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MATHEMATICAL MODEL OF WOOD SAWING ACCURACY ON HORIZONTAL BAND SAW MACHINES

Creation of the mathematical model of wood sawing accuracy on the horizontal band saw machines and its realization as an application program on a computer will enable to predict the accuracy of sawing, to determine effective ways of its increasing and to automate the regulation of cutting modes on these machines. Develop a mathematical model for the accuracy of wood sawing on the horizontal band saw machines to determine the nature of the influence of factors and find effective methods for increasing the accuracy of sawing. The energy method, the methods of analytical mechanics for determining forces acting on the saw, and the finite element method for studying the stiffness of the band saw using 3D modeling were used. The mathematical dependence of the accuracy of wood sawing on the horizontal band saw machines was established, on the basis of which the analysis of the influence a set of factors on the accuracy of sawing was made and methods of its increasing were determined. The obtained mathematical model of the accuracy of sawing of wood on the horizontal band saw machines allows to determine the value of sawing waviness, to establish rational modes of cutting of wood and to carry out automated regulation of sawing modes on machine tools.

Keywords: the mathematical model, the accuracy of wood sawing, sawing waviness, horizontal band saw machine, 3D modeling, finite element method, methods of analytical mechanics.

Nomenclature: $a_{1(2)}$ - distance between the contact points of the saw with the pulleys and adjacent guides; $a_{h1(2)}$ - distance between the axes of the pulleys and the adjacent guides horizontally; a_ρ - coefficient of blunting of lateral cutting edges of saw teeth; B - width of the saw; B_{eq} - equivalent width of the saw; D - diameter of the pulleys; E - elastic modulus of saw material; e - asymmetry of the location of the cutting area on the workpiece of the saw; H - cutting height; h - height of teeth; J_x - moment of inertia of the saw blade in the plane of its least stiffness; j - working stiffness of the saw; j_o - working stiffness of the saw in the case of symmetrical placing cutting area; j_s - initial stiffness of the saw; J_y - moment of inertia of the saw blade in the plane of greatest stiffness; L - length of the workpiece of the saw; l_1, l_2 - distances from contact points of the saw with pulleys to the adjacent guides; M_{p1}, M_{p2} - reaction moments; M – bending moment in the saw body on the pulleys; N - tension force of the saw; n_z - number of teeth on saw; P_x, P_y - lateral and normal components of cutting force; $P_{xm1(2)}$, $P_{ym1(2)}$ - allowable values of the lateral and normal components of the cutting force for each of the guides; $P_{r1\ (2)}$ - the force of pressing the saw to the guides; P_{cr} - critical force; P_z - tangent component of cutting force; p - fictitious force of cutting on rear surface of the tooth; p_z - coefficient, which depends on the shape and size of the teeth profile; p_s - specific pressure of sawdust on the side surface of the saw blade; R_1x, R_2x - reaction forces at the contact points of the saw with the pulleys; R - radius of pulleys; S - thickness of the saw; S_1, S_2 – size of bending of the saw teeth in the opposite sides; t - step of teeth of a saw; $u_{1\ (2)}$, u_0 - distance from rear edge of the saw to the line of action of the longitudinal force in zones of contact with the guides and cutting zone; v_s - feed rate; w - influence of each of the factors in percentage; y_0 - medium deviation of the saw; y_{+1}, y_{-1} - value of the deviation of the saw; y_1 - value of transverse displacement of contact points of the saw with guides; y_r – displacement of guides; y_s - initial deflection of the saw in the cutting zone; θ_{in} - angle between plane of the saw and velocity vector; θ_1 - angle between perpendicular to rear surface of the tooth and the plane of the saw; θ_2 - angle between perpendicular to front surface of the tooth and the plane of the saw; ρ - the radius of rounding of the main cutting edges of the teeth; σ_N - tensile strength of the saw; φ - angle between axes of pulleys.

Formulation of the problem. Creating a mathematical model for the accuracy of wood sawing on horizontal band saw machines to determine the nature of the impact on the accuracy of sawing a number of factors will provide an opportunity to identify effective ways to increase the accuracy of sawing, which is an urgent task to date.

