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Theoretical research on vibratory cutting of the plants stems in the dense environment: cutting with vibration

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A B S T R A C T

The second article of the current series deals with the issue related to the vibratory stems cutting of the plants in the dense environment, and in the water medium, in particular. A model and design schedule have been recommended, which enable to reveal the cutting effect with vibro-blade and the reasons promoting the significant decrease in the energy consumption of the cutting apparatus. As a result of theoretical investigations it has been found out that the vibro-cutting of the water plants (cane) stems enable to reduce the environmental resistance force factors in 10÷35 times and, therefore the energy efficiency grows up.

Keywords: Reservoirs and channels, Water plants, Dense medium, Vibro-cutting, Resistance forces, Energy efficiency

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Introduction

In the previous series of the current article it was already mentioned and justified that cleaning the reservoirs and channels from the water plants is an urgent issue worldwide [1].

The analyses of the operational indices and structures in the machines and particularly in their cutting apparatus designed for the solution of the mentioned problem indicate that they do not provide the needed efficiency and do not completely comply with the requirements of the technical and technological design.

The application of segmented cutting apparatus for the above mentioned purposes causes a number of difficulties both from the structural and technological perspectives. First, the imperative distance between the tractor and the cutting apparatus implies the use of a complex transmission mechanism with great marginal sizes, then such apparatus have got a high rate of rigidity in the knife blades, which doesn't allow to gage the segmented profile of the channels.

In this regard rotary cutting apparatus are preferable for cutting the plants stems and roots in the dense media (water, soil); anyhow, the experiments aimed at their application also doomed to failure [2], [3, 4]. The matter is, that in order to implement cutting without any pillars in the rotary cutting apparatus, the marginal cutting points should have 30÷50m/s linear velocity [2, 5]. Such velocities in the blades lead to an abrupt growth of resistance forces in the water and soil medium, which results in a rapid decrease of the rotation numbers in the rotor and hence, in the decrease of cutting velocities [1, 3]. In order to ensure the needed cutting velocity a rapid growth in the torque moment applied to the rotor's shaft or its equivalent horsepower should be provided. In the result of our theoretical and scientific-experimental investigations it has been proved that the double increase in the rotation numbers of the rotary cutting apparatus in the water environment leads to the growth of the torque moment or the horsepower in about five times [1,3].

All attempts to improve and update the existing cutting apparatus aimed at their efficiency increase in the dense environment were useless regarding the expected results [4]. Therefore, the only way to solve this problem is to design a fundamentally new cutting apparatus.

Throughout the long-term search for the problem solution and upon the laboratory and field research experiments it has been found out that the vibratory cutting is the most rational method for implementing efficient cutting with low energy consumption in such dense environments, like water (cutting of cane and cane-like plants) and soil (cutting of essential oil plants). In case of applying this method, the blade carries out moving (supplying) motion with low velocity (1÷5m/s) and vibratory motion in the cutting plane with low amplitude (2÷8mm) and relatively high frequency ($50 \div 500 s^{-1}$) [2, 3, 6].

In the result of theoretical researches carried out on the vibratory cutting, the apparent advantages of the abovementioned cutting methods have been justified and some expressions have been derived, which enable to determine the parameters of the cutting apparatus [2, 3]. Nevertheless, it is worth mentioning that these results are true for air medium, the density of which doesn't have any effect on the resistance forces of the blade. The only factor is the resistance force of the very stem cutting.

While studying field-related scientific works we haven't found any investigations related to the theoretical research on vibratory cutting in the dense environment.

Thus, for the complete solution of the problem it is necessary to disclose the effect of vibratory cutting in the dense environment through the theoretical researches, since it is the only way to specify the real optimal parameters of the cutting apparatus.

