Research of dynamic processes at cutting forest materials on horizontal band saw equipment

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Abstract. For processing small-scale wood, as well as wood from logging and sanitary logging, small enterprises are created that use fairly large and expensive band saws of various foreign firms and domestic production, which have a high energy intensity of the technological process. In this regard, the development of a resource-saving band saw machine that improves the quality of saw products and reduces the energy intensity of the technological process is an urgent task for the timber processing industry. To study the dynamics of the process of sawing wood on a horizontal band saw, it is necessary to create its dynamic model, which is a mathematical description of the interaction of the cutting process and the equivalent elastic system of the machine. The problem of the quality of wood sawing is both the accuracy of processing and the roughness of the surface to be processed. To assess the accuracy of wood sawing, two indicators were used: average and maximum undulation. As a result of the research, a new design of the band saw was developed using a dynamic model, which ensures resource saving, reducing the energy intensity of the technological process and improving the quality of the resulting saw products.

1. Introduction
Currently, the forest sector is experiencing a critical level of depletion of the resources of the most valuable wood in economically accessible forests, from the point of view of the costs of harvesting and transporting wood, the presence of which can ensure the economic viability of most enterprises of the forest complex. With the marked level of depletion, there is an acute shortage of wood, which is solved with a favorable market situation in the forest market due to supplies from remote and conditionally accessible forest areas. In an unfavorable situation, this wood is economically unavailable, which leads to mass bankruptcies of forest sector enterprises. The shortage of high-quality raw materials is becoming more acute every year due to the lack of effective reproduction of forest resources in previously developed areas. In this regard, there is a problem in the forestry sector of processing large volumes of low-quality small-batch wood to ensure the required quality indicators of sawn timber. For its processing, as well as wood from logging and sanitary logging, small enterprises are being created in agriculture and forestry, using rather large and expensive band saws of various foreign firms and domestic production. The first of them are difficult to access for small farms due to their low purchasing power, and domestic machines are inefficient, since they are designed for...
large volumes of processing and, as a result, have a high energy intensity of the technological process of sawing wood, which increases the cost of the saw products produced.

Band saws that are used in band sawing, there are five types: bimetallic band saws, band saws with HDPE hardened tooth, carbon band saws, band saws with a flattened tooth, band saws with a stellated tooth. Bimetallic band saws are manufactured using a special technology. High-speed steel M2 (“quick-cut”) hardness 66-67 HRC is welded to the spring steel strip by laser welding. Then the profile of the band saw tooth is milled. After milling, the band saw undergoes heat treatment. The band saw is hardened and released, as a result, the steel blade of the band saw acquires a hardness of 42-46 HRC, while the hardness of the upper part of the tooth is 52-56 HRC. The belt cloth with a red-hot tooth is made with a red-hot tooth from high-quality tool steel alloyed with chromium and is tempered at high-efficiency quenching plants to a tooth hardness of up to 60 HRC. Carbon band saws are band saws that have a tooth hardness of the band saw and the main blade of 42-46 HRC. These are the most common band saws that are used in band sawing. The teeth of these saws are notched by milling or pressing. Band saws with a flattened tooth are widely used in band sawmills, where it is necessary to use band saws with a width of 60 mm or more. The upper part of the band saw tooth is first crushed, and then formed. As a result, the upper part of the tooth becomes thicker than the main blade of the band saw. At the same time, the thickened upper part of the tooth acquires a hardness of 52-56 HRC, which allows band saws with a flattened tooth to work well and with high quality. Band saws with a stellated tooth are used mainly on band sawmills, where it is necessary to use band saws with a width of 100 mm or more. Stellite is a kind of cast iron, and has a high hardness, it is well sharpened. The operational characteristics of band saws with stellite are very high.

The main factors determining the quality of lumber when sawing wood on band saw equipment are its roughness and thickness [1]. Achieving the optimal value of these parameters is a complex engineering task, since various dynamic factors act on the band saw during operation [2-5].

One of the parameters that determine the quality of lumber is the cutting speed and feed rate, as well as the preparation of the cutting tool. The optimal combination of these parameters provides the required quality indicators of sawn timber [6, 7]. However, it is necessary to take into account the type of wood, humidity and ambient temperature [8]. Therefore, only after determining all the technological parameters that affect the quality of lumber in relation to dynamic processes, it is possible to obtain lumber of the required quality. Based on this, a new design of a horizontal band saw was developed, which ensures the required quality of saw products.

