Creation and experimental verification of a mathematical model of industrial debarking

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Abstract: In the context of more intensive use of forest biomass, efforts to combat global climate change, the desire for more rational use of wood and an increase in surplus value in wood products, it can be assumed that primary woodworking processes require optimization. The aim of this work is the creation and experimental verification of a mathematical model of rational debarking of a log. The proposed mathematical model is based on a semi-empirical theory of fracture mechanics, the conclusions of which the authors optimize for the task of separating bark from wood during industrial debarking. During the experiments, a specially created installation was used. The results of experimental studies showed good quantitative and qualitative coincidences with the study results of the developed mathematical model. Thus, the developed model allows evaluating, at the stage of theoretical research, one of the main parameters of group debarking of timber. Namely, the time of timber processing taking into account the structural elements of the drum, parameters of pulpwood, their properties and temperature.

Keywords: timber treatment, industrial process optimization, production process, timber mechanics.

1. Introduction

Modern forestry is increasingly confronted with problems that arise with intensive forest management and the progression of the effects of climate change. The forest sector is able to respond to changing conditions by adapting management, new planning standards, new approaches to the optimal structure of the forest, or planting new trees with higher resistance. The forest industry, the use of forest resources for wood production are of great environmental importance. In the fight against global climate change, humankind needs to increase the percentage of forest plantings for the purpose of carbon conservation (carbon dioxide is stored in wood pulp). The experts in forest management presuppose rather non-timber forest use, but thinning is nevertheless necessary, and moreover, younger plantings are more fruitful in the case of non-timber forest exploitation [9]. The relationship between forest conservation and the well-being of those closest to the forest is crucial to conserve biodiversity, reduce carbon emissions and contribute to sustainable development [12] and forest management still involves the production of a certain amount of wood. Moreover, if the goal is to preserve carbon, forest management should be intensified, because carbon conservation in wood occurs to a large extent during the growth of a young tree and stops when the tree reaches adulthood. Carbon conservation can even reverse when a mature tree becomes susceptible to various diseases, pests, rot and decay [15,32]. Therefore, from the point of view of combating global climate change and carbon conservation, the authors find it promising to expand forest stands and intensive felling in these stands. Namely, felling that supports the composition of forest stands at the prevalence of young trees that only start reaching maturity. Log debarking remains an important work item in the value chain in the timber industry. All sectors of the woodworking industry share the same commonality as wood for felling before it can be processed into other products [28].

The problem of rational mechanized debarking - relevant for modern European forest management [10]. Some common debarking methods used to separate bark from wood include drum barking, ring barking, high-pressure water use, debarking by compression and biodegradation. In most cases, the applied loads serve to weaken the bond of the wood bark by means of mechanical damage and/or separation of the bark from the wood [5]. The theory of fracture mechanics is becoming increasingly popular in solving applied problems of the timber industry. It is successfully used in solving problems of the interaction of forest machines' wheels with the soil of cutting areas [4, 20,21, 24, 25], the impact of solid indenters on a heterogeneous soil [1, 2,14] as well as in solving problems of the impact of woodworking on wood [22, 31]. In this article, the authors consider the use of fracture mechanics methods as applied to group mechanical debarking of timber in a debarking drum.

2. Materials and methods

Considering in more detail the widely used technology of continuous drum debarking, the authors note the main physical mechanisms during the implementation of this process. Namely, the collision of logs with each other and the impact of logs on the drum wall, including when placing special debarking knives on the last [25]. According to the results of studies [29] in the process of drum debarking, five different zones can be distinguished within the processing space. The fourth zone - the collapse zone, and the fifth zone - the impact zone - are the most interesting from the standpoint of the mechanics of logs interaction in a debarking drum. In the fourth zone – the logs collide with each other, in the fifth zone...
they hit the drum wall or its inner working parts. In particular, during dry debarking, the impact loads and friction forces caused by the interaction of logs are insufficient for high-quality debarking of raw materials, and special bark-notching knives on the inner surface of the drum must be used [6]. This is due to the fact that the dry bark of trees has a high adhesion to the adjacent layer of wood. A stochastic model of the process of logs collisions in a drum was proposed in Heß (2012), where the quality of debarking is associated with the processing time of logs. Based on the binomial distribution of the number of impacts per elementary area $\Delta s$ for a period of time $t$, a relation is obtained for determining the mathematical expectation (M) of the quality of debarking:

$$M = 100 \left( 1 - \exp(-\lambda t) \sum_{n=0}^{\infty} \frac{(\lambda t)^n}{n!} \right),$$

(1)

where $\lambda$ – the intensity of the impacts or their average number received in one section $\Delta s$ per unit time. The value $N$ – fundamental ratio parameter (1) - depends on the strength of the impact $P$ and the characteristics of the bark.

