 18. Then the voltage U_6 flows through the switching unit 14, which also switches the measuring channels with MC 1 to the internal ADC MC 1. Therefore, the value of the voltage U_6 generates a code N_6 that can be shown as follows:

$$N_6 = \frac{U_6}{r_u} = K_1 K_7 K_{10} K_{12} K_{13} K_{14} K_{16} \frac{K_{\rho o}}{\sqrt{1 + \left(\frac{B_{om} Z_1}{T_{oc} f \cos v_o} \right)^2}} \frac{U_m}{r_u}, \quad (5.7)$$

where K_{16} —oscillation conversion factor of the radiating piezoelectric transducer 6 and the receiving piezoelectric transducer 7; $K_{\rho o}$ —the coefficient of partial impact of the reflected ultrasonic waves from the warp threads 18 on the receiving piezoelectric transducer 7; v_o —the angle between the direction of the wave reflected from a set of warp threads 18 towards the signal, and the threads themselves.

The received measurement information in the form of digital codes $N_1, N_2, N_3, N_4, N_5, N_6$ through the microchip of logic level conversion 15 enters the PC 16, where it is processed with the help of special software and the main technological parameters are determined. The tension $P_{\kappa oc}$ of a number of reference warp threads 31 based on expression (5.1) can be shown as:

$$P_{\kappa oc} = \frac{\alpha_{13} \cdot P_{noc} c_{oc} T_{oc}}{2\pi Z_1 B_{oc} \cdot \left(\sqrt{\left(\frac{K_1 K_2 K_3 K_4 K_5 K_6 K_7 U_m}{U_1} \right)^2 - \left(\frac{T_{oc} f}{B_{oc} Z_1} \right)^2} - 1 \right)}. \quad (5.8)$$

When setting up the system when $U_{\max} = K_1 K_2 K_3 K_4 K_5 K_6 K_7 U_m$, then tension $P_{\kappa oc}$ can be represented as the code dependence by which this parameter will be determined by the program on the PC 16 as follows:

$$P_{\kappa oc} = \frac{P_{noc} N_{\alpha 1} N_{c1} N_{T1}}{2\pi N_{zb1} \cdot \left(\sqrt{\left(\frac{N_{\max}}{N_1} \right)^2 - \left(\frac{N_{T1} N_f}{N_{zb1}} \right)^2} - 1 \right)}, \quad (5.9)$$

where $N_{\alpha 1}$ —a code that corresponds to the initial attenuation factor α_{13} , the amplitude of oscillations in the material of the reference warp threads 31; N_{c1} —a code corresponding to the speed c_{oc} of ultrasonic waves propagation in the reference warp threads 31; N_{T1} —a code corresponding to the linear density T_{oc} of the reference warp threads 31; N_f —code corresponding to the frequency f of ultrasonic waves; N_{zb1} —code that corresponds to the parameter $B_{oc} \cdot Z_1$.

Codes that are not detected by ultrasonic sensors are recorded separately in the measurement information processing program.

The tension $P_{\kappa o}$ of a number of warp threads in the structure of the reference fabric 30 taking into account expression (5.3) can be represented as:

$$P_{\kappa o} = \frac{\alpha_{23} \cdot P_{no} \cdot c_{om} \cdot T_{oc}}{2\pi \cdot Z_1 \cdot B_{om} \cdot \left(\sqrt{\left(\frac{K_1 K_2 K_4 K_5 K_6 K_7 K_8 U_m}{U_2} \right)^2 - \left(\frac{T_{oc} f}{B_{om} Z_1} \right)^2} - 1 \right)}, \quad (5.10)$$

at the stage of initial settings taking into account when in addition $K_3 = K_8$, then tension $P_{\kappa o}$ can be presented in the form of dependence of codes on which this parameter will be defined by the program on the PC 16 so:

$$P_{\kappa o} = \frac{P_{no} N_{\alpha 2} N_{c2} N_{T1}}{2\pi N_{zb2} \cdot \left(\sqrt{\left(\frac{N_{max}}{N_2} \right)^2 - \left(\frac{N_{T1} N_f}{N_{zb2}} \right)^2} - 1 \right)}, \quad (5.11)$$

where $N_{\alpha 2}$ —the code that corresponds to the initial attenuation coefficient α_{23} , of the oscillation amplitude in the material of the warp threads in the structure of the reference fabric 30; N_{c2} —code corresponding to the speed c_{om} of the ultrasonic waves propagation in the warp threads in the structure of the reference fabric 30; N_{zb2} —code that corresponds to the parameter $B_{om} \cdot Z_1$.

The tension $P_{\kappa y}$ of a number of weft threads in the structure of the reference fabric 30 taking into account expression (5.4) can be represented as:

$$P_{\kappa y} = \frac{\alpha_{33} \cdot P_{ny} \cdot c_{ym} \cdot T_{ym}}{2\pi \cdot Z_1 \cdot B_{ym} \cdot \left(\sqrt{\left(\frac{K_1 K_2 K_4 K_5 K_6 K_7 K_9 U_m}{U_3} \right)^2 - \left(\frac{T_{ym} f}{B_{ym} Z_1} \right)^2} - 1 \right)}, \quad (5.12)$$

with additional settings, when $K_3 = K_9$, then the tension $P_{\kappa y}$ can be represented as the dependence of the codes by which this parameter will be determined by the program on the PC 16 as follows:

$$P_{\kappa y} = \frac{P_{ny} N_{\alpha 3} N_{c3} N_{T3}}{2\pi N_{zb3} \cdot \left(\sqrt{\left(\frac{N_{max}}{N_3} \right)^2 - \left(\frac{N_{T3} N_f}{N_{zb3}} \right)^2} - 1 \right)}, \quad (5.13)$$

where $N_{\alpha 3}$ is a code that corresponds to the initial attenuation coefficient α_{33} , of the amplitude of oscillations in the weft threads material in the structure of the reference fabric 30; N_{c3} —a code that corresponds to the speed c_{ym} of ultrasonic waves propagation in the weft threads in the structure of the reference fabric 30; N_{T3} —code corresponding to the linear density T_{ym} of weft threads in the structure of the reference fabric 30; N_{zb3} —code that corresponds to the parameter $B_{ym} \cdot Z_1$.

When setting the scanning system, depending on the percentage effect of the warp threads tension $P_{\kappa o}$ and the weft threads tension $P_{\kappa y}$ on the reference fabric structure 30, its resulting tension $P_{\kappa 1}$ is determined in accordance with the program algorithm of the computerized system. The program is responsible for determining the tension of the reference fabric 30 at each point in relation to its structure. This

allows determining the parameter deviation $\delta_{P_{\kappa 12}}$ by the difference between the value of the tension $P_{\kappa 1}$ obtained by the longitudinal sounding of the fabric 30, and the value of the tension $P_{\kappa 2}$ obtained by its transverse sounding. The tension in a certain range for the reference fabric 30 at each of its points on the transverse sounding of the material is determined as follows:

$$P_{\kappa 2} = P_{n2} \cdot \left(\frac{N_5}{N_{05}} \right)^3, \quad (5.14)$$

where N_{05} is the code generated by the reflection of ultrasonic waves from the surface of the reference fabric 30 at its initial tension P_{n2} ; N_5 is a code formed by the reflection of ultrasonic waves from the surface of the reference fabric 30 at its final tension $P_{\kappa 2}$.

The relative deviation $\delta_{P_{\kappa 12}}$ of the tension values of the reference fabric 30, which is determined by its transverse sounding, can be represented as:

$$\delta_{P_{\kappa 12}} = \frac{P_{\kappa 2} - P_{\kappa 1}}{P_{\kappa 1}} \cdot 100\%, \quad (5.15)$$

then the absolute value of this deviation can be represented as follows:

$$\Delta_{P_{\kappa 12}} = P_{\kappa 2} - P_{\kappa 1}. \quad (5.16)$$

The obtained deviation statistics $\Delta_{P_{\kappa 12}}$ for the tension range of the reference fabric 30, which are determined by its longitudinal and transverse ultrasonic sounding, affect the adjustment of the non-contact scanning system of the controlled fabric 19. These data are used for non-contact tension control $P_{\kappa 2}^*$ in a certain range. This is possible with the transverse sounding of the controlled fabric 19 on the equipment during production. In this case, it is possible to get the tension value $P_{\kappa 2}^*$ of the controlled fabric 19 in the form of calculations in a computerized system, taking into account (5.14) and (5.16) as follows:

$$P_{\kappa 2}^* = P_{n2}^* \cdot \left(\frac{N_5^*}{N_{05}^*} \right)^3 - \Delta_{P_{\kappa 12}}. \quad (5.17)$$

where N_{05}^* is the code generated by the reflection of ultrasonic waves from the surface of the controlled fabric 19 at its initial tension P_{n2}^* ; N_5^* is the code, formed by the reflection of ultrasonic waves from the surface of the controlled fabric 19 at its final tension $P_{\kappa 2}^*$.

Calculations taking into account the tabular deviations $\Delta_{P_{\kappa 12}}$ obtained by expression (5.16) for the structure and raw material composition of the reference fabric 30, corresponding to the controlled fabric 19, make it possible to adjust the tension readings in contactless transverse sounding of the material. This combined method should be used because the longitudinal sounding of the material on the equipment is very difficult to implement in textile fabrics production. Therefore, the readings deviations of the tension are possible, which is determined by the transverse sounding

of the material, from the true parameter value. These readings can be corrected using the values obtained by the longitudinal sounding of the material, due to the tabular values of the deviations recorded in the system memory associated with the reference fabric 30. That is, for each measured tension value of the controlled fabric 19 there is a particular tabular deviation value, which is written to the system memory, obtained using the BBA and the reference fabric 30 in previous studies.

As adjustments are made for the obtained tension values of the fabric 19 in contactless control, so corrections are made to the readings of the tension values of the warp threads 18 on textile machines. Moreover, a number of warp threads 18 are sounded during the non-contact control at a certain point in time that is synchronized with the textile equipment operation on which this fabric scanning system 19 is installed.

The calculation of the tension Q_o of a number of reference warp threads 31 and the deviation Δ_{Q_o} of this parameter, which were determined by transverse and longitudinal ultrasonic sounding of these threads, taking into account expression (5.9) when configured system, when $U_{\max} = K_1 K_7 K_{10} K_{12} K_{13} K_{14} K_{15} U_m$ and $K_{14} = K_{15} = K_{16}$ can be represented as:

$$Q_o = Q_T \cdot \left(1 + N_8 \cdot \left(\frac{N_5 \sqrt{1 - \left(\frac{N_6}{N_{\max}} \right)^2}}{N_{11} N_6 \sqrt{1 - \left(\frac{N_5}{N_{\max}} \right)^2}} - 1 \right)^{-1} \right) \times \\ \times \left(1 + N_9 \cdot \left(\frac{N_5 \sqrt{1 - \left(\frac{N_6}{N_{\max}} \right)^2}}{N_{11} N_6 \sqrt{1 - \left(\frac{N_5}{N_{\max}} \right)^2}} - 1 \right)^{-1} \right)^{N_{12}} \\ \times \frac{1}{N_{10}} \cdot \exp \left(\frac{N_7 N_{\max}}{N_5} \cdot \left(\frac{N_5}{N_{\max}} - \frac{N_{11} N_6 \cdot \sqrt{1 - \left(\frac{N_5}{N_{\max}} \right)^2}}{N_{\max} \cdot \sqrt{1 - \left(\frac{N_6}{N_{\max}} \right)^2}} \right) \right), \quad (5.18)$$

$$\Delta_{Q_o} = Q_o - \frac{P_{noc} N_{\alpha 1} N_{c1} N_{T1}}{2\pi N_{zb1} \cdot \left(\sqrt{\left(\frac{N_{\max}}{N_1} \right)^2 - \left(\frac{N_{T1} N_f}{N_{zb1}} \right)^2} - 1 \right)}, \quad (5.19)$$

where code N_7 is stored in the computer system and corresponds to the value $(\mu \beta \varphi) / \sin \beta$, code N_8 corresponds to the value $k \cdot (\sin \alpha_0 + \sin \alpha)$, code N_9 corresponds to the value $2k \sin \alpha$, code N_{10} corresponds to the value $(1 - \delta) \cdot \cos \alpha$, code N_{11} corresponds to the value $\cos \nu / \cos \nu_o$, code N_{12} corresponds to the value $n - 1$.

Values in the form of codes $N_7, N_8, N_9, N_{10}, N_{11}, N_{12}$ are entered into the memory of the computerized system and affect the calculation of tension values of the reference series of warp threads 31.

It is necessary to try to set up a contactless scanning system to $Q_o \approx P_{\kappa oc}$ and $\Delta_{Q_o} \rightarrow 0$. The tension of a number of controlled warp threads 18 on the equipment is then defined as follows:

$$Q_o^* = Q_{ok} - \Delta_{Q_o}, \quad (5.20)$$

where Q_{ok} is the tension of a series of controlled warp threads 18, which is initially determined by a scanning system without correction according to (5.18).

Controlling the tension of the warp threads 18 will keep the basis weight m_s of the controlled fabric 19 within the regulated limits in the production of textile fabrics.

The basis weight m_s of the fabric 19 in the weaving process, taking into account the change in tension can be determined without contact using ultrasonic sensors mounted on both sides of the fabric on moving platforms. They move thanks to MCU 17, which controls the stepper motors, which drives the platform with contactless sensors. In turn, MCU 17 is controlled by MC 2 according to a given algorithm. If we take into account the coefficients K_0 and K , which characterize the change in porosity at the initial tension of the fabric and the change in porosity at its final tension at the time of sounding the material by ultrasonic waves, the coefficient K is then responsible for changing the tension of the fabric 19 in some range. The coefficient K and change of tension of the fabric 19 on the equipment can be determined by the ratios of the reflected ultrasonic waves, or by changing the ratio of the codes that correspond to them. The coefficient K taking into account the tension of the fabric 19 can be presented as:

$$K = K_0 \frac{N_5^*}{N_{05}^*} \quad (5.21)$$

then the basis weight m_s of the textile fabric 19 taking into account the change in its tension can be represented as the dependence of the system codes as follows:

$$m_s = \frac{Z_1 N_{05}^* N_m \cdot \sqrt{\left(\frac{N_{\max}}{N_4}\right)^2 - 1}}{N_5^* f}, \quad (5.22)$$

where N_m is a code that corresponds to the value of a quantity $1/(K_0 \cos \nu)$ and is entered into the memory of the system for calculating the basis weight m_s of the controlled textile fabric 19.

The obtained measured data are stored in the memory of the system for each controlled fabric 19 with its structure and the corresponding reference sample 30, which can be produced on equipment with an installed computerized fabric scanning system. Information about the measured values of parameters at different humidity and ambient temperature is also entered in parallel. At the expense of the received data, it will be possible to enter corrections to certain values of parameters more precisely in the course of contactless scanning of textile fabric in production.

It should be noted that before starting work without placing textiles in the measuring channels with variable gain amplifiers 12, 28 a computerized system is so that there is no different incursion of the voltage amplitudes on the detectors 13, 29, which can cause the environment in these channels.

Therefore, it may be said that quick control of the warp threads' tension provides a technological impact that allows maintaining the basis weight of the fabric within the specified limits, the actual value of which can be determined without contact in the process of its production. This is possible if we solve a number of problems related to the integration of these technologies into technological complexes for the production of various fabrics in the textile industry. Non-contact computerized systems with movable platforms that allow scanning every point of the textile fabric are very promising. Contactless technologies will help to improve the quality of textile fabrics and increase their competitiveness in the domestic and world markets.

5.2 Development of a Computerized System for Scanning Textile Fiber Mass and Determining the Tension of Threads on Knitting Machines

For the light industry, the issue of operational control of technological parameters of various textile materials is a topical question and essential for the production process. Let us take the textile fiber mass: there is a need to control its basis weight, which will ensure the efficient use of raw materials to obtain quality finished products at the output. There is also a need to control the basis weight of knitted fabrics and to prevent defects in their structure on various textile machines. When ensuring this parameter and the homogeneity of the material within the established limits, it is necessary to control the tension of the threads on the process equipment. To solve this problem, it is possible to use a computerized system that can scan the textile fiber mass and determine its basis weight. In addition to this parameter, when changing the sensors with the appropriate fasteners in the form of brackets and in the form of waveguides, this system will be able to determine the tension of the threads on knitting machines in the process of making textile fabrics. The tension of the threads on knitting machines affects the possibility of defects in the structure of the knitted fabric, as well as the possibility of threads breakage, which can lead to a lack of fabrics and equipment downtime. Therefore, the task of creating a system with the ability to connect various waveguides and mounts in the form of a bracket with non-contact ultrasonic sensors is quite urgent. This, in turn, will control the various textile materials for their main parameters that affect the technological processes of production. In other words, when connecting sensors that are placed in the bracket, you can control the basis weight of the fiber (Fig. 5.2), and when connecting a number of waveguides, you can measure the tension of the threads (Fig. 5.3) by amplitude methods. It is also possible to contact the moment of thread breakage in the process of the production of the knitted fabrics [8–13].

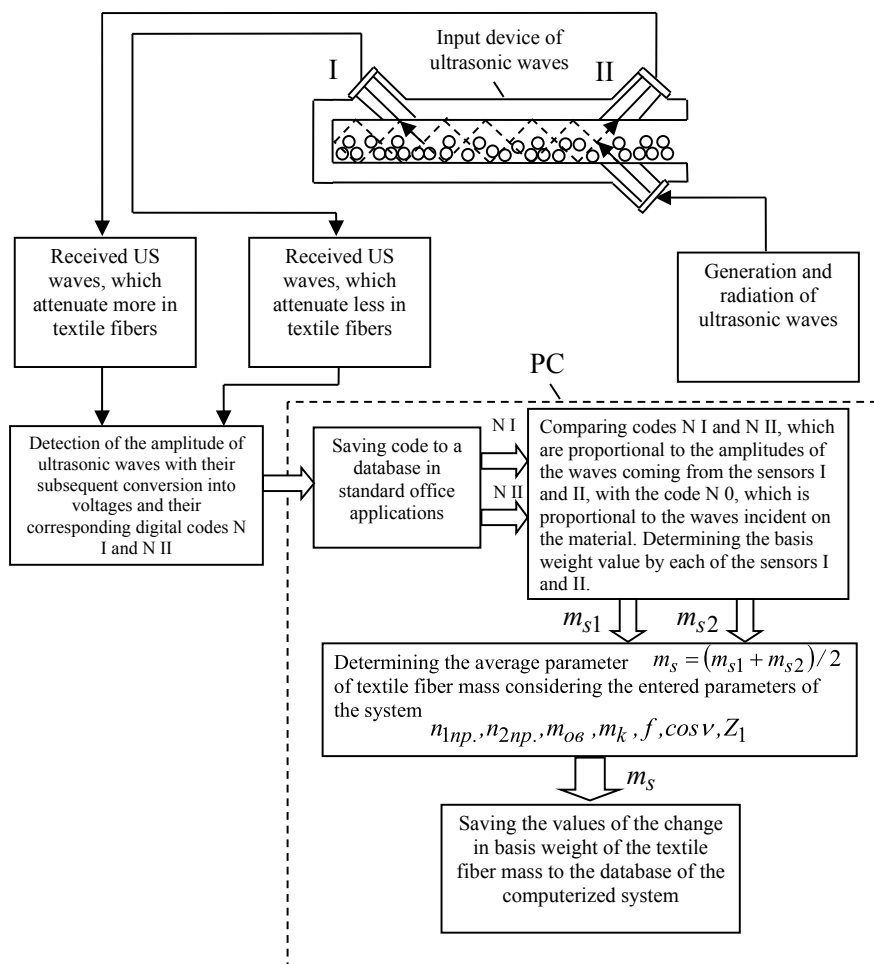


Fig. 5.2 The structure of the system operations to implement the amplitude method of controlling the basis weight of the textile fiber mass

The structure of such a computerized system (Fig. 5.4) can be described taking into account the possibility of its operation in two modes, to determine the basis weight of the textile fiber and to determine the tension of the threads on textile machines.

This system includes the following components: microcontroller 1 (MC 1), microcontroller 2 (MC 2), pulse signal generator 3, amplifier 4, piezoelectric transducers 5, 6, 7, bracket mounting 8, adjustable amplifiers 9, 10, amplitude detectors 11, 12, switching unit 13, logic level conversion chip 14, personal computer 15 (PC 15), motor control unit 16 (MCU 16) for the transport mechanism that moves the textile fiber mass 17.

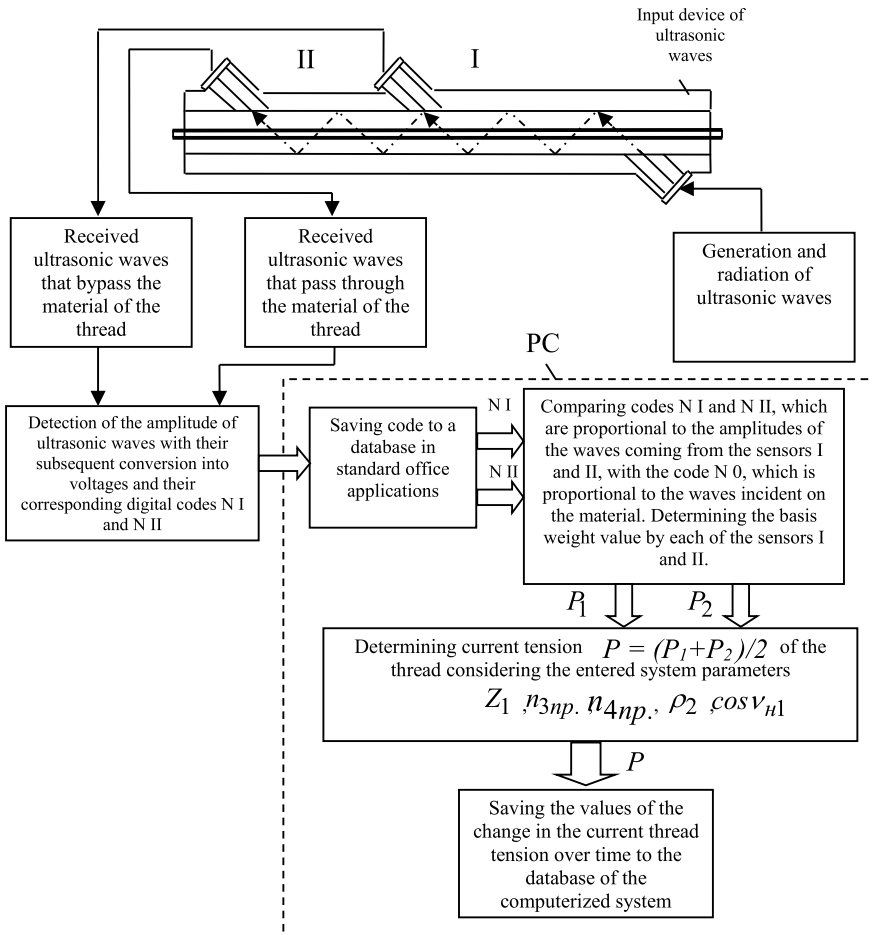


Fig. 5.3 The structure of system operations to implement the amplitude method of controlling the tension of threads with a high linear density on the process equipment

Together, the piezoelectric transducers 5, 6, 7, and the bracket mounting 8 are the first unit with ultrasonic sensors (UUS1), and the piezoelectric transducers 21, 22, 25, 26 together with the upper parts of the waveguides 23, 27, and their lower parts 24, 28 represent a second unit with ultrasonic sensors (UUS2). When UUS1 is connected to the general unit of information transmission and control (GUTC) and the unit of conversion and information processing (UCIP), the computerized system can determine the basis weight of the textile fiber mass on a non-contact basis. If this system is used for non-contact determination of thread tension with high linear density, then switching the keys 18, 19, 20 to the second position to the GUTC are connected to the emitting piezoelectric transducers 21, 25, and to the UCIP are connected to the receiving piezoelectric transducers 22, 26. When UUS2 is connected, then the

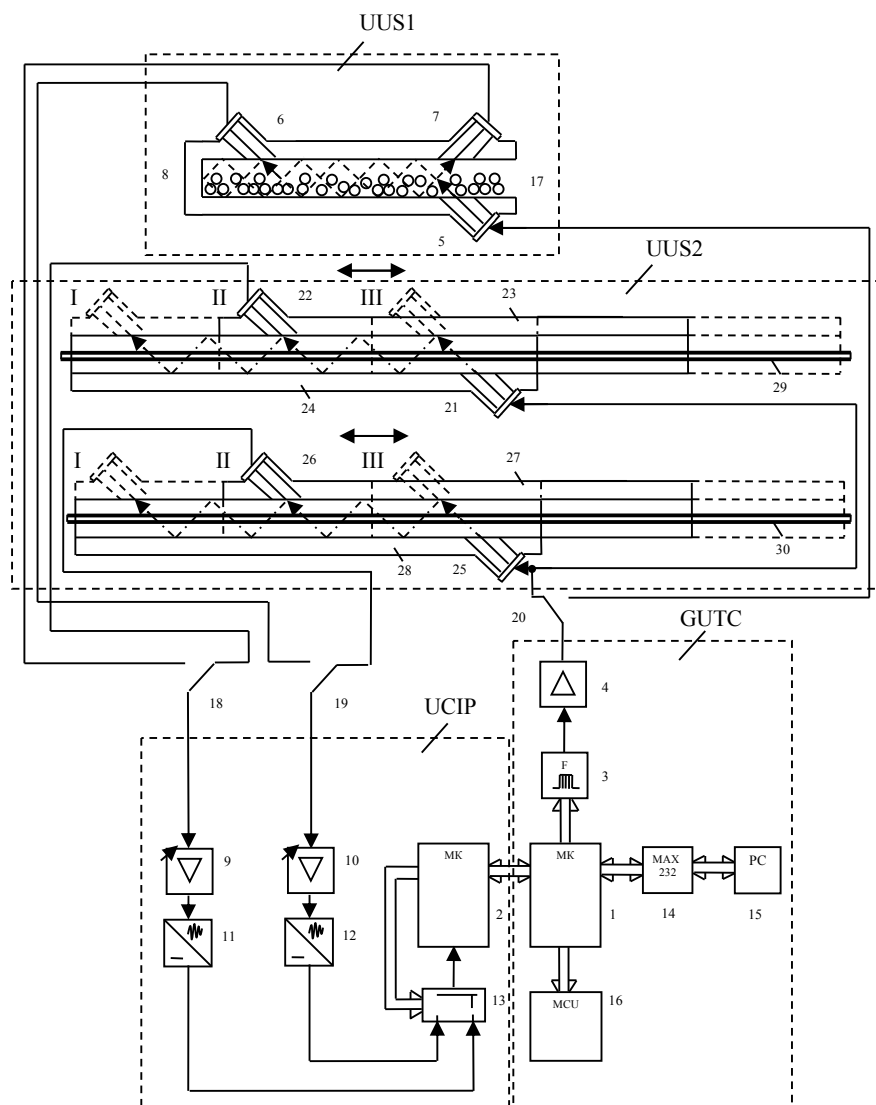


Fig. 5.4 Block diagram of a computerized scanning system of textile fiber mass and determining the thread tension in the process of knitted fabrics production

computerized system operates in the mode of determining the tension of two threads with high linear density based on the measured voltage amplitudes, which are proportional to the amplitudes of ultrasonic waves interacting with the fibers of the threads in the waveguides. Knitting machines connect additional switching units to the entire system to quickly monitor the tension of a large number of threads when they are at a certain distance from each other. This allows connecting other measuring channels

with waveguides. It is also possible to additionally connect many UCIP with sensors to GUTC if necessary that provides the principle of modularity and flexibility of system under technological processes of various textile machines.

UUS2 in Fig. 5.4 is considered as a single module for determining the tension of only two threads to describe the principle of operation of a computerized system in this mode. This connection principle will reduce the cost of development and production of new equipment through the use of basic modules GUTC and UCIP.

Next, let us separately consider the operation of the computerized system in the mode of determining the basis weight of the textile fiber mass and separately show how the system works in determining the tension of the threads.

Let us consider the principle of operation of the proposed system in the mode of non-contact determination of the basis weight of the textile fiber mass (mass of textile fibers per unit area). The ultrasonic frequency f pulses produced by MC 1 are transmitted to the pulse signal generator 3, then from the output of which voltage pulse packets U_m are transmitted to the amplifier 4. After amplification, the pulse signal is transmitted to the piezoelectric transducer 5 and is converted into ultrasonic waves. These waves pass through the textile fibers reflected from the upper and lower walls of bracket 8 and enter the first receiving piezoelectric transducer 6, and then get to, by further reflecting the oscillations with some attenuation, to the second receiving piezoelectric transducer 7. Thanks to the piezoelectric transducers 7, 8 ultrasonic waves are converted into electrical oscillations, amplified by power-regulated amplifiers 9, 10, then detected and converted into DC voltages U_1 and U_2 with the help of amplitude detectors 11, 12. DC voltages U_1 and U_2 are generated with a time delay and get to the switching unit 13, which switches channels alternately, connecting them to the input MC 2.

The delay in voltage generation U_1 and U_2 time is related to the different distance for ultrasonic waves that they go through before reaching the first 6 and second 7 receiving piezoelectric transducers, respectively. The moment of switching of measuring channels by means of the switching unit 13 and MC 2 is synchronized with time of formation of electric voltages U_1 and U_2 . The attenuation of the ultrasonic waves' amplitudes must be within the set operating range to be able to obtain unknown values of basis weight for the textile fiber mass. This parameter is also defined in the operating range for the computerized system. With the help of internal analog-to-digital converter (ADC) MC 2 voltage U_1 is converted into digital code N_1 as follows:

$$N_1 = \frac{U_1}{r_u} = \frac{K_1 K_2 K_4 K_6 K_8}{\sqrt{1 + \left(\frac{n_{1np} \cdot m_{o\beta} m_k f \cos v}{Z_1} \right)^2}} \frac{U_m}{r_u}, \quad (5.23)$$

where r_u —the unit of the least significant digit of the ADC MC 2 for voltage m_k is the surface quantitative density of the textile fiber 17; n_{1np} —the number of ultrasonic wave passes to the piezoelectric transducer 6 of the cross section of the waveguide, which is formed by the upper and lower walls of the bracket 8; $m_{o\beta}$ —average weight of one fiber; K_1 —the amplifier gain 4; K_2 —oscillation conversion factor of

the radiating piezoelectric transducer 5 and the receiving piezoelectric transducer 6; K_4 —the adjustable amplifier gain 10; K_6 —the voltage conversion factor of the amplitude detector 12; K_8 —the signal transmission factor of the switching unit 13.

The other voltage U_2 is converted using an internal ADC MC 2 into a digital code N_2 as:

$$N_2 = \frac{U_2}{r_u} = \frac{K_1 K_3 K_5 K_7 K_8}{\sqrt{1 + \left(\frac{n_{2np} \cdot m_{o\beta} m_k f \cos v}{Z_1} \right)^2}} \frac{U_m}{r_u}, \quad (5.24)$$

where n_{2np} is the number of passes of the ultrasonic wave to the piezoelectric transducer 7 of the cross-section of the waveguide, which is formed by the upper and lower walls of the bracket 8; K_1 —the amplifier gain 4; K_3 —the oscillation conversion factor of the radiating piezoelectric transducer 5 and the receiving piezoelectric transducer 7; K_5 —the adjustable amplifier gain 9; K_7 —the voltage conversion factor of the amplitude detector 11; K_8 —the signal transmission factor of the switching unit 13.

The received codes N_1 and N_2 are transmitted to MC 1, which produces a signal for MCU 16, which, in turn, controls the motors of the transport mechanism, which moves the textile fiber mass 17 for further probing of subsequent fibers. When working with other textile materials and when connecting UUS2 to a computerized system, MCU 16 can be disconnected from the motors of the transport mechanism and connected to the drives that adjust the waveguides to the desired operating mode.

From the MC 1 the received codes N_1 and N_2 are transmitted through the logic conversion circuit 14 to the PC 15, where the basis weight is determined m_s of textile fiber mass. When setting up the system, if $U_{\max} = N_{\max} \cdot r_u = K_1 K_2 K_4 K_6 K_8 U_m = 5B$, $K_2 = K_3$, $K_4 = K_5$ та $K_6 = K_7$, then basis weight m_s of textile fiber mass is determined by a special program on PC 15 by the following expression:

$$m_s = m_k m_{o\beta} = \frac{Z_1 N_m}{2f} \cdot \left(\left(\sqrt{\left(\frac{N_{\max}}{N_1} \right)^2 - 1} \right) \cdot N_{1np} + \left(\sqrt{\left(\frac{N_{\max}}{N_2} \right)^2 - 1} \right) \cdot N_{2np} \right), \quad (5.25)$$

where N_m —code that corresponds to the value of quantity $1/\cos v$ and is entered into the memory of the system for calculating the average basis weight m_s of textile fibre mass 17; N_{1np} —code that corresponds to the value of quantity $1/n_{1np}$ and is entered into the memory of the system, and also depends on the geometric dimensions of the bracket 8; N_{2np} —code that corresponds to the value of quantity $1/n_{2np}$ and is also entered into the system memory.

Before the measurement, the system is configured without a controlled fiber mass 17 inside the bracket 8. With the help of control amplifiers 9, 10 is provided $N_{\max} = N_1 = N_2$, then given this equality from expression (5.25) we obtain $m_s = 0$.

The computerized system can operate in the mode of determining the tension of the threads using the connected UUS2, with the possibility of contactless monitoring of the specified parameter in real-time.

Let us consider the principle of a computerized system operation when it works to obtain measurement information, which determines the current value of the threads' tension on the textile machine in the process of making a knitted fabric. The pulses of the ultrasonic frequency f generated by MC 1 are transmitted to the pulse signal generator 3, from the output of which the pulse packets with the voltage U_m go to the amplifier 4. Then the pulse signal is fed to the piezoelectric transducers 21, 25, which are converted into ultrasonic wave packets. These waves pass through the textile fibers of the threads 29, 30 in two waveguides, which, in turn, consist of the upper parts 23, 27 and the lower parts 24, 28, which are fixed. In the process of passing, ultrasonic waves are reflected from the upper walls of parts 23, 27, both waveguides, and from their lower walls of parts 24, 28. The waves can cross the waveguides reflected from their walls as many times as necessary for the maximum sensitivity of changing the oscillation amplitude to the change of the geometrical sizes of a thread in its tension. This is regulated by the three positions of the upper parts 23, 27 of the waveguides, which are driven and stopped in fixed positions (Fig. 5.4—positions I, II, III) due to the drives connected to them and controlled by MCU 16. Therefore, MC 1 can through the MCU 16 adjust the sensitivity of the contactless sensors, which are fixed in the upper parts 23, 27 of the waveguides, depending on the material and the linear density of the controlled thread.

After the ultrasonic waves pass through the controlled threads 29, 30, reflected several times in the waveguides, they enter the receiving piezoelectric transducers 22, 26, which convert the ultrasonic waves into electric oscillations, and then enter the adjustable amplifiers 9, 10, where they are amplified by power. These electrical oscillations are then detected and converted into DC voltages U_3 and U_4 by means of amplitude detectors 11, 12. The generated DC voltages U_3 and U_4 are transmitted to the switching unit 13, which switches the measuring channels alternately. They are connected to the input MC 2, where the voltages U_3 and U_4 are converted with a delay (depending on different positions of the sensors) using the internal ADC MC 2 in digital codes N_3 and N_4 , which can be represented by the following expressions:

$$N_3 = \frac{U_3}{r_u} = \frac{K_1 K_9 K_4 K_6 K_8}{\sqrt{1 + \left(\frac{n_{3np} \cdot d_{\gamma_{t1}} \rho_2 \pi^2 f \cos \nu_{\gamma_{t1}}}{4Z_1} \right)^2}} \frac{U_m}{r_u}, \quad (5.26)$$

$$N_4 = \frac{U_4}{r_u} = \frac{K_1 K_{10} K_5 K_7 K_8}{\sqrt{1 + \left(\frac{n_{4np} \cdot d_{\gamma_{t2}} \rho_2 \pi^2 f \cos \nu_{\gamma_{t2}}}{4Z_1} \right)^2}} \frac{U_m}{r_u}, \quad (5.27)$$

where n_{3np} , n_{4np} —the number of ultrasonic waves' passing to the piezoelectric transducers 22, 26 crosscuts of the first and second waveguides UUS2; K_9 —the conversion factor of the radiating piezoelectric transducer 25 and the receiving piezoelectric transducer 26; K_{10} —the conversion factor of the radiating piezoelectric transducer 21 and the receiving piezoelectric transducer 22; $\nu_{\gamma_{t1}}$, $\nu_{\gamma_{t2}}$ —the angles between the directions of the wave parts propagation which bypass the fibers of the threads in the

first and second waveguides UUS2, and the surface of the fibers; $d_{\mathcal{H}1}$, $d_{\mathcal{H}2}$ —equivalent thread diameters at certain parameters $\cos v_1$, $\cos v_2$ in the first and in the second waveguides UUS2.

Next, the codes N_3 , N_4 are transmitted through the conversion chip of the logic levels 14 to the PC 15, where the tension P_1 of the threads in the waveguides is determined. If we accept $U_{03} = K_1 K_9 K_4 K_6 K_8 U_m$, $U_{04} = K_1 K_{10} K_5 K_7 K_8 U_m$, then the conditional equivalent diameters of the threads $d_{\mathcal{H}1}$, $d_{\mathcal{H}2}$ with certain parameters $\cos v_{\mathcal{H}1}$, $\cos v_{\mathcal{H}2}$ in the waveguides, as well as the corresponding codes N_{d1} , N_{d2} are defined in PC 15 as follows:

$$\begin{aligned} d_{\mathcal{H}1} &= \frac{4Z_1 \cdot \sqrt{\left(\frac{U_{03}}{U_3}\right)^2 - 1}}{n_{3np} \cdot \pi^2 f \rho_2 \cdot \cos v_{\mathcal{H}1}}, & N_{d1} &= \frac{N_{m1} N_{3np} \cdot \sqrt{\left(\frac{N_{03}}{N_3}\right)^2 - 1}}{N_{zf\rho}}, \\ d_{\mathcal{H}2} &= \frac{4Z_1 \cdot \sqrt{\left(\frac{U_{04}}{U_4}\right)^2 - 1}}{n_{4np} \cdot \pi^2 f \rho_2 \cdot \cos v_{\mathcal{H}2}}, & N_{d2} &= \frac{N_{m2} N_{4np} \cdot \sqrt{\left(\frac{N_{04}}{N_4}\right)^2 - 1}}{N_{zf\rho}}, \end{aligned} \quad (5.28)$$

where N_{m1} is the code that corresponds to the value of the quantity $1/\cos v_{\mathcal{H}1}$ and is entered into the memory of the system to calculate the tension P_1 of the thread in the first waveguide; N_{m2} —code that corresponds to the value of the quantity $1/\cos v_{\mathcal{H}2}$ and is entered into the memory of the system to calculate the tension P_1 of the thread in the second waveguide; N_{3np} —code that corresponds to the value of the quantity $1/n_{3np}$ and is entered into the memory of the system depending on the position of the upper part 27 of the first waveguide (position I, II, or III); N_{4np} —code that corresponds to the value of the quantity $1/n_{4np}$ and is entered into the memory of the system depending on the position of the upper part 23 of the second waveguide (position I, II, or III); $N_{zf\rho}$ —code that corresponds to the value of the quantity $4Z_1/(\pi^2 f \rho_2)$ and is also entered into the memory of the system to calculate the tension P_1 .

