REAPER BLADE SYSTEM FOR HARVESTING SUNFLOWERS / НОЖОВА СИСТЕМА ЖАТКИ ДЛЯ ЗБИРАННЯ СОНЯШНИКУ

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ABSTRACT

The relevance of the study is due to the need to reduce the energy intensity of the process of cutting sunflower stalks by choosing a rational profile of knives. The research is based on a comparative analysis of experimental values of cutting forces for the proposed and manufactured design of the knife system and known knife systems. The studies have shown that the implementation of the retaining and main knives of the header in the form of a curved spiral of Archimedes allowed to reduce the cutting force. It was also found that the cutting force for the proposed design of the knife system, unlike other studied, practically does not change with the removal of the stem from the axis of rotation of the knives, which does not require an increase in energy costs for the cutting process.

РЕЗЮМЕ

Актуальність дослідження зумовлена необхідністю зменшення енергоємності процесу зрізання стебел соняшнику за рахунок вибору раціонального профілю ножів. Дослідження базуються на порівняльному аналізі експериментальних значень сил різання для запропонованої та виготовленої конструкції ножової системи та відомих ножових систем. Проведені дослідження довели, що виконання підпорного і основного ножів жатки у вигляді кривої спіралі Архімеда дозволило зменшити зусилля різання. Також встановлено, що сила різання для запропонованої конструкції ножової системи, на відміну від інших досліджуваних, практично не змінюється за умови віддалення стебла від осі обертання ножів що не потребує збільшення енергетичних витрат на здійснення процесу різання.

INTRODUCTION

World production of sunflower seeds is constantly growing. Ukraine, Russia, the European Union, and Argentina are the main seed-producing countries; Ukraine and Russia account for more than half of the world's sunflower seeds and almost 60% of oil production.

The high interest of agricultural companies in growing this crop can be explained by waste-free and, relatively, high profitability. Sunflower allows you to get not only oil but many related products - a protein-rich livestock feed, alcohol; potassium, and nitrate are extracted from sunflower ash; the flowers are used to make an extract that replaces quinine. Sunflower can also be used as a source of biodiesel, biogas, raw materials for the paper industry (*Kovacic D., Kralik D. et al., 2017; Perea-Moreno Manzano-Agugliaro, & Perea-Moreno, 2018; Pari Luigi, Latterini Francesco, Walter Stefanoni, 2020*).

In addition to being used as a source of oil, the plant remains of sunflower stalks, pre-shredded, are used to increase the content of organic matter in the soil (*Martens DA, Frankenberger WT, 1992*), as well as reducing the tightness of the soil surface (*Le Bissonnais and Arrouays, 1997*). In addition, the distribution of crushed remains of sunflower stalks in the field provides increased macroporosity and water infiltration (*Glab T., Kulig B., 2008*).

Scientists have also proven that grinding and mixing into the soil-plant waste (stubble) that remains after harvest in the field prevents erosion (*Gonulol E., Dalmis I.S. et al, 2009*).

Currently, after the passage of the combine with the reaper, quite strong sunflower stalks remain in the field, which complicates the preparation of the field for the next growing season (fig.1).

Fig. 1 - Sunflower stubble

Sunflower crop residues need to be shredded and incorporation into the soil after harvesting in order to decompose them quickly and prevent disease. At the same time, additional damage to the top layer of soil contributes to the development of water and wind erosion. Post-harvest treatment requires additional energy and human resources. In addition, it was found that additional mechanized tillage leads to deterioration of its nutrient content. Thus, in particular, Chinese scientists have found that the traditional mechanized system of agriculture will reduce the content of soil organic matter per year, on average, by 0.01–0.02% (*Honglei J, Chenglin L. et al., 2007*).

Post-harvest treatment involves the use of additional equipment. Most often used are disc harrows, toothed rotors, and cutters. The equipment is used after the harvest and this leads to additional costs of energy, material, and labour resources. All this prompted researchers to improve the design of sunflower headers in the direction of installing additional cutting-type working bodies for shredding sunflower stalks during the technological process of harvesting.

Dalmis, Kayisoglu et al., (2013), in their study proposed the installation under the reaper of a combine harvester shredder unit with knives. The introduction of this device allowed to grind the remnants of sunflower stalks.

