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SUBSTANTIATING OPTIMUM PARAMETERS AND EFFICIENCY OF ROTARY BRUSH CUTTERS

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The problem of untimely forest thinning is quite common in today's society. It leads to the emergence of the underbrush, which negatively impacts the growth and development of young trees. Therefore, this work aims to estimate the feasibility of applying a new rotary brush cutter model to eliminate excessive vegetation. The dependence of the tractor's speed when removing underbrush with different diameters of tree trunks was established by performing mathematical modeling to optimize the brush cutter parameters. Three types of flexible inertia cutting devices were investigated: flat knives, sprocket chains, and knife chains. Knife chains are the most optimal choice as they cut plants most efficiently (94.61% and 92.5% for two-year and three-year underbrush, respectively). They also show the lowest energy consumption for underbrush with a trunk between 1 and 2.4 cm in diameter. Further experiments are required to determine if the developed mathematical model can be used for more neglected forestry stands.

Keywords: cutting, efficiency, improvement, knife chains,modelling, removal cutting

1 INTRODUCTION

One of the key tasks of the forestry sector is the moderate use of forest resources and their replicability.Consequently, in recent years, the study of the sustainable development of forest ecosystems and their management principles has been conducted intensively [1,2]. The basic procedure is forest thinning, which provides better merchantability of wood and environmentally friendly conditions for growth [3,4].Furthermore, the appropriate logging organization enables the composition of ecosystem species to be regulated and used for restoration [5]. Forest thinning is performed with mechanized operations for better efficiency. It is important to consider their productivity, costs, as well as the level of tree damage [6]. Irregular exploitation causes undesirable vegetation, inhibits the development of major species, and affects their survival in these conditions [7,8]. Therefore, technologizing the process will reduce time costs and increase the efficiency of forestry operations.

Many researchers addressed issues of introducing new technological approaches for removing unwanted vegetation [9,10,11]. There are three types of machines that can be used during logging: manual, semi-automated, and remote (operated robotic systems) [12]. Semi-automated brush-cutting tractors, with circular or inertial saws and rotary cutters as the main active working elements, are typical of Russian forestry [13]. Despite their variety, passive attachments are relatively common due to the high process efficiency relative to low design complexity [14].

The operation of such devices can be described by considering them as a system of points and solids [15]. In so assessing the attachments of machinery, the low efficiency is reported characteristic only of passive elements used to remove vegetation with small trunk diameters. It means that the operating range of these devices is very limited [14]. The application of rotary saw blades results in the incomplete cutting of vegetation as they simply smooth it. However, they can be used to remove stubs from the soil [16]. The installed capacity in this process depends on the type and amount of woody matter [17]. Thus, nylon rope is perfect for removing weeds and grass, but the stony nature of the ground increases wear and tear, slowing down the operation [18].Saw chains are subjected to considerable stress when contacting wood, which predominates during shrub operations [19]. The application of the above saws depends upon soil state and cutting conditions. In contrast, inertial cutting elements are more efficient due to the possibility of avoiding hills, rocks, and other obstacles [20].

Research projects on the characteristics of inertial cutting tools as the most promising are insufficient for the analysis. Therefore, this study aims to calculate the features of the rotary brush cutters. The set objective includes the following tasks to be completed:

- Identifying indicators of forest plantations where no thinning is carried out;
- Developing methodology for calculating parameters of rotary brush cutters;
- Verifying the functioning of the chosen attachment design experimentally.

2 MATERIALS AND METHODS

As there is no method for calculating the principal parameters of inertial cutting elements, they shall be determined similarly to the pendulum copra. Prior to conducting the study, additional mathematical and applied research was required, namely:

- Establishing vegetation characteristics since they will be significantly different for both young and old-growth;
- Determining the most suitable parameters when establishing the above characteristics.

2.1 Determining the undergrowth forest inventory features

The number of sprouts was counted manually, with subsequent calculation of a mean value.The height was measured from the soil base to the top of the subsoil using a measuring tape, and the diameter was measured to a height of 40 cm using a caliper.