Based on the theoretical positions of this model in [29], it is rightly noted that the parameters $N$ and $\lambda$ do not fully reflect such a complex process as group debarking and do not sufficiently take into account the patterns of impacts in a debarking drum in the summer and winter seasons.

In this regard, a mathematical model of layer-by-layer mixing of timber in a debarking drum at positive and negative temperatures was proposed [29]. The humidity content of the timber, its physical, mechanical and strength properties are taken into account not differentially, but integrally by introducing special parameters. Thus, the ratios (obtained in the course of studies to determine the speed of movement of the bark and wood) contain a dimensionless parameter $\theta$, which is called in [29] the degree of resistance of the bark element to impact, and which is equal to cyclic oscillation frequency during the impact. The number of impacts $N$ is taken equal to the ratio of the impact impulse $I$, N·s (necessary for the appearance of debarking spot with an area $\Delta s$) to the magnitude of the impact impulse $I_o$, N·s, arising from a single impact of a log in the process of its collapse in a rotating drum. $I_o$ is determined taking into account the characteristic dimensions of the log and drum, as well as the angle of inclination $\alpha$ of collapse surface. $I_o$ is ultimately established experimentally in the process of directly applying accentuated impacts to the log with the help of specially created installations. Summed values $\sum I_i$ and $\sum \Delta s$ are integral characteristics of the required power costs to achieve the set technological and quality goals of the debarking over its full period of time $T_o$. Total number of impacts $N_\Sigma$, to which the whole set of elementary areas is exposed $\Delta s_i$, is determined by the geometric parameters of pulpwod and drum and can be estimated using the ratio:

$$N_\Sigma = \frac{360}{\arccos \left( 1 - \frac{\frac{K_d^2}{2(1-K_i)^2}}{K_i} \right)}$$

(2)

Where, the coefficients $K_d$ and $K_i$ represent, respectively the ratio of diameters $d/D$ and lengths $l/L$.

3. Results and discussion

Figure 1a presents the dependence of the value $N_\Sigma$ on coefficient $K_d$ in the range of its change 0.035-0.077 and coefficient $K_i$ in the range of its change 0.13-0.52. As follows from fig. 1a, in the process of debarking materials, significantly different conditions are realized by the factor of the number of impacts $N_\Sigma$, moreover, with a decrease in the size of pulpwod, the number of impacts increases rapidly. Bark volume $\sum V_b$ in the drum depends on the drum volume $V_d$, its filling coefficient $k_f$, the share of the bark $k_b$ in the total phytomass of the trunk and the coefficient of full-wood log laying in the drum, which is shown in fig. 1b, and also depends on dimensionless coefficients $K_d$ and $K_i$.

Summarizing the results of studies [29], it should be noted that they expand the range of use of the stochastic model [11]. However, the process of collision of logs both among themselves and with the structural elements of the drum turned out to be beyond the scope of theoretical consideration. The magnitude of the impulse $I_o$ and the process of debark spot formation are advisable to evaluate from the point of view of the mechanics of contact fracture of bark and timber. The indicated approach was somewhat reflected in [26], in which, based on the equations of motion of the finite element model, the regularities of the change in the forces of contact interaction of pulpwod during its collision in the debarking drum were studied.

The authors [26] rightly notes that to determine such forces, data are needed on the pulpwod rigidity, which is established experimentally.

At the same time, the pulpwod, while interacting with the surface of the drum, experiences significant load due to the higher rigidity of the drum. In turn, the log itself experiences collision forces that are unequal in surface distribution and the process of their so-called “grinding” is observed in its end parts. The main scientific result [26] is the forecast of the volume of pulpwod, during the processing of which the force of collisions may be insufficient for high-quality debarking of wood.