The authors performed a number of experiments in the field using specially manufactured cutting modules equipped with flat and curved blades. The relationship between the number of cutting modules, the configuration of blades and the height of cutting stems, fuel consumption was investigated. A significant influence of blade configuration on fuel consumption was found.

Due to the high energy intensity of the cutting process, the study of the process of cutting crop stems and devices for its implementation is of great scientific interest. The theory of cutting with a knife blade was initiated by academician *V.P. Goryachkin, 1968*.

The author divides the process of cutting fibrous materials into two types: the first - the knife blade moves in the direction of the cut only in the direction normal to its edge; the second - at the same time it moves parallel to the edge. The first type of cutting is chopping, the second is sliding cutting. It is proved that sliding cutting occurs with a decrease in friction force, part of the force is transferred in the direction perpendicular to the direction of the cut. As a result, the knife blade enters the material more easily.

This theory is confirmed in the works of many authors: *Johnson P.C., Clementson C.L., 2012; Zhang C.L., Chen L.Q. et al, 2019; Song S., Zhou, H.; Xu L., et al, 2022; Daipeng Lu, Wei Wang et al, 2022*.

In particular *Zhang C.L., Chen L.Q. et al, 2019,* during experiments with rice stalks studied the effect of the sliding effect during cutting and the value of the cutting angle on the cutting energy. It is proved that the energy per unit area of the stem was the lowest when sliding cutting without a support blade, with a cutting angle of 45°.

Daipeng Lu, Wei Wang, et al, 2022, in the course of multifactorial orthogonal experiment and mathematical modeling established the factors that affect the cutting stress: sliding angle, cutting edge angle, cutting speed. It was found that the factor of greatest importance is the sliding angle.

The influence of sliding and cutting angles, as well as the parameters of plant material on the energy consumption of the cutting process and the cutting force was proved by *Wang, Y., Yang, Y. et al, 2020; Song S., Zhou H., Jia Z. et al, 2022*.

Analysis of studies of the process of harvesting sunflower and machines and mechanisms for its implementation, found that improvements in the design of reapers for harvesting sunflower are also carried out in the direction of reducing losses and damage to seeds (*Shaforostov V. D., Makarov S.S., Yelizarov P.A., 2018; Startswv A.S., 2017; Nalobina O.O., Vasylchuk N.V. and others., 2019; Liu Y., Luo C., Zong W., et al, 2021; Ali K.A.M., Zong W. et al.,2021; Ali K.A.M., Zong W. et al., 2022; Stepanenko S., Aneliak M. et al., 2022.*

In particular, this problem is solved by reducing the length of the segment of the stem, which together with the head falls on the auger for threshing (*Shaforostov V.D., Makarov S.S., Yelizarov P.A., 2018*). The authors propose the design of a four-row reaper in which sunflower plants are captured at a height equal to the minimum height of the location of the heads above ground level during the movement of the combine. This is done by installing the inlet of the dividers with hydraulic cylinders to the desired height. Due to such a high grip, the heads fall into the area of action of the threshing auger with a minimum length of the stem, which allows to increase the efficiency of threshing and reduces seed injuries.

The model of the sunflower harvester was developed by the authors to solve two problems: 1) reducing the height of the stubble; 2) reducing the length of the segment of the stem that comes with the head for threshing (*Nalobina O.O., Vasylchuk N.V., and others, 2019*).

According to the analysis of known studies in sunflower harvesters, the stems are cut to separate the sunflower heads from the stem for further transport to the main part of the combine and some models of modern reapers use additional knives for completion of the collection process.

Cutting plant materials during production processes is one of the most energy-intensive and complex technological operations. Most often, modern reapers use flat-rotating cutters with the traditional rectilinear shape of the knife blade profile. Such knives are characterized by ease of manufacture and subsequent maintenance. The disadvantage is the high energy consumption of the cutting process.

Given the above, the task of reducing the energy consumption of the cutting process by choosing a rational profile of knives for cutting sunflower stalks is relevant.

MATERIALS AND METHODS

At the beginning of the study, the possibility of reducing the energy consumption of the cutting process by developing a knife support cutting system was hypothesized. It is necessary to use a shape of the knife at which the sliding angle (the ratio of radial and tangential cutting force) will be the same along the entire length of the cut for any point of the knife with a curved edge profile.

