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EVALUATION OF ENERGY REQUIREMENT OF TILLAGE WITH A ROTARY TILLER

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Keywords: L- type knife, rotary tiller.
Abstract. A rotary tiller with L-shaped blades was considered. A computer model of the movement of a rotary tiller knife, based on the equations of the knife point movement, was used to assess an energy requirement and a quality of soil treatment, taking into account the radius of the rotor, the size and the rake angle of the straight profile of the knife, the width of the knife, the distance from the rotor axis to the soil surface, the speed of a rotary tiller frame point, the tillage pitch, the number of knives on one side of a flange and the direction of a rotor rotation. It was found that the reverse rotation of a rotor is ineffective and an efficiency of soil treatment increases with the increase in the number of knives on one side of a flange.

ОЦЕНКА ЭНЕРГОЕМКОСТИ ОБРАБОТКИ ПОЧВЫ РОТОРНОЙ ФРЕЗОЙ

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Ключевые слова: Г-образный нож, почвенная роторная фреза.
Аннотация. Объектом исследования служила почвенная роторная фреза с Г-образными ножами и горизонтальной осью вращения. Цель исследования состояла в обосновании метода оценки энергоемкости и качества обработки почвы на основе разработанной компьютерной модели движения ножа. Установлено, что реверсивное вращение ротора неэффективно, и эффективность обработки почвы возрастает с увеличением числа ножей на окружности ротора.

1. Introduction. The quality of soil treatment can be assessed by the size of soil pierces. The soil treatment quality and energy requirement can be considered as main indicators of rotary tiller efficiency. The purpose of this study was to develop the computer model of soil treatment for investigation of effect of the number of L-type knives on one side of a flange, the rotor radius, the forward speed of a rotary tiller frame point, the tillage pitch, the direction of rotor rotation and some other parameters on the specific power and quality of soil cultivation. The basis was a computer model of knife movement. Among the knives of different types L-type knives are more common in rotary tillers because of its effectiveness [1]. Much attention is paid to the study of the geometric parameters of L-type knives of the rotary tiller [2-4]. Effect of rotary tiller kinematic parameters on a quality of soil treatment is also studied [5, 6]. However, the question of the combined effect of the tillage pitch, the number of knives on one side of a flange and the geometric parameters of the knife on energy consumption remains open and actual.

2. Mathematical model and methods. The following designations were introduced (Fig. 1): *Oxyz* – a fixed orthogonal system of Cartesian coordinates with the horizontal *Ox* axis, the downward vertical *Oy* axis and the perpendicular *Oz* axis, that is parallel to the axis of a rotor; *k* – a number of knives on one side of a flange; *H* – a distance from the rotor axis to the ground, [m]; *R*, *r* – a distance from the rotor axis to the blade and to the back of a knife respectively, [m]; *w* – a knife blade width, [m]; *s* – a tillage pitch (one tilling cut length), [m]; h_c – a ridge height, [m]; α – the L-type knife rake angle, [rad]; β – the rotor rotation angle measured from the axis *Ox* at the moment the first knife begins to penetrate into soil, [rad]; ω – an angular speed of a rotor, [rad s^{-1}]; *υ* – a speed of a rotary tiller frame point, [m s^{-1}]; ρ – soil density, [kg m^{-3}]; E_p, E_k – pressure forces work and impact forces work for one knife pass respectively, [J]; *W* – specific power of pressure forces and impact forces per unit of a knife width, [W m^{-1}].

