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RESEARCH OF PHYSICAL AND MECHANICAL PROPERTIES OF CUT GRASS DURING HAY HARVESTING BY ROTARY WORKING BODIES

In the process of harvesting feed from the interaction of the working bodies of machines and tools with plants, resistance arises, which entails certain energy costs. Therefore, for the development of technological processes, it is necessary to know the mechanical and physical properties of the processed environment under the influence of the working bodies of machines and tools.

Insufficient study of the properties of materials does not allow a more rational transition to new methods of work, hinders the development of fundamentally new technological processes and machines.

Knowledge of the physical essence of technological processes allows for a more reasoned development of machines, to apply rational methods of influencing their working bodies on the environment, to qualitatively improve the performance of the technological process. Knowledge of the physical and mechanical properties of agricultural materials is a necessary condition for the correct organization of the technological process and the creation of a rational design of the machine.

Agricultural materials are distinguished by a great variety and variability of their properties. Technological processes carried out by agricultural machines are aimed at changing the structure of agricultural materials. During processing, the harvested plant material undergoes a number of changes and is brought to a state that meets predetermined requirements.

Using the physical and mechanical properties of materials, they can be directed towards the construction of rational technologies and processing methods. In this case, various principles of the influence of the working bodies of machines on the material being processed can be applied. The need to study the properties of materials in different conditions, to clarify their impact on technology and mechanization is urgent. Knowledge of the properties of plant materials helps to choose the most economical methods of its processing.

The choice of the type of working body and the justification of its parameters depend on a large number of factors, in particular on the required productivity, nature, degree and state of material processing, coefficients of useful action of the machine, its energy needs. The article considers the theoretical and calculation bases of the working bodies of machines in the sequence of their impact on plant material when harvesting fodder from grasses. At the same time, the theory and calculation of the parameters of the working bodies are related to the physical and mechanical properties of the processed material and agrotechnical requirements for work processes and machines.

Keywords: *fodder grasses, hay, drying, technology, harvesting, physical and mechanical properties, moisture content, density, rotary working bodies, rakes.*

Introduction. In modern conditions of development of mechanization means, the harvesting of fodder from grasses is aimed at increasing the productivity of technological processes, obtaining high-quality products using new types of influence of working bodies on the material. All this requires a new approach to the design of technological processes, the use of modern materials in the design of working bodies of forage harvesting machines, and increasing energy consumption. Therefore, the theory of operation of both existing working bodies of fodder harvesting machines and new ones should be based on knowledge of the physical, mechanical and technological properties of the material that needs to be processed to obtain high-quality final products with the maximum reduction of losses of nutrients and vitamins contained in the grown harvest of grass fodder crops [1].

Theoretical analysis of the processes of harvesting fodder from stem crops shows the possibility of establishing calculated dependences of productivity on energy consumption and design parameters of working bodies of machines, if the physical, mechanical and technological characteristics of the processed material are known [1].

Further progress in promising technologies and technical means for harvesting fodder from stem crops requires the generalization of theoretical and computational developments of known processes, which will allow giving impetus to the creation of such means of mechanization that will ensure high productivity with the lowest costs of material and energy resources per unit of quality of fodder being harvested [2].

Analysis of recent research and publications. The desire to increase productivity, quality of technological process execution, reduce metal consumption, increase reliability, universalization and consideration of natural and climatic conditions led to the creation of a large number of machines for stirring, raking and turning over mowed grass, which differ in purpose, design features of working bodies, method of aggregation, principle of windrow formation and a number of other distinctive features [3]. The research of many scientists [1, 3-10] highlights theoretical developments on the main working bodies of machines for mowing grass, their flattening, stirring, raking into windrows, pressing, crushing when harvesting forage crops for making hay, silage, silage.

By purpose, machines for stirring, raking and turning over grass can be divided into the following groups: tedders, windrow rotators, transverse rakes, hay rakes. Tedders are rotary-type machines designed for stirring and spreading rolls of mowed grass. The working elements of the tedders are rotors, each of which is a disk with rakes, at the ends of which spring teeth are fixed. As a rule, tedders have an even number of rotors, each of which rests on a running wheel. The rotors of each pair rotate towards each other, driven by the tractor's power take-off shaft. During operation, the rakes of each pair of rotors perform a rotational movement towards each other. The rake teeth capture the grass lying in front of them and spread it behind the rotors. The rolls are spread in a similar way [4-6].

The purpose of research. The purpose of this study is investigation the influence of the design parameters of rotary working bodies on the quality of hay harvesting.

Presentation of the main material.

