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Theoretical Research on Vibratory Cutting of the Plants Stems in the Dense Environment: Vibrationless Cutting

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ABSTRACT

The first article of the series considers the results of theoretical research on the plants stems cutting in dense environment (water, soil). It has been proved that in case of necessary technological speeds in the blades of the rotary cutting apparatus the resistance forces of the environment are much more extensive than the force of the very stem cutting. The double increase in the rotation numbers of the rotor in the cutting apparatus brings about the increase in the resistance forces of the environment in about five times, which makes the use of the cutting apparatus of the mentioned series quite irrelevant from the technical and technological perspective.

Introduction

Cleaning the reservoirs and channels from the water plants, particularly from the canes and the plants of the same family is still an urgent issue worldwide.

The analysis of the work and structure of cutting apparatus used for the abovementioned purpose, provides a base to state that irrespective of the structural and operational characteristics, the current cutting machines are not applicable in the dense environment (water, soil) during the plant cutting process.

The trials on the application of the available cutting tools in water environment (for cleaning the reservoirs and channels from vegetation) and in the soil (for cutting and removal of the root crop tops, for single harvesting of tomato, as well as for that of different essential oil crops) haven't recorded any success, since in all cases a rapid deterioration in the technical and exploitative indices has been observed (Tarverdyan, 1996).

The aforementioned is mainly conditioned by the high values (30 ... 50 m/s) of the absolute speed in the blades of cutting machines.

In case of high speeds in blades the forces of motion resistance, therefore the rate of energy consumption rapidly grow up in the dense environment. The abrupt growth in the resistance forces leads to the decrease of the rotation frequency in the rotor of the apparatus, which in its turn entails to the deterioration of the cutting quality, particularly, the most part of the stalks remain uncut in the water environment, the plants harvesting technological process is disturbed; besides, the exploitative indices of the cutting apparatus sharply decrease.

All experiments aimed at the elimination of the mentioned shortcomings by means of structural improvements and changes of kinematic parameters in the existing apparatus have doomed to failure (International Scientific Research Institute of Economics and Technology (ISRITE), Moscow, 1978).

Consequently, a necessity has appeared to develop an apparatus with new structural and working principles in order to implement cutting of the plants in dense environment.

As a result of multiple experimental researches on cutting of thin and thick-stemmed stiff crops in laboratory conditions, in aquatic environment and in 10…20 cm soil stratum, it has been proved that the most rational cutting method with the least energy consumption is recorded when the blade carries out a complicated motion with vibration of high frequency and low amplitude and with a movement of relatively low velocity (Tarverdyan, 1996, Tarverdyan, 2014).

Upon the researches it has been found out that the cutting apparatus with plane rotors best meet the mentioned requirements.

Throughout the solution of the problem several variants of rotary vibrational cutting apparatus have been developed, prepared and put into practice under the production conditions (Tarverdyan, 1996, Tarverdyan, 2014).

The trials carried out in water and soil conditions have shown that the abovementioned tools provide full cutting of the stems with minimum energy consumption, at the same time providing high indices of exploitative reliability.

In the result of theoretical studies the apparent advantage of vibratory cutting has been stated and justified, as well as some expressions have been derived which enable to determine the optimal values of kinematic and dynamic parameters in the vibratory cutting equipment (Tarverdyan, 2014).

Materials and methods

It is worth mentioning that no theoretical investigations on vibratory cutting are carried out in dense environment and we have hardly ever found such research results while studying various volumable research works related to this sector. Thus, we have set a task to study the vibratory cutting processes in dense environment theoretically with the aim of disclosing the principle of vibratory cutting with low energy consumption in dense environment. It is clear that only after the identification of the characteristics and principle of the vibratory cutting it will be possible to develop and design a cutting apparatus with optimal parameters in order to work in dense environments. Despite the experiments which have indicated on the optimal features of the equipment, the holistic image of the discussed apparatus is possible to introduce only through the theoretical researches.

Based on the goals set the problem has been divided into two parts:

First, it is necessary to study the cutting process in dense environment (water) without the blade/knife/ vibration.

Second, it is necessary to study the process in the same conditions upon the blade vibration.

It is noteworthy that the vibration cutting of the plant stems in the aerial environment has been studied comprehensively and cutting theories have been developed, which enable to accurately describe and identify the vibro-cutting principle. Based on the obtained results and conclusions cutting apparatus have been designed. The results of the mentioned investigations are introduced thoroughly and explicitly in some research works (Tarverdyan, 1996, Tarverdyan, 2014). In the current study these results will serve as special basic control data.

