UDC 634.5
DOI: 10.15587/2706-5448.2025.329722

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JUSTIFICATION OF THE PARAMETERS OF THE ACTIVE CONICAL WOOD DEFORMER

The object of research is the parameters of mechanisms for the destruction of anisotropic materials by a conical mechanical deformer. One of the known renewable energy sources is a material of plant origin (wood). Based on this, the search for optimal operating parameters and design features of working bodies for mechanized splitting of logs is relevant. Therefore, a new solution to the scientific problem is proposed, which consists in substantiating the main geometric parameters of an active conical deformer for splitting logs from wood at the lowest energy costs for its drive.

The analysis conducted during the study showed a general positive feature of the principle of operation, in which the penetration of an active deformer of a conical shape perpendicular to wood fibers facilitates the destruction of their ties and has a more promising and productive design. A mathematical model for determining the force required to destroy a log of wood has been developed. The specified dependence takes into account the elastic characteristics of the material, the forces that exist between the fibers of anisotropic substance, the friction forces between the deformer material and wood, and its geometric parameters. It was determined that the necessary value that characterizes the physical and mechanical properties of wood is the force required to destroy the bonds between the fibers (coefficient of longitudinal destruction). Therefore, the values of the coefficient of longitudinal destruction were experimentally obtained, which were for pine – 2533 ± 66 N/m, oak – 5583 ± 145 N/m and aspen – 5000 ± 279 N/m.

According to the research results, analytical recommendations for the geometric parameters of the active deformer were obtained. For pine material with a diameter of 0.15 m, the optimal cone length is in the range of 0.02–0.20 m at a cone angle of 20–90°. At the same time, the theoretical force for its destruction is 568–864 N. Similar results were also obtained for aspen and oak materials. This provides the opportunity to design the design of a conical wood deformer according to the specified ranges, which are optimal for each material or their groups.

Keywords: *technology, biomass, wood, active deformer, anisotropic material, splitting, destruction force.*

Received: 07.02.2025
Received in revised form: 05.04.2025
Accepted: 27.04.2025
Published: 16.05.2025

How to cite
Padalka, V., Gorbenko, O., Ivankova, O., Dudnyk, V., Horiunov, B. (2025). Justification of the parameters of the active conical wood deformer. Technology Audit and Production Reserves, 3 (1 (83)), 46–51. https://doi.org/10.15587/2706-5448.2025.329722

1. Introduction

One of the main global challenges that exist in today's conditions is energy independence. As practice shows, the economic stability and security of the state directly depend on the ability to meet the needs of production and the social sphere with energy sources for the creation of goods and products, services. Ukraine, as a technologically productive state, balances between energy independence and increasing energy consumption of production [1, 2]. The national social sphere is constantly in search of an independent and efficient source of energy that would allow overcoming the challenges inherent in global production processes in the energy sector.

One of the well-known renewable energy sources [3] is plant material (wood). Unfairly forgotten in the era of gas industrialization, it has recently returned to private homes and small businesses, providing a sufficient and worthy replacement for fossil fuels. To obtain thermal energy, various forms of wood are used: logs, pellets, fragmented parts (logs) of the trunk and branches, residues of wood processing production, etc. The technologies for manufacturing fuel cells are mainly mechanized and have been generally studied by both scientists and practitioners. The search for optimal operating parameters and design features of working bodies for mechanized splitting of logs is an urgent scientific task. Its solution will allow designers and practitioners to manufacture such machines and obtain the lowest energy costs for their operation. The process of splitting anisotropic materials was studied in [4]. The described natural process of splitting tree branches turned out to be more complicated than the authors assumed. They studied the process of longitudinal splitting of fibers that are held together by the corresponding forces. It was found that this is not enough to maintain the integrity of the structure after their external mechanical destruction. The mechanism of strengthening wooden forks with additional devices to obtain restored natural contacts was considered. Theoretical description and experimental studies performed to maintain the strength of the structure are used in the work to study the process of splitting wood logs.

