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ВИЗНАЧЕННЯ ОСНОВНИХ ПАРАМЕТРІВ РІЗАЛЬНОГО АПАРАТА РОТАЦІЙНОЇ КОСАРКИ

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DETERMINATION OF THE MAIN PARAMETERS OF THE ROTARY MOWER CUTTING APPARATUS

Анотація.

В статті встановлено, що ефективна довжина ріжучої кромки ножа прямо пропорційна швидкості агрегатування косарки та обернено пропорційній кутовій швидкості ротора та кількості встановлених на ньому ножів. Перекриття шляхів руху ножів сусідніх роторів залежить від радіуса ротора; кількість встановлених на ньому ножів і кінематичний режим роботи ріжучого апарату. Більше того, збільшення радіуса ротора вимагає збільшення перекриття, а збільшення кінематичного режиму та кількості ножів призводить до зменшення перекриття між шляхами ножів.

Abstract.

It was found that the effective length of the cutting edge of the knife is in direct proportion to the aggregation speed of the mower and in inverse proportion to the angular velocity of the rotor and the number of knives mounted on it. The overlap of the paths of the knives of adjacent rotors depends on the radius of the rotor; the number of knives mounted on it and the kinematic mode of operation of the cutting apparatus. Moreover, an increase in the radius of the rotor requires an increase in the overlap, and an increase in the kinematic mode and the number of knives leads to a decrease in the overlap between the paths of the knives.

Ключові слова: *ротаційна косарка, ротор, ніж, скошена площа, перекриття, швидкість різання.*
Keywords: *rotary mower, rotor, knife, mown area, overlap, cutting speed.*

1. Introduction

For mowing grass during harvesting of hay or haylage, support-free mowers with rotary movement of knives are used mainly, the productivity of which is much greater than segment-finger mowers. Free-cutting apparatuses with rotational movement of knives can be the ones with rotation around the vertical (rotational) and horizontal (rotary) axes. Mowers that are equipped with rotary cutting devices grind grass significantly, so they are used in mower-grinders and lawn mowers. The purpose of the work is to substantiate the methodology for calculating the structural and kinematic parameters of rotary cutting devices that should correspond to the conditions of their use. The main parameters characterizing the operation of rotary cutting devices are: area, mown within one disk rotation cycle; knife effective length; overlap of adjacent rotors' knives; cutting speed. The following assumptions were made while determining the basic parameters of the rotary cutting apparatus of the mower. It was assumed that the angular speed of the rotor and the ground speed of the mower are unchanged, with the movement of the unit being straightforward. In addition, the cutting apparatus performs mowing in a plane parallel to the soil surface, which is perpendicular plane to most plant stems.

2. Target setting

Grass mowing is an integral part of any haymaking technology. It must be carried out with optimal timing and in compliance with agronomic requirements. Support free mowers with rotary knives movement are the most frequently used for this technique. They proved substantially more productive than segment finger mowers. Cutting apparatuses are among the major parts of mowers. They are updated in two directions: the first is to improve the cutting process due to optimization of the apparatus parameters and search for new ways of cutting and new types of cutting apparatus; the second one aims at improving the knife driver.

Support free cutting apparatuses with rotational movement of knives can have vertical (rotational) and horizontal (rotary) axes [1]. Mowers that are equipped with rotary cutting devices grind grass significantly, so they are used in mower-grinders and lawn mowers [2].

The differences in construction of the rotary mowers are most frequently based on the cutting apparatus design and the type of its drive. In terms of the tool drive location the rotary mowers can have upper, lower and combined drive. It must be noted that the drive defines the design of the cutting apparatus. The lower drive mowers have their cutting apparatus rotors disk shaped with articulated knives attachment, the cutting edges being located in the rotation plane. These apparatuses are cost effective, have simple design, are reliable and easy to maintain. The disks are the pressed structures, circle or oval shaped and equipped with strengthening ribs.

Cutting apparatus rotors of the upper drive mowers are made as cylinders with articulated attachment of knives.

The main parameters that describe the operations of rotary cutting apparatuses are: the area mown for one disk cycle; effective length of the knife, overlapping knives of adjacent rotors; cutting speed. The studies [3-8, 14, 15] substantiate the above parameters. It should be noted however, that the studies do not provide sufficient analysis of the rotor kinematics while the findings on correlation, enabling to calculate kinematic and geometrical indicators of cutting apparatus performance, have contradictions.