The purpose of the work:

1) develop a mathematical model for the accuracy of wood sawing on horizontal band saw machines, on the basis of which to perform the analysis of the influence of a set of factors on the accuracy of sawing;

2) improve the method of theoretical determination of the working stiffness of narrowband saws;

3) investigate, how the partial loss of contact between the saw blade and the guides affects the accuracy of sawing and to formalize the dependencies for determining the permissible cutting modes;

4) investigate the influence of asymmetry of the location of cutting zone on the working saw chain and the displacement values of the guides;

5) identify the main ways and effective ways to improve the accuracy of sawing on horizontal band saw machines.

Literature review. Investigating the establishment of true laws and predicting the accuracy of sawing on band saw machines was undertaken by different groups of scientists from the middle of the twentieth century. The significant contribution to the development of studies on the accuracy of wood sawing on band saw machines was made by A.E. Feoktistov, S.P. Pochekutov, B. Tunnell, G.F. Prokofiev [1-4], who first investigated the connection of the accuracy of sawing at a feed rate and concluded that there is a need to increase the stability of band saws to ensure the accuracy of sawing. G.F. Prokofiev [5] proposed a method for the theoretical determination of the accuracy of sawing on band saw machines, linking the size of the deviation of the saw from the initial position with its stability and stiffness, developed theoretical dependencies for the execution of calculations. His theory was found to be continued in the studies by A. A. Bannikov and I. S. Lobanova [6,7], but the inconsistency of the calculation schemes in studies of the hardness of pollen indicates the need for an additional analysis of the conditions of fixing the working branch of the band saw on the machine. The basic principles of the method of theoretical determination of the stiffness of pollen using the energy method are developed in [8]. In order to determine the stiffness of narrow band saw blades in order to ensure proper accuracy of the results, this technique needs to be improved, namely: taking into account the impact on the stiffness of the saw blade, the asymmetric placement of the cutting area on the saw blade, the displacement values of the guides, and the rationale for choosing the design circuit of the working line saws. I. T. Rebezhniuk [9] investigated the influence of features of preparation of band saws on the accuracy of sawing and proposed a new method of breeding the teeth of saws and rational sawing modes on the horizontal band saw machines.

On the basis of the performed analysis, it should be noted that most of the well-known studies on the accuracy of sawing wood by band saws [1-7] were carried out for wide-spread in the last century vertical sawing machines with wide saws. For horizontal band saw machines with narrow saws, which are widely used in modern sawmill production, the results of these studies can not be used because of significant differences in power-supply parameters of the sawing process, the size of band saws and conditions for extraction sawdust. The studies of the precision of wood sawing on the horizontal band saw machines with narrow saws [8, 9] showed, that the accuracy problem for these machines is even more urgent, but conclusions and recommendations for improving accuracy are based on a limited number of factors. In addition, optimized in terms of precision sawing modes do not ensure the use structural capabilities of the machine tools, which limits their performance. Therefore, in order to improve the accuracy of sawing on the horizontal band saw machines with narrow saws simultaneously with the provision of high productivity of sawing process, further theoretical and experimental research is required.

Materials and methods. The basis of the algorithm of the mathematical model were the characteristic reasons for reducing the accuracy of sawing (Fig. 1): as a result of deformation of the working saw branch under the action of cutting forces and partial loss of contact between the saw and the guides. To determine the value of the deformation of the instrument, the classical dependence [5] in the form of the ratio of the lateral force acting on the band saw in the cutting zone, to the working stiffness of the saw

$$y=P_x/J. \quad (1)$$

In the case of a partial loss of the saw contact with one of the guides, a sharp decrease in the stiffness of the saw [6] and a change in the position of the saw in relation to the feed rate direction, which results from the immersion of the saw in the workpiece (the phenomenon of "cutting" the saw). It is impossible to continue the sawing process in this case. Therefore, it is important to determine the conditions under which saw contact with guides and possible implementation of the process of sawing.

