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Failure Analysis of the Segment Finger Bar Mower and Force Interaction of the Blade Segment with the Plant Stem

Abstract. Scientific observations on the quality and reliability of combine harvesters have shown that of all the delays of equipment, 32...35% of the total operating time, technical failures account for 17.4...19.8%. Most of the failures were observed with the failure of combine parts, mechanical transmissions, hydraulic systems, etc. Quantitative analysis of harvester failures has shown that most failures occur in the operation of the cutting device, namely the finger bar mower. The working hypothesis is that it is possible to increase the reliability of the cutting device of harvesting machines in ordinary operating conditions and in the event of sudden failures by applying a coating on the blade segment, without significantly changing its geometric parameters, and performing notches that ensure both a decrease in the mass of the segment and its destruction without plastic deformation when foreign objects enter the cutting zone. The main problem of the reliability of segments of cutting device, harvesting equipment, is the cutting edge of the blade, which wears out and deforms during operation. From the above, it follows that the purpose of the study is to improve the reliability of segment finger bar mower machines by improving the mechanical properties of segments, these investigations are relevant and of practical interest. The study includes the use of mathematical probability and reliability theory, analysis, and a systematic approach to provide an analytical description of the operation of a cutting device segment. The consequence of this scientific investigation is an analysis of failures and malfunctions of the machinery, presented graphically, a diagram of how a plant stem segment is cut and the forces acting on the stem and the segment during the cutting process are depicted. These materials have scientific and informative content that would be of interest to engineers and scientists in the process of research and production of cutting device segments

Keywords: segment type cutting device, equipment reliability, harvesting equipment header, grain harvesting equipment, header failure, blade segment edge angle

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INTRODUCTION

A combine harvester is a complex technical system [1; 2], consisting of a large number of parts, components, and aggregates. Each node and mechanism does its own specific job. Contrary to this, one of the defining features of the machine's efficiency is its reliability [3].

The reliability of harvesting equipment is understood as the ability of equipment and its components to perform certain tasks [4], maintain operating parameters and conditions of their use due to maintenance, repair, storage, and transportation.

Currently, there is a tendency to reduce the total number of agricultural machinery and increase the average load on machinery by more than 2 times [5; 6]. All this is the reason for the decrease in its reliability and the increase in downtime conditioned by technical reasons.

Both Ukrainian and foreign researchers have not been able to solve the problem of sudden failures associated with foreign objects getting into the cutting zone.

The purpose of this study is to improve the reliability of the finger bar mower by improving the segment parameters.

The theoretical model of the formation of parametric failure as a result of the size of the working surfaces of the segment blade in contact with the stem material and depending on the rate of damage to its working surfaces is of scientific value. Theoretical model for improving the durability of a cutting device blade segment by creating a wear-resistant coating.

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The originality of this study is to increase the reliability of the cutting device of harvesting machines.

The conducted studies of the reliability of combine harvesters showed that 17.4...19.8% of total delays (inefficiencies) of the technique, representing 32...35% of the working time is due to a technical malfunction. According to the results of studies, the actual failure time of combine harvesters in Ukraine is 3...70 hours, and the readiness factor is 0.85...0.97, respectively. Most often, malfunctions occur in the harvesting part, mechanical gears, hydraulic systems, working bodies of the thresher, electrical and control devices (Fig. 1) [7].