The indicated parameters, as evidenced by the results of studies [6] in relation to mechanical debarking using both blunt pickers and cutters, have a significant impact on all ongoing processes of separation of bark from wood. It should be assumed that this influence is also significant in the impact interaction of logs, both between themselves and with the
drum, which may contain special devices and knives to improve the quality of debarking in difficult processing conditions.

Log as a set of cylinders with diameter and height \(d\) is presented as a set of layers equal by volume with diameter \(D_{lr}\) = \(d_{5,1}\). The number of layers per log is equal to the integer part plus the unit of the ratio of log volume \(V_l\) to the volume of the layer \(V_{lr}\). Let us call two extreme layers - end layers, the rest - internal. All layers of logs are accepted as soft in comparison to the hard surface of the drum.

Let us single out (Fig. 2a) the main schemes for the interaction of soft layers with the surface of the drum, which, in turn, is considered as a hard layer \(D_h\) with infinitely large diameter \(D_h = \infty\):
- scheme I: «\(D_{lr} – D_{lr}\)» – the interaction of two soft layers;
- scheme II: «\(D_{lr} – D_h\)» - the interaction of soft and hard layers;
- scheme III «\(D_{lr} – D_{hu}\)» – interaction of a soft sphere with a hard one, on the surface of which a knife is fixed.

The presented schemes are considered in the framework of quasistatic representation of impact interaction of two spherical contacting bodies \[18\]. To justify the mathematical model and assess its adequacy, while comparing with experimental data \[29\], the authors consider Scheme II (Fig. 2b).

When impact force \(P\) is applied, the main geometric parameters of the contact spot (its depth and radius) are the values of the contact approach \(h\) and the radius of the contact area \(a\). These parameters are functionally interconnected. However, impact processes in the mechanics of contact fracture \[18\] are calculated precisely using the approach value \(h\). From the point of view of debarking quality, the authors are interested in cleaning wood to the full depth of the bark. Therefore, the parameter \(h\) is taken as the main geometric characteristic of the contact. The authors assume \[18\] that, as the debarking spot forms, the contact force \(F\) grows and is defined as follows:

\[
F = k h^2, \quad (3)
\]

where the proportionality coefficient \(k\) depends on the elastoplastic characteristics of the soft layer (Young's modulus \(E\) and Poisson's ratio \(\mu\)) and its diameter \(D_{lr}\):

\[
k = \frac{4 E \sqrt{D_{lr} / 2}}{3(1 - \mu^2)} \quad (4)
\]

The differential equation of motion at the contact boundary (during the development of the debarking spot deep into the bark mass) takes the following form:

\[
\frac{dh}{d\tau} = \sqrt{\frac{v^2 - 4 k h v^2}{m}} \quad (5)
\]

where \(v\) - the speed of movement of a log of mass \(m\) at the moment of impact.
Highest value $h=h_0$ is achieved at a time when the approach speed $\frac{dh}{dt} = 0$, whence the value of maximum contact approach from a single impact is equal to:

$$h_0 = \left( \frac{5}{4\pi} \rho v^2 \right)^{\frac{1}{5}}.$$  \hspace{1cm} (6)

Total impact duration $r=r_0$ is as follows:

$$r_0 = 3.2 \left( \frac{m^2}{\rho v} \right)^{\frac{1}{5}}.$$  \hspace{1cm} (7)

Integration of differential equation (5), taking into account (6), under the following initial conditions: in the moment $r=0$, an approach $h=0$ allows getting the function of the change in time of contact approach $h=h(t)$:

$$h = h_0 \sin \left( \frac{\sqrt{\mu^2 - \frac{1}{\pi^2}}}{2,94 h_0} \right).$$  \hspace{1cm} (8)

which is considered in the increase section $h$ from 0 to $h_0$.

The radius of the contact area $a$ depends on $h$ and is described by the relation:

$$a = k \sqrt{ \frac{1}{E} \left( h - h_0 \right)^2 \frac{1}{h_0}}.$$  \hspace{1cm} (9)

Impact force $P$ is calculated as follows: first, from the law of conservation of energy, we determine the value $v=(2qH)^{0.5}$, where $H$ — log collapse height (maximum value $H=4.3$ m), and from the law of conservation of motion impulses, we take force $P=mv/r_0$, while $r_0$ is determined from (7).