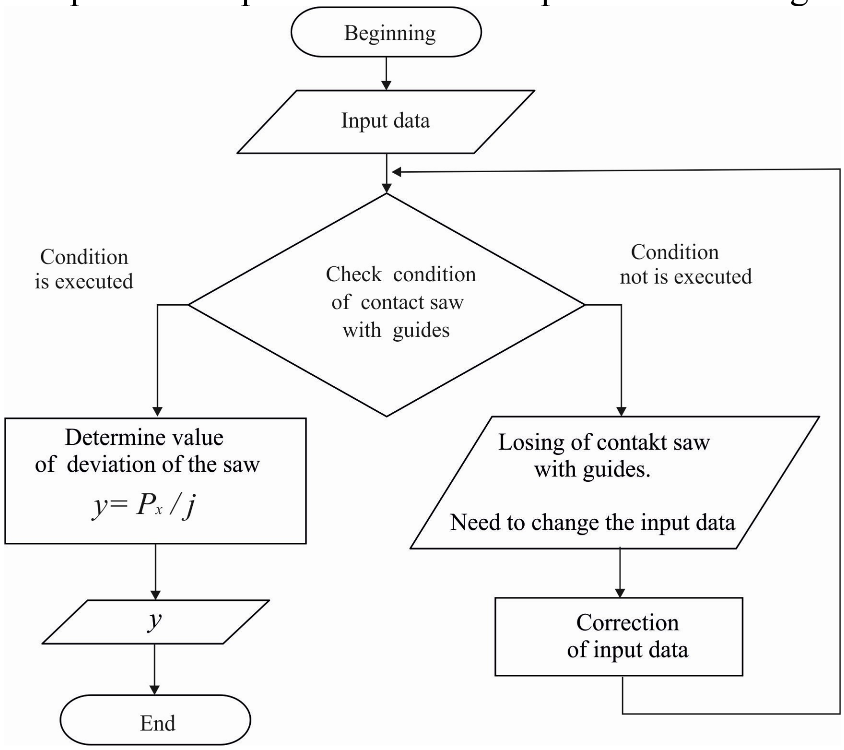


Fig. 1. Block diagram of the algorithm for the accuracy of sawing on horizontal band saw machines

Therefore, in order to develop a mathematical model for the accuracy of sawing on the horizontal band saw machines, it is necessary to establish: the conditions for the contact of the saw with guides, working stiffness of the saw and side force acting on the saw in the cutting zone. For theoretical studies of working stiffness of the saw, a calculation scheme of the working branch of a band saw, whose length is equal to the distance between the axes of pulleys (Fig. 2), is used. In the calculation scheme of the workpiece of the saw, the following conditions of fastening are given: tight pinching on both ends of the saw blade in a horizontal plane; hinged fixing on ends of the workpiece of saw in a vertical plane; hinged fixings in contact areas of saw with guides in the vertical plane. The following factors influence the working branch of the saw: longitudinal forces (force of tension and the tangent component of cutting force), transverse forces (lateral and normal components of force of cutting), moments arising from bending of saw on the pulleys. The cutting area is located on the workpiece of the saw with asymmetry.

