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BEATER-KNIFE CUTTING DEVICES OF FORAGE HARVESTING MACHINES AND WAYS FOR THEIR IMPROVEMENT

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Abstract. One of the main technological operations in the harvesting of stem fodder is harvesting with simultaneous chopping. Modern round balers, bale balers, and pickup trolleys are equipped with a beater-knife cutting apparatus. They are based on a rotating beater (a pipe with fingers fixed to it) and a number of knives installed in the channel, along which the fingers of the beater move in a rotational motion. In the process of developing the design of such a cutting apparatus, the beater has evolved from an analogue of a scraper-finger conveyor, a rotor with a controlled rake, into a rotor with a tubular shaft and fixed curved fingers radial to its base. The problem with such cutting machines is a significant increase in friction forces on the side surfaces of the knives with an increase in their number. The increase in the number of knives is caused by the need to reduce the length of the raw material to be cut. The research is aimed at determining the design features of the beater-knife cutting units of forage harvesters, the directions of their improvement by replacing the passive knife with an active disc knife and experimentally determining the effect of the circular speed of the knives on fuel consumption. The monographic method was used in the research. This made it possible to systematize the main design parameters of the beater-knife cutting machine, identify the main works carried out in the study of similar designs, and propose a technical solution that can significantly reduce the friction forces that occur on the side surface of the knives. By varying the distance between the knives of the prototype cutting machine, the weighted average cutting length of the resulting raw material was determined. The results obtained made it possible to determine the ratio between the dimensions of the cutting device (which are in the range of: length – 1120-2000 mm, diameter - 415-880 mm, minimum cutting length – 22-25 mm), experimentally confirm the performance of the cutting device with disc knives, establish the dependence of fuel consumption for picking up, cutting and feeding alfalfa on the circular speed of disc knives, and determine the minimum fuel consumption, which is 0.74 kg·h^{-1}.

Keywords: cutting, plant raw materials, beater-knife cutting machine, linear dependence, fuel consumption.

Introduction

Cutting of stem crops is the main operation in the preparation and feeding of stem forage. It is performed when mowing grasses, chopping raw materials during hay, haylage and silage harvesting and when preparing feed before it is distributed. Drum and disc cutters are widely used in forage harvesters. However, with the development of technical means for harvesting grasses and collecting grain straw, beater-knife cutting machines are becoming more common, which are used in balers, bale balers, and pick-up trolleys, the main characteristics of which are shown in Table 1. They organically combine the processes of transporting and cutting stalks. The cutting process and its various aspects have been studied by many authors, but even today, due to the diversity of stalk crops, variation in cutting conditions, development of new and improvement of existing cutting machines, there is a need to study certain aspects of this process. Thus, due to the need for cutting during energy cane harvesting and reducing the size of the cutting apparatus, the effect of the blade inclination, cutting speed, and stem diameter on the specific cutting energy was investigated [1]. The specific cutting energy obtained for different parameters ranged from 0.26 J·mm^{-2} to 15.0 J·mm^{-2}. It is concluded that optimising the cutting speed and blade angle can lead to significant savings in the cutting energy while improving cutting quality.

The authors of [2] studied the effect of the angle of inclination of the blade to the stem during unsupported cutting at three height levels. The angle of inclination of the blade to the stem was varied from 0º to 60º every 15º. It was found that the peak cutting force per unit area of the stem decreased with increasing cutting angle of the blade slide. When cutting without support, the minimum average cutting energy was 9.12 J·mm^{-1}2 at a sliding angle of 45°. When cutting with support, the cutting energy per unit area of the stem ranged from 6.57 to 12.54 J·mm^{-2}, and the peak cutting force per unit area of the stem varied from 2.46 to 0.98 N·mm^{-2}. It was concluded that the optimum cutting sliding angle was

45º when cutting without support and 30° when cutting with support.

In the work [3], the bionic principle of constructing the geometry of the cutting element was used to reduce energy consumption and reduce the effort for cutting corn stalks. The jaw profile of the leaf beetle was experimentally determined with the fourth-degree curve approximation. Based on this profile, a cutting element with a bionic working edge was developed. Comparison of forces and energy consumption for cutting corn stalks with a cutting element with a typical edge profile showed that the average maximum cutting force and energy consumption for cutting for the bionic blade were reduced by 12.89% and 10.73%, respectively. This confirms the prospects of using cutting elements with a bionic cutting edge.