Materials and methods

In the previous series of the current article it was already mentioned that the issue is going to be discussed from two perspectives [1]. In the first case the cutting process in the water environment has been examined without the blade vibration. When solving the problem from this perspective the factors of resistance force (without the force of the very stem cutting) affecting the blade throughout the environment have been derived, which are the following:

– resistance friction force along the blade sheet:

$$\boldsymbol{T_x = \frac{8}{15}\rho\omega^3 \cdot \sqrt{\frac{\upsilon b}{\omega}} \cdot \ell^2 \cdot \sqrt{\ell},} \quad (1)$$

– resistance moments of the rotor shaft:

$$\boldsymbol{M_1 = \frac{c\lambda\omega^2\rho\ell^4}{8} + 4b\sqrt{\mu\rho\omega^3} \cdot \ell^3,} \quad (2)$$

$$\boldsymbol{M_2 = \frac{4}{9}\omega^3\rho\sqrt{\frac{\upsilon b}{\omega}} \cdot \ell^4 \cdot \sqrt{\ell},} \quad (3)$$

where $\boldsymbol{\rho}$ is the density of the medium ($1000 kg/m^3$, the values are related to water medium), $\boldsymbol{\mu}$ is the coefficient of viscosity (0.1kg/m·s), $\boldsymbol{\upsilon}$ is the coefficient of kinematic viscosity, ($\mathbf{1 \cdot 10^{-6}} \mathrm{m}^2/s$), **c** is the constant coefficient and depends on the form and sizes of the blade (in our case c=1.45), $\boldsymbol{\omega}$ is the rotation frequency of the rotor's shaft ($0 \div 100\mathbf{s^{-1}}$), **b** is the width of the blade sheet (0.03m), $\boldsymbol{\ell}$ is the length of the blade sheet (cutting edge) (0.3 m), **λ** is its thickness (0.001m).

In case of the mentioned numerical values of the units, when $\boldsymbol{\omega}$=$100 s^{-1}$, we have received the following expression for the resistance force factors:

$$\boldsymbol{T_x = 450\mathrm{N/s}}\ ,\ \boldsymbol{M_1 = 47.1\mathrm{N}\cdot\mathrm{m}}\ ,\ \boldsymbol{M_2 = 34.0}N \cdot m/s,$$

besides, as it has been already mentioned when the value of $\boldsymbol{\omega}$ is doubled from the $50s^{-1}$ up to $100s^{-1}$, the resistance force factors increase in up to 5 times.

Before passing to the studies of vibratory cutting, let's determine the resistance forces in case of 5 m/s velocity in the cutting edge points of the blade. It is the maximum value upon which the vibro-blade carries out its moving (supplying) motion in the water medium, so when $\boldsymbol{v = 5m/s}$, $\boldsymbol{\omega = 25s^{-1}}$. In case of the mentioned value of $\boldsymbol{\omega}$ we have the following expression:

$$\boldsymbol{T_x = 14.0N/s\ ,\ M_1 = 5.0N \cdot m\ ,\ M_2 = 1.06N \cdot m/s.}$$

Even upon the most approximate estimations when decreasing $\boldsymbol{\omega}$ from $50s^{-1}$ (the maximum threshold limit where the stem cutting occurs) to $25s^{-1}$ (twice) the resistance force factors are reduced in about 5 times. So, the theoretical and experimental investigations evidence that in case of low moving velocities (1÷5m/s) of the blade the resistance of the dense environment rapidly declines.

Similarly, it is indisputable that in case of the mentioned velocities (1÷5m/s) it is impossible to cut the plants stems without pillars. Anyhow, when the blade receives vibratory movement in case of the mentioned velocities, it becomes possible to carry out clean cutting of the stems with low energy consumption [2,3].

In the result of our theoretical researches we have derived the following expression for the critical forces of the stems vibratory cutting [3].

$$\begin{aligned} P_{cr} = {} & \frac{D}{2b}\delta\cdot\Delta\cdot\sigma_p + \frac{2D^2{\sigma_p}^3\cos\gamma}{2\pi E^2\cos\varepsilon}(ctg\,\gamma\cdot\cos\gamma+\mu\sin\gamma)\cdot \\ & \cdot\Big\{[\sin\varepsilon-\cos\gamma\,tg\,\varphi\,(1-\cos\varepsilon)]\sin\gamma\,tg\,\varphi\cos\omega t+ \\ & +\left[\sin\varepsilon\cos\gamma+\frac{2}{\pi}tg\,\varphi\,(\sin^2\gamma+\cos\varepsilon\cos^2\gamma)\cos\omega t\right]+ \\ & +[tg\,\varphi\cos\omega t\,(\cos\varepsilon-\sin\varepsilon\cos\gamma\,tg\,\varphi)]\Big\}, \end{aligned} \tag{4}$$