Rotary rakes with rakes controlled during operation have one or more rotors that rotate around vertical axes. Each rotor consists of a disk, in the radial plane of which 6…12 rods are hingedly mounted. The end of the rod, directed towards the axis of rotation of the rotor, has a crank with a cam that moves along a curved profile track. At the opposite (outer) end of the rod, rakes are fixed, made in the form of double spring teeth [4]. When the rotor rotates, the rods, thanks to the cam mechanism, rotate around their longitudinal axis, as a result of which the spring teeth occupy a vertical or horizontal position. In the vertical position, the spring teeth rake the grass, the transition to the horizontal position, which occurs when the rod is turned by an angle $\alpha = \pi$ ensures the release of the teeth from the grass and the formation of a swath [9, 10].

The relationship between the kinematic and design parameters of the rake is presented in the calculation diagram (Fig. 1), which shows one of the rotors of the rake, which moves translationally with the machine speed V and rotates with an angular velocity ω.

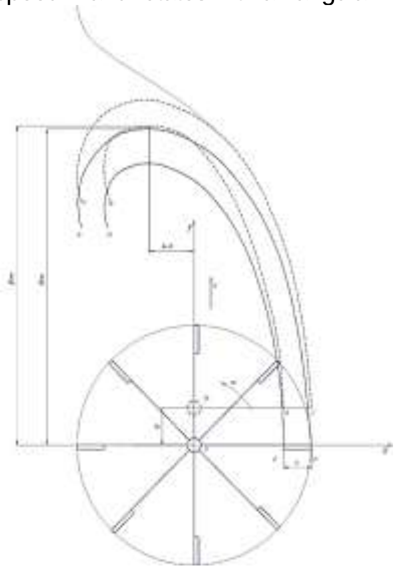

Fig. 1. Calculation diagram of a rotary rake with controlled rakes [11]

Let us place the origin of the moving coordinate system in the center of the rotor at the initial moment t = 0, and direct the Y axis in the direction of the machine's forward motion. At the ends of each of the rods are rakes with a gripping width of b. The first rake rakes the grass in the square aa′d′d, and the second rakes it out of the area - cc′k′k. For high-quality implementation of the technological process by the rake, it is necessary that there are no untreated gaps between these areas. This is achieved with certain ratios of the translational and circular speeds of the rotor, its diameter D=2R, the number of rods z and the rake grip width b. To fulfill the specified condition, the trajectory of the end of the first rake (point a) must touch the trajectory of the beginning of the second rake (point k), i.e. be as equal as possible to each other [10]:

$$y_{amax}= y_{kmax}. \quad (1)$$

When analyzing the operation of the rakes, we will make the following assumptions. We will assume that the angular and translational velocities are constant, and the movement of the machines is rectilinear.

Let us examine the projections onto the XOY plane of the cycloidal curves that describe the ends of the rake fingers under these assumptions.

The end of the outer finger of the first rake (point a) describes a curve in the projection onto the XOY plane, which is given in parametric form by the following equations [10]:

$$X_a = R\cos\omega t, \quad (2)$$

$$Y_a = Vt + R\sin\omega t, \quad (3)$$

where X_a *і* Y_a - projections on the X and Y axes of the absolute movement of the point a;

V - translational speed of the machine.

The parameters of the motion of the end of the outer finger of the second rake (point k) are determined by the following equations [10]:

$$X_k = (R-b)\cos(\omega t-2\pi/z), \quad (4)$$

$$Y_k = Vt + (R-b)\sin(\omega t -2\pi/z), \quad (5)$$

where X_b,Y_b - projections on the X and Y axes of moving a point *b*;

z – the number of rakes installed on the rotor rim.

To determine the maxima of the curves that describe the points a i k differentiate equations (2 - 5) with respect to time and equating the resulting expressions to zero and solving them with respect to the independent variable t, we will have [10]:

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

$$t = \frac{1}{\omega}\arccos\left(-\frac{V}{\omega R}\right). \quad (6)$$

$$t = \frac{2\pi}{\omega z} + \frac{1}{\omega}\arccos\left[-\frac{V}{\omega(R-b)}\right]. \quad (7)$$

Maximum ordinates of both trajectories [10]:

$$y_{a\max} = \frac{V}{\omega}\arccos\left(-\frac{V}{\omega R}\right) + R\sin\left[\arccos\left(-\frac{V}{\omega R}\right)\right], \quad (8)$$

$$y_{a\max} = \frac{V}{\omega}\arccos\left(-\frac{V}{\omega R}\right) + R\sin\left[\arccos\left(-\frac{V}{\omega R}\right)\right], \quad (9)$$