Let's consider the vibro-blade/knife as an object at rest plunged in the boundless water environment, which receives motion. So, in the first considered case the blade/ knife receives only rotational shifting motion without any vibratory motion (Fgure 1).

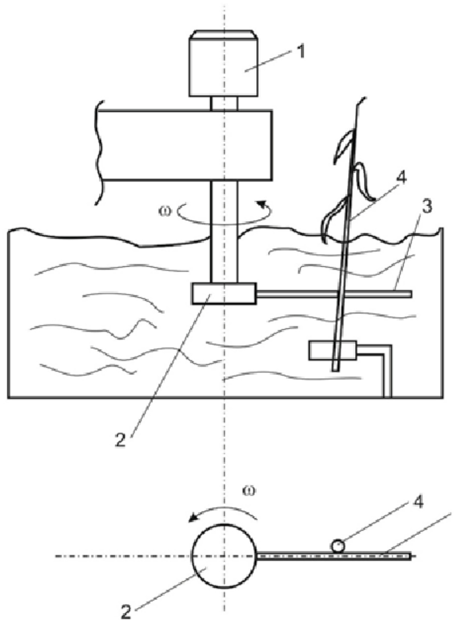

Figure 1. Diagram of the plant for the study of plants stem cutting in water environment (*composed by the authors*).

The motion from the electrical motor 1 is transferred to the rotor 2, which rotates in the water medium and its blade/knife 3 cuts the plant 4 enrooted in the water. In order to transmit rotational motion to the blade a certain energy amount is needed, so as to cut the plant stems and to handle the resistance. The conclusion about the drag force exerted by the liquid towards the body moving just in its medium was drawn still by Newton stating that the drag/resistance force should be proportional to the projection surface of the body on the plane which is vertical to the movement, to the liquid density and to the squared velocity of the body movement (Milne-Thomson, 1964, Prandtl, 2000).

Anyhow, later on it was found out that it didn't address the real image of the body and liquid interactions and that the drag force of the liquid/fluid is resulted from the discrepancy of the pressure and tangential stresses caused throughout the fluid streamline. Besides, the component caused by the difference of pressures in the resistance is predominant.

This difference is proprtional to the dynamic pressure $\frac{\rho v^2}{2}$, therefore, the resistance is proportional to the product of the pressures difference and to the body surface area which is influenced by it (Milne-Thomson, 1964, Prandtl, 2000).

$$F = c \cdot A \cdot \frac{\rho v^2}{2},$$

where c is the resistance coefficient and it depends on the Reynolds number: $R = \frac{v \cdot b}{\upsilon}$, where v is the velocity of the body movement (cm/s), b is the body length towards the movement (in our case it is the blade width) expressed in cm, υ is the kinematic viscosity of the fluid expressed in cm^2/s; for water under the conditions of 20 ^{0}C $\upsilon=0.01$ cm^2/s ($\upsilon = \frac{\mu}{\rho}$, μ is the viscosity coefficient, for water μ=0.01 g/cm·s).

In our case the blade carries out rotational movement, moreover the blade plane overlaps with that of rotational movement. In the blade motion zone the speed of the fluid movement drifting apart from the blade surface through vertical directions gradually equals to 0, which is related to the friction forces. The distribution epure for the speeds is presented in figure 2.

If the boundary zone of the velocity changes comes forth as a value of δ type and the body size (the blade width) towards the movement is b, then the friction force per a volume unit will be (Prandtl, 2000):

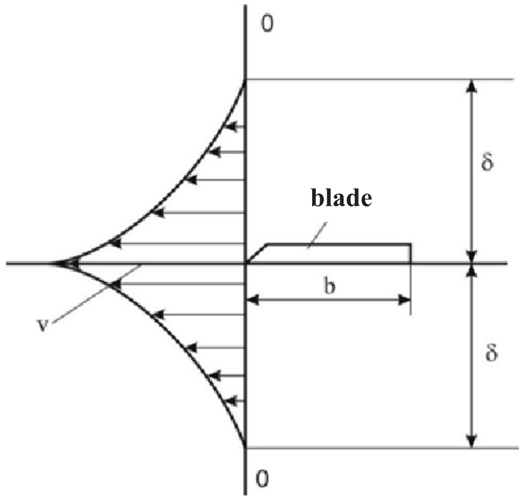

Figure 2. The epure of the fluid motion velocity in the vicinity of the blade moving in its medium (*composed by the authors*).