where $\boldsymbol{D}$ is the diameter of the cutting stem (D=20mm, the mentioned and further numerical data are related to our experiments conducted on the stem cutting of the cane), b is the amplitude of the blade vibration- b=8mm, $\boldsymbol{\delta}$ is the thickness of the blade - $\boldsymbol{\delta = 0.1}mm$, Δ is the width throughout the blade teeth - $\Delta = \mathbf{3.0}mm$, $\boldsymbol{\sigma_p}$- is the decomposition strain in the matter of the cane stem (mainly sclerenchyma and epidermis) - $\boldsymbol{\sigma_p} = \mathbf{20}N/mm^{\mathbf{2}}$, E is the elasticity module of the cane stem - $\boldsymbol{E} = \mathbf{200}N/mm^{\mathbf{2}}$, $\boldsymbol{\varphi}$ is the friction angle of the cane with the steel - $\boldsymbol{\varphi} = \mathbf{45}^{\circ}$, $\boldsymbol{\gamma}$ is the angle formed by the forward movement of the blade cutting edge and the cutting apparatus - $\boldsymbol{\gamma} = \mathbf{0} \div \mathbf{90}^{\circ}$, $\boldsymbol{\varepsilon}$ is the blade fixation angle - $\boldsymbol{\varepsilon} = \mathbf{30}^{\circ}$, $\boldsymbol{\omega}$ is the frequency of the blade vibration - $\boldsymbol{\omega} = \mathbf{0} \div \mathbf{100}s^{-\mathbf{1}}$.

The diagram of the changing value in critical force $\boldsymbol{P_{cr}}$ during a stem cutting of the cane depending on the vibration frequency of the blade in terms of the mentioned numerical values in the air medium is introduced in fig. 1. The experiments have been conducted on two blade types: flat blade and that of with toothed cutting edges.

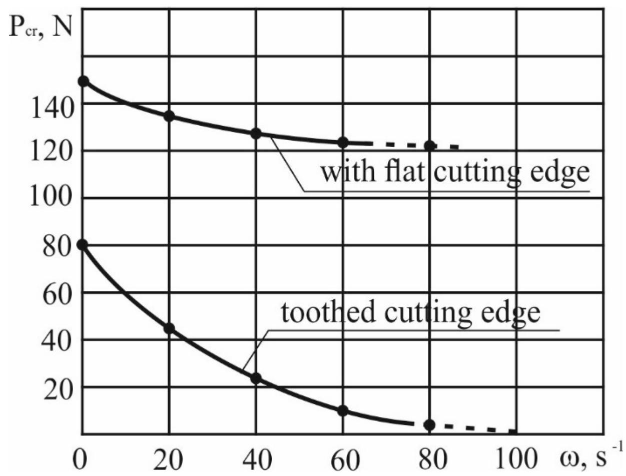

Fig. 1. *The dependence of the critical force P_{cr} of a stem cutting in the cane on the blade vibration frequency ω, (ε=30°, γ=45°) (composed by the author).*

The diagram (Fig. 1) shows that though in both cases the changing regularity of the critical force depending on the vibration frequency is the same, the critical force declines parallel to the frequency increase and their absolute values are quite different.

In case of the toothed cutting edge the value of the critical force is much lower, moreover, together with the increase of the value in $\boldsymbol{\omega}$ the discrepancy grows up. For example, when $\boldsymbol{\omega} = \mathbf{20}s^{-1}$, the critical force for the toothed cutting edge is lower in about 2.8 times, while when $\boldsymbol{\omega} = \mathbf{80}s^{-1}$, the declining discrepancy makes about 13 times [3].

The research experiments have shown that in case of vibratory cutting the blade should have toothed cutting edge which is of utmost practical significance.

In water environment the ratio of the cutting critical forces in the very stem is not subjected to considerable changes. The needed power (torque moment) transmitted to the rotor of the cutting apparatus rapidly grows up due to the environmental resistance. Besides, the latter exceeds the real cutting forces in 4÷5 times [1, 3, 6].