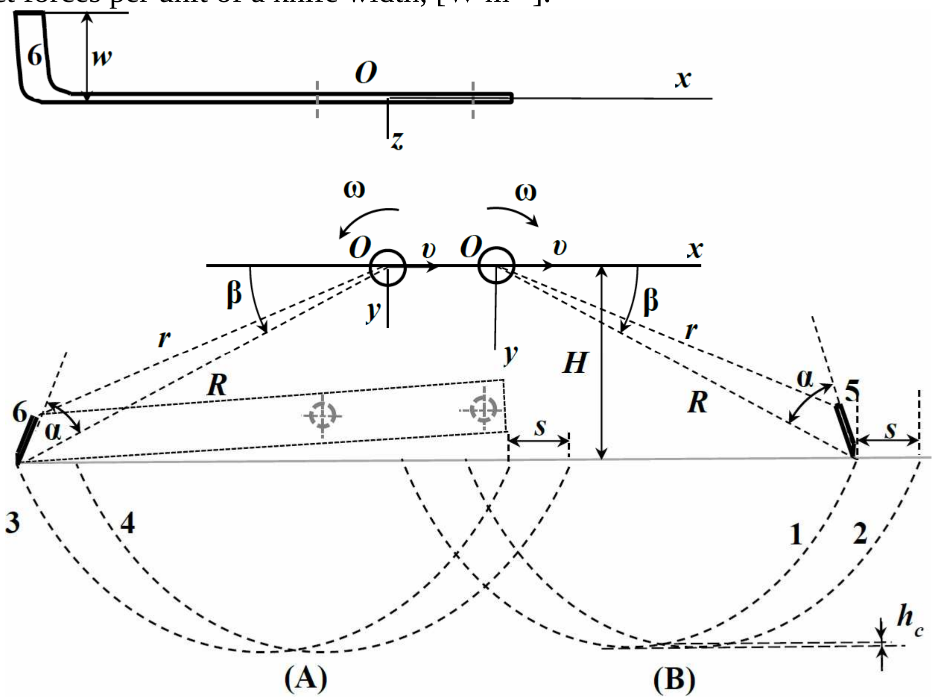

Fig. 1. Two nearest trajectories 1, 2 of blade points at the forward rotation of a rotor (A) and trajectories 3, 4 at the reverse rotation of a rotor (B)

By definition,

$$\beta = \arcsin(H/R); \tag{1}$$

$$s = 2\,\upsilon\,\pi/(k\,\omega). \tag{2}$$

Equations of the trajectory 1 of the blade point with coordinates x_1, y_1 at the forward rotor rotation can be written in the parametric form with the parameter φ_1:

$$\begin{cases} x_1 = \dfrac{sk\varphi_1}{2\pi} + R\cos(\beta + \varphi_1), \\ y_1 = R\sin(\beta + \varphi_1), \end{cases} \tag{3}$$

where $0 \le \varphi_1 \le \pi - 2\beta$.

Equations of the nearest trajectory 2 of the blade point with coordinates x_2, y_2 at the forward rotor rotation can be written in the parametric form with the parameter φ_2:

$$\begin{cases} x_2 = s + \dfrac{sk\varphi_2}{2\pi} + R\cos(\beta + \varphi_2), \\ y_2 = R\sin(\beta + \varphi_2), \end{cases} \tag{4}$$

where $0 \le \varphi_2 \le \pi - 2\beta$.

Equations of the trajectory 3 of the blade point with coordinates x_3, y_3 and the trajectory 4 of the blade point with coordinates x_4, y_4 at the reverse rotor rotation can be written as equations (3), (4), if $R = -R$ for x_3 and x_4.

A straight knife was considered with the profile of a segment of a straight line in the rotation plane. The back of the knife does not hit the ground at the forward rotor rotation, if the coordinate of the back point on the *Ox* axis at the time of entry into the soil does not exceed the coordinate of the blade point on the *Ox* axis at the time of the entry into the soil:

$$\sqrt{r^2 - H^2} + \frac{v}{\omega}\left[\arcsin\frac{H}{r} - \left(\beta + \alpha - \arcsin\frac{R\sin\alpha}{r}\right)\right] \le \sqrt{R^2 - H^2}, \tag{5}$$

The back of the knife does not hit the ground at the reverse rotor rotation, if the coordinate of the back point on the *Ox* axis at the time of the exit from the soil does not exceed the coordinate of the blade point on the *Ox* axis at the time of exit from the soil:

$$\sqrt{r^2 - H^2} + \frac{v}{\omega}\left[\arcsin\frac{H}{r} - \left(\frac{\pi}{2} - \beta - \arcsin\frac{R\sin\alpha_r}{r} + \alpha\right)\right] \le \sqrt{R^2 - H^2}. \tag{6}$$

Knife back point trajectory equations can be recorded as equations (3), (4), in which the value of R needs to be changed to the value of r, and β – to $(\beta - \Delta\varphi)$, where $\Delta\varphi = [\arcsin(R \sin \alpha/r) - \alpha]$. Equations (3), (4) can be used to calculate the ridge height at the forward and reverse rotation of the rotor:

$$h_c = R - y_1 \text{ and } h_c = R - y_3, \tag{7}$$

where the value of y_1 can be calculate altogether with the values of y_2, x_1, x_2, φ_1, φ_2 from equations $x_1 = x_2$; $y_1 = y_2$ and (3), (4), and the value of y_3 can be calculated similarly.