Scientific explorations [5] are aimed at determining the influence of the anatomy and density of wood on the process of destruction with the corresponding applied forces applied in geometric space relative to the longitudinal arrangement of the fibers of the material. Using electronic research tools, the authors substantiated the causes of fracture of samples and their differences depending on the species and physicomechanical properties of the material. The research methodology proposed by them, which was carried out at the energy level, was partially used in this experiment to determine the destruction of forces between wood fibers.

The process of crack formation in brittle materials was studied in the works [6]. The general theory of crack development in the material put forward by them was considered in conditions of stability to the selected limitations and criteria. A monotonic increase in the force on the fracture leads to the prediction of the direction of the split. The proposed cyclic loading method is of scientific interest when considering the theoretical provisions of the destruction of anisotropic substances with a fibrous structure and structure during the gradual impact of a conical deformer on a wooden log.

Scientific studies of the properties of beams made of wood [7] have shown a significant influence of their spatial arrangement on strength. Wood branches withstand bending due to the elasticity of the fibers and the forces that exist between the fibers of their structure. The authors studied the critical states of the material that exist in building beams for their strength. In our study, the strength criteria, and especially the forces that arise between the fibers of the material, are basic for establishing the energy characteristics of the destruction of logs of different diameters and in the presence of structural inclusions, etc.

The mechanics of a material that can withstand controlled division into several parts is described in studies [8]. Cutting or felling allows to assess the energy aspects of the processes accordingly. Crack formation in materials of different origins is considered from the standpoint of their strength. The physical and mechanical properties and their influence on the fracture of biological material with an anisotropic structure are taken into account in the further scientific hypothesis of the fracture mechanics of fibrous materials.

Modeling the bearing capacity of wooden structures of various profiles was studied in the work [9]. The principles of linear and nonlinear fracture mechanics are proposed, and the limitations of their application are described. The considered principles of research were taken into account when constructing the energy laws of the fracture of wood logs and the rupture of bonds between fibers in the longitudinal direction.

The heterogeneity of the wood structure is considered in the scientific work [10]. The influence of wood species, structural features and natural defects, physical and mechanical features that affect the overall strength of structures were studied using original methods of mechanical destruction and methods for evaluating their results. The energy indicators of material destruction at the microscopic level were established. The applied methods were taken into account when planning experimental studies of the indicators of material resistance to splitting.

The strength indicators of reinforced materials, which are similar to the structure of wood in terms of process physics, were studied in [11–13]. Original methods of planning and conducting experimental studies are described, the advantages and disadvantages of the proposed technological features of their conduct are determined, taking into account the specific gravity and some other parameters.

The scientific paper [14] presents a methodology for testing the strength and destruction of samples with various shapes. The energy indicators of the processes and the directions of the distribution of internal stresses in wood fibers were determined. The formation and propagation of microcracks in anisotropic materials were reflected in the planning of an experiment to determine the physical and mechanical properties of wood materials.

The processes of deformation transition from plastic forms to wood destruction are described in works [15]. Using special research methods, the dependence of the process of stress creation and material deformation, the formation of cracks in wood was established.

Studies of processes performed by active working machines have become widespread in various applied fields [16–18]. Their results confirm the energy efficiency of implementation. The combination of types of oscillations in processes that describe the mechanical properties of materials has a high economic effect.

The process by which the destruction of anisotropic materials is described has been studied at the theoretical level in the works of scientists [8–14]. They are mainly aimed at studying processes occurring in anisotropic materials with a symmetrical arrangement of fibers or crystal chains (veneer, the process of wood planing, etc.). For the conditions of splitting a log made of plant material, let's consider and use a simplified theory of the course of the studied process [19].

The aim of research is to substantiate the main geometric parameters of an active conical deformer for splitting logs of wood origin with the lowest energy costs for its drive.

2. Materials and Methods

The object of research is the parameters of mechanisms for the destruction of anisotropic materials by a conical mechanical deformer (Fig. 1), which performs rotational motion and has applied helical spirals.