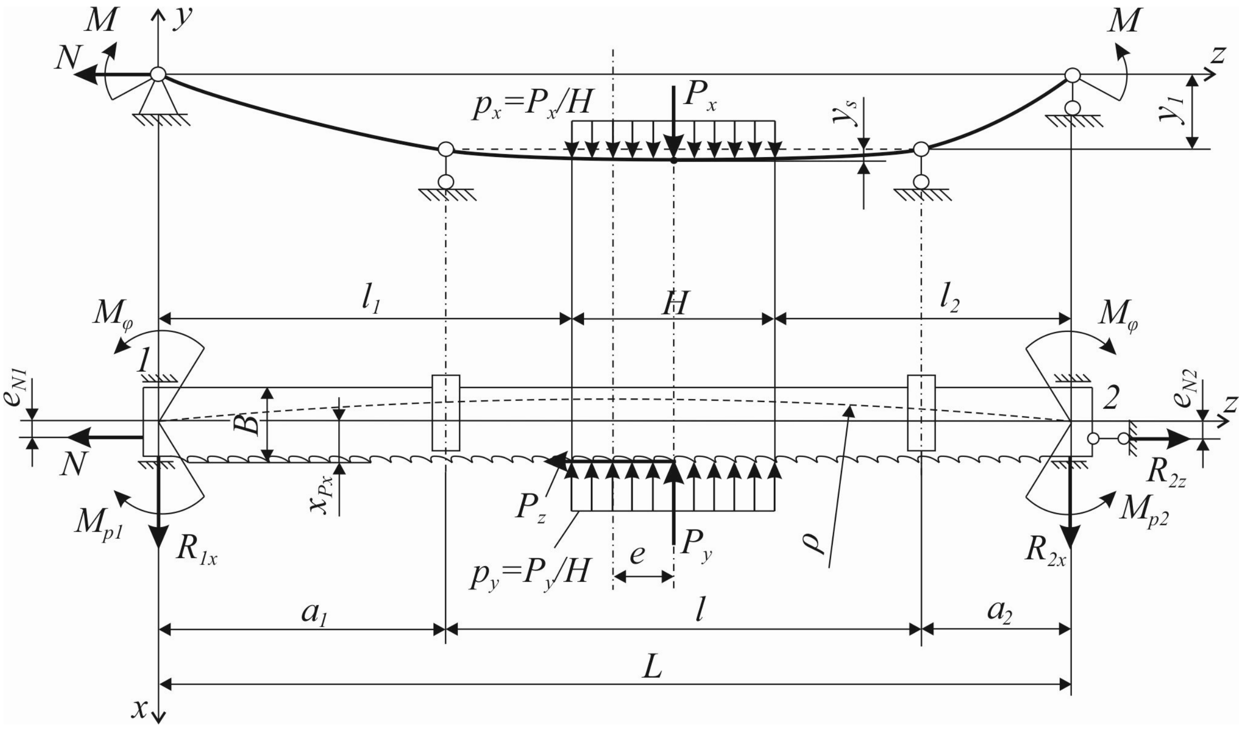


Fig. 2. The calculation scheme of the working branch of the band saw to determine its stiffness

Since both ends of the workpiece of the saw in the horizontal plane are tightly pinched, the calculation scheme in this plane is a statically uncertain system. As a result of the disclosure of static uncertainty with the use of the force method and the rules of Vereshchagin [10], we determine the forces and moments of the reaction of the supports at the points of contact of the saw with the pulleys. Consequently, the calculation scheme of the working branch of a band saw with its definite static uncertainty makes it possible to examine the conditions of the contact of the saw with the guides on the horizontal band saw machines.

The method of determining the lateral force and working stiffness of the band saw is developed taking into account new components such as: the pressure on the saw blade, which remains in the saw blade; uneven load on the saw teeth due to their dilution method through one uncut tooth; initial deflection of the saw in the cutting zone.

The method of determining the working stiffness of band saws is improved, taking into account the impact on the stiffness of the saw blade, the asymmetry of placing the cutting zone on the saw blade and eccentricity of the saw tension as a variable, depending on the cutting mode and the angle between the axes of the pulley pulleys.

Based on the analysis of working conditions of the saws on horizontal band saw machines, rational conditions for its attachment were established for the construction of the calculation scheme of the saw: at the ends of the saw in places of contact with pulleys - the hinged fixing in vertical plane and stiff contraction in horizontal plane; in places of contact with guides - hinged attachment of the saw in vertical plane. Taking into account these requirements, a three-dimensional virtual model of working tape of a band saw has been created to study its hardness by computer solid-state simulation using the Solid Works environment.

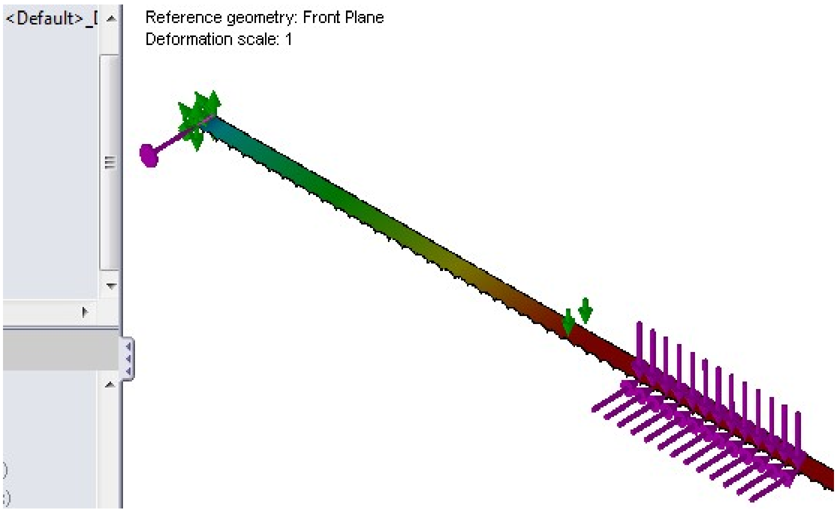


Fig. 3. The image of the virtual three-dimensional model of the workpiece of the band saw in the Solid Works environment