2.2 Operating principle of the inertia cutter tool for the brush cutter

During operation, the attachment bends in two planes (vertical and horizontal). It is associated with the rotational and translational motion of the rotor. Its schematic layout is provided in Fig. 1.

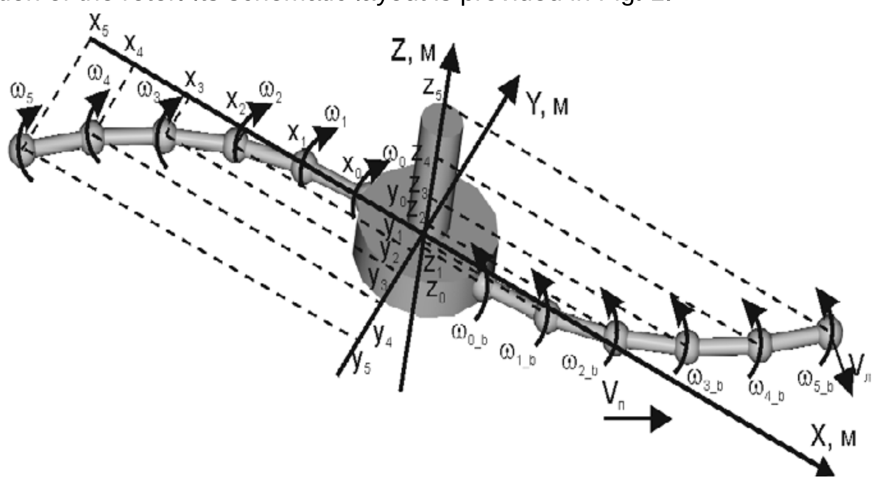

Fig. 1. The general layout of the rotary attachment with the inertial effect

For building a mathematical model of the material point projection coordinates at a specific time *t*, it should be considered that the motion occurs in three-dimensional space. The speed of the saw's lowering can be neglected:

$$\begin{cases} x_k = r_k \cdot sin(\omega_k \cdot t) \cdot cos(\omega_{к-1} \cdot t - \omega_к \cdot t) \\ y_k = r_k \cdot cos(\omega_k \cdot t) \cdot cos(\omega_{к-1} \cdot t - \omega_к \cdot t) \\ z_k = \sqrt{(x_k - x_{k-1})^2 + (y_k - y_{k-1})^2} \cdot sin(\omega_{k\_b} \cdot t) \end{cases} \quad (1)$$

where x_k, y_k, $z_k$are position coordinates of point $k$in space, m; $r_k$is the distance between point $k$and the central axis of the attachment, m*;* $\omega_k$is the angular velocity of point $k$in the xy plane, s-1;$\omega_{k_b}$is the angular velocity of point $k$of the $z$plane, s-1; $r_k$is thedistance between the outermost points of the attachment, m.

he diameter of the attachment$r_k$is assumed to be constant ($r_k = const$). Therefore, the conditions of mutual rotation of points $k$relativetoeach other shall be set. It will allow calculating the diameter of the attachment during movement based on the values from the system of equations(1):

$$R_k = \sqrt{(x_k - x_{k-1})^2 + (y_k - y_{k-1})^2 + (z_k - z_{k-1})^2} \tag{2}$$

Theobtainedparameter is then introduced intothesystemofequations(1)bycalculating the ratio of the attachment length $r_k$to the length of R_k. It will allow scaling the coordinates of thepoints:

$$\begin{cases} x_k = r_k \cdot sin(\omega_k \cdot t) \cdot cos(\omega_{к-1} \cdot t - \omega_к \cdot t) \cdot r_k / R_k \\ y_k = r_k \cdot cos(\omega_k \cdot t) \cdot cos(\omega_{к-1} \cdot t - \omega_к \cdot t) \cdot r_k / R_k \\ z_k = \sqrt{(x_k - x_{k-1})^2 + (y_k - y_{k-1})^2} \cdot sin(\omega_{k\_b} \cdot t) \cdot r_k / R_k \end{cases} \tag{3}$$

