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Geometric and kinematic parameters of vibrating knife in the development of cutting machines

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Abstract

The process of cutting with a blade is largely applied in agricultural equipment and is used to process raw materials with different physical and mechanical properties. Nonetheless, the functional relation between the kinematic parameters of a vibroblade and the crucial power parameters of the vibration processing has not yet been studied in great depth so far. This type of studies is essential to create databases for further investigation and design of novel cutting machinery or technologies to ensure effective processing of vibrocutting. Our objective was to obtain the power characteristics of vibrocutting through laboratory experiments [using the example of vibrocutting of common reed (*Phragmites australis*)] and define the combination of factors (*i.e.,* vibration amplitude, frequency and the blade feeding speed) at the minimum cutting force. The following relation of the blade feeding speed (V) and vibration speed of the toothed blade (V_t) has been established as optimal kinematic regime: $K \cong 0.004$. Tests have indicated that use of toothed blades for vibrocutting of the raw products of plant origin offers a greater advantage over the blades with flat edges. An optimal cutting regime, when energy expenses are at a minimum, was ensured with the following parameters of the vibroblade: vibration amplitude: 14 mm, frequency: 33.32 s^{-1}, the blade feeding speed: 7.5×10^{-3} *m*.

Introduction

A wide use of mechanized equipment in the agricultural production processes is critical to increase the efficiency of this sector in the short term. For such progress, it is necessary to create a set of machinery with high technical and economic indicators that can ensure high efficiency and quality of implementation of the required technological processes.

Numerous theoretical and experimental studies have been carried out on the issues of chopping and cutting materials with a blade, and considerable experience has been gained (Reznik, 1975; Tarverdyan, 2004; Igathinathane *et al.*, 2011). However, vibrocutting of materials as a specific and prospective version of cutting with a blade has not sufficiently investigated.

The applications of vibration are varied in terms of the sector, technology, and the working parameters (Blekhman, 2013). For instance, in soil cultivation, vibration harrows, cultivators and plows are widely known, with their working body subjected to self-excited vibrational motion (Vibrations in the technology, 1978; Loveykin and Dyachenko, 2013; Fedorenko, 2016; Vasilenko *et al.*, 2018).

There are a wide number of machines working on the basis of the principle of vibration technology (Tarverdyan, 2014; Vasilenko *et al.*, 2018), such as soil cultivation machines used in agriculture, vibrodrills, as well as mowers, cutting devices with blades, *etc*. However, for their dimensioning, the principles of rheological modeling of processed material are not used at all or not enough taken into consideration.

In general, the development and design of agricultural vibration equipment of agricultural significance involve several challenges due to a number of reasons.

First of all, the interaction between the working bodies of the machines based on the principle of vibration and the cultivated medium (the soil, plants, *etc.*) is complicated. In this case a complicated interaction occurs between the vibration working bodies and the cultivated medium with transfer of mass, impulse and energy, *etc.*

The other factor is the variety and the diversity of the physical, mechanical and rheological properties of the cultivated medium - the soil, agricultural crops, materials and raw products. This makes it difficult to establish a causal relationship between the parameters of the machine working process and the final result of its action.

The resistance of the working environment and the contact force, the combination of properties (viscosity, plasticity and elasticity), the demonstration of the slip, the relaxation of stress and thixotropic properties lead to nonlinear deferential equations and, as a consequence, make their estimation and analysis difficult. On the other hand, nonlinearity is a source of numerous positive

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impacts and demonstrations of vibration, which are available in different technologies.

The results of the research works have shown (Blekhman, 1994; Yarullin, 2007) that the effective values of vibration amplitude and frequency in technological equipment based on the vibration principle in the food and agriculture sector do not exceed 10 mm and 300 rad sec^{-1} (or 47.75 Hz), respectively, except for some technological processes (Figure 1). The author also indicates an empirical formula that establishes a correlation between the optimal parameters of vibration:

$$A = \frac{0.39}{\omega} \tag{1}$$

where A is the amplitude, m, and w is the frequency, rad sec^{-1}.

