

CALCULATION OF SOILS CUTTING FORCE BY KNIFE TYPE CUTTING ELEMENTS OF THE EARTHMOVING MACHINE

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ABSTRACT: The application of bucketless bottom unloading rotor with oblique cutting knife type cutting elements on the earthmoving machine allows enhancing significantly its excavation quantities in the road construction compared with widely used machinery as bulldozers, auto-graders. A loading diagram of the forces acting on an oblique cutter installed on a bucketless bottom unloading rotor is given. The action of forces is considered with account for the complex movement made by the cutting element in space as a result of the rotational movement and the end feed on the rotor along straight-line trajectory during layer by layer excavation of the soil by rotor cutter. The dependences were obtained for determining the components of the digging force by a single oblique cutting element of a bucketless bottom unloading rotor under straight-line end feed. The bucketless bottom unloading rotor with diagonal cutting knife type cutting elements, installed on the earthmoving machine's frame, moving straightforwardly, allows not only to increase its output via rotation velocity of the bucketless bottom unloading rotor but also to excavate highly stiff soils, inaccessible for existing earthmoving machines.

Keywords: Rifle-free rotor, Lower unloading, Oblique cutting, Cutting force, Oblique cutting knife

1. INTRODUCTION

Despite the vastness of previously conducted studies of rifle-free rotors, not all the reserves incorporated in their design have been fully identified [1-4].

In connection with the tasks set in this paper, some previously unexplored factors are considered, which primarily include the process of cutting the ground with knife cutting elements of oblique cutting, proposed for use in a rifle-free rotor of the bottom discharge.

In the works of Doctor of Technical Sciences Taukeleva R.N. a formula for calculating the specific resistance to cutting with a knife with scraper rotor has been proposed [1]:

$$K_{FP} = C_0(K_{\tau 1} + E_b K_{\tau 2}) \quad (1)$$

where $K_{\tau 1}$ and $K_{\tau 2}$ - coefficients depending on the angle of the knives on the rotor, hail;

E_b - coefficient determining chip width to thickness ratio a_0 ;

C_0 - soil friction coefficient.

But this formula refers to a head-cutting knife.

The formulas for calculating cutting forces intended for durable soils, where the destruction is carried out by oblique cutting teeth [5]. The proposed technique provides the possibility of its use for slanting knives and forms the basis of this study. The analysis of the above derived formulae for

calculation of the tangential, end and normal forces on the thrower rotor indicates to the forces contributing to reduce the cutting resistance of the soil under chippings separation by the least energy-consuming diagonal semi-free cutting with the BBUR cutting element shaped as a deteriorated diagonal wedge performing a complex movement; improve the BBUR's work stability and explain the best dynamic properties compared to the rotors of other design [6-12].

2. INVESTIGATION

In this regard, a cutting element in the form of a flat knife with a beveled front cutting face with a gripping angle φ , called an oblique cutting knife, was taken as the object of study based on the analysis of previous materials. The slanting knife is mounted on a rifle-free bottom rotor and makes a complex movement.

Figure 1-4 show the design diagrams of the forces acting on the slanting knife mounted on the rotor at an angle θ to the plane of its rotation. A knife with a sharpening angle α , cutting angle α_p , rear cutting angle δ is considered. The cutting process, more precisely, the cutting angle of the knife is influenced by the presence of the kinematic angle θ_k resulting from the speed of the transverse (end) feed V_n of the rotor to the bottom.

The knife face facing the breast of the heading has an obliquity to the path of rotation of the knife nose at an angle of δ , which prevents excessive

friction of the knife face over the heading during rotation when removing chips [13, 14].

The rotor rotates around the Y_p axis, parallel to the adopted Y axis in the XYZ coordinate system. For convenience and clarity of consideration, the cutting element of oblique cutting with a gripping angle φ is considered in the position when the knife edge is at point 0 of the origin of coordinates when the rotor rotates around the Y_p axis with angular velocity ω_p and linear velocity ϑ_p on the tip. The kinematic angle θ_k also influences the picture of the acting forces, since its increase leads to an increase in the resistance of the face (heading) when the lateral feed R_b . From the design scheme it can be assumed that [15]:

$$\tan \theta_k = \frac{V_n}{\omega_p(R_{j_i} + b + h)} \quad (2)$$

or

$$\tan \theta_k = \frac{V_n}{\omega_p(R_{ob} + h_t + aK)} \quad (3)$$

where ω_p - rotor speed, 1/c;

R_{ob} - radius of the rotor shell, m;

h_t - the gap between the cutting edge and the shell, m;

K - coefficient determining the position of the current section (ranges from 0 to 1).