The calculations using relations (3), (9) were performed in such a way as to take into account the experimental data to the maximum extent [29], in particular, in relation to the conditions for processing summer pine pulpwood with humidity $W=40-60\%$, diameter $d=0.12$ m, length $l=2$ m, in a debarking drum with a diameter $D=2.2$ m and length $L=4.3$ m. With this diameter of the log, the thickness of the pine bark is accepted as $h_0=0.02$ m. The physical mechanical properties of pine bark were taken according to [16, 19, 30], taking into account the effect of humidity $W$ on the change in bark density $\rho_b$. Thus, for dry bark with $W=10\%$, the value of $\rho_b=370$ kg/m$^3$, with $W=40-60\%$ density increases to $\rho_b=687$ kg/m$^3$. Then the mass of the log reaches $m=15.55$ kg.

Calculations show that at the moment of impact the collision velocity was $v=6.39$ m/s, and the duration of the impact - $r=9.62$ ms. Contact force reached $P=10.32$ kN and ensured the achievement of maximum depth of contact approach $h_0=0.021$ m, exceeding the thickness of the bark $h_0$, i.e., in this case, the condition is achieved $h_0 \geq h_0$. Fig. 3 shows the dependences of the change in time $h(t)$ and $a(t)$. As can be seen, the contact approach in $z$ direction lags behind the development of the contact area in the radial direction $r$ (Fig. 2b). If shear loads $q_z$, occurring in the bark mass during impacts, are sufficient for its destruction, then it can be assumed that there will be a separation of this section to the maximum depth $h_0$. Given that $h_0 \leq a$ at any $r$, the sizes of destructible areas will be evaluated through the value $h$ (description below). The value of the average vertical pressure $q_z$, in the impact interaction of layers (Fig. 2 b), is defined through the parameters $h$ and $D_0$ [8,13]:

$$q_z = \frac{P}{\pi h_0 D_0}.$$  \hspace{1cm} (10)

The value of the radial (horizontal) pressure with a sufficient degree of accuracy is determined through the mechanism of lateral strut[7]:

$$q_r = - \frac{V}{1-v} q_z,$$  \hspace{1cm} (11)

after which the shear pressure $q_s$ on the element of the bark is defined as the reduced pressure:

$$q_s = \sqrt{q_r^2 + q_z^2}.$$  \hspace{1cm} (12)

Fig. 4 shows the dependence of change over time $q_s(t)$ (calculations are made at $\mu=0.25$ and $E=33.29$ MPa) of timber (established through correlation of those parameters) with specified physical and mechanical characteristics [16,19,30]. Comparing the obtained values $q_s$ with the ultimate strength of the non-frozen pine bark for chipping $\sigma_{ch}=0.33$ MPa [3],

![Figure 3. Change of contact approach values and the radius of the contact area in time of impact: 1 - $h(t)$; 2 - $a(t)$](image1)

![Figure 4. Change in time of impact of reduced pressure in the massif of the summer pine bark](image2)
it can be concluded that from the initial moment of impact until the maximum approach is reached, the following condition is met:

$$q_i \geq \sigma_{ch}$$

(13)
i.e. to the full depth of approach $h_o$, the area with the size $\Delta s = \pi h_o^2 = 1385 \times 10^{-6}$ m$^2$ will be completely barked. The magnitude of the impact impulse in this case is $I_I = 99.34$ Ns.

It is appropriate to note that for frozen pine pulpwood, the value $\sigma_{ch} \geq 1.1$ MPa [3] and grows to 1.8 MPa with decreasing temperature to $T = 20^\circ C$. This means that under such conditions, the set values $q_i$ are not sufficient to implement the shear mechanism within the elementary area and do not provide proper debarking of this section of the bark. In this case, it is necessary either to increase the force effect, including the use of special knives (Scheme III in Fig. 2a) or to improve the condition of the pulpwood by treating it with steam or hot water in order to reduce the value $\sigma_{ch}$ to the required level. In both cases, this requires additional costs, and when using knives, it leads to an increase in wood loss and “fringing” of the end parts of the logs.

The effect of temperature on the cohesion forces of the bark and the processes of its destruction are considered in detail in [23], and the features of contact destruction in the case of static indenter penetration are described in [6].

Returning to the analysis of the processing conditions for summer pine pulpwood when condition (13) is met, we see that for debarking an elementary section, one hit on a hard surface of the drum is enough. The total volume of bark in the processed pulpwood for these calculation conditions was $\sum V_s = 0.059$ m$^3$ with the following values of technological coefficients: $k_s = 0.5$, $k_h = 0.15$ and $K_h = 0.36$.