By numerous experiments [2, 3] it has been stated that in the air medium the blade vibration can be accompanied with high velocities (30÷80m/s), while in the dense environment it doesn't work due to the high rate of environmental resistance forces and unjustified energy consumption.

As it has been mentioned above, according to the expressions (1), (2) and (3) the decrease of the rotation frequency in the rotor already leads to the abrupt reduction of the environmental resistance forces. Anyhow, it is worth mentioning that the main reason for the decrease in the environmental resistance force caused by the blade vibration is not possible to explain through the mentioned expressions.

Results and discussions

For the solution of the current problem let's make use of a design schedule. Since we have already proved that it is relevant to conduct the plant stem cutting in the mutually vertical directions of the blade cutting edge in conditions of balanced oscillations [3], it is necessary to select the blade vibration through the elliptic law in order to disclose the vibro-cutting effect [2, 3, 7, 8].

Upon the mentioned law the vibration movement is transmitted to the blade by means of electromagnetic vibro-generator installed in the waterproof case of the rotor in the laboratory unit used for the study of plants stems vibro-cutting in the water medium [1].

The cutting edge points of the vibro-blade carry out complex movements which consist of the following moving modes:

- rotational or supplying movement of the blade with $\boldsymbol{\omega}$ angular velocity,
- vibratory complex movement along the blade cutting edge with $\boldsymbol{a}_{(x)}$ amplitude and $\boldsymbol{\omega}_{(x)}$ frequency,
- blade movement in vertical direction against the cutting edge with $\boldsymbol{a}_{(z)}$amplitude and $\boldsymbol{\omega}_{(z)}$ frequency.

The velocity of the arbitrary C point of the cutting edge in the vibro-blade will be determined in the following way:

$$\bar{\mathbf{v}}_{\mathbf{c}} = \bar{\mathbf{v}}_{\mathbf{c}}^{\mathrm{rot}} + \bar{\mathbf{v}}_{\mathbf{c}}^{\mathrm{vibr}}, \tag{5}$$

where $\bar{\mathbf{v}}_{\mathbf{c}}^{\mathrm{rot}} = \boldsymbol{\omega}\mathbf{r}$ (r is the rotation radius of the C point), $\bar{\boldsymbol{v}}_{\boldsymbol{c}}^{\mathrm{vibr}} = \bar{\boldsymbol{v}}_{\boldsymbol{a}(\boldsymbol{x})} + \bar{\boldsymbol{v}}_{\boldsymbol{a}(\boldsymbol{z})}$.

The vibration velocities in the direction of x and z axes will be:

$$\begin{aligned} \bar{\mathbf{v}}_{\mathbf{a(x)}} &= \mathbf{a}_{(\mathbf{x})} \cdot \bar{\boldsymbol{\omega}}_{\mathbf{x}} \sin \boldsymbol{\omega}_{\mathbf{x}} \mathbf{t}, \\ \bar{\mathbf{v}}_{\mathbf{a(z)}} &= \mathbf{a}_{(\mathbf{z})} \cdot \bar{\boldsymbol{\omega}}_{\mathbf{z}} \cos \boldsymbol{\omega}_{\mathbf{z}} \mathbf{t}\,. \end{aligned} \tag{6}$$

The diagram on the determination of the vibro-blade kinematic parameters is introduced in figure 2.