As a result of analysing the known research directed on the substantiation of choosing an optimum profile of cutting knives (*Goriachkin V.P., 1958, Lvov D.V., 2009, Braginets M.V., 2013; Zhang C.L., Chen L.Q. et al, 2019; Daipeng Lu, Wei Wang et al, 2022*) it is proposed to execute a knife system consisting of a supporting knife and cutting knives made in the form of an Archimedes spiral. This design, according to the conceptual hypothesis of the research, will ensure the maximum quality of cutting and will minimize energy consumption throughout the cutting area of the stem for both the main and the support knife.

In order to test the accepted hypothesis, studies were conducted to determine the cutting forces for different configurations of knives: John Deer S690I and Massey Ferguson 1006 reapers; knife system made according to the recommendations of the founder of agricultural mechanics, Goryachkina V.P. (*Goryachkin V.P., 1968*) and the knife system proposed by the authors.

In the knife system, made according to the recommendations of *Goryachkin V.P. (1968),* (Fig. 2), the profile of the cutting knife is made in the form of an Archimedes spiral, which allows cutting by sliding along the entire length of the cut. Support knife 1 (Fig. 2) is made in the form of a concentric curve. This allows you to ensure complete cutting of the stem and also prevents the stem from slipping out from under the knives. To construct a curve of a cutting knife Goryachkin's technique will be used (*Goryachkin V.P., 1968*).

The optimal curve according to the author's research is the Archimedean spiral. The equation of such a spiral: $r = r_0 + A\Theta$, where r_0 initial knife radius, A- helix pitch, Θ - the polar flow (Fig. 2,a).

Cutting with such a knife occurs with sliding, and it is the Archimedean spiral that gives the same coefficient of sliding τ when turning the knife to any angle. Therefore, the energy intensity of cutting will be uniform along the entire length of the cut without maximum and minimum points, which allows the use of a lower power drive.

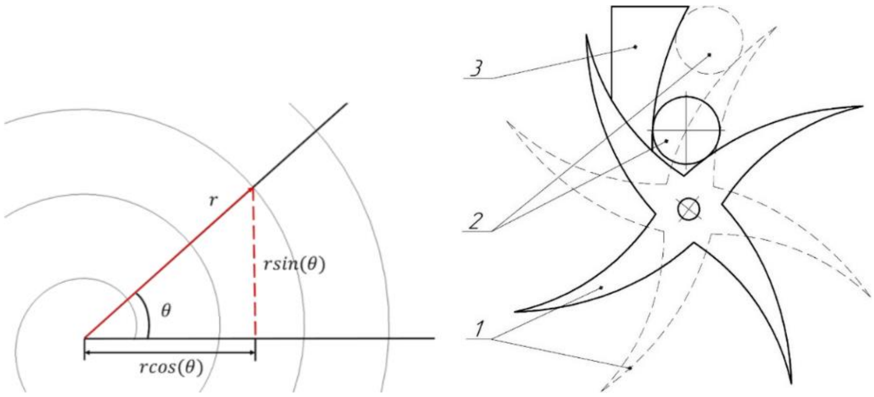

Fig. 2 - Scheme of the knife system according to Goryachkin's recommendations
1 - support knife, 2 - sunflower stalk, 3 - cutting knife

This design of the knife system has a drawback. As the distance from the cut to the axis of rotation of the knife increases, the total cutting angle decreases.

It is proposed to make a knife system in which the support knife serves not only to support the sunflower stalk but is fully used in the cutting process and also has the shape of an Archimedes spiral. The total cutting angle is 50° (Fig. 3).

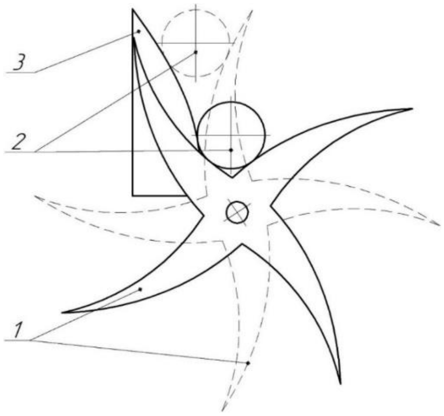

Fig. 3 – The proposed scheme of the knife system
1 - support knife, 2 - sunflower stalk, 3 - cutting knife