2. Design development

Voronezh State Forestry Academy has developed new designs of small-sized band saws that are protected by utility model with the specified design and technological parameters (figure 1) [9].

The new design of the horizontal band saw contains a bed 1, a saw unit 2 with a drive 3 and a tension 4 pulleys, on which the saw blade 5 is mounted. The machine has a drive 6 of the saw assembly 2. The machine is equipped with a hydraulic tension mechanism 7 of the saw blade, a vertical adjustment drive of 8 saw node 2. On the saw node 2 on the inside there is a propellant 9 with a lifting mechanism 10. The saw unit moves along the guide rail of the rail type; the sawn material is fixed on the guide path using special clamps.

To justify the parameters of band saw equipment, the studies of sawing wood process were carried out. The most important factors affecting the quality of the resulting saw products are the following factors: the feed rate $U$, m/min ($X_1$); the cutting width $B_{as}$, mm ($X_2$); the ambient temperature $t$ °C ($X_3$). To conduct a full-factor experiment to study the process of high-quality wood sawing, the second-order $B_k$ plan was used, with the number of factors $k = 3$. The second-order polynomial was used to describe this process mathematically. The output thicknesses were taken as the thickness $\lambda$ and roughness $R_{m\max}$ of the lumber.
3. Material and methods
Sawing wood with a narrow band saw is accompanied by a force interaction. With proper operation of a rationally prepared saw, the forces of interaction between the chip and the body with the cut walls, if not completely absent, have a minimum value. The forces acting on the edges of the teeth of the band saw are mainly decisive in the process of sawing wood.

The parameters of the gear ring are considered in the main tool plane and the cutting plane. Since the tool and static coordinate systems coincide for the toothed crown of band saws, common definitions and parameter designations are used to characterize the teeth in these two systems (figure 2).

For the teeth of narrow log-saw band saws, the WM profile is now common (figure 3a), besides, it is recommended as a universal one for sawing both hard and soft wood species. The profiles of the teeth of narrow log-saw band saws, made by manufacturers from different countries and now common in Russia (as an example: by the Swedish firms “SANDVIK” and “UDDEHOLM”, the German company “BANHOLZER”, the Italian “LUIGI PESSINAACCIAI”), have their own designations and special non-essential features. In Russia, since 2004, two profiles of the teeth of band saws have been offered as the most versatile “Superprofil” and “Supercobra” for narrow log-saw band saws (figure 3b, c).
In the profiling of a toothed crown, the values of their angular and linear parameters are an integral component of the formation of the tooth line. Angular parameters are the determining components in ensuring rational conditions for cutting a saw tooth with a blade. In narrow log-saw band saws, the value of the front angle $\gamma$ according to the recommendations of the American company “Wood-Mizer” is: 8-12° – for hard rocks, 12-15° – for soft wood of an open structure. The value of the rear angle $\alpha$ is equal to 20-30°, where the lower values are chosen for sawing hard rocks, the larger ones for soft and loose.

Linear parameters are the determining components in creating the capacity of the interdental cavity of band saws. For the pitch of the teeth of narrow log-saw band saws with a width of up to 60 mm, the following well-established recommendations can be distinguished. At a linear speed of a band saw up to 30 m/s, it is recommended to use a tooth pitch of 15-19 mm for hard rocks, and 20-22 mm for soft rocks, and at a speed of more than 30 m/s, a tooth pitch of 25 mm for both hard and soft rocks. It should be noted that the pitch of the teeth $t = 22.22$ mm has become universal for both soft and hard rocks, but at a belt speed of no more than 30 m/s.

The height of the teeth $h$, according to the recommendations of “Wood-Mizer”, for narrow band saws with a tooth pitch $t = 22.22$ mm is equal to: $h = 4.8$ mm – in the case of sawing hard or frozen wood; $h = 4.8 - 6.4$ mm – medium-hard wood; $h = 6.4$ mm – soft wood.

The teeth of thin saws, which are usually used to ensure sufficient rigidity and stability, should have a small height and pitch. In general, for narrow log band saws with a width of 32-60 mm, the fair dependencies are: $h = (0.2 - 0.29) t$; $t = (18-28) S$.