Previous theoretical research in this area was focused (Tarverdyan, 2004; Tarverdyan and Altunyan, 2009; Altunyan, 2009; Tarverdyan, 2014) on the analysis of the vibrocutting force with blade. According to the data from theoretical analyses and calculations, the dependence of the normal and tangential components of contact forces occurring on the surface of the blade in the vibrocutting process on the index of kinematic regime describing the vibrocutting process has been defined as:

$$K = \frac{V}{V_t} \tag{2}$$

where V is the normal speed of cutting, ms^{-1}, and V_t is the speed amplitude of the longitudinal vibration motion of the cutting edge, ms^{-1}.

Studies have revealed that below the $K \approx 0.55$ value of the index of kinematical regime, the normal component of contact force decreases and, vice versa, the value of the tangential component increases.

The aim of this research work is to define the impact of vibrocutting on the power of cutting as well as the change of its normal and tangential components based on some laboratory experiments. Common reed (*P. australis*) was selected as a sample, considering that the cleaning of reservoirs and natural canals from reed-type plants is a topical issue. Although, those plants are chemically controlled, the mechanical cleaning option remains obviously the preferred one, given the known disadvantages of this method, such as environmental pollution and uselessness of the cut materials. The plant mass collected in this way can be used as feed or for other purposes.

Materials and methods

Given the above-mentioned results and theoretical research, we conducted laboratory scientific trials to confirm the data obtained and the patterns deriving from theoretical research and to disclose the real force at work in the vibrocutting process.

In fact, an orthogonal central plan/matrix was selected for the implementation of the experiments. The number of observations in the plan/matrix was N=17, of which $n_0=3$ scientific experiments were completed at *point zero*. In general, the experiments were repeated three times at every level for each blade to ensure the required accuracy of the results. The relevant signals characterizing the values of the normal and tangential components of the vibrocutting force were recorded independently and simultaneously. According to the management of the levels of factors influencing the optimization parameters of the scientific experiments, the form of active experiments was conducted, to allow the investigator to manage personally any change in the levels of those factors. According to the goal of the study, extremum scientific experiments were carried out to identify the combination of managed factors influencing optimization parameters that will ensure an optimal vibrocutting operation.

In the scientific experiments, the following optimization parameters were chosen: the normal, Y_1 (N) and the tangent, Y_2 (N), components of the cutting force of the serrate blade. The factors influencing the optimization paramters (Y_1, Y_2) selected were amplitude of vibrocutting, X_1 (mm), frequency of the serrate blade vibration, X_2 (s^{-1}) and the blade feeding speed X_3 (m s^{-1}).

The objective of the laboratory tests was to measure through foil strain gauges the values of the normal and tangential components of the cutting force needed during the vibrocutting process in case of a change in the abovementioned three factors.

The values of determination of the set of factors impacting the optimization parameters and the differences in their levels are presented in Table 1.

A literature review (Igathinathane *et al.*, 2011) indicated that the precision needed for the theoretical description of the investigated topic and for presenting the results of the scientific experiments can be ensured only if the mathematical modeling is based on the application of a second class polynome as follows:

$$y = b_o + \sum_{1<i<N} b_i x_i + \sum_{1<i<j<N} b_{ij} x_i x_j + \sum_{1<i<N} b_{ii} x_i^2 \tag{3}$$

where b_o, b_j, b_{ij} and b_{ii} are the unknown coefficients of the

Table 1. Values of the determination of the set of factors and the differences in their levels.

| Matrix parameters	Code	Vibrocutting amplitude, X_1, mm	Vibration frequency, X_2, s^{-1}	Normal component of cutting speed, X_3, ×10^{-1}, ms^{-1}
Value of difference	-	-	4.17	−2.5
Main level	0	10	29.16	5
Upper level	+1	14	33.32	2.5
Lower level	−1	8	25	7.5

polynome to be calculated,
x_i is the i-th factor of the plan/matrix of the scientific experiments,
N is the number of trials in the plan/matrix,
and i and j is the serial number of the factors in the plan/matrix, $i < j$.