Since the basic module UCIP has only two channels through which it is possible to measure the tension for two threads, the connection of similar modules in the required number to the module GUTC will determine the tension of all threads used in the process. This principle of connecting similar modules allows showing the flexibility of such systems to configure them for different textile machines. The tension P_1 of the threads in the waveguides, using the previously discussed expressions (5.26), (5.27), (5.28), is defined in PC 15 using all codes as:

$$\begin{aligned} P_1 &= P_0 + \left(N_R + \frac{N_{di}}{2}\right) (N_{\mu\varphi} - 1) \cdot \left(N_R + \left(1 - P_0 \cdot \left(N_R + \frac{N_{di}}{2}\right)\right.\right. \\ &\quad \left.\left. \times \left(P_0 \cdot \frac{N_{di}}{2} + N_{Eb} \cdot \left(N_R + \frac{N_{di}}{2}\right)^2\right)^{-1}\right) \cdot \frac{N_{di}}{2}\right)^{-1} \end{aligned}$$

$$\begin{aligned} & \times \left(P_0 - N_{B_0} \cdot \left(N_R + \left(1 - P_0 \cdot \left(N_R + \frac{N_{di}}{2} \right) \right. \right. \right. \\ & \times \cdot \left. \left. \left. \left(P_0 \cdot \frac{N_{di}}{2} + N_{Eb} \cdot \left(N_R + \frac{N_{di}}{2} \right)^2 \right)^{-1} \right) \cdot \frac{N_{di}}{2} \right)^{-2} \right), \end{aligned} \quad (5.29)$$

where the following are entered in the PC 15: the value of tension P_0 , code N_R , which corresponds to the radius of curvature of the guide R , code $N_{\mu\varphi}$, corresponding to the value $e^{\mu_T \varphi_T}$, code N_{Eb} , corresponding to the value $E_1 b_k$, code N_{B_0} , corresponding to the value $B_0/2$. Code N_{di} corresponds to the diameter $d_{\gamma i}$ ($i = 1, 2 \dots$, measuring channel number) and is determined programmatically by expression (5.28) in PC 15.

The values, which in the form of codes N_R , $N_{\mu\varphi}$, N_{Eb} , N_{B_0} are entered into the memory of the computerized system and affect the calculation of the values of the threads tension P_1 in the waveguides UUS2.

Ultrasonic transducers UUS2 can also be configured to detect the breakage of the threads in the waveguide at certain received values of the codes N_3 and N_4 to be able to stop the process equipment.

The proposed computerized ultrasonic system allows for operational non-contact control of important parameters for various textile materials in the production process. Two modes of operation of the scanning ultrasonic system are applied, so the specified is reached through switching UUS1 and UUS2 depending on the set task.

If we consider the advantages of the ultrasonic sensors of the system, they can be used for a long time compared to existing contacts. This is due to the lack of contact of ultrasonic sensors with the controlled material. In comparison, for contact sensors, there is a set time after which their characteristics may exceed the permissible limits as a result of contact with the material. Therefore, further integration of contactless technologies for determining the tension of threads on textile equipment will improve the quality of textile fabrics and increase the service life of such systems compared to similar contacts. Non-contact determination of the basis weight of textile fiber mass will improve technological processes while reducing the cost of raw materials in the production process.

5.3 Development of a Computerized System for Scanning Textile Materials with the Determination of Their Basis Weight by Phase and Amplitude-Phase Ultrasonic Methods

The analysis showed that determining the basis weight of textile materials using the non-contact phase method, in which the fabrics are irradiated with ultrasonic waves, gives a number of advantages over the standard weighing method. The main advantage is the efficiency of the technological parameter control. The textile material

is irradiated with ultrasonic waves and the value of the technological parameter is determined by the phase shift of the ultrasonic waves that have passed through the material if its structure is homogeneous. To control a textile material with a complex structure, in the presence of through pores in it, it is necessary to use a combined method that will take into account the characteristics of the structure and its impact on the probing signal passing. The combined method can be based on two informative parameters of oscillations, such as phase shift and change of amplitude of the reflected ultrasonic wave that gives the chance to consider features of material structure influence on the basis weight measurement [14–20].

For operative control of technological parameters of textile homogeneous mass and characteristics of different fibers, the application cases of the phase method are known [7, 8]. Although these works gave the indicator “surface quantitative density”, which differs from the basis weight, the nature of the dependences is similar to the phase shift of oscillations, and is close to linear, for a certain range of input values. The following studies [7, 8] of the dependence of the phase of ultrasonic waves on the linear density of the fibrous tape are also known. However, in the above sources, the cases of only the registration of the ultrasonic waves phase shift for a homogeneous fiber mass were considered, and for textile fabrics with a complex structure, such studies were not provided.

For non-contact operative control of the basis weight of various textile materials both with homogeneous fiber mass and textile fabrics with complex structure with the through pores, it is necessary to apply theoretical researches of ultrasonic waves propagation in environments with several crossing lines between them. Such studies should reflect the dependence of the change in phase shift on the basis weight of the material with and without considering the through pores in the textile fabric itself. This is an essential problem, which today does not allow the creation of high-precision technological control devices adaptive to the structure of the material. Such devices could be used in the light industry in the process of operational non-destructive technological control of various textile materials. Therefore, such studies, which were presented earlier, and the development of a new contactless computerized control system of the basis weight of textile materials will in the future open up new opportunities for maintaining high-quality textiles of domestic production.

To control the basis weight of different textile materials, you can use the phase method using the amplitude of the ultrasonic signal reflected from the surface of the material. This signal is used to determine part of the ultrasonic waves passing through the pores of the material. Determination of porosity is necessary to control materials with a complex structure, which are textile fabrics, because the passing of ultrasonic waves through them is a complex process that can be partially described by the principle of superposition of two signals, the first of which passes through the threads in the fabric, and the second one passes through the pores of the material. Therefore, if it is necessary to control the basis weight of a homogeneous textile mass, it is possible to use only the phase contactless method, and if it is needed to control textile fabrics with a complex structure, it is necessary to use a combined amplitude-phase method. Let us consider these two cases below.

To determine the basis weight of a homogeneous textile mass, it is possible to use the dependence obtained for the phase shift of the ultrasonic waves of the pulse signal passing through the textile material relative to the incident waves:

$$\begin{aligned} \varphi_W = \arctg & \left(\sum_{N=0}^{\infty} \left(\frac{Z_2 - Z_1}{Z_1 + Z_2} \right)^{2N} \cdot \exp \left(- \frac{\left(\frac{K m_s (b(2N+1) \cos \nu + 1)}{\pi Z_2} - t \right)^2}{\left(\frac{\tau_0}{2 \ln \sqrt{2}} \right)^2} \right) \right. \\ & \left. - \frac{\alpha_3 \cdot (2N+1) K m_s \cos \nu}{\pi \rho_2} \right) \cdot \sin \left(\omega_0 \left(\frac{K m_s (b(2N+1) \cos \nu + 1)}{\pi Z_2} - t \right) \right) \\ & \times \left(\sum_{N=0}^{\infty} \left(\frac{Z_2 - Z_1}{Z_1 + Z_2} \right)^{2N} \cdot \exp \left(- \frac{\left(\frac{K m_s (b(2N+1) \cos \nu + 1)}{\pi Z_2} - t \right)^2}{\left(\frac{\tau_0}{2 \ln \sqrt{2}} \right)^2} \right) \right. \\ & \left. \left. - \frac{\alpha_3 \cdot (2N+1) K m_s \cos \nu}{\pi \rho_2} \right) \cdot \cos \left(\omega_0 \left(\frac{K m_s (b(2N+1) \cos \nu + 1)}{\pi Z_2} - t \right) \right) \right)^{-1}, \end{aligned} \quad (5.30)$$

where for this case: t —ultrasonic signal propagation time; Z_1 —acoustic resistance of the environment (air); Z_2 —acoustic resistance of the fiber material; α_3 —the attenuation coefficient of ultrasonic waves in the fiber material; K —coefficient that considers the volume of air in the fiber material; ν —the angle between the vector of waves reflected from the fibers of the material and passing through them; ρ_2 —the bulk density of the fiber material.

At $\alpha_3 = 0$ dependence (5.30) can be shown as follows:

$$\begin{aligned} \varphi_W = \arctg & \left(\sum_{N=0}^{\infty} \left(\frac{Z_2 - Z_1}{Z_1 + Z_2} \right)^{2N} \cdot \exp \left(- \frac{\left(\frac{K m_s (b(2N+1) \cos \nu + 1)}{\pi Z_2} - t \right)^2}{\left(\frac{\tau_0}{2 \ln \sqrt{2}} \right)^2} \right) \right) \\ & \times \sin \left(\omega_0 \left(\frac{K m_s (b(2N+1) \cos \nu + 1)}{\pi Z_2} - t \right) \right) \\ & \times \left(\sum_{N=0}^{\infty} \left(\frac{Z_2 - Z_1}{Z_1 + Z_2} \right)^{2N} \cdot \exp \left(- \frac{\left(\frac{K m_s (b(2N+1) \cos \nu + 1)}{\pi Z_2} - t \right)^2}{\left(\frac{\tau_0}{2 \ln \sqrt{2}} \right)^2} \right) \right) \\ & \times \cos \left(\omega_0 \left(\frac{K m_s (b(2N+1) \cos \nu + 1)}{\pi Z_2} - t \right) \right) \right)^{-1}. \end{aligned} \quad (5.31)$$

Figure 5.5a shows a dependence graph of the phase shift φ_W of ultrasonic waves on the basis weight m_s of a homogeneous fiber mass.

To show how the pulse signal changes over time in amplitude with a certain phase shift φ_W depending on the basis weight m_s of the textile material, provided that $\alpha_3 = 0$, then the expression for the pulsed ultrasonic signal is shown as:

$$A_1(t) = \frac{4 Z_1 Z_2}{(Z_1 + Z_2)^2} \sum_{N=0}^{\infty} \left(\frac{Z_2 - Z_1}{Z_1 + Z_2} \right)^{2N} \cdot \cos \left(\omega_0 \left(\frac{K m_s (b(2N+1) \cos \nu + 1)}{\pi Z_2} - t \right) \right)$$

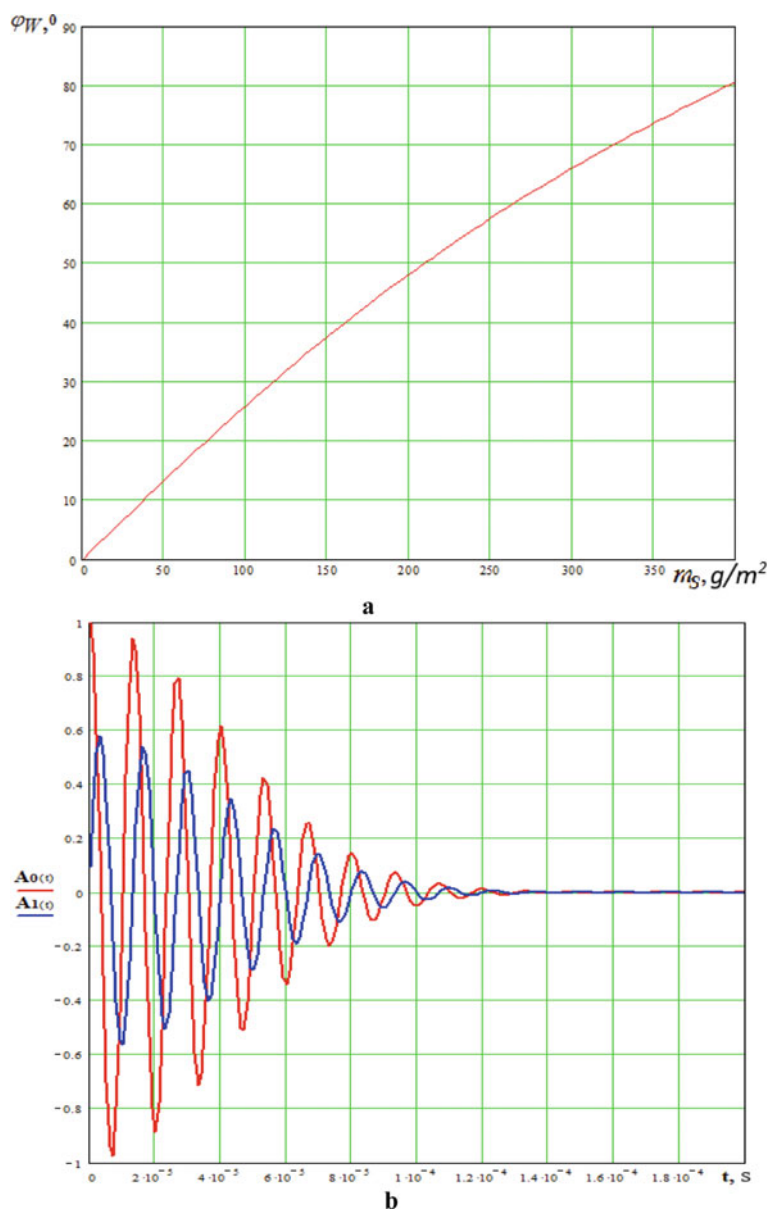


Fig. 5.5 Interaction of ultrasonic waves with a homogeneous fiber mass: **a** phase shift dependence φ_W of the ultrasonic waves from basis weight m_s of the homogeneous fiber mass; **b**—pulsed ultrasonic signals, the first $A_0(t)$ of which is emitted, and the second $A_1(t)$ has already passed through the fibrous material with a basis weight $m_s = 400 \text{ g/m}^2$

$$\times \exp \left(- \frac{\left(\frac{K m_s (b(2N+1) \cos v + 1)}{\pi Z_2} - t \right)^2}{\left(\frac{\tau_0}{2 \ln \sqrt{2}} \right)^2} \right). \quad (5.32)$$

Figure 5.5b shows a comparison of pulsed ultrasonic signals, the first of which is emitted, and the second one has already passed through the fibrous medium of the material with a basis weight of 400 g/m².

From the graphs in Fig. 5.5b it can be seen that the phase shift for this case will be $\phi_W \approx 80^\circ$, and the amplitude of the ultrasonic waves that have passed the fiber mass $A_1 = 0.58$, relative to the unit amplitude of the ultrasonic incident waves $A_0 = 1$. It is seen that by changing the phase of the pulse signal, it is possible to determine the basis weight m_s of textile materials.

For computerized control of textile fabrics (continuous scanning of the fabric in the process of its production and processing of the received information with further decision-making) with a complex structure of the material, it is necessary to use a combined amplitude-phase method. For this method, the dependence of the complex coefficient modulus $|W|$ of the ultrasonic wave passing through the textile fabric with a complex structure can be represented as follows:

$$|W| = \frac{1}{\sqrt{1 + \left(\frac{K m_s f \cos v}{Z_1} \right)^2}}, \quad (5.33)$$

then the real $\text{Re}W$ and imaginary $\text{Im}W$ parts of the complex coefficient of passing W can be represented as:

$$\text{Re}W = \frac{1}{1 + \left(\frac{K m_s f \cos v}{Z_1} \right)^2}, \quad \text{Im}W = \frac{\left(\frac{K m_s f \cos v}{Z_1} \right)}{1 + \left(\frac{K m_s f \cos v}{Z_1} \right)^2}, \quad (5.34)$$

where can we express the phase shift for a textile fabric with a complex structure and show the following dependence:

$$\varphi_W \approx \arctg \left(\frac{K m_s f \cos v}{Z_1} \right) \cdot \frac{4}{3}. \quad (5.35)$$

Figure 5.6 shows the dependences of the change of phase shift φ_W depending on the basis weight of textile fabrics with different porosity.

Figure 5.6 shows that the graphs are close to linear with different angles of inclination depending on the material porosity. Graphs with a larger phase shift at the same basis weight correspond to materials with smaller pores.

Therefore, to exclude the influence of the parameter of the porosity change between the threads in the textile fabrics on the result of phase shift measurements and determination of the basis weight m_s it is necessary to apply the amplitude of the

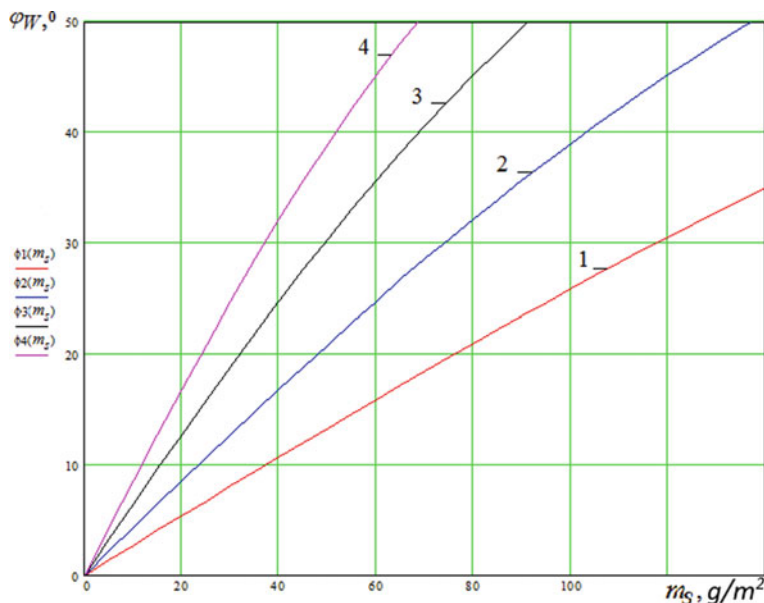


Fig. 5.6 Dependences for the phase shift φ_W of ultrasonic waves that have passed through different textile materials with different pores between the threads, on the basis weight m_s : 1—dependence of the phase shift φ_1 of ultrasonic waves on the basis weight m_s of the textile fabric with the pore sizes taken as a reference; 2—dependence of the phase shift φ_2 of ultrasonic waves on the basis weight m_s of the textile fabric with pore sizes 1.59 times smaller than the reference; 3—dependence of the phase shift φ_3 of ultrasonic waves on the basis weight m_s of the textile fabric with pore sizes 2.39 times smaller than the reference; 4—dependence of the phase shift φ_4 of ultrasonic waves on the basis weight m_s of the textile fabric with pore sizes 3.18 times smaller than the reference

reflected ultrasonic signal. It will allow adjustments to be made for a coefficient K that takes into account the volume of air in the material and is included in expression (5.35). This dependence of the coefficient K correction on the change in pore size can be given as follows:

$$K = \frac{K_0 Q_{0p}}{Q_p} = \frac{K_0 |V|}{|V_0|}, \quad (5.36)$$

where for this case:—the coefficient K_0 of the reference textile fabric, which takes into account the distance and volume of air between the threads of the reference fabric; Q_{0p} , Q_p —porosity of reference and controlled textile materials; $|V_0|$, $|V|$ —modules of coefficients of ultrasonic vibrations reflection from the reference and controlled textile fabrics.

Considering the dependence (5.36) for most textile fabrics with a basis weight $m_s \leq 300 \text{ g/m}^2$, for which the calculation error should not exceed $\delta_\varphi \leq 2\%$, the expression (5.35) can be given as follows:

$$\varphi_w = \arctg\left(\frac{K_0 |V| m_s f \cos v}{Z_1 |V_0|}\right) \cdot \frac{4}{3}. \quad (5.37)$$

Using the above combined amplitude-phase method (Fig. 5.7), it is possible to determine the basis weight m_s of textile fabrics with a complex structure that have through pores between the threads. The block diagram of the computerized system, which can be used to control the basis weight m_s of textile materials by phase and amplitude-phase methods, is presented in Fig. 5.8, and the scanning algorithm is shown in Fig. 5.9.

The scanning system includes a pulse signal shaper 1, a power amplifier 2, a radiating and receiving transducer 3, a radiating transducer 4, receiving transducers 5 and 6, adjustable amplifiers 7, 13, 14, phase shifters 8, phase detectors 8, and phase detectors. detectors 15 and 16, voltage difference unit 11, voltage ratio unit 17, microcontrollers (MC) 12 and 18, logic level conversion chip 19, personal computer 20 (PC 20), and motor control unit for stepper motors for moving scanning platforms 21 (MCU 21), controlled textile material 22.

Let us describe the operation of this computerized system for scanning textile materials. The electrical oscillations from the pulse signal shaper 1 are amplified by the power amplifier 2 and fed to the emitting transducer 3. The emitted ultrasonic oscillations are received by the transducer 5 after passing through the controlled textile material 22. Radio pulses are also fed to the radiating transducer 4, and emit ultrasonic oscillations, which enter the receiving transducer 6 after passing through the environment.

Electrical oscillations from the second receiving transducer 6 are transmitted to one input of the ratio unit 17 after amplification by an adjustable amplifier 13 and detection followed by their conversion by the amplitude detector 15 to DC voltage, the other input is supplied to the output DC voltage of the amplitude detector 16, after converting the pulses of the receiving transducer 3 to amplify them with an adjustable amplifier 14. The output voltage of the ratio unit 17 can be represented as the product of the base voltage and the ratio of the amplitudes of the ultrasonic waves reflected from the surface of the textile material to the amplitude of the waves incident on the fabric surface. By comparing this voltage, it is possible to determine the change in the porosity of the controlled material 22 relative to the reference material. This occurs in the process of constant movement of the scanning platforms relative to the fabric with transducers of ultrasonic waves into electrical oscillations, using the control unit MCU 21.

Electrical oscillations from the receiving transducer 6 are also fed to the phase shifter unit 8 and phase detector 10, the output voltage of which is proportional to the phase shift of the ultrasonic oscillations passing through the environment and falling on the textile material of the fabric 22. The voltage from phase detector 10 gets to one input of the voltage difference unit 11, the voltage from the output of phase detector 9 gets to the second input after amplifying the oscillations with the adjustable amplifier 7, which gets to its input.

The output voltage of detector 9 is proportional to the phase shift of the ultrasonic oscillations passing through the environment and the textile material of the fabric 22.

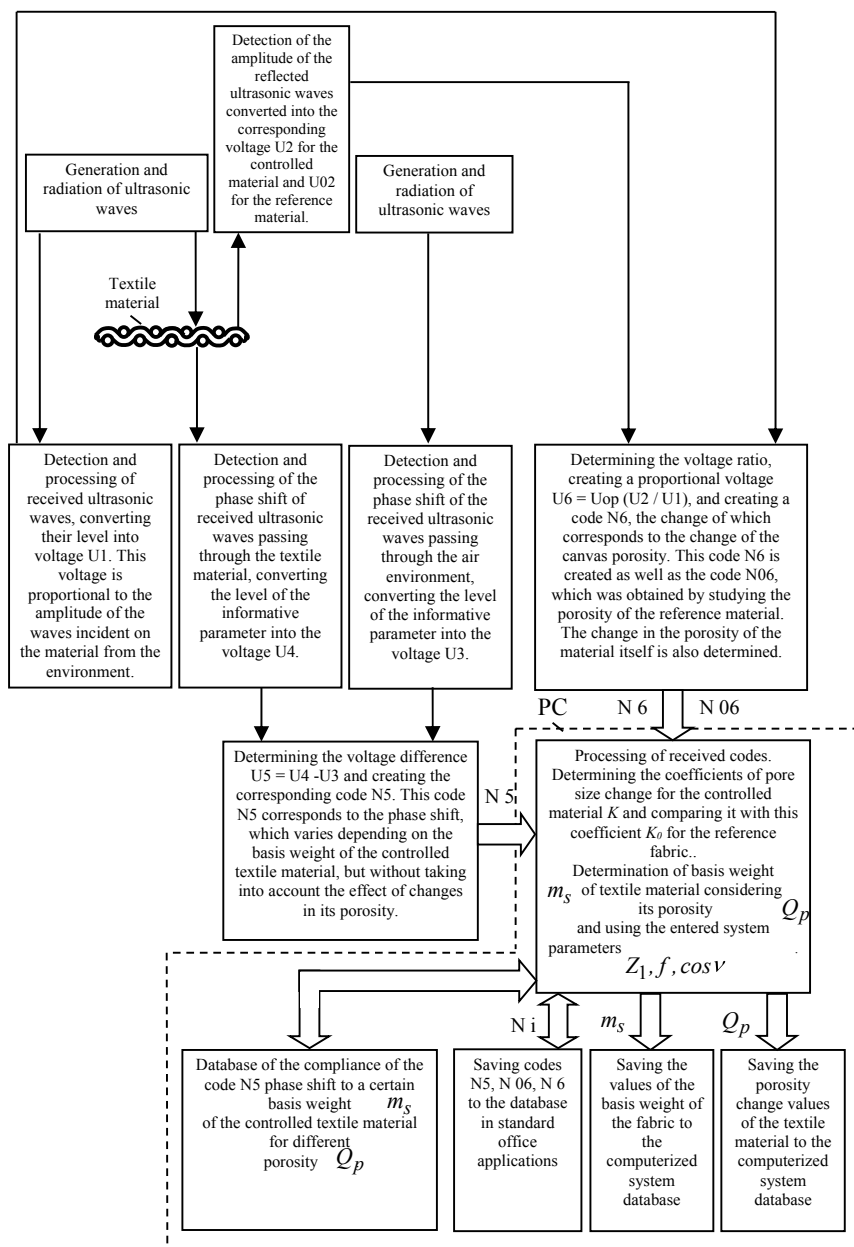


Fig. 5.7 The structure of system operations for implementing the amplitude-phase method of controlling the basis weight fabrics

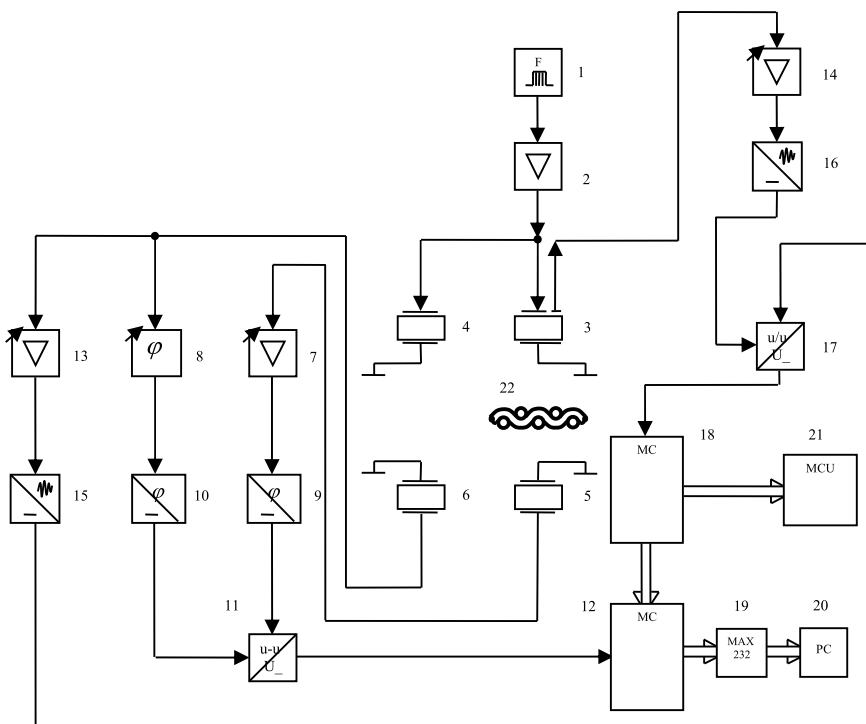


Fig. 5.8 Block diagram of a computerized system that helps to control the basis weight m_s of textile materials by phase and amplitude-phase methods

The voltages from the difference unit 11 and the ratio unit 17 are transmitted to the analog inputs of microcontrollers 12 and 18 respectively. With the help of internal analog-to-digital converters (ADC) of microcontrollers, digital codes are created that take part in determining the basis weight m_s of textile fabrics with different through pores between the threads.

Moreover, the value of the porosity change is transmitted in the form of a code to the first MC 12 from the second MC 18. The signal of the setting program for the MCU 21 also comes from MC 18. From the output of MC 12 to PC 20, through the logic level conversion chip 19, the value of the basis weight m_s of the textile fabric 22 is transmitted. This parameter value is determined using the received codes in the microcontroller using tabular values, which are written to the system memory using the dependence (5.37).

The phase shifter 8 and the adjustable amplifiers 7, 13 and 14 help to set up a properly computerized system for automated scanning before starting measurements to zero readings.

To determine the basis weight of textile materials by the phase method, the ratio $|V|/|V_0| = 1$ is taken in expression (5.37) for basis weight $m_s \leq 150 \text{ g/m}^2$. At the same time, the error for the phase shift φ_W should not exceed $\delta_{\varphi_W} \leq 2.5\%$, and the

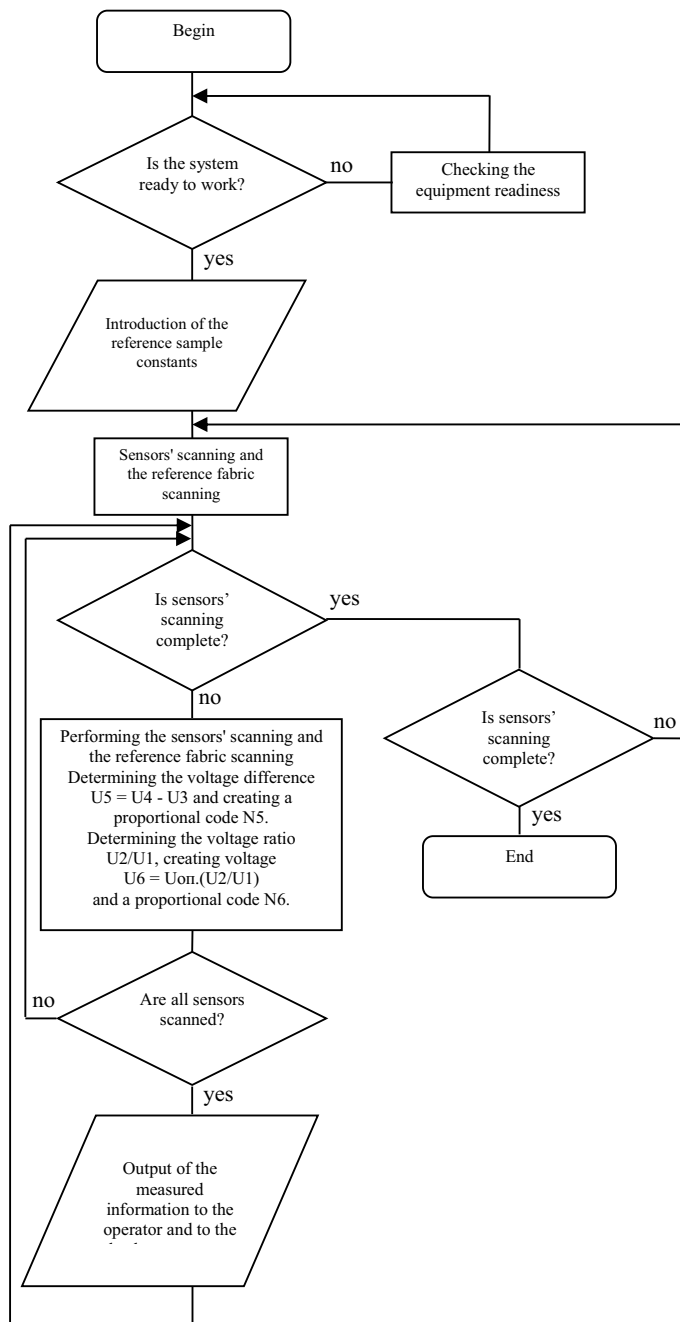


Fig. 5.9 Algorithm of the process of ultrasonic scanning of textile materials by a computerized system with amplitude-phase control method

channel for measuring the amplitude of the reflected ultrasonic waves is turned off. If it is necessary to determine the basis weight non-contact $m_s \leq 400 \text{ g/m}^2$ using the phase method with an error that should not exceed $\delta_{\varphi_w} \leq 1.5\%$, then it is necessary to apply the dependence (5.31) to calculate the values of the unknown parameter.

The paper presents the results of non-contact basis weight m_s control studies for a homogeneous textile fiber mass using the ultrasonic phase method. The principle of a computerized scanning system operation has been shown, as well as the study of the contactless control possibility of the textile fabrics' basis weight m_s . In these conditions, the through pores between the threads are considered using a combined amplitude-phase method.

The problem of determining the basis weight m_s of the fabric is solved by using a change in the ultrasonic wave amplitude, which is reflected from the surface of the controlled material. At the same time, the sizes of fabric pores may change in comparison with the reference sample which, in turn, influence the amplitude of the reflected ultrasonic wave. Then, taking into account the influence of textile porosity on the general readings of measuring instruments, it is possible to determine the value of the basis weight m_s of the material by changing the phase of the waves passing through the fibers and the pores of the fabric.

Summarizing the above, the studies on the possibility of contactless control of the fabric's basis weight m_s have shown that by changing the amplitude of reflected ultrasonic waves from materials with complex structure and by changing the phase shift of waves passing through these materials, it is possible to determine this technological parameter taking into account through pores between threads of the fabric.

The analysis proves the feasibility of creating new contactless phase methods and systems of operational computerized control. These new methods and control systems of the main technological parameters for various textile materials can be applied directly in the production process.

5.4 Development of an Ultrasonic Computerized System for Controlling the Bulk Density of Textile Materials

To control most of the materials used in modern industry, the parameter of basis weight is used, although this is the one indicator that determines both the performance and quantitative characteristics of various sheet and textile materials. When determining this technological parameter, the thickness of the material itself is neglected, but there are cases when it is necessary to determine the bulk density of the material in production (when calculating and creating composite structures for various industrial tasks). Bulk density provides information about the quality of the material, and the material thickness is considered in the definition process [21–26].

To control the bulk density of textile materials by contact destructive method, it is necessary to cut control samples of material from the fabric, to measure the geometric

dimensions of the samples using micro-sections with the following weighing of these samples on the scales.

Today, there is no standard non-contact method for determining the bulk density of textiles, which would allow you to quickly control this parameter of textiles and would be easy to implement and operate. Therefore, to control a textile material with a complex structure, it is necessary to apply a method that will take into account the characteristics of the structure and its impact on the informative parameters of the sounding signal during measurement.

There is a method of determining the bulk density of textile materials, which consists in the fact that the radioactive radiation falls on the sample of textile material with a certain thickness, and the change in the intensity of the radiation that passes through it, determines the bulk density. However, this method of determining the bulk density of textile materials has disadvantages, which are mainly related to the harmful effects of radioactive radiation on humans and the need to protect them from it.

There is also a method of determining the bulk density of textile materials, which consists in the fact that a flat sound wave with a fixed amplitude falls on a sample of the textile material with a certain thickness, and the amplitude of the wave that passed through the material determines its bulk density. However, this method of determining the bulk density of textile materials does not take into account the change in amplitude attenuation caused by different pore sizes of materials and does not take into account changes in geometric dimensions and location of threads in their structure, which may affect the control result. The method of ultrasonic control of the bulk density of textile materials in [7, 8] is also described.

The method consists in sounding the textile material with ultrasonic waves perpendicular to its surface, and the waves are reflected from it, then converting the received ultrasonic vibrations into electric voltage, and its amplitude and the propagation time of ultrasonic vibrations in the material can determine its bulk density. However, this method of ultrasonic control of the bulk density of textile materials does not ultimately take into account the effect of changes in the geometric dimensions of the textile material threads on the amplitude of the reflected ultrasonic waves.

The method and device for determining the change in the speed of ultrasonic waves propagation in a fiber textile mass [7, 8] are also known.

This method makes it possible to indirectly determine the bulk density of textile materials without taking into account their structure, which is a significant drawback and can lead to significant errors in determining the required parameter.

For non-contact operative control of the bulk density of various textile materials, it is necessary to research ultrasonic waves propagation in several systems of threads. This will allow in the future to create high-precision technological control devices adaptive to the material structure. Such devices could be used in the operational control process of the bulk density of various textile materials, which will increase the competitiveness of finished products with the specified quality characteristics.

The ultrasonic method for determining the bulk density of textile materials (Fig. 5.10), which would be able to exclude the influence of tension and porosity

of the fabric threads on the amplitude of the waves that passed through them, will increase the probability of bulk density control.

Figure 5.11 shows a block diagram of a computerized system that implements the method of controlling the bulk density of textile materials. The algorithm of the scanning process is shown in Fig. 5.12.

The computerized system includes microcontrollers (MCs) 1 and 2, a sound pulse generator 3, a power amplifier 4, a radiating piezoelectric transducer 5, receiving piezoelectric transducers 6 and 7, adjustable power amplifiers 8 and 13, amplitude

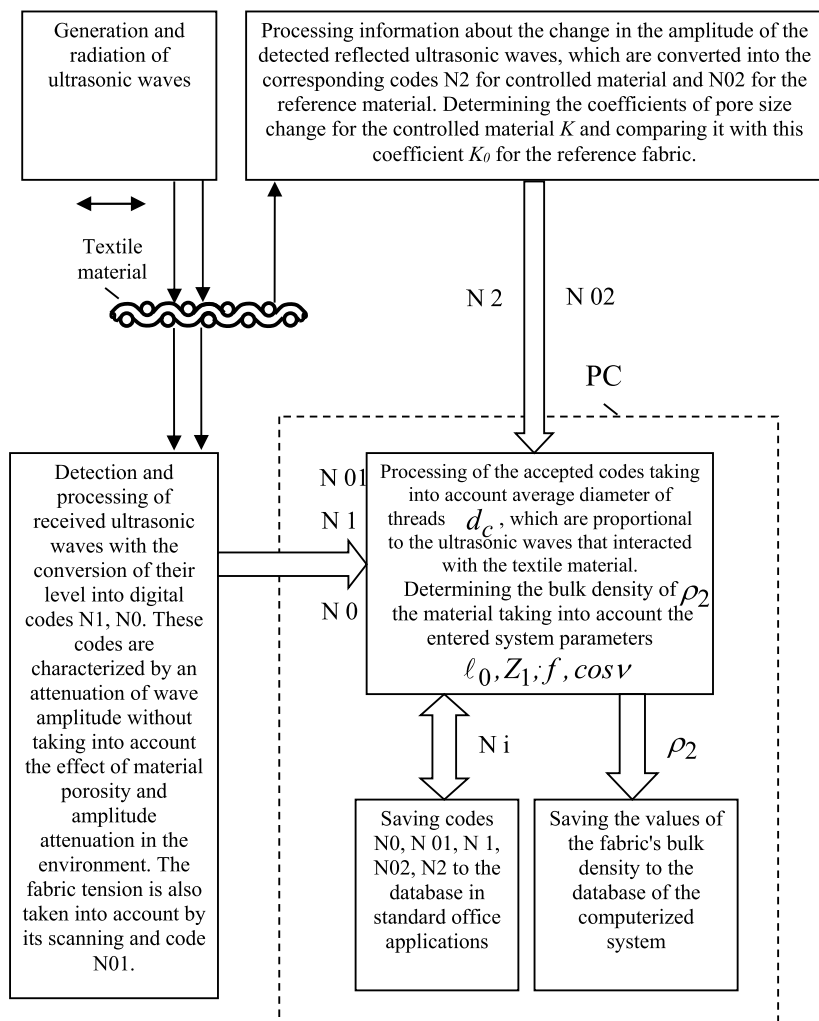


Fig. 5.10 The structure of system operations to implement the amplitude control method of bulk density of textile materials

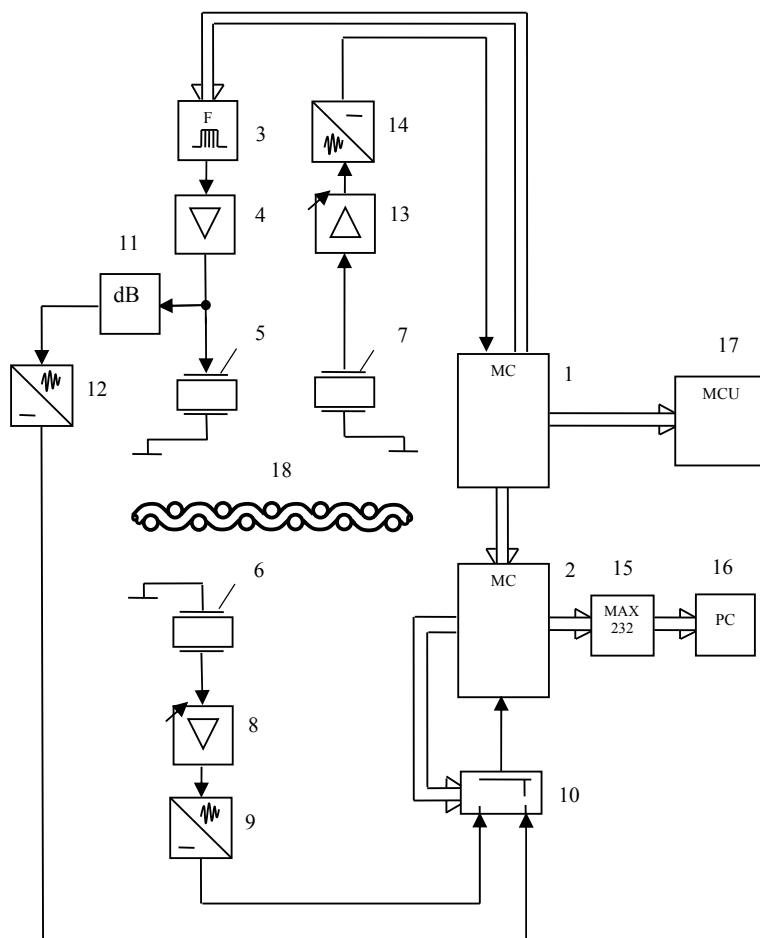


Fig. 5.11 Block diagram of a computerized system that enables control of the bulk density of textile fabrics

detectors 9, 12, and 14, attenuator 11, switching unit 10, logic level conversion chip 15, personal computer 16 (PC 16), motor control unit 17 (MCU 17) for a scanning mechanism that moves non-contact ultrasonic transducers over the entire area of the textile fabric 18.