The radius of rounding of the lower surface of the interdental cavity should be such that the stresses are not concentrated on a small area. To ensure high operational properties, narrow log band saws are made of both carbon and alloy steels.

There are many manufacturers of steel strips for the production of band saws and it is not possible to list all of them. Well-known: “UDDEHOLM” (Sweden), “SANDVIK” (Sweden), “KRUPP” (Germany), “HUGO” (Germany), “EBERLE” (Germany), Nizhny Novgorod (Russia), “LUIGI PESSINA ASSIAG” (Italy), “BANSO” (Germany).

Let's compare the chemical composition of a steel strip produced by different companies. If we do not take into account the “Russian” steel, which has a high content of phosphorus and sulfur, all other companies produce steel with approximately the same chemical composition. Phosphorus and sulfur make steel very brittle and brittle. The German company “HUGO” offers two types of steel strips of the brand “C75” and “HS”.

“HS” is a high-alloy steel with a low carbon content, with the presence of tungsten. Mechanical characteristics, hardness, fluidity, are the same as that of steel “C75”. This steel for band saws is used by the company “WOOD-MIZER”. Approximately the same chemical composition is used in band saws for metal, but in band sawing for metal, very much attention is paid to the fight against vibration. This steel is quite fragile and you need to work with it carefully. In the matter of the quality of the
steel strip, it is very important that the processes of quenching, tempering and machining of the edges of the steel strip are carried out correctly. The mechanical ones were observed – width, thickness, straightness. The main parameters of band saws are presented in table 1.

| Tooth pitch, mm | Width, mm | Thickness, mm |
|----------------|-----------|---------------|
| 19             | 32-34     | 0.9-1.1       |
| 22             | 32-50     | 0.9-1.1       |
| 22             | 35-50     | 0.9-1.1       |

The tooth of the band saw is separated at a height equal to one third or half of the tooth height. This line is defined from the top of the tooth. It was noticed that the band saw does not blunt so quickly, the first thing that goes away is a divorce. In some cases, it was enough to restore the divorce and you can continue working. The divorce should be carried out with an accuracy of about 0.02 mm. When sawing very soft rocks, the tooth separation is 0.021”-0.023”, with an average hardness of wood-0.019”-0.021”, with very hard and frozen wood-0.016”-0.018”.

To study the dynamics of the wood sawing process on a horizontal band saw, you need to create a dynamic model of it. The dynamic model of the machine is a mathematical description of the interaction of the cutting process and the equivalent elastic system of the machine. The characteristic feature of cutting wood with a band saw is the constant thickness of the wood layers, cut off by the blades of the teeth. However, the variability of cutting speeds and feed rates, as the main components of forming the thickness of the cut layer, will cause it to change, and therefore change the components of the cutting force. Also, the amount of the cutting force components is affected by the wood layering and the collision of the teeth of the band saw with the wood during the sawing process.

The quality problem of wood sawing is both the machining precision and the roughness of the treated surface. There are two indicators were used to evaluate the accuracy of sawing wood: average and maximum waviness. The thickness difference of sawn products obtained due to wandering of the saw tape was determined by measuring each board using a vernier caliper. At least 12 measurements were made in six sections of the board at 0.3 m length at a distance of 10 mm from the edges. The number of repeated observations in the experiment, i.e. the number of sawn boards in one experiment, ranged from 6 to 10, which provided an indicator of accuracy of all measurements within 5%. As a result of measuring the board thickness, a number of numerical values were obtained that characterize the range of size dispersion in the batch due to the saw wobble.

The most important characteristic of size dispersion, both in a batch and a single board, is the standard deviation from the grouping center, which can numerically coincide with the average board thickness or board batch. Experimentally, these roughness parameters of the treated surfaces were studied after sawing wood with narrow log-saw band saws with different ways of expanding the teeth, depending on the order of their dilution in the toothed crown. As a result of measuring the board roughness, a number of numerical values were obtained that characterize the range of size dispersion in the batch.

The required number of measurements was determined based on a sample of 10 experiments, when $\mu = 90^\circ$, $S_e = 0.018$ mm.