For the analysis, methods of mathematical analysis and statistical processing of experimental data were used.

Fig. 1. General view of the active conical deformer (prototype)

Scientific research does not sufficiently cover the material on determining the coefficients of longitudinal fracture of wood. It is proposed a methodology for laboratory research and its experimental determination for common types of such material. The research was conducted on the following samples: pine (*Pinus sylvestris*), oak (*Quercus robur*), aspen (*Populus tremula*).

To achieve the aim, a methodology for experimental research was proposed that takes into account the properties of wood materials of different species. The research methodology includes: justification of the design of the experimental wood sample, equipment for determining the studied indicator, methodology for determining and statistical processing of the results.

It was assumed that the wood sample should be rectangular in shape with a cutout that will serve as a concentrator of deformable stress and a programmable place of fracture of the sample along its fibers. The specified cutout is made in the direction that corresponds to the location of the wood fibers (Fig. 2).

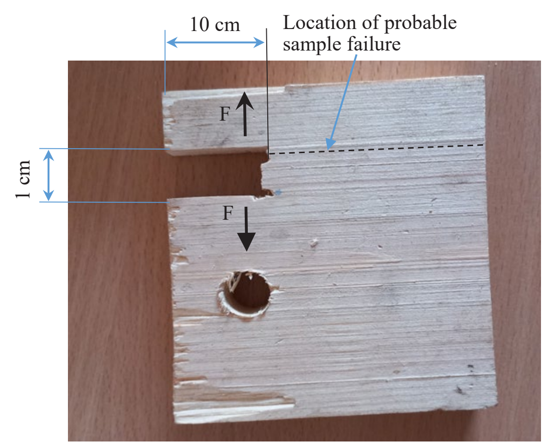

Fig. 2. A sample of the studied wood for determining the coefficient of longitudinal destruction measuring 18 × 18 cm

For the research, factors influencing their results were determined. The thickness of the sample and the material are the initial variable factors. Wood moisture, uneven structure, cracks and other defects were not included in the research tasks.

ISSN-L 2664-9969; E-ISSN 2706-5448

The coefficient of longitudinal destruction was determined by calculating the ratio of the maximum force (F) required to destroy the sample, applied to its opposite parts, shown in Fig. 1, and the thickness of the material to which the force is applied. The rupture of the sample parts is predicted along the Location of probable sample failure line.

The manufactured samples of different wood species were fixed on the УММ-20 testing machine with a mechanical load drive, which is designed for static tests of metal and other samples for tension, compression, bending and tight bending (Fig. 3). The device was set up and calibrated in accordance with the technical description and operating instructions for the electrical equipment.

Fig. 3. УММ-20 testing machine with a fixed wood sample

The experiments were conducted in six-fold repeatability for three types of wood [20].

3. Results and Discussion

The following assumptions were made for analytical modeling of the process. For the destruction of the beam, according to the energy concept, two types of destructive energy are used. One is applied through a conical deformer to rupture the anisotropic substance (wood) along the fiber and bend an imaginary beam of semicircular cross-section. The geometric designations of the quantities are shown in Fig. 4.

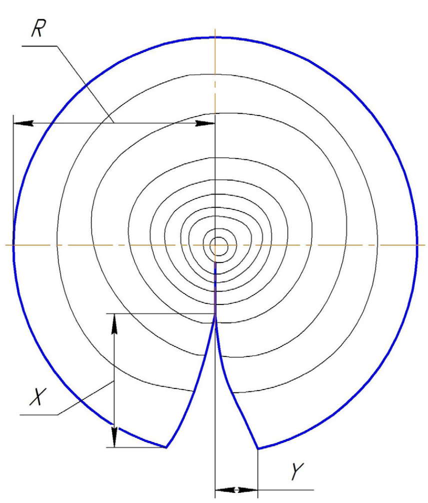

Fig. 4. Designation of geometric quantities on the log section (deformer not shown)

For mathematical modeling of the process, let's make some notations:

- R – wood log radius;
- X – crack length in the plane perpendicular to the log axis;
- Y – deflection of a beam part in the plane perpendicular to its axis;
- E_{reg} – energy required to split the beam;
- E_{bend} – energy for bending the semicircular part of the log in the direction opposite to its axis;
- E_{sum} – total energy for splitting the log.