The system works as follows. The electric pulses with frequency f , which are generated by MC 1, are transmitted to the input of the sound pulse generator 3, from the output of which the packets of pulse signals are transmitted with voltage U_m , which is amplified by power amplifier 4 and transmitted to the radiating piezoelectric transducer 5.

The controlled textile fabric 18 is inserted between the radiating piezoelectric transducer 5 and the receiving piezoelectric transducer 6 of the measuring ultrasonic

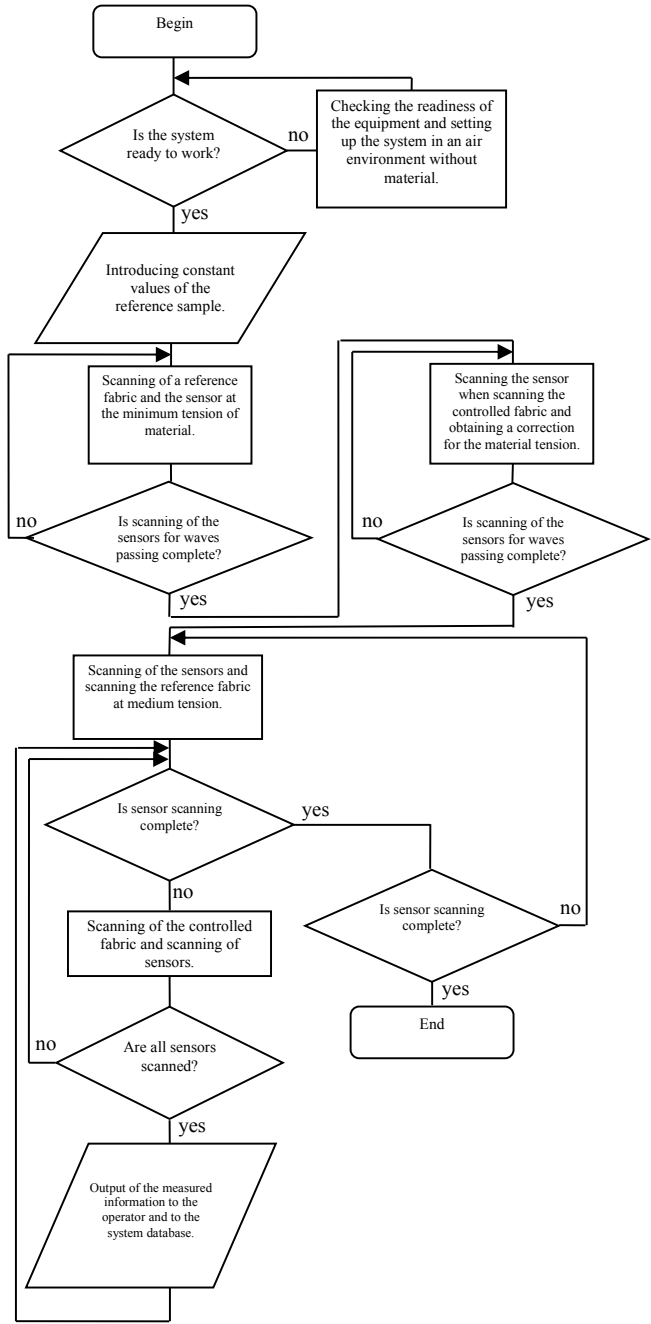


Fig. 5.12 Algorithm of the process of ultrasonic scanning of textile materials by a computerized system with the amplitude control method

channel. The ultrasonic oscillations emitted by the piezoelectric transducer 5 pass through the controlled textile material 18 and enter the receiving piezoelectric transducer 6, where they are converted into electrical oscillations, after amplification by an adjustable amplifier 8, then they enter the amplitude detector 9, where they are converted into DC voltage U_1 .

The generated voltage U_1 is transmitted to the switching unit 10, which at a certain point in time passes it to the input MC 2, where it is converted by an internal analog-to-digital converter (ADC) MC 2 into the code N_1 . In turn, MC 2 synchronizes such switching of the channel using the switching unit 10 with the time of transmitting ultrasonic waves to the receiving piezoelectric transducer 6 with the subsequent voltage U_1 formation.

Before that, the voltage U_0 is fixed, which is generated after the attenuation of the sounding pulses by the attenuator 11 and passing the amplitude detector 12. The amplitude is proportional to the amplitude of the ultrasonic oscillations emitted by the radiating piezoelectric transducer 5.

Then the voltage U_0 gets to MC 2, where it is converted into the digital code N_0 . The corresponding codes can be shown by the following dependencies:

$$N_0 = \frac{U_0}{r_{u2}} = K_1 K_2 K_6 K_7 \frac{U_m}{r_{u2}}, \quad (5.38)$$

$$N_1 = \frac{U_1}{r_{u2}} = K_1 K_3 K_4 K_5 K_7 \frac{1}{\sqrt{1 + \left(\frac{K m_s f \cos v}{\rho_1 c_1} \right)^2}} \frac{U_m}{r_{u2}}, \quad (5.39)$$

where r_{u2} —the unit of the least significant digit of ADC MC 2 by voltage; K_1 —the amplifier gain 4; K_2 —attenuation ratio of attenuator 11; K_3 —oscillation conversion factor of the radiating piezoelectric transducer 5 and the receiving piezoelectric transducer 6; K_4 —the adjustable amplifier gain 8; K_5 —the voltage conversion factor of the amplitude detector 9; K_6 —the voltage conversion factor of the amplitude detector 12; K_7 —the signal transmission factor of the switching unit 10.

A part of the ultrasonic oscillations is reflected from the controlled textile fabric 18 and gets to the receiving piezoelectric transducer 7, through which they are converted into electrical oscillations, and then they are amplified by power-adjustable amplifier 13 and get to the amplitude detector 14, where they are converted into DC voltage U_2 . This voltage is transmitted to the MC 1 input, where it is converted into a digital code using its own internal ADC chip. This can be represented as follows:

$$N_2 = \frac{U_2}{r_{u1}} = K_1 K_8 K_9 K_{10} \frac{K_\rho}{\sqrt{1 + \left(\frac{\rho_1 c_1}{K m_s f \cos v} \right)^2}} \frac{U_m}{r_{u1}}, \quad (5.40)$$

where r_{u1} is the unit of the least significant digit of ADC MC 2 by voltage; K_ρ —a coefficient that characterizes the dependence of the reflected ultrasonic vibrations, which get to the receiving piezoelectric transducer 7, on the structure of the controlled

textile material 18 and its position; K_8 —oscillation conversion factor of the radiating piezoelectric transducer 5 and the receiving piezoelectric transducer 7; K_9 —the adjustable amplifier gain 13; K_{10} —the voltage conversion factor of the amplitude detector 14.

To eliminate the effect of the textile fabric tension 18 on the bulk density ρ_2 measured values readings, before the main measurements of the required parameter, MC 1 moves the piezoelectric transducers 5 and 6 along the entire area of controlled textile material using MCU 17. This happens according to a system algorithm. The area of the textile fabric 18 with the most deformed threads by the tension on the process equipment is determined, using piezoelectric transducers 5 and 6. With increasing tension of the fabric 18 in a certain area where the deformation of the threads is the greatest, the amplitude of the ultrasonic vibrations that have passed through it decreases in magnitude, respectively, the voltage U_1^* and code N_1^* corresponding to this section of the fabric 18 will also decrease. The code N_1^* is compared with the code N_{01}^* formed by the voltage U_{01}^* when the ultrasonic waves pass through the reference material of the fabric without tension or at its minimum values. Next, the values N_1^* and N_{01}^* introduce the correction for the tension of the controlled fabric 18 in determining its bulk density by the ultrasonic sounding of the material.

Also, to determine the bulk density ρ_2 of the textile fabric 18, it is necessary to exclude the effect of its porosity Q_p changes relative to the reference fabric porosity Q_{0p} . This effect can be eliminated by controlling the change in the coefficient K (towards the reference textile fabric), which mainly changes with decreasing or increasing pores between the threads of the controlled textile fabric 18. This change can be recorded by the change of the ultrasonic signal which is reflected from the controlled textile fabric 18 and get to the receiving piezoelectric transducer 7 in regard to the ultrasonic signal which is reflected from the reference textile fabric and get to the receiving piezoelectric transducer 7 before. The change in the value of the coefficient K of the controlled textile fabric 18 can be determined by changing the value of the DC voltage U_2 or code N_2 relative to the DC voltage U_{02}^* or the code N_{02}^* that was formed when sounding the reference textile material. Knowing that the controlled fabric 18 porosity Q_p and the reference fabric porosity Q_{0p} are directly related to the coefficient K , then the expression of their ratio can be shown by the dependence (5.36). Taking into account expression (5.36), it is possible to determine the value of the coefficient K of the controlled textile fabric 18 by relating it to voltages U_2 , U_{02}^* and N_2 , N_{02}^* as follows:

$$K = \frac{U_2}{U_{02}^*} \cdot K_0 = \frac{N_2}{N_{02}^*} \cdot K_0. \quad (5.41)$$

The value of the coefficient K_0 of the reference textile material is determined once. Since the bulk density ρ_2 of the controlled textile fabric 18 is directly related to the basis weight m_s , and their relationship can be shown by the following expression:

$$\rho_2 = \frac{4K m_s}{\pi^2 d_{oy}}, \quad (5.42)$$

where d_{oy} is the sum of the diameters of the warp threads and weft of the controlled textile fabric 18, then, taking into account the dependence (5.42), the bulk density ρ_2 can be set as follows:

$$\rho_2 = \frac{4\rho_1 c_1 \sqrt{\left(\frac{U_0}{U_1}\right)^2 - 1}}{\pi^2 d_{oy} f \cos \nu} = \frac{2\rho_1 c_1 \sqrt{\left(\frac{U_0}{U_1}\right)^2 - 1}}{\pi^2 d_c f \cos \nu}. \quad (5.43)$$

To exclude the effect of changing the geometric dimensions of the textile fabric threads 18 and to control its bulk density ρ_2 with the help of ultrasonic waves, it is also necessary to use them to determine the average diameter d_c of the warp and weft threads of material. Studies have shown that the ratio of the average diameter d_c of the controlled textile fabric threads 18 to its average side length of the square through pore can be represented as:

$$\frac{\sqrt{K}}{2} = \frac{d_c}{\ell}, \quad (5.44)$$

or

$$\sqrt{K} = \frac{d_{oy}}{\ell},$$

then the average diameter d_c of the controlled textile fabric threads 18, taking into account the change in threads' tension, is determined by the reflected ultrasonic signal by the following expression:

$$d_c = \frac{\ell_0 U_1^* \sqrt{K}}{2 U_{01}^*} = \frac{\ell_0 U_1^* \cdot \sqrt{\frac{U_2}{U_{02}^*}} \cdot K_0}{2 U_{01}^*}, \quad (5.45)$$

where the side length ℓ_0 of the square through the pore of the reference textile fabric is determined once.

Studies have shown that for controlled textile fabrics with a basis weight m_s in the range from $m_s = 120 \text{ g/m}^2$ to $m_s = 280 \text{ g/m}^2$, with a long side length of the square through the pore of the reference fabric for the pore length of the controlled fabric $\ell_0 > \ell$, it is possible to determine exactly the average diameter d_c of threads with relative error 5%.

According to the voltages that are proportional to the ultrasonic signals interacting with the controlled and reference textile fabrics, taking into account the change in threads' tension of the fabric 18, the coefficient K and at $\rho_1 c_1 / (f \cos \nu) = \text{const}$, the bulk density ρ_2 , taking into account (5.45) and (5.43), can be determined as follows:

$$\rho_2 = \frac{4\rho_1 c_1 U_{01}^* \cdot \sqrt{\left(\left(\frac{U_0}{U_1}\right)^2 - 1\right) \frac{U_{02}^*}{U_2 K_0}}}{\pi^2 \ell_0 U_1^* f \cos \nu} = \frac{4\rho_1 c_1 N_{01}^* \cdot \sqrt{\left(\left(\frac{N_0}{N_1}\right)^2 - 1\right) \frac{N_{02}^*}{N_2 K_0}}}{\pi^2 \ell_0 N_1^* f \cos \nu}. \quad (5.46)$$

Therefore, knowing the value of the coefficient K_0 , of the side length ℓ_0 of the square through the pore of the reference textile fabric, the frequency intersection f and $\cos \nu$, the speed of propagation of ultrasonic vibrations in the air c_1 , the value of bulk air density ρ_1 , we can from expression (5.46) according to the received codes $N_0, N_1, N_1^*, N_{01}^*, N_2, N_{02}^*$ of the systems determine the bulk density of the controlled textile fabric 18.

The proposed computerized system can transmit codes that are proportional to the amplitudes of the ultrasonic vibrations that interact with the controlled textile fabric 18 through the logic level conversion chip 15 to the PC 16, where the measurement information will be further processed. The computer system can also process data autonomously using the MC 2 chip. The program algorithm of textile fabric 18 scanning and processing of measuring information may include the mobility mode of the system unit component for easy transportation and installation on various technological equipment without connection to a PC 16. This approach will provide flexibility to control various technological parameters in production which may include a developed ultrasonic component unit. It will give a chance for its additional use in laboratory control of textile fabrics in the light industry if necessary.

The ultrasonic method and a computerized system for determining the bulk density ρ_2 of textile fabrics can be used for non-contact control of this parameter and will allow:

- to exclude the influence of changes in the tension of the controlled textile fabrics threads on the amplitude of ultrasonic waves that interact with these materials;
- to exclude the influence of the controlled textile materials porosity and the influence of changes in the geometric dimensions of their threads on the amplitude of ultrasonic waves that interact with these materials and by which the bulk density is determined;
- to provide contactless operative control of the bulk density of textile fabrics on the technological equipment, directly in the manufacturing process.

5.5 Development of an Ultrasonic Computerized System for Controlling the Porosity of Textile Fabrics

Also today there is a need for automated control of technological parameters of various filter fabrics and products with a complex structure, as well as for sorting these materials directly in production. To implement this task, it is possible to use robotic systems with contactless sensors, which will optimize the sorting process and simplify the task of technical implementation of such systems. The various materials

that need to be controlled can have a complex structure. The complex structure for many materials used in filters for different purposes has the form of a grid, which may have different porosity. Porosity and basis weight must be taken into account when controlling filter textile materials for various purposes, both for cleaning gases, liquids, bulk solid materials, and for controlling products with a complex structure. Therefore, for sorting filter materials, as well as increasing the efficiency of control, it is possible to use the contactless method of determining the porosity of controlled products.

Pneumatic methods and tools can be used to sort materials with different porosity. However, the disadvantages of pneumatic methods and tools include low sensitivity, a small range of measured value, and operation complexity. Optical methods and tools can be used to determine the change in porosity of products with a complex structure by changing the intensity of optical radiation coming from a light source. However, their main disadvantages are low sensitivity to the measured value and errors that occur with significant dust content in the environment. It is advisable to use ultrasonic methods and tools that are easy to operate, have high measurement accuracy, as well as reliable operation for a long time in production conditions. Therefore, non-contact ultrasonic methods and tools can be used for further design and creation of computerized robotic systems for controlling and sorting the complex structure materials directly in production.

One of the informative parameters of the ultrasonic signal must be used for non-contact control and sorting of materials with a structure that is a conditional grid. By changing the amplitude of the reflected ultrasonic wave relative to the amplitude of the wave reflected from the reference material, the porosity of which was determined earlier, it is possible to determine the change in the porosity of the controlled material. If we measure the value and compare it with the standard, then, in this case, we can accurately determine the change in controlled porosity. Determination of the porosity change of filter materials using the ultrasonic non-contact method will allow to recognize and sort finished products by their purpose, as well as to identify defective products [27–30].

The amplitude of the ultrasonic wave, which normally falls on the controlled textile material and is reflected, knowing that the ratio of acoustic resistance of air and material $(\rho_1 c_1)/(\rho_2 c_2) \ll 1$, $\chi = (d_o + d_y) \frac{\pi}{4} \cos \nu$ for filter fabrics $\chi = H \cos \nu$ and nonwoven material can be represented as a modulus $|V|$ of complex reflection coefficient as follows:

$$\begin{aligned}
 |V| = & \left(1 + \left(1 - \left(ch \alpha_3 \chi + \frac{\rho_2 c_2}{2 \rho_1 c_1} \cdot sh \alpha_3 \chi \right) \cdot 2 \cos \frac{2 \pi f \chi}{c_2} \right) \right. \\
 & \times \left(\left(\left(ch \alpha_3 \chi + \frac{\rho_2 c_2}{2 \rho_1 c_1} \cdot sh \alpha_3 \chi \right) \cdot \cos \frac{2 \pi f \chi}{c_2} \right)^2 \right. \\
 & \left. \left. + \left(\left(sh \alpha_3 \chi + \frac{\rho_2 c_2}{2 \rho_1 c_1} \cdot ch \alpha_3 \chi \right) \cdot \sin \frac{2 \pi f \chi}{c_2} \right)^2 \right)^{-1} \right)^{\frac{1}{2}}, \quad (5.47)
 \end{aligned}$$

If we take into account that for filter materials the value $[(2\pi f/c_2) + \alpha_3] \chi \ll 1$, then expression (5.47) can be given as:

$$|V| = \sqrt{1 - \frac{1 + \alpha_3 \cdot \frac{\rho_2 c_2}{\rho_1 c_1} \chi}{\left(1 + \alpha_3 \cdot \frac{\rho_2 c_2}{2\rho_1 c_1} \chi\right)^2 + \left(\frac{2\pi f}{c_2} \cdot \frac{\rho_2 c_2}{2\rho_1 c_1} \chi\right)^2}}. \quad (5.48)$$

When the attenuation in the controlled material is less 2% and can be neglected $\alpha_3 \approx 0$, then the dependence (4.48) can be shown as follows:

$$|V| = \frac{1}{\sqrt{1 + \left(\frac{\rho_1 c_1}{\pi f \rho_2 \chi}\right)^2}} = \frac{1}{\sqrt{1 + \left(\frac{\rho_1 \lambda_1}{\pi \rho_2 \chi}\right)^2}}, \quad (5.49)$$

where λ_1 —the length of ultrasonic wave in the air.

Thus, with decreasing porosity of the controlled material, the amplitude of the reflected ultrasonic wave increases and vice versa. This dependence can be shown as:

$$\frac{|V|}{|V_0|} = \frac{Q_{0p}}{Q_p}, \quad (5.50)$$

where $|V_0|$ is the modulus of the complex coefficient of the ultrasonic wave reflection from the reference material with a known porosity; Q_{0p} , Q_p —known porosity and porosity of the controlled material.

Expression (5.50), considering the coefficients that characterize only the partial receipt of the reflected ultrasonic signals to the receiver, can be presented as follows:

$$\frac{|V| K_\rho}{|V_0| K_{\rho 0}} \approx \frac{Q_{0p}}{Q_p}, \quad (5.51)$$

where $K_{\rho 0}$, K_ρ is the coefficients of the reference and controlled materials which characterize the receipt of the reflected ultrasonic signal to the receiver of sound vibrations from the structural parameters of the materials and their position relative to the receiver.

When measuring, the amplitudes of the reflected ultrasonic vibrations are determined from the reference and controlled materials, which are proportional to the values $|V_0| K_{\rho 0}$ and $|V| K_\rho$.

Substituting the dependence (5.49) into (5.50) taking into account the condition $((d_o + d_y) \frac{\pi}{4})_0 = H_0$, $((d_o + d_y) \frac{\pi}{4})_2 = H_2$, if values $H_0 \approx H_2$ and $\rho_0 \approx \rho_2$ are almost the same (the difference is less 5%) for both reference and controlled materials, then we can represent the ratio of the coefficient modules of ultrasonic vibrations reflection in the following form:

$$\frac{|V|}{|V_0|} = \sqrt{\frac{((\pi f_0 \rho_0 H_0 \cos v_0)^2 + (\rho_1 c_1)^2) \cdot (\cos v_x f_0)^2}{((\pi f_0 \rho_0 H_0 \cos v_x)^2 + (\rho_1 c_1)^2) \cdot (\cos v_0 f_0)^2}}, \quad (5.52)$$

причем $\cos v_0$, $\cos v_x$ are values that characterize the pore size of the reference and controlled materials; f_0 —the frequency of ultrasonic waves that irradiate the reference and controlled materials (when performing the first measurements). In order to be able to determine exactly how much the pore size has changed in the controlled material, it is necessary by adjusting the frequency f_x of oscillations to ensure equality, which can be represented as follows:

$$\frac{|V|^*}{|V_0|} = \sqrt{\frac{(\pi f_0 f_x \rho_0 H_0)^2 + \left(\frac{f_x \rho_1 c_1}{\cos v_0}\right)^2}{(\pi f_0 f_x \rho_0 H_0)^2 + \left(\frac{f_0 \rho_1 c_1}{\cos v_x}\right)^2}} = 1, \quad (5.53)$$

where $|V|^*$ —modulus corresponding to the amplitude of the ultrasonic wave reflected from the controlled material, which changes during the frequency f_x control process.

At a certain position of the sensors and the controlled material, the following condition can be fulfilled $\frac{K_p}{K_{p0}} \approx 1$, and then:

$$\cos v_x = \sqrt{\frac{(f_0 \rho_1 c_1)^2}{\left(\pi f_0 f_x \rho_0 H_0 \frac{|V_0|}{|V|^*}\right)^2 + \left(\frac{f_x \rho_1 c_1}{\cos v_0} \frac{|V_0|}{|V|^*}\right)^2 - (\pi f_0 f_x \rho_0 H_0)^2}}. \quad (5.54)$$

If $\frac{|V|^*}{|V_0|} = 1$, then expression (5.54) can be written as:

$$\cos v_x = \frac{f_0}{f_x} \cdot \cos v_0. \quad (5.55)$$

Determining how much the pore size changes in the controlled material compared to the standard is possible after finding the value $\cos v_x$, and the total porosity can be found from the following expression::

$$Q_p = \frac{|V_0|}{|V|} \cdot Q_{0p}. \quad (5.56)$$

Based on the above, the relative change δ_Q in the porosity of the controlled material in percent can be presented as follows:

$$\delta_Q = \left(\frac{Q_{0p} - \frac{Q_{0p} |V_0|}{|V|}}{Q_{0p}} \right) \cdot 100\% = \left(1 - \frac{|V_0|}{|V|} \right) \cdot 100\%, \quad (5.57)$$

and the absolute change Δ_Q can be shown as follows:

$$\Delta_Q = Q_{0p} \cdot \left(1 - \frac{|V_0|}{|V|}\right). \quad (5.58)$$

Therefore, by changing the amplitude of the reflected ultrasonic wave, it is possible to contactless determine the change in the porosity of the controlled material. Surfaces that show the effect of changes in the frequency f and size of the pores through the magnitude $\cos \nu$ of the ultrasonic wave amplitude, which is reflected from the controlled textile fabric and is represented by the module $|V|$, are shown in Fig. 5.13. Modeling the effect of changing the frequency of waves reflected from the surface of the material and the effect of changing the pore size of the controlled fabric on the amplitude of sounding oscillations showed that non-contact control of the different textile materials structure can be performed by controlling the frequency of these oscillations.

The given amplitude-frequency method of control (Fig. 5.14) can be used for producing the robotic complexes which aimed to recognition of filtering fabrics with inadmissible pore size. As a component of such complexes, a computerized system can be introduced using a microcontroller (MC) for recognizing defective fabrics. The scheme of this system is shown in Fig. 5.15, a, and the scanning algorithm is presented in Fig. 5.16. Figure 5.15b shows a surface with the same effect of two parameters (wave frequency f and pore size $\cos \nu$ through the parameter) on the amplitude of oscillations in the form of digital codes operated by the system.

Ultrasonic system for determining the change in porosity of textile fabrics consists of the following components: microcontroller 1 (MC 1), sound pulse generator 2, the power amplifier 3, radiating and receiving piezoelectric transducers 4 and 6, the adjustable power amplifier 7, amplitude external analog-to-digital converter 9 (ADC9), LCD display indicator 10, logic level conversion chip MAX232 11, personal computer 12 (PC 12), controlled fabric 5.

The computerized system shown in Fig. 5.15 works as follows. First, the porosity of the reference textile fabric is determined by finding the volume of air in the pores of the material sample, scanning it on both sides, and making micro-cuts, followed by multiple magnification and data processing on PC 12. The value of total porosity Q_{0p} , module $|V_0|$, which corresponds to it, and the parameter $\cos \nu_0$ are entered in MC 1 in the form of codes N_0 , $N\nu_0$, $N_{\cos \nu_0}$. Next, the algorithm of the entire system is set, first involves sounding of the controlled material with ultrasonic waves with a frequency f_0 specified by the code N_{f_0} from MC 1 when setting the unit of the pulse signal generator 2, then pulses are transmitted to the power amplifier 3, and then after they get to the ultrasonic emitter 4. The ultrasonic oscillations emitted by the piezoelectric transducer 4 enter the receiving piezoelectric transducer 6, after their reflection from the surface of the controlled textile fabric 5. The amplitude of the electric oscillations formed after the ultrasonic signal reflection from the controlled fabric 5, proportional to the amplitude after amplification by the adjustable amplifier 7, the voltage of electric oscillations U_1 detected by the amplitude detector 8 enters

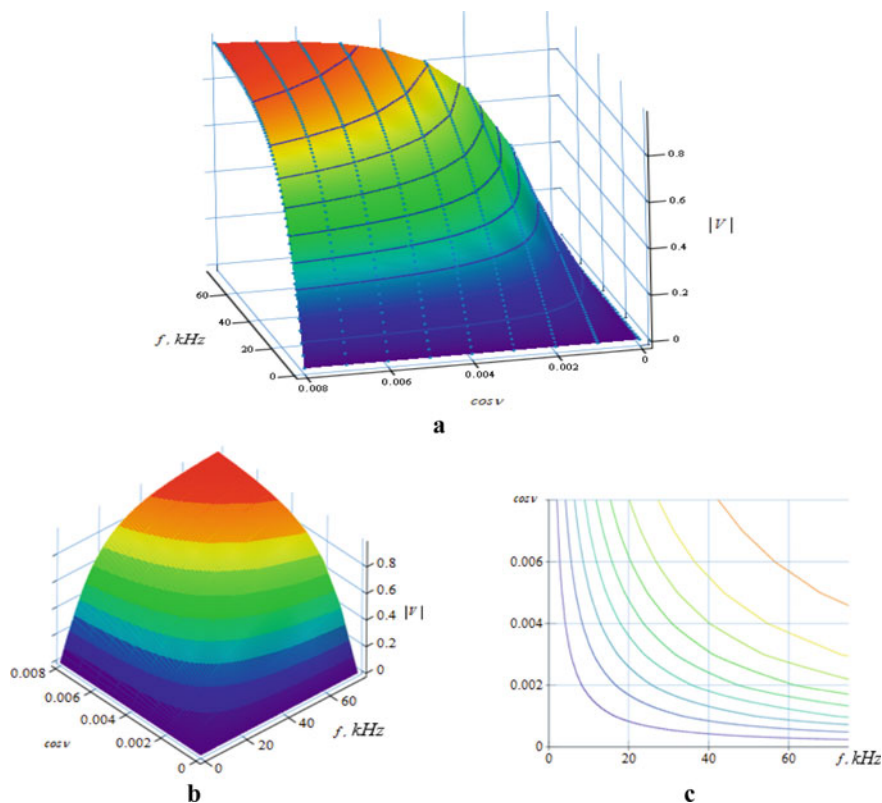


Fig. 5.13 Surfaces that show the effect of changes in the frequency f and size of pores due to the value $\cos v$ on the ultrasonic wave amplitude, which is represented by the modulus of the complex reflection coefficient $|V|$: **a** the surface with levels of pore size and amplitude; **b** the surface with amplitude levels; **c** projections of amplitude levels on the coordinates of influential parameters f and $\cos v$

the external ADC 9, through which it is converted into a digital code N_{vx} getting to the MC.

Given the transfer coefficients of the various parts of the system, the voltage U_1 and digital code N_{vx} can be represented as follows:

$$N_{vx} = \frac{U_1}{r_1} = K_1 K_2 K_3 K_4 \frac{1}{\sqrt{1 + \left(\frac{\rho_1 c_1}{\pi f \rho_2 \chi} \right)^2}} \frac{U_m}{r_1}, \quad (5.59)$$

where U_m —the amplitude of the electric oscillations voltage at the output of the pulse shaper 2; K_1 —the amplifier gain 3; K_2 —the conversion factor of blocks 4, 6; K_3 —the adjustable amplifier gain 7; K_4 —the detection factor of the amplitude detector 8; r_1 —the unit of least significant digit ADC 9.

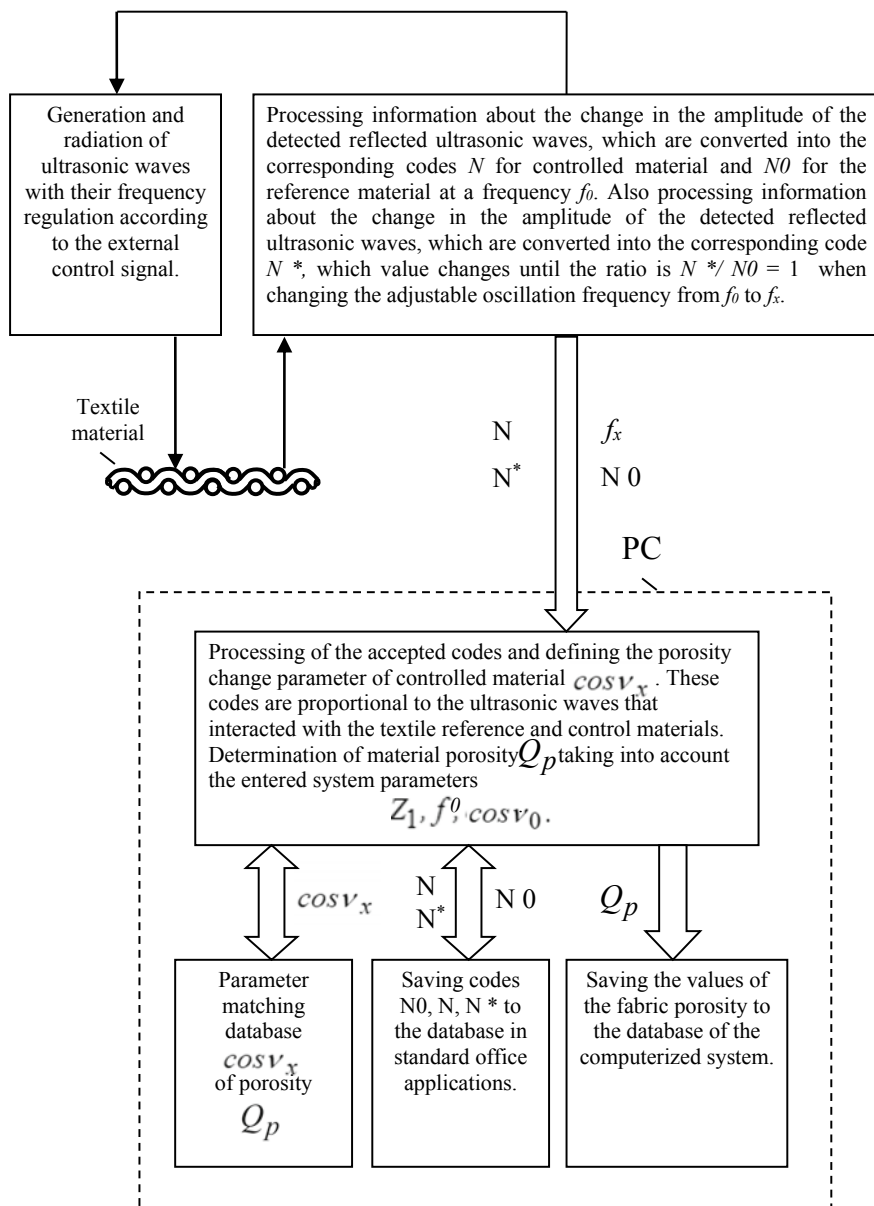


Fig. 5.14 Structure of system operations for performing the amplitude-frequency control method of changing porosity of textile fabrics

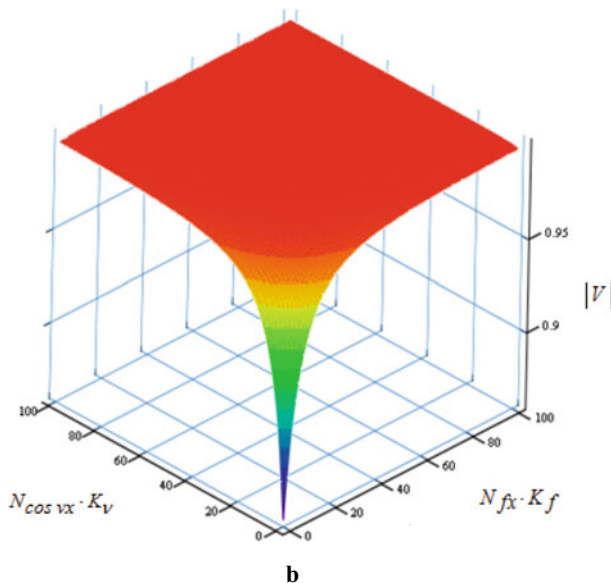
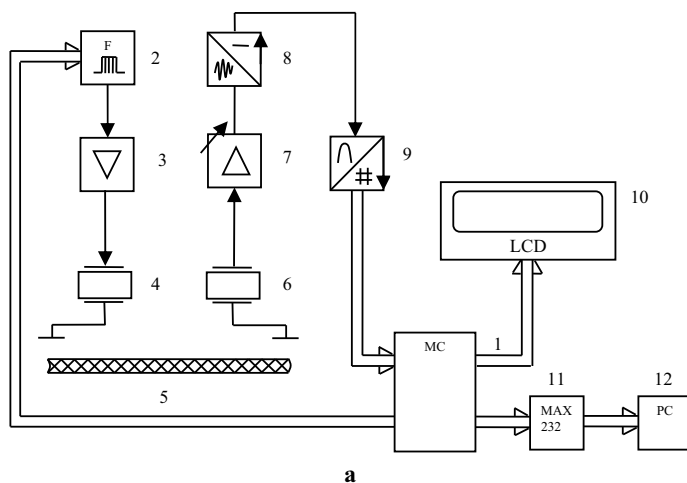


Fig. 5.15 Block diagram of a computerized control system for changes in the porosity of textile fabrics by amplitude-frequency method and a surface that shows the influence of the wave frequency and pore sizes of the material on the amplitude level of reflected ultrasonic vibrations: **a** a block diagram of a system for controlling changes in the porosity of the fabrics; **b** surface, which shows the influence of the wave frequency and pore sizes of the material on the amplitude level of the reflected ultrasonic vibrations in the form of digital codes, which MC 1 operates when sounding the controlled fabric

Next, the sounding is repeated, but with a decrease in the ultrasonic wave frequency f_x , which is regulated by the code N_{f_x} of MC 1, until the codes that are proportional to the amplitudes of the reflected ultrasonic waves are not equal to each other ($N_{v_0} = N_{v_x}$). When sounding stops MC 1 defines the parameter $\cos v_x$ in the form of a code as follows:

$$N_{\cos v_x} = \frac{N_{f_0}}{N_{f_x}} \cdot N_{\cos v_0}. \quad (5.60)$$

The parameter $\cos v_x$ can determine the pore size of the controlled fabric 5 and their change, and its total porosity Q_p is determined in the form of a code as follows:

$$N_x = \frac{N_{v_0}}{N_{v_x}} \cdot N_0. \quad (5.61)$$

Digital codes $N_{\cos v_x}$, N_x are displayed on the LCD screen 10, and also transmitted through the serial port and chip MAX232 11 and recorded on a PC 12, where information is processed and stored.

The intersection of the code value $N_{\cos v_x}$ and the proportionality factor K_v , which corresponds to the change in pore size of the material, as well as the intersection of the code value N_{f_x} and the proportionality factor K_f , corresponding to the change of the ultrasonic vibrations frequency, show the equivalent effect on the amplitude of the reflected waves (Fig. 5.15b), within the limits corresponding to the non-contact range of sounding fabrics with a porous structure.

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Chapter 6

Development of Experimental Samples of Computerized Systems and Non-contact Control Over Technological Parameters of Textile Materials



6.1 Development of an Experimental Sample of a Scanning Computerized System of Textile Fabrics for Control Over Their Porosity and Tension of Threads with High Linear Density

The implementation of computerized systems for scanning and recognizing different textile materials with different porosity and checking them for defects can help solve the problem of continuous technological control over finished products in production. The analysis showed that the non-contact ultrasonic method can be used for automated control over technological parameters of various filter materials, as well as for the detection of defective products in the process of sorting. The basis of the method is to compare the change in the amplitude of the ultrasonic wave reflected from the surface of the controlled material with the amplitude of the wave reflected from the reference sample. To perform the task, this method can be used applying microprocessor technology. This can be implemented in hardware on the basis of modern integrated circuits, which make it possible to simplify the design of the required technical system. This makes it simple to apply the principle of modularity of the components of the hardware units of the proposed system with flexible determination of the values of various parameters of textile materials due to the parameters of the waves [1–6].

