UDC 674: 534.6

DETERMINATION OF ANISOTROPIC ELASTIC PROPERTIES OF WOOD ACOUSTIC METHOD

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On the basis of theoretical and experimental studies establishing new relationships between velocity of acoustic waves and mechanical properties of wood in a wide range of temperature and humidity, which can be used to improve processes and operations of timber production and the development of new methods of quality control.

Wood tensor of elastic moduli, anizotropnist, temperature, humidity, acoustic methods, the speed of propagation of acoustic waves.

Problem. Intensive use of wood as a construction material leads to a shortage of wood resources. In such circumstances, the question of rational use of wood and wooden products. One of the areas in solving this problem is to improve, develop and implement energy-saving technologies in the woodworking industry. The introduction of such technology is inextricably linked to the operational definition and control of physical and mechanical properties of wood in various manufacturing processes and operations of timber production.

Experimental and theoretical studies conducted over the past decade have shown a relationship between the physical and mechanical properties of solids and velocity of acoustic waves. Due to the connection of acoustic waves with physical and mechanical properties of materials, acoustic methods of nondestructive testing characterized by reliability and speed of information acquisition, performance monitoring, the possibility of re-measurement. This type of control is applied to materials, including wood, well spend acoustic wave. Therefore, identifying and establishing relationships between the physical and mechanical properties of wood and velocity of acoustic oscillations in varying temperature and humidity conditions creates conditions for active regulation of various technological processes wood and quality control.

The purpose and objectives of research. Theoretical and experimental determination of anisotropic elastic properties of wood acoustic method and improved methods of monitoring the speed of propagation of acoustic waves.

Achieving this goal requires solving the following main objectives: 1) to analyze the literature to determine the mechanical properties of wood by acoustic nondestructive methods; 2) synthesize wood as an anisotropic elastic material, mathematical model of the acoustic waves; 3) develop a mathematical model of acoustic wave propagation in a viscoelastic wood; 4) develop and improve methods of determining the speed of propagation of acoustic waves in the wood in order to increase the accuracy of measurements; 5) to design and develop the experimental setup for acoustic research; 6) for a series of experimental studies with variable climatic conditions to design and develop a laboratory climate chamber; 7) develop a methodology of experimental studies of the propagation velocity of acoustic waves in the wood; 8) to conduct experimental studies to elucidate the connection speed of propagation of acoustic waves of mechanical properties of wood.

Results. Improved spatial mathematical model propagation of acoustic waves in anisotropic elastic materials on wood, which establishes a relationship between the mechanical properties of wood and velocity of acoustic waves.

The equations of motion, which is derived from the fundamental law of dynamics, in view of Hooke's law can be written as

$$\rho \frac{\partial^2 u_i}{\partial t^2} = c_{ijkl} \frac{\partial^2 u_l}{\partial x_j \cdot \partial x_k} \qquad (1)$$

where: ρ - Density of material (mass unit volume) $\partial^2 u_i / \partial t^2$ - Acceleration along the axis i, u_i - Move, c_{ijkl} - Elastic tensor components, t - Time.

Spread flat creeping wave can be written as:

$$u(x,t) = F\left(t - \boldsymbol{n}x / v_{\phi}\right) \qquad (2)$$

where: v_{ϕ} - The phase velocity of propagation, $F\left(t - \boldsymbol{n}x / v_{\phi}\right)$ - A function that describes the wave propagating in the positive direction of the axis x, $\boldsymbol{n}$ - Unit vector perpendicular to the wavefront.

The way wave propagation in wood covered in rectangular Cartesian coordinates to in (2) enter the coordinates of (x_1, x_2, x_3 - Components of vector $\boldsymbol{x}$) And the direction cosines (n_1, n_2, n_3 - Components of vector $\boldsymbol{n}$).

$$u(x,t) = F\left(t - \frac{n_1 x_1 + n_2 x_2 + n_3 x_3}{v_{\phi}}\right) \qquad (3)$$

In the case of excitation in wood plane sinusoidal wave equation (3) can be written as

$$u_i = A \cos \omega\left(t - \boldsymbol{n}x / v_{\phi}\right) = A \cos\left(\omega t - kx\right) \qquad (4)$$

where: A - Amplitude waves k - Wave vector, ω - Cyclic frequency.

$$k = \omega \boldsymbol{n} \,/\, v_{\phi} = 2\pi \boldsymbol{n} \,/\, \lambda = k\boldsymbol{n} \quad (5)$$

where: λ - Wavelength.