The total energy required to split a log of wood is calculated by the expression

$$E_{sum} = E_{reg} + E_{bend}. \tag{1}$$

The fracture energy E_{reg} depends on the log radius R, the length of the resulting crack X and the radial coefficient of longitudinal fracture A_f

$$E_{reg} = 2R \cdot A_f \cdot X. \tag{2}$$

The energy required to bend the semicircular part of the log: (let's determine it from the assumption that the resulting particles deviate from the axis according to the law of a fixed beam and only its part is deformed)

$$E_{bend} = F \cdot Y. \tag{3}$$

The force F required to break an anisotropic material along the fibers can be determined by the expression

$$F = \frac{3E \cdot I \cdot Y}{X^3}, \tag{4}$$

where E – Young's modulus, X – crack length, Y – deflection of the beam part, I – moment of beam inertia of semicircular cross-section.

According to the obtained formulas, the total energy E_{sum} for splitting the log will have the expression

$$E_{sum} = 2R \cdot A_f \cdot X + \frac{3E \cdot I \cdot Y^2}{X^3}. \tag{5}$$

As a rule, obtaining optimal parameters of the wood splitting process occurs at a minimum total energy consumption. Therefore, the crack should propagate until the sum of these two forms of energy is minimized. The energy of deflection of the beam particles is obtained according to elastic laws and is partially used to increase the length X and width Y of the crack. In practice, having a formed crack, it is energetically more expedient to expand it due to the conical shape of the deformer

$$\frac{dE_{sum}}{dx} \to \min. \tag{6}$$

The total energy takes on a minimum value when the deformation energy relative to the crack length X is equal to zero

$$\frac{dE_{sum}}{dx} = 2R \cdot A_f + \frac{9E \cdot I \cdot Y^2}{X^4} = 0. \tag{7}$$

After performing the transformation, let's obtain

$$X = \left(\frac{9E \cdot I \cdot Y^2}{2R \cdot A_f} \right)^{1/4}. \tag{8}$$

The moment of inertia of a semicircular beam is determined from the expression

$$I=\frac{9\pi^2-64}{72\pi}R^4\approx 0.109R^4. \quad (9)$$

Let's obtain the expression for the crack length

$$X=0.838\left(\frac{E\cdot R^3\cdot Y^2}{A_f}\right)^{1/4}. \quad (10)$$

The force F required to split a log is determined from the expression

$$F=0.559\left(\frac{E\cdot R^7\cdot A_f^{\,3}}{Y^2}\right)^{1/4}. \quad (11)$$

The obtained force expression naturally increases with increasing log size, increasing the coefficient of longitudinal destruction for a certain type of wood and decreases by the square root of the length of the formed crack.

In practice, when a round log is split into two semicircles, they do not have plastic deformation and deviate from the axis by an angle of 2α (Fig. 5).

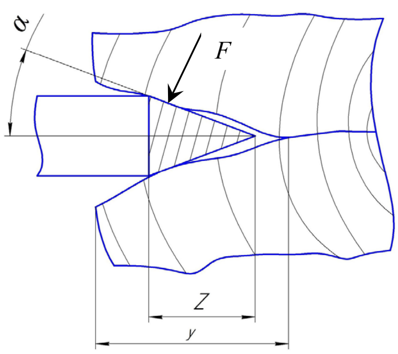

Fig. 5. Formation of a crack in a log when screwing in a conical deformer

The distance of deviation of the semicircular beam from the axis is determined from the expression

$$y=z\tan\alpha. \quad (12)$$

From the expression (9) the crack length X after penetration of the conical deformer will have the value