To compare the cutting efficiency of the selected knife system designs (John Deer S690I, Massey Ferguson 1006, Goryachkin knife system, and our proposed design), the total cutting force in each case was determined. Cutting forces (Fig. 4) were determined from experimental studies by measuring cutting angles α (fig.4), for stem diameters of 10, 20, 30, 40, and 50 mm and at a distance of 60, 80, 100, 115, and 125 mm from the axis of rotation of the knives. To make experimental studies, a laboratory setup was made (Fig. 4, a), which was equipped with knives corresponding to the knives of the above designs (Fig. 4, b shows a knife whose edge is made in the form of an Archimedean spiral)

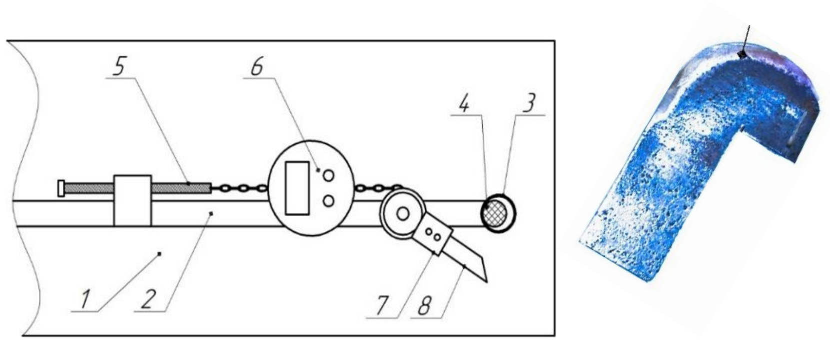

Fig. 4 - Study of the cutting force of the stem
a - scheme of the laboratory installation; b - knife, the edge of which is made in the form of an Archimedean spiral
1 - platform; 2 - frame; 3 - glass for installing the stem; 4 - stem; 5 - screw-nut transmission; 6 - dynamometer

Below is a diagram of the forces acting on the sunflower stalk during retaining cutting (Fig. 5) and diagrams for determining the cutting angles for the knives that were subject to the study (Figs. 6-8).

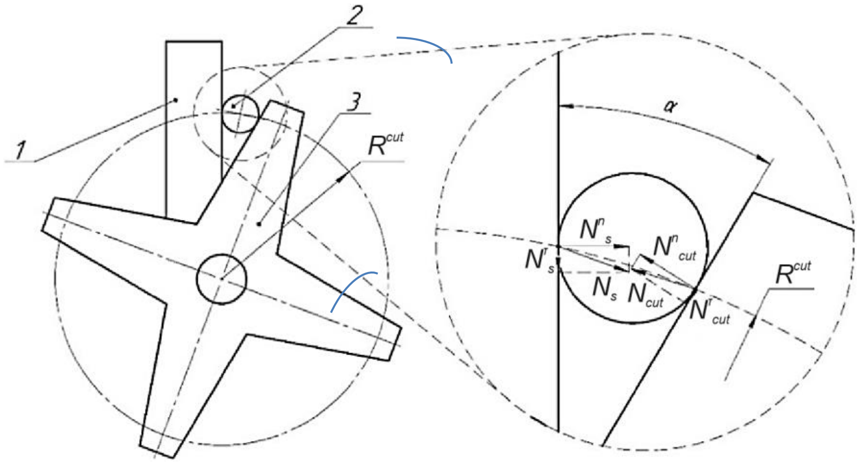

Fig. 5 - Scheme of forces acting on the sunflower stalk during support cutting:
1 - support knife, 2 - the stem, 3 - cutting knife, R^{cut} - distance from the axis of the knife to the axis of the stem, N^n_{cut}, N^τ_{cut}, N_{cut}, N^n_s, N^τ_s, N_s - respectively normal, tangential, equivalent cutting forces of the cutting and support knife

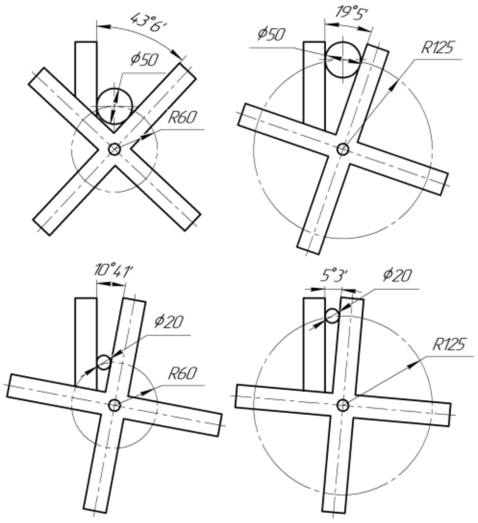

Fig. 6 - Diagram for determining the cutting angles for John Deer S690I reaper blades

We see that with increasing distance from the axis of rotation of the knives to the cutting point and increasing the diameter of the stem, the angle between the knives decreases, which will increase the total cutting force.