In complex form (4) is written in the following form.

$$u_i = A_i \cdot e^{i(\omega t - kx)} = A_i \, exp[\, i(\, \omega t - kx\,)] \quad (6)$$

where: $i^2 = -1$.

Substituting relation (6) (1) and taking into account (5), we obtain

$$-\rho A_i \omega^2 \, exp[\, i(\, \omega t - kx\,)] + c_{ijkl} A_l \left(\omega / v_{\phi}\right)^2 n_k n_j \, exp[\, i(\, \omega t - kx\,)] = 0 . \quad (7)$$

Given that $exp[\, i(\, \omega t - kx\,)] \neq 0$ After mathematical transformations we obtain the equation of the following form

$$c_{ijkl} A_l n_k n_j - \rho A_i {v_{\phi}}^2 = 0 \quad (8)$$

Introducing the second rank tensor $\Gamma_{il} = c_{ijkl} n_k n_j$, Equation (8) can be written as follows

$$A_l \Gamma_{il} - \rho \delta_{il} A_l {v_{\phi}}^2 = 0, \quad (9)$$

where: δ_{il} - Kronecker symbol, defined as $\delta_{il} = \begin{cases} 1, i = l \\ 0, i \neq l \end{cases}$.

Since the amplitude can write $A_i = AP_m$ Where $P_m(\, p_1, p_2, p_3\,)$ - Component unit vector in the direction of displacement (polarization), the equation (9) can be written as

$$\left(\Gamma_{il} - \rho \delta_{il} {v_{\phi}}^2\right) P_m = 0 \quad (10)$$

Expression (10) is a system of three homogeneous linear equations that provide the relationship between the components of the tensor of elasticity c_{ijkl} and phase velocity v_{ϕ} acoustic waves propagating in a homogeneous anisotropic elastic medium.

To ensure that the system of equations (10) have a solution other than $p_1 = p_2 = p_3 = 0$ Requires that the determinant, which consists of $\left(\Gamma_{il} - \rho \delta_{il} {v_{\phi}}^2\right)$, was zero.

$$\left|\Gamma_{il} - \rho \delta_{il} {v_{\phi}}^2\right| = \begin{vmatrix} \Gamma_{11} - \rho {v_{\phi}}^2 & \Gamma_{12} & \Gamma_{13} \\ \Gamma_{21} & \Gamma_{22} - \rho {v_{\phi}}^2 & \Gamma_{23} \\ \Gamma_{31} & \Gamma_{32} & \Gamma_{33} - \rho {v_{\phi}}^2 \end{vmatrix} = 0 \quad (11)$$

Because of the symmetry of the elastic moduli tensor Γ_{il} also characterized by symmetry conditions $\Gamma_{li} = c_{ljki} n_j n_k = c_{kilj} n_j n_k = c_{ikjl} n_j n_k = c_{ijkl} n_j n_k = \Gamma_{il}$.

Tensor components $\Gamma_{il} = c_{ijkl} n_k n_j$ get sad indices j and k

$$\Gamma_{il} = c_{i11l} n_1^2 + c_{i22l} n_2^2 + c_{i33l} n_3^2 + (\, c_{i12l} + c_{i21l}\,) n_1 n_2 + (\, c_{i13l} + c_{i31l}\,) n_1 n_3 + (\, c_{i23l} + c_{i32l}\,) n_2 n_3 \quad (12)$$

Since wood is viewed as an orthotropic material, the number of independent components of the tensor elastic modulus decreases with twenty one to nine.