2.3 Brushcutter's drive model

Given that the structure of the brush cutter includes a hydraulic motor, it is necessary to calculate the dynamic processes during operation, taking into account hydraulic pressure, volume, and other parameters. The obtained system of differential equations will be as follows:

$$\begin{cases} \dfrac{dp}{dt} = \dfrac{1}{K_p}\left(q_p \omega_p - q_s \omega_m - K_l p\right) \\ \dfrac{d\omega}{dt} = \dfrac{1}{J_s} \cdot \dfrac{\eta_t q_m p}{2\pi \eta_v} - \dfrac{1}{J_s} \cdot \dfrac{F_d \cdot J_{el}}{m \cdot R} \end{cases} \tag{4}$$

where $K_p$is the plasticity factor of flexible elements of hydraulic drive m/Pa; q_i (*i = p, m, s*) is the cubic capacity of the pump and the hydraulic motor, specific volume of the hydraulic motor, respectively, m^3/rev; ω_i(*i = p, m*) is the angular speed of the pump shaft and the hydraulic motor, respectively, s^{-1}; $K_l$is the leakage factor, m^3/(s Pa); $p$is the hydrostatic pressure, MPa; J_i(*i= s, el*) is the mass moment inertia and rotational inertia of the attachment, respectively, kg m^2; η_i (*i = t, v*) is the total and volumetric efficiency of the hydraulic motor, respectively; $F_d$is the dynamic cutting force, N; $m$is the mass of the flexible attachment, kg; $R$is the distance between the shaft and attachment rotation axes, m.

2.4 Cutting process simulation

The linear speed ratios of the process are the main conditions for the cutting. They include the speed of the vegetation stem V_{tr} obtained during cutting and of the cutting element itself V_{el}(5), the mass inertia F_{in}, determining the force of the collision with the trunk, and the cutting force during the dynamic process F_d(6):

$$V_{tr} < V_{el} \tag{5}$$

$$F_{in} \geq F_d \tag{6}$$

Under other conditions, the stem will crush.

Forcalculatingstaticcuttingforce,Reznik'sformula was modified by adding withthevalue of the tensile strength obtainedexperimentally:

$$F_s = \Delta\ell \cdot \delta \cdot \sigma_s + \frac{1}{1+\frac{1}{n}}\left(\frac{E}{h_t}\right)^{\frac{1}{n}} h_t^{1+\frac{1}{n}} \cdot [tg(\beta) + f\, sin^2(\beta) + \mu(f + cos^2(\beta))] \tag{7}$$

where $\Delta\ell$is the depth of the attachment contact with the woody material, m; δ is the width of the attachment, m; σ_s is an ultimate strength, MPa; *E*is the modulus of deformation, MPa; $h_t$is the height of the trunk shear cut, m; $\mu$is the Poisson's ratio; $\varphi$is the friction angle, rad; $\beta$is the angle of bevel inclination, rad; $f$is the coefficient of mass friction against knife material, $f = tg\varphi$.

Based on the dependency of dynamic cutting force on static one, the theory of impulse cutting suggests a similar indicator for the experiment by introducing the coefficient of cutting dynamics K_{dc}:

$$F_d = F_s \cdot K_{dc} \tag{8}$$

The collision force emerging during the rotation of the attachment is determined according to the formula:

$$F_{in} = m_{el} \cdot \sqrt{\left(\frac{\Delta V_{el}}{t_{im}}\right)^2 + \left(\frac{\Delta V_{el}^2}{R}\right)^2} \quad (9)$$

where ΔV_{el} is the decrease in linear speed (m/s) of the attachments's flexible part by mass m_{el}(kg) during its contact t_{im}(s) with undergrowth.

GiventheLawofConservationofMomentum,theundergrowth gainsvelocity V_{tr} calculated by the formula:

$$V_{tr} = \frac{F_d \cdot h_t^2}{m_t \cdot l_t^2} \cdot t_{im}, \quad (10)$$

where $l_t$is the tree trunk length, m; $m_{cm}$is its mass, kg.

2.5 Experimental set-up and result processing

All results were captured on a computer and processed using the variation statistics.