The values of the required tension forces and moments from the bending of the saw on the pulleys are calculated according to the formulas

$$N = \sigma_N S B_{eq} \ , \tag{2}$$

$$M = \frac{2EJ_x}{D} = \frac{EB_{eq}S^3}{6D} \ . \tag{3}$$

The working stiffness of the saw during research using solid state modeling was determined according to the dependence

$$j = \frac{P_x}{\Delta y_1 - \Delta y_0} \ . \tag{4}$$

Accordingly, in order to obtain a single value of the stiffness of the saw, the determination of the value of displacement of the teeth of the saw was performed twice - without the action of lateral force and with the applied lateral force.

The accuracy of the finite element method depends on the size of elements [11]. During body sampling, two basic parameters are used for elements: global size and tolerance. Values of these parameters, in accordance with recommendations given in [11], are as follows: tolerance of 0,25 mm, global size - 5,0 mm.

Results. Determination of value of transversal deformation of the saw in cutting zone is preceded by a check of the condition for ensuring the contact of the saw with guides. The condition for a contact of the saw with the guides is fulfilled if the value of lateral force and normal component of a cutting force are less than certain allowable values for each of the guides of the saw:

$$P_x < P_{xm1} \ , \ P_x < P_{xm2} \ , \ P_y < P_{ym1} \ , \ P_y < P_{ym2} \ . \tag{5}$$

Acceptable values of the lateral force and the normal component of the cutting force for each of the guides, which for one-sided directions are equal

$$P_{xm1(2)} = \frac{2P_{r1(2)}u_{1(2)} - P_y\left(y_1 + y_s\right)}{B - u_0 + u_{1(2)} + P_y / j}\ ,\ P_{ym1(2)} = \frac{2P_{r1(2)}u_{1(2)} - P_x\left(B - u_0 + u_{1(2)}\right)}{y_1 + y_s + P_x / j} \quad (6)$$

The initial deflection of the saw in the cutting zone due to bending in the zones of contact with the guides is determined from the dependence

$$y_{s1(2)} = \frac{S}{4R}\sqrt{\frac{E}{\sigma_N}} \cdot \left(\sqrt{\left(2a_{h1(2)} - S\sqrt{\frac{E}{\sigma_N}}\right)^2 + 8Ry_r - \frac{ES^2}{3\sigma_N}} - 2a_{h1(2)} + S\sqrt{\frac{E}{\sigma_N}}\right). \quad (7)$$

The force of pressing a saw to one-sided directions is determined taking into account the own stiffness of the saw blade, thus eliminating an error of up to 14%, which may be in the present method of determining this force. Dependence is established

$$P_{cr1(2)} = \frac{1}{a_{1(2)}}\left[N\left(y_1 + y_s\right) - \frac{EJ_x}{R}\right]. \quad (8)$$

In case of the condition of providing contact of the band saw with guides, the value of transverse deformation of the saw blade (1) is determined.

The side force acting on saw during sawing on horizontal band saw machines is determined taking into account new components specific to horizontal band saw machines with narrow saws: due to the initial bending of the saw in the cutting zone, the uneven distribution of sawdust in the saw blade on both sides of the saw blade, a method of cultivating the teeth of a saw through one uncut tooth. The obtained dependence for determining the lateral force has the form

$$P_x = P_y\left(\pm\theta_{in} \pm \theta_1 \pm \frac{\left(S_2 - S_1\right)}{B} \pm \frac{y_s}{B}\right) \pm P_z\theta_2 - B_{eq}Hp_s \pm 1{,}635\frac{n_z S_z H a_\rho^2}{t}\left(a_\rho - 0{,}8\right)p\ , \quad (9)$$

To determine the working stiffness of band saws, ensuring the proper accuracy of the results of the study, account is taken of characteristic differences of modern horizontal band saw machines from the vertical, namely: the impact of the toothed crown, the asymmetry of the location of the cutting area on the workpiece of the saw, the eccentricity of the tension of the saw, which is defined as the value of the variable in sawing process. To take into account the effect of the toothed crown, the stiffness of the saw is proposed to be determined using their equivalent width

$$B_{eq} = B - p_z h\ B_{екв} = B - p_з h_з\ . \quad (10)$$

The coefficient, which depends on the shape and size of the teeth profile (for saw with a WM profile, the value of p_z = 0.849 is set).