4. Results and discussion

As a result of processing the obtained data, the coefficients of the regression equations and their significance are determined. The regression equations that adequately describe the process of sawing hardwood (oak) and coniferous (pine) species on small-sized band saw equipment have the following form:

for oak:
\[ \lambda_{dHar} = 0.116 + 0.437 U - 0.00116 B + 0.000263 B U - 0.0161 U^2 + 9.60 \times 10^7 B^2; \]  
(1)

\[ R_{m_{max}}^{Har} = 45.62 + 180.9 U - 0.02246 B + 0.006853 B U - 16.83 U^2 + 0.0000482 B^2; \]  
(2)

for pine:

\[ \lambda_{dCon} = -0.6099 + 1.103 U - 0.0006134 B + 0.0002896 B U - 0.0933 U^2 + 1.045 \times 10^6 B^2; \]  
(3)

\[ R_{m_{max}}^{Con} = 196 + 427.7 U - 0.3038 B - 42.92 U^2 + 0.0001736 B^2 + 0.1154 B U, \]  
(4)

where \( R_{m_{max}}^{Har}, R_{m_{max}}^{Con} \) – permissible roughness of sawn products of hardwoods and softwoods; \( \lambda_{Har}, \lambda_{Con} \) – different thickness permissible value of saw products of hardwoods and softwoods; \( U \) – feed rate, \( B \) – cutting width.

To study the dynamics of sawing wood process on a horizontal band saw, it is necessary to create a dynamic model of it. The dynamic model of the machine is a mathematical description of the cutting process interaction and the equivalent elastic system of the machine. The characteristic feature of cutting wood with a band saw is the constant thickness of the wood layers, cut off by the blades of the teeth. However, the variability of cutting speeds and feed rates, as the main components of forming the thickness of the cut layer, will cause a change in the components of the cutting force. Also, the amount of the cutting force components is affected by the wood layering and the collision of the band saw teeth with the wood during the sawing process. Therefore, the components \( P_z \) and \( P_y \) wood cutting forces, which are functions of time, primarily depend on the degree of tool bluntness, as well as on the moisture wood content, the front angle and the feed to the tooth.

The design diagram of a horizontal band saw (figure 4) consists of two systems: the elastic system of the cutting mechanism and the elastic system of the feed mechanism [10].

![Figure 4. Block diagram of the band saw equivalent dynamic system.](image)

All parameters of the calculation scheme are given values. In the cutting mechanism, the reduction is made to the motor shaft. The elastic element – a band saw – is replaced by a section of the shaft with a coefficient of reduced equivalent torsional stiffness \( c_2 \). The moments of mass inertia, the stiffness coefficients of the elastic links and the resistance are constant values. Since the torque fluctuations were studied during steady motion, the torque from the engine is constant.

Differential equations of the machine elastic system motion in steady motion during sawing wood, which are obtained on the basis of the Lagrange equation of the second kind, have the form:
The general concavity of the trailing edge (which is due to the internal stress state of the blade) is insufficient to consider a one-dimensional version of its movement. The value of internal stresses must correspond to the stiffness coefficient in the feed mechanism, \( \frac{H \cdot m}{r} \); \( c_i \) – reduced stiffness coefficient in the feed mechanism, [H/m]; \( k_i, k_2 \) – given resistance coefficients in the cutting mechanism, \( \frac{H \cdot m \cdot s}{r} \); \( k_j \) – reduced resistance coefficient in the feed mechanism, \( \frac{H \cdot s}{m} \).

During the sawing process, forces act on the band saw to move it off the pulleys. To prevent the saw from sliding off the pulleys, initial stresses are created in the saw blade, and the pulleys are tilted towards the feed direction of the material being cut. The value of internal stresses must correspond to the profile and angle of inclination of the pulleys. This changes the movement of the saw under load, which affects its stability on the pulleys and the ability to carry out the cutting process. The non-straightness of the teeth and the trailing edge significantly affects the band saw stability and strength. The general concavity of the trailing edge (which is due to the internal stress state of the blade) is unacceptable due to the stability of the saw on the pulleys.

It is proposed to use an iterative method (sequential approximation) to identify the saw cutting mechanism. Given the flat cross section of the band saw it is sufficient to consider a one-dimensional version.