Three types of attachments were used in the experiment:

- a regular link chain fixed to the rotor using a flat knife attached by a carabiner to the free end of the chain;
- a similar variant, but with a star-shaped knife instead of a flat knife;
- a chain attached to the rotor with knife plates acting as links with a flat knife attached by a carabiner to the free end of the chain, similar to the first type.

For the continuous operation of the hydraulic motor, a pump fed a regulated quantity of water.

Once laboratory research was completed, field experiments were conducted in plots of the forest areas in the Republic of Sakha, withatotalareaof150 m^2 throughout 2019, 2020, and 2021. Attachments were mounted on a rotary brush cutter, acting as a prototype.

The constant speed of the tractor during the field study was 3.2 km/h, the rotation speed of all three attachment variants was 20 s–1.

3 RESULTS AND DISCUSSION

The assessment results of forest inventory indicators are presented in Fig. 2.

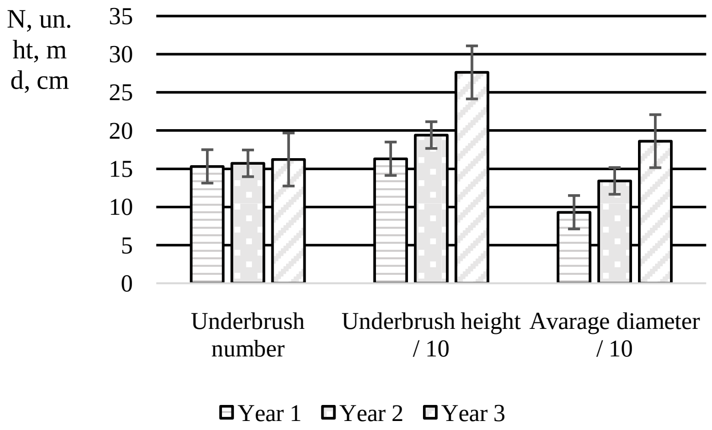

Fig. 2. The main forest inventory indicators for the experimental site reduced to 1 m2

As shown, if the undergrowth is not cut, its quantity increases insignificantly. However, a height and diameter growth is approaching the exponential. The values difference was (in %): 2.61 and 5.88 for quantity; 19.02 and 69.32 for height; 44.09 and 100 for average diameter in the second and third year compared to the first year,respectively.

The acceleration of the attachment at the beginning of the rotor turning is characterized by the dependency shown in Fig. 3.

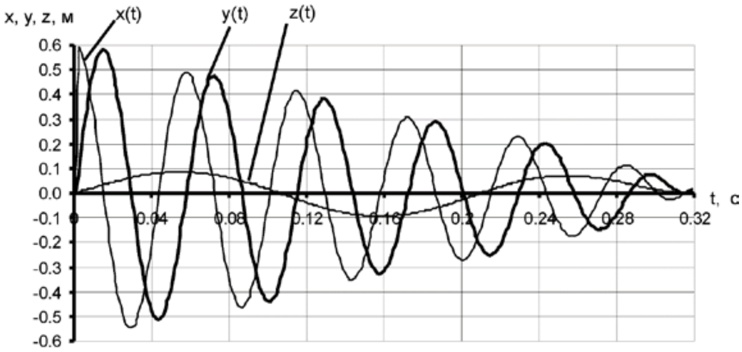

Fig. 3. Oscillatory transformation of attachment's single point position

The calculation of the system of equations (4) relative to hydraulic pressure resulted in an equation describing the water pressure dependence in the pipes over time. For the convenience of writing, the notation Q was introduced:

The summand $e^{-\frac{K_y}{2\cdot K_p}t}\cdot[sin(Q\cdot t)-cos(Q\cdot t)]$ describes the pressure transformation in the system during acceleration from the initial surge to further stabilization. The summand $\frac{F_d\cdot J_{el}\cdot 2\cdot\pi\cdot\eta_v}{m_{el}\cdot R\cdot\eta_t\cdot q_m}$ illustrates the growthofpressureduring cutting that occursbychangingthedynamic force.

