Analytical calculation of the coefficient of increasing the moment of resistance to milling the ground when the cutter hits the stump

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Abstract. One of the main operations in peat soil processing is milling. The entire subsequent production process depends on the quality of the milling. The presence of wood inclusions in the soil greatly complicates the work. The sharply increased moment of loading that occurs when the cutter hits the stump is capable of removing both the transmission elements and the drive of the milling unit from the operational state. Therefore, at the design stage, it is necessary to take into account the dynamic loads arising from the meeting of the cutter with wood inclusions. Attempts to describe this fact were made earlier by various authors, but due to mathematical and methodological errors, they were not crowned with success. In this article, an attempt was made to "work on errors", which allowed one, taking into account all the previous errors and inaccuracies, to achieve the desired result.

1. Introduction

Milling is one of the key and most critical stages in the development of peat soils. On the whole, the entire production technological cycle depends on the quality of its implementation, since conditions are laid for the subsequent normal operation of machines and mechanisms.

An important role in the milling process is played by the stumpiness of peat soils, which determines the intensity of the collision of the cutter with wood inclusions. In this case, there is an instant increase in the moment of resistance to milling and, accordingly, increased loads in the entire transmission of the milling unit. Naturally, the question arises about the reliability and durability of milling machines, which are significantly reduced [1]. The sharply expressed alternating nature of the loads is capable of instantly destroying or deactivating the working and executive bodies, transmission elements, and even a cardan-telescopic transmission, through which the torque is transmitted from the tractor to the milling unit. Therefore, taking into account that the collision with a stump is absolutely necessary at the design stage of machines.

These issues are typical not only of peat soils, but also of all work related to milling the black earth, roadbed, rocks, when a working body meets with a denser and more durable inclusion [2]. An attempt to theoretically consider the issue of the collision of a cutter with a wood inclusion in a peat deposit has already been undertaken earlier [3]. However, due to errors of a mathematical and methodological nature, it did not lead to success, that is why this article is considered again, taking into account the "work on errors".
2. Materials and methods

We consider the process of layer-by-layer passing milling of a peat deposit with a cutter, having a peripheral speed \( v \) and a forward speed \( W \) (figure 1). As a simplification of the process of interaction of a cutter of radius \( R \) with a wood inclusion, the latter is considered rigidly fixed at point \( O \). The radius \( R \) is understood as the radius of inertia. For a hollow thin-walled cylinder, which is, in essence, a cutter, the radius of inertia is equal to the radius of the outer shell of the cutter. From the contact that has arisen, the cutter throws up, and it behaves like a skidding driving wheel, trying to "move" over the obstacle [4]. In this case, the cutter receives a shock impulse \( P \), which is decomposed into two components: horizontal and vertical, located in the direction of movement of the router and in the vertical plane [5, 6]. The contact of the cutter with the stump ends after a time \( \Delta t \), when the radius \( OC \) takes a vertical position due to the rotation of the cutter by a certain angle \( \alpha \) relative to the axis passing through point \( O \).

\[
\begin{align*}
\text{(1)} & & mv_{kx} - mv_{0x} &= P_x, \\
\text{(2)} & & mv_{ky} - mv_{0y} &= P_y,
\end{align*}
\]

where \( m \) – cutter weight; \( v_{0x} \) and \( v_{0y} \) – initial horizontal and vertical components of the speed of the center of gravity \( C \) of the cutter before impact; \( v_{kx} \) and \( v_{ky} \) – horizontal and vertical components of the speed of the center of gravity \( C \) of the cutter after impact; \( P_x \) and \( P_y \) – horizontal and vertical components of the pulse.

The relationship between \( P_x \) and \( P_y \) can be obtained from (1) and (2) through the coefficient \( q \):

\[
q = \frac{P_x}{P_y} = \frac{(v_{kx} - v_{0x})}{(v_{ky} - v_{0y})},
\]

or:

\[
P_x = qP_y.
\]

Then the absolute value of the impulse \( P \) is expressed by the equation:

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**Figure 1.** Design scheme for the interaction of a cutter with a fixed stump: 1 – peat deposits; 2 – fixed stump.
\[ P = (P_x^2 + P_y^2)^{1/2} = (P_y^2 + q^2P_x^2)^{1/2} = P_y(1 + q^2)^{1/2}. \]  