$$X=0.838\left(\frac{E\cdot R^3(z\tan\alpha)^2}{A_f}\right)^{1/4}. \quad (13)$$

The force P required to screw in a conical deformer into a log will be determined as the product of the forces required to split the log (10) and the friction force between the screw surface and the log material ($F_{Friction}$)

$$P=F\tan\alpha+F_{Frictoin}. \quad (14)$$

The friction force between the deformer surface and the log is directly dependent on the friction coefficient and the contact area (lateral surface)

$$F_{Frictoin}=F\cdot S_{lateralsurface}\mu, \quad (15)$$

where the contact area of the conical deformer with the wood surface

$$S_{lateralsurface}=\pi z^2\tan\alpha. \quad (16)$$

Considering that the conical crack formed in the material contacts only part of the deformer surface, and expression (11), the friction force $F_{Friction}$ will be determined from the expression

$$F_{Frictoin}=0.559\mu\left(E\cdot z^2R^7A_f^{\,3}\tan^2\alpha\right)^{1/4}. \quad (17)$$

The force P required to screw in a conical deformer into a log, taking into account expressions (13) and (17), will have the general form

$$P=0.559\left(\frac{E\cdot R^7\cdot A_f^{\,3}}{(z\tan\alpha)^2}\right)^{1/4}\tan\alpha+1.41\mu\left(E\cdot z^2R^7A_f^{\,3}\tan^2\alpha\right)^{1/4}. \quad (18)$$

The total force required to fracture an anisotropic substance (log) is directly dependent on the Young's Modulus (characterizes the elastic properties of anisotropic substances), the log diameter, the coefficients of longitudinal fracture and the geometric parameters of the conical deformer. The main components that affect its value are the force directed to the bending of the semicircular part of the beam and the friction force that arises as a result of screwing in the conical deformer made of metal and wood material.

The results of studies on determining the values of the coefficient of longitudinal fracture of wood are listed in Table 1.

Table 1

Results of laboratory determination of the values of the longitudinal fracture coefficient of wood

Wood type	Sample thickness, m	Destructive force F, N	Coefficient of longitudinal destruction, N/m	Average value, N/m	Average deviation
Pine	0.02	50	2500	2533	66
	0.02	50	2500		
	0.02	48	2400		
	0.02	53	2650		
	0.02	51	2550		
	0.02	52	2600		
Oak	0.016	90	5625	5583	145
	0.016	88	5500		
	0.016	95	5937		
	0.016	84	5250		
	0.016	89	5562		
	0.016	90	5625		
Aspen	0.02	100	5000	5000	279
	0.025	130	5200		
	0.025	141	5640		
	0.037	165	4459		
	0.024	120	5000		
	0.034	160	4705		

According to the results of laboratory research, it was found that under experimental conditions, the coefficient of longitudinal fracture of anisotropic material (wood) made of pine was 2533 ± 66 N/m, oak – 5583 ± 145 N/m, and aspen, respectively, 5000 ± 279 N/m.

The results of modeling the process of splitting logs (wood) are depicted in the form of graphs, which are made for the experimental conditions. In particular, the characteristics of the elasticity of anisotropic material in the longitudinal direction have the following values: $E=2$ MPa, $2R=0.15$ m, $\mu=0.03$, $A_f=2533$ N/m. Calculations were performed for the conditions of the deformer cone angle α (5–50°) and the length of the cone part z (0.01–0.20 m). Based on the research results, three-dimensional graphs of the distribution of the values of the indicators α, z on the material fracture force along the fiber and

ISSN-L 2664-9969; E-ISSN 2706-5448

a graph of the distribution of forces in the projections of the values of the indicators were constructed (Fig. 6).

Under the specified conditions of mathematical modeling of the process, it is possible to identify the zone of optimal ratio of the deformer cone angle and its length to the energy indicators of the process performance (Fig. 7).