The signals received from the strain gauges were processed through an analog-to-digital coverter, in addition to using also a amplifier mainly for strengthening the signal received from the strain gauge (7) to record the tangential component of the vibrocutting force. The data obtained based on the scientific experiments were processed according to the regression and dispersion analysis methods. The experimental data were analyzed by the SPSS 22 software, the significance of the regression coefficients was tested according to the Student's t-test and all non-statistically significant coefficients were removed from the equation. The compliance of the final equation was reviewed according to the F-test.

To conduct the trials, a laboratory equipment was designed
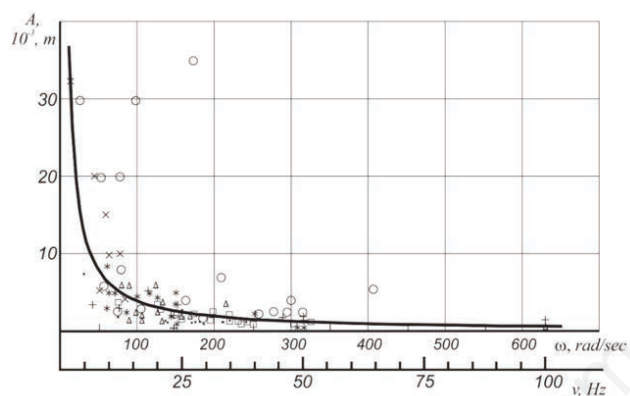
Figure 1. Optimal values of vibration amplitude and frequency (according to R.B. Yarulin) in the technological processes applied in the agro-industrial complex. Δ – livestock, * – engineering and road construction, + – equipment repair, x – centrifugal vibro-machines, □ – smoothly sieving vibrating machines, ● – friction machines.
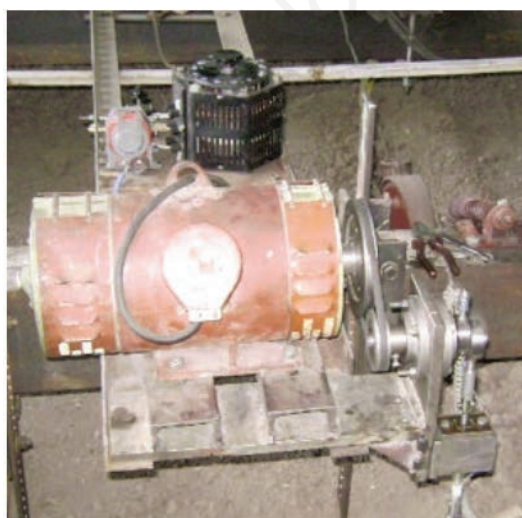
Figure 2. General view of the experimental device for determining the specific force of vibrocutting for plants with thick stems.

(Figure 2) to change the vibration frequency and amplitude of the cutting tool and manage the blade feeding speed.

During the trials, two types of serrate blades were used as cutting tools (Figure 3), having the following geometric parameters: i) *fine-toothed blade*: tooth spacing - 2 mm, height of tooth - 2 mm; ii) *large-toothed blade*: tooth spacing - 4 mm, height of tooth - 4 mm.

A vibrational movement is transmitted to the cutting tool through the slider-crank connecting (3) mechanism, which in turn is connected to the asynchronous (1) direct current engine through the pulley (2) (Figure 4).

The vibrocutting amplitude (X_1) was regulated with the help of custom-made pliers, on which excentric holes were previously made with the ideal amplitude sizes for the experiments.

It is important to mention that during the laboratory experiments also a 2.5 mm amplitude vibrocutting process was considered. As indicated by the results of the research, the vibrocutting process was taking place with extremely high values compared to the normal component of the cutting force, thus failing to cut the reed in many cases.

During the trial, the vibration frequency (X_2) of the toothed blade (6) changed between $25 \div 33.32$ s^{-1}. The foil strain gauge (7) to record the analog value of the normal component of the vibrocutting force was glued on the pulley attached to the blade.