Applying the equivalent width, the error of determining the stiffness of narrow band saws is reduced to 3-7%, while the full width and width of the saw blade without the height of the teeth, the stiffness is overestimated, respectively, 33-37% and 20-26%.

The influence of asymmetry of location of cutting zone on workpiece of the saw was established using the solid-state modeling method, resulting in the dependence

$$j = j_0\left(\frac{P_y}{P_{cr}}\frac{e^2}{L^2} + 1\right)\ . \quad (11)$$

The eccentricity of tension of the band saw during cutting is variable depending on position of the saw on pulleys and the angle between axes of pulleys:

$$e_N = \frac{1}{N}\left[\frac{M_{p1} + M_{p2}}{2} + \frac{e}{L}\left(M_{p2} - M_{p1}\right) - EJ_y\frac{\varphi}{L}\right]. \quad (12)$$

The obtained mathematical model of accuracy of sawing wood on horizontal band saw machines has the form

$$y=\frac{P_y\left(\pm\theta_{in}\pm\theta_1\pm\frac{\left(S_2-S_1\right)}{B}\pm\frac{y_s}{B}\right)\pm P_z\theta_2-B_{eq}Hp_s\pm 1{,}635\frac{n_zS_zHa_\rho^2}{t}\left(a_\rho-0{,}8\right)p}{j_s\left(1-\frac{P_y}{P_{cr}}\right)\left(\frac{P_y}{P_{cr}}\frac{e^2}{L^2}+1\right)}\ . \qquad (13)$$

The algorithm of developed mathematical model of precision sawing is realized on a computer in the form of a macro in programming language Visual Basic for Applications.

Discussion. Using the established mathematical model of accuracy (13), we analyze the influence of factors on the size of deviation of the saw in the cutting zone. The degree of influence of each of the factors will be expressed as a percentage of change in the value of the deviation of the saw due to change in the value of the factor within the area of interest, to the mean deviation of the saw y0, when the values of all factors are average:

$$w=\frac{y_{+1}-y_{-1}}{y_0}\cdot 100\%\ . \qquad (14)$$

The results of the study (Fig. 4) showed that the greatest influence on the accuracy of sawing is the feed rate, the height of the saw, the thickness and width of the band saw, the tensile stress, and the radius of rounding of the main cutting edges of the saw teeth. The degree of influence of each of the factors during sawing is gradually increased as a result of the bluntness of the teeth of the saw. Increasing the feed rate, cutting height and bending radius of main cutting edges of the saw teeth leads to a reduction in the accuracy of sawing.