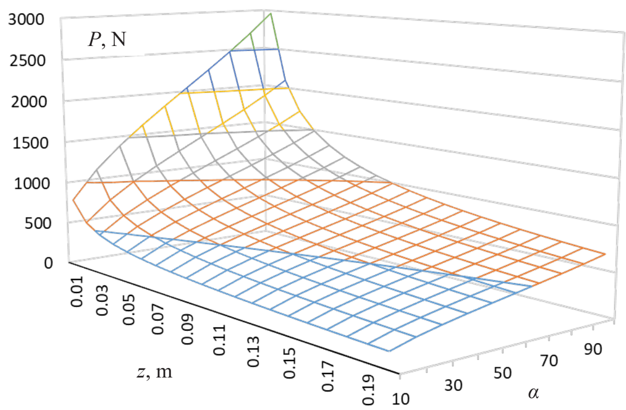

Fig. 6. Distribution of the force of wood destruction from the geometric parameters of the deformer α – cone angle and z – cone part length

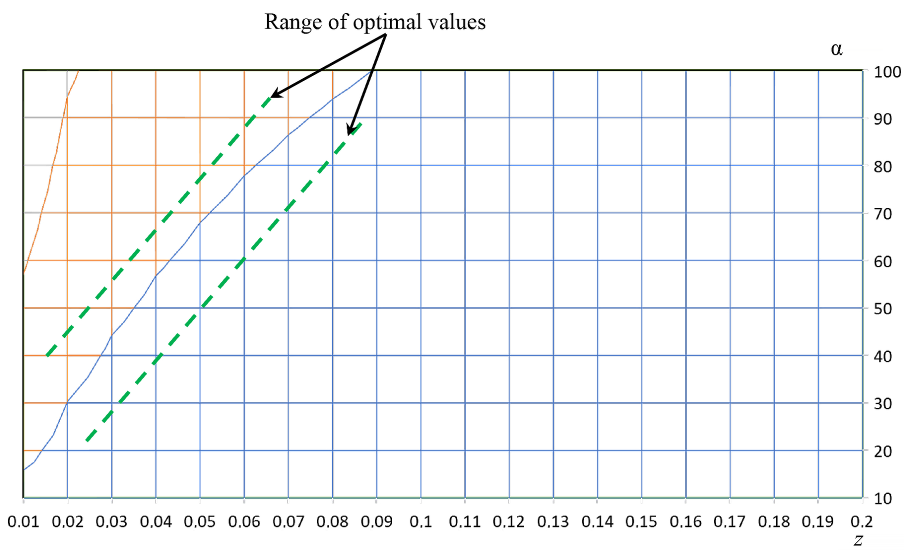

Fig. 7. Projection of the wood fracture force from the geometric parameters of the deformer α – cone angle and z – cone part length

Analysis of the obtained results allows to conclude that the geometric parameters of the conical deformer have a direct effect on the wood fracture force, which is associated with the mechanical properties of each of the studied wood species. Thus, the lower values of the forces for pine (568–864 N) are explained by its lower density and elasticity compared to hardwoods, in particular oak (945–987 N). Aspen demonstrates intermediate characteristics (840–973 N), which corresponds to its moderate density and flexibility.

These results confirm the general ideas about the physical and mechanical properties of wood, but differ from those known from the literature in that for the first time clear optimal ranges of the cone length and angle parameters have been established, which ensure the minimization of the fracture force for each individual type of wood. In most previous studies, similar parameters were considered from the point of view of their strength and stability of structures, applied load to products made of the mentioned materials.

An analysis of the structures of tools and their working bodies, which have practical implementation in wood splitting technologies, was carried out. The analysis showed a general positive feature of such a principle of operation, in which the penetration of an active conical deformer perpendicular to the wood fibers facilitates the destruction of their ties and has a more promising and productive design.

Using a simplified theory of the course of the studied process using the method of energy assessment of its performance indicators, a mathematical model for determining the force required to destroy a wooden log was developed. The specified dependence takes into account the elastic characteristics of the material, the forces that exist between the fibers of an anisotropic substance, the friction forces between the deformer material and wood, and its geometric parameters.