The material feeding speed was selected in the range of $2.5 \div 7.5$ mm s^{-1}. The values of the blade feeding speed (X_1) were provided by transmitting the necessary rotations to the cylinder

A) $S = 4$ mm, $h = 4$ mm   B) $S = 2$ mm, $h = 2$ mm
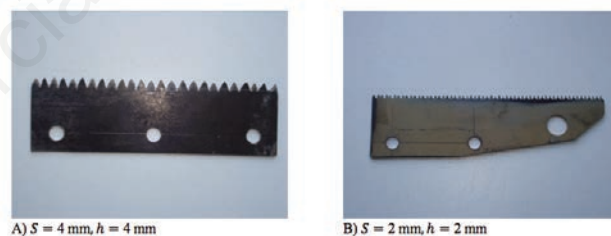
Figure 3. Types of toothed blades used for vibrocutting.
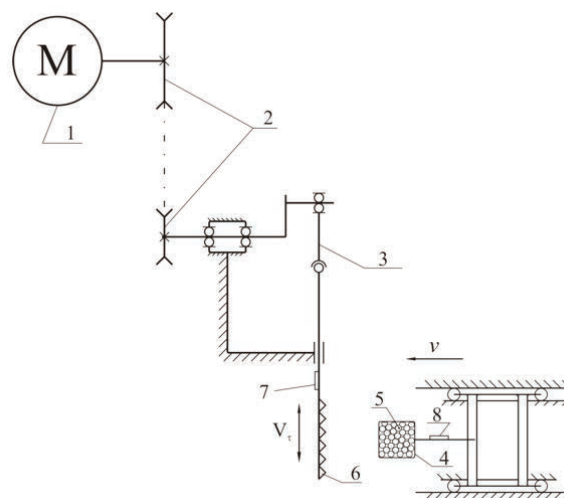
Figure 4. The general scheme of the experimental vibrocutting device (the meaning of each number represented in the scheme is explained in the text).

which turned using electrical power and moved the laboratory vibrocutting device mounted on the cart system through V type belt. The common reed (*P. australis*) was conveyed through a specially prepared metal container (4), where the samples (5) to cut had been placed. A foil strain gauge (8) was glued on the connection of the handle to the container to record the analog value of the tangential component of the vibrocutting force (Figure 4).

Results and discussion

The research comprises two phases where the same plan/matrixes were composed to perform vibrocutting with a large-toothed blade in one case (Figure 3A) and with a fine-toothed blade in another case (Figure 3B).

Cutting process with a large-toothed blade

Data from scientific experiments carried out using a *large-toothed* blade to detect a normal component of the vibrocutting force were analyzed using the statistical software SPSS 22. The statistical considerations about these experimental data are summarized in the Table 2.

We have obtained the following regression equation as a result of vibrocutting with the *large-toothed* blade for the normal component of the cutting force (Figure 3A):

$$Y_N^L = 127,98 - 30,626X_1 - 9,542X_2 - 7,816X_3 - 20,34X_1X_2 + 12,59X_1X_3 + 18,97X_2X_3, (N). \quad (4)$$

The analyses of the obtained regression equation as well as the resulting graphs (Figure 5) indicate that the normal component of the vibrocutting force is largely impacted by the vibration amplitude of the blade due to its linear impact and the value of its coefficient is the largest in terms of absolute size: $b_1 = -30.626$. In fact, the subsequent factors in terms of linear impact are the vibration frequency and the blade feeding speed. Within the linear impact factors only the blade feeding speed has a negative impact. The analyses indicate a significant increase in the cutting force, while the blade feeding speed actual value is growing, which has a negative effect.

The regression equation shows that, among the interacting efficiency factors, the couple amplitude-frequency, $b_{12} = -20.34$, has the largest impact. All interacting efficiency factors have a positive impact, *i.e.,* the increase of their actual value results in the decrease of the normal component.

None of the square effect factors was significant according to the Student's *t*-test.

The obtained equation and '*OriginPro*' software were used to plot the family of curves depicting the values of the normal component of the force for vibrocutting the tested common reed.

Data from scientific experiments carried out using the *large-toothed* blade to identify a tangential component of the vibrocutting force were analyzed using the statistical software SPSS 22. The statistical considerations concerning these experimental data are summarized in the Table 3.