Structure charts of the developed sample system for scanning textile materials with the ability to control their technological parameters on textile machines are shown in Fig. 6.1. The created sample of the system allows to observe both the porosity of the fabric and the thread tension by replacing the ultrasonic sensors and reconfiguring the automated scanning to measure the amplitudes of the waves in the waveguides with a controlled thread.

The developed sample of the scanning system of textile fabrics, shown in Fig. 6.1a, works as follows. The digital generator of electric pulse packets 1 of the ultrasonic frequency generated at its output feeds them to the adjustable power amplifier 2, after which they are fed to the piezoelectric transducer 3, by means of which they are

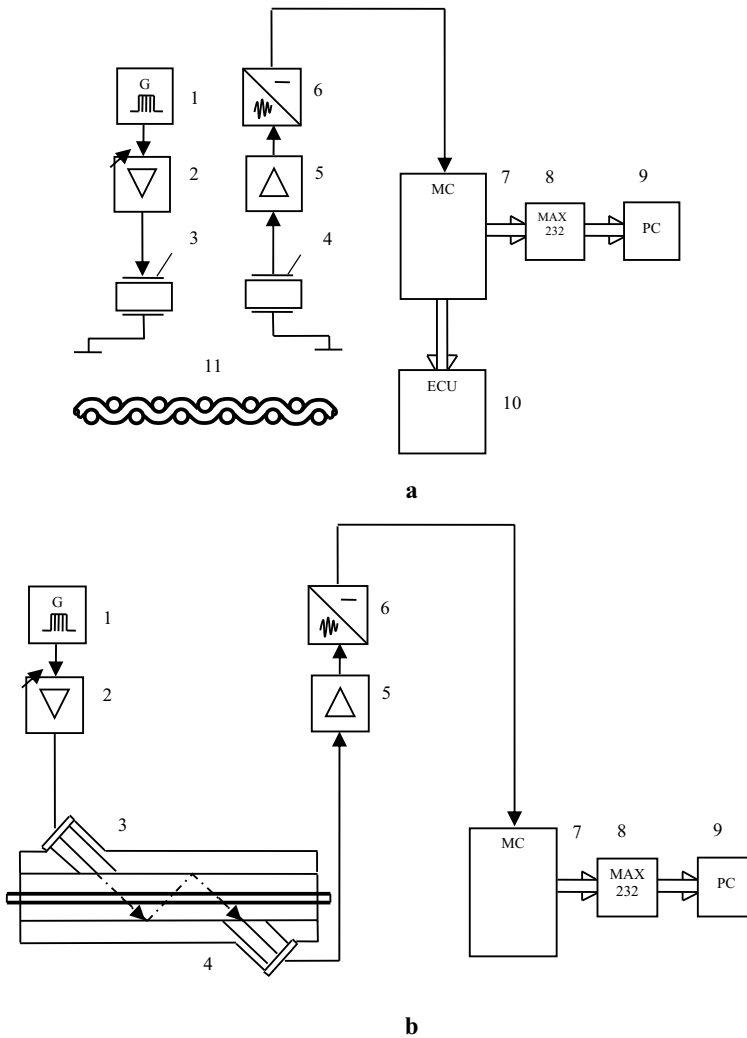


Fig. 6.1 Structure charts of an experimental sample of a computerized system for scanning textile fabrics to control their porosity and thread tension: **a** structure chart of a sample system for scanning fabrics to control their porosity; **b** structure chart of an ultrasonic sample system for non-contact control of thread tension with high linear density

converted into ultrasonic waves. They radiate and fall on the surface of the controlled textile fabric 11. Then part of the ultrasonic waves is reflected from the surface of the fabric 11 and falls on the piezoelectric transducer 4, through which they are again converted into electrical oscillations, which are amplified by the power amplifier 5. Next, these oscillations fall on the amplitude detector 6, which is proportional to the amplitude of ultrasonic oscillations reflected from the surface of the textile fabric 11.

The generated voltage enters the input of the microcontroller 7 (MC 7), where using its internal analog-to-digital converter (ADC) is converted into a digital code. The code is stored in the MC 7 memory and it was formed after the reflection of ultrasonic waves from the reference sample of the fabric, according to which in comparison with the previous code, the value of the change in porosity of the textile fabric 11 relative to the reference sample is determined.

The current porosity value of the textile fabric 11 is transmitted through the conversion chip of logic levels 8 into a personal computer 9 (PC 9), where it is recorded in a database and displayed as a graph in real time. The MC 7 also controls the engine control unit 10 (ECU 10), which moves the ultrasonic piezoelectric transducers 3 and 4 on the scanning platform along and across the width of the controlled fabric 11. The electrical block schematic diagram of the units 7, 8, 10 is shown in Annex B.

When disconnecting the ECU 10 from the scanning system and when connecting new piezoelectric transducers 3 and 4 in the waveguide with the replacement of the control program in the MC 7, an ultrasonic system for non-contact determination of thread tension with high linear density on textile machines is obtained (Fig. 6.1b). For this ultrasonic system, the change in thread tension is determined by the change in the amplitude of the ultrasonic wave emitted by the piezoelectric transducer 3 and passes several times through the thread thickness as it propagates in the waveguide and then enters the piezoelectric transducer 4. Next, this wave is converted into electrical oscillations, amplified by the amplifier 5, and by means of the amplitude detector 6 they are converted into DC voltage, which enters the MC 7 and is converted into a digital code. The new code is compared with the code formed during the initial tension of the thread, and determines the current change in its tension, the value of which is transmitted through the conversion chip of logic levels 8 on the PC 9.

According to the structure charts shown in Fig. 6.1, electronic units in the form of electric boards were developed for the corresponding scanning system using one MC 7.

The design of the electrical circuits with both one MC and three MCs for a more complex scanning system, which will be discussed later in the work, and the corresponding boards to them was made in the program Proteus 7.7. Using the program Inkscape, the necessary images of board models and G-code were created for milling on a machine with computer numerical control (CNC). This machine, in turn, was made in the course of this work for the manufacture of experimental units of a computerized system.

Simulation of the boards milling without connection of the CNC machine was carried out using the JCNC program for debugging of the technological process. This simulation of cutting boards with the trajectory of the cutting tool in the JCNC program was with the display of the execution of the G-code line of the program for the CNC machine. Next, the obtained G-code, after simulating the process of the boards milling, was opened in the program grblControl and used by this program to control the CNC machine itself. The type of visualization of the board code in the grblControl program is shown in Fig. 6.2.

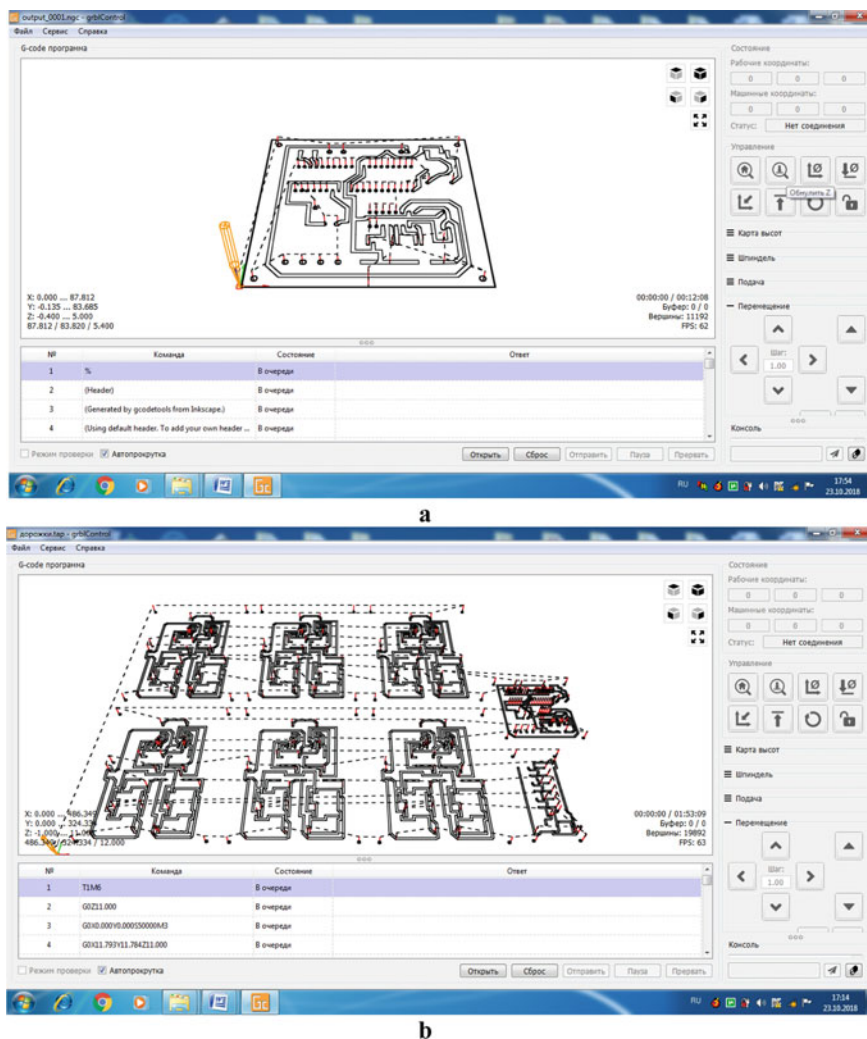


Fig. 6.2 Visualization of electric boards of the experimental system with one MC in the program gblControl to control the milling process: **a** full visualization of the electrical board with the MC 7 and the conversion unit 8; **b** visualization of the electric board tracks (the first stage of the CNC machine work)

The milling process of electric boards for the scanning ultrasonic system in the working field of the CNC machine is divided into three stages, which involve the replacement of different cutting tools at each stage. These three stages of the milling process of the scanning system boards can be conditionally shown as follows:

- the first stage—cutting the tracks of the boards (Fig. 6.2b);

- the second stage—through cutting of openings for withdrawal of board components;
- the third stage—cutting the board contours, the final operation on the CNC machine.

The CNC machine itself and the process of execution of three-stage programs of board manufacturing of the automated system for textile material scanning is shown in Fig. 6.3. Textolite sheets were used to make the boards. After milling the tracks of the boards, the textolite sheet was subjected to further processing. The appearance of the board tracks in the milling process and the final result are presented in Fig. 6.4.

In addition, 3D printers were made to perform waveguides and sensor housings of various shapes for experimental samples of ultrasonic systems for controlling the tension of high linear density threads and controlling the basis weight of textile fabrics. One of these created 3D printers is shown in Fig. 6.5. The process of printing experimental waveguides according to their created 3D project is shown in Fig. 6.6. It should be noted that the printing of two waveguides with their upper and lower parts took place with the use of appropriate supports of complex shapes, which after the printing process came off the main part of the waveguides. Thus, complex waveguides were obtained with the location of the mounts for non-contact sensors on one side of the controlled thread, and the location of the mounts on different sides. In this case, one of the waveguides makes it possible to change the distance between the sensors due to its two parts.

Such waveguides with controlled thread and propagation of ultrasonic waves have been theoretically considered in this work earlier. Therefore, the created waveguides together with ultrasonic units made it possible to experimentally confirm the theoretical studies of such systems, which will be described later in this section.

Experimental waveguides made it possible to determine the change in the thread tension with a high linear density and its breakage, which is necessary for the technological process of knitting fabrics on textile machines. This control takes place on modern equipment mainly with the help of contact sensors that can sometimes fail, which automatically leads to a defective textile fabric.

The waveguide with mounts for ultrasonic sensors (piezoelectric transducers), which are located on different sides of the controlled thread, makes it easy to adjust the sensitivity of the sensors to a particular material and the linear density of the controlled thread at the same radiated signal power. This is due to the change in the distance between the ultrasonic sensors, and hence in the distance and number of transmissions of the controlled thread wave with a subsequent decrease or increase in its amplitude. The change in the distance between the sensors is caused by the movement of the upper part of the waveguide relative to the lower one. The loose connection between the thread and the ultrasonic sensors makes it impossible for such a system to malfunction, as this can happen with contact sensors.

Also, when scanning the material itself and controlling the change in its porosity relative to the reference value, the consumption of dyes used to give a certain color to the textile fabric can be reduced. In addition, the change in porosity can control the quality of filtering fabrics and other materials. Therefore, the experimental model

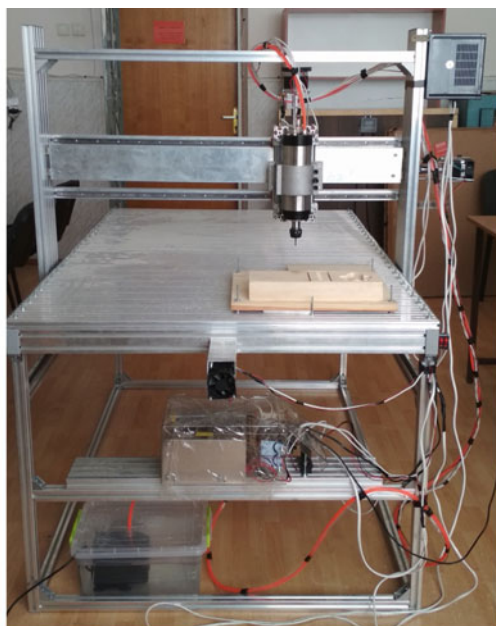
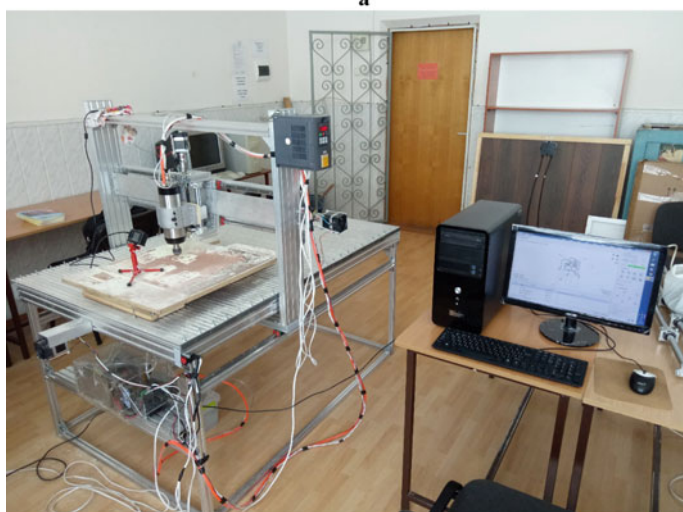
**a****b**

Fig. 6.3 CNC machine and milling of the system electric boards: **a** front view of a homemade CNC machine; **b** milling of electric board tracks using a CNC machine

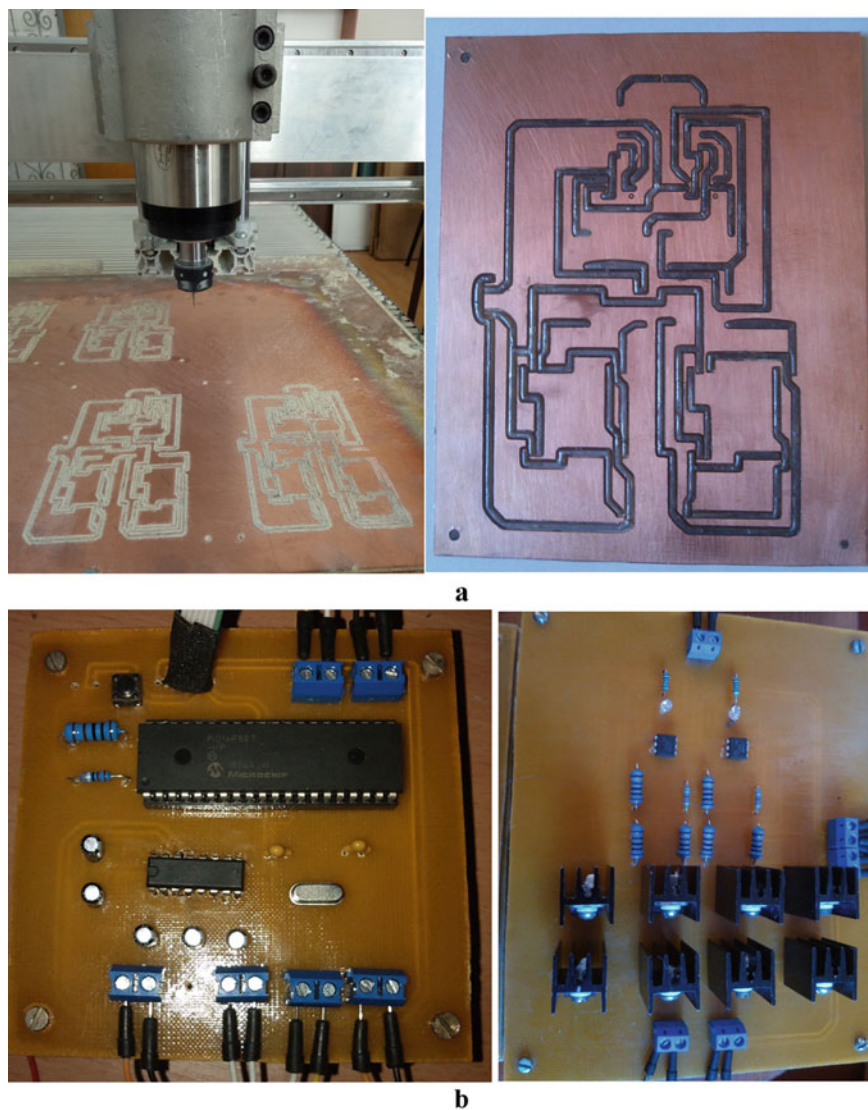


Fig. 6.4 The appearance of electric board tracks in the process of milling with a CNC machine and the final result: **a** view of electric circuit tracks during and after milling; **b** ready electric boards of the scanning system (control module with MC 7 and conversion unit 8, as well as the board with power keys of the ECU module 10)

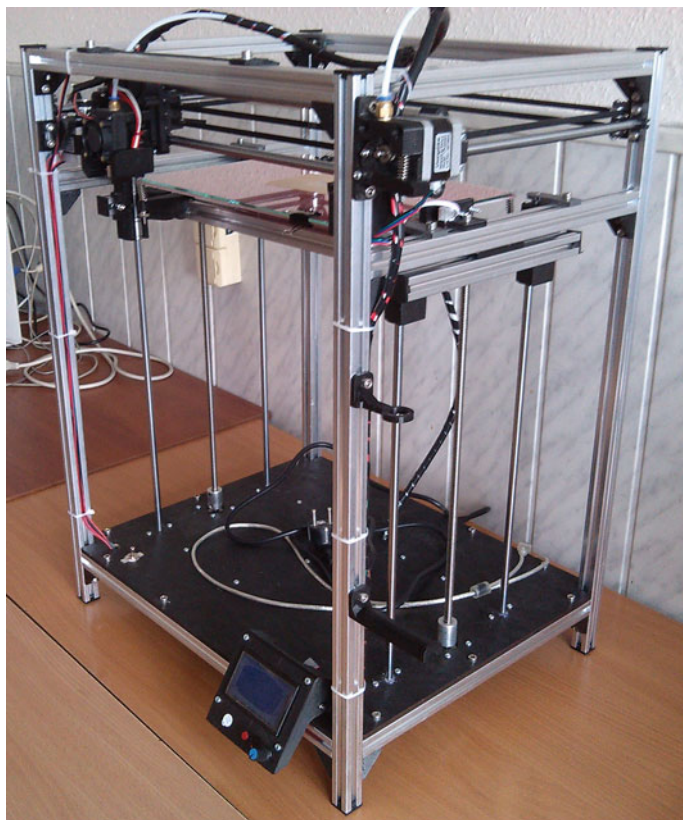


Fig. 6.5 3D printer, which was created to print various forms of ultrasonic sensor housings, their mounts and waveguides

of the system, which can work as a non-contact scanning system for changing the porosity of the fabrics, and as an ultrasonic system for determining the change in thread tension, is promising for its further implementation.

6.2 Development of an Experimental Sample of a Computerized System for Controlling the Basis Weight and Porosity of Textile Materials on Technological Equipment in the Production Process

For non-contact control over the basis weight of textile fabrics in the production process, it was necessary to create a scanning computerized system with three measuring channels. This system should provide non-contact measurement of the



Fig. 6.6 The process of printing experimental waveguides to determine the tension of threads with high linear density on a 3D printer and the finished print result: **a** view of the upper parts of the waveguides after 3D printing with working support of complex shapes; **b** ready printed waveguides with fastenings for ultrasonic sensors both on one side of the controlled thread, and fastenings on its different sides

porosity of textile fabrics, change in the fabric tension on textile equipment and measurement of basis weight taking into account the previous parameters. The implementation of this scanning system will allow to carry out both operative technological control on production, and laboratory control over fabric samples. Determination of the basis weight of the finished samples of textile fabrics can be carried out without determining the change in their tension using non-contact ultrasonic sensors (Fig. 6.7).

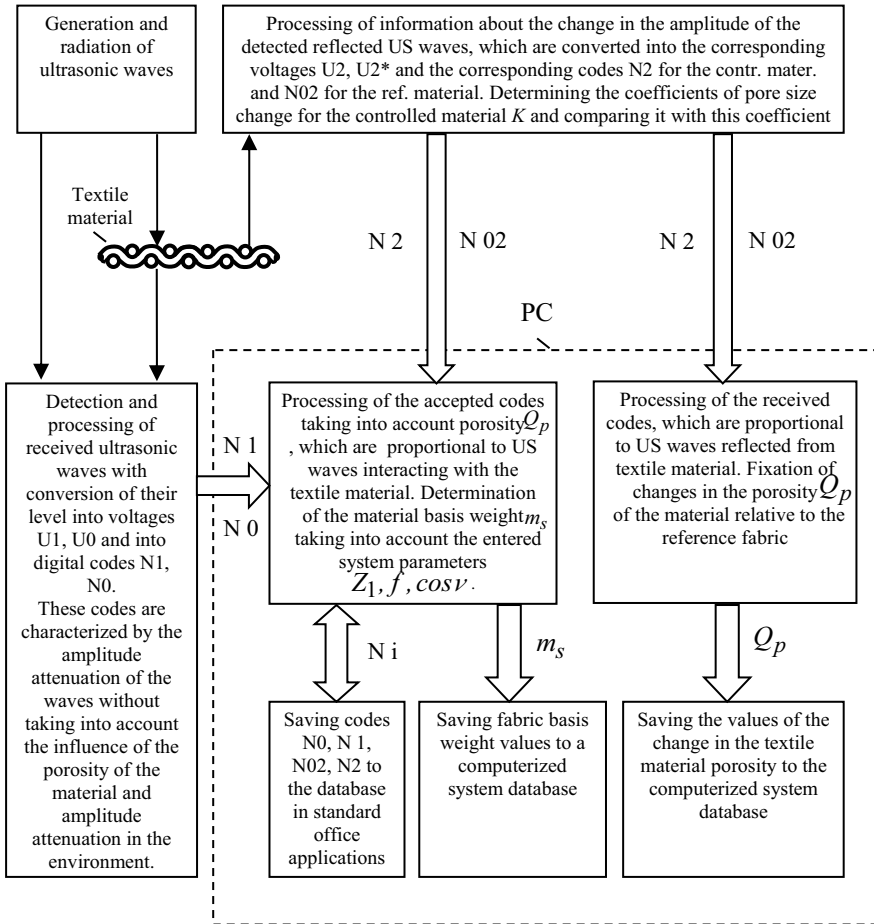


Fig. 6.7 The structure of system operations for the implementation of the amplitude method of controlling the basis weight and porosity of textile materials

The developed sample of a non-contact computerized system for controlling the basis weight of textile fabrics is shown in Fig. 6.8, and the algorithm of the material scanning process—in Fig. 6.9. The finished component block of this sample system is shown in Fig. 6.10a. This sample system works as follows. The external digital generator 1 produces pulse packets, which through the power amplifier 2 fall on the piezoelectric transducer 3, which converts them into ultrasonic waves that are emitted into the environment. These ultrasonic waves pass through the controlled textile fabric 23 and enter the piezoelectric transducer 4, which converts them back into electrical oscillations, after which they enter the adjustable amplifier 8, where the oscillations are amplified by power and then to a simple amplitude detector 9. By means of the amplitude detector 9, the oscillations are converted into a unipolar

voltage, which gradually decreases due to the capacity of the charging capacitor of the detector 9 and the duration of the received packages of electrical oscillations.

The optimal duration of the oscillation package can be adjusted using a digital generator 1 (Fig. 6.11), which is associated with the distance between the textile fabric 23 and piezoelectric transducers 3 and 4. This is necessary to reduce the amplitude error on the one hand and, on the other hand, it is necessary to watch that the phenomenon of reflections of probing waves (Fig. 6.12) with their subsequent imposing did not occur.

The voltage at the output of the amplitude detector 9 is supplied to the microcontroller 15 (MC 15) of the first measuring channel of the scanning system, and is also supplied to the standard reassembling block 21 (m-DAQ12).

Using the internal ten-bit analog-to-digital converter (ADC) MC 15, this voltage is converted into a digital code, which is transmitted, in turn, to the microcontroller

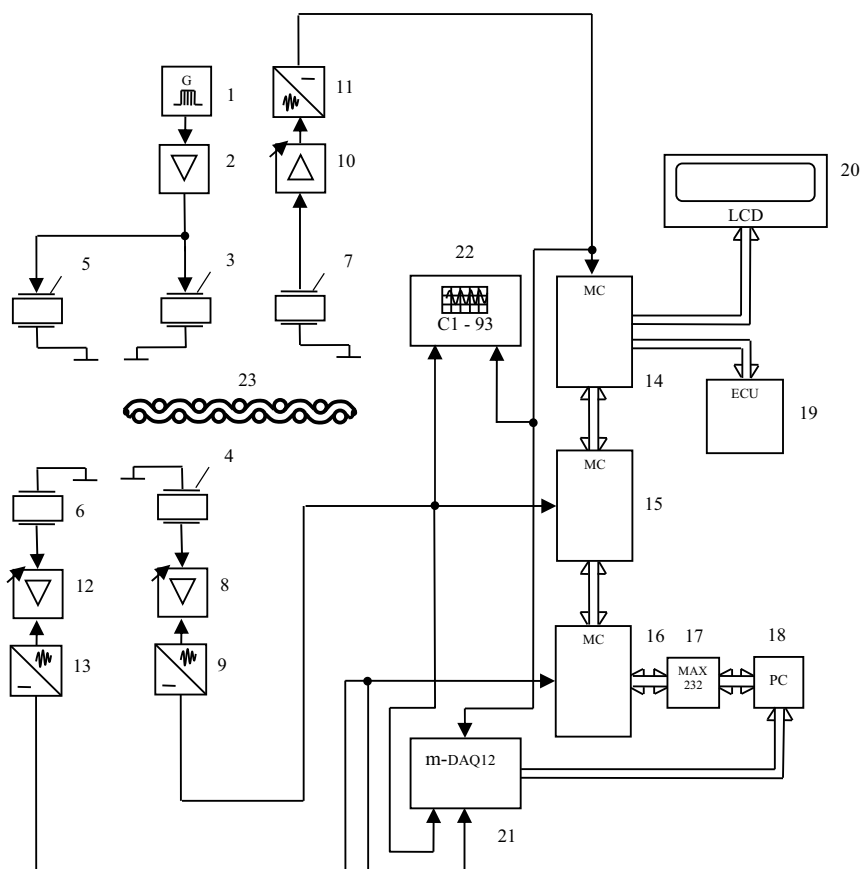


Fig. 6.8 Structure chart of a sample computerized control system for basis weight and porosity of textile materials

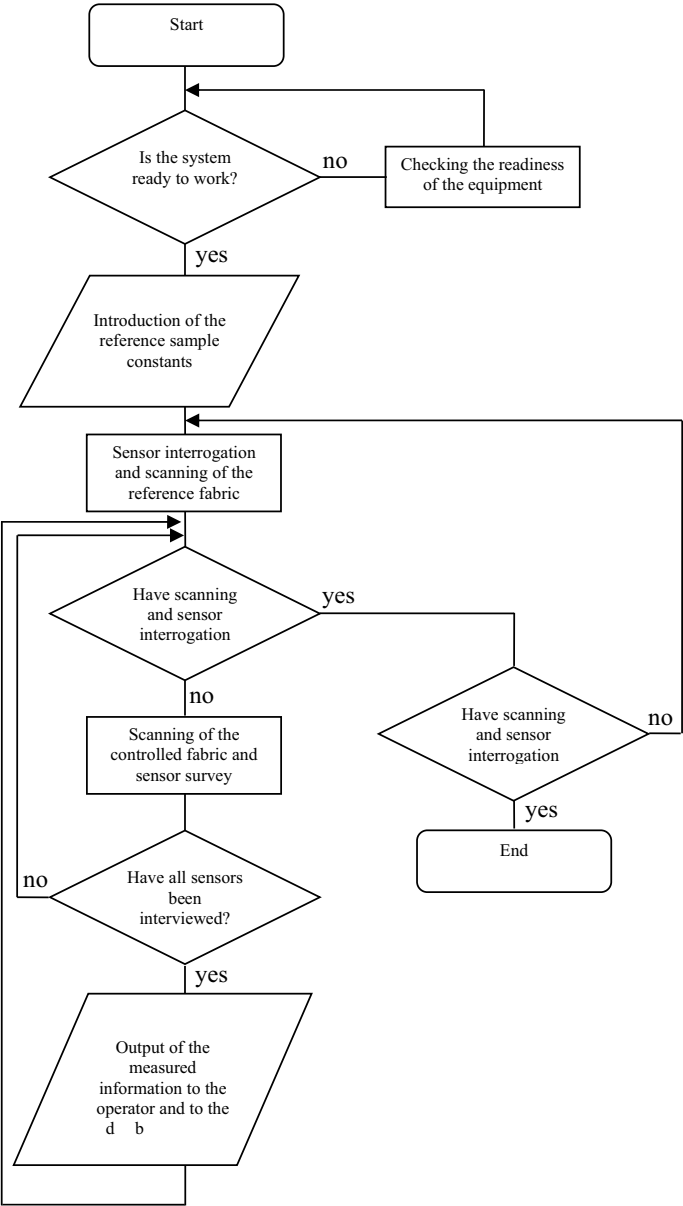


Fig. 6.9 Algorithm of the process of ultrasonic scanning of textile materials by the developed model of the computerized control system

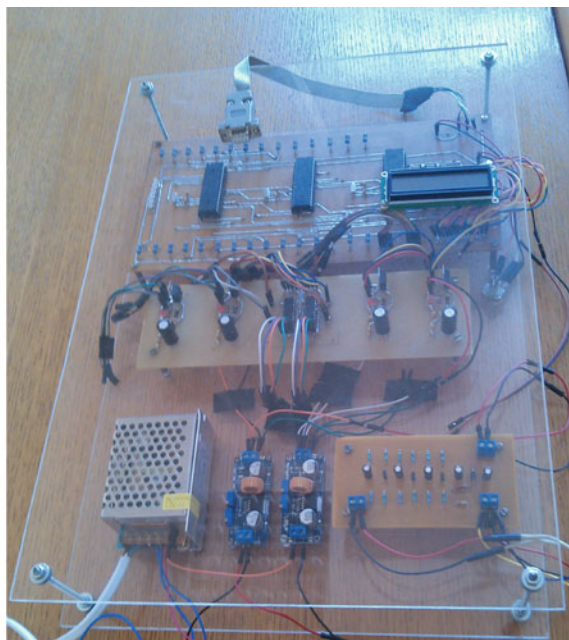
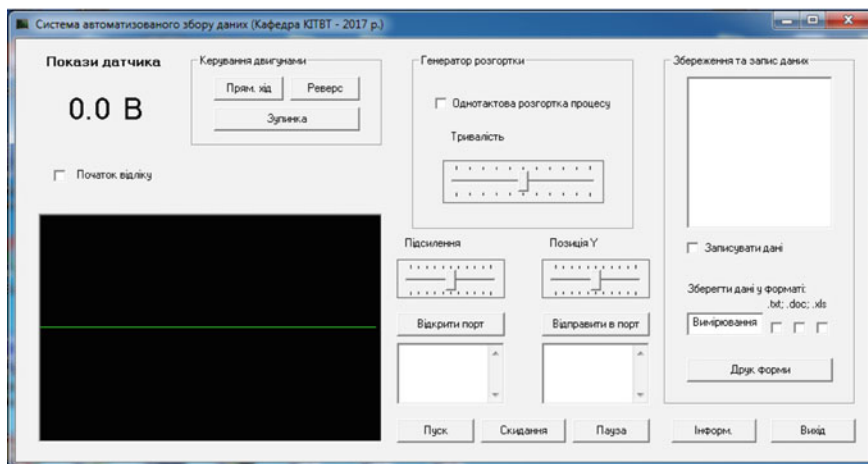
**a****b**

Fig. 6.10 The ready component block and the program for the measuring information collection of the computerized system sample of textile fabrics have been developed: **a** view of the developed ready component block of the fabric scanning system sample; **b** view of the window of the developed program for collecting measuring information and controlling motors for moving the sample scanning system sensors

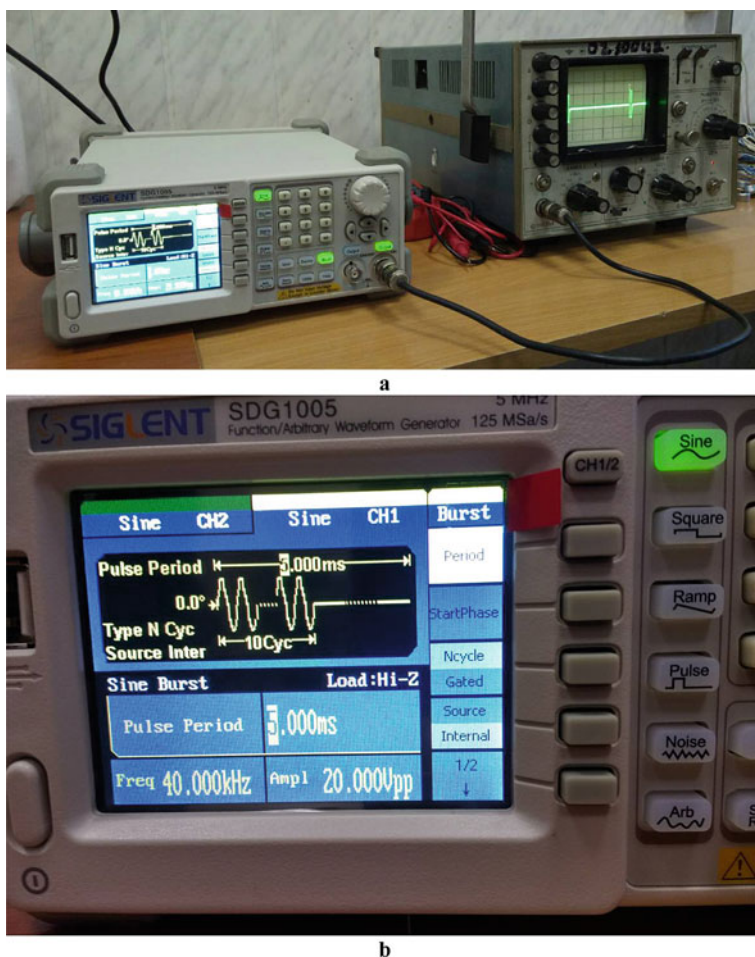


Fig. 6.11 Setting the optimal duration of the oscillation package using the digital generator 1 (ultrasonic pulse generator): **a** electric oscillation generation unit—SDG1005 Siglent and electrical process visualization unit—oscilloscope C1-77 for setting a system of textile fabrics scanning; **b**—digital generator screen 1 (SDG1005 Siglent)

16 (MC 16), from the output of which through the logic level conversion chip 17 it enters the personal computer 18 (PC 18). This measuring information is processed by a specially designed program (Fig. 6.10b). Since the twelve-digit ADC of the data acquisition unit 21 allows parallel processing of the voltage entering its input at a sufficiently high speed relative to the transient process of the detector 9, it provides a digital graph of this voltage on the PC monitor 18 in digital oscilloscope mode. Also, this voltage graph can be compared with the images of the voltage change on a standard oscilloscope C1-93 (Fig. 6.13a). Discrete voltage levels in a certain order from the smallest to the largest ones for several cycles of incoming packets of

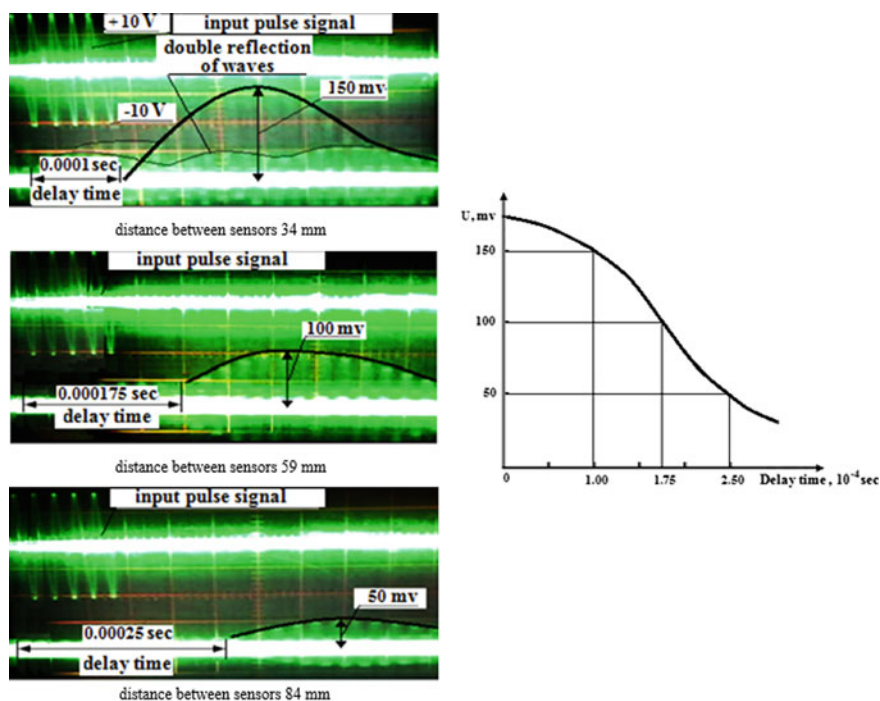


Fig. 6.12 Study of the amplitude attenuation of ultrasonic waves in the air and application of reflected waves at different distances between the sensors (oscilloscope C1–55, where the first channel—oscillograms from the output of the digital generator 1, the second channel—oscillograms from the output of the piezoelectric transducer 4)

waves in ascending order are displayed in the form of a graph in the window of the created program (Fig. 6.13b) to determine the largest value. The speed of the sensors' scanning is regulated by software. With a quick scanning of the sensors by the system, the image in the program window will be as that in an oscillograph. At the same time, these voltage values are displayed on the LCD screen 20. The created software module additionally forms a database of voltage levels from different sensors of the three measuring channels at a certain point in time and stores them in the main applications MS Office PC 18 (Fig. 6.13c).

According to how the voltage amplitude is measured, which is proportional to the amplitude of the ultrasonic waves passing through the controlled fabric 23, the voltages and other measuring channels of the scanning system are measured and converted into a digital code.