Consequently, during both processes, there is an increase in pressure in the hydrodynamic system of the brush cutter, but their magnitude varies. The scale of the difference Mcan be estimated bysolving therelation:

$$M=\frac{p_{max}}{\frac{F_d\cdot J_{el}\cdot 2\cdot\pi\cdot\eta_v}{m_{el}\cdot R\cdot\eta_t\cdot q_m}} \qquad (11)$$

where p_{max} is the maximum pressure during the rotor acceleration.

The value of M will be different for each specific case, given that the underbrush diameters are different and the force applied to them varies, respectively. Based on this, the pressure curve of the system during acceleration was obtained (Fig. 4).

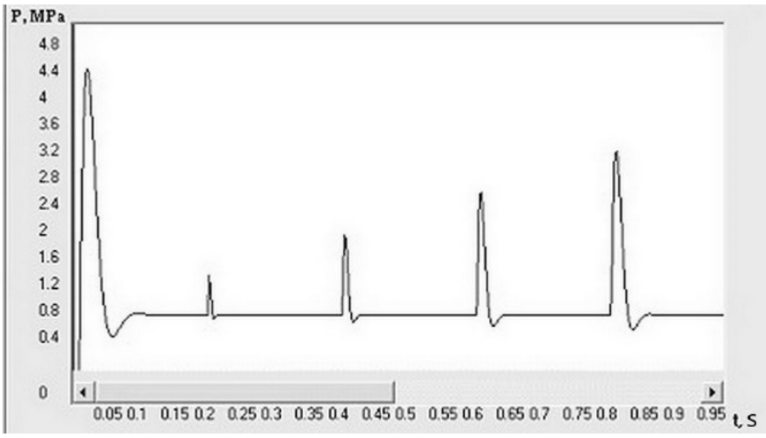

Fig. 4. Pressure transformation in the brush cutter's hydraulic drive during rotor acceleration

Based on the formulas and irregularities (5-9), the cutting will occur if:

- the speed of the attachment exceeds the speed received at contact; the force of the collision allows the sharp parts of the attachment to sink further into the undergrowth;
- the degree of underbrush decline is not enough for a fracture.

The same equations provide the optimal cutting parameters.

Given that the attachment is a flexible element, the period of full rotation can be calculated, that is, the time the point set will be in the initial position after rotor start-up:

$$T_{el}=\frac{1}{N_{el}\cdot n_m} \qquad (12)$$

where $N_{el}$is the number of cutting elements, units; $n_m$is the rotation frequency of the cutting elements, s^{-1}.

It follows that the saw's lowering speedis limited by the specific amount of underbrush and the period of full rotation:

$$V_l^{max} \leq \frac{n_s}{T_{\text{H}}} \tag{13}$$

where n_s is the number of underbrush per 1 m^2.

Sincepartoftheenergyislosttocontactandistransferredtotheunderbrush, the rotation speed of the attachment decreases. Therefore, it is necessary to restore thepreviousrotation speedbeforeanewcollision.Thetimet_t requiredforthisprocess is calculated as:

$$t_r = \frac{F_d \cdot t_{im} \cdot J_s}{m_{el} \cdot R \cdot M_m} \tag{14}$$

where M_m is the torque on the hydraulic motor shaft, $N \cdot m$.

It follows that the attachment's lowering speed is also limited by the specific amount of underbrush and the time required to return to the previous mode of operation:

$$V_l^{max} \leq \frac{n_s}{t_r} \tag{15}$$

Considering formulas (7-11, 12-15) allows obtaining target function, which depends on all the above parameters:

$$V_l(V_{el}, F_{in}, F_s, F_d, F_{im}, V_{tr}, T_{el}, t_r) \rightarrow max \tag{16}$$

The factors were optimized, taking into account all the constraints. Therefore, the final result is found to depend on a system of functions of the following kind:

$$\begin{gathered} F_{im} = f(m_{el}, V_s, R, t_{im}) \\ F_s = f(\Delta l, \delta, \sigma_s, n.E, h_t, \beta, f, \mu) \\ V_s = f(F_d, h_t, m_t, l_t, t_{im}) \\ t_r = f(F_d, t_{im}, J_s, m_{el}, R, M_m) \end{gathered} \tag{17}$$

Based on the system (17), the optimal speed of the brush cutter was obtained, depending on the underbrush diameters (Fig. 5).