The maximum possible volume of the destroyed bark within the contact zone as a result of a single impact is $V_s = \pi h_o^2 = 127 \times 10^{-6}$ m$^3$, i.e. minimum number of impacts for all elementary pulpwood areas $N_s = 465$, which is in satisfactory agreement with the data in Fig. 1 a, at the value of the coefficients $K_f = 0.055$ and $K_f = 0.47$.

Let us compare the results obtained with the experimental data [29], which show that for debarking of similar pulpwood, one hit on the elementary part of the bark is also sufficient with the magnitude of the impact impulse $I_I = 106$ Ns with the formation of a barking spot $\Delta s = 1486 \times 10^{-6}$ m$^2$. Theoretical calculations are consistent with experimental data - relative error $\delta$ when evaluating the impulse is 6.7%, when evaluating spot sizes $\delta$ is 7.3%.

Let us perform a similar calculation for the debarking conditions of aspen summer pulpwood with bark density $\rho_b = 758$ kg/m$^3$ at $W = 40\text{-}60\%$ and thickness $h_o = 0.05$ m. Elastic-plastic characteristics: $\mu = 0.25$, $E = 146.83$ MPa. The mass of the logs will be $m = 17.15$ kg, the impact time $t_s = 5.52$ ms at maximum strength $P = 19.82$ kN and impact impulse $I_I = 109.5$ Ns.

![Figure 5](image-url). The changes in contact approach (1) and reduced pressure (2)

The calculated data, similar to the data in Fig. 3 and 4 are combined and presented in Fig. 5 at the same time scale ($t$) and combined scale: curve 1 - $h(t)$ in cm and curve 2 – $q_i(t)$ in MPa. As can be seen, the maximum contact approach is $h_o = 0.0112$ m, and the value $q_i$ has reached 1.26 MPa, but at the same time exceeded the value of the strength characteristics of the non-frozen aspen bark in the entire range of its change $\sigma_{ch} = 0.79$ MPa. For the frozen aspen bark already at $T \leq 10^\circ C$ value $\sigma_{ch} \geq 1.6$ MPa. Thus, for summer conditions of aspen logs processing, destruction within the elementary area $\Delta s = 456 \times 10^{-6}$ m$^2$ to the depth $h_o$ will occur likewise as when debarking pine. At the same time, in one impact, the cleaning of the bark massif will be carried out only to a depth $h_o = 1.12$ cm and for debarking pulpwood to full depth, $h_o = 5$ cm, at least $N = 5$ impacts will be needed. At this stage of the justification of the mathematical model, the authors will not take into account the mechanisms of bark compaction during cyclic impact interaction with the rigid surface of the drum (indenter). That is, the authors accept that on each new cycle the impact process is reproduced in full.

Then: $\sum I_I = \sum I_I = 548$ Ns and $\sum \Delta s = \sum \Delta s = 2284 \times 10^{-6}$ m$^2$.

The obtained results are compared with the experimental data [29] for debarking aspen logs under similar conditions, where the following indicators of bark destruction are established: $N = 7$, $\sum I_I = 630$ Ns ($\delta = 14.96\%$) and $\sum \Delta s = 2350 \times 10^{-6}$ m$^2$ ($\delta = 2.89\%$).

Comparing the calculation errors during debarking of pine and aspen logs, it is seen that during mechanical reproduction of impact processes, higher discrepancies between theoretical and experimental data are observed. However, the calculation results should be considered satisfactory. Further, to determine the required number of impacts $N$ and increase the accuracy of estimates, the mathematical model should include the following:

- the features of bark destruction under cyclic loads;
- bark compaction;
- a change in the elastic-plastic and strength properties.
The mathematical model developed above describes the process allows us to examine in more detail the proposed schemes of impact interaction I-III (Fig. 2a) for various technological conditions of group timber debarking. In particular, when debarking frozen logs from various species of trees, which is a complex and labor-intensive technological process. One of the main indicators of group timber processing is the duration of debarking \( T_d \). Winter pulpwod processing is characterized by an increase in \( T_d \) due to a significant (2-3 or more times) increase in ultimate strength \( (\sigma_{bl}) \) of bark on winter pulpwod chipping compared to summer one. In practice, this leads to a number of negative consequences - an increase in wood losses with an increase in total costs, skewing, fringing of the ends of the logs, etc. In order to intensify the processes of separation of bark from wood at low temperatures \( (T) \), special knives on the drum surface are used, which, along with the achieved positive effect, cause additional destruction of the wood, which reduces the efficiency of the debarking process.