$$F_{fr} = \mu \frac{\partial^2 u}{\partial y^2},$$

which has the following value: $\frac{\mu \cdot v}{\delta^2}$, while the inertia force per a volume unit will be $\frac{\rho v^2}{b}$ and since in the boundary stratum these two forces are values of similar category, hence:

$\frac{\mu v}{\delta^2} = k \cdot \frac{\rho v^2}{b}$, from which $\delta = \sqrt{\frac{\mu b}{k \rho v}}$ or $\delta = \sqrt{\frac{\upsilon b}{k v}}$, from which $\frac{\delta}{b} = \sqrt{\frac{\upsilon}{k v b}} = \frac{1}{\sqrt{kR}}$, since k is a constant coefficient of relativity, therefore $\frac{\delta}{b}$ is a function only from the Reynolds number. This dependence is true for all boundary strata in case of constant movement (Prandtl, 2000).

The overall complexity and peculiarity of our task consists in the fact that the blade carries out rotational movement, consequently the points of the cutting margin along the whole cutting length have variable speeds, which change upon the rotation axis with the following regularity: $v = \omega \cdot r_x$, where ω is the rotational frequency in the rotor, r_x is the current distance of the marginal point in the cutting blade from the rotation axis.

When the speed becomes a variable value δ and R also become variable values which significantly alters the principle of the task.

In case of stabilized working regime in the cutting apparatus the expression of δ will look like this: $\delta = \sqrt{\frac{\upsilon b}{k\omega \cdot r_x}}$, from which it can be inferred that the Reynolds number becomes variable along the blade cutting margin:

$$R = \frac{(\omega \cdot r_x \cdot b)}{v}.$$

Thus, the regularities of the fluid movement and resistance undergo significant changes along the longitude of the cutting edge. The fluid movement is generated not only throughout the blade width, but also throughout the length of the cutting edge; besides, the movement is generated in two ways, namely upon centrifugal forces and upon the gradient of the pressures related to the ratio of circumferential speeds. The mentioned two movements, i.e., the vertical towards the blade cutting edge and the movement along the blade cause turbulent motion in the fluid, which in its turn sharply enhances the resistance force of the blade movement.

Due to the torque moment M applied in the rotor shaft the blade conducts rotational movement in the water environment as a result of which in addition to the resistance force of stem cutting (P_c) resistance forces in the friction of water environment occur as well in the longitudinal direction of the blade cutting edge - T_x, in the vertical direction of the cutting edge - T_z, the hydrodynamic resistance force - P_d of the water medium and inertial forces (Figure 3).

Under the concept of inertial forces those generated by the speed transmitted to the water mass are meant. In case of constant working regime of the apparatus (*ω=const*) the circumferential speed is equal to 0. As in our study the speed of the blade and consequently that of the fluid movement is much higher towards the direction of z than towards the other two directions and it changes greatly in the direction of *x* axis, only one equation out of those about stress state of fluids (Milne-Thomson, 1964, Prandtl, 2000) plays a great role in the resistance determination:

$$\frac{\partial z_x}{\partial x} = \mu \frac{\partial^2 u_z}{\partial x^2},$$

where z_x is the tangential stress, u_z is the deformation towards the z_s (it is worth mentioning that in case of liquids the stresses are directly proportional not with the deformations but with their speeds).