Thus tensor Krystofelya wood as an orthotropic material in view of (12) takes the form:

$$\Gamma_{11} = c_{11}n_1^2 + c_{66}n_2^2 + c_{55}n_3^2, \Gamma_{22} = c_{66}n_1^2 + c_{22}n_2^2 + c_{44}n_3^2, \Gamma_{12} = (c_{12} + c_{66})n_1n_2,$$
$$\Gamma_{33} = c_{55}n_1^2 + c_{44}n_2^2 + c_{33}n_3^2, \Gamma_{13} = (c_{13} + c_{55})n_1n_3, \Gamma_{23} = (c_{23} + c_{44})n_2n_3, \quad (13)$$
$$\Gamma_{21} = \Gamma_{12}; \Gamma_{31} = \Gamma_{13}; \Gamma_{32} = \Gamma_{23}.$$

Consider the system of equations (10) in the case of bulk acoustic wave propagation along the axis of symmetry of wood. Substituting the appropriate values Krystofelya tensor of (13) we obtain:

$$(c_{11}n_1^2 + c_{66}n_2^2 + c_{55}n_3^2 - \rho v_\phi{}^2) \times (c_{66}n_1^2 + c_{22}n_2^2 + c_{44}n_3^2 - \rho v_\phi{}^2) \times$$
$$(c_{55}n_1^2 + c_{44}n_2^2 + c_{33}n_3^2 - \rho v_\phi{}^2) = 0 \quad (14)$$

From equation (14) it follows that along each axis of symmetry depending on the polarization fluctuations may have three types of acoustic waves, longitudinal and transverse two. So considering the propagation of acoustic waves along the axis of symmetry of wood, can be defined six diagonal tensor components elastic modulus $c_{\alpha\alpha} = \rho v_\phi{}^2, a = 1 \ldots 6$.Diagonal tensor components elastic modulus can be calculated, provided the acoustic wave propagation in the direction which does not coincide with the axes of symmetry [0].

Actual currently remains the problem of propagation of acoustic waves in wood with regard to its viscoelastic properties. Sysnezovana mathematical model of propagation of acoustic waves, taking into account the type of exponential relaxation wood core.

Solution equation of motion (1) can be represented as:

$$u(x,\tau) = G(x,\tau) ** F(x,\tau) + \gamma^2 \left[\dot{G}(x,\tau) * \varphi(x) + G(x,\tau) * \psi(x)\right]; \quad (15)$$

$$\sigma(x,\tau) = G_\sigma(x,\tau) ** F(x,\tau) + \gamma^2 \left[\dot{G}_\sigma(x,\tau) * \varphi(x) + G_\sigma(x,\tau) * \psi(x)\right], \quad (16)$$

where: $G(x,\tau)$ - Impact function to move, $F(x,\tau)$ - Mass forces $G_\sigma(x,\tau)$ - The function of receptors for stress φ and ψ - Scalar and vector potential displacement vector u , γ - Setting the ratio of the velocity of propagation of acoustic waves * - convolution in time.

To find these functions must consistently apply integral Fourier transform to the spatial coordinate x (q - Conversion option), mark "F" marked transformation Fourier) and Laplace Time τ (s - Conversion option, the sign "L" marked transformation Laplace).

Inverse transformation produce consistently. We first determine the impact of the original function by Fourier

$$G^L(x,s) = \frac{k(s)}{2s\gamma} e^{-\gamma s|x|k(s)}; \; G_\sigma^L(x,s) = -\frac{sign(x)}{2\eta_\alpha} e^{-\gamma s|x|k(s)}. \quad (17)$$

where: $sign(x)$ - Signature x, η_α - Parameter that depends on Poisson, $k(s)$ - A function which takes into account the relaxation wood core.

For the inverse Laplace transform, first, calculate the original function $exp[-syk(s)]$ Where $y = \gamma \mid x \mid$.