The regression equation obtained for the tangential component of the vibrocutting force is as follows:

$$Y_T^L = 34,167 - 11,081X_2 - 5,471X_3 - 9,05X_1X_2, (N). \quad (5)$$

The researchers concluded on the basis of the analysis of this regression equation and its associated graphs (Figure 6) that the factor of vibration amplitude has a great linear impact on the tangential component of vibrocutting, which has a contributes to the decrease of cutting force. The other significant linear impact factor is the blade feeding speed. However, its increase has a negative effect on the tangential component of the force (Figure 6). In fact, the impact of the vibration amplitude on the value of the tangential component is not significant.

The couple amplitude-frequency factor is the only significant interacting efficiency factor, having a positive effect on the decrease of the value of the tangential component.

In addition, none of the square effect factors has a significant impact on the tangential component of the vibrocutting force.

Table 2. Descriptive statistics for normal component of the cutting force.

	Minimum Statistic	Maximum Statistic	Sum Statistic	Mean Statistic	Standard error	Standard deviation Statistic
Y_N^L	36.89	178.15	2183.22	128.4247	8.92609	36.80321

Table 3. Descriptive statistics for tangential component of the cutting force.

	Minimum Statistic	Maximum Statistic	Sum Statistic	Mean Statistic	Standard error	Standard deviation Statistic
Y_T^L	7.26	64.94	536.25	31.5441	3.93458	16.22270

Table 4. Descriptive statistics for normal component of the cutting force.

	Minimum Statistic	Maximum Statistic	Sum Statistic	Mean Statistic	Standard error	Standard deviation Statistic
Y_N^F	77.11	232.30	2722.35	160.1382	9.94917	41.02149

Cutting process with a fine-toothed blade

The second phase of the scientific experiments was dedicated to vibrocutting with a *fine-toothed* (Figure 3B) blade. It was carried out with the same methodology and plan/matrix as for the large-toothed blade. The statistical considerations about these experiments are summarized in the Table 4.

As a result of processing and analyzing the obtained statistical data, we have calculated the regression equations of the normal and tangential components. The regression equation obtained for the normal component of the vibrocutting force is as follows:

$$Y_N^F = 161,65 - 36,84X_1 + 29,54X_2X_3 + 11,45X_2^2 \ (N). \quad (6)$$

The analysis of the equation and the curve of the surface reaction (Figure 7) indicates that vibration amplitude is the most significant and impactful due to a linear effect. Its effect on the tangential component of the cutting force is positive. The coefficients of the remaining linear effect factors, such as vibration frequency and the blade feeding speed, are not significant according to the Student's *t*-test.

Among the interacting efficiency factors, only the frequency-the blade feeding speed combination is significant, having a positive effect on the normal component of the cutting force.

Among the square impact factors, only the vibration frequency is significant, despite its effect on the normal component is negative.

The statistical considerations about the experimental data of the tangential component of vibrocutting force using a fine-toothed blade are summarized in the Table 5. The regression equation obtained for the tangential component of vibrocutting force is as follows:

$$Y_T^F = 14,22 + 6,44X_2X_3 + 8,95X_2^2, \ (N). \quad (7)$$

The equation explicit, the factor of vibration amplitude is not part of the equation as it is not significant according to the Student's *t*-test.

None of the factors has a linear effect. Among the interacting efficiency factors, only the frequency-speed combination is significant. Its effect on the force of the tangential component is positive (Figure 8). Among the other factors, only vibration frequency has a square effect, having the largest absolute value among their coefficients. However, its effect is negative on the force value of the tangential component.

The obtained regression equations give a general idea of the vibrocutting force for common reed as well as information about the patterns of change in the cutting force in case of vibrocutting of thick-stemmed plants. The regression expressions do not refer to vibrocutting of only one stem but multiple stems where cutting width needs to be 10 cm (see container pictures provided in Figures 2 and 4).