The ultrasonic waves reflected from the surface of the controlled fabric 23 enter the piezoelectric transducer 7 of the second measuring channel, where they are converted into electrical oscillations, which are then amplified by an adjustable amplifier 10 and enter the amplitude detector 11. With the amplitude detector 11, electric oscillations are converted into unipolar voltage with an amplitude that is proportional to the

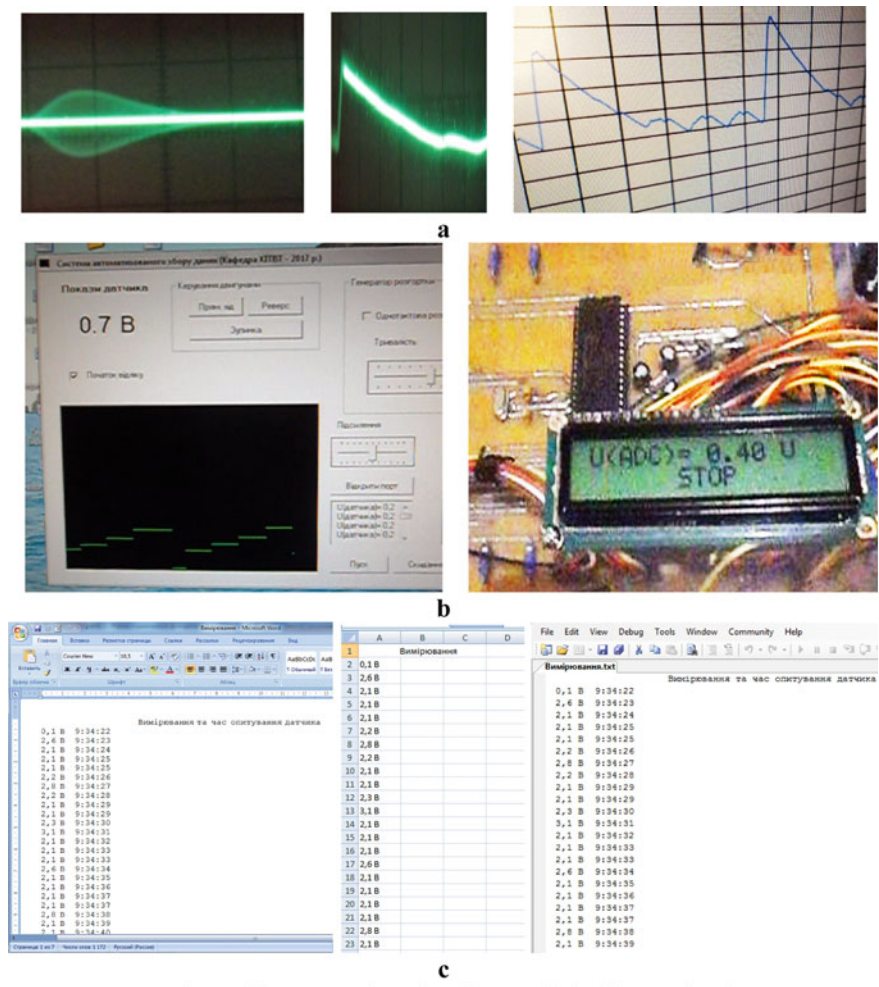


Fig. 6.13 Conversion of the measuring signal into a digital format by the system: **a** ultrasonic sounding waves and the output voltage of the amplitude detector 9, which is displayed on the oscilloscope screen C1–93 and on the PC 18 monitor; **b** selective sampling of the output voltage from the detector 9 and its display on the LCD screen 20 marked STOP of the scanning platform stop; **c** storage of data array on voltage values from sensors by the program in standard MS Office applications

amplitude of the ultrasonic waves received by the piezoelectric transducer 7. This voltage, in turn, enters the internal ten-bit ADC microcontroller 14 (MC 14), where it is converted into a digital code received first on the MC 15, and then on the MC 16, where it falls on the chip conversion of logic levels 17, and then on the PC 18. This digital code makes it possible to determine the porosity of the controlled textile fabric 23 by its change relative to the porosity of the reference fabric.

The third measuring channel of the scanning system is the reference one. The packages of electric oscillations coming from the system amplifier 2 to the piezoelectric transducer 5 are converted into ultrasonic waves that pass only the ambient air and enter the piezoelectric transducer 6. Next, the ultrasonic waves are again converted into electric oscillations and amplified by the adjustable amplifier 12.

Then the waves fall on the amplitude detector 13, where they are converted into a unipolar voltage supplied to the internal ten-bit ADC MC 16, which converts it into a digital code. The magnitude of this code is proportional to the amplitude of the ultrasonic wave, which only falls on the controlled textile fabric 23. The code in the formed reference channel comes through the conversion chip of logic levels 17 to the PC 18. In parallel, the measurement information comes from the second and third measurement channels 21.

The data acquisition unit 21 displays the measured voltages from the three channels of the system in the form of graphs on the PC monitor 18.

The change in tension is determined by the change in the amplitude of the ultrasonic waves that passed through the controlled fabric 23, compared with the amplitude of the waves that passed through the reference fabric without tension or at its lowest values.

Next, according to the obtained values of voltage amplitudes from the three measuring channels, the technological parameters of textile fabrics can be automatically calculated using the developed program, which runs on the PC 18 and works with office documents with stored data.

The controlled textile fabric can be scanned by width and length by moving the platform with ultrasonic sensors forward, this is the responsibility of ECU 19 when pressing the “Direct route” button in the window of the developed program. Also, the fabric can be scanned in width and length by moving the platform with the sensors back, this is the responsibility of ECU 19 when pressing the “Reverse” button, and when scanning is stopped, the “Stop” button in the window of the created program is pressed. The LCD screen 20 displays these scan commands as “Direct route”, “Reverse”, “Stop”.

Before the start of measurements, the amplitude advances in the measuring channels are reduced by adjustable system amplifiers.

Additionally, two measuring channels (for the transmission of waves and their reflection) were connected to the oscillograph 22 (oscillograph C1–93) to compare the graphs of the developed sample scanning system of textile fabrics with the readings of this device.

Knitted fabrics can be scanned on flat knitting machines, and various fabrics can be scanned on looms in the course of their production. If it is necessary to control the porosity of knitted fabrics on circular knitting machines using a developed sample of a computerized system (Fig. 6.14), the radiating and receiving piezoelectric transducers of the second measuring channel are fixed immovably (Fig. 6.15).

In this case, the controlled fabric itself moves relatively to the piezoelectric transducers. This is the process of a fabric scanning on a circular textile machine.

A common point to note when comparing the reflection of ultrasonic waves from a knitted fabric with the reflection of waves from a fabric is that for the first case

Fig. 6.14 The appearance of the developed model of the computerized scanning system for porosity deviation detection of a knitted fabric on the circular knitting textile machine



Fig. 6.15 Position of non-contact ultrasonic sensors, emitter and receiver of ultrasonic waves, relative to the knitted fabric during the operation of the circular textile machine



the sensors need to be placed much closer to the surface of the fabric. This is due to the fact that the knitted fabric has a more complex spatial structure with threads in the form of courses, which can scatter the reflected ultrasonic waves more than the fabrics of simple weaving fabrics.

It should also be noted that it is possible to programmatically change the operation of the computer system model. It can, without connection to the PC 18, perform scanning of textile fabrics according to a certain algorithm, process the obtained data of voltage values from sensors and independently determine the technological parameters of the controlled fabrics.

The created model of the computerized scanning system allowed to show experimentally that it is possible to carry out operative non-contact control over technological parameters of textile fabrics. Taking into account the tension of the material (mainly for knitted fabrics due to the fact that the material stretches well compared to the textile fabric) and its porosity, it is possible to more accurately determine the basis weight of the textile fabric in the course of production.

Also, the developed ultrasonic means of a system model give the chance to carry out point control in laboratory conditions of finished fabrics depending on industrial necessity.

Considering the possibility of mobility of the computer system model for its further installation on the technological equipment, the size of the developed and implemented electronic unit of the system can be reduced by about four times for industrial designs.

Other results of the research, which were obtained with the help of the developed computerized system model, will be given later in the section.

6.3 Non-contact Control Over Porosity and Basis Weight of Textile Materials by Experimental Means

In the course of the work, studies were conducted on the possibility of using non-contact control over porosity and basis weight of textile fabrics with the help of experimental scanning tools. Since many samples of fabrics were studied in the laboratory, which were not subjected to tension during the measurements, it was not taken into account, but only the porosity of the material when determining their basis weight. Samples of knitted fabrics and samples of various textile fabrics were studied [7–16].

The porosity of the samples of different fabrics Q_p was determined in comparison with the porosity of the reference sample Q_{0p} . The values of the parameters Q_p and Q_{0p} were found in stages. In the first stage, the volumes of through pores and the total porosity of the textile reference $Q_{0p}(sm)$ and controlled materials $Q_p(sm)$ with the square of 1 mm² were determined by the optical scanning and microsections. The second stage was to determine the amplitudes of the ultrasonic waves that interacted with the materials and their ratios to the ratios of the total pore

volumes of the materials. Porosity $Q_p(nm)$ was determined by means of modules of complex coefficients of wave reflection from the controlled material $|V|$ and the reference sample $|V_0|$, which are related to their proportional voltages U_2 and U_2^* from the ultrasonic system detector. These voltages are formed during the measurement of the amplitudes of the ultrasonic waves reflected from the textile controlled and reference materials. Thus, the total porosity and its deviation were determined as follows:

$$Q_p(nm) = \frac{|V_0|}{|V|} \cdot Q_{0p}(sm) = \frac{U_2^*}{U_2} \cdot Q_{0p}(sm); \quad (6.1)$$

$$\delta_{Q_p} = ((Q_p(nm) - Q_p(sm)) / Q_p(sm)) \cdot 100 \%. \quad (6.2)$$

The main parameters of ultrasonic low-power sensors used in the study of the porosity of textile fabrics are:

- the current value of the electrical sinusoidal signal voltage at the input of the sensor—not more than 5 V (it is advisable to use low-power sensors for textile materials);
- input electrical resistance at the frequency of the maximum radiation of a non-contact sensor 380 Ω ;
- the maximum frequency of ultrasonic oscillations for radiation by the non-contact sensor—40 kHz;
- frequency of the maximum reception of waves by the sensor—42 kHz at the loading resistance of 3.9 kOhm;
- the optimal repetition time of the ultrasonic wave packet—20 ms.

Probing of textile samples can be carried out in the automatic mode on 50 measurements of peak values of voltage amplitudes from detectors of the ultrasonic system per second. After digitization of measurements, one peak value of the amplitude per 3 s or 20 peak values of voltage amplitudes per 1 min was selected to reduce the array of data processed by the system.

The results of studies for determining the ratios of the porosity parameters $Q_{0p}(sm)/Q_p(sm)$ of fabric samples and the voltage ratios U_2/U_2^* are shown in Table 6.1 and Fig. 6.16.

Taking into account the change in the average porosity of the textile fabric relative to the reference sample, which is characterized by the value of the voltage ratio, U_2^*/U_2 , it is possible to contactlessly determine the basis weight m_s of the material.

The standard method for determining the basis weight is the weighing method. By weighing the control sample with a certain area, the basis weight of the material $m_s(sm)$ was calculated under normal conditions for the possibility of comparing its values with the measurements $m_s(nm)$ of non-contact means.

Experimental studies were based on the comparison of contact and non-contact methods for determining the basis weight m_s of different fabrics. The non-contact method involves determining the transmission module $|W|$, which is characterized by the ratio of voltages U_1/U_0 from the detectors of the ultrasonic system. The

Table 6.1 Indicators of porosity and amplitude ratios of the detected voltages

Samples of fabrics	Q_{0p} (sample 1), Q_p (samples 2, 3, 4, 5), mm^3 per 1 mm^2 of the area	Q_{0p}/Q_p	U_2^* (sample 1) U_2 (samples 2, 3, 4, 5), V	U_2/U_2^*
1 (reference sample)	0.3744	–	0.70	–
2	0.2138	1.75	1.25	1.79
3	0.5840	0.64	0.45	0.64
4	0.6558	0.57	0.41	0.59
5	0.3717	1.01	0.70	1.00

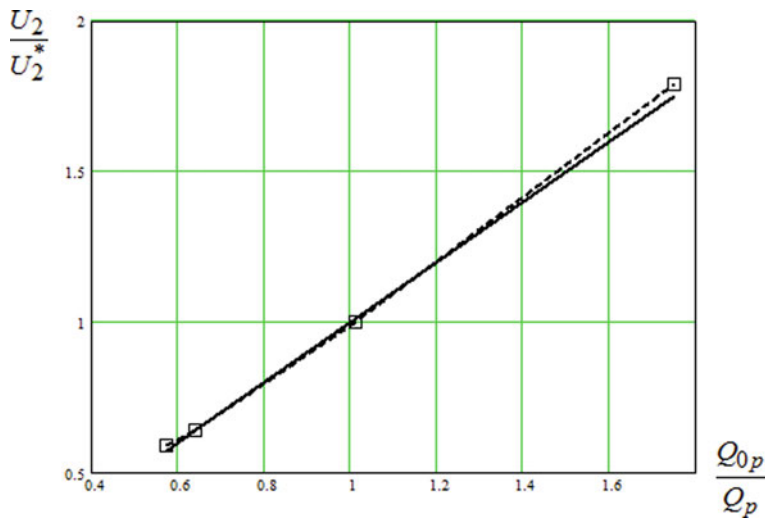


Fig. 6.16 Dependence of the amplitude ratio of voltages U_2/U_2^* on the ratio of fabric pore volumes Q_{0p}/Q_p : ———; theoretical dependence; — — —; experimental dependence ($\square$ —points, which are determined by the measured values of voltages and measured pore sizes of the fabrics under study)

first voltage U_1 is proportional to the amplitude of the ultrasonic waves that passed through the material, the second voltage U_0 is proportional to the amplitude of the waves that are just incident on the controlled material. The basis weight m_s of the fabrics was calculated by the amplitudes of the waves and is shown taking into account the expressions (6.1) and (6.2), as well as its deviation δ_{m_s} , as:

$$m_s(nm) = \frac{Z_1 \cdot \sqrt{\frac{1}{|W|^2} - 1}}{K f \cos v} = \frac{Z_1 U_2^* \cdot \sqrt{\left(\frac{U_0}{U_1}\right)^2 - 1}}{K_0 U_2 f \cos v}, \tag{6.3}$$

$$\delta_{m_s} = \frac{m_s(nm) - m_s(sm)}{m_s(sm)} \cdot 100\%. \tag{6.4}$$

Comprehensive studies of changes in the porosity of fabric samples both by their microsections and the determination of this parameter using the amplitudes of the detected voltages are shown in Table 6.2. On this basis, an adjustment was made to the calculation of the values of the basis weight m_s of fabric samples obtained by the measured voltages. The results were compared with the standard method, which is also given in Table 6.2 (this is an extension of the studies shown in Table 6.1).

After analyzing the obtained experimental data in Table 6.2, it is necessary to additionally determine for the reference and controlled fabric samples by energy the transmission coefficients $|W_0|^2$, $|W|^2$ of ultrasonic waves and their reflection coefficients $|V_0|^2$, $|V|^2$ from the specified textile materials using the measured voltages U_0 , U_1^* , U_2^* , U_1 , U_2 . This is necessary to determine the dispersion of ultrasonic energy for optimal adjustment of a non-contact measuring system to the structure of the controlled textile fabric.

One such setting may be the correct placement of the sensors relative to the fabric surface, as well as determining their optimal number and sensitivity as needed. These parameters can be determined from the measured voltages as follows:

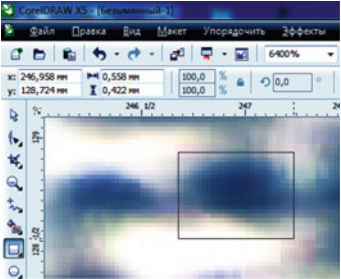
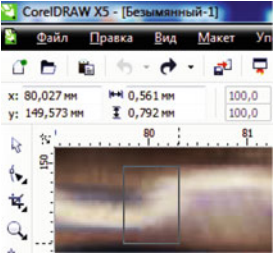
$$\begin{aligned} |W_0|^2 &\approx \left(\frac{U_1^*}{U_0}\right)^2, |W|^2 \approx \left(\frac{U_1}{U_0}\right)^2, |V_0|^2 \approx \left(\frac{U_2^*}{U_0}\right)^2, \\ |V|^2 &\approx \left(\frac{U_2}{U_0}\right)^2. \end{aligned} \quad (6.5)$$

It should be noted that a small part of the sound energy is not perceived by the ultrasonic sensor due to its attenuation in the medium of wave propagation. Even the measured value of the voltage U_0 is by a small value less than the real one, which is characterized by the amplitude of the wave incident on the material. These parameters of ultrasonic waves are given in Table 6.3 and in Figs. 6.17, 6.18.

It is seen from Table 6.3 and Fig. 6.18 that the sum of the coefficients of transmission and reflection by energy for some samples obtained from the measured values of voltages, is by a small value greater than one. This can be explained by the fact that a small part of the energy of the ultrasonic wave, which is proportional to the wave incident on the controlled material, is further lost in the process of its passage through the air of the reference channel and its subsequent conversion into an electrical quantity. There may be a slight discrepancy between the distances between the transducers of the measuring and reference channels of the ultrasonic system. If such loss of sound energy does not lead to an increase in the measurement error, which will exceed the permissible limits, it can be neglected. With a significant increase in the measurement error, it is necessary to better control it with adjustable amplifiers before starting the ultrasonic system. This can be done by setting the initial adjusted values of the output voltages on the detectors for each of the measuring channels, or by setting a correction code when processing digital measuring information by the system.

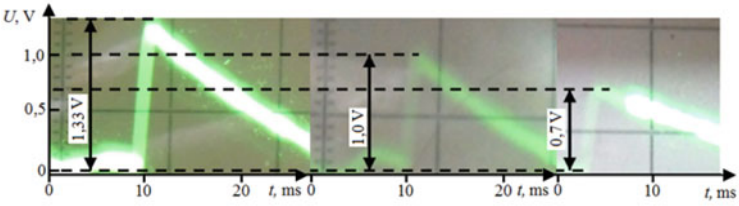
It can be also seen that for some samples of fabrics with a fancy weaving, or for samples of knitted fabrics (Table 6.4), the sum of the coefficients of transmission and reflection by energy is less than one. This may indicate additional dispersion

Table 6.2 Analysis of fabric samples with the comparison of contact destructive and non-contact methods for determining their porosity and basis weight

№	Analysis of fabric samples	
1	2	
1	Sample of the fabric №1 (reference)	
	Measurement of geometric dimensions of fabric pores using scanned samples and microsections	
	A unit of the fabric area of 1 mm², which has an average of 3.7 volumes of through pores 	Boundaries of the through pores in their widest place 
	Thickness of the fabric sample is shown in the micro section 	Boundaries of the through pores in their narrowest place 

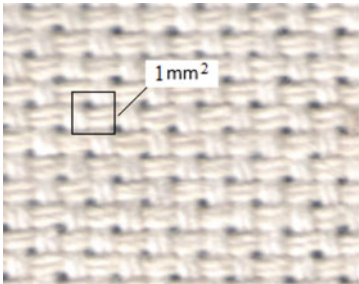
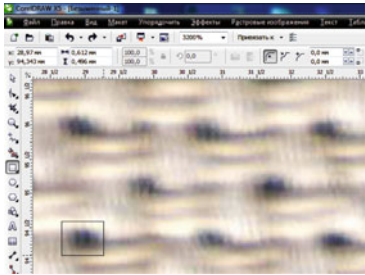
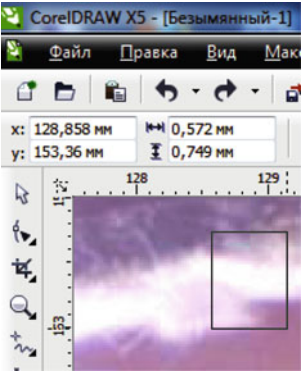
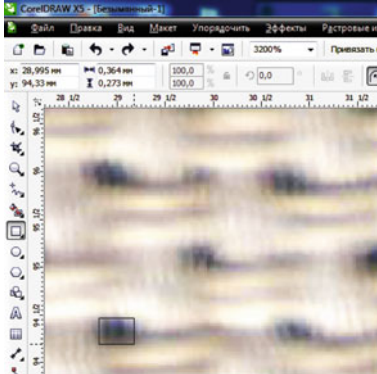
(continued)

Table 6.2 (continued)

1	2
	Measurement of the detected voltages U_0, U_1^*, U_2^* obtained by a computerized system model with an example of calculating the basis weight m_s of a fabric sample and the deviation δ_{m_s} by the expressions (1), (2), (3), (4)
	 $U_0 = 1.33 \text{ V}; \quad U_1^* = 1 \text{ V}; \quad U_2^* = 0.7 \text{ V};$ $Q_{0cp} \approx 0.1012 \text{ mm}^3$ (volume for one through pore); $Q_{0p} \approx 0.3744 \text{ mm}^3$ (pore volume in the fabric with an area of 1 mm^2) Example of calculations basis weight of the fabric by amplitude ratios ultrasonic waves in MATHCAD $\frac{\left[\sqrt{\frac{1}{(0.752)^2}} - 1 \cdot 420 \right]}{2.65 \cdot 40000 \cdot 0.0147} = 0.236 \quad \frac{1}{1.33} = 0.752$ $\frac{(0.236 - 0.2382) \cdot 100}{0.2382} = -0.924 \quad \frac{0.7}{0.7} = 1$
	Contact method: pore volume in the fabric area of 1 mm^2 $Q_{0p}(sm) = 0.3744 \text{ mm}^3$; basis weight $m_s(sm) = 238.2 \text{ g/m}^2$ Non-contact method: basis weight $m_s(nm) = 236 \text{ g/m}^2$; deviation $\delta_{m_s} = -0.92 \%$

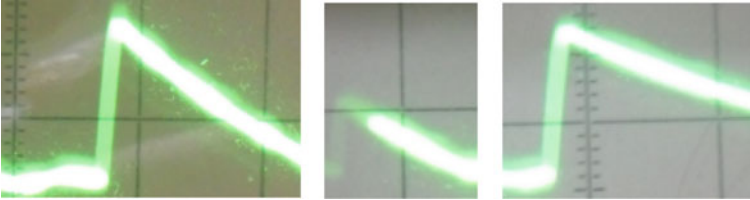
(continued)

Table 6.2 (continued)

1	2
	Sample of the fabric №2
	Measurement of geometric dimensions of fabric pores using scanned samples and microsections
2	A unit of the fabric area of 1 mm 2, which has an average of 1.5 volumes of through pores  Boundaries of the through pores in their widest place  Thickness of the fabric sample is shown in the micro section  Boundaries of the through pores in their narrowest place 

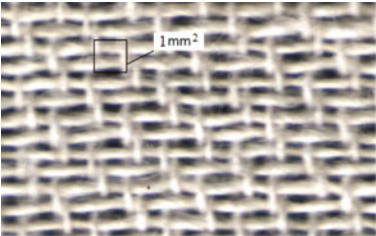
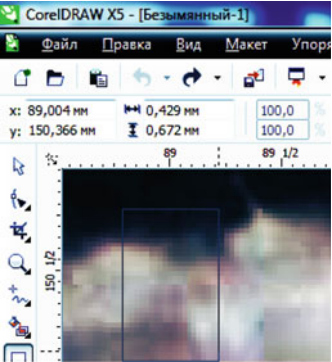
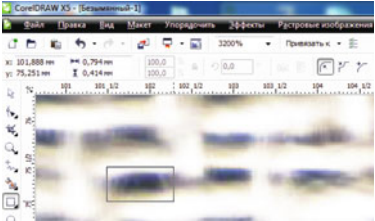
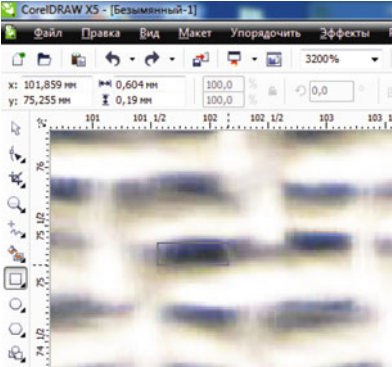
(continued)

Table 6.2 (continued)

1	2
	Measurement of the detected voltages U_0, U_1, U_2 obtained by a computerized system model with an example of calculating the change in porosity Q_p, basis weight m_s of the fabric sample and deviation δ_{m_s} by the expressions (1), (2), (3) , (4)
	 $U_0 = 1.33 \text{ V}; \quad U_1 = 0.6 \text{ V}; \quad U_2 = 1.25 \text{ V};$$Q_{cp} \approx 0.1425 \text{ mm}^3 \text{ (volume for one through pore);}$$Q_p \approx 0.2138 \text{ mm}^3 \text{ (pore volume in the fabric with an area of 1 mm}^2\text{)}$ Example of calculations basis weight of the fabric by amplitude ratios ultrasonic waves in MATHCAD $\frac{\left[\frac{1}{(0.451)^2} - 1 \cdot 420 \right]}{2.65 \cdot 1.786 \cdot 40000 \cdot 0.0147} = 0.299 \qquad \frac{0.6}{1.33} = 0.451$$\frac{(0.299 - 0.2922) \cdot 100}{0.2922} = 2.327 \qquad \frac{1.25}{0.7} = 1.786$$U_2 / U_2^* = 1.25 \text{ V} / 0.7 \text{ V} = 1.79 \qquad Q_{0p} / Q_p = 0.3744 \text{ mm}^3 / 0.2138 \text{ mm}^3 = 1.75$
	Contact method: pore volume in the fabric area of 1 mm² $Q_p(sm) = 0.2138 \text{ mm}^3$; basis weight $m_s(sm) = 292.2 \text{ g/m}^2$ Non-contact method: pore volume in the fabric area of 1 mm² $Q_p(nm) = 0.2097 \text{ mm}^3$; deviation $\delta_{Q_p} = -1.93 \%$; basis weight $m_s(nm) = 299 \text{ g/m}^2$; deviation $\delta_{m_s} = +2.33 \%$

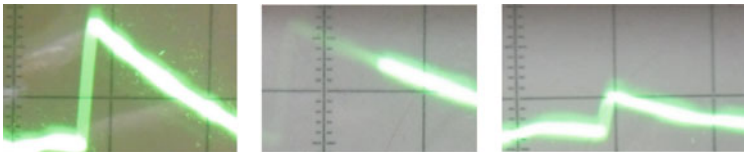
(continued)

Table 6.2 (continued)

1	2	
3	Sample of the fabric №3	
	Measurement of geometric dimensions of fabric pores using scanned samples and microsections	
	A unit of the fabric area of 1 mm², which has an average of 3.47 volumes of through pores  Thickness of the fabric sample is shown in the micro section 	Boundaries of the through pores in their widest place  Boundaries of the through pores in their narrowest place 

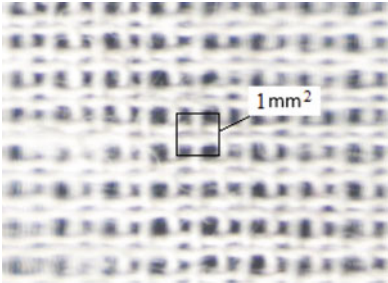
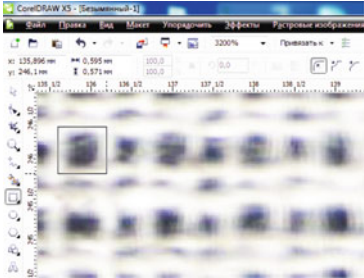
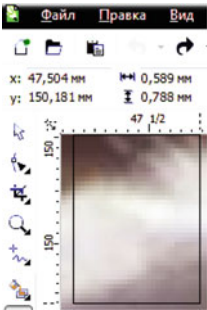
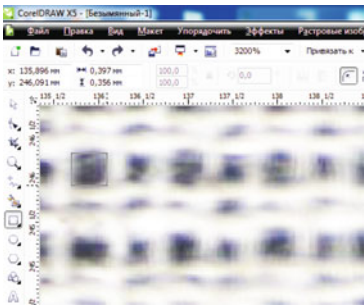
(continued)

Table 6.2 (continued)

1	2		
	Measurement of the detected voltages U_0, U_1, U_2 obtained by a computerized system model with an example of calculating the change in porosity Q_p, basis weight m_s of the fabric sample and the deviation δ_{m_s} by the expressions (1), (2), (3), (4)		
	 $U_0 = 1.33 \text{ V}; \quad U_1 = 1.25 \text{ V}; \quad U_2 = 0.45 \text{ V};$$Q_{cp} \approx 0.1683 \text{ mm}^3 \text{ (volume for one through pore);}$$Q_p \approx 0.5840 \text{ mm}^3 \text{ (pore volume in the fabric with an area of 1 mm}^2\text{)}$ Example of calculations basis weight of the fabric by amplitude ratios ultrasonic waves in MATHCAD $\frac{\left[\sqrt{\frac{1}{(0.94)^2}} - 1 \cdot 420 \right]}{2.65 \cdot 0.643 \cdot 40000 \cdot 0.0147} = 0.152 \quad \frac{1.25}{1.33} = 0.94$$\frac{(0.152 - 0.146) \cdot 100}{0.146} = 4.11 \quad \frac{0.45}{0.7} = 0.643$$U_2 / U_2^* = 0.45 \text{ V} / 0.7 \text{ V} = 0.64 \quad Q_{0p} / Q_p = 0.3744 \text{ mm}^3 / 0.5840 \text{ mm}^3 = 0.64$		
	<table><tr><td> Contact method: pore volume in the fabric area of 1 mm² $Q_p(sm) = 0.5840 \text{ mm}^3$; basis weight $m_s(sm) = 146 \text{ g/m}^2$ </td><td> Non-contact method: pore volume in the fabric area of 1 mm² $Q_p(nm) = 0.5824 \text{ mm}^3$; deviation $\delta_{Q_p} = -0.27 \%$; basis weight $m_s(nm) = 152 \text{ g/m}^2$; deviation $\delta_{m_s} = +4.11 \%$ </td></tr></table>	Contact method: pore volume in the fabric area of 1 mm² $Q_p(sm) = 0.5840 \text{ mm}^3$; basis weight $m_s(sm) = 146 \text{ g/m}^2$	Non-contact method: pore volume in the fabric area of 1 mm² $Q_p(nm) = 0.5824 \text{ mm}^3$; deviation $\delta_{Q_p} = -0.27 \%$; basis weight $m_s(nm) = 152 \text{ g/m}^2$; deviation $\delta_{m_s} = +4.11 \%$
Contact method: pore volume in the fabric area of 1 mm² $Q_p(sm) = 0.5840 \text{ mm}^3$; basis weight $m_s(sm) = 146 \text{ g/m}^2$	Non-contact method: pore volume in the fabric area of 1 mm² $Q_p(nm) = 0.5824 \text{ mm}^3$; deviation $\delta_{Q_p} = -0.27 \%$; basis weight $m_s(nm) = 152 \text{ g/m}^2$; deviation $\delta_{m_s} = +4.11 \%$		

(continued)

Table 6.2 (continued)

1	2	
4	Sample of the fabric №4	
	Measurement of geometric dimensions of fabric pores using scanned samples and microsections	
	A unit of the fabric area of 1 mm², which has an average of 3.62 volumes of through pores 	Boundaries of the through pores in their widest place 
	Thickness of the fabric sample is shown in the micro section 	Boundaries of the through pores in their narrowest place 

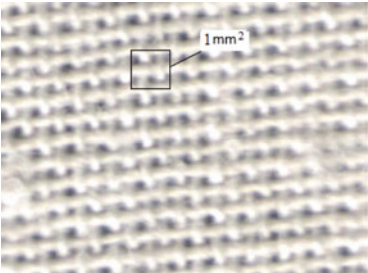
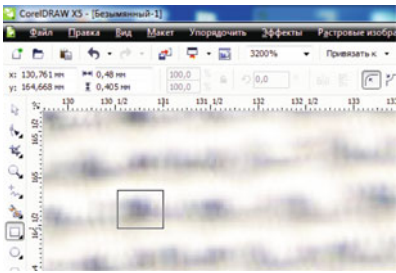
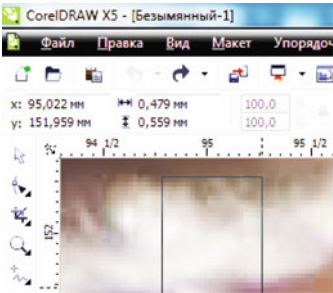
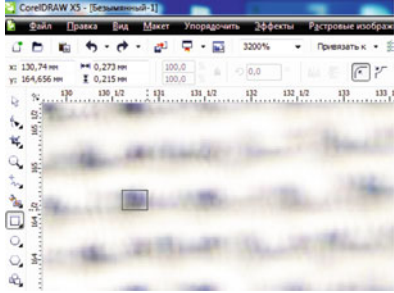
(continued)

Table 6.2 (continued)

1	2				
	Measurement of the detected voltages U_0, U_1, U_2 obtained by a computerized system model with an example of calculating the change in porosity Q_p, basis weight m_s of the fabric sample and deviation δ_{m_s} by the expressions (1), (2), (3), (4)				
	 $U_0 = 1.33 \text{ V};$ $U_1 = 1.30 \text{ V};$ $U_2 = 0.41 \text{ V};$ $Q_{cp} \approx 0.1814 \text{ mm}^3$ (volume for one through pore); $Q_p \approx 0.6558 \text{ mm}^3$ (pore volume in the fabric with an area of 1 mm^2) Example of calculations basis weight of the fabric by amplitude ratios ultrasonic waves in MATHCAD $\frac{\left[\sqrt{\frac{1}{(0.977)^2}} - 1 \cdot 420 \right]}{2.65 \cdot 0.586 \cdot 40000 \cdot 0.0147} = 0.1 \quad \frac{1.3}{1.33} = 0.977$$\frac{(0.1 - 0.0947) \cdot 100}{0.0947} = 5.597 \quad \frac{0.41}{0.7} = 0.586$ $U_2 / U_2^* = 0.41 \text{ V} / 0.7 \text{ V} = 0.59$$Q_{0p} / Q_p = 0.3744 \text{ mm}^3 / 0.6558 \text{ mm}^3 = 0.57$ <tr><td></td><td><table><tr><td>Contact method: pore volume in the fabric area of 1 mm^2 $Q_p(sm) = 0.6558 \text{ mm}^3$; basis weight $m_s(sm) = 94.7 \text{ g/m}^2$</td><td>Non-contact method: pore volume in the fabric area of 1 mm^2 $Q_p(nm) = 0.6392 \text{ mm}^3$; deviation $\delta_{Q_p} = -2.53 \%$; basis weight $m_s(nm) = 100 \text{ g/m}^2$; deviation $\delta_{m_s} = +5.60 \%$</td></tr></table></td></tr>		<table><tr><td>Contact method: pore volume in the fabric area of 1 mm^2 $Q_p(sm) = 0.6558 \text{ mm}^3$; basis weight $m_s(sm) = 94.7 \text{ g/m}^2$</td><td>Non-contact method: pore volume in the fabric area of 1 mm^2 $Q_p(nm) = 0.6392 \text{ mm}^3$; deviation $\delta_{Q_p} = -2.53 \%$; basis weight $m_s(nm) = 100 \text{ g/m}^2$; deviation $\delta_{m_s} = +5.60 \%$</td></tr></table>	Contact method: pore volume in the fabric area of 1 mm^2 $Q_p(sm) = 0.6558 \text{ mm}^3$; basis weight $m_s(sm) = 94.7 \text{ g/m}^2$	Non-contact method: pore volume in the fabric area of 1 mm^2 $Q_p(nm) = 0.6392 \text{ mm}^3$; deviation $\delta_{Q_p} = -2.53 \%$; basis weight $m_s(nm) = 100 \text{ g/m}^2$; deviation $\delta_{m_s} = +5.60 \%$
	<table><tr><td>Contact method: pore volume in the fabric area of 1 mm^2 $Q_p(sm) = 0.6558 \text{ mm}^3$; basis weight $m_s(sm) = 94.7 \text{ g/m}^2$</td><td>Non-contact method: pore volume in the fabric area of 1 mm^2 $Q_p(nm) = 0.6392 \text{ mm}^3$; deviation $\delta_{Q_p} = -2.53 \%$; basis weight $m_s(nm) = 100 \text{ g/m}^2$; deviation $\delta_{m_s} = +5.60 \%$</td></tr></table>	Contact method: pore volume in the fabric area of 1 mm^2 $Q_p(sm) = 0.6558 \text{ mm}^3$; basis weight $m_s(sm) = 94.7 \text{ g/m}^2$	Non-contact method: pore volume in the fabric area of 1 mm^2 $Q_p(nm) = 0.6392 \text{ mm}^3$; deviation $\delta_{Q_p} = -2.53 \%$; basis weight $m_s(nm) = 100 \text{ g/m}^2$; deviation $\delta_{m_s} = +5.60 \%$		
Contact method: pore volume in the fabric area of 1 mm^2 $Q_p(sm) = 0.6558 \text{ mm}^3$; basis weight $m_s(sm) = 94.7 \text{ g/m}^2$	Non-contact method: pore volume in the fabric area of 1 mm^2 $Q_p(nm) = 0.6392 \text{ mm}^3$; deviation $\delta_{Q_p} = -2.53 \%$; basis weight $m_s(nm) = 100 \text{ g/m}^2$; deviation $\delta_{m_s} = +5.60 \%$				

(continued)

Table 6.2 (continued)

1	2	
5	Sample of the fabric №5	
	Measurement of geometric dimensions of fabric pores using scanned samples and microsections	
	A unit of the fabric area of 1 mm², which has an average of 5.64 volumes of through pores 	Boundaries of the through pores in their widest place 
	Thickness of the fabric sample is shown in the micro section 	Boundaries of the through pores in their narrowest place 

(continued)

Table 6.2 (continued)

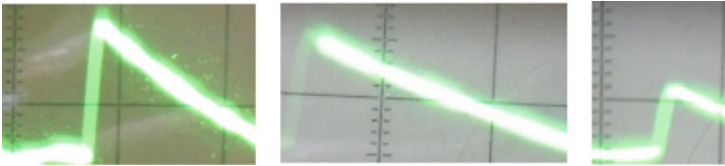
1	2		
	Measurement of the detected voltages U_0, U_1, U_2 obtained by a computerized system model with an example of calculating the change in porosity Q_p, basis weight m_s of the fabric samples and deviations δ_{m_s} by the expressions (1), (2), (3), (4)		
	 $U_0 = 1.33 \text{ V}; \quad U_1 = 1.15 \text{ V}; \quad U_2 = 0.7 \text{ V};$$Q_{cp} \approx 0.0659 \text{ mm}^3 \text{ (volume for one through pore);}$$Q_p \approx 0.3717 \text{ mm}^3 \text{ (pore volume in the fabric with an area of 1 mm}^2\text{)}$ Example of calculations basis weight of the fabric by amplitude ratios ultrasonic waves in MATHCAD $\frac{\left[\sqrt{\frac{1}{(0.865)^2}} - 1 \cdot 420 \right]}{2.65 \cdot 1 \cdot 40000 \cdot 0.0147} = 0.156 \quad \frac{1.15}{1.33} = 0.865$$\frac{(0.156 - 0.1562) \cdot 100}{0.1562} = -0.128 \quad \frac{0.7}{0.7} = 1$$U_2 / U_2^* = 0.7 \text{ V} / 0.7 \text{ V} = 1 \quad Q_{0p} / Q_p = 0.3744 \text{ mm}^3 / 0.3717 \text{ mm}^3 = 1.01$		
	<table><tr><td> Contact method: pore volume in the fabric area of 1 mm² $Q_p(sm) = 0.3717 \text{ mm}^3$; basis weight $m_s(sm) = 156.2 \text{ g/m}^2$ </td><td> Non-contact method: pore volume in the fabric area of 1 mm² $Q_p(nm) = 0.3744 \text{ mm}^3$; deviation $\delta_{Q_p} = + 0.73 \%$; basis weight $m_s(nm) = 156 \text{ g/m}^2$; deviation $\delta_{m_s} = - 0.13 \%$ </td></tr></table>	Contact method: pore volume in the fabric area of 1 mm² $Q_p(sm) = 0.3717 \text{ mm}^3$; basis weight $m_s(sm) = 156.2 \text{ g/m}^2$	Non-contact method: pore volume in the fabric area of 1 mm² $Q_p(nm) = 0.3744 \text{ mm}^3$; deviation $\delta_{Q_p} = + 0.73 \%$; basis weight $m_s(nm) = 156 \text{ g/m}^2$; deviation $\delta_{m_s} = - 0.13 \%$
Contact method: pore volume in the fabric area of 1 mm² $Q_p(sm) = 0.3717 \text{ mm}^3$; basis weight $m_s(sm) = 156.2 \text{ g/m}^2$	Non-contact method: pore volume in the fabric area of 1 mm² $Q_p(nm) = 0.3744 \text{ mm}^3$; deviation $\delta_{Q_p} = + 0.73 \%$; basis weight $m_s(nm) = 156 \text{ g/m}^2$; deviation $\delta_{m_s} = - 0.13 \%$		

Table 6.3 Indicators of wave transmission and reflection coefficients by energy

Samples of fabrics	$ W_0 , W $	$ W_0 ^2$ (sample 1), $ W ^2$ (samples 2, 3, 4, 5)	$ V_0 , V $	$ V_0 ^2$ (sample 1), $ V ^2$ (samples 2, 3, 4, 5)
1 (ref. sam.)	0.752	0.565	0.526	0.277
2	0.451	0.204	0.940	0.883
3	0.940	0.883	0.338	0.114
4	0.977	0.955	0.308	0.095
5	0.865	0.748	0.526	0.277

of reflected ultrasonic waves from the surface of the controlled fabric, interacting with the complex structure of the fabric (with a complex interweaving of threads) or knitwear (with courses of the fabric). It is difficult to use the amplitude of the reflected ultrasonic waves in comparison with the fabrics of simple weaving to control knitted fabrics. The difficulty is that for the waves reflected from the material, the radiating and receiving transducers must be placed near the controlled fabric at a very short distance.