It was assumed that the energy requirement was composed of two components: the work of the press forces and the work of the impact forces acting on the ground from the knives. The close positions 1 and 2 of one knife in the soil were considered (Fig. 2). Additional designations were accepted: ψ_1, ψ_2 – an angle of the rotor rotation at the moment of taking the knife position 1, 2 respectively after the knife entry into the ground; A_1A_2, B_1B_2 – the knife profile section at 1, 2 positions respectively; A_1B_1, A_2B_2 – a trajectory of the point A_1, A_2 respectively; r_1, r_2 – a distance from the rotor axis to the point A_1, A_2 respectively; F − an area of the flat figure $A_1A_2B_2B_1$; e_p – the work of press forces(to displace the soil by a knife from the area $A_1A_2B_2B_1$), [J]; e_k – the work of impact forces that is equal to kinetic energy of soil particles in the area $A_1A_2B_2B_1$ after hitting particles with a knife [J]. It was suggested, that the value of F is small, if a difference $(\psi_2 - \psi_1)$ is equal to a small value, and the value of F with a sufficient accuracy can be equated to the area of the quadrangle $A_1A_2B_2B_1$:

$$F = |(x_{A2} - x_{B1})(y_{A1} - y_{B2}) + x_{A1} (y_{B1} - y_{A2}) + x_{B2} (y_{A2} + y_{B1})|/2, \qquad (8)$$

where x_{A1}, y_{A1} – coordinates of the point A_1, x_{A2}, y_{A2} – coordinates of the point A_2, x_{B1}, y_{B1} and x_{B2}, y_{B2} – coordinates of the point B_1 and B_2 respectively.

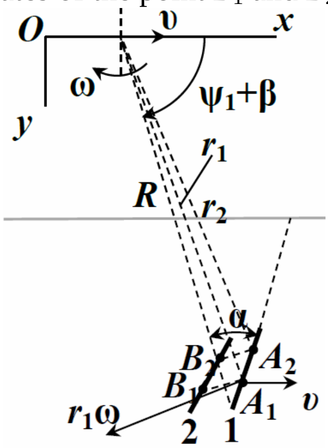

Fig. 2.

Coordinates of the points A_1, A_2, B_1, B_2 at forward rotor rotation can be found from equations (3). Studies have shown that work of press forces is directly proportional to the volume of the area, the average depth of the area and the proportionality coefficient, the value of which is equal to 4043000 J/m^4 for loamy soil [7]:

$$e_p = 4043000\ [y_{A1} + y_{A2} + y_{B1} + y_{B2})/4 - H]\ F\ w. \qquad (9)$$

By definition,

$$e_k = \rho\ F\ w\ \upsilon_n^{2}/2, \qquad (10)$$

where υ_n – velocity of the area $A_1A_2B_2B_1$ center of mass.

It was accepted that the value of υ_n is equal to the projection of the knife point A_1 on the outer normal to the knife profile in the rotor rotation plane. At the forward rotor rotation the formula for the value of υ_n can be written as follows (at the reverse rotation the second term is added):

$$\upsilon_n = \omega\ [(r_1^{2} - (R \sin \alpha)^{2}]^{1/2} - \upsilon \sin (\psi_1 + \beta + \alpha), \qquad (11)$$

where $\omega = 2\pi\ \upsilon/(s\ k)$.

It was assumed that the kinetic energy of the soil in the area $A_1A_2B_2B_1$ is not equal to 0 under the next condition:

$$\upsilon_n > 0. \qquad (12)$$

The work of the press and impact forces in one turn of the knife equals to the corresponding amount of work for all areas $A_1A_2B_2B_1$:

$$W = (\sum e_p + \sum e_k)\ \upsilon/(s\ w). \qquad (13)$$

The next algorithm of power calculation was realized.