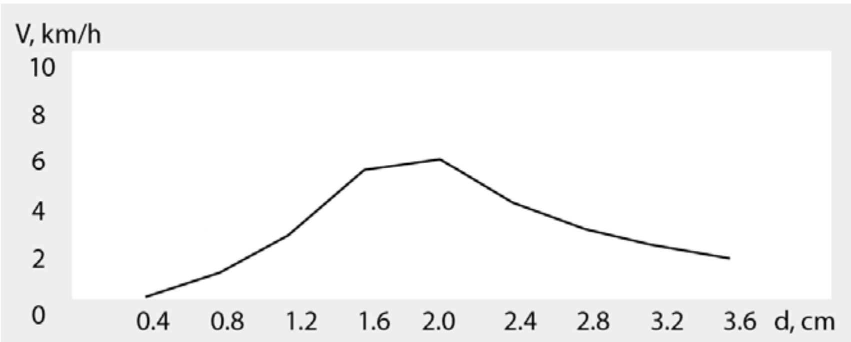

Fig. 5. Optimized cutting process

By assessing the results in more detail, additional optimal parameters of the attachment and the tractor (Table 1) were established.

Table 1. Optimizing the additional parameters for cutting underbrush with a diameter of 2.8 cm.

Parameter name		**Units of measure**	**Parameter value**	
			Knife chain	**Chain with thick striker**
Cutting element	**Thickness**	mm	4	10
	Length	m	1	0.5

Parameter name		Units of measure	Parameter value	
			Knife chain	Chain with thick striker
	Sharpening angle	deg.	30	75
Hydraulic drives	Torque	N □m	70	70
	Rotation speed	s^{-1}	14	20
Tractor speed		km/h	3.43	2.8

As can be seen, the knife chain is a more efficient cutting element for the underbrush with a diameter of 2.8 cm since the hydraulic drive speed indicator is 30% less thanfortheotheroption.Thistypeofattachmentallowsfastercuttingasthetractor's speed during operation is higher by22.5%.

The evaluation of the underbrush properties determined the minimal effort required for cutting (Fig. 6).

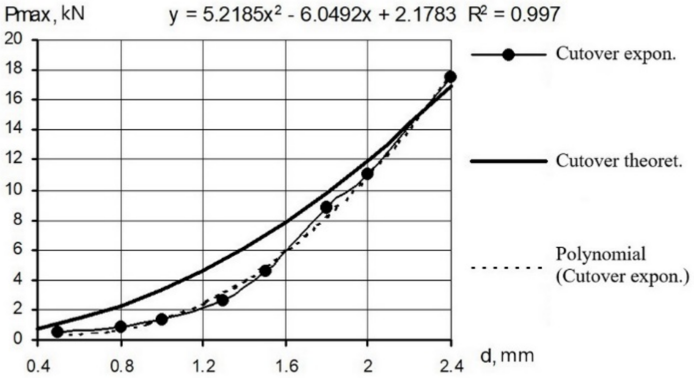

Fig. 6. The force required for cutting relative to the underbrush diameter

As can be seen, the resulting dependency has a strict polynomial character, very similar to the exponential one. It also differs from the theoretical shape influenced by the properties of the underbrush itself, especiallyfordiametersof8-18mm with a lower cutting force. With trunk diameters of 24mm, the required force goes beyond the mathematical model.

In order to calculate the energy intensity of the studied process, an experiment of cutting 20 mm of underbrush using a chain sprocket was conducted. The resultant curve is depicted in Fig. 7.