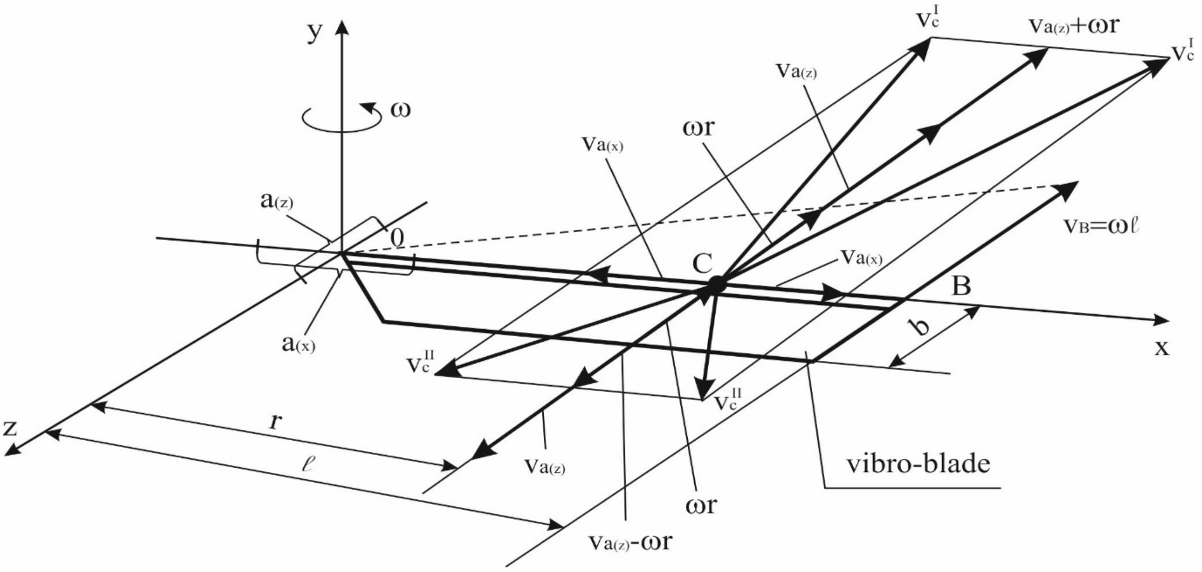

Fig. 2. *The diagram on the determination of vibro-blade kinematic parameters (composed by the authors)*

Upon the previously conducted theoretical and experimental investigations it has been proved that efficient vibro-cutting occurs, when $a_{(z)} = 0.1a_{(x)}$, $\boldsymbol{\omega}_{(x)} = \omega_{(z)} = \omega_1$ [3, 6].

Taking into account the aforementioned, for the C point of the vibro-blade cutting edge we'll get the following expression:

$$\bar{\mathbf{v}}_{\mathbf{c}} = \bar{\boldsymbol{\omega}}\boldsymbol{r} + \mathbf{a}_{(\mathbf{x})}\bar{\boldsymbol{\omega}}_{\mathbf{1}} \sin \boldsymbol{\omega}_{\mathbf{1}}\boldsymbol{t} + \mathbf{0.1a}_{\mathbf{x}}\bar{\boldsymbol{\omega}}_{\mathbf{1}} \cos \boldsymbol{\omega}_{\mathbf{1}}\boldsymbol{t}. \quad (7)$$

The last expression testifies that depending on the vibration's phase-frequency ratio in the mutually vertical directions the velocity of the C point will have different directions and values. The 4 extreme values and directions of the mentioned velocities are depicted in figure 2. Thus, the values of the velocities will be:

$$\boldsymbol{v_c^I} = \sqrt{(\boldsymbol{\omega r} + \boldsymbol{v_{a(z)}})^2 + \boldsymbol{v_{a(x)}}^2}, \quad \boldsymbol{v_c^{II}} = \sqrt{(\boldsymbol{v_{a(z)}} - \boldsymbol{\omega r})^2 + \boldsymbol{v_{a(x)}}^2},$$

or by inserting the abovementioned values we'll have:

$$\boldsymbol{v_c^I} = \sqrt{(\boldsymbol{\omega r} + \mathbf{0.1}\boldsymbol{a_x \omega_1 \cos \omega_1 t})^2 + (\boldsymbol{a_x \omega_1 \sin \omega_1 t})^2},$$
$$\boldsymbol{v_c^{II}} = \sqrt{(\mathbf{0.1}\boldsymbol{a_x \omega_1 \cos \omega_1 t} - \boldsymbol{\omega r})^2 + (\boldsymbol{a_x \omega_1 \sin \omega_1 t})^2}. \quad (8)$$

The received expressions show that the changing picture in the velocities of the cutting edge points of the blade is complicated, i.e. the velocity vector varies not only in the given point, but also along the cutting edge due to $\boldsymbol{\omega r}$ component ($0 \leq \boldsymbol{\omega r} \leq \boldsymbol{\omega l}$).