Table 6.4 shows the samples of knitted fabrics rib 1 + 1 and plain, which were studied for the interaction of a textile material with ultrasonic waves. The results indicate that the dispersion of reflected waves from knitted fabrics is greater than from controlled fabrics.

When probing the jersey, only for the transmission of ultrasonic waves through the material with a certain porosity, the control of its basis weight will be little different from this process for simple fabrics. In this case, the dispersion of ultrasonic waves will not significantly affect the measurement error for a material with a small thickness. Therefore, for knitted fabrics it is advisable to use the method with a measuring channel for the passage of ultrasonic waves through the controlled material to be used in the textile industry.

The porosity of different textile fabrics should be determined to adjust the non-contact control of the basis weight of different textile fabrics with different weave construction. A possible option for simplifying the hardware of the scanning system is to divide its measuring channels into separate parts. One part will take into account the attenuation of ultrasonic waves that have passed through the controlled fabric and will operate in its scanning mode, and the other part can determine the porosity pointwise by means of the amplitude of the reflected ultrasonic wave before starting the system to better adjust it. This can greatly simplify the hardware of automated scanning systems to control textile fabrics with the same porosity. The implementation of the measuring part of the system, which will determine the porosity of the fabric per unit area, can be based simply on the usual blocks of the ratio of detected voltages with digital voltmeters at the output of the channel. For such a simplified implementation, it is necessary to bring the dependence of the module $|V|$ of the complex wave reflection coefficient on the pore volume Q_p in the fabric sample with a unit area of 1 mm^2 , which is shown in Fig. 6.19, a, to a linear form. The inverse value $|V|^{-1}$, which

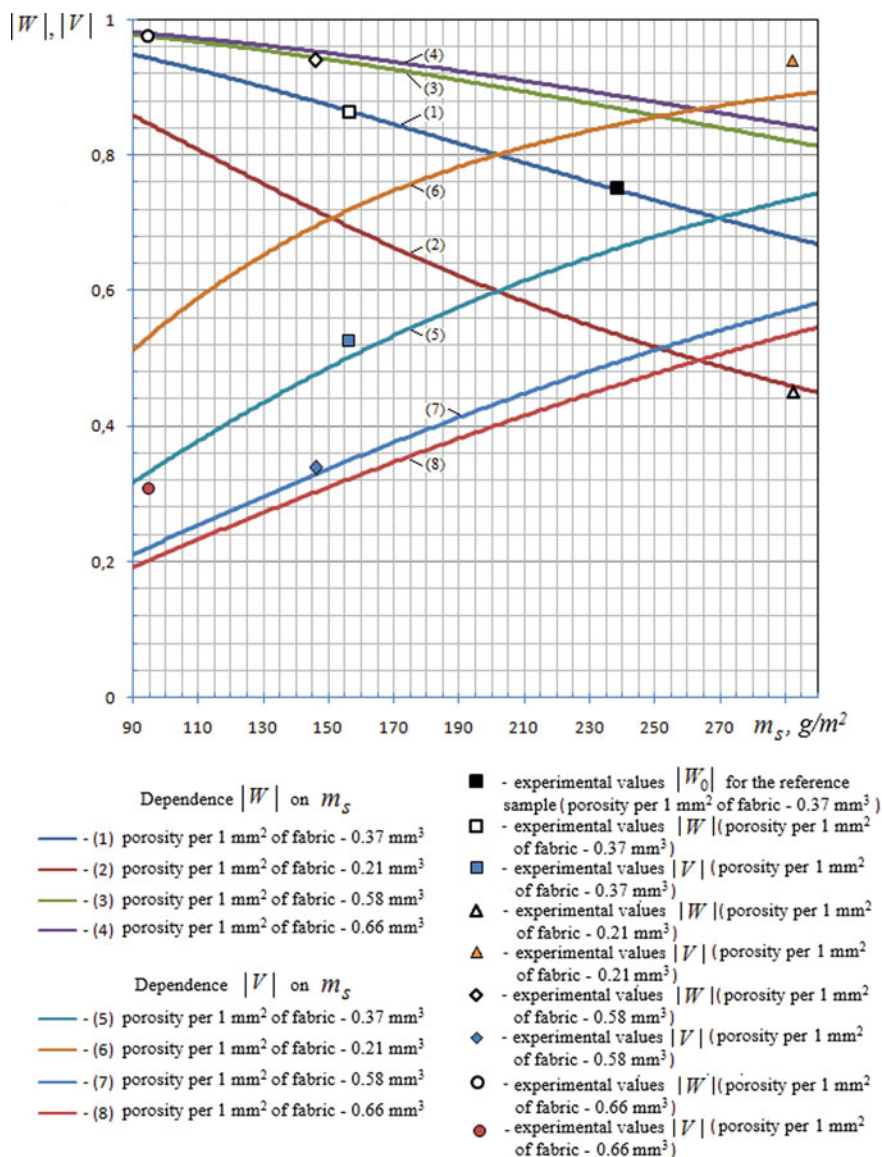


Fig. 6.17 Theoretical dependences of modules $|W|, |V|$ on the basis weight m_s of different fabrics and their experimental values, which are obtained using the measured voltages $U_0, U_1^*, U_2^*, U_1, U_2$

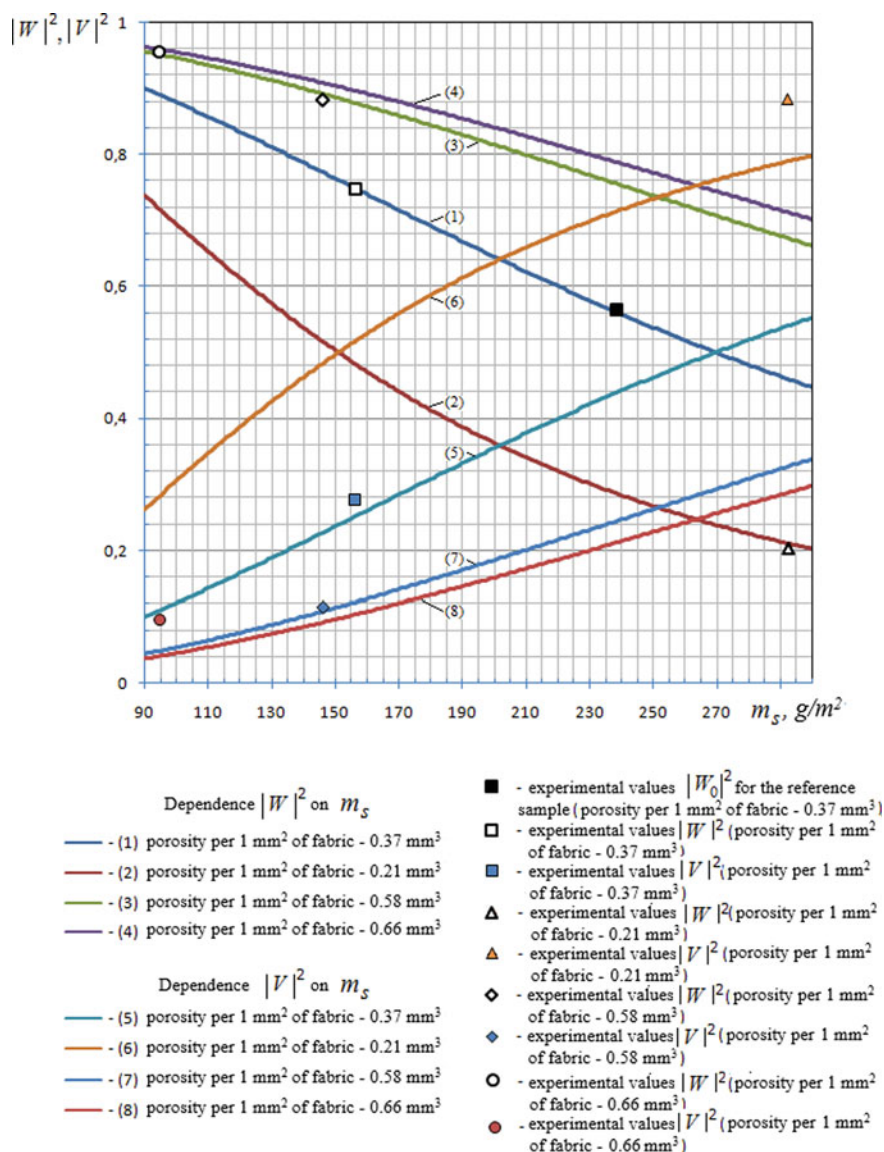
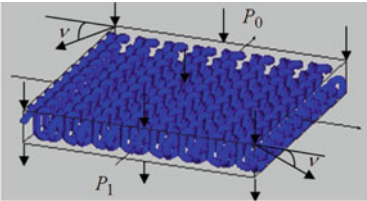
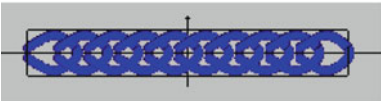
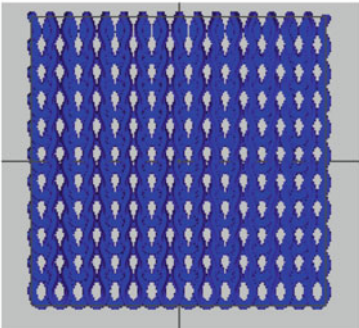
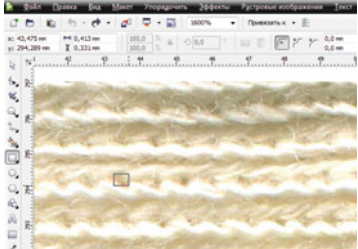
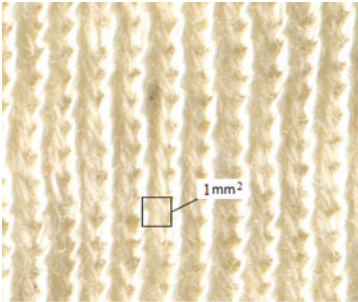


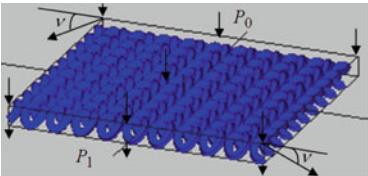
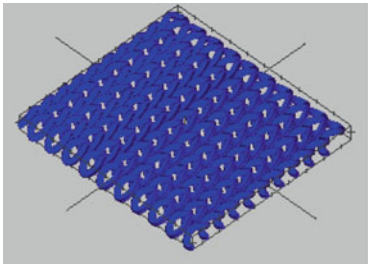
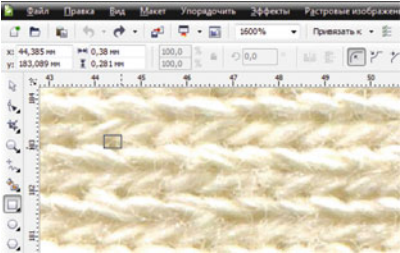
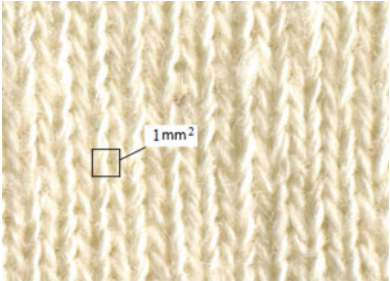
Fig. 6.18 Theoretical dependences of coefficients $|W|^2$, $|V|^2$ by energy on the basis weight m_s of different fabrics and their experimental values, which were obtained using the measured voltages U_0 , U_1^* , U_2^* , U_1 , U_2

Table 6.4 Analysis of the samples of knitted fabrics with a comparison of contact destructive and non-contact methods for determining their porosity and basis weight

№ Analysis of the samples of knitted fabrics		
1	2	3
1	Sample of the fabric № 1	
	Rib 1+1 (the transmission of ultrasonic waves through the textile material)  Side view  Top view 	Boundaries of the through pore  A unit of the fabric area of 1 mm², which has an average of 4 volumes of through pores  Voltage waveforms at the outputs of the detectors during irradiation of the sample  U0 = 1.33 V U1 = 1.1 V U2 = 0.55 V

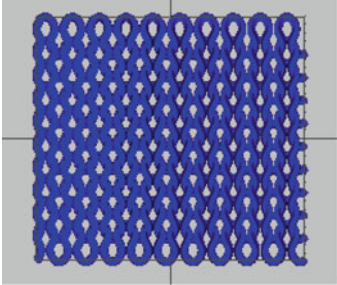
(continued)

Table 6.4 (continued)

1	2	3
	$Q_{cp} \approx 0.1230 \text{ mm}^3$ (volume for one through pore); $Q_p \approx 0.4921 \text{ mm}^3$ (pore volume in the fabric with an area of 1 mm^2)	
	Contact method: pore volume in the fabric area of 1 mm^2 $Q_p(sm) = 0.4921 \text{ mm}^3$; basis weight $m_s(sm) = 226 \text{ g/m}^2$	Non-contact method: pore volume in the fabric area of 1 mm^2 $Q_p(nm) = 0.4765 \text{ mm}^3$; deviation $\delta Q_p = -3.168 \%$; basis weight $m_s(nm) = 233 \text{ g/m}^2$; deviation $\delta m_s = +3.097 \%$
	Sample of the fabric № 2	
2	Plain (the transmission of ultrasonic waves through the textile material)  3D model view 	Boundaries of the through pore  A unit of the fabric area of 1 mm^2, which has an average of 4 volumes of through pores 

(continued)

Table 6.4 (continued)

1	2	3
	Top view 	Voltage waveforms at the outputs of the detectors during irradiation of the sample  U0 = 1.33 V U1 = 1 V U2 = 0.7 V
	$Q_{cp} \approx 0.0961 \text{ mm}^3$ (volume for one through pore); $Q_p \approx 0.3844 \text{ mm}^3$ (pore volume in the fabric with an area of 1 mm^2)	
	Contact method: pore volume in the fabric area of 1 mm^2 $Q_p(sm) = 0.3844 \text{ mm}^3$; basis weight $m_s(sm) = 229 \text{ g/m}^2$	Non-contact method: pore volume in the fabric area of 1 mm^2 $Q_p(nm) = 0.3744 \text{ mm}^3$; deviation $\delta Q_p = -2.6 \%$; basis weight $m_s(nm) = 236 \text{ g/m}^2$; deviation $\delta m_s = +3.057 \%$

is determined using the ratios of the measured detected stresses ($|V|^{-1} \approx U_0/U_2$), makes it possible to obtain a linear characteristic of the initial value from the change in pore volume Q_p in different samples of textile fabrics, as shown in Fig. 6.19b.

This will allow, without the use of expensive integrated circuits and complex software, directly using only a block of voltage ratios and a simple voltmeter to determine the porosity of textile fabrics. Without such adjustment of the system, the error of basis weight measurements m_s will be significant (Fig. 6.20a). Figure 6.21a shows the effect of wave energy dispersion for the studied samples of fabrics and knitwear, and Figs. 6.20, 6.21b show the deviations $\delta Q_p, \delta m_s$ of non-contact measured parameters Q_p and m_s in comparison with their existing definition.

Studies have shown that in practice it is possible to apply non-contact ultrasonic methods and means of control over the porosity of various textile fabrics and their basis weight.

It is also experimentally proven that knitted fabrics, with the help of courses in their structure, disperse the reflected ultrasonic waves more than the fabrics of simple weaving. This, in turn, complicates the practical implementation of methods of receiving such ultrasonic waves reflected from the material. Therefore, for knitted

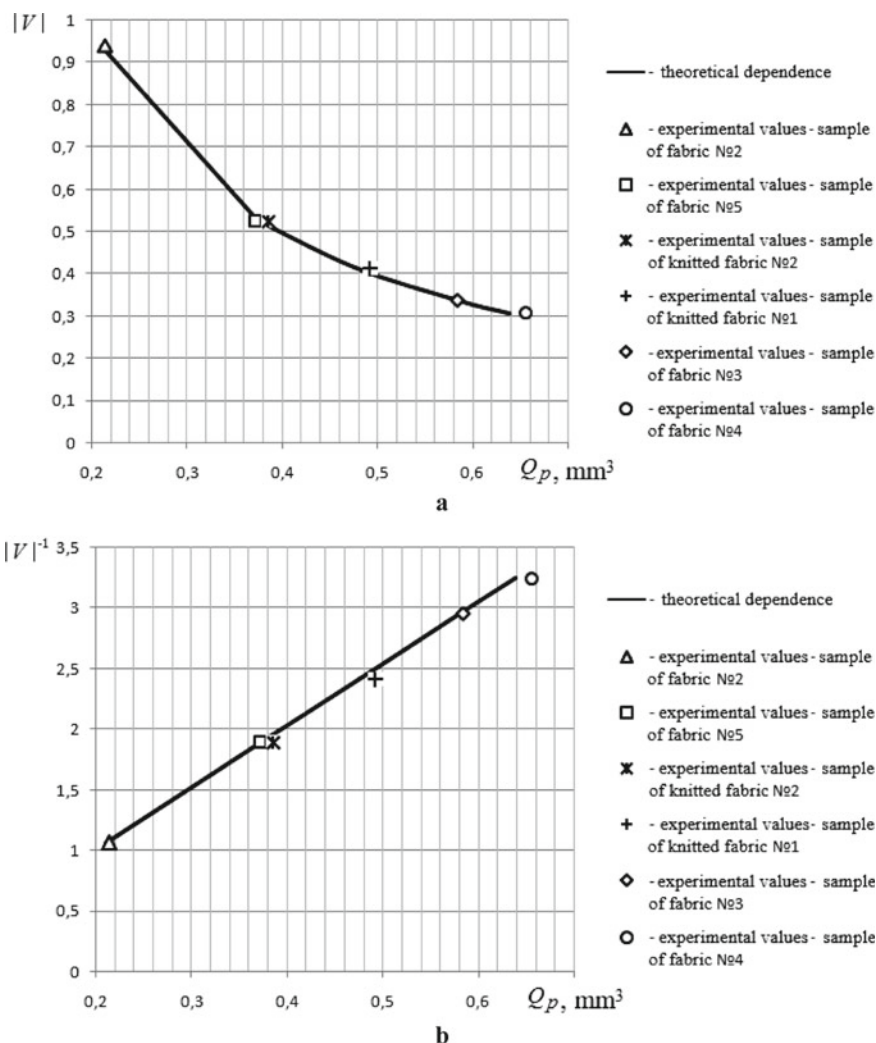


Fig. 6.19 Dependences of the module $|V|$ and the value $|V|^{-1}$ of the complex reflection coefficient on the pore volume in the fabric sample Q_p per unit area of 1 mm^2 : **a** dependence of the module $|V|$ on the pore volume Q_p, mm^3 in different materials; **b** dependence of the inverse value of the module $|V|^{-1}$ on the pore volume, mm^3 in different materials

fabrics, it is advisable to determine the point of porosity before scanning with the help of separate non-contact measuring instruments. Such means for determining the unknown porosity of the controlled fabric relative to the reference sample can be implemented without the use of microprocessor technology and complex processing of measuring information. This can be done only by using simple circuit solutions

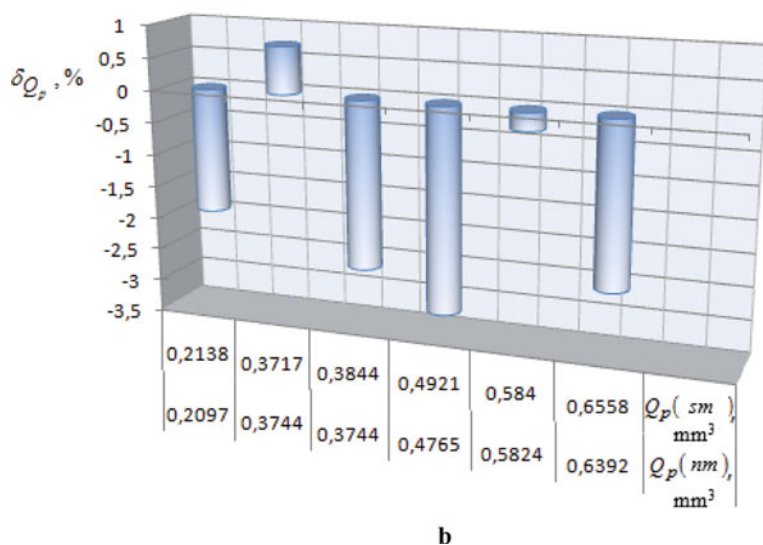
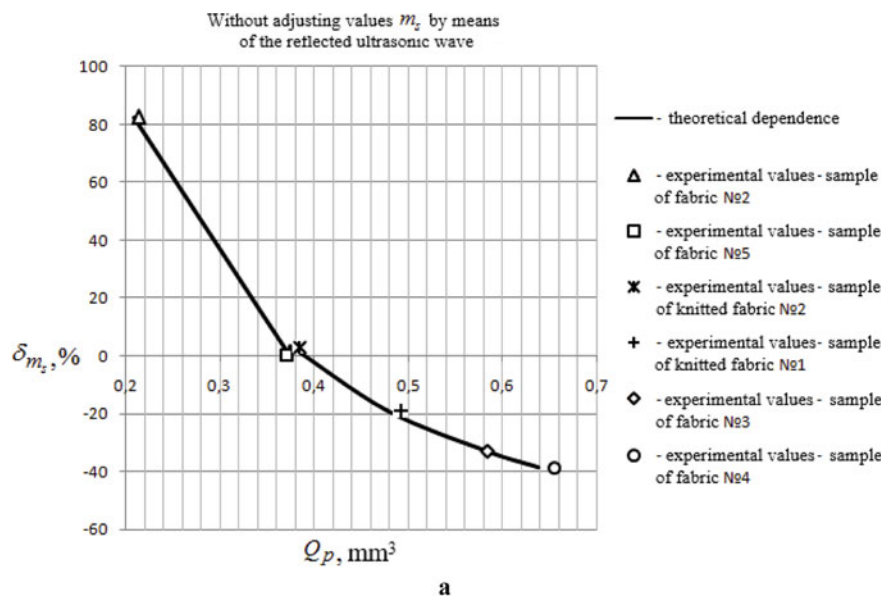


Fig. 6.20 Dependencies of deviations δ_{m_s} and δ_{Q_p} on the pore volume Q_p in the fabric sample per unit area of 1 mm^2 : **a** dependence of the deviation δ_{m_s} on Q_p without correction m_s by means of the reflected ultrasonic wave; **b** dependence of the deviation δ_{Q_p} on the pore volume Q_p

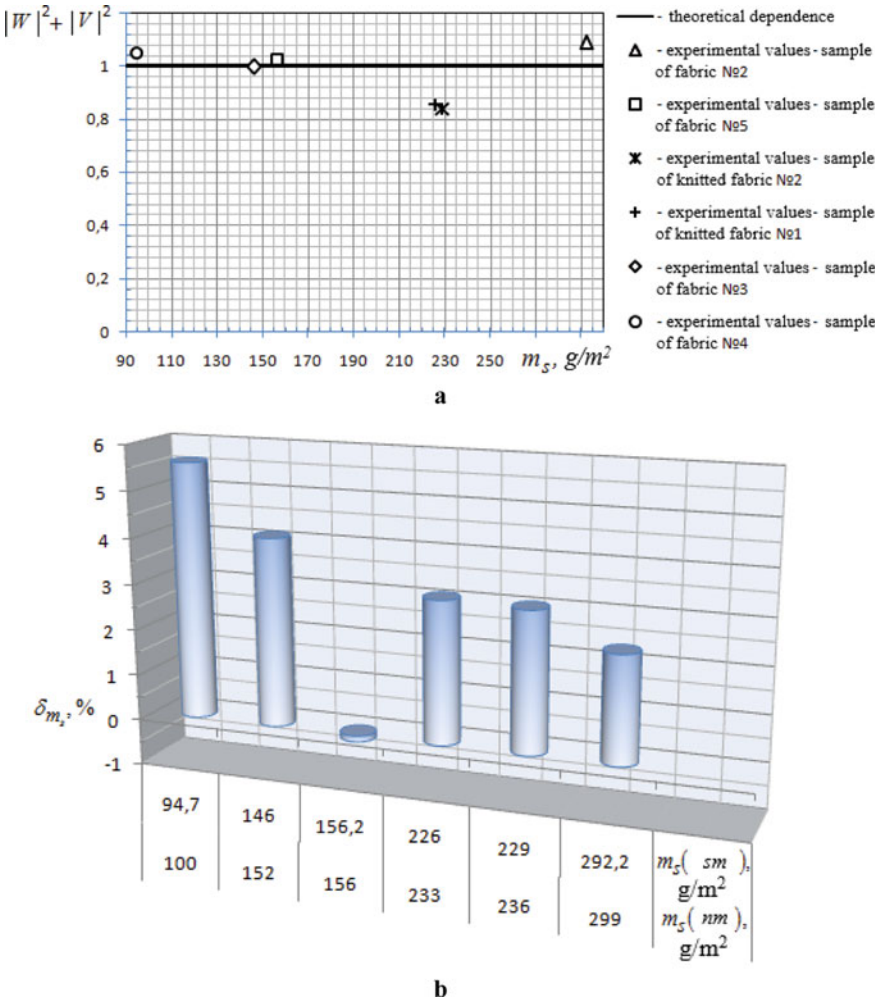


Fig. 6.21 Dependences of the sum of coefficients by energy $|W|^2 + |V|^2$ and deviation δ_{m_s} from basis weight of various samples of fabrics: **a** dependence of the parameter $|W|^2 + |V|^2$ on the basis weight m_s of different samples of fabrics; **b** dependence of the deviation δ_{m_s} on the basis weight m_s with the adjustment of its value using the reflected ultrasonic wave

by means of voltmeters to indicate the values of controlled parameters. The voltage on the voltmeter indicator will be proportional to the porosity of the textile fabric.

Experimental data make it possible to conclude that for fabrics of simple weaving it is possible to implement adaptive ultrasonic control over their basis weight. This is due to the fact that the surface of the fabric can well reflect ultrasonic waves compared to knitted fabrics. Therefore, with the help of reflected waves, it is possible to determine how much the porosity of the material itself relative to the reference sample changes. It was shown that the change in the porosity of the fabric, which

can change with the change of its structure, has the greatest impact on the error of non-contact measurements of the basis weight of the textile material.

The non-contact method of basis weight control can give high accuracy of measurements on the basis of the exact position of the ultrasonic sensors relative to the textile material and minimize the errors of the measuring channels of the scanning system. This non-contact method can provide both operational control of the parameter in production, and its point control.

6.4 Non-contact Measurement of Thread Tension with High Linear Density by Means of Experimental Ultrasonic Devices Using Waveguides

Adherence, within the appropriate limits of basis weight, to one of the important technological parameters of textile fabrics, depends on the tension of the threads on the textile machines on which they are produced. Excessive tension of the threads can cause them to break on the technological equipment, which leads to a lack of textile fabric and downtime of textile machines. Even uneven tension of threads on knitting machines leads to the formation of loops of different sizes in the fabric itself, which can also lead to uneven basis weight and flaws. Systems for measuring and adjusting the tension of threads on various textile machines are mainly only contact and mechanical. This means that it is very difficult to quickly determine the actual value of this parameter and control it during the operation of such systems.

There are contact devices for determining the tension of the threads, but they do not make it possible to install them without affecting the textile material. This leads to an additional increase in tension when measuring it. This can make a significant error from the contact pressure of the sensor on the material itself. There are also optical non-contact devices for determining various parameters of the threads, but they can have significant errors due to the dustiness of the environment under production conditions [17–23].

The tension can be determined by changing the diameter of the thread and its density (can vary by reducing the interfiber porosity of the material). The change in the thread diameter, in turn, affects the change in the amplitude of the sounding ultrasonic wave, which can propagate in the waveguide, where the controlled material itself is located. When conducting research, a method for non-contact measurement of thread tension with high linear density was applied using specially made waveguides. The proposed method was partially described in the paper earlier. It consists in the repeated transmission of an ultrasonic wave through the cross section of the waveguide, where the controlled thread is located, and in determining the tension of the textile fibers of the material by attenuating the sounding ultrasonic waves. It is clear that it is necessary for such cases to use ultrasonic waves that pass through the fibers of the material, as well as those waves that bypass the thread itself. To increase the sensitivity of the sensors, it is advisable to use waveguides. Waveguides

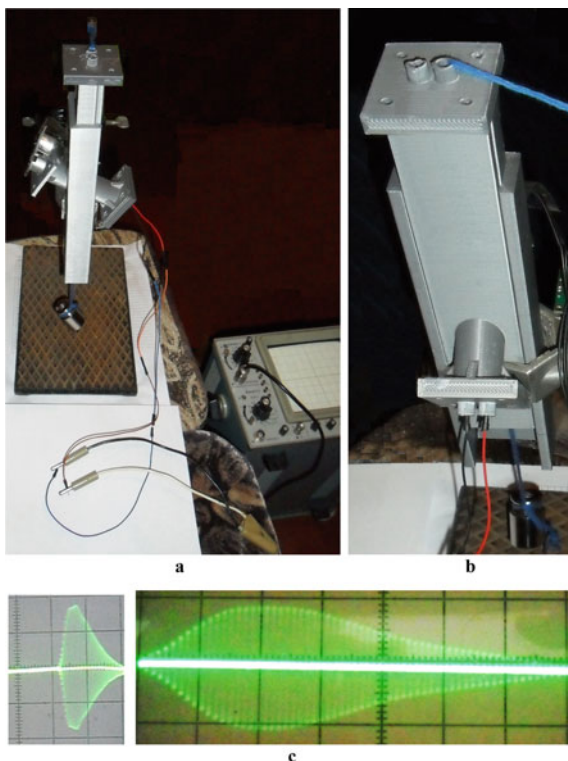
of different shapes and sizes can be used to determine the thread tension on knitting machines in the production of textile fabrics. In practice, to increase the sensitivity of ultrasonic waves to changes in the thread diameter, it is advisable to use low-power sensors and corresponding waveguides. Waveguides that have a rectangular cross section are quite effective. Figure 6.22 shows a waveguide that was made by 3D printing for experimental studies and non-contact measurement of thread tension with high linear density. In this waveguide, the ultrasonic piezoelectric transducers are located on different sides of the controlled thread. The distance between the sensors can be changed, but in the initial position it is designed for triple transmission of the wave through the waveguide cross section at an angle with double reflection of it from its walls. Changing the distance between the ultrasonic sensors, when the upper and lower parts of the waveguide move relatively to each other, it is possible to adjust the measuring channel to the sensitivity of ultrasonic waves by their amplitude (Fig. 6.23a, b) to the textile material. Thus, for a more effective method of measuring the thread tension, which was also developed during the research and experimentally confirmed, ultrasonic pulse signals of complex shape with two different peaks of amplitude (Fig. 6.23c) can be used. By these peaks of the signal amplitudes, it will be possible to take into account the part of the ultrasonic waves that passes through the controlled thread with a high linear density, and the part of the waves that bypasses the textile material of the thread. This is necessary in order to measure the value of the thread tension with a small error using a waveguide.

Without the use of a waveguide, the amplitude of the ultrasonic wave passing through the controlled thread remains almost unchanged. Also, as can be seen from Fig. 6.21, when the ultrasonic wave passes through the medium with textile fibers of the material, without its reflections from the walls of the waveguide and without repeated interaction of the wave with the thread, there is little change in its amplitude.

For transverse sounding of high-density thread material in the waveguide, it is advisable to determine the optimal number of wave transmissions through the controlled material, taking into account the thread thickness and the strength of the sounding signal at a constant wave frequency, for their greater sensitivity to textile fiber tension change. In the course of research it was established that the amplitude ratios of ultrasonic waves that interact with different textile threads are influenced by their linear density T , which is expressed in terms of the thread thickness h or nominal diameter d (it can be shown in terms of the nominal radius r), and the parameter $\cos \nu$. It should be noted that the parameter $\cos \nu$ depends on the porosity of the material, the frequency f of ultrasonic waves and their power. The parameter $\cos \nu$ changes with the change of the part of the waves bypassing the thread, and the nominal diameter d affects the change of the part of the waves passing through the textile fibers and interfiber pores. To determine the change in the parameter $\cos \nu$ and the nominal radius r of the thread, a pulse ultrasound signal with two different peaks of wave amplitudes can be used.

Pulse ultrasonic signals of complex shape with two different peaks of wave amplitudes, shown in Fig. 6.23, were used for experimental measurements of the current thread tension P^* in the created waveguides (Figs. 6.24 and 6.26). Visually with the help of oscilloscope C1-93 the largest change of amplitudes of peaks of sounding

Fig. 6.22 Created waveguide in the process of sounding the thread using ultrasonic waves without their reflections in it: **a** created waveguide in the process of its operation, side view; **b** front view of the created waveguide in the process of its operation; **c** pulse signal at different scales, received by the piezoelectric transducer without ultrasonic wave reflections

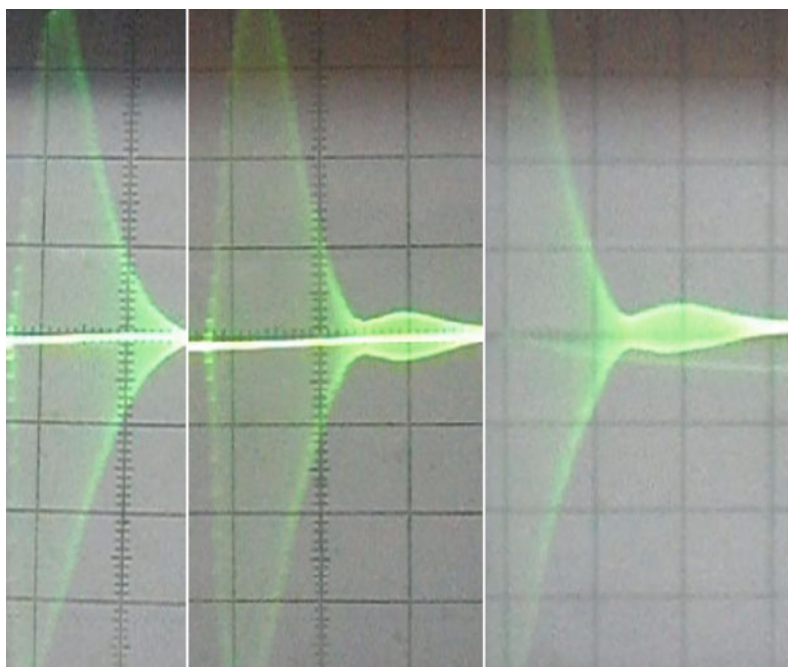


signals for different waveguides was determined (Figs. 6.25 and 6.27). It has been determined that for non-contact measurement of a thread with a linear density of 445 tex, a waveguide with sensors located on different sides of the material is more suitable.