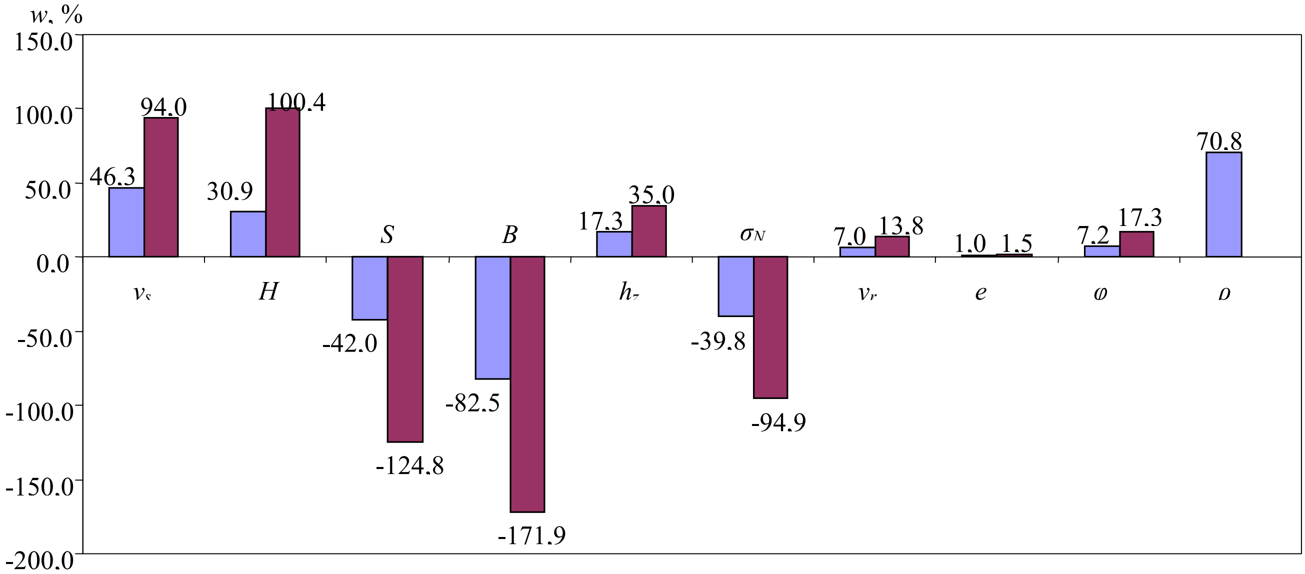
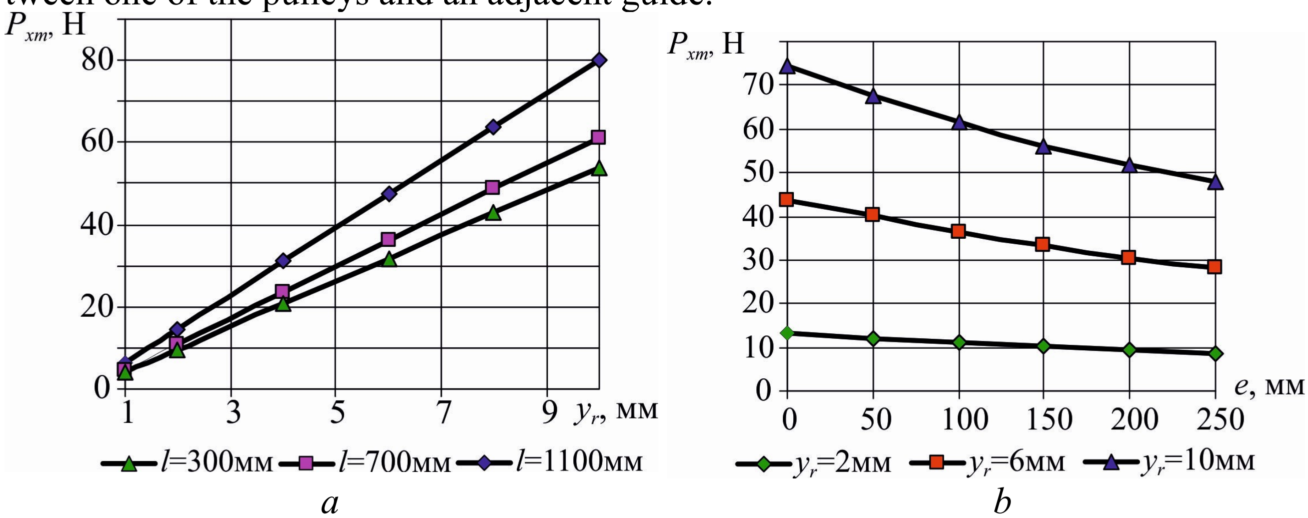


Fig 4 - The degree of influence of factors on the accuracy of sawing wood on horizontal band saw machines (■ – ρ = 20 μm; ■ – ρ = 40 μm)

Increasing the tensile strength, width and thickness of the saw provide increased accuracy of sawing. An increase in the height of the teeth of the saw causes a reduction in the accuracy of sawing, as the stiffness of the saw decreases. Increase in deviation of the saw also results in an increase in the values of such factors as the magnitude of bias of the guides, the angle between the plane of rotation of the pulley pulleys, the asymmetry of the location of the cutting area on the working saw chain. The magnitude of the deviation of the saw has a linear dependence on the magnitude of displacement of guides and angle between planes of rotation of pulleys. In addition, the degree of influence of the displacement of guides increases with the increase in the width of the saw.