After a series of mathematical operations end result can be presented in such a way

$$G_\sigma^L(x,s) = -\frac{sign(x)}{2\eta_\alpha} e^{-syk(s)} = -\frac{sign(x)}{2\eta_\alpha} e^{-sy} f^L(y, s+\beta) \qquad (18)$$

$$f^L(y,s) = f_1^L(y,s) f_2^L(y,s);$$

$$f_1^L(y,s) = e^{-syk_1(s-\beta)} = e^{-sy\sum_{m=1}^{m*} a_m \left[s^L(s-\beta) \right]^m} = e^{-sy\sum_{m=1}^{m*} a_m \left(\frac{A}{s}\right)^m} = e^{\sum_{m=1}^{m*} -ya_m A^m s^{1-m}};$$

where: $f_2^L(y,s) = e^{-syk_2(s-\beta)} e^{\beta y[k_1(s-\beta)+k_2(s-\beta)]} = \sum_{m=0}^{\infty} \frac{c_m(y)}{s^m} =$

$$= \sum_{j=0}^{\infty} \frac{1}{j!} \left[\frac{-y(s-\beta)A^{m_*+1}}{s^{m_*+1}} \sum_{m=0}^{\infty} \frac{a_{m+m_*+1} \cdot A^m}{s^m} \right] \cdot \sum_{k=0}^{\infty} \frac{1}{k!} \left[\beta y \sum_{m=1}^{m*} \frac{a_m A^m}{s^m} \right]^k,$$

Odds $c_m(y)$ determined by the rules of action POWER series, A, a, β - The physical properties of the material.

$$G^L(x,s) = \frac{1}{2s\gamma} k(s) e^{-syk(s)} = \frac{1}{2s\gamma} e^{-sy} g^L(y, s+\beta) \qquad (19)$$

$$g^L(y,s) = f_1^L(y,s) g_2^L(y,s); \; g_2^L(y,s) = k(s-\beta) e^{-syk_2(s-\beta)} e^{\beta y\left[k_1(s-\beta)+k_2(s-\beta)\right]} =$$

where: $= \sum_{m=0}^{\infty} \frac{d_m(y)}{s^m} = \left(1 + \sum_{m=1}^{m*} \frac{a_m A^m}{s^m} + \frac{A^{m_*+1}}{s^{m_*+1}} \sum_{m=0}^{\infty} \frac{a_{m+m_*+1} \cdot A^m}{s^m} \right) \times$

$$\times \sum_{j=0}^{\infty} \frac{1}{j!} \left[\frac{-y(s-\beta)A^{m_*+1}}{s^{m_*+1}} \sum_{m=0}^{\infty} \frac{a_{m+m_*+1} \cdot A^m}{s^m} \right] \cdot \sum_{k=0}^{\infty} \frac{1}{k!} \left[\beta y \sum_{m=1}^{m*} \frac{a_m A^m}{s^m} \right]^k.$$

Odds $d_m(y)$ determined by the rules of action POWER series [1].

Development of experimental equipment. To provide a series of experimental studies of acoustic variables in climates designed and developed experimental setup acoustic studies (Figure 1) and laboratory climate chamber at the Department OTiMTP NLTUUkrayiny (Fig. 2).

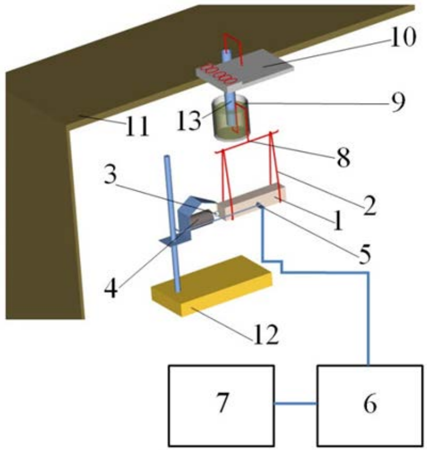

Fig. 1. axonometric block diagram of the experimental set-acoustic research: 1 - a pattern that has the shape of a parallelepiped; 2 - suspension; 3 - pendulum mechanism; 4 - electromagnet; 5 - microphone; 6 - filter; 7 - Frequency; 8 - draft shutter oil weighing models in a climate chamber; 9 - bath with oil; 10 - electronic weight; 11 - climatic chamber wall; 12 - anchor installation; 13 - oil tube grip.

Key indicators of climatic chambers: the size of the working area of 0.51 * 0.21 * 0.18 m; Camera dimensions 0.85 * 0.85 * 0.38 m; Temperature range $+10 \div +125^0 C$; humidity control range $2 \div 98\%$. To control mechanisms and systems used dual camera controller RD2 production NPF "REHMYK", the controller is equipped with interface RS232 / RS485 / USB connection to the PC. This allows you to use the PC software "system of data collection," which makes it possible to read, view, record information from the device and sensor temperature and humidity; display information in tabular or graphical form; conduct timely regulatory change unit parameters.