Given that the equivalent of the vibrocutting force is the square root from the square sums of the normal and the tangential components:

$$F = \sqrt{Y_N^2 + Y_T^2}, (N) \quad (8)$$

then we can calculate the values of the relevant factors providing the minimum value of that equivalent force. Using the '*Minimize*' command of the MathCAD software, as well as (4), (5), (6) and (7) equations, the values of those factors can be found.
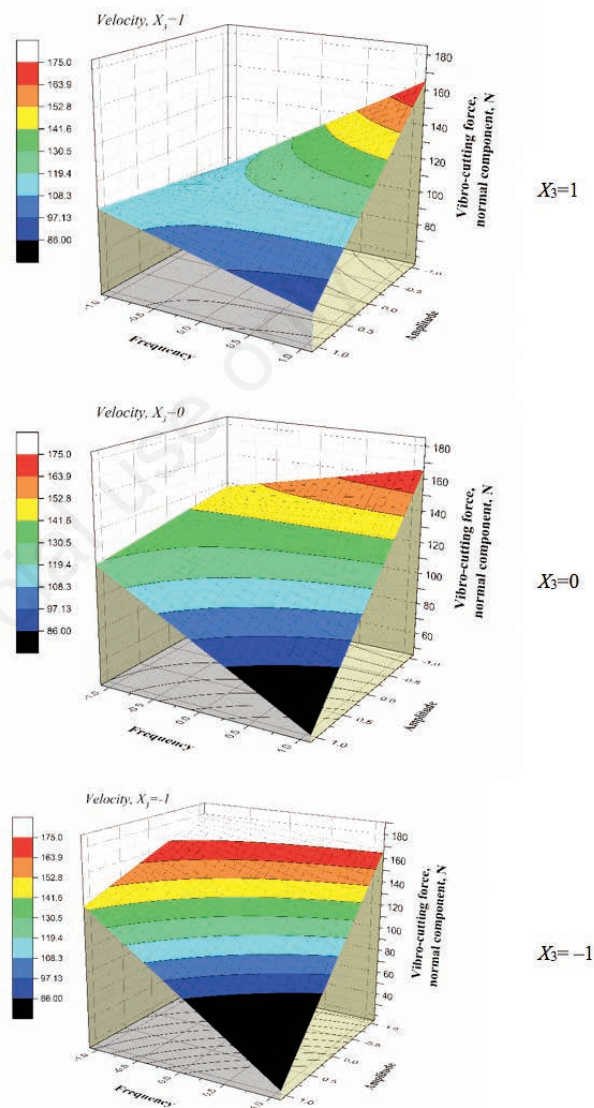

Figure 5. The family of curves of surface reaction (for large-toothed blade), which characterizes the normal component of the cutting force (Y_N^L), depends on vibration amplitude (X_1) and vibration frequency (X_2), in case of fixed values of the normal component (X_3) of the cutting speed.

Table 5. Descriptive statistics for tangential component of the cutting force.

	Minimum Statistic	Maximum Statistic	Sum Statistic	Mean Statistic	Standard error	Standard deviation Statistic
Y_T^F	4.71	41.10	339.42	19.9659	2.75067	11.34130

As a result, the following optimal regimes were obtained, when the angle between the vibrational (tangential) and normal components of the cutting speed was 90°.

Large-toothed blade

Vibration amplitude: A = 14 mm, (coded value: +1);
Vibration frequency: n = 33.32 s^{-1}, (coded value: +1);
Normal component of the cutting speed: V=7.5×10^{-3} m s^{-1}, (coded value: –1).

Fine-toothed blade

Vibration amplitude: A = 14 mm, (coded value: +1);
Vibration frequency: n = 25 s^{-1}, (coded value: –1);

Normal component of the cutting speed: V=2.5×10^{-3} m s^{-1}, (coded value: +1).