If, before the impact, the cutter rotated about an axis passing through the center of gravity with an angular velocity \( \omega \), then the cutter rotates about an axis passing through point \( O \) at a certain angular velocity \( \omega_p \). According to the diagram, shown in figure 1, initial and final velocities (before and after impact) included in (1) and (2):

\[ v_{0x} = W, \]  

since before the impact, the center of gravity of the cutter \( C \) moved forward rectilinearly and uniformly at a speed \( W \);

\[ v_{0y} = 0, \]  

since before the impact, the center of gravity of the cutter \( C \) did not move in the vertical plane;

\[ v_{kx} = bo_p, \]  

\[ v_{ky} = a\omega_p, \]  

where \( a \) and \( b \) – geometric shoulders (figure 1), determined from simple geometric relationships and the Pythagorean theorem:

\[ b = R - h, \]  

\[ a = (R^2 - b^2)^{1/2}, \]  

where \( h \) – milling depth.

Before and after impact, the peripheral speed \( v \) of the cutter, including at point \( O \), was determined by the angular speed of rotation of the cutter \( \omega \) and its radius \( R \):

\[ v = \omega R. \]  

At the moment of impact, the cutter begins to rotate about the axis passing through point \( O \), the speed of point \( O \) is zero; that is why, this point is the instantaneous center of speeds. Based on this, the peripheral speed of point \( B \):

\[ v = 2\omega_p R, \]  

from where:

\[ \omega_p = \frac{v}{2R}. \]  

Taking into account (6–9), expressions (1) and (2) can be written in the form:

\[ mb\omega_p - mW = m(b\omega_p - W) = P_x, \]  

\[ mv_{ky} = ma\omega_p = P_y. \]  

The angle of rotation of the cutter \( \alpha \) is determined from the geometric relationships:

\[ \alpha = \arccos \frac{b}{R}. \]  

Considering that the angular velocity \( \omega_p \) and the angle of rotation of the cutter during the impact are already known, it is possible to determine the impact time \( \Delta t \):

\[ \Delta t = \frac{\alpha}{100\omega_p}. \]  

Force acting on the cutter when hitting a fixed stump \( F \):

\[ F = \frac{P}{\Delta t}. \]  

Moment acting on the cutter during impact on the stump \( M_h \):

\[ M_h = FR. \]  

Relatively constant moment, acting on the cutter in the process of milling an equally strong monolith (peat, black earth, clay, etc.) \( M_g \):

\[ M_g = \frac{N_gR}{v}, \]  

where \( N_g \) – average power, required for milling an equal strength monolith without inclusions.

A small note should be made here. In fact, instead of the circumferential speed of rotation of the cutter in the formula (21) there should be a geometric sum of the circumferential and forward speeds of the cutter, but since the circumferential speed is much higher than the forward speed \( (v \gg W) \), then it is taken as the only parameter.
So, the coefficient, which takes into account the increase in the load moment, when the working body meets wood inclusions $k$:

$$k = \frac{M_h}{M_g}.$$  \hspace{1cm} (22)

3. Results and discussion

As an example, let us give the calculation of the dynamic forces acting on the cutter of a surface-layer milling cutter of the MTF-17 type when the cutter meets a fixed wood inclusion. Initial data:

- cutter weight, $m = 440$ kg;
- outer radius of cutter shell, $R = 0.17$ m;
- rotational speed of the cutter about an axis, passing through its center of gravity, $n = 514$ RPM;
- forward speed of the miller, $W = 12$ km/h = 3.33 m/sec;
- milling depth, $h = 0.011$ m;
- average power for milling a monolith without inclusions, $N_g = 35$ kW.

It is necessary to determine the coefficient, taking into account the increase in the load moment when the cutter meets the wood inclusion.

1. Initial angular speed of rotation of the cutter $\omega$:

$$\omega = \frac{\pi n}{30} = \frac{3.14 \times 514}{30} = 53.8 \text{ sec}^{-1}.$$

2. Initial horizontal and vertical components of the speed of the center of gravity of the cutter before impact $v_{0x}$ and $v_{0y}$, m/sec:

$v_{0x} = W = 1.56$ m/sec; $v_{0y} = 0$.

3. Geometric contact arms $b$ and $a$ (10, 11):

$b = R - h = 0.17 - 0.011 = 0.159$ m; $a = (R^2 - b^2)^{\frac{1}{2}} = (0.17^2 - 0.159^2)^{\frac{1}{2}} = 0.06$ m.