Table 1

Main parameters of beater-knife cutting machines for cutting stem raw materials

Manu-facturer (brand)	Model	Working width, m	Feed rotor diameter/working length, mm	Number of knives, pcs.	Theoretical cutting length, mm	Required aggregation power, kW
Trolleys-pickers						
Claas	Cargos 8000 9000	2.0 2.0	860/1580 860/1580	40 40	38 38	-
Pottinger	Boss Junior Boss Faro Jumbo	2.0	-/-	12 31 31-11 48-65	120 43-172 45-135 34-25	15-44 51-96 66-110 147-368
Krone	AX ZX	1.8 2.12	760/1500 880/1910	16/32 24/48	90/45 74/37	59-74 155-175
Bergmann	Royal Carex	1.94 2.05	600/1428 850/1470	41	34 35	59-132 110-257
Malone	Trojan MT 35 MT 52	2.0	-/2000	35	40	64 97
Roc	CT	-	-/2000	18	-	-
Large-bag pickers						
Claas	QUADRANT 5300	2.35	-/1120	51, 26, 13, 12	22, 44, 88	-
	4200 RC	2.35	500/1200	25, 13, 12, 6	44, 88	-
Krone	BIG Pack 890 XC	1.95/2.35	550/800	16, 8	44, 88	95
	1270 VC	2.35	550/1200	51, 26	22	135
	1290 HDP II XC	2.35	720/1200	26, 13	44, 88	190
New Holland	Bigbaler 870	1.96	-/-	6	114	80
	1290 CropCutter	2.35	-/1200	29, 15	39, 78	110
Kuhn	SB 890	2.30	-/1200	15	min 45	88
	SB 1290 iD	2.30	-/1200	23, 12, 11	min 45	141
Roll pickers						
Krone	Fortima 1250 MC	2.05	415/1200	17, 15, 7	64	36
	VariPack V 165XC	2.15	530/1200	17, 9, 8	64, 128	67
	V 190 XC Plus	2.15	530/1200	26, 13, 13	42, 84	74
Claas	ROLLANT 620RC	2.10	-/1200	25, 15, 14	44, 70	-
	455 RC	2.10	-/1200	25, 13, 12	44, 70	-
Pottinger	Impress F 3130F	2.05/2.30	650/1200	16, 8, 8	72	59
	3160V PRO	2.30	650/1200	32, 16, 16	36	59
New Holland	Roll-Belt 150	2.30	455/1400	15	65	75
	190 CropCutter	2.30	520/1400	25, 12, 13	41, 83	88
Kuhn	Roll Baler FB 3135	2.30	-/1220	14, 7, 7, 4 23, 12, 11, 7	min 70 min 45	65 65
	VBP 2295	2.30	-/1200	23, 14	45, 70	68

Machine development requires not only knowledge of individual processes, but also the coordination of individual units. An example of coordinating the operation of a drum cutting machine and a roller feeder is given in the study [4]. The study solved the problem of ensuring a uniform productive supply of stem feed by a five-roll feeder and high-quality cutting by a drum chopper. The authors determined the profile of the ellipsoidal cutting edge of the knife installed obliquely to the cutting drum. It has been established that the rational parameters of the feeding and cutting apparatus are the feed speed of 3.39 $m \cdot s^{-1}$, the rotational speed of the chopping drum of 1016.17 rpm, the feed rate of 8.04 $kg \cdot s^{-1}$, and the deviation of the direction of feeding into the drum from the radial direction of 52.2°. At the same time, the cutting length of the raw material was 95.35% of the specified one, and the energy consumption for the process was 37.63 kJ/kg.

The development of forage harvesting machines has led to the creation and use of beater-knife cutting machines that organically fit into the technological scheme of picking up and feeding grass mass to the compaction chambers of baling and bale balers and the bodies of pickup trolleys. In the process of developing the design of such a cutting apparatus, the beater has evolved from an analogue of a scraper-finger conveyor (a rotor with a controlled rake) into a rotor with a tubular shaft and fixed curved fingers, radial at its base and deviated against the direction of rotation at the top [5]. At the same time, the blades of the knives were transformed from rectilinear to curved sickle-shaped, with double-sided sharpening (Fig. 1). The knives are installed in one or more rows at the bottom of the beater for transporting stem feed on a special beam. Each knife is spring-loaded and can be deflected to avoid damage if foreign hard objects hit the cutting unit. If the beams in early designs of cutting machines were only tilted downward during maintenance, modern designs allow the beams to be removed from under the cutting machine.