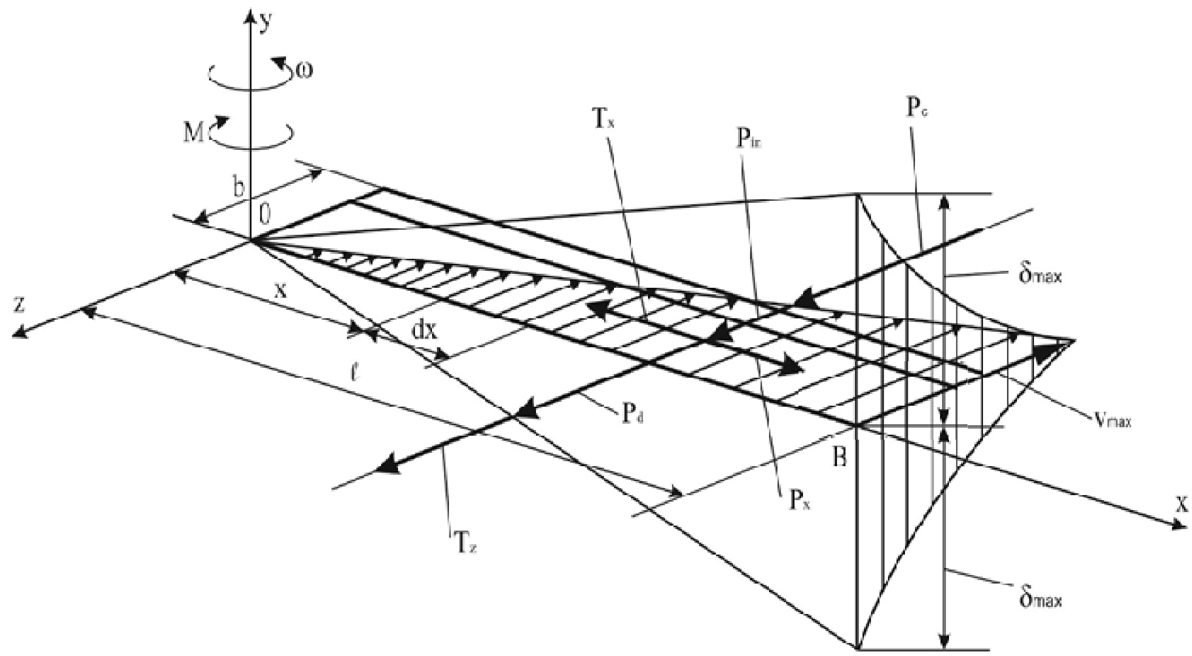

Figure 3. Diagram of resistance forces in the blade of rotational cutting apparatus in water environment (*composed by the authors*).

Results and discussions

Since in the considered case the impact of water medium on the dynamic indicators of the cutting apparatus is studied, the cutting force P_c can be ignored as a factor, because it has practically the same value both in aerial and aquatic environments. In other words we are interested only in such force factors which are generated upon the effect of water environment. In figure 3 the boundary zone of the moving fluid mass resulted from the blade rotational movement at the top point of the blade cutting edge is δ_{max} illustrated.

In order to determine the resistance forces let's cut *a* section from the blade starting point to the current *x* distance, then let's provide *x* with elementary progress, second section (Fgure 3) and consider the equilibrium terms of the movement in the isolated section (Fgure 4).

In order to determine the friction, movement resistance and inertial forces, first, it is necessary to determine the fluid mass of the isolated section being in motion as a result of the blade movement.

It is worth mentioning that in such problems we don't deal with constant static mass but with so called mass flow (Milne-Thomson, 1964, Prandtl, 2000).

The water mass flow in the movement with elementary volume will be:

$$d_m = \rho \cdot d_Q, \qquad (1)$$

where ρ is the water density, d_Q is the water volume flow involved in the elementary moving volume.

Considering the isolated part as a pyramid intersected with parabolic triangle bases we can have the following expression:

$$d_Q = \left[A_x + \left(A_x + dA_x \right) + \sqrt{A_x \cdot \left(A_x + dA_x \right)} \right] \cdot \frac{d_x}{3}, \qquad (2)$$

where A_x and $A_x + dA_x$ are the areas of the intersected pyramid bases (Fg. 4):

$$A_x = \frac{2}{3} \cdot \delta_x \cdot \mathbf{v}_x, \qquad (3)$$

where δ_x is the height of boundary stratum in the speed changes of the water movement caused by the blade motion in one face of the blade plane,

$v_x = \omega \cdot x$ is the speed of the x coordinate point of the blade cutting edge, ω is the rotation frequency of the rotor (it is accepted as a constant value).