The frequency and amplitude of the natural oscillations of the saw belt in the idle mode (without contact of the cutting tool with the log) are a function of the cross section, the free length of the saw branches, the tension force and the speed of its movement. To reduce the amplitude of transverse vibrations, the working area of the saw is limited by guides and a calming roller is used. Analyzing the records of saw vibrations, we can conclude that the frequency of vibrations is not less than 60 Hz, i.e. it fits into the sound frequency range.

To substantiate the dynamic characteristics of the problem, we propose a hypothesis of a quasi-stationary state of a standing wave, i.e., the absence of movement of the first harmonic and the rest.

\[
\begin{align*}
J_1 \ddot{\phi}_1 + k_1 (\dot{\phi}_1 - \dot{\phi}_2) + c_1 (\phi_1 - \phi_2) &= M_{en}^r; \\
J_2 \ddot{\phi}_2 - k_2 (\dot{\phi}_2 - \dot{\phi}_1) + k_2 (\phi_2 - \phi_1) - c_2 (\phi_1 - \phi_2) + c_2 (\phi_2 - \phi_3) &= -M_{P_z}^\nu; \\
J_3 \ddot{\phi}_3 - k_2 (\phi_2 - \phi_3) - c_2 (\phi_2 - \phi_3) &= 0; \\
m_1 \ddot{s}_1 - k_1 (\dot{s}_1 - \dot{s}_2) - c_1 (s_1 - s_2) &= -P_y^{\nu}. \\
\end{align*}
\]

The last system equation can be written as follows:

\[
m_1 \ddot{s}_2 + k_1 \ddot{s}_1 + c_1 s_2 = k_1 \cdot \omega_2 \cdot r \cdot \cos(\omega_2 t) + c_1 \cdot r \cdot \sin(\omega_2 t) - P_y^{\nu}. \tag{6}
\]

Taking into account (2), the system of differential equations of the machine elastic system motion will take the form:

\[
\begin{align*}
J_1 \ddot{\phi}_1 + k_1 (\dot{\phi}_1 - \dot{\phi}_2) + c_1 (\phi_1 - \phi_2) &= M_{en}^r; \\
J_2 \ddot{\phi}_2 - k_2 (\dot{\phi}_2 - \dot{\phi}_1) + k_2 (\phi_2 - \phi_1) - c_2 (\phi_1 - \phi_2) + c_2 (\phi_2 - \phi_3) &= -M_{P_z}^\nu; \\
J_3 \ddot{\phi}_3 - k_2 (\phi_2 - \phi_3) - c_2 (\phi_2 - \phi_3) &= 0; \\
m_1 \ddot{s}_2 + k_1 \ddot{s}_1 + c_1 s_2 &= k_1 \cdot \omega_2 \cdot r \cdot \cos(\omega_2 t) + c_1 \cdot r \cdot \sin(\omega_2 t) - P_y^{\nu}. \tag{7}
\end{align*}
\]

In the system of differential equations (3), the following designations are accepted: \( J_i, J_2, J_3 \) – inertia moments of the rotating masses of the cutting mechanism brought to the motor shaft, [kg\cdot m^2]; \( \phi_i, \varphi_i, \varphi_3 \) – rotation angles of the corresponding reduced rotating masses, [\( \text{rad} \)]; \( m_1 \) – machine carriage weight driven to the feed shaft, [kg]; \( s_1 \) – feed mechanism moving, [m]; \( s_2 \) – reduced mass moving \( m_1 \), [m]; \( c_1, c_2 \) – given coefficients of torsional rigidity in the cutting mechanism, \( \frac{H \cdot m}{r} \); \( c_3 \) – reduced stiffness coefficient in the feed mechanism, [H/m]; \( k_i, k_2 \) – given resistance coefficients in the cutting mechanism, \( \frac{H \cdot m \cdot s}{r} \); \( k_j \) – reduced resistance coefficient in the feed mechanism, \( \frac{H \cdot s}{m} \).

\( M_{en} \) – reduced torque on the engine shaft, [H\cdot m]; \( M_{P_z} \) – given moment of resistance from the main component \( P_z(t) \) of the cutting force, [H\cdot m]; \( P_y^{\nu} \) – reduced normal component of the cutting force, [H].