Analyzing the possibility of increasing the accuracy of the horizontal band saw machines, it should be noted that certain factors such as thickness and width of the saw, the distance between pulley axes are defined the design of the machine and must be taken into account at the design stage of the machine. Tension stress is determined by the properties of the saw material, and its rational limits are recommended by manufacturers of band saws in terms of their durability. The height of the teeth is determined by the cutting mode and the properties of the wood, since the volume of the intercostal cavity should be sufficient for the propagation of sawdust. Cutting height refers to the characteristics of the workpiece and is an uncontrollable factor. Improved accuracy can be accomplished by the use of band saws as much width and thickness (within the permissible specifications of the machine) and a choice of rational values speed feeder.

Results of the study of a partial loss of contact the saw with the guides (Fig. 5) show that in case of unilateral guides permissible lateral force which is provided by contact between saw and guides decreases with decreasing offset of guides and distance between guides. For typical characteristics of horizontal band saw machines, when changing the parameters of adjustment of guides, the permissible lateral force varies within the limits of 4,12 ... 80,07 N, that is, in 19,4 times. Increasing asymmetry placing the cutting area on the working branch saws permissible lateral force decreases maximum asymmetry value of 250 mm permissible lateral force is 36% less compared to the symmetrical placement of the cutting area. This is due to an increase in the distance between one of the pulleys and an adjacent guide.



a *b*

Fig. 5. Dependence permissible lateral force provided ensuring contact with the guides saw the magnitude of displacement guides (a) and asymmetric placement of cutting area on working branch of saw (b)

Based on analysis of the results of performed mathematical modeling, the following rational methods for improving the construction of horizontal band saw machines are defined in order to improve the accuracy of wood sawing process:

- Design a saw new construction of guides that provide saws eliminate bending in contact with guides and the loss of contact between them during sawing and limit displacement saw on pulleys under the normal component of cutting force;

- Implementation of automatic control of feed speed for precision sawing.

Conclusions. The mathematical model of accuracy of wood sawing on horizontal band saw machines with narrow pulley saws has been developed, which allowed to describe the nature of impact on the accuracy of sawing a number of factors, to choose rational ways to increase the accuracy of sawing and to determine the rational modes of cutting with accuracy. The method of theoretical determination of working stiffness of band saws is improved, in which, unlike the known: the effect of height and type of teeth profile is taken into account using an equivalent saw blade width; the eccentricity of tension of the saw is given as a variable value, depending on cutting forces and angle between axes of pulleys; the influence of asymmetry of location of cutting zone on the saw is taken into account. The method of determination of lateral force in the cutting area of wood was also improved, which takes into account the new components that are characteristic of horizontal band saw machines: the pressure of sawdust on the saw blade, bending of teeth through one unalloyed tooth, initial deflection of the saw in cutting zone. For the first time, it was investigated how the accuracy of sawing on band saw machines affects the partial loss of contact between the saw blade and the guides, which made it possible to determine the conditions for the provision of this contact and to formalize the dependencies for determining the permissible cutting modes.

Prospects for further research are the creation of new methods for analyzing and predicting the accuracy of sawing on horizontal band saw machines and developing effective structural solutions for the even higher accuracy of sawing.

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Математична модель точності пиляння деревини на горизонтальних стрічкопилкових верстатах

Створення математичної моделі точності пиляння деревини на горизонтальних стрічкопилкових верстатах та реалізація її у вигляді прикладної програми на ЕОМ дасть можливість прогнозувати точність пиляння, визначити ефективні способи її підвищування та автоматизувати регулювання режимів різання на даних верстатах. Розробити математичну модель точності пиляння деревини на горизонтальних стрічкопилкових верстатах для встановлювання характеру впливу чинників та визначання ефективних способів підвищування точності пиляння. Було застосовано енергетичний метод, методи аналітичної механіки для визначання сил, що діють на робочу вітку пилки, а також метод скінченних елементів для дослідження жорсткості пилки за допомогою 3D-моделювання. Встановлено математичну залежність точності пиляння деревини на горизонтальних стрічкопилкових верстатах, на основі якої виконано аналіз впливу сукупності чинників на точність пиляння та визначено способи її підвищування. Отримана математична модель точності пиляння деревини на горизонтальних стрічкопилкових верстатах дає змогу визначати величину хвилястості пропилу, встановлювати раціональні режими різання деревини та виконувати автоматизоване регулювання режимів пиляння на верстатах.

Ключові слова: математична модель, точність пиляння деревини, хвилястість пропилу, горизонтальний стрічкопилковий верстат, 3D-моделювання, метод скінченних елементів, методи аналітичної механіки.

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