So by placing the values we'll have:

$$A_x = \frac{2}{3} \omega \cdot \delta_x \cdot x, \qquad (4)$$

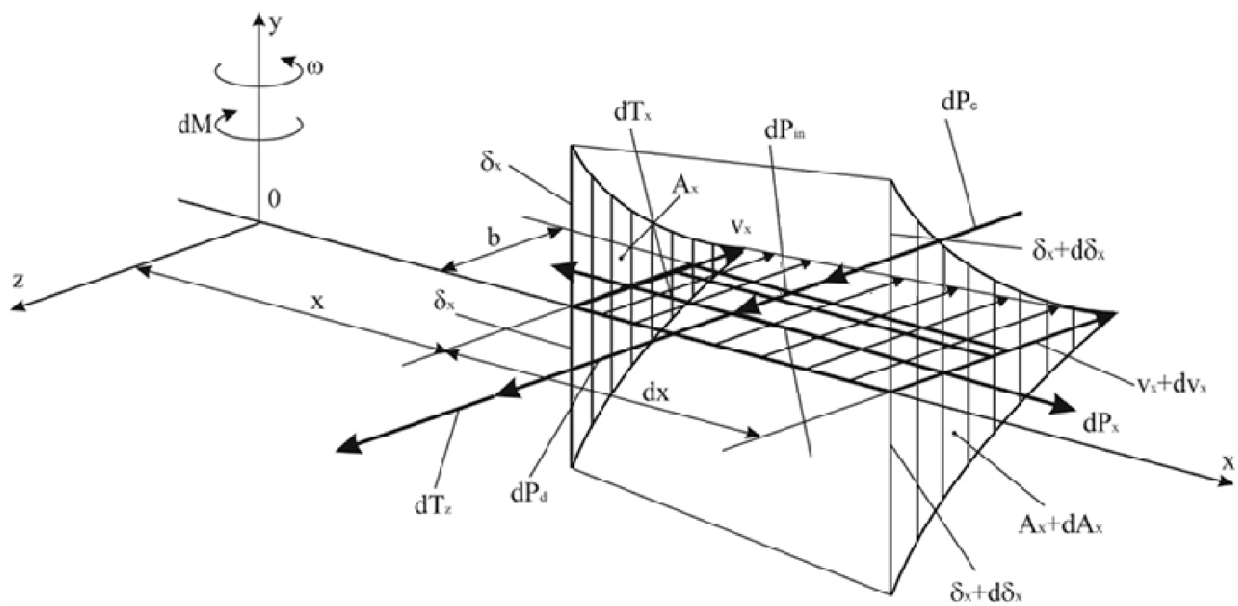

Figure 4. Diagram of the determination of the blade motion resistance forces in the rotational cutting apparatus in water environment (*composed by the authors*).

$$A_x + dA_x = \frac{2}{3}\left(\delta_x + d\delta_x\right)\left(\mathbf{v}_x + d\mathbf{v}_x\right). \quad (5)$$

The derived expression (5) is too extensive for the volume flow and consequently for the mass flow, which is not relevant for practical computations. Taking into account the abovementioned circumstance and the fact that the expression (5) in its open form contains nonfinite members of the second class, with some approximation (with deficiency) the isolated part can be considered as a prism with base. In that case we'll have:

$$dQ_s = A_x \cdot dx$$

or $$dQ_s = \frac{2}{3}\mathbf{v}_x \delta_x dx = \frac{2}{3}\omega\delta_x \cdot x \cdot dx. \quad (6)$$

For the elementary d_m mass we'll have:

$$d_m = \frac{2}{3}\omega\rho\delta_x \cdot dx,$$

considering that $\delta_x = \sqrt{\frac{\upsilon b}{\omega x}}$, for d_m we'll have:

$$d_m = \frac{2}{3}\omega\rho\sqrt{\frac{\upsilon b}{\omega x}}x \cdot dx. \quad (7)$$

The isolated elementary mass is influenced by the centrifugal force dP_x, the friction resistance force along the blade sheet length dT_x, hydrodynamic resistance force of the blade rotational movement dP_d, resistance force of the stem (s) cutting P_c, resistance force of the water movement in the transverse direction of the blade dT_z and by the relative inertial force of water and blade dP_{in}.

The equations of the movement equilibrium for the isolated section will be the following:

$\sum x=0, dP_x\text{-}dT_x=0$ or $dT_x=dP_x$, where the centrifugal force dP_x is determined in the following way (Biderman, 1980):

$$dP_x=2d_m \cdot \omega^2 \cdot xd_x. \quad (8)$$

The product 2 indicates that the friction forces appear along the blade sheet and in upper and lower surfaces; the next equation is $\sum M_y=0$ or:

$$dM_y=(dP_d+dT_z+dP_{in}) \cdot x. \quad (9)$$

The hydrodynamic resistance force is determined through the following expression (Prandtl, 2000):

$$P_d = c \cdot A_1 \cdot \frac{\rho \mathrm{v}^2}{2}, \quad (10)$$

where A_1 is the area of the facial part of the blade cutting edge: $A_1=l \cdot \lambda$,

λ is the thickness of the blade sheet.