Since our discussions are related particularly to the vibration effect on the movement and resistance of the water environment, it is relevant to consider the moving components separately to simplify the solution of the problem. The effect of the velocity reduction in the blade's rotational movement on the rapid decrease of the resistance forces in the water environment has been already considered above. Let's turn to the design schedule used in the previous series of the related article to disclose the impact of the vibration movement on the resistance forces in the water environment [1, Figure 4].

When discussing the first part of the problem it has been found out that the resistance forces of the environment are mainly related to the liquid mass put into motion as a result of the blade movement [9, 10]. The liquid layer passing close to the blade surface gets the blade velocity and due to the internal friction of the fluid particles in the vertical direction to the blade surface the velocity gradually declines getting equal to zero in the distance of $\boldsymbol{\delta} = \sqrt{\frac{\boldsymbol{vb}}{\boldsymbol{k\omega r}}}$ [1].

The design schedule of the case study will look as follows (Fig. 3) (composed by the authors).

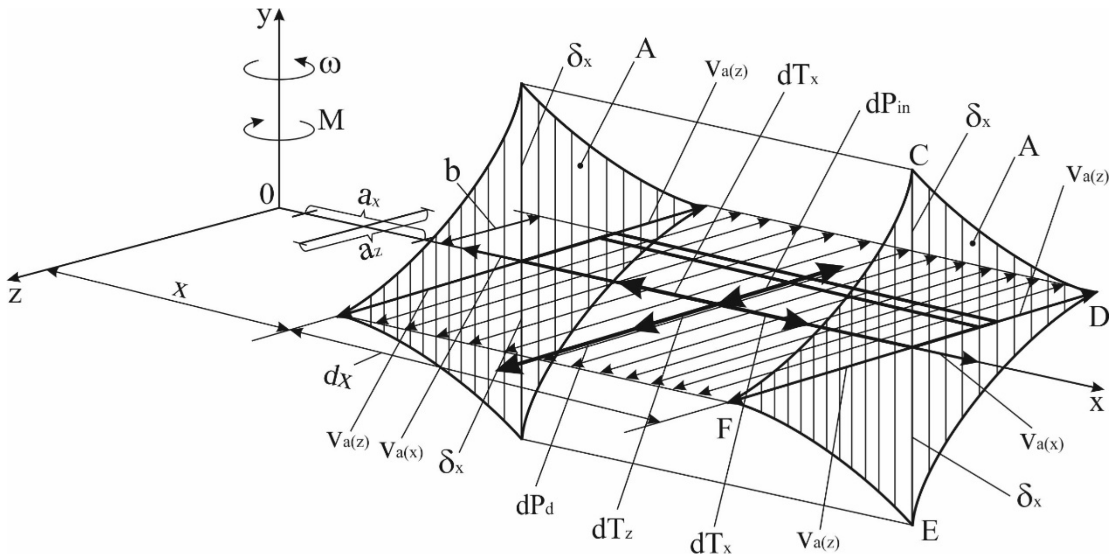

Fig. 3. *The diagram on determination of the resistance forces of the vibro-blade movement in the rotary cutting apparatus in water medium (composed by the authors).*

The water mass flow with basic volume in motion will be [1]:

$$\boldsymbol{dm = \rho\, dQ.} \tag{9}$$

In case of the blade vibration the moving water mass is surrounded by the surface with A base (unlike the first part of the discussed problem, in this case A is constant $along\ \ the\ \boldsymbol{l}$ length of the blade) and is within the volume of elementary prism $\boldsymbol{dQ}$ with dx height. The prism base is a combination of four parabolic triangles with δ_x and $v_{a(z)}$ sides, besides, the water mass within the prism volume changes the moving direction during one oscillation phase $\boldsymbol{t = \frac{1}{\omega_1}}$ caused by the vibratory movement and hence, the epure of the liquid motion velocities towards the vertical directions of the blade sheet will look as introduced in Fig. 4.