If you determine with the help of a waveguide the change in tension of a particular thread branch using sounding the material with an ultrasonic pulse signal with two different peaks of amplitude, the expressions for this parameter $P^*(nm)$ and its deviation δ_{P^*} relative to the value $P^*(sm)$ obtained by the existing contact method can be written down as:

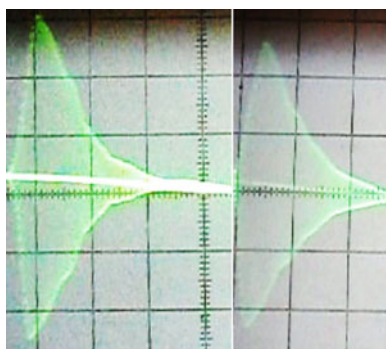
$$P^*(nm) = \frac{P}{2} \cdot \left(\left(\frac{r}{r^*} \right)^3 + \left(\frac{\cos v_2}{\cos v_2^*} \right)^3 \right),$$

$$P^*(nm) = \frac{P r^3}{2} \cdot \left(\sqrt{\frac{T}{\frac{Z_1}{\pi f r n \cdot \cos v_1} \cdot \sqrt{\frac{1}{|W_1|^2} - 1}}} \right)^{-3}$$



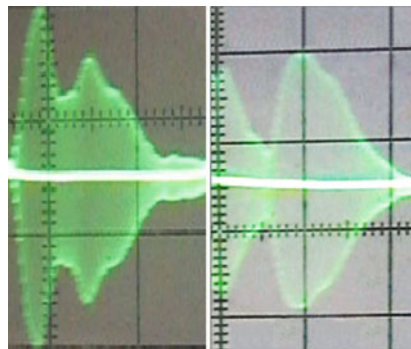
without thread with thread without tension ($P^* = 0$) $P^* = 98 \text{ cN}$

a



without thread with thread without tension without thread without thread

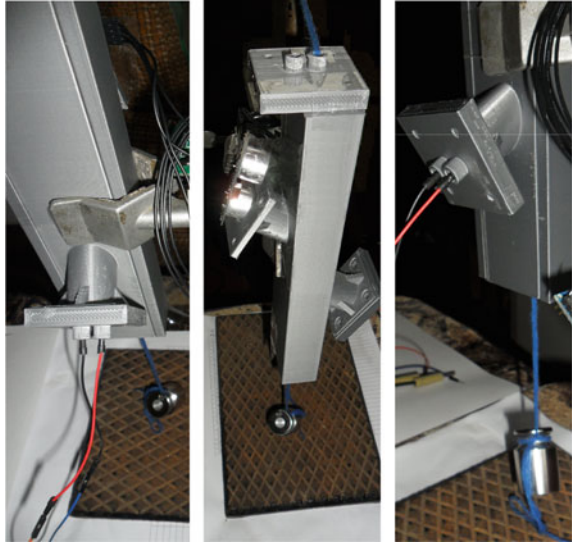
b



c

Fig. 6.23 Pulse ultrasonic signals in the waveguide received by the piezoelectric transducer: **a** pulse ultrasonic signals that are received without rereflections; **b** ultrasonic signals that pass three times through the cross section of the waveguide reflecting twice from its walls; **c** sounding ultrasonic signals of complex shape with two peaks of amplitudes fed to two different waveguides

Fig. 6.24 The process of non-contact measurement of the thread tension that causes the weight on it (using ultrasonic waves that pass three times through the cross section of the waveguide and are twice reflected from its walls with textile material inside). A waveguide with adjustable distances between sensors on different sides of the thread is used



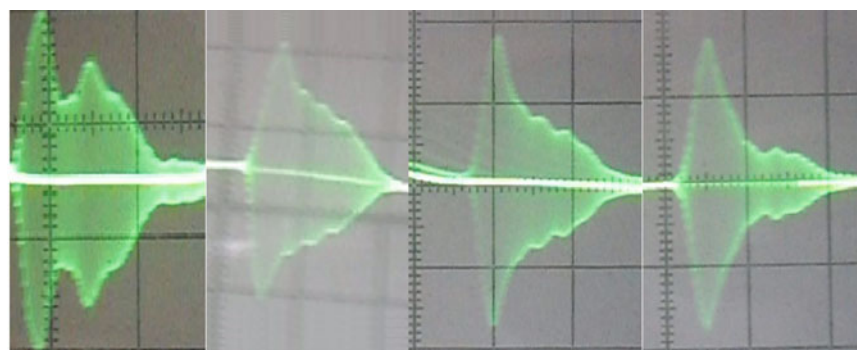
$$\begin{aligned}
 & + \frac{P}{2} \cdot \left(\frac{\pi^2 f r n \rho_2 \cos v_2}{Z_1} \right)^3 \cdot \left(\sqrt{\frac{1}{\left(|W_2| - \frac{P_{1w}}{K_V P_{01w}^*} \right)^2} - 1} \right)^{-3}, \\
 P^*(nm) = & \frac{P r^3}{2} \cdot \left(\sqrt{\frac{T}{\frac{Z_1}{\pi f r n \cos v_1} \cdot \sqrt{\left(\frac{U_1}{U_i} \right)^2 - 1}}} \right)^{-3} \\
 & + \frac{P}{2} \cdot \left(\frac{\pi^2 f r n \rho_2 \cos v_2}{Z_1} \right)^3 \cdot \left(\sqrt{\frac{1}{\left(\frac{U_i^*}{U_i^*} - \frac{U_i}{K_V U_i^*} \right)^2} - 1} \right)^{-3}, \quad (6.6)
 \end{aligned}$$

$$K_V = K_p \left(\frac{P_{01w}}{P_{1w}} \right) = K_p \left(\frac{U_1}{U_i} \right), \quad (6.7)$$

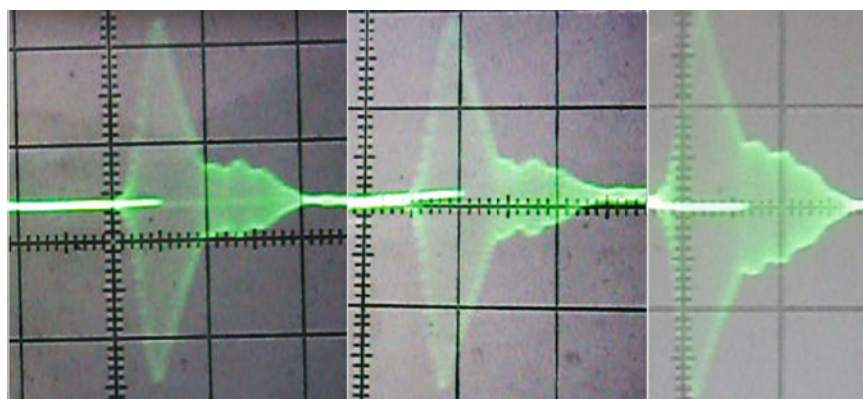
$$\delta_{P^*} = \frac{P^*(nm) - P^*(sm)}{P^*(sm)} \cdot 100 \%. \quad (6.8)$$

where $i=2, 3, 4, \dots$, the number of the value of the voltage amplitude from the receiving converter when changing the tension of the thread branch relative to its previous state; U_1 —the amplitude of the voltage, which is proportional to the smaller peak of the pulse ultrasonic signal when it propagates in a waveguide without a thread; U_i —the amplitude of the voltage, which is proportional to the smaller peak of the pulse ultrasonic signal when it propagates in the waveguide with a thread with a

Ultrasonic pulse signal with two pronounced amplitude peaks



without thread with thread without tension $P^* = 19.6 \text{ cN}$ $P^* = 49 \text{ cN}$



$P^* = 68.6 \text{ cN}$

$P^* = 98 \text{ cN}$

$P^* = 98 \text{ cN}$

(larger twist of thread)

Fig. 6.25 Analysis of the change in the shape and amplitude of the pulse ultrasonic signal depending on the change in the tension magnitude P^* , cN of the thread with a linear density $T = 445 \text{ tex}$ (mg/m) in the waveguide. An ultrasonic pulse signal with two different amplitude peaks and a waveguide with sensors on different sides of the thread are used for sounding the thread

change in its tension, the different values of which are associated with the sequence number i ; U_1^* —the amplitude of the voltage, which is proportional to the greater peak of the pulse ultrasonic signal when it propagates in a waveguide without a thread; U_i^* —the amplitude of the voltage, which is proportional to the greater peak of the pulse ultrasonic signal when it propagates in a waveguide with a thread with a change in its tension, the different values of which are associated with the sequence number i ; $|W_1|$ —the module of the complex coefficient of ultrasonic wave transmission, which is equal to the voltage ratio U_i/U_1 ; $|W_2|$ —the module of the complex coefficient of ultrasonic wave transmission, which is equal to the voltage ratio U_i^*/U_1^* ; v_1 —the

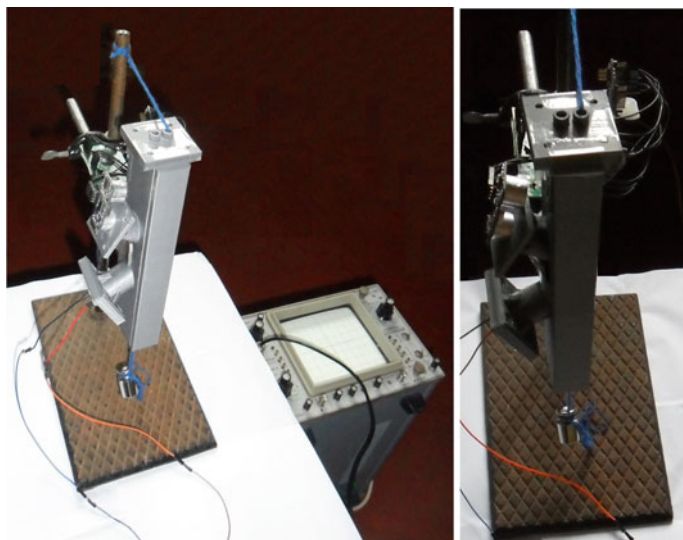


Fig. 6.26 The process of non-contact measurement of the thread tension that causes a weight on it (using ultrasonic waves that pass through the cross section of the waveguide four times and are reflected three times from its walls with textile material inside). A waveguide with sensors on one side of the thread is used

angle between the direction of the part of the waves bypassing the fibers of the thread in its middle, and the surface of these fibers; ν_2 —the angle between the direction of the part of the waves bypassing the thread itself from its outer side and the surface of the whole material; ν_2^* —the angle between the direction of the part of the waves bypassing the thread itself from its outer side and the surface of the whole material during the change of fiber tension; r —nominal radius of the controlled thread in the absence of tension; n —the number of the ultrasonic wave transmissions through a cross section of the waveguide with the thread, which is necessary for the oscillations to enter the receiving transducer; K_V —the coefficient of the air volume between the thread fibers; K_p —the initial coefficient of interfiber porosity of the thread material; T —linear thread density; P —initial thread tension; P_{01w} —the pressure amplitude in the wave of the smaller peak of the pulse signal that passes through the waveguide without a thread; P_{1w} —the pressure amplitude in the wave of the smaller peak of the pulse signal that passes through the waveguide with the thread when its tension is changed; P_{01w}^* —the pressure amplitude in the wave of the larger peak of the pulse signal that passes through the waveguide without a thread.

With the help of the obtained expression (6.6) it is possible to determine in practice the change of the current tension $P^*(nm)$ of the thread with a high linear density T . This method is suitable for non-contact measurement of the thread tension on the technological equipment if it is necessary to use it for the production process. It is also possible to further investigate the change in the interfiber porosity of different threads during their tension.

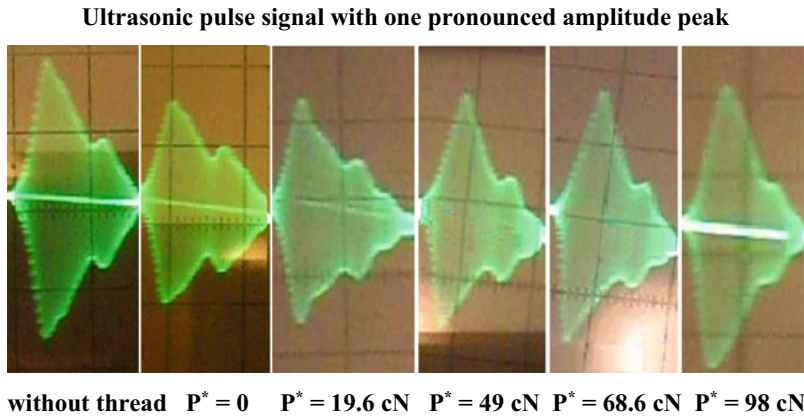
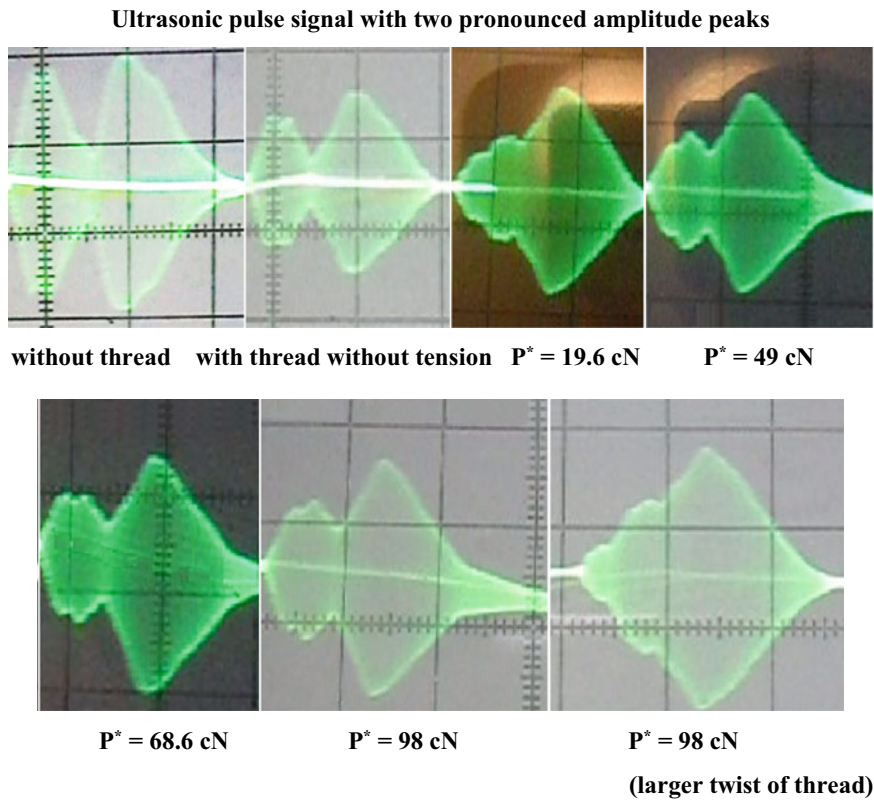


Fig. 6.27 Analysis of the change in the shape and amplitude of the pulse ultrasonic signal depending on the change in the tension magnitude P^* , cN of the thread with a linear density $T = 445 \text{ tex}$ (mg/m) in the waveguide. A waveguide with sensors on one side of the thread is used

As shown in Figs. 6.25 and 6.27, a larger change in the two peaks of the ultrasonic signals when changing the thread tension was observed using a waveguide with the location of the sensors on different sides of the material fibers. Therefore, studies for this case are discussed in Table 6.5 in more detail, and in other cases it is necessary to determine the best distance between the sensors experimentally. This is necessary to adjust the optimal sensitivity of the ultrasonic piezoelectric transducers to the density and size of a particular thread.

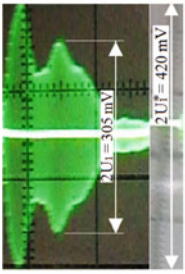
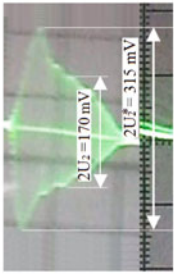
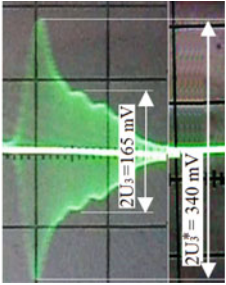
These results show that it is possible to create an accurate non-contact method for determining the tension of the thread with a high linear density. The part of the ultrasonic signal that passes directly through the structure of the thread itself can also be used to determine changes in the interfiber porosity of threads. This effect of determining the change in interfiber porosity during the thread tension is experimentally recorded using ultrasonic pulse signals of a complex shape.

Non-contact determination of the thread tension using a waveguide, the results of which are given in Table 6.5, is shown with all the oscillograms of pulse ultrasonic signals. It is possible to see from the general comparison of pulse signals correspondence of each of their oscillogram to the current value of the thread tension in a waveguide. It is clearly seen that the first peak of the amplitude of the ultrasonic signal decreases, and the second peak of the amplitude increases. The combination of measuring information about the amplitude informative parameters of the two peaks of ultrasonic waves makes it possible to take into account the part of the oscillations that bypasses the controlled material, and to reduce the error in tension measurement. An increase in the amplitude of the second peak of the ultrasonic signal of complex shape shows an increase in tension and a decrease in the nominal diameter of the thread, and a decrease in the amplitude of the first peak of the ultrasonic signal shows a decrease in the interfiber porosity with an increase in tension and deformation.

Figure 6.28 shows graphically the theoretical dependences using the expression (6.6) and the experimental data, which were also given in Table 6.5. From the obtained parameters it can be seen that in the area of the curve, when the thread tension is in the range from 20 to 50 cN, its diameter and interfiber porosity significantly decrease. At the beginning of the thread tension process, when the interfiber porosity is significant, some of the waves pass through the pores between the fibers, so the higher peak of the amplitude further increases. At the tension of 50 cN, the higher peak of the amplitude increases due to the part of the waves bypassing the thread with a reduced diameter from the outside of its surface. The other part of the oscillations, which initially further increased the amplitude of this peak, now passing through the reduced pores between the fibers of the material from the middle, reduces the resulting amplitude. Therefore, the graph in Fig. 6.28 shows that the amplitude of this peak during the action of tension on the thread in this range of its values (20–50 cN) remains the same.

Studies have shown that with the help of pulse ultrasonic signals it is possible to determine not only the tension of threads with high linear density, but also the degree of twist of complex threads by changing their interfiber porosity, which, in turn, can be controlled by changing the amplitudes of ultrasonic waves (Figs. 6.25 and 6.27).

Table 6.5 The results of research on non-contact measurement of thread tension

Parameter	Experimental data		
$T, \text{mg/m}$	445		
r, mm	1.50		
f, kHz	40		
$\cos V_2$	0.00335		
K_p	2.8		
P, cN	19.6		
n	3		
i	-	2	3
$P^*(sm), \text{cN}$	-	0	19.6
r^*, mm	-	1.50	1.47
$\cos V_2^*$	-	0.00335	0.00334
Oscillograms of ultrasonic signals			
Voltage amplitude	$2U_1 = 305 \text{ mV}$ $2U_1^* = 420 \text{ mV}$	$2U_2 = 170 \text{ mV}$ $2U_2^* = 315 \text{ mV}$	$2U_3 = 165 \text{ mV}$ $2U_3^* = 340 \text{ mV}$
$ w_1 = \frac{U_i}{U_1}$	1	0.557	0.541
$ w_2 = \frac{U_i^*}{U_1^*}$	1	0.750	0.810
$P^*(nm), \text{cN}$	-	0	20.364
Deviation $\delta_{P^*}, \%$	-	0	3.9

(continued)

Table 6.5 (continued)

i	4	5	6		
$P^*(sm), cN$	49.0	68.6	98.0		
r^*, mm	1.02	0.99	0.95		
$cosV_2^*$	0.00282	0.00222	0.00183		
Oscillograms of ultrasonic signals					
Voltage amplitude	$2U_4 = 90\text{ mV}$ $2U_4^* = 340\text{ mV}$	$2U_5 = 85\text{ mV}$ $2U_5^* = 365\text{ mV}$	$2U_6 = 80\text{ mV}$ $2U_6^* = 380\text{ mV}$		
$ w_1 = \frac{U_i}{U_1}$	0.295	0.279	0.262		
$ w_2 = \frac{U_i^*}{U_1^*}$	0.810	0.869	0.905		
$P^*(nm), cN$	47.904	68.333	98.544		
Deviation $\delta_{P^*}, \%$	-2.2	-0.39	0.56		
comparison of pulse ultrasonic signals of a complex shape (with two amplitude peaks, which determine the tension and change of interfiber porosity of the thread) after the transmission and reflection of waves in the waveguide					
Waveguide	Change of a pulse ultrasonic signal when changing the thread tension				
without thread	$P^* = 0$	$P^* = 19.6\text{ cN}$	$P^* = 49\text{ cN}$	$P^* = 68.6\text{ cN}$	$P^* = 98\text{ cN}$

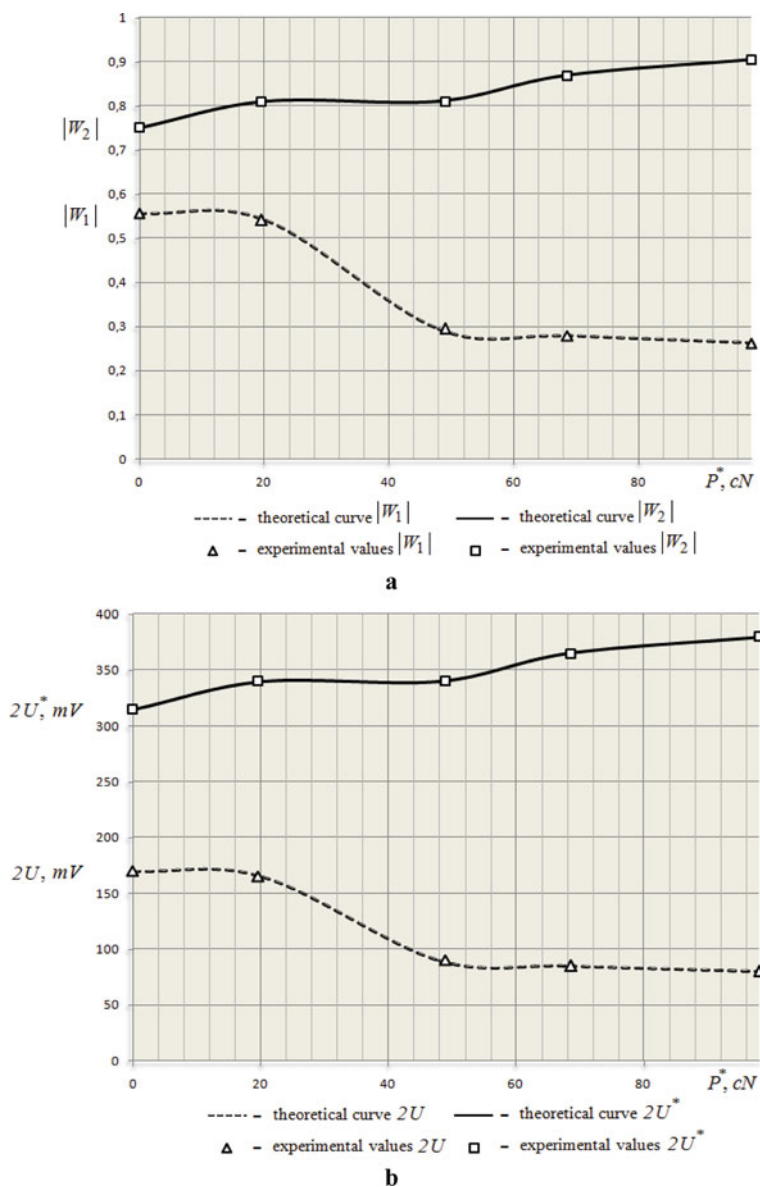


Fig. 6.28 Dependences of amplitude parameters on the thread tension in a waveguide: **a** dependences of wave modules $|W_1|$, $|W_2|$ on the thread tension P^* (full calculation); **b** dependences of voltage parameters $2U$, $2U^*$ on the thread tension P^* (full calculation)

One peak of the ultrasonic signal amplitude to determine the tension $P^*(nm)$ of the thread with less accuracy (Figs. 6.29 and 6.30a) can be used. To do this, an ultrasonic measuring channel with a waveguide is set up for the passage of waves through the fibers with interfiber pores of the textile material. Given the above, the current thread tension $P^*(nm)$ can then be determined as follows:

$$P^*(nm) = P \cdot \left(\frac{r}{r^*}\right)^3 = P r^3 \cdot \left(\sqrt{\frac{T}{\frac{Z_1}{\pi f r n \cos v_1} \cdot \sqrt{\frac{1}{|W_1|^2} - 1}}} \right)^{-3}. \quad (6.9)$$

The tension $P^*(nm)$ can be determined with less accuracy and at another peak of the ultrasonic signal amplitude, which characterizes the part of the waves that bypasses the thread. This expression for the current thread tension $P^*(nm)$ can be shown as:

$$P^*(nm) = P \cdot \left(\frac{\cos v_2}{\cos v_2^*}\right)^3 = P \cdot \left(\frac{\pi^2 f r n \rho_2 \cos v_2}{Z_1}\right)^3 \cdot \left(\sqrt{\frac{1}{\left(|W_2| - \frac{P_{1w}}{K_V P_{01w}^*}\right)^2 - 1}} \right)^{-3}. \quad (6.10)$$

Let us consider how the sound energy of the sounding waves is distributed in the process of gradually increasing the thread tension in the waveguide. One can say that there is a gradual flow from one part of the textile material to the environment with greater bypassing of the obstacle in the form of thread fibers. In this case, the peak of the ultrasonic signal amplitude and its energy coefficient $|W_1|^2$, which characterizes the transmission of waves through the fibers with interfiber pores of the thread, will decrease. The larger peak of the ultrasonic signal amplitude and its energy coefficient $|W_2|^2$, which characterizes the bypassing of waves of the nominal diameter of the thread, will gradually increase. It should be noted that the total sound energy that passes through the medium with the thread in the waveguide, remains almost at the same level in magnitude, with different tension values of textile fibers. Approximately the total energy transmittance $|W|^2$ for an ultrasonic signal of complex shape with two amplitude peaks of the waves can be determined as follows:

$$|W|^2 \approx |W_{12}|^2 = \frac{|W_1|^2 + |W_2|^2}{2}. \quad (6.11)$$

The change of the energy transmission coefficients $|W_1|^2$, $|W_2|^2$ during the thread tension for individual parts of the signal with the corresponding peaks of the wave amplitude, as well as the change of the approximate energy coefficient $|W_{12}|^2$ for the total sounding signal, are shown in Fig. 6.29b.

Pulse ultrasonic signal with two different peaks of wave amplitudes, which are adjusted to the linear density of the thread and its conditional radius, will allow the use

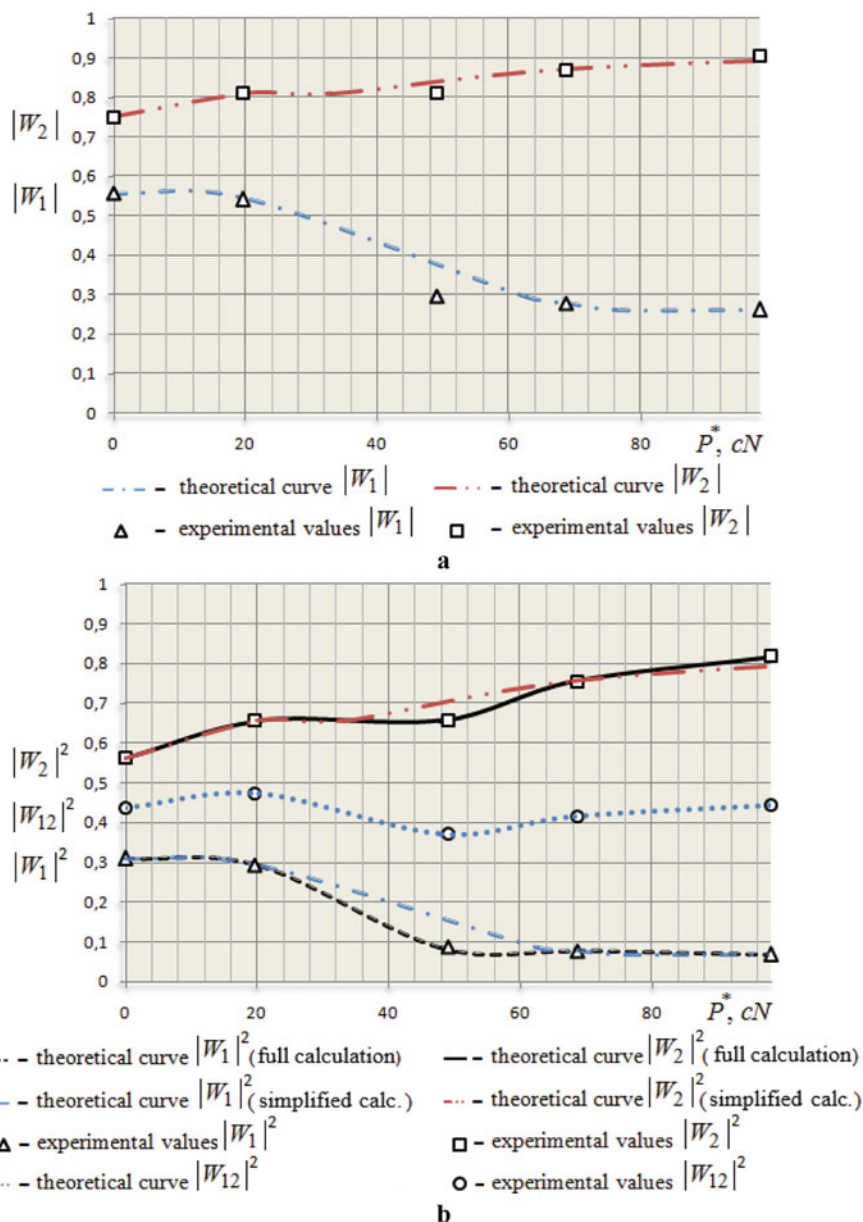


Fig. 6.29 Dependences of parameters of ultrasonic waves on the thread tension: **a** dependences of modules $|W_1|$, $|W_2|$ on the thread tension P^* (simplified calculation); **b** dependences of energy coefficients $|W_1|^2$, $|W_2|^2$, $|W_{12}|^2$ on the thread tension P^*

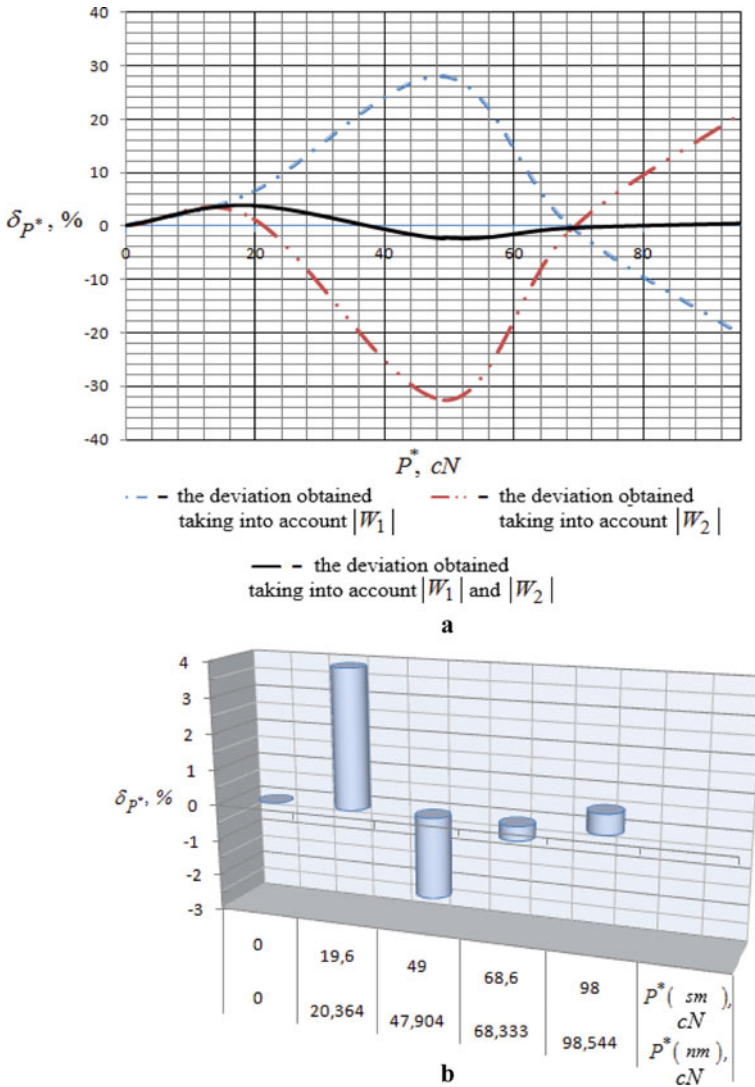


Fig. 6.30 Dependence of the deviation δ_{P^*} on the thread tension P^* in the waveguide: **a** the dependence of the deviation δ_{P^*} on the thread tension P^* taking into account $|W_1|$, $|W_2|$ separately and both of these parameters at the same time; **b** the dependence of the deviation δ_{P^*} on the thread tension P^* (P^* is determined by the expression (6.6))

of ultrasonic methods and tools for rapid control of thread tension in the production of different textile fabrics. Various design solutions for the structure of waveguides will make it possible to measure the thread tension contactlessly and increase the sensitivity of the sensors.

6.5 Non-contact Measurement of the Tension of Knitted Fabric Samples Using the Amplitude of Ultrasonic Waves that Have Passed Through the Textile Material

Nowadays, the urgent task is to create a continuous monitoring of both the thread tension on various textile machines, and the tension of the fabric itself. This will make it possible to control the uniform tension of the fabric on knitting machines, which depends on the homogeneity of the structure, porosity and compliance with the same value of basis weight at each point of the material. To be able to provide operational control over the fabric tension on textile machines, it is advisable to use non-contact technologies [24–30].

Non-contact ultrasonic transducers are safe for humans and fairly easy to set up and operate. When comparing common optical sensors with ultrasonic ones, their sensitivity to textile material is limited due to the wavelength, which will be reflected from the smallest thread of the material and will not pass through the thickness of its layer. Optical sensor readings can also be affected by dust in the room where they are installed. Other existing sensors used to determine the tension of textiles are contact ones. This makes their use for operational control a rather difficult task. Based on the above, we can say that non-contact ultrasonic systems for determining the tension of textile fabrics are promising for obtaining information about the value of the parameter at each point of the fabric in the process of its production. This will, in turn, ensure the quality characteristics of the produced fabrics at a fairly high level and improve the technological equipment for various processes in the textile industry.

One of the tasks for non-contact control of the textile fabric tension is to exclude the influence of the structure of the fabric itself on the change in the size of its pores during the stretching of textile fibers. By changing the interfiber distances and the size of the through pores in the structure of the material, the magnitude of its tension can be determined. The porosity of a textile material per unit area, or its change at a certain point in time affects the amplitude of the ultrasonic waves that pass through the controlled fibers of the material. Also, the size of the through pores affects the amplitude of the wave that passes through them. If the pores of the fabric and the interfiber distance increase or decrease when the textile fibers are stretched, the amplitude of the probing wave will change accordingly. There is a possibility when the through pores can expand and the interfiber distances will decrease.

In this case, their complex effect will be reflected in the amplitude of the waves that have passed through the structure of the knitted fabric with a certain tension. With a much greater effect of tension on the change in interfiber distances than the size of the pores themselves, or when the distances between the fibers of the material and the pores themselves decrease equally with the fabric tension, the unknown parameter can be determined better by the amplitude of probing waves.

In the course of the research, there have been performed experimental measurements of the amplitude of ultrasonic waves, which passed through the fabric samples of different materials during their stretching. The samples of knitted fabrics were

irradiated with a pulse ultrasonic signal with a wave frequency in the package of 40 kHz. The samples of fabrics with Kevlar threads and polyethylene yarn were used as a basis for the research.

All measurements of the amplitude of ultrasonic oscillations were performed with its comparison with the amplitude of the waves that passed through the sample of the fabric under the effect of the initial tension. After that, the current value of tension was determined for each sample of knitted fabric in its three zones (Fig. 6.31). Next, the tension distribution was determined in the second zone of the courses (designation 2 for this zone), as well as in the extreme first and third zones of the material (designations 1 and 3 for the extreme zones), where there are boundaries of more deformed courses of the sample.

The three zones of the samples that were sounded by the ultrasonic waves could be used to work closer to the upper mounting of the material or to the lower one. The extreme positions of the three sounding zones (above or below, next to the fastening) by the ultrasonic waves of the samples of knitted fabrics were not taken.

Two weights were hung to the samples at the edges, which caused local tensions P_1^* , P_3^* in the zone 1, 3 the most, and in the zone 2 of the material in part. The approximate current total value of the sample tension $P^* \approx P_1^* + P_3^*$ and its components P_1^* , P_3^* were determined using the amplitude dependences of the waves passing through the zones 1 and 3 on the fabric. These components of the tension can be shown as follows:

$$P_1^* = P_1 \cdot \left(\frac{U_{1k}}{U_{1k+1}} \right)^3, \quad P_3^* = P_3 \cdot \left(\frac{U_{3k}}{U_{3k+1}} \right)^3, \quad (6.12)$$

where P_1 , P_1^* is the initial and current tensions of the fabric sample, which are connected with the first and partially with the second zones of the knitted fabric sample; P_3 , P_3^* —initial and current tensions of the fabric sample, which are connected with the third and partially with the second zones of the knitted fabric sample; k —the value of the initial reference index, which is associated with the first value of the current tension of the sample fabric to be determined, and with the amplitude of the ultrasonic wave passing through the material; U_{1k} —a voltage that is proportional to the amplitude of the ultrasonic waves that passed through the fabric of the sample in its first zone, as indicated by the first index 1, to change the first current value of tension, as indicated by the second index k ; U_{1k+1} —a voltage that is proportional to the amplitude of the ultrasonic waves that have passed through the fabric of the sample in its first zone, as indicated by the first index 1, after changing the current value of tension, as indicated by the second index $k + 1$; U_{3k} —a voltage that is proportional to the amplitude of the ultrasonic waves that have passed the fabric of the sample in its third zone, as indicated by the first index 3, to change the first current value of tension, as indicated by the second index k ; U_{3k+1} —a voltage that is proportional to the amplitude of the ultrasonic waves that have passed through the fabric of the sample in its third zone, as indicated by the first index 3, after changing the current value of tension, as indicated by the second index $k + 1$.

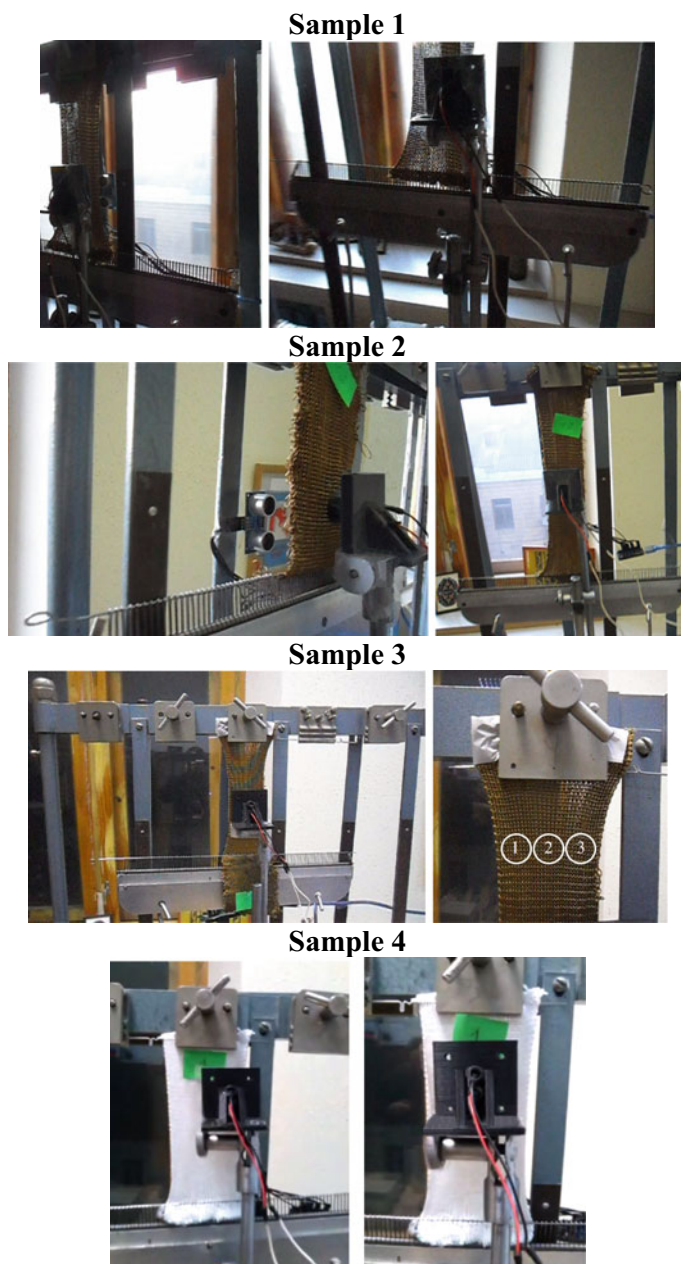


Fig. 6.31 Ultrasonic measurement of the tension of samples 1, 2, 3 of knitted fabrics with Kevlar threads (sample 3 shows the zones 1, 2, 3 of the material sounding) and the tension of the knitware sample 4 of polyethylene yarn

The values of the amplitudes of the waves passing through the controlled material were compared at its different tension, which was determined using the contact method, and with the tension, which was determined using the non-contact ultrasonic method. The total tension P^* of the sample was determined using the dependence (6.12), which is shown in Fig. 6.32. Presenting the value of the deviation δ_P of the tension readings between the determination of this parameter by existing and ultrasonic methods, it can be given as:

$$\delta_P = \left(\frac{P_1^* + P_3^* - P_{m1} - P_{m3}}{P_{m1} + P_{m3}} \right) \cdot 100\%, \quad (6.13)$$

where P_{m1} , P_{m3} are the tensions of the fabric sample, which are connected to the first, third and second zones of the knitted fabric sample, which are determined by the existing method due to the mass of two suspended weights to the material.