For the isolated mass we'll have: $dP_d = c\lambda\rho\frac{\mathrm{v}_x^2}{2}dx$ or

$$dP_d = c\lambda\omega^2\rho\frac{x^2}{2}dx. \quad (11)$$

The friction resistance force is determined through the following formula:

$$T_z = 2kb\sqrt{\mu\rho\mathbf{v}^3},$$

k is the coefficient, which depends on the form and sizes of the object (blade) moving in water. In our case $k=3$ (Kochin, et al., 1942).

For the elementary isolated mass we'll have:

$$dT_z = 6b\sqrt{\mu\rho x\mathbf{v}_x^3} \text{ or } dT_z = 6b\sqrt{\mu\rho\omega^3}2xdx. \quad (12)$$

The inertial force of the relative water movement is determined through the following expression (Biderman, 1980):

$$P_{in} = -m\left(\frac{\partial^2 u_z}{dt^2}\right),$$

u_z is the shift in the direction of circular movement.

In the discussed problem the movement of the water particles on the b latitude of the blade spear point is of particular interest. The speed change of the fluid particles on the mentioned part will be $\frac{\mathrm{v}_x^2}{\mathrm{b}}$, since at the cutting edge of the blade $v_x=0$, while at the opposite edge (after crossing the b way) it acquires the maximum v_x value.

Based on these judgments for dP_{in} we'll have:

$$dP_{in} = -dm \cdot \frac{\mathrm{v}_x^2}{\mathrm{b}}. \quad (13)$$

Inserting the received values in (8), (9) and (13) expressions we'll have:

$$dT_x = \frac{4}{3}\rho\omega^3\sqrt{\frac{\upsilon b x^3}{\omega}}dx \quad (14)$$

$$dM_1 = \left(c\lambda\omega^2\rho\frac{x^3}{2} + 6b\sqrt{\mu\rho\omega^3} \cdot 2x^2\right)dx \quad (15)$$

$$dM_2 = \left(\frac{2\omega^3\rho x^3}{b}\sqrt{\frac{\upsilon b}{\omega \cdot x}} \cdot x\right)dx \quad (16)$$

$$dP_{in} = -\frac{2\omega^3 x^3 \rho}{b}\sqrt{\frac{\upsilon b}{\omega \cdot x}}dx. \quad (17)$$

The equation of the equilibrium moments in the movement was introduced through one expression (9), while the last equations for the rotation or resistance moment are presented through two equations (15) and (16). It is conditioned by the fact that the moment towards the y axis has obtained [Nm] measurability from the powers of P_d and T_z, because the expressions don't contain force factors resulted from the mass flow *dm,* meanwhile P_{in} is just related to the *dm* mass and the component of moment obtains [Nm/s] measurability from that force (dM_2).

If we assume that the impact of resistance force factors per time unit (*1 s*) is discussed, their impacts on the total resistance moment will become equal. It is necessary to consider that in the dM_2 expression the sign of dP_{in} is positive because in the diagram (Figure 3, 4) its direction is already changed.

By integrating the derived (14), (15), (16) expressions we'll have:

$$T_x = \frac{4}{3}\rho\omega^3 \int_0^{\ell} \sqrt{\frac{\upsilon b x^3}{\omega}}dx$$

$$\text{or } T_x = \frac{4}{3}\rho\omega^3 \sqrt{\frac{\upsilon b}{\omega}} \cdot \frac{2}{5}\ell^2\sqrt{\ell}, \qquad (18)$$

$$M_1 = \frac{c\lambda\omega^2\rho}{2}\int_0^{\ell} x^3 dx + 12b\sqrt{\mu\rho\omega^3}\int_0^{\ell} x^2 dx$$

$$\text{or } M_1 = \frac{c\lambda\omega^2\rho\ell^4}{8} + 4b\sqrt{\mu\rho\omega^3}\cdot\ell^3, \qquad (19)$$

$$M_2 = 2\omega^3\rho\sqrt{\frac{\upsilon b}{\omega}}\int_0^{\ell} x^{7/2} dx$$

$$\text{or } M_2 = \frac{4}{9}\omega^3\rho\sqrt{\frac{\upsilon b}{\omega}}\ell^4\sqrt{\ell}\ . \qquad (20)$$

In the laboratory plant developed and prepared by us the numerical values of the figures in (18), (19) and (20) expressions are as follows: ρ=1000 kg/m^3, υ=1·10^{-6} m^2/s, *c=1.45* (the value is related to the b/ℓ ratio; in our case it is 0.1, which corresponds to the value of 1.45 (Prandtl, 2000)), μ*=0.1 kg/m·s, b=0.03 m, l=0.3 m,* λ*=0.001 m,* $\omega \to 0 \div 100\ s^{-1}$.