3. The analysis of the most recent research

Knife is the main functional element of the cutting apparatus of a mower and performs the function of mowing plants. It is equipped with a cutting edge, which is set at an angle ψ to the radial direction and has a sharpness angle β (Fig. 1). The following are the rational values of the angles: ψ = 0,44…0,53 rad, β = 0,35…0,70 rad [3].

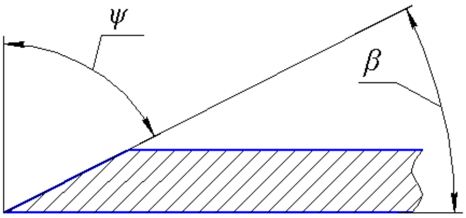

Fig. 1. Cutting edge angles of the knife

Edge sharpness is an important parameter of the knife. In order to secure high quality grass mowing at the speed of 40 m/sec the edge sharpness should be within 100…200 microns [4]. However, the width of the edge stops influencing the cutting apparatus performance when the cutting speed is increased to 80 m/s [5, 6, 7].

According to the findings, the critical support free grass cutting speed is within 20 m/s while the speed at which the stubble height is almost the same as the set height of cutting stays within the range of 45…60 m/s [7].

The work [8] defines the optimal cutting speed for sharp knives as 60 and for blunt ones 80 m/s.

The rational cutting speed depends on the grass in-feed to the cutting apparatus and, thus, on the mower's load speed and the grass yield. The in-feed increase requires relevant increase in cutting speed. With the in-feed of 4.2 kg per second the rational cutting speed is 50…60 m/s [9].

Rotary cutting apparatuses have a number of weaknesses, one of which is grinding grass during the mowing process, which results in bigger yield loss. The explanation is the incoherence of the knives' circular speed and the mower's load speed. The above effect is also observed when the number and the length of knives is bigger than the optimal. The attempts to reverse the parameters may result in fail patches, i.e. unmown segments of the field [10].

Thus, a fundamental task is to identify the coherence of constructive and kinematic parameters of rotary cutting apparatuses and their use conditions.

4. Basic research

The main factors of rotary mower performance are the shear area of one knife for one rotation cycle, the effective length of the knife and the speed of support free cutting. These factors define the workload on the knife by the cutting power and the energy spent on the grass mowing.

In order to identify the main parameters of the rotary cutting apparatus we refer to the figure 2, which provides the scheme of one of the mower rotors, that moves translationally with the speed of V and rotates with the circular speed of ω.

To define the main parameter of the rotary cutting apparatus of the mower the assumptions are as follows. We shall assume that the angular speed of the rotor and the translational speed of the mower are unchanged, while the unit movement is straightforward. The cutting apparatus also mows in the plane parallel to the ground surface, i.e. across the most stalks of plants.

The origin of coordinates is placed according to the picture. Y-axis is directed towards the translational movement (the load) of the mower.

Mowing with support free rotational apparatuses is the result of the impact interaction between the knife and the grass stalks. One of the main factors of this mode of mowing is the cutting speed. For comparison purposes among different apparatuses the speed is normally defined for extreme outer points of the knives' cutting edges.

Since the travel speed of the mower V is much lower than the circular speed of the knives, all the points thereof trace out cycloidal trajectories in the absolute motion. The equation of the trajectory of the point of the knife 1 (point a) in parametric form is written as:

$$x_a = R\cos\omega t \quad (1)$$

$$y_a = Vt + R\sin\omega t\,, \quad (2)$$

where x_a and y_a – are movement projections of the point a on coordinate axis, м;

R – the radius of the circle made by point a during the circular movement, м;

t – time, s.