Adjusting the kinematic angle θ_k is possible by changing the ratio of the rotor speeds of rotation ω_p and feeding V_n .

In accordance with the theory of an oblique wedge, we assume that the following forces act on an oblique cutting knife, which position in space is connected with the rotor's structural elements, the face and the coordinate system:

- the force of soil resistance to the destruction of N_n (Figure 1), which acts on the front face and is directed perpendicular to it. Due to the relatively small size of the front face of the knife, we will consider it applied to the pointed part of the cutting edge. In this case we will consider a knife with a sharp cutting edge [16];

- resistance force of the end feed of the rotor R_t (Figure 2), directed perpendicular to the trajectory of rotation of the knife;

- the force of squeezing the knife from the face R_3 (Figure 3), directed along the normal to the tip of the knife;

- friction forces F_n, F_{ny}, F_B , acting in the front, side and rear planes of the knife in the directions

opposite to its movement relative to the face (Figure 4). The remaining components of the resistance forces, due to their small size, can be neglected. The actions of all applied forces are considered in three directions: tangent (along the X axis), lateral (along the Y axis) and normal (along the Z axis) with respect to the direction of movement of the knife. The total force of normal pressure N_n is applied perpendicular to the front plane of the knife, and the total friction force of chips F_n is located on this plane of the knife and is at an angle $(90 - \omega - \varphi)$ to the direction of the rotor radius (or otherwise to the axis OZ), where the ω - from the theory of an oblique wedge is the angle between the friction force on the front face of F_n and the normal to the knife blade.

We write the projections of these forces on the X, Y, Z coordinate axes:

$$R_x = N_n \sin \alpha_p + F_n \sin (90 - \omega + \varphi) \cos \alpha_p \quad (4)$$

$$R_y = N_n \cos \alpha_p + F_n \sin \alpha_p \cos (90 - \omega + \varphi_k) \quad (5)$$

$$R_z = F_n \cos (90 - \omega + \varphi) \quad (6)$$

Denote $\varphi_k = 90 - \varphi$

Then the forces on the front edge of the knife can be written down:

$$R_z^n = N_n \sin \alpha_p + F_n \cos (\omega + \varphi) \cos \alpha_p \quad (7)$$

$$R_y^n = -N_n \cos \alpha_p + \sin \alpha_p \quad (8)$$

$$R_z^n = F_n \cos (\omega + \varphi) \quad (9)$$

On the side of the knife, the forces will be:

$$R_x^T = N_b^n \sin \delta + F \cos (\omega + \varphi) \cos \delta \quad (10)$$

$$R_y^T = -N_b \cos \delta + F \sin \delta \quad (11)$$

$$R_z^T = F \cos (\omega + \varphi) \quad (12)$$

In accordance with the theory of an oblique wedge, we can write, considering the tangent component R_{nx} equal to the cutting force R:

$$R_{nx} = R_p = N_n \sin \alpha_p + \mu_b N_n \cos (\omega + \varphi) \cos \alpha_p \quad (13)$$

and the lateral R_{ny} and normal R_{nz} components are as follows:

$$R_{ny} = N_n \cos \alpha_p + \mu_b N_n \sin \alpha_p \cos (\omega + \varphi) \quad (14)$$

$$R_{nz} = F_n \cos (\omega + \varphi) \quad (15)$$

We can express the component R_{ny} and R_{nx} through R_{nx} :

$$R_{ny} = \frac{\cos \alpha_p + \mu_b \sin \alpha_p (\cos \omega + \varphi_x)}{\sin \alpha_p + \mu_b \cos (\omega + \varphi_x) \cos \alpha_p} R_{nx} \quad (16)$$

Simplified formulas (21 and 22) greatly facilitate the calculations and make them convenient in engineering practice. Now we can proceed to the determination of the total components of the forces R_x^c, R_y^c, R_z^c , acting on the oblique knife, located in the face.