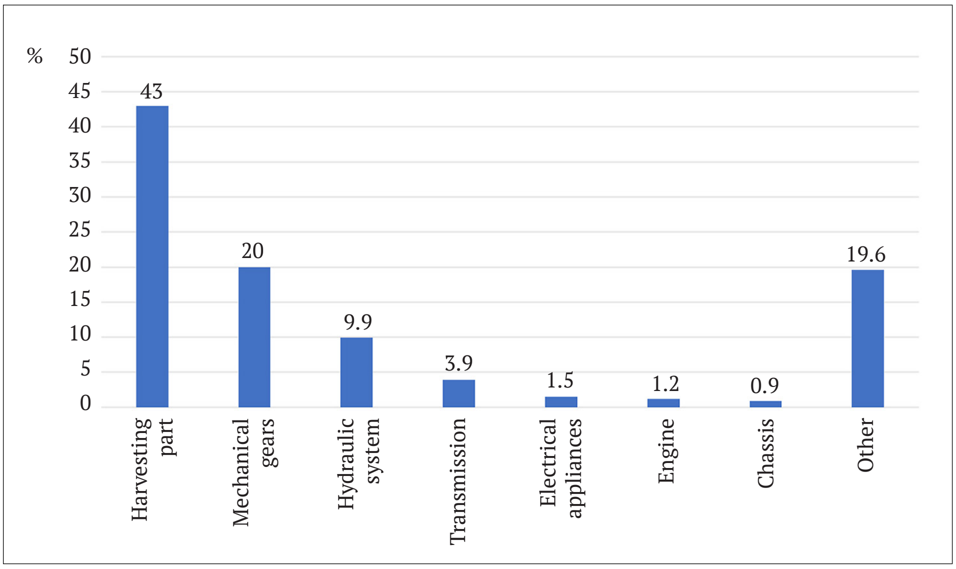

Figure 1. Distribution of combine harvester failures

Source: [7]

Quantitative analysis of malfunctions of combine parts showed that the maximum number of failures belongs to the parts of the cutting device, that is, to segments and counter-cutting parts and fingers (Fig. 2) [7]. Notably, the failure of counter-cutting parts and fingers mainly occurs as a result of force contact of segments deformed under the influence of foreign bodies in the cutting zone [8].

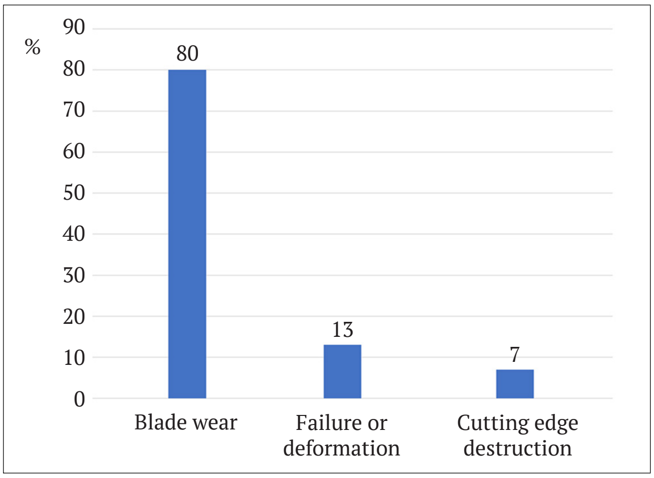

Figure 2. Main types of malfunctions

Source: [7]

Wear of the cutting edge of the blade segments of the cutting machine, their geometric deformation or destruction due to accidents, and loosening of attachment to the knife bar are the main failures of the cutting machine.

THEORETICAL FRAMEWORK

Wear of the blade segment usually occurs as a result of friction during the cutting of the plant stem (Fig. 3). When the blade moves together, the lower cutting edge of segment 1 interacts with the plant stem and the counter-cutting plate 3. In this regard, the wear of the lower part of the segment is significantly greater in relation to the upper part. As a result of wear, the sharpening angle of the blade β and the sharpness of the blade edge δ change, which leads to a decrease in the reliability of the cutting device. There is a possibility of foreign objects (stones, parts of agricultural machinery, etc.) entering the cutting zone when using harvesting equipment on poorly mown and uneven areas of the field due to the flatness of cereals and grass.

The segment curved in the vertical plane when the blade moves back and forth collides with the elements of the finger, destroys it and destroys itself.

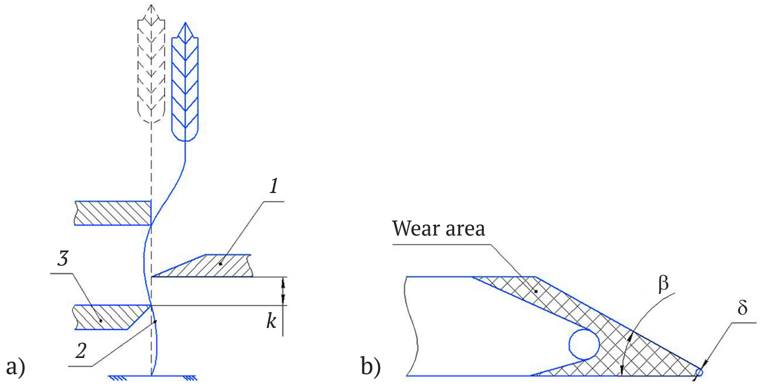

Figure 3. Graphic representation of the operation of the cutting device segment
a) interaction of the blade segment with the plant stem: b) wear of the blade segment.
1 – segment; 2 – plant stem; 3 – anti-cutting plate; *k* – gap in the cutting blades

Segments fail and break off on the back side near the fasteners, the counter-cutting parts of the finger quickly wear out and sometimes break at the edge (Fig. 4). All these processes lead to an increase in the time of repairing the combine and eliminating the malfunction. However, both Ukrainian and foreign manufacturers of grain harvesting machines could not fully solve the problem of preventing foreign objects from entering the working bodies, and therefore, protecting them from emergency failures [9].