Based on condition (2.1):

$$\frac{V}{\omega}\arccos\left(-\frac{V}{\omega R}\right) + R\sin\left[\arccos\left(-\frac{V}{\omega R}\right)\right] = \frac{V}{\omega}\arccos\left(-\frac{V}{\omega R}\right) + R\sin\left[\arccos\left(-\frac{V}{\omega R}\right)\right].$$

After simplification, we get:

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

$$\frac{2\pi\lambda}{z} = \sqrt{1-\lambda^2} - \sqrt{K^2-\lambda^2} - \lambda\arccos\left[\frac{1}{K}\left(\lambda^2 + \sqrt{1-\lambda^2}\sqrt{K^2-\lambda^2}\right)\right]. \quad (10)$$

Having marked $\frac{V}{\omega R} = \lambda$ i $\frac{R-b}{R} = K$, we obtain the condition for the contact of the trajectories:

$$\lambda\arccos\left(-\frac{\lambda}{R}\right) + \sqrt{1-\lambda^2} = \frac{2\pi\lambda}{z} + \lambda\arccos\left(-\frac{1}{R-b}\right) + K\sqrt{1-\lambda^2}.$$

Transforming this expression, we arrive at an equation that relates in dimensionless form the geometric and kinematic parameters of rotary rakes with steerable rakes [10].

This equation makes sense when $\lambda<1$ i $K>>\lambda$. In the opposite case, the trajectories of the forks degenerate into curves that have no maxima relative to the Y axis. An example of such a trajectory is indicated in Fig. 1 by a thin line.

The required width of the bar can be determined based on the following. According to agrotechnical requirements, the total grass loss during raking should not exceed 2.5% [1]. To achieve this, it is necessary that the maximum ordinates of the trajectories of adjacent bars are equal to each other, i.e. the trajectory of the inner finger (point k) of the next bar touches the trajectory of the outer finger (point a) of the previous bar [2].

Energy consumption for the rake drive. When observing the work of the rake, it was found that during the raking process, hay gradually accumulates in front of the rake in the form of separate portions. The first ones are firmly attached to the teeth, and the subsequent ones are kept from mutual displacement only by friction forces.

We will assume that after filling the rake with hay, its entire width b takes part in the work (Fig. 2).

The following forces act on a portion of hay with a mass m, which are applied to its center of gravity: *G* - weight force, $G = mg$; F_1- friction force on stubble, $F_1= f_1mg$; *R* - friction force on stubble, $R = m\omega^2r$, *Q* - Coriolis force, $Q = 2m\omega r'$; F_2 - the friction force of one portion of hay against another, $F_2 = 2f_2m\omega r'$; f_1 i f_2 – coefficients of friction of hay on stubble and hay on hay, r' - the speed of radial displacement of a portion of hay on the stubble [11-13].

The normal and radial components of the

friction force of hay on the stubble:

$F_{1H} = F_1 cos\psi$, $F_{1P} = F_1 sin\psi$, where ψ - the angle between the direction of the hay movement speed vector (tangential to the movement path) and the perpendicular to the rake.

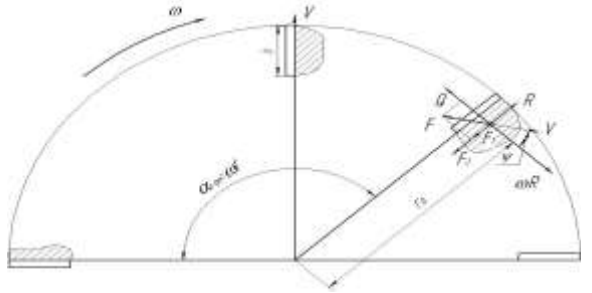

Fig. 2. Diagram of the forces acting on the rake [11]

The equation of motion of the hay relative to the moving radius can be written in the form of a linear inhomogeneous differential equation of the second order:

$$mr'' = R - F_2 - F_{1H}f_2 - F_{1P} \quad (11)$$

$$r'' + 2f_2\omega r' + f_2 f_1 g - \omega^2 r = 0 \quad (12)$$

The general solution r is the sum of the solutions of the corresponding homogeneous equation r_1 and one of the partial solutions r_2:

$$r_1 = C_1 e^{p_1 t} + C_2 e^{p_2 t}, \quad (13)$$

where C_1 i C_2 – arbitrary steels;

p_1 i p_2 – roots of the characteristic equation.

$$r = r_1 + r_2 = C_1 \omega e^{n_1 \omega t} + C_2 \omega e^{n_2 \omega t} + \frac{f_1 f_2 g}{\omega^2}. \quad (14)$$

Radial displacement speed of hay:

$$r' = C_1 n_1 \omega e^{n_1 \omega t} + C_2 n_2 \omega e^{n_2 \omega t}. \quad (15)$$

$$r = \frac{\omega^2 r_0 - f_1 f_2 g}{\omega^2 (n_2 - n_1)} \left(n_2 e^{n_1 \omega t} - n_1 e^{n_2 \omega t}\right) \frac{f_1 f_2 g}{\omega^2}. \quad (16)$$

The movement of the portion of hay will continue until its center of mass moves beyond the rake, that is, by the value r=R. During this time, the rake will rotate at an angle $\alpha = \omega t$.