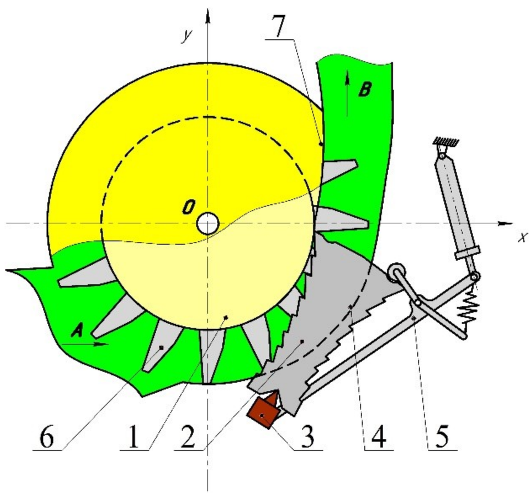

Fig. 1. **Scheme of a modern beater-knife cutting machine (cross-section):** 1 – beater; 2 – knife; 3 – beam for installing knives; 4 – pallet; 5 – knife springing mechanism; 6 – beater finger; 7 – upper plate of the channel for movement of cut raw materials

The rotors of the cutting machines have a length that corresponds to the design features of the machine on which they are installed. During operation, the rotor fingers pass alongside the knife to ensure high-quality cutting. In some modern models of machines, the fingers are doubled, and they pass simultaneously on both sides of the knife. The length of the fingers reaches of up to 150 mm. It is close to radial in shape at its base and is deflected against the direction of rotation at the tip. This shape ensures that the raw material is pressed against the bottom of the cutting machine and the blade exits the cut mass, which is pushed through the discharge channel.

The cutting machine has a system of individual knife springing, which, if necessary, simultaneously serves to remove them from the stalk mass transportation channel. During operation, the roll of dried or dry grass is fed by the pickup in the direction indicated by the letter A (Fig. 1). The rotor 1, rotating counterclockwise, captures the mass with fingers 6 and directs it to the channel formed by the cylindrical surface of the rotor 1 and the pallet 4. Pulling the mass through the channel, the fingers 6 direct it to the knives 2, which block the channel from the pallet 4 to the rotor surface. The knives are supported by a rigidly mounted beam 3, to which the levers of the knife spring mechanism 5 are connected. The mass flow is cut into separate strips and pushed into the discharge channel (direction B) by the fingers 6. The fingers 6 exit the discharge channel through slots in its upper plate 7.

The difference between the cutting apparatus, the design of which is considered, and the drum and disk cutting apparatus widely used in forage harvesting is that cutting occurs in the longitudinal plane of the raw material flow, which is divided into separate, narrowed flows by cutting elements. In this way, the cutting length can be adjusted by changing the distance between the installed knives, while in a drum or disk cutting machine, the cutting length is regulated by the speed of the feed rollers.

Smooth operation of the cutting apparatus is ensured by the alternate operation of each of the knives and sliding cutting, which is the result of using knives with a curved blade. By modelling the shape of the knife blade and checking it experimentally, it was found [6] that the use of the developed knife blade profile reduces the specific cutting force, which leads to a decrease in the fuel consumption. It has also been confirmed that the smoothness of the cutting apparatus has increased, and the resulting stem feed meets the requirements of modern livestock production.

The determination of energy consumption by a beater-knife cutter (rotary feeding and cutting system – RFCS) during straw cutting in a combine harvester is the subject of works [7; 8]. To do this, the physical and mechanical properties of the raw material were determined under the conditions of the cutting apparatus, and experimental studies were conducted. A model has been developed that allows determining energy consumption when changing the parameters and operating modes of the cutting unit.