1. Initialization of input variables k, H, R, r, s, w, υ, α, ρ. 2. Calculation of the value of β by the formula (1), ω from the equality (2) and verification of the

condition (5) at forward rotor rotation and condition (6) − at reverse rotor rotation. 4. Calculation of the value of h_c by the formula (7). 5. Specifying the numbers of iterations n, m and calculation of the values of steps Δ_r, Δ_φ by the formulas $\Delta_r = (R - r)/m$; $\Delta_\varphi = (\pi - 2\beta)/n$. 6. Initialization of the number of i of the first iteration and the values of E_p; E_k: $i = 0$; $E_p = 0$; $E_k = 0$. 7. Calculation of the values of ψ_1, ψ_2 by the formulas $\psi_1 = \beta + i\,\Delta_\varphi$; $\psi_2 = \psi_1 + \Delta_\varphi$. 8. Initialization of the number of j of the first iteration: $j = 0$. 9. Calculation of the values of r_1, r_2 by the formulas $r_1 = R - j\,\Delta_r$; $r_2 = r_1 - \Delta_r$. 10. Calculation of coordinates x_{A1}, y_{A1}, x_{A2}, y_{A2}, x_{B1}, y_{B1}, x_{B2}, y_{B2} by the formulas (3) at a forward rotor rotation and at a reverse rotor rotation. 11. Calculation of the value of F by the formula (8). 12. Calculation of the value of υ_n by the formula (11). 13. Calculation of the value of e_p by the formula (9) and addition of the value of e_p to the value of E_p, if $H \le y_{A2}$; $H \le y_{B2}$; $\psi_2 \le \pi/2 - \beta$. 14. Calculation of the value e_k by the formula (10) and addition of the value of e_k to the value of E_k, if $H \le y_{A1}$; $H \le y_{B1}$; $H \le y_{A2}$; $H \le y_{B2}$. 15. Increase in number of j by one and reiteration of items 9, 10, 11, 12, 13, 14, 15, if $j < m$. 16. Increase in number of i by one and reiteration of items 8, 9, 10, 11, 12, 13, 14, 15, 16, if $i < n$. 17. Calculation of the value of W by the formula (13) under condition (12).

3. Results and discussion. It can be seen, that at forward rotor rotation the values of the tillage pitch and ridge height decrease with the increase in the number of knives when specific power does not change (Fig. 3). For example, with an increase in the number of knives from 2 to 3 a tillage pitch decreases from the value of s_2 to the value of s_3 and a ridge height decreases from the value of h_2 to the value of h_3 while a specific power remains equal to 10 kW/m. Thus, an increase in the number of knives on one side of a flange makes it possible to increase the quality and efficiency of soil treatment. An opposite effect is achieved at reverse rotation of the rotor: for example, with an increase in the number of knives from 2 to 3 the tillage pitch increases from s_2 to s_3 and the ridge height – from h_2 to h_3 while the specific power remains equal to 20 kW/m.

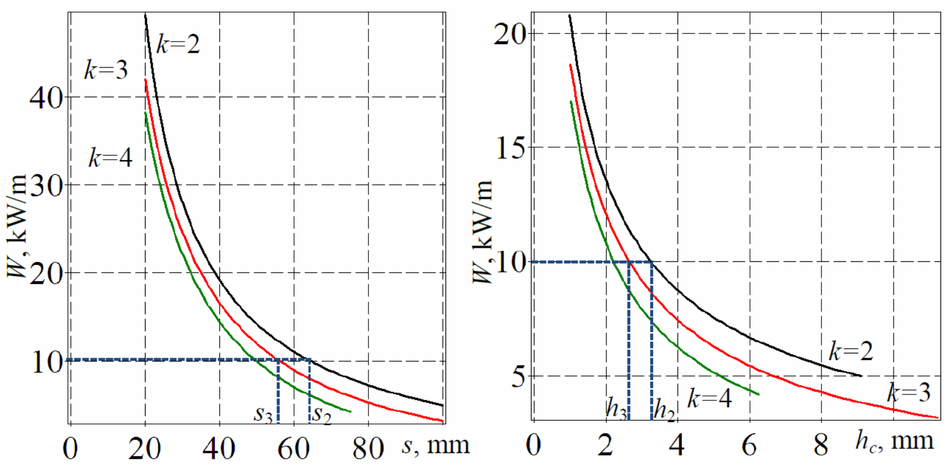

Fig. 3. Effect of the tillage pitch s (left) and the ridge height h_c (right) on specific power W at the forward rotor rotation

4. Conclusions. 1. A computer model of the movement of a rotary tiller knife, based on the equations of the knife profile point movement, can be used to assess the energy requirement and the quality of soil treatment, taking into account the radius of a rotor, the size and the rake angle of the straight profile of a knife, the width of a knife, the distance from the rotor axis to the soil surface, the speed of a rotary tiller frame point, the tillage pitch, the number of knives on one side of a flange and the direction of a rotor rotation. 2. The reverse rotor rotation is ineffective. 3. An efficiency of the soil treatment increases with the increase in the number of knives on one side of a flange.

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