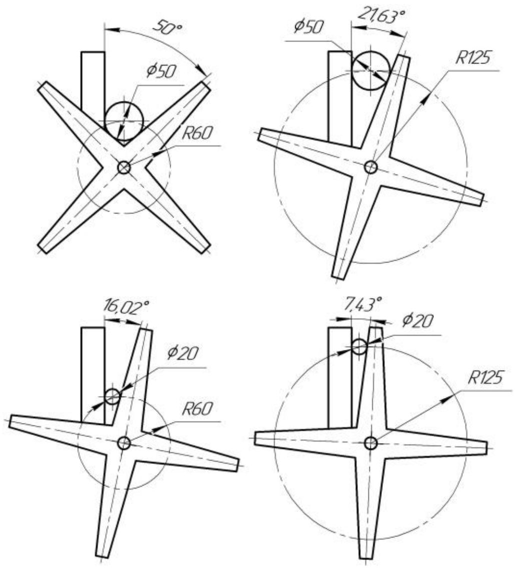

Fig. 7 - Diagram for determining the cutting angles for Massey Ferguson 1006 reaper blades

The pattern of reducing the angle between the blades from the stem diameter and the distance from the centre of the blades to the cutting point is maintained for Massey Ferguson 1006 reaper blades. However, the value and the law itself is slightly different from similar values for John Deer S690I cutterbars.

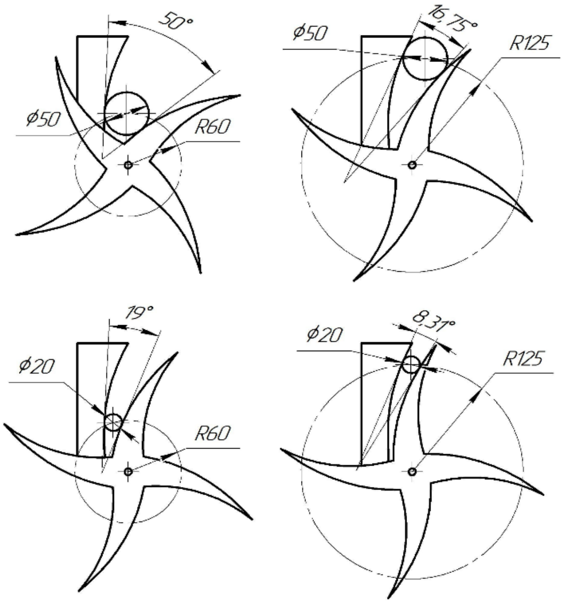

Fig. 8 – Scheme for determining the cutting angles for knives according to Goryachkin's scheme

The angles between the cutting and support knives, than in the similar positions for the knives Massey Ferguson 1006 and John Deer S690I, but they are smaller than for the knife system of our proposed design (Fig. 8).

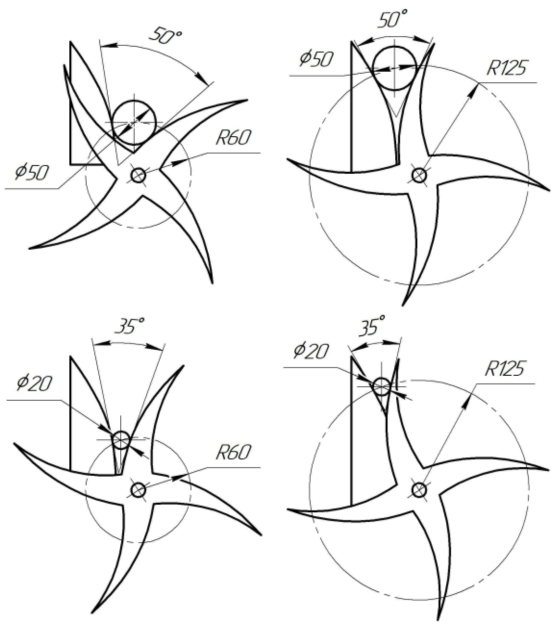

Fig. 9 - Scheme for determining the cutting angles for knives

For the experiments, stems were selected in the field during the period when 14% of plants with yellow heads remained in the field (which corresponds to the agrotechnical requirements for harvesting).