When developing a multifunctional forage harvester [9], the distribution of forces and deformations of the rotor of a beater-knife cutter were analysed by means of finite element modelling (Autodesk 2015). It was found that for the proposed design, the safety factor is 3.97, which significantly exceeds the standard value of 2.6 for maximum load. The maximum strain and stress values were 1.8 mm and 172.39 MPa, respectively.

Along with the positive characteristics of the above-mentioned beater-knife cutting machine, it also has disadvantages. To achieve minimum cutting lengths, the knives are installed at a small distance from each other. In this regard, the cost of friction on the side walls of the knives increases significantly, and the energy demand during the operation of the cutting machine increases.

Materials and methods

The monographic method was used during the research. This made it possible to identify the main works carried out in the study of similar structures, to systematize the main design parameters of the beater-knife cutting machine and to propose a technical solution that can significantly reduce the friction forces that occur on the side surface of the knives. The design and construction approach was used to develop a prototype of the cutting apparatus, which was installed on a roll picker and used in field experimental studies.

The picker equipped with a disk cutting unit was tested on alfalfa swaths of the second cut with a moisture content of 44.7-52.3%. The weight of a running meter of swath ranged 2.37-3.84 $kg \cdot m^{-1}$. The picker was combined with a tractor and a 45 m3 trailer. The tractor speed ranged 5.35-5.42 $km \cdot h^{-1}$ (1.49 to 1.51 $m \cdot s^{-1}$). The direction of rotation of the disk knives helped move the mass of alfalfa. The disk knives with a diameter of 500 mm, a thickness of 3.0 mm and a weight of 5.3 kg had chamfers sharpened at an angle of 29-30º. The design features of the rake and the stiffening ribs of the channel plane allowed the discs to be installed at four different distances: 100, 190, 200, and 270 mm from each other. Samples of the cut mass were taken from each respective strip, and disassembled by length, and the weighted average cutting length was determined based on the information obtained. The circular speed of the cutting edge of the circular knives was 5.34, 7.70, and 12.82 $m \cdot s^{-1}$. The change in the circular speed was achieved by changing the driven sprockets on the shaft of the disk knife battery. The circular speed of the disk knives was higher than the average speed of pushing the mass through the channel (0.68 $m \cdot s^{-1}$). The average cutting length of the stem raw material particles was determined according to [10; 11].

Results and discussion

A significant step forward in the technical development of the design of the beater-knife cutting machine was made when the IMPRESS round baler was created [12]. Due to the transportation of the raw material flow by the rotor during its clockwise rotation, the knives are located above the rotor instead of below. This ensures that the direction of feeding the raw material flow into the bale chamber coincides with the direction of movement of the bale surface, which reduces energy consumption for bale formation. The increased space for the knives allows for the installation of 32 knives at a distance of 1.2 m, which provides a design cutting length of 36 mm. The extension to the left side of the beam to install the knives at a height of about 1.2-1.4 m makes it much easier to replace or rotate the knives on it.

Having processed the information of manufacturers and scientific and technical literature [13-19], the main parameters of the beater-knife cutting machines used in stem forage harvesting machines were systematized. Some of the results obtained are summarised in Table 1. Its analysis shows that the working width of forage harvesters ranges from 1.8-2.3 m, with smaller values being typical for earlier machines. The length of the rotor corresponds to the size of the chamber into which the cut mass is fed. The smallest values are in round balers (bale height 1.0-1.2 m), the largest – in trolley balers – up to 2.0 m. Accordingly, the rotor diameters are larger in longer rotors and reach 880 mm. The pitch of the fingers on the beaters is smaller in modern designs, which ensures a more even supply of raw materials to the knife. A graphical interpretation of the relationship between the beater length and diameter is shown in Fig. 2.