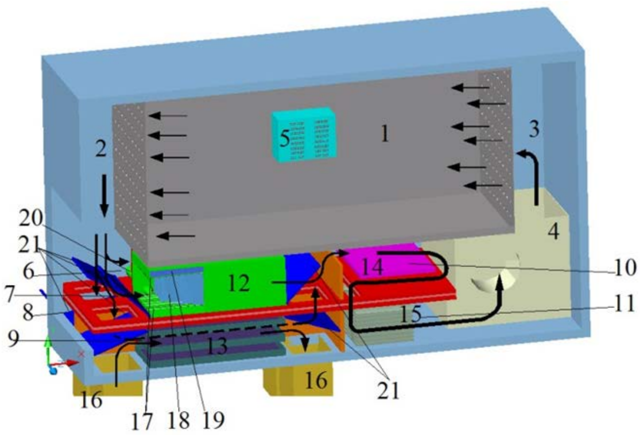

Fig. 2. axonometric block diagram working area and channel airflow circulation climate chamber 1 - camera work area; 2, 3 - capacity equalization of air pressure stream lenses; 4 - dvohshvydkisnyy fan; 5 - Signal connectors; 6 - direct channel; 7 - channel moisture, 8, 9 - two

drainage channels; 10 - channel heat; 11 - channel cooling; 12 - Cassette wetting; 13 - Cassette drying №1; 14 - heating element heating tape; 15 - aluminum radiators installed in the cold side of the six elements Pelt'ye; 16 - channel units and silica in cassettes drying; 17 - two rows of knitting needles; 18 - vyparuvacha canvas; 19 - holding tank cartridges; 20 - One of three drainage pipes; 21 - door opening and closing synchronous channels.

Obtained by free oscillation data rate of passage of acoustic waves in the temperature range (from 18 to 60^0C) And moisture content of wood (within $5 \div 90\%$) Is shown in (Figure 3). Proven practical value of the developed technique of acoustic studies [2,3].

The propagation velocity of acoustic oscillations (SHPAH) (acoustic method of free oscillations) was determined using frequency and sample size in that direction:

$$C = 2 \cdot l \cdot f = 2 \cdot l \cdot (n / T) \qquad (20)$$

where: C - Velocity of acoustic oscillations; l - The size of the sample in the direction of oscillation; f - Resonant frequency; n - The number of periods in the selected area of temporal charts; T - The length of time selected area chart.

Done metrological support of experimental research. The relative error of the propagation velocity of vibrations in the formula (20) can be calculated as:

$$\partial C = \pm[\delta f + \partial l] = \pm[\Delta f / f + \Delta l / l] \qquad (21)$$

where: ∂C - Relative error propagation velocity fluctuations; ∂l - The relative error of the sample size in the direction of oscillation; δf - Relative error of center frequency; Δl - Absolute error of the sample size; Δf - Absolute error of the resonance frequency.

Time diagram experiments conducted investigated digital oscilloscope with a sampling frequency of 10 MHz, a sound card and a computer with a clock frequency of 192 kHz.

For sound card relative error of the resonance frequency $\delta f = \{n / t\} = \partial n + \partial t = \Delta t / t = [(1/192000)/0.032375] \cdot 100\% = 0.02\%.$ For example, the absolute error of the size of the sample is measured caliper 0.05 mm at the size of the sample $l = 101$ mm is $\partial l = \Delta l / l = (0.00005 / 0.101) \cdot 100\% = 0.0495\%.$

The relative error of SHPAH impressed for each measurement by the formula (21) $\partial C = \pm 0.0695\%$. Absolute error SHPAH sample values for 1234,79m / s is $\pm \Delta C = \pm C \cdot \partial C = \pm 1234.79 \cdot 0.0695\% = \pm 0.86 м / с$ That is an order of magnitude less than the known studies.