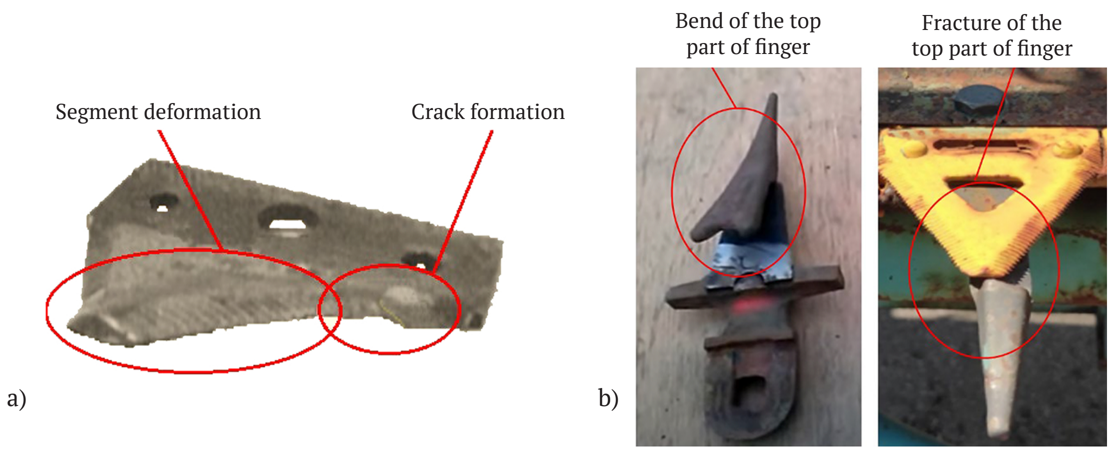

Figure 4. Result of sudden failure: a) damage to the segment; b) damage to the finger elements

Thus, the analysis of the information under study indicated that the weakest component in harvesting machines is the cutting device segment.

MATERIALS AND METHODS

The study involves the use of the theory of probability and reliability, mathematical analysis, and a systematic approach that provides an analytical description of the operation of the cutting device segment, standard bench and operational testing methods on modern equipment, and experimental planning methods, mathematical statistics for processing the results obtained.

RESULTS AND DISCUSSION

A certain amount of energy *A* needs to be spent to destroy the stem of the plant under the edge of the blade A_{blade} and overcome the resistance forces A_{res} caused by plant deformation [10; 11]:

$$A=A_{blade}+A_{res}, \tag{1}$$

The first term of this expression is characterised by the strength properties of the material, which are estimated by such an indicator as the ultimate strength σ_{ult}. The ultimate strength does not depend on the method of impact on the processed material and the parameters of the cutting tool and is determined by the properties of the material itself:

$$A_{blade}=f(\sigma_{ult}). \tag{2}$$

The second term considers the properties of the plant material, the parameters of the cutting tool, and the operating modes:

$$A_{res}=f(\delta, \beta, h_{cmp}, h_{layer}, l, \mu, E, \tau, v_s, k, s_{bend}, b), \tag{3}$$

where δ – blade edge sharpness, m; β – blade sharpening angle, deg; h_{cmp} – compression of the material preceding destruction, m; h_{layer} – thickness of the cut layer, m; l – length of the blade that came into contact with the material, m; μ – Poisson's ratio; E – elasticity modulus of the material, MPa; b – distance from the top of the finger to the segment blade, m; k – gap between the segment and the anti-cutting plate, m; v_s – segment speed, m/s; s_{bend} – amount of bending of the stem, m; τ – time of impact of the cutting tool on the stem, s.