The necessary value characterizing the physical and mechanical properties of wood is the force required to destroy the bonds between the fibers (coefficient of longitudinal fracture).

A method for experimentally determining this value is proposed and the values obtained for the conditions of relative humidity of wood (≤ 12%). The obtained values of the coefficient of longitudinal fracture for pine are 2533 ± 66 N/m, oak – 5583 ± 145 N/m and aspen – 5000 ± 279 N/m. The proposed research methodology can be used to determine the specified coefficient for other materials and their properties.

According to the research results, analytical recommendations for the geometric parameters of the active deformer were obtained under experimental conditions. For pine material with a diameter of 0.15 m, the optimal cone length is in the range of 0.02–0.20 m at a cone angle of 20–90°. At the same time, the theoretical force for its destruction is 568–864 N. For material made of aspen, with a log diameter of 0.15 m, the optimal cone length range is 0.02–0.15 m at a cone angle of 20–75°. At the same time, the force for its destruction is 840–973 N. For material made of oak, with a log diameter of 0.15 m, the optimal cone length range is 0.02–0.15 m at a cone angle of 20–70°. At the same time, the force for its destruction is 945–987 N. Increasing the cone length by more than 0.07 m does not significantly affect the reduction of the fracture effort of most wood species. When the deformer cone angle is within 90°, the process of its penetration into the material at the initial stage is complicated.

From a practical point of view, the obtained results are important for design engineers of woodworking equipment. They can be used to develop adaptive wood splitting systems that automatically adjust to the wood species due to the variable deformer parameters. This allows to significantly increase production efficiency and reduce costs, as well as increase the reliability of mechanisms in industrial conditions. In addition, the developed recommendations can be integrated into training programs for training specialists in the logging and woodworking industries.

The research results have both theoretical and applied value, laying the foundation for further scientific research in the field of optimizing the designs of wood fracture mechanisms.

The main limitation of research is that the process of wood fracture was considered mainly along the fibers of anisotropic material. This limits the versatility of the proposed model. In addition, the study covers only three types of wood, which requires additional research for other types. The influence of wood moisture, which can significantly change the physical and mechanical characteristics of the material, was also not taken into account. In the future, it is advisable to expand the range of materials under study to include other types of wood and the influence of moisture on the process of wood destruction. It is also promising to create adaptive structures of deformers with the ability to adjust geometric parameters and surface characteristics for specific operating conditions and types of raw materials. A possible direction is the integration of the obtained results of model research into software for automated design.

4. Conclusions

A new solution to the scientific problem is proposed – justification of the optimal geometric parameters of an active conical deformer for effective splitting of wood with minimal energy consumption.

A mathematical model has been developed that describes the force required to destroy a log of wood, taking into account the anisotropic properties of the material, the friction force and the geometric parameters of the deformer.

A method for experimentally determining the coefficient of longitudinal destruction of wood has been proposed. The following coefficient values have been established for wood with a humidity of $\leq 12\%$: pine – 2533 ± 66 N/m, oak – 5583 ± 145 N/m, aspen – 5000 ± 279 N/m.

The optimal geometric parameters of the deformer have been determined. For deformation of pine ($\varnothing = 0.15$ m), the recommended cone length is 0.02–0.20 m, angle is 20–90°, and the force will be 568–864 N. For aspen ($\varnothing = 0.15$ m), the length is 0.02–0.15 m, angle is 20–75°, and the force is 840–973 N. For oak ($\varnothing = 0.15$ m), the length is 0.02–0.15 m, angle is 20–70°, and the force is 945–987 N.

It has been established that increasing the cone length by more than 0.07 m has a negligible effect on reducing the fracture force, and an excessive increase in the angle (up to 90°) makes it difficult for the deformer to penetrate the wood at the initial stage.

Conflict of interest

The authors declare that they have no conflict of interest regarding this research, including financial, personal, authorship or other, that could influence the research and its results presented in this article.

Financing

The research was conducted without financial support.

Data availability

Data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

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