The current values of the tangential resistance to clean cutting with a knife only from the separation of chips is determined by the formula [20]:

$$R_{nxi} = K_F \alpha_0 b \sin \beta_i \quad (24)$$

where K_F is the specific cutting resistance by a single cutting element at normal cutting speeds (up to 2 m / s), MPa;

b - the width of the chip, cm;

α_0 - chip thickness at the level of the rotor axis, cm;

β_i - the current values of the angle of rotation of the knife on the cutting arc, deg.

We will determine the current total tangential cutting resistance R_{nxi}^c :

$$R_{nxi}^c = R_{nxi} + F_{xi}^c \quad (25)$$

where F_{xi}^c is the projection on the X axis of the total friction force of the soil along the front, side and rear faces, kN.

We will find the total end resistance:

$$R_{yi}^c = R_T - R_{ny} \quad (26)$$

where R_T – resistance to the end feed of the knife, defined as resistance to indentation of the side face of the knife into the face, kN.

$$R_T = \sigma_b b_T l_T \quad (27)$$

where σ_b - specific resistance to indentation, MPa;
 b_T - the width of the side platform of the contact of the knife with the bottom, mm;
 l_T - contact length, mm.

$$R_{yi}^c = R_T - R_{ny} = \sigma_b b_T l_T - k_y R_{nx} \quad (28)$$

The total normal resistance will be equal to:

$$R_{zi}^c = R_3 - R_{nz} \quad (29)$$

where R_3 is the knife pressing force [18] from the face the face along the radius of rotation of the rotor, which can be determined similarly to R_y by the resistance to indentation of the rear horizontal area of the knife:

$$R_3 = \sigma_b b_3 l_3 \quad (30)$$

where b_3 is the thickness of the knife, mm;
 l_3 - the length of the horizontal area of the rear edge of the knife, mm.

$$R_{zi}^c = \sigma_b b_3 l_3 - k_z R_{nz} \quad (31)$$

The total force of friction of the knife on the face can be determined by projecting the friction forces on the front - F_n , butt - F_T and the rear faces - F_3 of the knife on the respective axes [20-22]. The total friction force along the X axis will be equal to the sum of the projections of the friction forces on the front, end and rear edges of the knife:

$$F_{xi}^c = F_{nx} + F_{\delta x} + F_x \quad (32)$$

or

$$F_{xi}^c = \cos \delta_3 + + F_3^b \quad (33)$$

where $\cos \gamma_1 = \cos \alpha_p + \varphi_x$ is the angle between the X axis and the direction of the chip movement along the front edge of the knife, direction of force F_n .

$$F_{nx} = \mu_m N_n \sin \gamma_1 = \mu \sqrt{R_{nx}^2 + R_{ny}^2 + R_{nz}^2} \sin \gamma_1 \quad (34)$$

$$N_n = R_{nx} \sqrt{1 + k_y^2 + k_z^2} \quad (35)$$

The projection of the friction force acting on the front face on the X axis:

$$F_{Tx} = \mu_m R_y^c = \mu_m (R_T - R_{ny}) \quad (36)$$

or

$$F_{Tx} = \mu_m (\sigma_b b_T l_T - k_y R_{nx}) \quad (37)$$

The projection of the friction force acting on the rear face on the X axis:

$$F_{3x} = \mu_m R_z^c = \mu_m (R_3 - k_z R_{nz}) \quad (38)$$

or

$$F_{3x} = \mu_m (\sigma_b b_3 l_3 - k_z R_{nz}) \quad (39)$$

When calculating the sum of the projections of the friction forces on the Y axis, the projection of the component of the friction force on the front face F_n to this axis can be neglected and we can calculate the total friction force as consisting of only one friction force on the rear blade area when the rotor feeds by the formula:

$$F_{3y} = \mu_m R_z^c = \mu_m (R_3 - R_{nz}) \quad (40)$$

or

$$F_{3y} = \mu_m (\sigma_b b_3 l_3 - k R_{nz}) \quad (41)$$

We design all the resistance forces acting on the knife on the X, Y, Z axis and determine their resulting values:

$$R_{nx}^p = R_n = R_{nx} + F_x^c = R_{nx} + (F_{nx} + F_{Tx} + F_{3x}) \quad (42)$$

$$R_T^p = R_y^c + F_{3y} \quad (43)$$

$$R_{nz}^p = R_z^c \quad (44)$$

To determine the tangential, face and normal cutting forces with a single knife relative to the axis of rotation of the rotor, it is necessary to design the resulting forces on the axes X', Y', Z': respectively X' - parallel to the plane of rotation of the rotor, Y' - coinciding with the direction of the lateral feed of the rotor, Z' - directed along the rotor radius:

$$P_k = R_{kx}^p \cos \theta_k \quad (45)$$

$$P_T^l = R_{Tz}^p \cos \theta_k \quad (46)$$

$$P_i = R_{hz}^p \quad (47)$$

In expanded form, these formulas will be written:

$$P_k = (R_{nx}^c + F_{nx} + F_{Tx} + F_{3x}) \cos \theta_k \quad (48)$$

$$P_T^l = R_y^c + F_{3y} = (R_{Ty} - R_{ny} + F_{3y}) \cos \theta_k \quad (49)$$

$$P_i = R_z^c \quad (50)$$

Substituting in the right side of the expressions below for the constituent components:

$$P_{Ti} = \sigma_b b_3 l_b - k_y R_{nx} + \mu_m \sqrt{1 + k_y^2 + k_z^2} \sin \alpha_p \quad (51)$$

$$P_i^l = \sigma_b b_3 l_3 - k_z R_{nx} \quad (52)$$

Substituting the value R_{nx} from formula (23), we can write in general form of the expressions for tangential, face and normal effort on a single oblique cutting knife:

$$P_{ki}^1 = (K_F a_0 b \sin \beta_i (1 + \mu_m \sqrt{1 + k_y^2} + k_z^2 \cos \alpha_p \cos(\omega + \varphi_x) + \mu_m (\sigma_b b_3 l_b - K_y K_F a_b \sin \beta_i) \cos \theta_k) \quad (53)$$

$$P_{Ti}^l = (\sigma_b b_T l_T - k_y k_F a_0 b \sin + \mu_m \sqrt{1 + k_y^2 + k_z^2} \sin \alpha_p \cos(\omega + \varphi_x) \cos \theta_k) \quad (54)$$

$$P_i^l = \sigma_b b_{3m} l_n - K_z K_F a_0 b \sin \beta_i \quad (55)$$

The components of the total friction force are determined for the corresponding faces.

3. CONCLUSION

Thus, the action of the forces acting on the cutting element in the form of an oblique cutting knife is considered for the first time, taking into account the complex movement that it performs in space as a result of the rotational movement and the end feed of the rotor during the development of the soil which shown in Table 1. The dependences obtained above for determining the components of the cutting force by a single cutting element of oblique cutting allow us to proceed to the determination of the cutting forces on the rotor. The application of bucketless bottom unloading rotor with diagonal cutting knife shaped cutting elements on the earthmoving machine allows to enhance significantly its excavation capacities within road construction compared with widely used machinery as bulldozers, autogriders.

the bucketless bottom unloading rotor with diagonal cutting knife shaped cutting elements, installed on earthmoving machine's frame, moving straightforwardly, allows not only to increase its output via rotation velocity of the bucketless bottom unloading rotor but also to excavate high strength soils, inaccessible for existing earthmoving machines.

Table 1- Main parameters

Parameter	Equation
Total friction force along the X axis	$F_{xi}^c = F_n \cos \gamma + F_T \cos \delta_3 + F_3^b$
The projection of the friction force acting on the front face on the X axis:	$F_{Tx} = \mu_m (R_T - R_{ny})$
The expressions for tangential, face and normal effort on a single oblique cutting knife:	$P_i^l = \sigma_b b_{3m} l_n - K_z K_F a_0 b \sin \beta_i$

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