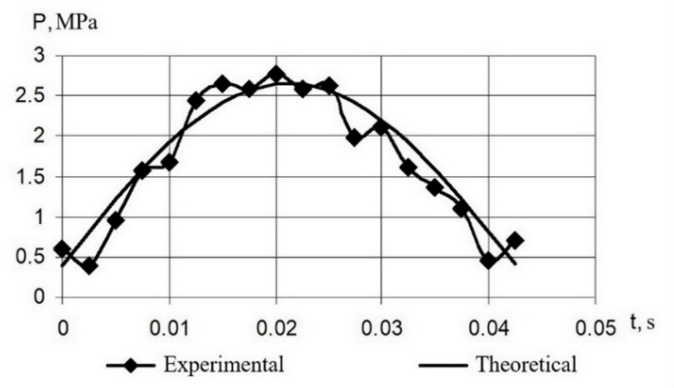

Fig. 7. Dependence of hydraulic pressure on cutting time

The graph has a sinusoidal shape with a clear peak at 0.02 s and subsequent stabilization of the pressure in the system. It allows establishing a theoretical formula to describe this process:

$$y(t, P_{max}) = P_{min} + (P_{max} - P_{min}) \cdot sin\varphi \quad (18)$$

where P_{max} is the pressure during cutting at the moment t, MPa; P_{min} is the pressure at idling, MPa; $\varphi = \varphi_0 + \pi \cdot t_{st}/t_t$, where φ_0 is the coefficient at the zero moments of time, $t_t$is the duration of the pressure surge, s; $t_{st}$is the time interval between the pressure measurements, s.

The dependence of the hydraulic system pressure at a given moment on the pressure without load, the duration of the surge, and stabilization of pressure were achieved.Integration ofthisfunction allowsestablishingtheworkperformed during cutting. The limits of the defined integral will be the surge values (start and end times). The results of this transaction are shown in Fig. 8.

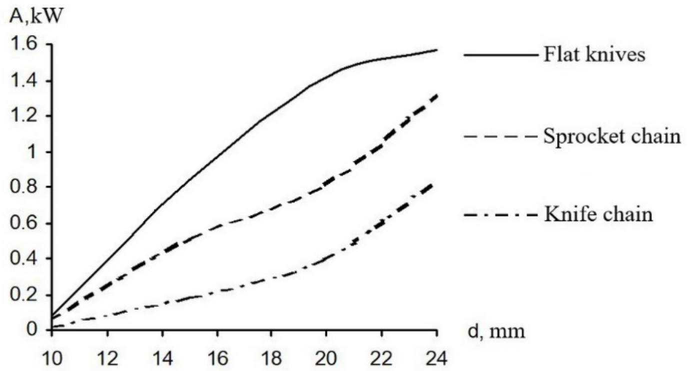

Fig. 8. Efforts of the cutting by three attachment options versus underbrush diameter

It is shown that for cutting underbrush with a small diameter (less than 1 cm), the required energy intensity is negligible for all types of cutting elements. In contrast, larger diameters require more cutting efforts, which is associated with the rotation of the cutting element.

The use of a flat knife results in the highest energy expenditure as the unsharpened side of the knife was in contact with the vegetation.In the case of the sprocket chain, two cutting edges struck each other, which slightly reduced energy consumption.A similar phenomenon was seen, but with only one end of the knife chain in contact.

The results of the field experiments are shown in Fig. 9.