In case of the mentioned values of the factors, we obtained that the optimal force of the vibrocutting force for a large-toothed blade was F=47.87 N, in which case the value of the normal component was 43.7 N and that of the tangential component was 19.51 N. For the fine-toothed blade the optimal vibrocutting force obtained was F=108 N, in case of which the normal component was 106.73 N, and the tangential component was 16.74 N. It should be clarified that the obtained force parameters do not refer to the cutting of just one stem of common reed but of a sheaf placed in a container (Figure 4), where the cutting width is 10 cm (the height of the container).
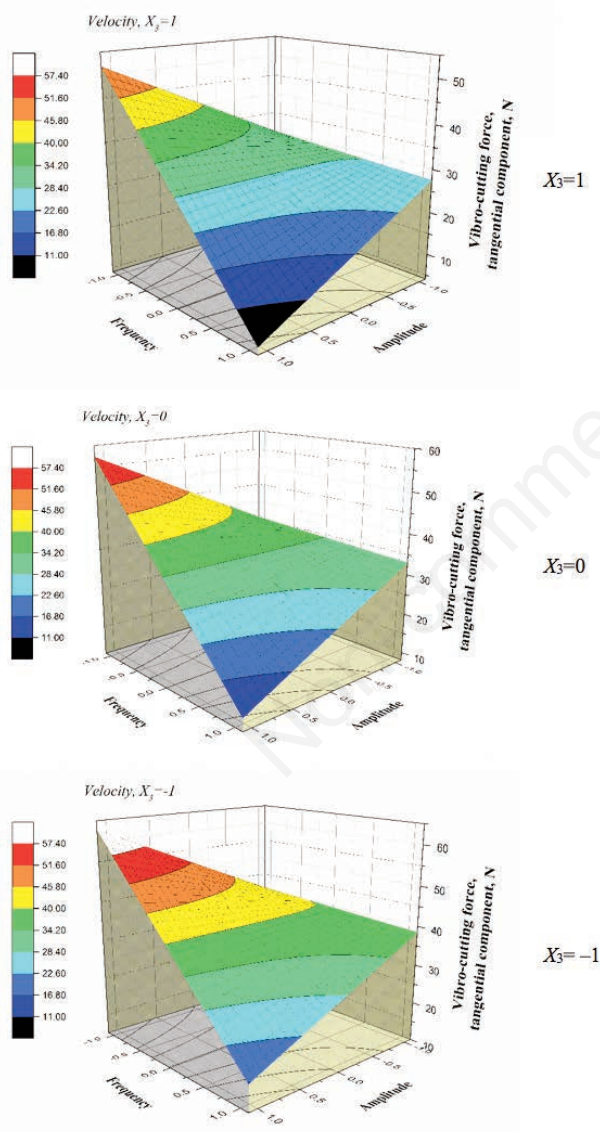

Figure 6. The family of curves of surface reaction (for large-toothed blade), which characterizes the tangential component of the cutting force (Y$_T$^{L},N), depends on vibration amplitude (X_1) and vibration frequency (X_2), in case of fixed values of the normal component (X_3) of the cutting speed.

Figure 7. The family of curves of surface reaction (for fine-toothed blade), which characterizes the normal component of the cutting force (Y$_N$^{F},N), depends on vibration amplitude (X_1) and vibration frequency (X_2), in case of fixed values of the normal component (X_3) of the cutting speed.

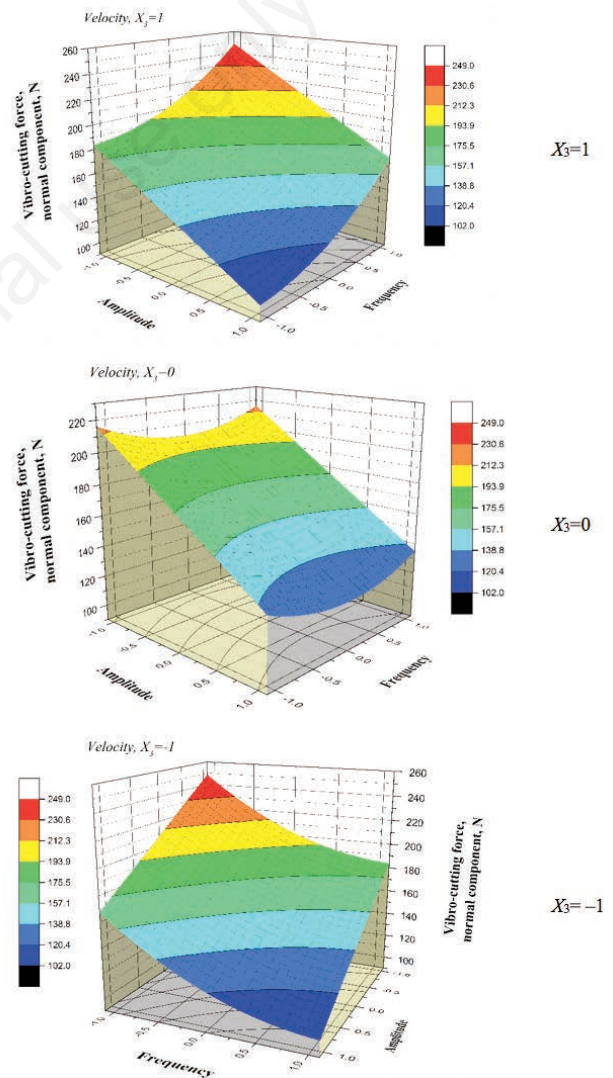During the research study the value of the tangential component of the cutting speed was calculated using the following expression, which took into account the structural characteristics of the experimental device:

$$V_\tau = nA\left(1 + \frac{A\cos\alpha}{\sqrt{\ell^2 - A^2\sin^2\alpha}}\right)\sin\alpha, \qquad (9)$$

where n is the rotation speed of rotation, s^{-1},
A is the vibration amplitude, mm,
ℓ is the length of pulley, ($\ell = 10$ mm) (Figure 4), and
a is the rotation angle of the crank, deg.

We have averaged the value of the tangential component of the speed on the p section of the vibration periodicity. Taking into consideration the values of the factors of the optimal vibrocutting force (*i.e.*, $A = 14$ mm, $n = 33.32$ s^{-1} and $V = 7.5\times10^{-3}$ m s^{-1}), we obtained $V_t = 1.866$ m s^{-1}, while the index of the kinematic mode was:

$$K = \frac{V}{V_\tau} = \frac{7{,}5\times10^{-3}}{1{,}866} = 0{,}004. \qquad (10)$$

The obtained value is within the desirable values of $K<0.55$ of the index of the kinematic mode as a result of theoretical research.

Conclusions

The research indicates a regression relationship between vibrocutting force, force components and the three main factors of common reed vibrocutting.

It is noteworthy that the the process of vibrocutting with a 2.5 mm amplitude gave no positive results with a sharp increase of the normal component of the cutting force. We then tested vibrocutting with several times larger amplitudes, *i.e.,* 8 mm, 10 mm and 14 mm. These experiments revealed that the minimum energy load of
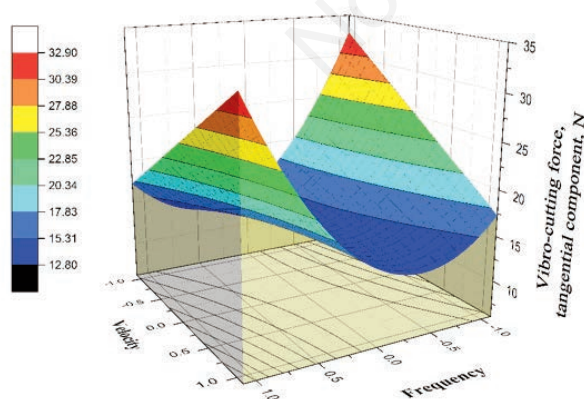
vibrocutting is obtained if $A = 14$ mm, $n = 33.32$ s^{-1} and $V = 7.5\times10^{-3}$ m s^{-1}, in case of vibrocutting with a toothed blade having a height of 4mm and a tooth spacing of 4 mm.

As a result of the theoretical research, the defined desirable value of $K<0.55$ of the index of the kinematic mode was confirmed by the results of scientific and experimental studies of the vibrocutting force with an experimental value equal to $K\cong0.004$.

The analyses of the laboratory results indicated that vibration frequency had a comparatively great impact on the tangential component of the cutting force during vibrocutting, while the normal component was largely affected by the vibration amplitude.

The obtained results can serve as a basis for designing cutting devices based on the principle of vibrocutting, as well as for conducting further research works in this sector.

These results will serve as a basis for further research works, in particular for studying and calculating plant vibrocutting devices in a dense medium (*e.g.,* water, soil).

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Figure 8. The family of curves of surface reaction (for fine-toothed blade), which characterizes the tangential component of the cutting force (Y_T^L,N), depends on normal component (X_3) of the cutting speed and vibration frequency (X_2).