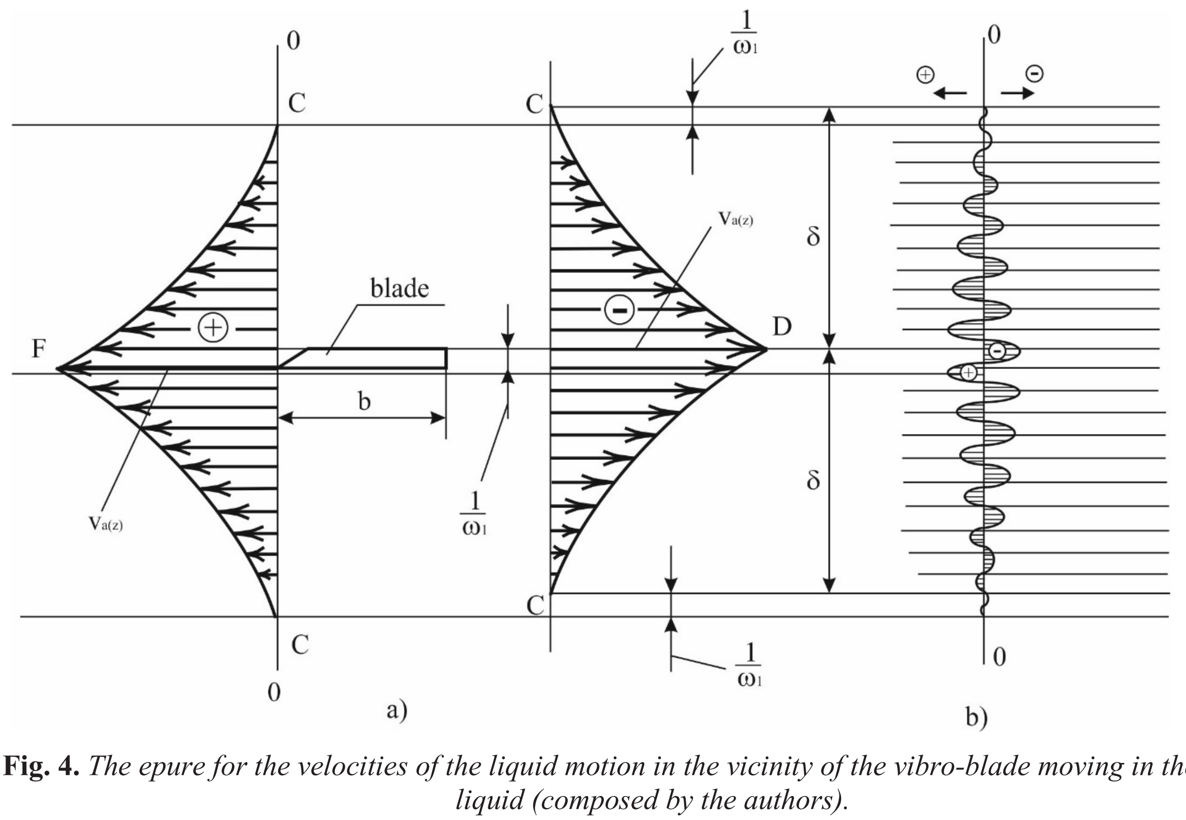

Fig. 4. *The epure for the velocities of the liquid motion in the vicinity of the vibro-blade moving in the liquid (composed by the authors).*

The particles of the liquid, getting in touch with the surfaces of the upper and lower b·dx (for the entire blade $\boldsymbol{b} \cdot \boldsymbol{l}$) blade areas. receive a motion in one direction $\frac{1}{2\omega_1}$, and after a second the new layers getting in touch with the mentioned surfaces get a motion in the opposte direction, while the particles of the former layers lose the velocity due to the lack of impulse signal in the previous direction, and the velocity gradually equals to zero. To get the summary epure of the velocities for the liquid particles in the vibro-blade vicinity it is necessary to reset the successive epures of the velocities considering their phasal deviation. As a result we'll get the summary epure for the velocities (Fig. 4 b).

It is easy to notice that the total area of the summary epure can be practically accepted as equal to zero, besides, the higher the vibration's frequency ω_1 is, the more reliable the abovementioned assumptions are. So, if the volume of the vibration-induced moving liquid is practically equal to zero (summary area of the elementary prism base: A→0), then the fluid mass in motion is $\boldsymbol{dm = 0}$ and all force factors, which are related to the fluid mass flow and generate resistance forces in the environment, practically become equal to zero. The afore mentioned is similarly applicable to the vibration towards the blade longitudinal direction.