RESULTS

As a result of the research, the values of the cutting force were obtained under the condition of changing the diameters of the stem and the distance from the axis of rotation of the knives. Depending on the cutting angles, the values of the tangent and normal components and the resulting one for all cases were obtained. The average values of cutting forces are given in Table 1.

Table 1

Cutting force values (N)

Distance from the axis of rotation to the centre of the stalk (mm)	**Stalk diameter (mm)**				
	50	40	30	20	10
The Massey Ferguson 1006 system					
60	7282	4987	2918	1303	332
80	8057	5285	2995	1315	332
100	8367	5403	3028	1320	336
115	8494	5452	3042	1322	338
125	8553	5475	3048	1323	338
The John Deer S690I knife system					
60	7674	5170	2980	1317	333
80	8232	5373	3023	1322	333
100	8482	5458	3049	1335	338
115	8571	5487	3155	1339	340
125	8624	5512	3169	1342	340
For Goryachkin knife system					
60	7282	5369	2952	1313	331
80	8126	5373	2991	1329	332
100	8325	5422	3022	1332	332
115	8583	5468	3049	1422	338
125	8677	5496	3052	1422	338
For the proposed blade system					
60	7182	4666	2687	1209	312
80	7182	4666	2687	1209	312
100	7182	4666	2687	1209	312
115	7184	4667	2687	1209	312
125	7184	4667	2687	1209	312

From the data presented in tab. 1 we can see that the smallest cutting force was obtained by using the proposed knife system; in addition, its value remains virtually unchanged with the removal of the stem from the axis of rotation of the knife, which does not require an increase in energy for the cutting process.

Below, figs. 10-12 show the graphical dependences of the cutting force on the diameter of the sunflower stem and the distance from the knife rotation to the stem axis: for the proposed knife system of normal and tangential components of the main knife cutting force and the distance from the axis of rotation of the knife system for a stem diameter of 40 mm and the cutting force depending on the diameter of the sunflower stem and the distance from the knife rotation to the stem axis.

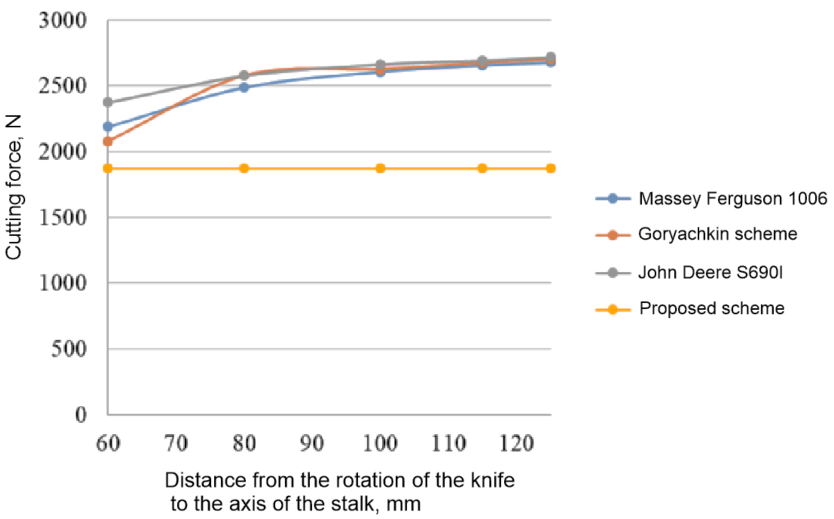

Fig. 10 - Dependence of the normal component of the main knife cutting force and the distance from the axis of rotation of the knife system for a stem diameter of 40 mm