Dependences of deviations δ_P on the growth of total tension P^* for the samples of different knitted fabrics are shown in Fig. 6.33.

When the current tensions in the zones 1 and 3 are equal to $P_1^* = P_3^*$, taking into account the amplitude of the waves that have passed through the middle zone 2 of the sample, the expression (6.12) can be shown as follows:

$$P_1^* = P_3^* = \frac{(P_1 + P_3)}{2} \cdot \left(\frac{U_{2k}}{U_{2k+1}} \right)^3, \quad (6.14)$$

where U_{2k} is a voltage that is proportional to the amplitude of the ultrasonic waves that have passed through the fabric of the sample in its second zone, as indicated by the first index 2, to the change of the first current tension value, as indicated by the second index k ; U_{2k+1} —voltage that is proportional to the amplitude of the ultrasonic waves that have passed through the fabric of the sample in its second zone, as indicated by the first index 2, after changing the current tension value, as indicated by the second index $k + 1$.

It should be noted that the dependence (6.14) in the calculation will give a less accurate result (Fig. 6.34), because the tension from zones 1 and 3 to zone 2 of the fabric sample is distributed unevenly through the courses, which can lead to significant deviations of the controlled parameter. Based on the above, it can be said that the lower tension in zone 2 of the sample less deforms the threads and pores of the material. Therefore, the amplitude of the wave passing through this zone will often be larger for different materials. Writing the amplitude deviation δ_U of the waves passing through zone 2 and proportional to the voltage U_{2k} , in comparison with the waves passing through zones 1 and 3 of the sample fabric and proportional to the voltages U_{1k} , U_{3k} at $P_1^* = P_3^*$, this expression can be shown as:

$$\delta_U = \left(\frac{U_{2k} - U_{1k}}{U_{1k}} \right) \cdot 100\% = \left(\frac{U_{2k} - U_{3k}}{U_{3k}} \right) \cdot 100\%. \quad (6.15)$$

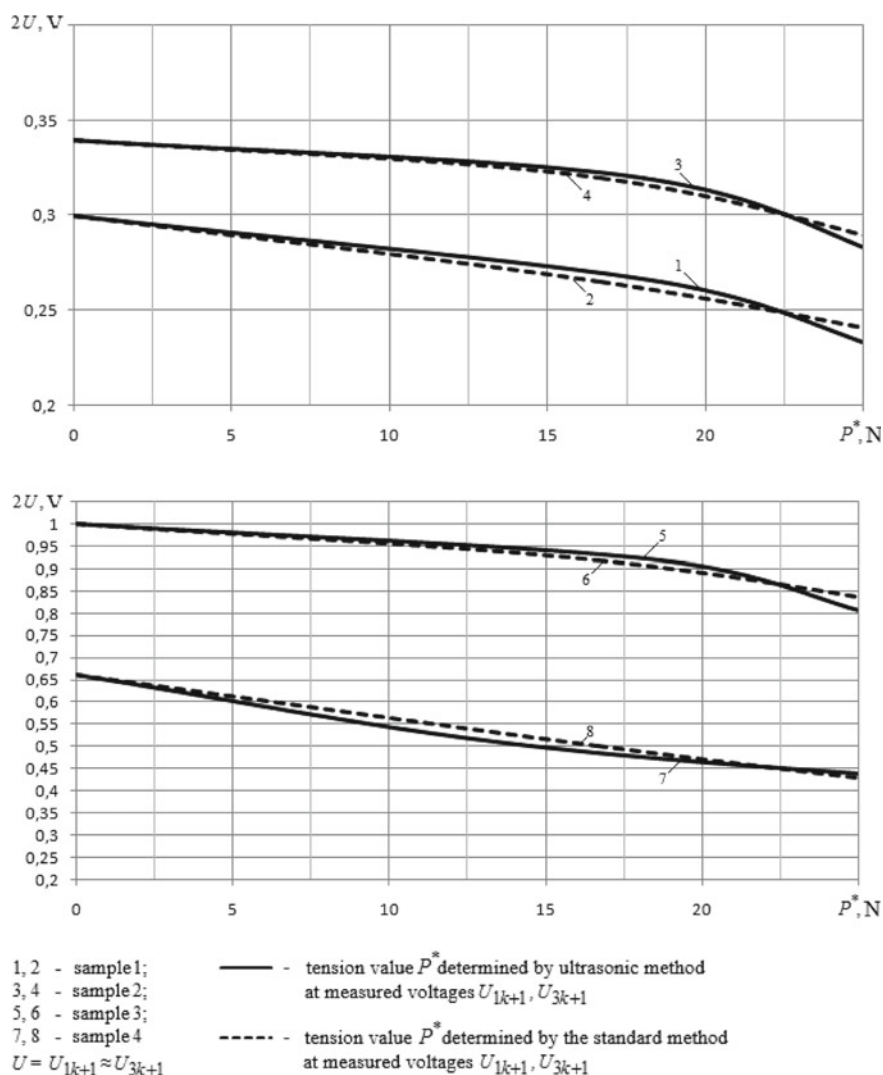


Fig. 6.32 Dependences of the voltage amplitude $2U$ on the tension P^* of the samples of knitted fabrics when they are sounded in the zone 1 and 3 of the material

Dependences of deviations δ_U from the increase in the total tension P^* of the samples of different knitted fabrics are shown in Fig. 6.35. Table 6.6 presents the oscillograms of ultrasonic waves, which passed the samples of different knitted fabrics when stretching the material and at rest without tension in different areas of the courses (zones 1, 2 and 3). Oscillograms of waves that interacted with three samples of knitted fabrics with Kevlar threads 58×2 tex, and waves that passed the sample of polyethylene yarn 44 tex.

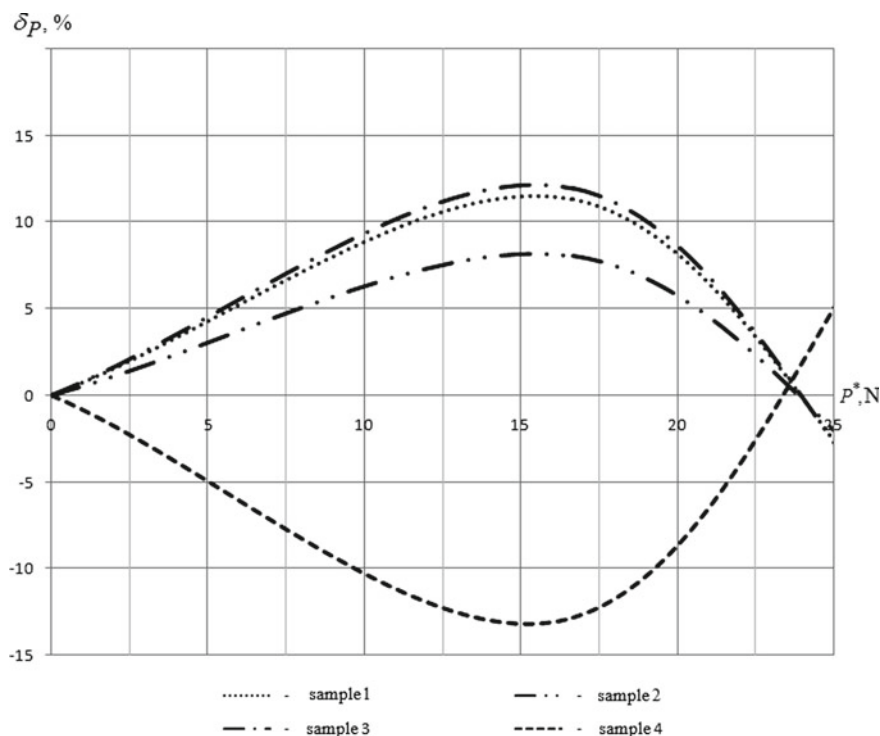


Fig. 6.33 Dependences of relative deviation δp on the tension P^* of samples of jersey fabrics at their sounding in the zone 1 and 3 of the material

The amplitude magnitude of the resulting ultrasonic signal depends on the superposition of the oscillations that pass through the pores of the fabric, the waves that pass through the interfiber distances, and the waves that pass through the fibers of the textile material. The influence of the structure of the fabric samples on the amplitude of the sounding waves can also be seen from their oscillograms in Table 6.6.

Studies have also been conducted on the possibility of using the amplitude of ultrasonic waves reflected from knitted fabrics to determine various parameters of the material. Practical results indicate that the ultrasonic radiation reflected from the knitwear is difficult to use because it can be strongly dispersed from the fabric structure.

In order to contactlessly determine how the tension is distributed in zones 1, 2 and 3 of the fabric sample, it is necessary to compare the amplitude of ultrasonic waves passing through these zones of the material. Different pore sizes and interfiber distances in zones 1, 2, 3 of the sample make it possible to compare different values of the amplitudes of ultrasonic waves passing through them. This characterizes the different distribution of tension across the width of the fabric. Figure 6.36, a shows how the magnitude of voltages that are proportional to the amplitudes of the ultrasonic

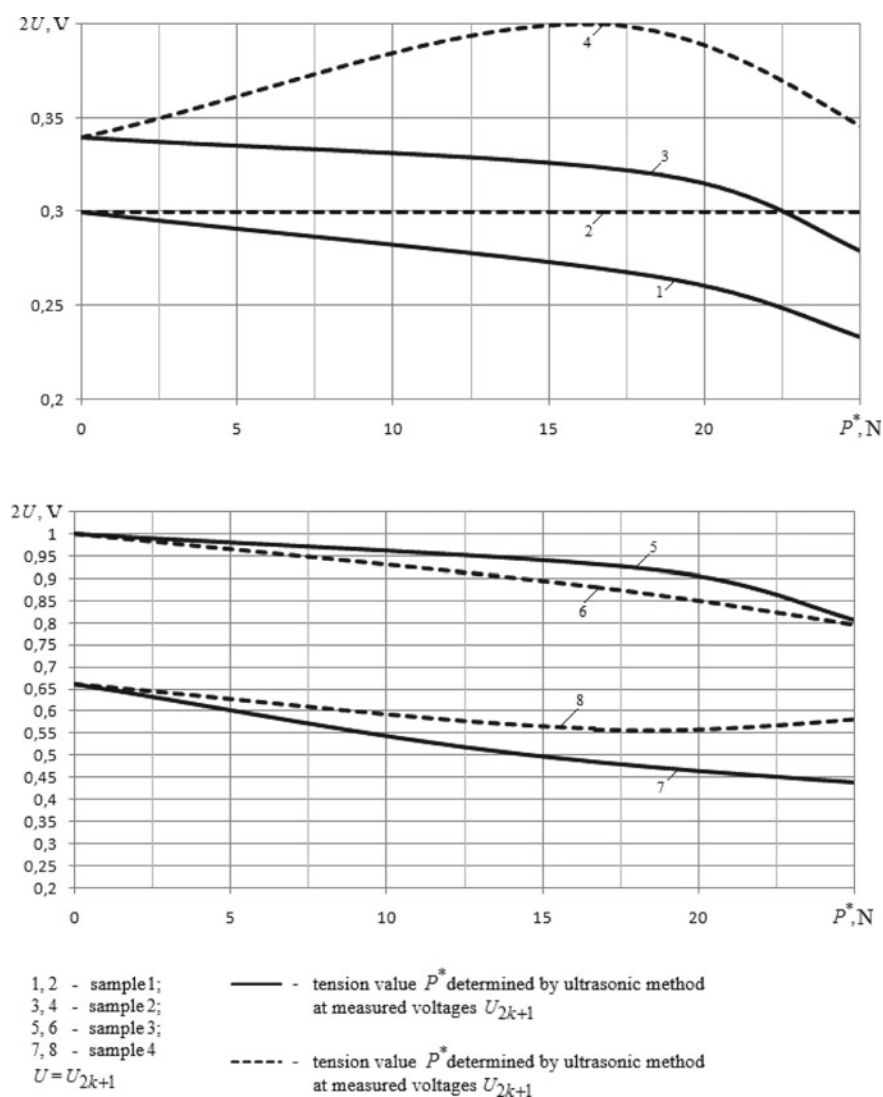


Fig. 6.34 Dependences of the voltage amplitude $2U$ on the tension P^* of the knitted fabric samples when they are sounded in zone 2 of the material

waves that passed through the material in zones 1, 2 and 3 of the fourth sample shown in Fig. 6.31.

The distribution of tension on the knitted fabric sample for each zone of the material using the amplitudes of the sounding ultrasonic waves at $P_1^* = P_3^*$ or $U_{1k+1} = U_{3k+1}$ can be calculated in the following way:

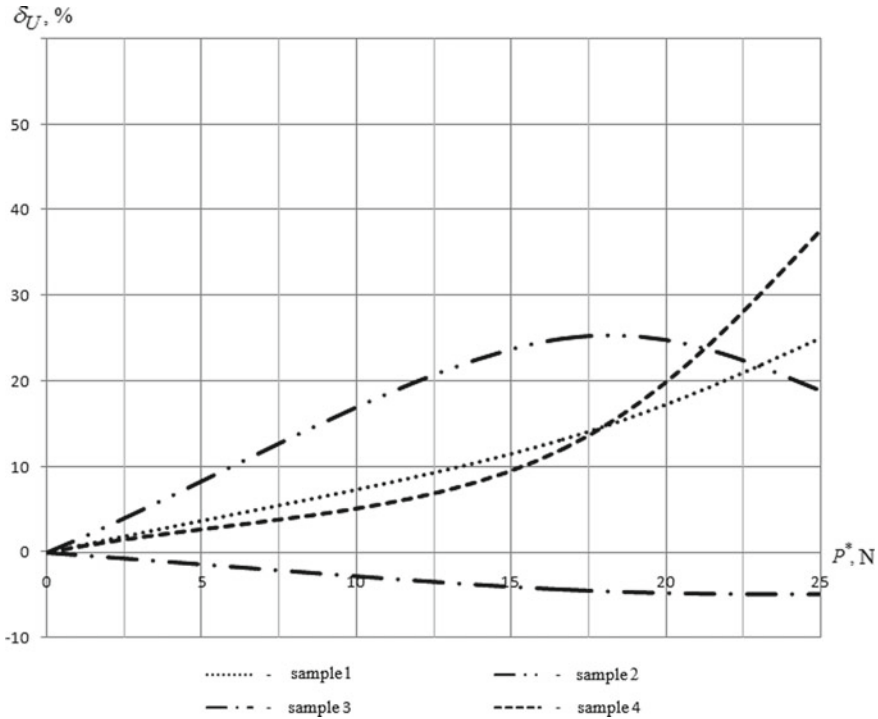


Fig. 6.35 Dependences of relative deviation δ_U on the tension P^* of the samples of jersey fabrics at their sounding in the zone 2 of the material

$$P_{1z}^* = P_{3z}^* = \frac{(P_1^* + P_3^*)}{2N_z} \cdot \left(N_z - \left(1 - \frac{|U_{2k} - U_{2k+1}|}{U_{1k+1}} \right)^3 \right), \quad (6.16)$$

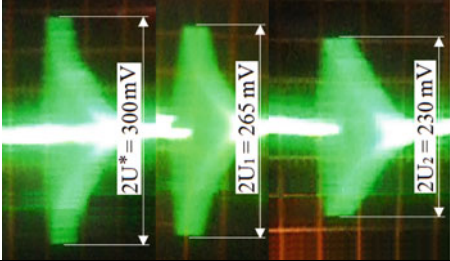
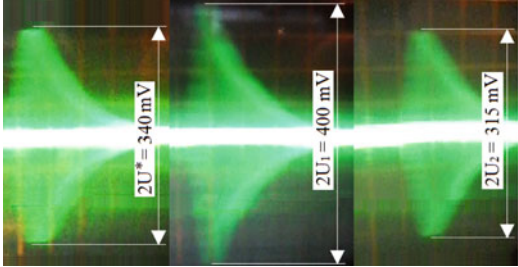
$$\begin{aligned} P_{2z}^* &= \frac{(P_1^* + P_3^*)}{N_z} \cdot \left(1 - \frac{|U_{2k} - U_{2k+1}|}{U_{1k+1}} \right)^3, \\ P_{2z}^* &= \frac{(P_1^* + P_3^*)}{N_z} \cdot \left(1 - \frac{|U_{2k} - U_{2k+1}|}{U_{3k+1}} \right)^3, \end{aligned} \quad (6.17)$$

where P_{1z}^* is the value of the tension of the fabric sample in the first zone; P_{2z}^* —the value of the tension of the fabric sample in the second zone; P_{3z}^* —the value of the tension of the fabric sample in the third zone; N_z —the number of fabric zones that are sounded by waves, and in which the change in tension is determined, its uneven distribution (for this case $N_z = 3$).

The obtained expressions (6.16) and (6.17) can be used to calculate the distribution of tension over the entire width of the controlled fabric.

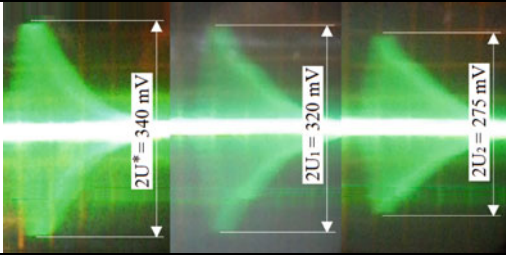
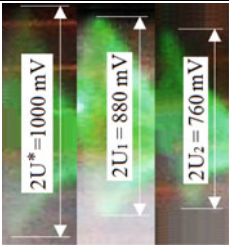
Figure 6.36b shows the distribution of tension in three zones of the fourth sample of knitted material of polyethylene yarn 44 tex with different total loaded fabric.

Table 6.6 The results of research on non-contact measurement of the knitwear tension

№	Analysis of the transmission of ultrasonic waves through samples of knitted fabrics under tension		
1	Sample 1		
	Voltage waveforms proportional to the amplitudes of the ultrasonic waves that have passed zone 2 of the knitted fabric sample 1 with Kevlar threads 58x2 <i>tex</i>		
	$2U^* = 2U_{20} = 300 \text{ mV}$	$2U_1 = 2U_{21} = 300 \text{ mV}$	$2U_2 = 2U_{22} = 300 \text{ mV}$
	-	$\delta_U = 13.1 \%$	$\delta_U = 30.43 \%$
	Voltage waveforms proportional to the ultrasonic waves that passed through zone 3 of knitted fabric sample 1 with Kevlar threads 58x2 <i>tex</i>		
			
	$2U^* = 2U_{30} = 300 \text{ mV}$	$2U_1 = 2U_{31} = 265 \text{ mV}$	$2U_2 = 2U_{32} = 230 \text{ mV}$
	Determination of tension by the contact method		
	$P^* = 0$	$P^* = 16.8 \text{ N}$	$P^* = 28.4 \text{ N}$
	Determination of tension by the non-contact ultrasonic method		
	-	$P^* = 18.57 \text{ N}$	$P^* = 25.51 \text{ N}$
	-	$\delta_P = 11.32 \%$	$\delta_P = -10.17 \%$
2	Sample 2		
	Voltage waveforms proportional to the ultrasonic waves that have passed zone 2 of knitted fabric sample 2 with Kevlar threads 58x2 <i>tex</i>		
			

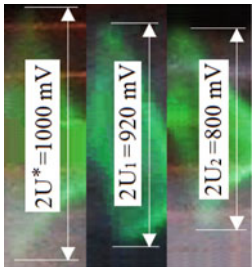
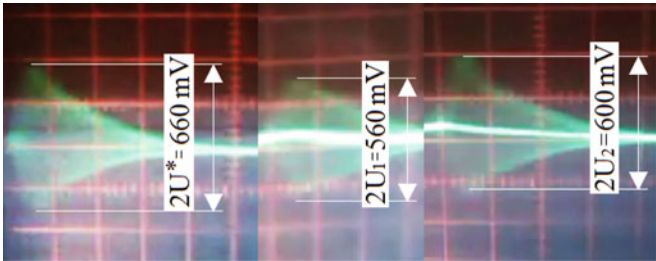
(continued)

Table 6.6 (continued)

	$2U^* = 2U_{20} = 340 \text{ mV}$	$2U_1 = 2U_{21} = 400 \text{ mV}$	$2U_2 = 2U_{22} = 315 \text{ mV}$
	Determination of tension by the contact method		
	$P^* = 0$	$P^* = 16.8 \text{ N}$	$P^* = 28.4 \text{ N}$
	Determination of tension by the non-contact ultrasonic method		
	-	$P^* = 13.87 \text{ N}$	$P^* = 34.15 \text{ N}$
	-	$\delta_P = -16.85 \%$	$\delta_P = 20.26 \%$
	-	$\delta_U = 25 \%$	$\delta_U = 14.55 \%$
	Voltage waveforms proportional to the ultrasonic waves that have passed through zone 1 of knitted fabric sample 2 with Kevlar threads 58x2 tex		
			
	$2U^* = 2U_{10} = 340 \text{ mV}$	$2U_1 = 2U_{11} = 320 \text{ mV}$	$2U_2 = 2U_{12} = 275 \text{ mV}$
	Determination of tension by the contact method		
	$P^* = 0$	$P^* = 16.8 \text{ N}$	$P^* = 28.4 \text{ N}$
	Determination of tension by the non-contact ultrasonic method		
	-	$P^* = 18.03 \text{ N}$	$P^* = 26.28 \text{ N}$
	-	$\delta_P = 8.06 \%$	$\delta_P = -7.46 \%$
3	Sample 3		
	Voltage waveforms proportional to ultrasonic waves which have passed zone 2 of a knitted fabric sample 3 with Kevlar threads 58x2 tex		
			

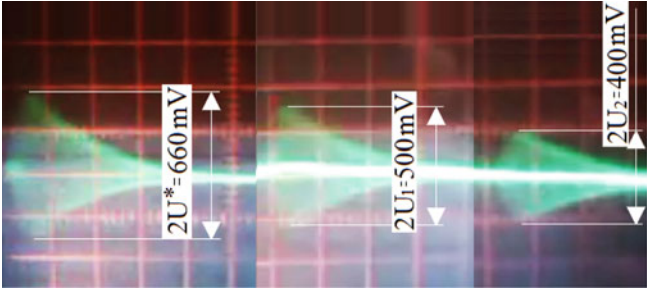
(continued)

Table 6.6 (continued)

	$2U^* = 2U_{20} = 1000 \text{ mV}$	$2U_1 = 2U_{21} = 880 \text{ mV}$	$2U_2 = 2U_{22} = 760 \text{ mV}$
	Determination of tension by the contact method		
	$P^* = 0$	$P^* = 16.8 \text{ N}$	$P^* = 28.4 \text{ N}$
	Determination of tension by the non-contact ultrasonic method		
	-	$P^* = 18.29 \text{ N}$	$P^* = 25.89 \text{ N}$
	-	$\delta_P = 9.68 \%$	$\delta_P = -8.82 \%$
	-	$\delta_U = -4.35 \%$	$\delta_U = -5 \%$
	Voltage waveforms proportional to ultrasonic waves which have passed zone 3 of a knitted fabric sample 3 with Kevlar threads 58x2 <i>tex</i>		
			
	$2U^* = 2U_{30} = 1000 \text{ mV}$	$2U_1 = 2U_{31} = 920 \text{ mV}$	$2U_2 = 2U_{32} = 800 \text{ mV}$
	Determination of tension by the contact method		
	$P^* = 0$	$P^* = 16.8 \text{ N}$	$P^* = 28.4 \text{ N}$
	Determination of tension by the non-contact ultrasonic method		
	-	$P^* = 18.67 \text{ N}$	$P^* = 25.36 \text{ N}$
	-	$\delta_P = 11.95 \%$	$\delta_P = -10.68 \%$
4	Sample 4		
	Voltage waveforms proportional to the ultrasonic waves that have passed through zone 2 of knitted fabric sample 4 of polyethylene yarn 44 <i>tex</i>		
			
	$2U^* = 2U_{20} = 660 \text{ mV}$	$2U_1 = 2U_{21} = 560 \text{ mV}$	$2U_2 = 2U_{22} = 600 \text{ mV}$
	-	$\delta_U = 12 \%$	$\delta_U = 50 \%$

(continued)

Table 6.6 (continued)

Voltage waveforms proportional to the ultrasonic waves that have passed through zone 3 of knitted fabric pattern 4 of polyethylene yarn 44 tex		
		
$2U^* = 2U_{30} = 660 \text{ mV}$	$2U_1 = 2U_{31} = 500 \text{ mV}$	$2U_2 = 2U_{32} = 400 \text{ mV}$
Determination of tension by the contact method		
$P^* = 0$	$P^* = 16.8 \text{ N}$	$P^* = 28.4 \text{ N}$
Determination of tension by the non-contact ultrasonic method		
-	$P^* = 14.54 \text{ N}$	$P^* = 32.58 \text{ N}$
-	$\delta_p = -12.83 \%$	$\delta_p = 14.71 \%$

From the above Fig. 6.6. 36 it can be seen that the tension of the sample along its edges, which correspond to zones 1 and 3 of the fabric, increases. This can be explained by the greater stretching of the textile fibers of the knitted fabric sample in its extreme areas, which are sounded by ultrasonic waves. The tension distribution can be determined across the entire width of the fabric by comparing the amplitudes of the ultrasonic waves from different sound zones of the sample.

Studies have shown the complexity of the implementation of non-contact tension control of knitted fabrics with different structure and raw material composition with one adjusting of the non-contact system for different samples of materials. This is due to the fact that under the influence of the fabric structure, the through pores can expand or decrease more compared to the interfiber distances of the textile material under tension. In turn, this affects the amplitude of the ultrasonic waves that pass through such controlled fabrics.

For example, let us consider the effect of the fabric structure on the change in the amplitude of the sounding waves in the interaction of oscillations with the fourth sample of knitwear, when its second zone is sounded on the material itself, compared with other samples with Kevlar threads. For the polyethylene sample in the second zone, the through pores are stretched more in comparison with the reduction of the interfiber distances of the material. Therefore, at first the amplitude of the waves decreases, and then with increasing tension also increases. Based on these reasons, the change in the amplitude of the ultrasonic waves passing through the testing material was first analysed for each sample separately.

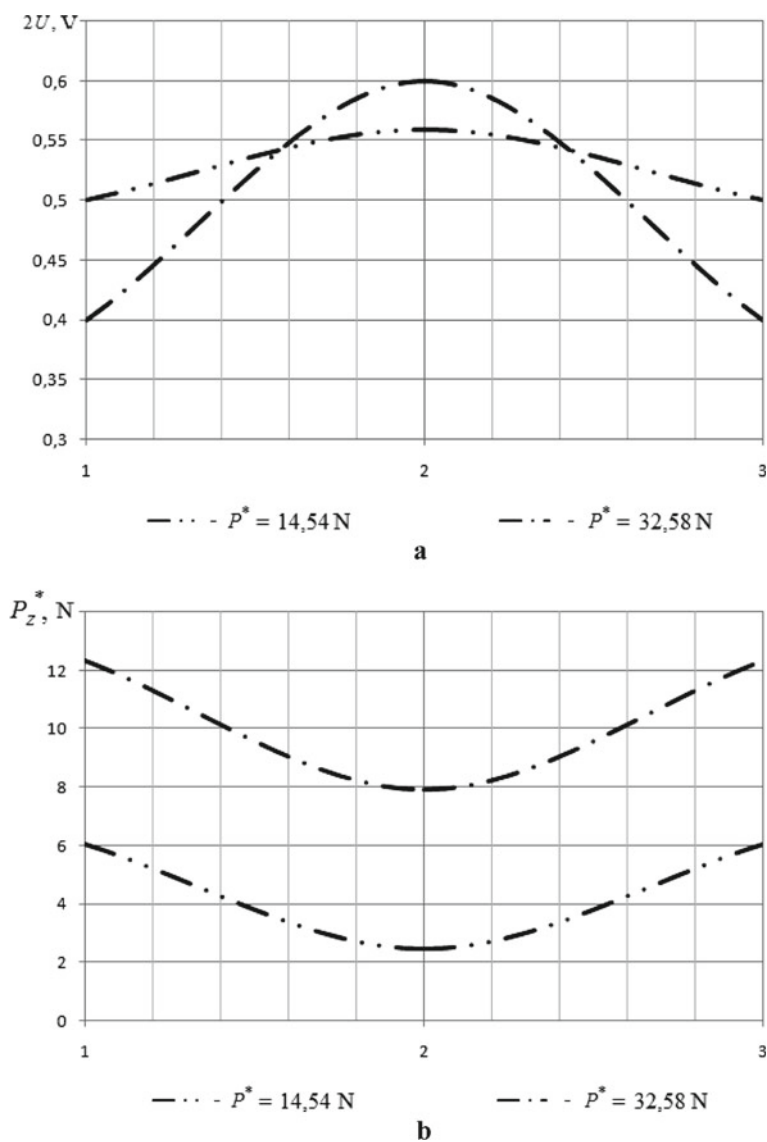


Fig. 6.36 The change in the voltage amplitude $2U$, which is proportional to the amplitude of the waves, and the change in the distributed tension P_z^* on the zones 1, 2, 3 of the sample fabric under the action of the total tension P^* : **a** voltage range dependence $2U$ on the zones 1, 2, 3 of the sample fabric at the tension P^* ; **b** dependences of distributed tension P_z^* on the zones 1, 2, 3 of the sample at the tension P^*

This method for determining the total tension of the fabric sample and the possibility of non-contact measurement of tension values in its certain areas is a very important task for the light industry. Only measuring systems with non-contact sensors can provide this operative control of tension at each point of a fabric on various textile machines.

Studies have shown the possibility of using a non-contact ultrasonic tension control of knitted fabrics to monitor the technological process of their production on textile machines. This will make it possible to integrate new non-contact measuring systems into various technological equipment, which will be able to increase the quality characteristics of the finished fabrics. The proposed non-contact method is to sound ultrasonic waves of the textile fabric in several of its control zones and further determine the current value of the knitwear tension. An unknown parameter is determined by the change in the amplitude of the ultrasonic waves passing through the material under the action of tension, which also changes during the movement of the mechanical equipment. The proposed non-contact method is quite promising because it has a number of significant advantages over the existing contact ones. Also, this method makes it possible to save significant funds on the development of new equipment without the use and adjustment of contact sensors to determine the textile material tension, which is quite cumbersome and difficult.

6.6 Probability Estimation of Control Over Basis Weight, Porosity of Textile Materials and Probability Estimation of Control Over Tension of Threads with High Linear Density

One of the main quantitative estimates of the probability of non-contact control is the absolute probability, which is the probability of making the right decision to find the controlled parameter 'in tolerance' or 'out of tolerance' for the material itself. It is very important to correctly estimate the probability of control over technological parameters for different textile materials. The expression for the absolute probability of control can be shown as follows:

$$D_{\kappa} = 1 - P_{\Delta}, \quad (6.18)$$

where P_{Δ} is the probability of erroneous decisions in control.

The probability of erroneous decisions, in turn, can be represented as:

$$P_{\Delta} = \alpha_{\kappa} + \beta_{\kappa}, \quad (6.19)$$

where α_k is an error of the first kind (technological parameter of the controlled material, which is within the tolerance, recognized as exceeding these limits); β_k —error of the second kind (technological parameter of the controlled material, which goes beyond the tolerance, is recognized as one that falls within these limits).

For engineering calculation of errors of the first and second kind, it is possible to use their approximate dependences considering symmetrical tolerance for the controlled parameters:

$$\alpha_k = \frac{0,3 \rho_k (1 + r_k \rho_k)}{1 + 0,6 \rho_k (\rho_k - 0,1) \cdot \sqrt{r_k} (1,9 - r_k)} \cdot e^{-\frac{r_k}{2}}, \quad (6.20)$$

$$\beta_k = \frac{0,3 \rho_k \left(1 - 0,1 \cdot \frac{\rho_k}{r_k}\right)}{1 + 0,8 r_k \rho_k} \cdot e^{-\frac{r_k}{2}}, \quad (6.21)$$

from where

$$r_k = \frac{d_k}{\sigma(X)}, \quad \rho_k = \frac{\sigma(\delta)}{\sigma(X)},$$

where $\sigma(X)$ is a standard deviation of the controlled parameter X ; $\sigma(\delta)$ —c standard deviation of the measurement error δ .

The value of the set values of basis weight and porosity of the controlled material may differ from the actual value of the parameter depending on many factors in the process of material production. The change of these parameters can be especially influenced by the further processing of unbleached cloths at a final stage of production. The tolerances of the basis weight m_s and porosity Q_p of the controlled material must be set so that they are within 5% deviation from the true value. Taking into account the magnitude of the amplitude of oscillations of the tension of the threads with different frequencies in the production of textile materials, it can have an average variation of current values up to 25% in steady-state equipment, due to many factors: different radius of curvature and friction. guiding working bodies of the textile machine; the force of the thread friction on the surface of the thread tensioner; different thickness of the thread along its entire length; different speed of the thread at a certain point in time when it is fed, and other factors. The tolerance of the measured values of tension on average should not exceed 5%. In this case, the definition of these technological parameters can be considered reliable. Then, calculating the expressions (6.20), (6.21) and (6.18), it is possible to obtain the values α_k , β_k and D_k for the basis weight m_s and porosity Q_p of different textile materials, which are given in Tables 6.7, 6.8, as well as in Fig. 6.37 show dependences α_k , β_k and D_k for measuring control from the tension of the thread P^* with a linear density of 445 tex.

As it can be seen from Tables 6.7, 6.8 and Fig. 6.37, the indicators α_k , β_k and D_k demonstrate the possibility and feasibility of using non-contact methods for the control over technological parameters of textile materials to ensure high quality of finished fabrics in the production process. These methods in combination with

Table 6.7 Control probability estimation of basis weight of textile materials

Nº	Textile material	Basis weight m_s , g/m ²	r_k	ρ_k	α_k	β_k	D_k
1	Fabric №1 (reference)	236	3.33	0.06	0.00009	0.00006	0.9998
2	Fabric №2	299	1.68	0.08	0.00648	0.00516	0.9884
3	Fabric №3	152	2.00	0.16	0.00885	0.00523	0.9859
4	Fabric №4	100	1.43	0.16	0.02118	0.01445	0.9644
5	Fabric №5	156	1.06	0.06	0.01	0.009	0.9810
6	Knitted fabric №1	233	2.00	0.12	0.00629	0.00418	0.9895
7	Knitted fabric №2	236	1.85	0.11	0.00738	0.00519	0.9874

Table 6.8 Probability estimation of the material porosity control

Nº	Textile material	Porosity Q_p , mm ³ per 1 mm ² of the area	r_k	ρ_k	α_k	β_k	D_k
1	Fabric №1 (reference)	0.3744	1.90	0.004	0.00019	0.00018	0.9996
2	Fabric №2	0.2097	1.60	0.065	0.00596	0.00497	0.9891
3	Fabric №3	0.5824	1.11	0.12	0.0221	0.01744	0.9605
4	Fabric №4	0.6392	1.43	0.14	0.01879	0.01325	0.9680
5	Fabric №5	0.3744	1.88	0.14	0.00869	0.00572	0.9856
6	Knitted fabric №1	0.4765	1.44	0.11	0.01400	0.01058	0.9754
7	Knitted fabric №2	0.3744	1.88	0.10	0.00583	0.00429	0.9899

computerized control systems will help to establish compliance between the actual state of the technological parameter of the textile material to its specified norm. At the same time in the automated mode many different states of the technological parameter of textile materials depending on the set technical task on production can differ. Since the control is the error-free determination of the actual values of technological parameters, taking into account the possible shortcomings of the developed methods and means of non-contact determination of these parameters, it can be characterized by probabilistic characteristics, the main of which is the probability of control.

The obtained probability reflects the degree of objectivity of the results of control of technological parameters of textile materials. Reliability of control is characterized by control errors, which are random events. Control errors can depend on many factors, which can affect both the means of control and lead to their errors, as well as the compliance of control tolerances with their required value.

The control probability D_k for basis weight, porosity of different textile materials and control probability D_k for the thread tension were determined using the developed samples of experimental computerized systems. The obtained values of control probability D_k showed the possibility of providing technological parameters of various textile materials within the necessary regulated limits, taking into

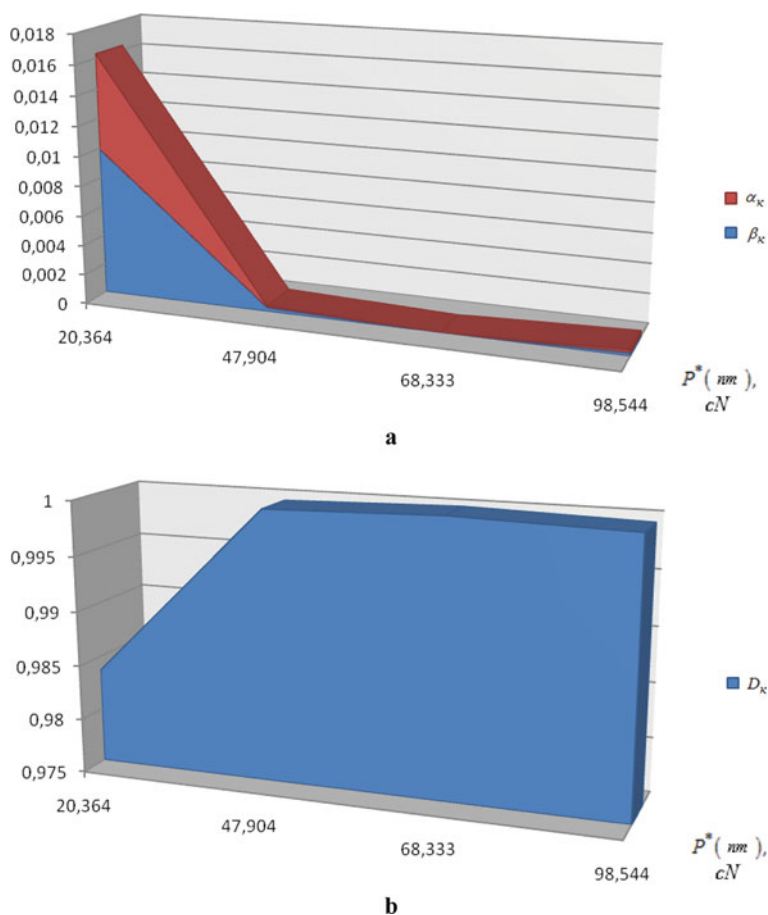


Fig. 6.37 Dependences of errors of the first α_k , second β_k kind and probability D_k for measuring control on tension P^* , cN of a thread with linear density 445 tex: **a** dependences of the first α_k , second β_k kind on the thread tension P^* ; **b** the dependence of the probability D_k of measuring control on the thread tension P^* .

account errors of the first α_k and second β_k kind. These control errors decrease when increasing the basis weight m_s of fabrics and increasing the thread tension P^{**} , and increasing porosity Q_p , on the contrary, they may increase.

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