Thus, the implementation of the cutting process is possible provided that the force P applied to the blade would contribute to the occurrence of a destructive contact stress on its edge σ_d, exceeding the tensile strength of the material $\sigma_d>\sigma_{ult}$, and the destruction itself occurred with minimal deformation of the material $(s_{bend}, h_{cmp})\rightarrow min$.

According to [12], to cut the stem of a plant with a segment of the cutting device, it is necessary that it overcomes the resistance force of the blade entering the material P_{cr}, the bending resistance force of the stem P_{bend} and the inertia force of the stem P_{cin}:

$$P=P_{cr}+P_{bend}+P_{cin}. \tag{4}$$

When cutting, the plant stem rests on two supports, the upper part of the finger (support 1) and the anti-cutting plate (support 2), so it can be represented as a beam that rests freely on two supports (Fig. 5).

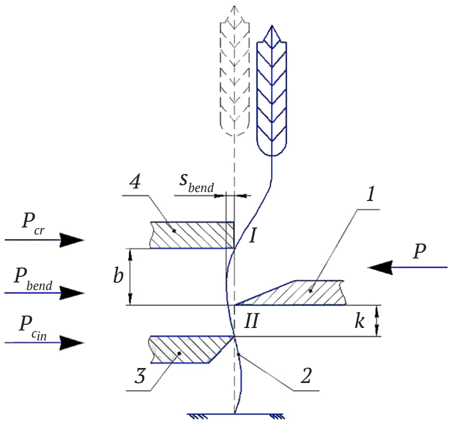

Figure 5. Stem cutting diagram 1 – segment; 2 – stem; 3 – anti-cutting plate; 4 – upper part of the finger

Then the bending resistance of the stem is determined by the following equation:

$$P_{bend} = \frac{3s_{bend}EJ}{bk^2\left(1-\frac{k}{b}\right)^2}, \tag{5}$$

where s_{bend} –amount of bending of the stem, m; E – elastic modulus of the stem, MPa; J – polar moment of inertia of the transverse stem, m4; b – distance from the top of the finger to the blade segment, m; k – gap between the segment and the anti-cutting plate, m.

The moment of inertia of the stem [13] is determined by the equation:

$$P_{c_{in}} = \frac{17m_{I-II}v_H}{35\tau}, \tag{6}$$

where m_{I-II} – weight of the stem of section 1-2, kg; v_H – segment speed, m/s; τ – time of impact of the cutting tool on the stem, s.

According to [14], when a single-face blade is deepened into a layer of material, forces act on it (Fig. 6 and 7): P_{blade} – resistance to destruction under the edge of the blade, directed opposite to the movement of the blade; P_{comp} – compression forces of the blade material that have a vertical direction and act on the edge of the blade; P_{res} – force of resistance of the material to compression by the blade, also directed opposite to the movement of the blade:

$$P_{cr}=P_{blade}+(P_{comp}+P_{res}). \tag{7}$$

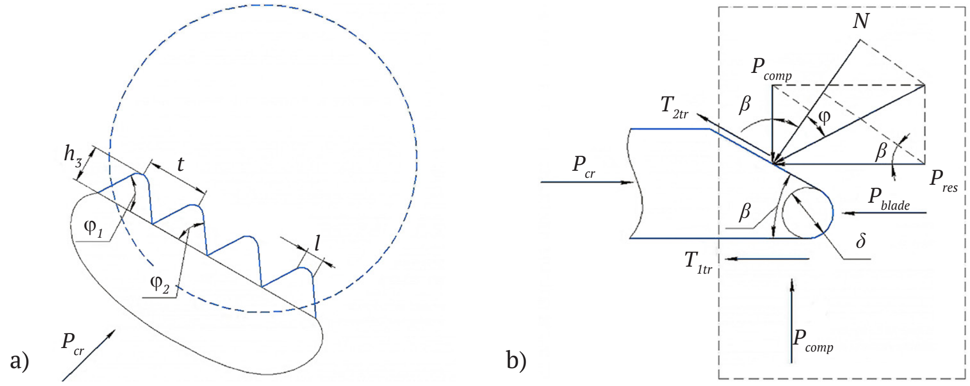

Figure 6. Force interaction of the blade with the plant stem a) forces acting on the blade; b) forces acting on the chamfer of the blade T_{1tr}, T_{2tr} – friction forces, N – normal power