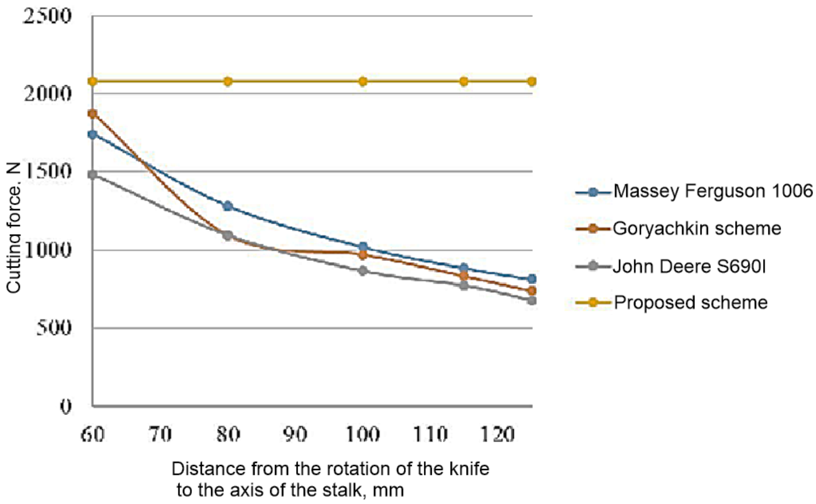

Fig. 11 - Dependence of the tangential component of the main knife cutting force and the distance from the axis of rotation of the knife system for a stem diameter of 40 mm

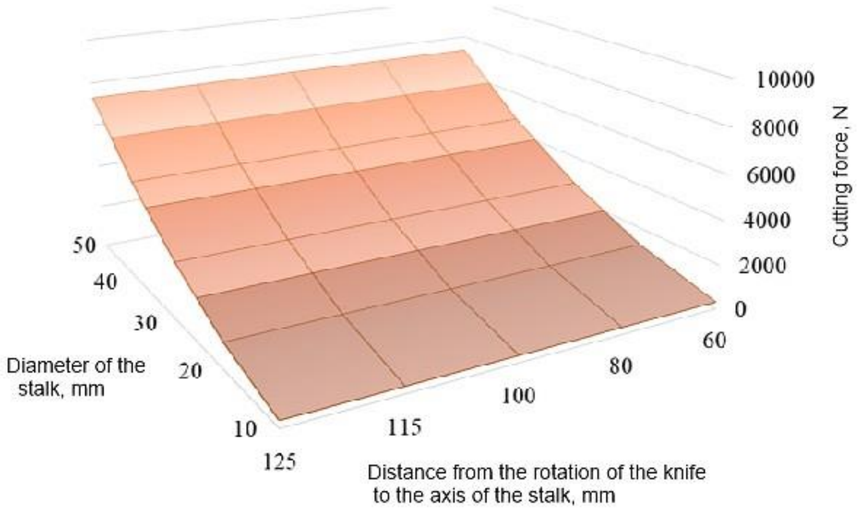

Fig. 12 - The value of cutting force depending on the diameter of the sunflower stem and the distance from the knife rotation to the stem axis: for the proposed knife system

CONCLUSIONS

The analysis of the results allows us to draw the following conclusions:

1. The use of a knife system where the retaining and main knives are made according to the Archimedes spiral allows cutting with less effort.

2. Compared to the knife system of the Massey Ferguson 1006 cutterbar, the reduction in cutting force is: 1.3 - 16% (for stems with a diameter of 50 mm), 6.4-14.8% (40 mm), 7.9-11.8% (30 mm), 6.02 -7.7% (10 mm).

3. Compared to the knife system of the John Deer S690I cutterbar, the reduction in cutting force is: 6.4-16.7% (50 mm), 9.7-15.3% (40 mm), 9.8-15.2 (30 mm), 8.2-9.9 (20 mm), 6.3-8.2% (10).

4. In comparison with the Goryachkin knife system: the reduction in cutting force is: 1.4-17.2% (50 mm), 13.1-15.1% (40 mm), 8.97-11.9 (30 mm), 7.9-14.97% (20 mm), 5.7-7.7% (10 mm).

5. The cutting force for the proposed design of the knife system, unlike the other studied, practically does not change with the removal of the stem from the axis of rotation of the knives, which does not require an increase in energy consumption for the cutting process.

6. The installation of the proposed design of the knife system where the profiles of the support and cutting knives are made according to the Archimedes spiral will allow to ensure complete cutting of the stem, and also makes it impossible for the stem to slip out from under the knives; to perform sliding cutting along the entire length of the cut with the least effort.

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