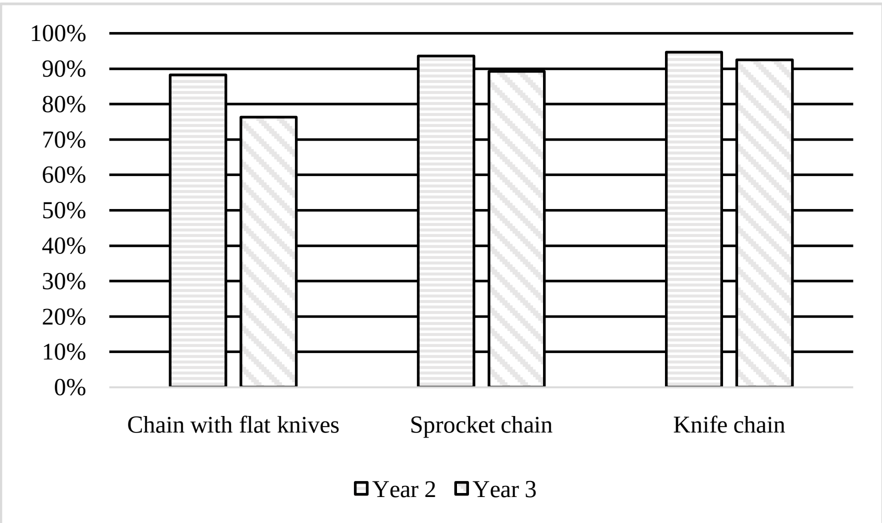

Fig. 9. Degree of underbrush cutting by different types of cutting elements

The larger underbrush diameter results in lower cutting quality for all attachment options.The biggest difference is typical of flat knife chains (88.2% for the second-year and 76.25% for the third-year underbrush). Furthermore, they displayed the lowest cutting efficiency for the second-year and third-year underbrush. As for the sprocket chains and knife chains, the cutting rate was almost identical in the second year of underbrush growth (93.59% and 94.61%, respectively). Using a knife chain to remove the three-year underbrush is more effective, with a cutting efficiency of 92.5%. For sprocket chains, this figure was slightly lower at89.25%.

Guo and Liu [21] performed mathematical modeling of the brush cutter operation and subsequently studied the motion speed of the rotary harvester with a dual eccentric cutting mechanism.They demonstrated that this mechanism considerably reduces working time compared to the manual method.The angular rotation velocity of the shaft was 0.52 rad/s (0.0827 s^{-1}). The mechanism proposed in this study also simplifies the process of underbrush. However, when using other cutting attachments, the frequency of their rotation increases significantly 170-242 times.

Camposetal. [22] haveshownthat a hydraulicsysteminaconventional brush cutter improves the quality and speed of the process. Besides, it allows for betterprocess management due to the possibility of controlling pressure. This study suggests using hydraulic pressure to determine the operational efficiency and estimate costs that may arise when cutting large-diameter underbrush.

In the work of Skvortcov and Serebrennikov [14], the operation of a brush cutter with a passive attachment was simulated, with a subsequent study of the collision force between device andunderbrush.However, consideration should be given to their rotational speed when working with active elements.

Dixit et al. [23] evaluated the efficiency of the modified brush cutter for rice harvesting. Authors argue that little knowledge is required to operate the machine hence, it can be easily adapted by local farmers in developing agro-industrial countries to eliminate manual harvesting.

Furmanov et al. [24] examined the reduction of power consumption of rotary brush cutters. The lowest cost and highest productivity were observed in thinning operations with the removal of each 5th row and selective thinning between these rows, while the highest productivity for the forwarder was obtained with the removal of each 7th row and selective thinning between these rows.

4 CONCLUSIONS

This study presents the theoretical simulation of cutting underbrush considered undesirable vegetation in forest plantations.Due to the low intensity of forest thinning, there is an increase in theamount and size of young growths.

After three years of neglecting the forest,the amount of underbrush exceeds 16 pcs/m^2. Their height reaches almost 3 m, and their diameter is 2 cm.

The cutter motion study showed its capability to slow down the rotation as early as 32 s after a start, with subsequent stabilization of the point positions. In addition, the acceleration process is accompanied by a sharp surge of hydraulic pressure in the motor. It has a periodical character, with a much lower amplitude but with a tendency to rise to the maximum value.

A comparative analysis of different types of knives showed that flat knife chains are more efficient at a tractor motion speed of 3.43 km/h. At the same time, this variant demands the greatest amount of energy when cutting the growth greater than 1 cm in diameter. It also responds to the task in the lowest quality (the degree of cutting is below 90%). The use of a knife chain is the most efficient intermsofthe efforts required (upto0.8kW)andthecutting quality(for two- and three-year-old sprouts, the cutting percentage is more than90%).

Based on these findings, the following design was developed: supporting knife, frame, rotor with flexible inertial cutting elements.

The model can be applied to remove aspen underbrush in the first, second, and third year of their growth. Further experiments should be carried out to establish whether it can be used for more neglected forest variants.

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