In the previous series it was mentioned that the blade moving in the liquid medium is affected by the following resistance forces [1,9,10]:

1. friction forces in the longitudinal direction of the blade sheet:

   $\boldsymbol{T_x = \frac{8}{15}\rho\omega^3 \cdot \sqrt{\frac{\upsilon b}{\omega}}\ell^2 \cdot \sqrt{\ell} = 0}$, because $\boldsymbol{T_x}$ is related to the mass flow in motion which is equal to zero.
2. inertia forces $\boldsymbol{P_{in}} = -\frac{2\omega^3 x^3 \rho}{b} \cdot \sqrt{\frac{\upsilon b}{\omega x}}\boldsymbol{dx},$ upon the same reason those forces are also equal to 0: $\boldsymbol{P_{in} = 0}$.
3. friction force in the latitudinal directions of the blade sheet: $\boldsymbol{T_z = 6b\sqrt{\mu\rho\omega^3 l^3} \neq 0}$, which is related to the rotation velocity of the blade.
4. Hydrodynamic resistance force:

   $\boldsymbol{P_d = c\lambda\omega^2\rho\frac{l^3}{2} \neq 0}$, this is also related to the blade rotary movement.

Thus, from the resistance force factors of the blade motion only $\boldsymbol{M_1}$ is available in case of vibration, the value of which is related to $\boldsymbol{T_z}$ and $\boldsymbol{P_d}$ forces [1].

$$\boldsymbol{M_1 = \frac{c\lambda\omega^2\rho\ell^4}{8} + 4b\sqrt{\mu\rho\omega^3} \cdot \ell^3}. \quad (10)$$

As it has been already mentioned, in case of vibratory cutting the blade rotation velocity (1.0-5.0m/s) is much lower than that of the stem cutting velocity (30-50m/s) without any pillars, as a result of which the resistance forces of the water environment rapidly decrease. Assuming that the rotary movement velocity in the vibro-blade is 3.0m/s ($\omega = 10\text{s}^{-1}$) and inserting the numerical values of the units - $\boldsymbol{\rho} = 1000\text{kg/m}^3$, $c = 1.45$, $\boldsymbol{\mu} = 0.1\text{kg/m} \cdot \text{s}$, $\text{b} = 0.03\text{m}$, $l = 0.3\text{m}$, $\lambda = 0.001\text{m}$ [1] in the expression (10), we'll have $M_1 = 1.315\text{N} \cdot \text{m}$.

In case of cutting without vibration the values of the resistance moment will be as follows:
when $\omega = 50\text{s}^{-1}$, $M_1 = 15.13\text{N} \cdot \text{m}$, when $\omega = 100\text{s}^{-1}$, $M_1 = 47.1\text{N} \cdot \text{m}$,
that is, in case of vibratory cutting not only a number of resistance forces are neutralized, but also the current force factor is also reduced in 10-35 times depending on the critical velocity needed for cutting.

Thus, the model and design schedule recommended for the solution of the problem enable to disclose the reasons for abrupt decrease of resistance forces in the water environment during the vibratory cutting.

The obtained results and particularly the summary epure for the velocities of the fluid motion in the vibro-blade vicinity serve as a background for conducting further discussions and finding new solutions for the current problem. Considering the fluid movement in the vertical directions against the upper and lower areas of the vibro-blade sheet as a shock (dying) oscillations, the problem can be theoretically interpreted otherwise, which can result in a more precise interpretation on the vibro-cutting effect in the dense medium and in the new opportunities for disclosing its consequences. The chapter related to the mentioned research aspects will be presented in the upcoming series.

Conclusion

1. A model and design schedule has been recommended, which enable to theoretically disclose and describe the stem's vibro-cutting effect in the dense environment.
2. Theoretical expressions have been derived, which enable to determine the factors of the resistance forces in the dense medium and their decline in case of stem cutting with vibratory blade. Particularly, it has been stated, that in case of implementing vibratory cutting in the water environment some part of environmental resistance force factors are missing at all, while the others decrease in 10÷35 times related to the cutting velocity.
3. The results obtained through the theoretical researches match up with those enhanced through scientific-experimental way with only 5 % deviation.

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