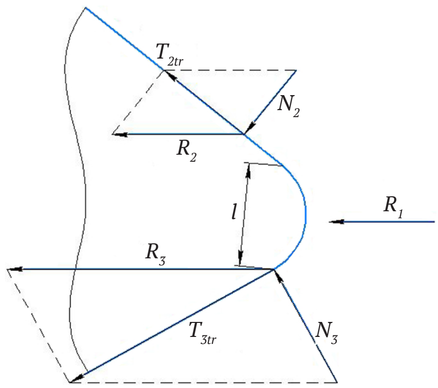

Figure 7. Forces acting on the notch of the blade segment.
T_{2tr}, T_{3tr} – friction forces, R_1, R_3, R_l – resultant forces, N_1, N_3 – normal forces

In the transformed form, equation (7) has the form:

$$P_{cr} = l\delta\sigma_d + \frac{E}{2}\cdot\frac{h_{cmp}^2 l}{h_{layer}}\left[tg\beta + f\sin^2\beta + \mu\left(f + \cos^2\beta\right)\right]. \tag{8}$$

where δ – sharpness of the blade edge, m. σ_d – destructive contact stress, $\frac{H}{m^2}$; l – length of the blade in contact with the material, m; E – elasticity modulus of the material, MPa; h_{cmp} – compression of the material preceding destruction, m; h_{layer} – thickness of the cut material layer, m; μ – Poisson's ratio [15]; f – coefficient of friction of the cut fibres of the stem against the edges of the wedge; β – blade sharpening angle, deg.

The first part of equations (7 and 8) reflects the processes occurring on the edge of the blade, and the second part reflects its chamfer. Considering the fact that the blade segment has a notch, the amount of force P_{blade} will depend on its geometric parameters and the number of blades that come into contact with the stem, the latter is determined by the diameter of the stem to be cut, d_cmp and notch spacing t_H. Then equation (7) will take the form:

$$P_{cr} = \frac{d_{cmp}}{t_H}\left(P_{blade} + \frac{E}{2}\cdot\frac{h_{cmp}^2 l}{h_{layer}}\left[tg\beta + f\sin^2\beta + \mu\left(f + \cos^2\beta\right)\right]\right). \tag{9}$$

where d_{cmp} – diameter of the cut stems, m; t_H – notch spacing of the blade segment, m; P_{blade} – resistance to destruction of the stem under the edge of the blade, N; E – elastic modulus of the material, MPa; h_{cmp} – compression of the material preceding destruction, m; h_{layer} – thickness of the cut material layer, m; μ – Poisson's ratio; f – coefficient of friction of the cut fibres of the stem against the edges of the wedge; β – blade sharpening angle, deg.

To calculate the force acting from the stem of the cut plant on the notch P_{blade}, it is assumed that the specific pressure of the plant mass is distributed evenly over the surface of the tooth section.

Under the influence of normal forces N_2 and N_3, friction forces occur on the side faces of the tooth T_{2tr}, T_{2tr}. Forces R_2 and R_3 accordingly are the resultant forces N_2, N_3 and T_{2tr}, T_{3tr}.

$$R_2 = T_{2tr} + N_2, \tag{10}$$

$$R_3 = T_{3tr} + N_3. \tag{11}$$

Then

$$P_{blade} = R_1 + R_2 + R_3, \tag{12}$$

where R_1 – force acting on the top of the tooth, *N*.

Force R_1 can be represented as the product of the contact area of the tooth with the stem F_k for destructive contact stress σ_p:

$$R_1=\sigma_p F_k=\sigma_p \delta l, \tag{13}$$

where δ – sharpness of the blade edge, m; *l* – length of the tooth tip, m.

Size of normal forces N_2 and N_3 is determined by the equations:

$$N_2 = \sigma_p \delta \frac{h_3}{\sin\varphi_1}, \tag{14}$$

$$N_3 = \sigma_p \delta \frac{h_3}{\sin\varphi_2}, \tag{15}$$

where φ_1 and φ_2 – angles of inclination of the side faces of the tooth, deg; h_3 – notch tooth height, m.

Tangential friction forces can be found by equations:

$$T_{2tr}=fN_2, \tag{16}$$

$$T_{3tr}=fN_3, \tag{17}$$

where *f* – coefficient of friction between the notch and the plant stem.