Results. Conducted statistical analysis of experimental results allowed to obtain regression dependence third-order coefficient of multiple determination $R^2 = 0{,}9985$.

$$c = b_0 + b_1 \cdot W + b_2 \cdot W^2 + b_3 \cdot W^3 + b_4 \cdot T^3 + b_5 \cdot W \cdot T^3 + b_6 \cdot W^2 \cdot T^3 \qquad (22)$$

where: $b_0 = 1303{,}52;\, b_1 = -12{,}04;\, b_2 = 0{,}1132;\, b_3 = -0{,}0004;$
$b_4 = -0{,}0005;\, b_5 = 8{,}89E-06;\, b_6 = -7{,}86E-08;$

Note that conducted an experimental study made it possible to establish the dependence of the elastic moduli tensor component c_{55} changes of temperature and moisture content of wood pine. Thus, using established patterns of communication between the velocity of acoustic waves and elastic modulus $c_{\alpha\beta}$ You can define other tensor components modules elasticity. Because $c_{55} = G_{13}$ We will continue to record G_{13}.

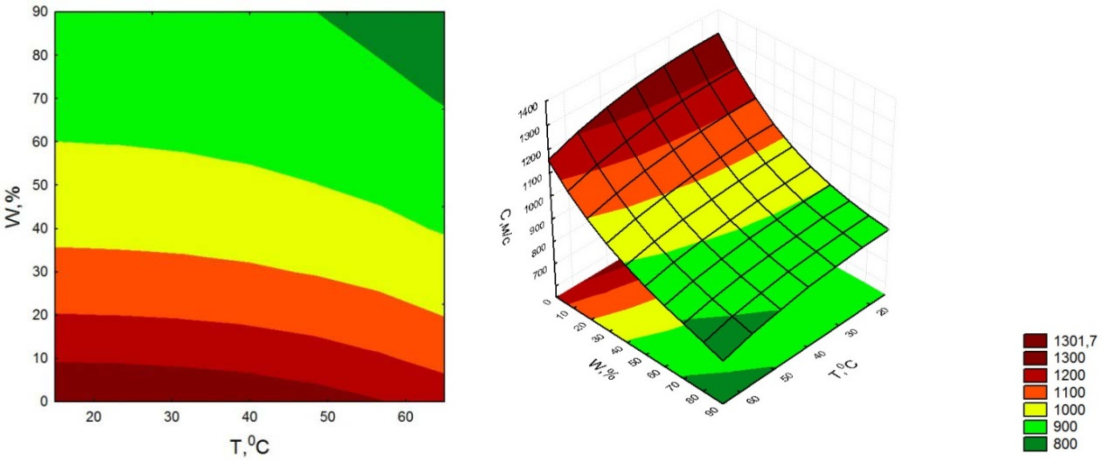

Fig. 3. Dependence SHPAH (VLT) of changes in temperature and moisture content of wood pine (acoustic method of free oscillations).