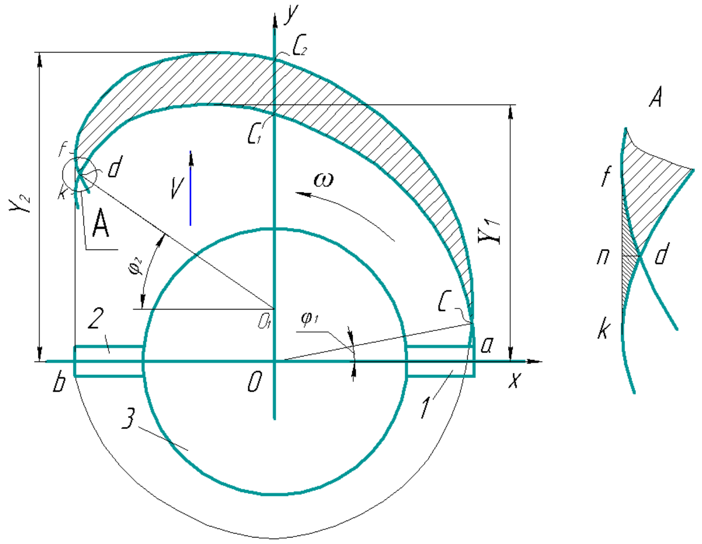

Fig. 2. The scheme of defining the main parameters of rotary cutting apparatus: 1, 2 – knife, 3 – disk

After differentiating between 1 and 2 in time, we obtain:

$$\frac{dx_a}{dt} = -R\omega \sin \omega t, \quad (3)$$

$$\frac{dy_a}{dt} = V + \omega R \cos \omega t. \quad (4)$$

Absolute speed of the point *a* at any moment of time

$$V_{abs} = \sqrt{\left(\frac{dx_a}{dt}\right)^2 + \left(\frac{dy_a}{dt}\right)^2}. \quad (5)$$

When we apply the figures of the speed projection from (3) and (4) to (5), we obtain

$$V_{abs} = \sqrt{R^2\omega^2 + 2VR\omega\cos\omega t + V^2}. \quad (6)$$

The absolute speed will reach the maximum value at $\omega t = 2\pi k$, where $k = 0; 1; 2\ldots$, i.e. $V_{abs} = R\omega + V$. V_{abs} will have the minimum value at $\omega t = \pi + 2\pi k$, i.e. $V_{abs} = R\omega - V$.

Therefore, the absolute speed of any point of knife varies from the maximum value, equal to the sum of the circular speed of this point and the mower's aggregation speed, to the minimum, which is the difference of the above speeds.

Point of knife trajectory equation 2 (point *b*) in parametric form is written as:

$$x_b = R\cos\left(\omega t - \frac{2\pi}{z}\right), \quad (7)$$

$$y_b = V + R\cos\left(\omega t - \frac{2\pi}{z}\right), \quad (8)$$

where y_b, y_b – are movement projections of the point *b* on coordinate axis *b;*

z – the number of knives mounted on the rotor.

One of the main parameters of the rotary mower performance is the area mown with a knife for one rotation cycle. As we can see on picture 2, the area mown by a knife for one cycle of the rotor is limited with absolute movement trajectories (cycloids) of point *a* and *b* of the knives *1* and *2*, graph cc_1dc_2c. Therefore, the blade of each knife cuts plants from the field segment that is limited by two trochoids shifted towards the mower's aggregation speed.

The coordinates of the points *c* and *d* (the cycloid cross points) are defined by the angles φ_1 and φ_2. According to the data [12]:

$$\varphi_{1,2} = \frac{\pi}{z(\lambda \pm 1)}, \quad (9)$$

where λ is kinematic parameter, $\lambda = \omega R / V$.

The sign (+) in this formula corresponds to the point *c*, while the sign (-) corresponds to the point *d*.

We use well known Fundamental theorem of calculus [11] to identify the area of the figure cc_1dc_2c

$$S_{cc_1dc_2c} = \int_{-R\cos\varphi_2}^{R\cos\varphi_1} [u(x) - f(x)]dx, \quad (10)$$

where *u(x)* and *f(x)* – are the function that describes the curves cc_2d and cc_1d respectively.

To identify the formula for the function *u(x)* and *f(x)* we exclude the parameter *t* from the equations (1) and (7) and apply the obtained values of time to (2) and (8) respectively. As a result, we obtain:

$$f(x) = \frac{V}{\omega}\arccos\frac{x}{R} + \sqrt{R^2 - x^2}, \quad (11)$$

$$u(x) = \frac{V}{\omega}\left(\frac{2\pi}{z} + \arccos\frac{x}{R}\right) + \sqrt{R^2 - x^2}. \quad (12)$$