Total cutting force P_blade of fibre stem by tooth notch:

$$P_{blade} = \sigma_p \delta l + \sigma_p \delta \frac{h_3}{\sin\varphi_1} + \sigma_p \delta \frac{h_3}{\sin\varphi_2} + f\sigma_p \delta \frac{h_3}{\sin\varphi_1} + f\sigma_p \delta \frac{h_3}{\sin\varphi_2} = \sigma_p \delta \left[l + h_3(1+f)\left(\frac{1}{\sin\varphi_1} + \frac{1}{\sin\varphi_2}\right)\right]. \tag{18}$$

Substituting the values of all opposing forces P_{cr}:

$$P_{cr} = \frac{d_{cmp}}{t_H}\left(\sigma_p \delta \left[l + h_3(1+f)\left(\frac{1}{\sin\varphi_1} + \frac{1}{\sin\varphi_2}\right)\right] + \frac{E}{2d_{cmp}} h_{cmp}^2 l tg\beta + f\frac{\mu E}{2d_{cmp}} h_{cmp}^2 l + f\left(\frac{E}{4d_{cmp}} h_{cmp}^2 l tg\beta \sin 2\beta + \frac{\mu E}{2d_{cmp}} h_{cmp}^2 l \cos^2\beta\right)\right). \tag{19}$$

Converting the resulting equation:

$$P_{cr} = \frac{d_{cmp}}{t_H}\sigma_p \delta \left[l + h_3(1+f)\left(\frac{1}{\sin\varphi_1} + \frac{1}{\sin\varphi_2}\right)\right] + \left(\frac{E h_{cmp}^2 l}{2d_{cmp}} \cdot \frac{E h_{cmp}^2 l}{2d_{cmp}}\left[tg\beta + f\sin^2\beta + \mu(f+\cos^2\beta)\right] + \frac{3s_{bend}EJ}{bk^2\left(1-\frac{k}{b}\right)^2} + \frac{17m_{I-II}v_H}{35\tau}\right). \tag{20}$$

where d_{cmp} – diameter of the cut stems, m; t_H – notch spacing of the blade segment , m; σ_p – breaking contact stress, N/m²; δ – sharpness of the blade edge, m; *l* – length of the tooth tip, m; h_3 – notch tooth height, m; *f* – coefficient of friction of the cut fibres of the stem on the wedge boundary; φ_1, φ_2 – angles of inclination of the side faces of the tooth, deg; *E* – elasticity modulus of the material, MPa; h_{cmp} – compression of the material preceding destruction, m; *β* – blade sharpening angle, deg; μ – Poisson's ratio; s_{bend} – amount of bending of the stem, m; *J* – polar moment of inertia of the transverse stem, m⁴; *b* – distance from the top of the finger to the segment blade, m; *k* – gap between the segment and the anti-cutting plate, m; m_{I-II} – weight of the stem on the section 1-P, kg; v_H – segment speed, m/s; *τ* – time of impact of the cutting tool on the stem, s.

This expression reflects and defines the main parameters that affect the process of destruction of the stem when cutting it with a segment of the cutting device: constructive – *β*, δ, t_H, *l*, h_3, φ_1, φ_2; physical and mechanical – *E*, μ, *f*, σ_p, and operation mode – d_{cmp}, h_{cmp}, *τ*, v_H, *k*, *b*.

The first term of equation (20) defines phenomena that directly lead to the destruction and splitting of the material under the action of notch teeth and can be characterised as useful. The second defines phenomena associated with the deformation of plant material in the direction of movement of the blade, which negatively affect the reliability indicators of the cutting process, such as energy intensity and cut purity.

Determining the optimum shape of cutting device components has been the work of many researchers, who have subsequently laid the foundation for the standardisation of segments and finger plates in harvesting machines.

In [16], the advantage of an oblique cut over an end cut is substantiated, including the cutting speed, angles of inclination and sharpening of the blade, and the height of the cutting part of the segment. In particular, P.V. Sysolin found that in the cutting device of harvesting machines, when the knife speed is less than 3.4 m/s, cutting takes place on the principle of scissors. Similar experiments were conducted by professor V.I. Duganets [17]. The researcher also concluded that at low knife speeds, it is necessary that the plants are pressed by the segment against the anti-cutting plate. In [18], the width of the front part of the segment, both with a smooth and notched blade, is substantiated, and the value of the angles of clamping of steppe grasses is determined.

The study [19] is devoted to substantiating the optimal thickness of the cutting tool. It provides recommendations for choosing the optimal thickness of the blade and its strength. The researcher notes that if there is an angle between the direction of movement of the knife and its rear plane, the thickness of the knife does not play a role, since the rear plane of the knife loses contact with the mass layer, while contact with the front plane increases.