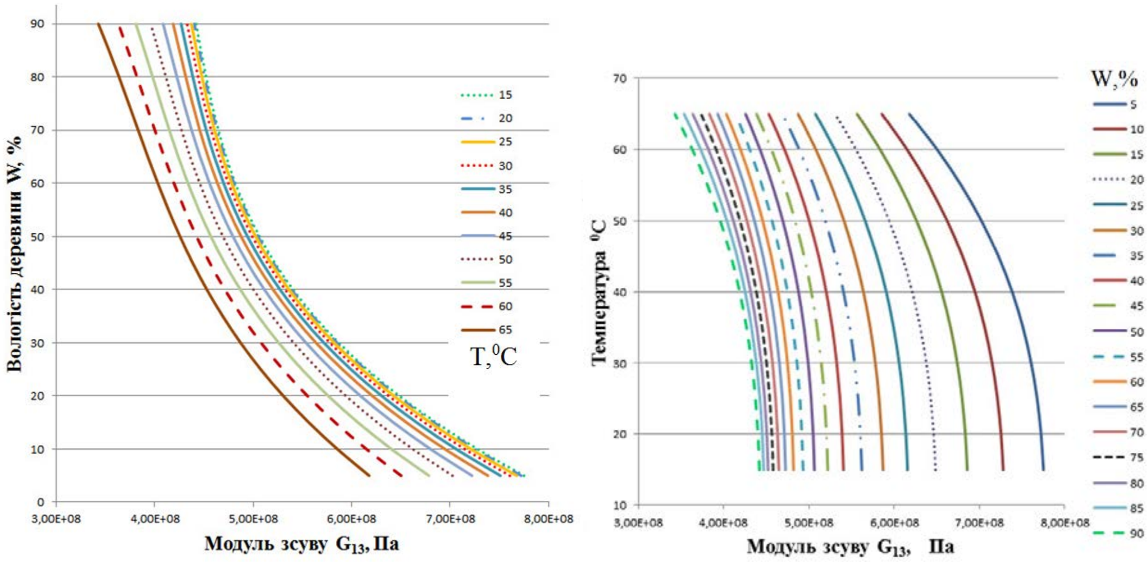

Fig. 4. The dependence of the shear modulus G13 from changes in temperature and moisture content of wood pine.

Conclusions

A mathematical model of acoustic wave propagation in wood as an orthotropic elastic material allows for measuring the velocity of acoustic oscillations to determine the elastic modulus tensor coefficients wood based variable temperature and humidity environmental conditions. To assess the influence of viscoelastic properties of wood in wave process developed a new mathematical model of acoustic wave propagation in wood. The core relaxation wood taken into account in this model in exponential form.

Designed and developed acoustic device research provides contactless determination SHPAH in wood. This unit devoid of known deficiencies, including, it is no direct mechanical contact instrument excitation and receiving vibrations from the sample. In the device is used as a parameter frequency information, which is not changed by changing environments and provides a measurement error SHPAH in a short sample length of 10 cm is not greater for $\pm 1 м/с$.

The method for acoustic experimental research in wood processing algorithms and acoustic signals that allow for measuring the phase velocity of acoustic oscillations in the range of 100 Hz to determine the coefficients 3MHts tensor of elasticity of wood as an orthotropic body. The regularities can be used to improve processes and operations of timber production and the development of new methods of quality control.

Designed and developed a camera provided within climate: temperature range $+10 \div +125°C$ and humidity range $2 \div 98\%$. The design of the camera and developed specialized modules allow for acoustic studies of wood and wood-based materials in a wide range of changes in temperature and humidity directly in the work zone camera without removing samples.

The influence of temperature and humidity fields in elastic properties of wood by acoustic method, including:

– humidity in the range of 0% to 90% has a dominant influence, pronounced nonlinear dependence, as a result of both solid wood skeleton and replaced the solid mass loading of the skeleton, as well as changing the whole system deformability capillary filling with water. Significant influence of humidity there is absolutely dry state to the point of saturation, and manifests itself in reduced elastic properties and higher zapovilnyuyetsya change;

– the effect of temperature in the range of $10^\circ C$ to $70^\circ C$ is also due to lower non-linear and mechanical properties of wood. In the range of $10^\circ C$ to $45^\circ C$ it is small, further increase in temperature leads to a rapid decrease in elastic properties.

Based on the established relationships between SHPAH and mechanical properties of wood, a new method of quality control, including acoustic way to sort of coniferous and deciduous wood structural purpose rectangular in strength according to standard EN338.

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Based on provedennыh Theoretically эksperymentalnыh of research and ustanovlenы New zakonomernosty Between skorostyu Distribution akustycheskyh waves and mechanical properties of wood in wide ranges of temperature and humidity. Naydennыe zakonomernosty mogut bыt yspolzovanы for usovershenstvovanyya of technological processes and operations derevoobrabatыvayuscheho production, as well as for development novyh kvalymetryy methods.

Timber tensor modules upruhosty, anyzotropyya, temperature, humidity, akustycheskye methods, velocity Distribution akustycheskoy volnы.

Based on carry out theoretical and experimental researches, were found new regularities between a rate of spread of acoustic waves and strength properties of wood in changing circumstances of temperature and humidity that could be used for improvement of technological processes and operations of woodworking and also development new methods of qualimetry.

Wood, tensor of elastic moduluses, anisotropy, temperature, humidity, ultrasonic methods, velocity of distribution of ultrasonic wave.