By inserting the numerical values we'll have:

$T_x=4.5\cdot10^{-3}\ \omega^{5/2}$ N/s, assuming that $\omega=50$ s^{-1}, $T_x=79.55$ N/s, $\omega=100\ s^{-1}$, $T_x=450\ N/s$.

$$M_1 = 1.47\cdot10^{-3}\omega^2 + 32.4\cdot10^{-3}\sqrt{\omega^3}\ \ Nm.$$

If $\omega=50\ s^{-1}$, $M_1=15.13\ Nm$, $\omega=100\ s^{-1}$, $M_1=47.1\ Nm$.

If we take into account that for implementing efficient cutting the blade plane with that of stem latitudinal cross section should make 22÷28^0 (Tarverdyan, 1996, Tarverdyan, 2014) in the expression of M_1 we should place $b\cdot sin\alpha$ instead of λ, since in that case hydrodynamic resistance comes forth by the area of $bl\cdot sin\alpha$ (projection of the blade sheet surface area on the vertical plane of the movement). Assuming that $\alpha=26^0$, for M_1 we'll get:

$$M_1 = 19.3\cdot10^{-3}\omega^2 + 32.4\cdot10^{-3}\sqrt{\omega^3}\ Nm,$$

if $\omega=100\ s^{-1}$, $M_1=225.4\ Nm$.

So the effect of hydrodynamic resistance increases in about 5 times.

$M_2=0.34\cdot10^{-3}\ \omega^{5/2}\ \ Nm/s$. If $\omega=50\ s^{-1}$, $M_2=6\ \ Nm/s$, $\omega=100\ s^{-1}$, $M_2=34\ \ Nm/s$.

The retrieved data with the deviation of 5÷10 % coincide with the results of the preliminary experimental researches (Tarverdyan, 1996, Tarverdyan, 2014, Altunyan, 2009).

Conclusion

The numerical numbers derived for T_x, M_1, and M_2 show that the double increase of the blade speed in water environment entails to the increase of the resistance force factors in the mentioned environment in 5 times, which apparently implies an equal increase in the amount of power needed to perform cutting.

Thus, the existing cutting apparatus are not relevant at all for cleaning the channels and reservoirs from the water plants from both technical-technological and energy saving perspectives.

References

1. Tarverdyan, A.P. (1996). Technical and Technological Fundamentals of Creating Cutting Apparatus for Harvesting Machines and Mowers. Doc. thesis. Yerevan, - 383 p.
2. Tarverdyan, A.P. (2014). Application of the Vibration Theory in Agricultural Mechanics. Publishing House "Gitutyun" NAS RA, Yerevan, - 381 p.
3. Milne-Thomson, L. M. (1964). Theoretical Hydrodynamics. Publishing House "Mir", M. - 643 p.
4. Prandtl, L. (2000). Hydro Aeromechanics (translated from the second German edition of G.A. Volnert). Scientific and Publishing Center "Regular and Chaotic Dynamics", Moscow, - 576 p.
5. Biderman, V.L. (1980). Theory of Mechanical Vibrations. Moscow, "Higher School", - 480 p.
6. Kochin, N.E., Loitsanekiy, L.G. (1942). About an Approximate Method for Calculating a Laminar Boundary Layer. Reports of USSR Academy of Science, - vol. XXXVI, M.
7. Directions for the Development of Designs of Cutting Apparatus for Agricultural Machines (foreign practice: overview). Bulletin of International Scientific Research Institute of Economics and Technology. Tractor and Agricultural Machines, - Issue 10, - Moscow, 1978.
8. Altunyan, A.V. (2009). Development of the Technology and a Working Part for Stem Cutting in a Dense Environment. Ph.D. - Yerevan, - 152 p.

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