Applying (11) and (12) to (10), we obtain:

$$F_{cc_1dc_2c} = \int_{-R\cos\phi_2}^{R\cos\phi_1} \left[\frac{V}{\omega}\left(\frac{2\pi}{z} + \arccos\frac{x}{R}\right) + \sqrt{R^2 - x^2} - \frac{V}{\omega}\arccos\frac{x}{R} + \sqrt{R^2 - x^2}\right]dx =$$

$$= \frac{2\pi VR}{\omega z}\left(\cos\varphi_1 + \cos\varphi_2\right).$$

Then, with consideration of (9) the knife mows the following area for one rotation

$$F_{cc_1dc_2c} = \frac{2\pi R^2}{\lambda z}\left(\cos\frac{\pi}{z(\lambda+1)} + \cos\frac{\pi}{z(\lambda-1)}\right). \quad (13)$$

The effective length of the cutting edge of the knife should be bigger or equal to the difference between the maximum ordinates of the absolute movement of the points of adjacent knives (Fig. 2), i.e.:

$$h_p \geq Y_2 - Y_1, \quad (14)$$

where h_p – effective length of the cutting edge of the knife, м;

Y_1, Y_2 – maximum ordinates of the absolute shifts of the points of the first and the second knife respectively, м.

After we differentiate (7) from (8) in time, we obtain:

$$\frac{dx_b}{dt} = -R\omega\sin\left(\omega t - \frac{2\pi}{z}\right), \quad (15)$$

$$\frac{dy_b}{dt} = V + R\omega + \cos\left(\omega t - \frac{2\pi}{z}\right). \quad (16)$$

In the points of the trajectories of the points of knives, that have maximum ordinates, the derivatives $\frac{dy_a}{dx_a}$ and $\frac{dy_b}{dx_b}$ are equal to zero, i.e.:

$$\frac{V + R\omega\cos\omega t}{-R\omega\sin\omega t} = 0,$$

$$\frac{V + R\omega\cos\left(\omega t - \frac{2\pi}{z}\right)}{-R\omega\sin\left(\omega t - \frac{2\pi}{z}\right)} = 0.$$

As long as the denominators of these fractions cannot be equal to zero, and having set the numerators of the obtained fractions to zero and solved them for time, we obtain:

$$t_a = \frac{1}{\omega}\left(\pi - \arccos\frac{V}{R\omega}\right), \quad (17)$$

$$t_b = \frac{1}{\omega}\left[\pi - \arccos\left(\frac{V}{R\omega} + \frac{2\pi}{z}\right)\right], \quad (18)$$

where t_a, t_b – the time, needed for the points *a* and *b* to reach the maximum ordinates.

We apply the values of time t_a and t_b from (17) and (18) to (2) and (8) and obtain:

$$Y_1 = \frac{V}{\omega}\left[\pi - \arccos\left(\frac{V}{\omega R}\right)\right] + R\sqrt{1 - \left(\frac{V}{\omega}\right)^2}, \quad (19)$$

$$Y_2 = \frac{V}{\omega}\left[\pi - \arccos\left(\frac{V}{\omega R} + \frac{2\pi}{z}\right)\right] + R\sqrt{1 - \left(\frac{V}{\omega R}\right)^2}. \quad (20)$$

We apply (19) and (20) to (14) and, after transformation, we obtain:

$$h_p \geq \frac{2\pi V}{\omega z}. \quad (21)$$

Thus, the effective length of the edge of the knife is in direct proportion to the aggregation speed of the mower and is in reverse proportion to the angular speed of the rotor and the number of knives mounted on it.

If we switch from the angular speed of the rotor to the circular frequency, we obtain:

$$h_p \geq \frac{60V}{nz}, \quad (22)$$

where n – the circular frequency of the cutting apparatus' rotor, rotations per minute.

The path points of the adjacent knives, which have the maximum ordinates should have equal abscisses. Let us verify this. We apply the found values of time from (17) and (18) respectively to (1) and (7) and make sure that the abscisses of both points are equal to each other.

$$x_a = x_b = -V/\omega. \quad (23)$$

The Figure 3 shows the graphic correlations between the changes of minimal effective length of the cutting edge of the knife and the change in rotation speed of the mower's rotor, built according to (22).

The graphs assume that two knives are mounted on the rotor, i.e. $z = 2$. As we can see according to the presented data, the effective length of the cutting edge of the knife decreases as the circular frequency of the rotor increases.

During the operations of the rotary mower the knives' trajectories of the adjacent rotors must overlap by the value Δ. If they don't, there will be fail patches on the field, i.e. the unmown areas. As we can see on the fig. 2 after the mower passes over the unmown areas there will be curvilinear triangles *kfd* left on the field.