Studies by the researchers have shown that productive cutting can improve stem use and lead to energy savings. The authors of this study investigated the mechanical properties of the plant stem and the angle of inclination of the blade in relation to the cut stems. It was observed that the shear stress decreases from the lower part of the body to the upper part, and the shear force and energy in the lower part are significantly higher than in other regions, due to cross-sectional parameters. Cutting plant stems in high or low humidity conditions can save energy. As the blade angle increases, the cutting force decreases. However, the specific cut energy first decreased, and then gradually increased with increasing angle of inclination of the blade segment.

However, the authors do not provide a theoretical substantiation for the conditions for cutting plant raw materials by sliding. In addition, the studies do not show the influence of plants on the segment of the cutting machine from the standpoint of preserving the strength that is lost during the operation of the segment, which is affected by thermal energy from friction processes, chemical effects on the surface of the blade and the knife itself, which is affected by moisture released during mowing (stem juice). As a result, its reliability is lost and its service life is reduced.

CONCLUSIONS

As a result of the study, the distribution of failures of harvesting equipment and the main types of its malfunctions were highlighted. A diagram of the operation of the cutting device segment is constructed and it is also determined that a certain amount of energy A must be spent to destroy the plant stem under the edge of the blade. Using a graphical representation of the stem cutting scheme, the distribution of forces acting on the segment is constructed and, as a result, the cutting force of the stem is calculated. The analysis of the process of operation of the cutting device of harvesting machines from the standpoint of considering it as a complex system, the lowest elements of which in its hierarchical scheme are the working surfaces of the segment, determined their intended purpose in terms of increasing its reliability in case of gradual wear, reducing material costs, and restoring working capacity in case of sudden failures. The mathematical dependences of cutting resistance forces and power consumption for the cutting device drive are clarified, which determined the areas for improving its reliability by preserving the shape parameters and properties of the blade segment notch during a given period of operation.

In further studies of the finger bar mower, the possibilities of improving the reliability and operability of segments by strengthening them on the surface will be considered, since they are subjected to chemical corrosion during operation, which leads to their failure.

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Аналіз відмов сегментно-пальцевого ріжучого апарату та силова взаємодія леза сегмента зі стеблом рослини

Анотація. Наукові спостереження за якістю і надійністю зернозбиральних комбайнів показали, що з усіх затримок техніки, що становлять 32...35 % загального часу роботи, технічних відмов припадає на частку 17,4...19,8 %. Більшість відмов спостерігалося з виходом з ладу деталей комбайна, механічних трансмісій, гідросистеми та ін. Кількісний аналіз відмов жатки показав, що найбільше відмовлень виникає в роботі органів ріжучого апарату, а саме сегментно пальцевого різального апарата. Робоча гіпотеза полягає в тому, що підвищити надійність ріжучого апарату збиральних машин у рядових умовах експлуатації та при виникненні раптових відмов можливо за рахунок нанесення покриття на лезо сегмента, без істотної зміни його геометричних параметрів, та виконанням просічок, що забезпечують як зниження маси сегмента, так і його руйнування без пластичної деформації при попаданні до зони різання сторонніх предметів. Головним проблемою надійності сегментів різального апарату, збиральної техніки, є ріжуча кромка леза, яка зношується та деформується в процесі експлуатації. З сказаного вище випливає, що мета дослідження цілеспрямована на підняття надійності сегментно-пальцевих різальних апаратів за рахунок покращення механічних властивостей сегментів, дані дослідження є актуальними та становлять практичний інтерес. Дослідження включають використання математичної теорії ймовірності та надійності, аналізу та системного підходу для забезпечення аналітичного опису роботи сегмента різального апарату. Наслідком даного наукового матеріалу є розбір відмов та несправностей техніки, який подано у графічній формі, а також зображено схему зрізу сегментом стебла рослини та сили які діють на стебло та сегмент під час зрізу. Ці матеріали мають науково-інформативне наповнення, яке буде цікаве інженерам і науковцям у процесі дослідження та виробництва сегментів машин для різання

Ключові слова: ріжучий апарат сегментного типу, надійність техніки, жниварка збиральної техніки, зернозбиральна техніка, відмова жатки, кут кромки леза сегмента