It should be noted that depending on the development of the kinematic scheme of the cutting mechanism (figure 2), the value of the reduced coefficient of torsional rigidity \( c_1 \) will be different.
points of the higher harmonics at the coordinate $0 \leq x \leq L$, where $L$ is the length of the saw between the support points. The proposed hypothesis allows us to preserve the uniformity of the wave equation.

In the stationary state and in the absence of external influences, the transverse displacements of the elastic string satisfy the one-dimensional wave equation:

$$ \frac{\partial^2 \Phi}{\partial x^2} - \frac{1}{c^2} \frac{\partial^2 \Phi}{\partial t^2} = 0, $$

(8)

initial conditions:

$$ \Phi(x, 0) - \Phi_0(x), \frac{\partial \Phi}{\partial t} \bigg|_{t=0} = v_0(x), (0 \leq x \leq L) $$

(9)

and boundary conditions:

$$ \Phi(0, t) = \Phi_a(t), \Phi(L, t) = \Phi_b(t). $$

(10)

In the particular case when the boundary conditions are given by the equality

$$ \Phi_a(t) = \Phi_b(t) = 0 $$

(11)

the standing waves of the one-dimensional wave equation (5) correspond $\gamma_2 = -\frac{\pi}{2}$, and half the wavelength $\frac{\lambda}{2} = \frac{\pi}{k}$ an integer number of times fits the string length $L$, while

$$ k = \frac{n \pi}{L}, \omega = kc = \frac{n \pi c}{L}, (n = 0, 1, 2, \ldots). $$

(12)

The equation solution is the sum of particular solutions, i.e. sum of harmonic standing waves excited by given initial conditions

$$ \Phi(x, t) = \sum \left( a_n \cos \frac{n \pi c}{L} t + b_n \sin \frac{n \pi c}{L} t \right) \sin \frac{n \pi x}{L}. $$

(13)

The coefficients $a_n$ and $b_n$ are determined from the initial conditions, according to the Fourier formulas:

$$ a_n = \frac{2}{L} \int_0^L \hat{\Phi}_0(x) \sin \frac{n \pi x}{L} dx, (n = 0, 1, 2, \ldots) $$

(14)

$$ b_n = \frac{2}{n \pi c} \int_0^L v_0(x) \sin \frac{n \pi x}{L} dx, (n = 0, 1, 2, \ldots) $$

(15)

In a second approximation, it is necessary to take into account the disturbing influences during the movement of the band saw, which are exerted by its joint formed during welding of the beginning and end of the saw. Hitting a pulley, it exerts a stepwise effect on the system, which must be taken into account in boundary conditions (7). At this stage, it is proposed not to consider transient transients caused by the collision of the joint of a band saw with a pulley. Then, the right-hand side (heterogeneity) does not appear in wave equation (5) and the solution of equation (10) does not need to be supplemented by a particular solution of the new inhomogeneous equation.

In the third approximation, the transition from the idle mode considered to the present moment to the operating mode is carried out. To do this, it is necessary to take into account the contact of the band saw with restrictive stops, a soothing roller and sawn lumber, which will lead to the «division» of the movement modes of the band saw according to the principle of piecewise approximation.

5. Conclusion

Thus, the proposed machine differs from domestic and foreign analogues of this class in a simplified and reliable saw tension unit consisting of a tension pulley connected by an axis to a carriage moved along a fixed guide. The connection between the carriage and the guide is in the form of a “dovetail”, and the tension spring is calibrated for different sawing speeds and cutting forces. The dovetail
assembly and the tapped spring serve as both a tensioner and a compensator for the linear expansion of the band saw. The dynamic model of the elastic system of a horizontal band saw for following free vibrations, dynamic loads of elastic links, and changes in cutting and feeding speeds allows us to determine that the design of the cutting mechanism, in which the shaft of the drive saw pulley operates as an axis, is rational, since it has a lower (by 6.5%) dynamic load compared to the design in which the specified shaft transmits torque. The article presents a theoretical generalization and a new solution to the problem of improving the accuracy and productivity of sawing wood with band saws on band saws. The problem is solved on the basis of the results of complex studies of wood sawing, taking into account the orientation of the tool relative to anisotropic wood material and dynamic phenomena in the equivalent elastic system of a horizontal band saw, which can be applied by the international community in the design of new equipment for sawing timber that provides resource saving and energy consumption reduction.

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