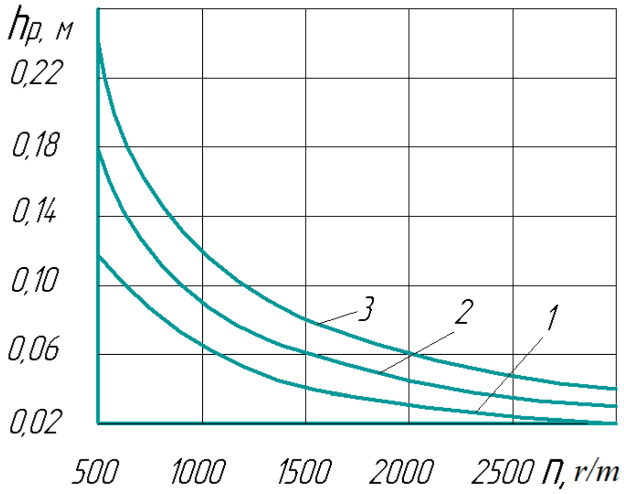

Fig. 3. The graphs of variance between the minimal effective length of the cutting edge of the rotary cutting apparatus h_p and the circular frequency of the rotor n: 1 – V = 2 м/s, 2 – V = 3 м/s, 3– V = 4 м/s

That same picture makes it evident that the knives' overlap *Δ* must be bigger than the double projection of the interval *nd* on the absciss [13]:

$$\Delta \geq 2\left|x_n - x_d\right|,$$

where $|x_n| = R$ – the absciss of the farthermost trajectory point from the axis *OY*;

$|x_d|$ – the absciss of the two adjacent knives' trajectories cross point.

From the fig. 2 we have:

$$\left|x_d\right| = R\cos\varphi_2 .$$

Then

$$\Delta \geq 2R\left(1 - \cos\frac{\pi}{z(\lambda - 1)}\right). \qquad (24)$$

From (24) we conclude that the path overlap of the adjacent rotors' knives depends on the rotor radius; the number of the knives, installed thereon and the kinematic operation mode of the cutting apparatus. Besides, the increase in the rotor radius requires the increase in the overlap while the growth of the kinematic mode rate and the number of knives results in reduction of the knives' path overlap. This is described in graphs on the fig. 4.

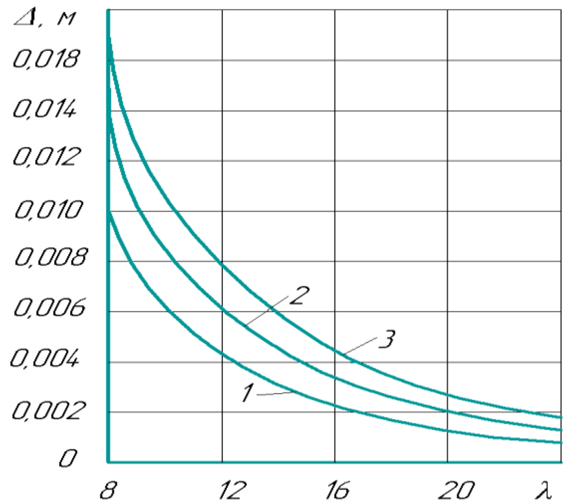

Fig. 4. The variance of the path overlap of the adjacent rotors knives Δ in correlation with kinematic mode λ and rotor radius R (z = 2): 1- R=0,2, 2- R = 0,3, 3- R = 0,4 м

5. Conclusions

1. The main parameters that describe the operations of rotary cutting apparatuses are the area mown by a knife for one disk cycle, knife's effective length, adjacent rotors knives overlap, cutting speed.

2. The cutting speed of any point of knife varies from the maximum value, which is equal to the sum of the circular speed of this point and the mower's aggregation speed, to the minimal one, which is the difference between the above speeds.

3. The effective length of the cutting edge of the knife is in direct ratio to the mower's aggregation speed and in reverse ratio to the angular speed of the rotor and the number of knives, installed thereon.

4. The adjacent rotors knives overlap depends on the rotor's radius, the number of the knives, installed thereon and the kinematic mode of operation of the cutting apparatus. The increase in the rotor radius requires the increase in the overlap while the increase in the kinematic mode rate and the number of knives results in the reduction of the overlap of the knives' trajectories.

5. We obtained the correlation that allows to identify the area mown by one knife for one cycle of the rotor.

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