The intensity of wood removal from bark, the quality of debarking and the loss of wood during drum debarking depend on the necessary and sufficient number of impacts \( (N) \), force \( P \) on a log of a certain diameter \( (d) \) and length \( (L) \) for a period of time \( (t) \) in a drum, whose diameter and length are respectively \( D \) and \( L \).

Values \( N \) and \( P \) in turn, depend on the physicomechanical, structural and strength properties of the raw materials, their condition (humidity \( W \) and temperature \( T \)), as well as the capacity of the drum, the degree of loading and angular velocity of rotation \( \omega \) (number \( n \) of rotations), determining speed in aggregate \( (v) \) collisions of logs as between themselves and with structural elements of the drum. As a result of studies[29] in the framework of the mathematical model of layer-by-layer mixing of wood in debarking drum at positive and negative temperatures to determine the necessary debarking time \( T_d \), a relation is obtained that can be structurally represented as a complex function:

\[
T_d = f_i(N, D, L) f_3(D, K) ,
\]

where

\[
f_i(N, D, L) = \frac{8n\Delta s}{100} \frac{1}{\alpha \ln \left( 100 \frac{K^2 + K - 1}{100 - K} \right)},
\]

\[
f_3(D, K) = \frac{N.K}{100}
\]

moderately, the parameter

\[
\alpha = \frac{N.K}{100}
\]

average number of impacts during debarking \( T_{in} \).

\[
f_3(D, K) \text{, } i=1, 2, 3, 4, \text{ - dimensionless coefficient function: drum filling } (K1), \text{ shares of bark in the total phytomass of a tree trunk } (K3), \text{ the relationship of the thickness of the bark and the diameter of the log } (K4).
\]

An analysis of relations (14) (16) shows that the main physicomechanical characteristics of the impact process during group debarking are parameters \( N \) and \( \Delta s \), which in [29] are determined in the course of experimental work on a special installation. Theoretical studies of impact processes based on the provisions of contact fracture mechanics were performed earlier and described in [19]. Where it was established that the final parameters \( N \) and \( \Delta s \) depend on the ratio between the thickness of the bark \( h_b \) and the maximum depth of the zone of contact approach \( h_a \) (fig. 2).

From the considered basic schemes (Fig. 2a) of logs interaction (soft layers with a diameter \( D_h \) ) with a drum surface (a hard layer with an infinitely large diameter \( D_h=\infty \), incl. layer \( D_{cu} \), equipped with a knife - a solid indenter), at the first stage of research, the authors consider Scheme II with a smooth surface for a debarking drum. The mathematical model of Scheme II is based on the solution of quasistatic problems of impact interaction of two spherical contacting bodies [18]. Under the impact with force \( P \), the main geometric parameters of the contact spot (its depth and radius) are the contact approach \( h \) and contact area radius \( a \). In that case (Fig. 1b), if under the action of a force \( P \), within the contact spot size \( \Delta s=\pi h_b^2 \), shear force \( q_s \) is formed, not less than \( \sigma_{bl} \) over depth \( h_b \), then there is an effective process of separating the bark from the wood to full depth \( h_b \).

**Figure 6.** Dependencies \( \Delta s \) from \( \sigma_{bl} \) for bark: a – pine tree; b – aspen.
The temperature $T$ effects value of ultimate strength $\sigma_{ch}$ and, as a result, the process of forming the depth of contact approach $h_o$. These studies were carried out on the basis of data [3] in accordance with the provisions of [16,18,30] on the influence of the temperature factor $T$ on the change in the properties of the bark and its destruction process. Fig. 6 shows the dependences $\Delta s$ from $\sigma_{ch}$ obtained during mathematical modeling for pine and aspen bark. Established exponential nature $\Delta s(\sigma_{ch})$ indicates that during group debarking of frozen pulpwood in the process of impact interaction of logs, the destruction volumes sharply decrease. As a result of which the number of necessary impacts for cleaning the elementary section of wood from the bark will increase. This conclusion was confirmed when evaluating the dependence of the parameter $N(T)$ for the following conditions of debarking pulpwood from pine and aspen [25]: $d=0.12$ m, $l=2$m, $D=2.2$ m, $L=4.3$ m, $n=10$ rpm, $K_1=0.5$, $K_2=0.1$ for pine and $K_2=0.18$ for aspen, $K_3=0.35$, $K_4=0.0175$ for pine and $K_4=0.0415$ for aspen. The set quality is assumed constant and equal $K=90\%$.