The limiting angular speed of rotation of the rotor ω_{max}, at which a high-quality roll is formed is:

$$\omega_{max} = \sqrt{\frac{2 f_1 f_2 g}{2R + \frac{bQ_1}{1 - Q_1}}}. \quad (17)$$

where $Q_1 = \frac{n_2 e^{n_1 \alpha} - n_1 e^{n_2 \alpha}}{n_2 - n_1}$.

The maximum load on one rake will be:

$$F_{max} = qb\pi \left(R - \frac{b}{2}\right)\left(f_1 + \frac{2\omega r'}{g}\right). \quad (18)$$

Let's determine the total drive torque required to perform the technological process with one rotor:

$$M = (F_1 + Q)R. \quad (19)$$

$$M = b\pi q R \left(R - \frac{b}{2}\right)\left(\frac{Z+2}{4} + \frac{2\omega r'}{g}\right). \quad (20)$$

The power required to drive one rotor is:

$$N = M\omega = b\pi q R\omega \left(R - \frac{b}{2}\right)\left(\frac{Z+2}{4} + \frac{2\omega r'}{g}\right). \quad (21)$$

Conclusions. An integral stage of hay harvesting technologies is the drying of mowed grass in field conditions. This process is accompanied by losses of nutrients, the magnitude of which is proportional to its duration. An effective way to reduce the duration of field drying of grass is to flatten, stir, rake and turn it over. To perform these operations, it is advisable to use rotary mower-conditioners and rake-tillers.

Studies of the mechanisms of harvesting fodder from grass crops have confirmed the importance of optimizing the design and kinematic parameters of the working bodies of rotary machines. The results of the analysis show that the efficiency of the technological process depends on the physical, mechanical and technological properties of the processed material, as well as on the characteristics of the working bodies, which ensure the quality of operations with the lowest energy costs.

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ДОСЛІДЖЕННЯ ФІЗИКО - МЕХАНІЧНИХ ВЛАСТИВОСТЕЙ СКОШЕНИХ ТРАВ ПРИ ЗАГОТІВЛІ СІНА РОТАЦІЙНИМИ РОБОЧИМИ ОРГАНАМИ

Впровадження передових технологій у сучасних умовах є ключовим для досягнення високої продуктивності та збереження поживної цінності кормів. Невід'ємною операцією будь якої технології заготівлі сіна є скошування трави, від якості виконання якого залежить збір сіна з одиниці площі, а також відростання отави та врожайність трави в наступні роки. Ротаційні ворушилки, граблі та обертачі валків довели свою ефективність у заготівлі сіна та інших кормових культур завдяки інноваційним підходам до проєктування їх робочих органів.

Подальший розвиток галузі потребує узагальнення теоретичних моделей, розробки нових методів розрахунку параметрів і вдосконалення конструкцій машин. Це дозволить створити більш універсальні, надійні та енергоефективні технічні засоби, які забезпечуватимуть стабільну якість кінцевої продукції та відповідатимуть вимогам сучасного сільськогосподарського виробництва.

Використовуючи фізичні та механічні властивості матеріалів, можна направити їх на побудову раціональних технологій та прийомів обробки. При цьому можуть бути застосовані різні принципи впливу робочих органів машин на матеріал, що обробляється. Актуальним є необхідність вивчення властивостей матеріалів у різних умовах, з'ясування їхнього впливу на технологію та механізацію. Знання властивостей рослинних матеріалів сприяє вибору найбільш економних прийомів його обробітку.

Вибір типу робочого органу та обґрунтування його параметрів залежать від великої кількості факторів, зокрема від необхідної продуктивності, характеру, ступеню та стану обробки матеріалу, коефіцієнтів корисної дії машини, її енергетичної потреби. У статті розглянуто теоретичні та розрахункові основи робочих органів машин у послідовності їх впливу на рослинний матеріал при заготівлі кормів із трав. При цьому теорія та розрахунок параметрів робочих органів пов'язані з фізико-механічними властивостями оброблюваного матеріалу та агротехнічними вимогами до робочих процесів та машин.

Ключові слова: *кормові трави, сіно, сушіння, технологія, заготівля, фізико-механічні властивості, вологовміст, щільність, ротаційні робочі органи, граблі.*

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