4. The peripheral speed of rotation of the cutter about the axis, passing through the center of gravity (12):

$$v = \omega R = 53.8 \times 0.17 = 9.15 \text{ m/sec}.$$

5. The angular speed of rotation of the cutter about the axis, passing through a rigidly fixed stump (14):

$$\omega_p = \frac{v}{2R} = \frac{9.15}{2 \times 0.17} = 26.91 \text{ sec}^{-1}.$$

6. The angle of rotation of the cutter around the point $O$ in contact with a rigidly fixed wood inclusion $\alpha$ (17):

$$\alpha = \arccos \frac{b}{R} = \arccos \frac{0.159}{0.17} = 20.72^\circ.$$

7. Impact time (18):

$$\Delta t = \frac{\pi a}{180 \omega_p} = \frac{3.14 \times 20.72}{180 \times 26.91} = 0.013 \text{ sec}.$$

8. Final horizontal and vertical components of the speed of the center of mass of the cutter after impact $v_{kx}$ and $v_{ky}$ (8, 9):

$v_{kx} = b\omega_p = 0.159 \times 26.91 = 4.28$ m/sec; $v_{ky} = a\omega_p = 0.06 \times 26.91 = 1.61$ m/sec.

9. The vertical component of the impulse upon impact $P_y$ (16):

$$P_y = m v_{ky} = 440 \times 1.61 = 708.4 \text{ N} \cdot \text{sec}.$$

10. The coefficient $q$ of the ratio of the projections of the impulse (3):

$$q = \frac{P_y}{P_x} = \frac{(v_{kx} - v_{0x})}{(v_{ky} - v_{0y})} = \frac{(4.28 - 1.56)}{(1.61 - 0)} = 1.69.$$

11. The absolute value of the pulse $P$ (5):

$$P = P_y (1 + q^2)^{\frac{1}{2}} = 708.4(1 + 1.69^2)^{\frac{1}{2}} = 1391.08 \text{ N} \cdot \text{sec} \approx 1.39 \text{ kN} \cdot \text{sec}.$$

12. Force, acting on the cutter during impact $F$ (19):

$$F = \frac{P}{\Delta t} = \frac{1391.08}{0.013} = 106.92 \text{ kN}.$$

13. The moment, acting on the cutter during impact $M_h$ (20):

$$M_h = FR = 106.92 \times 0.17 = 18.18 \text{ kN} \cdot \text{m}.$$
14. Relatively constant moment, acting on the cutter in the process of milling an equal strength monolith (peat, black earth, clay, etc.) $M_g$ (21):

$$M_g = \frac{N_a R}{\nu} = \frac{35.0.17}{0.15} = 0.65 \text{ kN-m.}$$

15. The coefficient, which takes into account the increase in the load moment, when the working body meets wood inclusions $k$ (22):

$$k = \frac{M_h}{M_g} = \frac{18.18}{0.65} = 27.97 \approx 28.$$ 

This example very clearly illustrates how much the load on the drives and working bodies of machines increases during milling (cutting, digging, planning) of a heterogeneous rock due to impact.

4. Conclusion

As a result of the study, the conditions for the theoretical interaction of the cutter with a fixed wood inclusion were clarified. Methods for calculating the coefficient of increasing the load moment on the cutter when colliding with a wood inclusion have been worked out. This method can be used in calculating the interaction of milling organs with wood inclusions at the machine design stage.

References

[1] Gorlov I V and Rakhutin M G 2017 The effect of stumpiness deposits on the reliability of peat machines Mining Informational and Analytical Bulletin (Sci and Tech J) 12 39-145

[2] Yong Sun and Li X S 2017 A probabilistic approach for assessing failure risk of cutting tools in underground excavation Tunnelling and Underground Space Technology 70 299-308

[3] Samsonov L N 1985 Milling of Peat Deposits (Moscow: Nedra)

[4] Yong Sun and Li X S 2018 Experimental investigation of pick body bending failure Int J of Mechanical Engineering and Robotics Research 7-2 184-188

[5] Zhengu Luo, Lirong Wan, Qingliang Zeng, Xin Zhang and Kuidong Gao 2018 The structural optimization of roadheader conical picks based on fatigue life Int J of Modeling, Simulation and Scientific Computing 9-2 17

[6] Xueyi Li, Yonggang Lv, Qingliang Zeng and Jintao Wang Research on the strength of roadheader conical picks based on finite element analysis The Open Mechanical Engineering 9 521-526