![Figure 7](image_url)  
**Figure 7.** The required amount of logs’ impacts according to pulpwood temperatures

As can be seen, when processing frozen pulpwood, the duration of logs’ impact interaction increases by several times, which requires a corresponding increase in technological time $T_o$ of materials’ debarking, taking into account the quality of their processing.

![Figure 8](image_url)  
**Figure 8.** Dependence of debarking time on the temperature of pulpwood: 1 - pine; 2 – aspen

Fig. 8 presents the dependence of debarking time $T_o$ on the temperature $T$, when debarking pine and aspen with a given quality $K=90\%$. From fig. 8 it follows that in the group debarking of frozen pulpwood, both from pine and aspen, the parameter $T_o$ significantly increases with decreasing $T$. In particular, when debarking aspen at temperatures below -10 $^\circ$C, this parameter exceeds the value $T_o=60$ min. Higher debarking quality requirements also require longer $T_o$. Fig. 9 presents the dependence of pine pulpwood debarking time $T_o$ on debarking quality $K$ and pulpwood temperature $T$. A comparative analysis of the data in Fig. 9 and curve 1 in Fig. 8 allows evaluating the degree of increase in the parameter $T_o$ with changing $K$ and $T$.

Fig. 8 and 9 allow estimating the dependence of $T_o(K, T)$ for debarking aspen pulpwood. In this case, the values of $T_o$ on average increase in 1.4-1.6 times compared with similar conditions for debarking pine pulpwood.

The high-quality debarking of frozen pulpwood is very time-consuming and hence costly. It was noted above that under these conditions, in the debarking process, special knives are used on the surface of the drum (Scheme III in Fig. 2 a). In this regard, at the second stage of research, the authors consider the process of impact interaction of a bark mass (with thickness $h_o$) with a knife, placed on the surface of the drum. Let us assume that the knife has a sharpening angle (sharpening) $\phi_1$ and interacts with the surface of the bark at an angle $\phi_2=\pi-\phi_1/2$.

![Figure 9](image_url)  
**Figure 9.** The dependence of the time of debarking of pine pulpwood on the temperature and quality of the latter
In [27], the Boussinesq quasistatic problem was solved of introducing a solid indenter (cone, pyramid, wedge) into a flexible elastic bark mass with milling technologies for processing timber. In a flat setting in the system of normal (vertical) \( z \) and radial (horizontal) \( r \) coordinates, the values of the corresponding axial pressures were determined - \( q_z \) and \( q_r \), after which the value of the resulting reduced pressure was established \( q_o \), causing the destruction of the elementary layer of the bark to the maximum depth of contact approach \( h_o \). Using the methodological provisions [27], let us establish the regularities of the influence of the knife sharpening angle \( \phi_1 \) on the value of reduced pressure \( q_o \).

Vertical pressure \( q_z \) is defined in the following form:

\[
q_z = -\frac{q_o f(z_0, \rho)}{2(1 - \nu^2)},
\]

where \( f(z, \rho) = 2 \)-d function of dimensionless coordinates - vertical \( z = \frac{z}{h_o} \) and horizontal \( \rho = \frac{\rho}{h_o} \):

\[
f(z, \rho) = 0.5 \ln \left( \frac{b_2 + 2b_0b_1 \cos(\beta - \alpha) + b_1^2}{\sqrt{z^2 + \rho^2} + 1 - \frac{1}{\sqrt{z^2 + \rho^2}} \cos \alpha} \right).
\]

Values \( b_0, b_1, \alpha \) and \( \beta \), included in (18), are determined by the ratios:

\[
b_1 = 1 + z^2; \quad b_0 = (z^2 + \rho^2 - 1)^2 + 4z^2; \quad \varphi_0 \beta = 1; \quad (z^2 + \rho^2 - 1)g \alpha = 2z.
\]

Initial contact pressure \( q_o \) is determined as:

\[
q_o = \frac{3k}{\pi D_0} \left( \frac{5mv^2}{4k} \right)^{1/5}
\]

where \( E \) - Young's modulus, \( \mu \) - Poisson's ratio, \( m \) - log's mass and \( v \) - the speed of its impact.

Horizontal pressure \( q_r \) is defined through the side thrust mechanism:

\[
sr = -\frac{v}{1-\nu} sr_z
\]

after which the shear pressure \( q_s \) on the bark element is defined as the reduced pressure:

\[
q_s = \sqrt{q_z^2 + q_r^2}
\]

The results of the studies for pine and aspen are presented in Fig. 10.

Curve 1 in Fig. 10 reflects the dependence of the dimensionless coefficient \( k_o \) that characterizes the growth of \( q_o \) as the angle decreases \( \phi_1 \) from 90° (drum surface does not contain knives) to 10° (sharp wedge). Curve 2 reflects the dependence of the dimensionless coefficient \( k_o \) that characterizes the growth of \( h_o \) with a similar decrease in angle \( \phi_1 \). Fig. 10 indicates that the use of knives leads to a significant (up to 3 or more times) increase in contact pressure and almost doubles the maximum dimensions of contact approach. This, in turn, contributes to an increase in the size of the contact area \( \Delta s \). Identified growth trend of \( \Delta s \), when using special knives in accordance with formula (15), leads to a corresponding reduction in debarking time \( T_o \). Fig. 11 shows studies of the degree of this influence and the performed calculations for conditions for aspen pulpwood debarking without using knives and with their use at an angle of sharpening 30°.

During the experiments, a specially created setup was used [17]. It included an indenter of mass \( m \), rigidly connected to the rod, which, while falling, struck a sample of wood. Two options were considered: with a fixed sample and with a free impact. Indenter material - St5 (steel). Indenter mass \( m \) and sharpening angle \( \alpha \) ranged from 1 to 9 kg and from 15 to 75°, respectively. After the impact, the penetration depth of the indenter \( h \) and the width of the scar \( b \) (left by the indenter) were measured (with an accuracy of 0.02 mm) by a trammel. The obtained values were rounded to tenths of a millimeter. The experiments were carried out for pine and aspen samples at a temperature of -5 and 20 °C. The results of experimental studies showed good quantitative and qualitative coincidences with the results of studies of the developed mathematical model (see Fig. 10). According to the research data of the developed mathematical model, ceteris paribus, the ratio of the difference in the depth of penetration of the indenter into the bark mass (depending on

![Figure 10](image-url)  
**Figure 10.** The influence of the angle of knife sharpening on the parameters of contact destruction of the bark

![Figure 11](image-url)  
**Figure 11.** Debarking time for aspen pulpwood: 1 - using knives; 2 – without using knives
the sharpening angle) is 1.94 times, with a change in the sharpening angle from 15 to 75°. Laboratory test results showed a difference of 2.27 times, which gives a difference of less than 7%. This suggests that the developed mathematical model is adequate to the object of study.

4. Conclusions

As a result of the above theoretical studies of the process of group mechanical debarking of timber in debarking drums, the following conclusions can be drawn:

1. The magnitude of the shear pressure of the elementary section of the bark decreases in time in accordance with the power function, and for a fairly short period of time (not more than 0.5 ms), the pressure changes by 80%.
2. The exponential nature of the decrease in the size of the debarking spot has been established with the increase in wood's ultimate strength, while the sizes of the spots of fragile wood are 2.5-3 times larger than the corresponding spots in high-strength wood.
3. When revealing the features of frozen pulpwod debarking, it was found that with decreasing temperature from 0 to -30 °C, the debarking time of pines increases from 8 to 60 minutes, and aspen - from 25 to 90 minutes.
4. The data of theoretical studies indicate that the use of special knives on the surface of the debarking drum leads to a significant (up to 3 or more times) increase in contact pressure. The use of knives also almost doubles the maximum dimensions of contact approach, which leads to a corresponding increase in the size of the contact spot.
5. Mathematical modeling of the debarking process shows that the use of knives reduces the time of pulpwod processing in average in 1.5-2 times, increases the efficiency of technological processes and reduces the total cost of debarking.

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