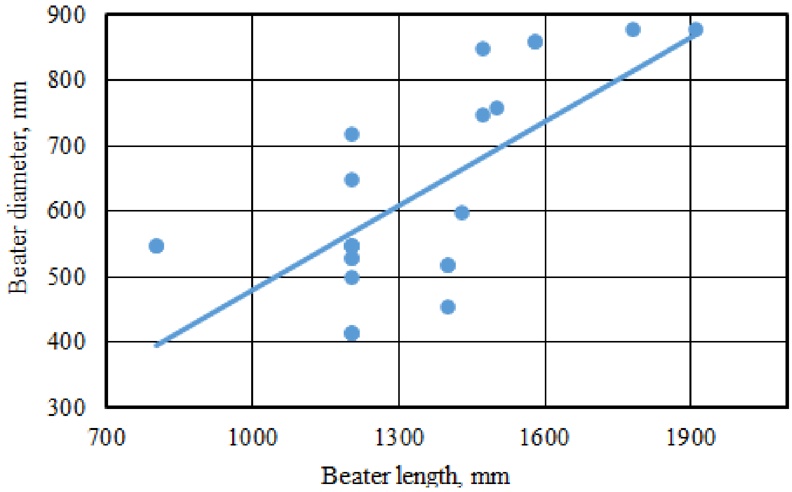

Fig. 2. **Dependence of the cutting machine beater diameter on its length**

Figure 2 shows that most cutters have a length of 1200 mm (the height of bales formed by bale balers) and 1400-1500 mm (one side of the cross-section of large bales). Increasing the length of the beater leads to an increase in its diameter, and, accordingly, to an increase in the ability to push the raw material through. However, the directions of development of the cutting machine do not solve the problem of reducing the friction of raw materials on the side surfaces of the knife. We proposed a cutting machine with rotating disk knives [20]. This reduces friction forces. The disks are arranged in two or three rows and are assembled on shafts. Each battery is mounted on rolling bearings, spring-loaded and has an individual drive. A special feature of the picker used to test the technological process of cutting with circular knives is the transportation of the selected raw materials by pushing. The raw material is pushed by a packer, the edges of the tine fingers of which move along an ellipsoidal closed path. The knives were installed outside across the plane inclined to the horizon at an angle of 60º (Fig. 3), which feeds the raw material to the discharge channel.

During the study of fuel consumption during the process of picking up raw material rolls, cutting them and transporting them, the disc knives rotated in the direction of raw material movement. The fuel consumption was measured when the machine was running at idle. The dependence of fuel consumption for the feeding and cutting process on the circular speed of the circular knife is shown in Fig. 4. The resulting dependence is well described by a linear function, with the reliable approximation value $R^2 = 0.982$.

Fig. 4 shows that reducing the knife edge speed to the value of the mass transportation speed leads to a decrease in fuel consumption for the process. This is due to an increase in the cost of friction of the mass on the surface of the disk with an increase in the relative speed of the mass on the disk. The minimum fuel consumption is achieved when the knife battery operates without a drive. In this case, the rotation of the disks is achieved due to the cutting forces acting on the edge of the knife and the friction forces acting on the side surface of the knife. It was also found that the costs directly related to the process make up only 9.0-12.8% of the total fuel consumption by the unit.

The research results [21], which relate to the ratio of the distance between the knife disks and the actual average cutting length, show that the latter is 1.2-1.4 times greater than the distance between the knives. This is due to the arrangement of alfalfa stalks in the flow at the time of feeding to the disk knife.

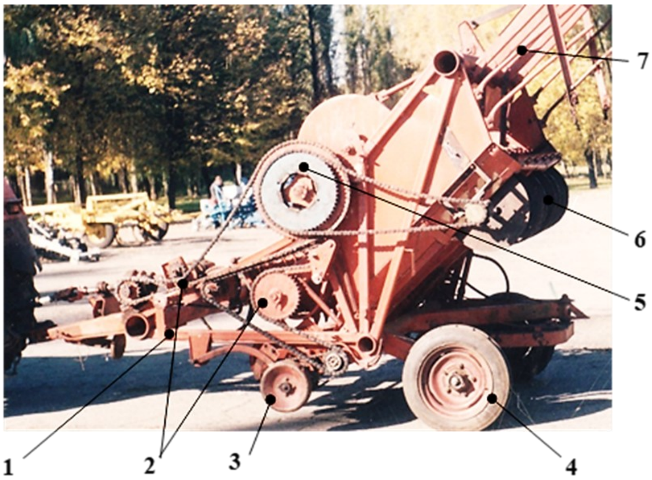

Fig. 3. **General view of the swath picker (without protective shields and the lower tray of the discharge channel):** 1 – frame, 2 – picker and packer drive, 3 – surface tracking picker wheel, 4 – support wheel, 5 – knife battery drive, 6 – disk knife battery, 7 – discharge channel

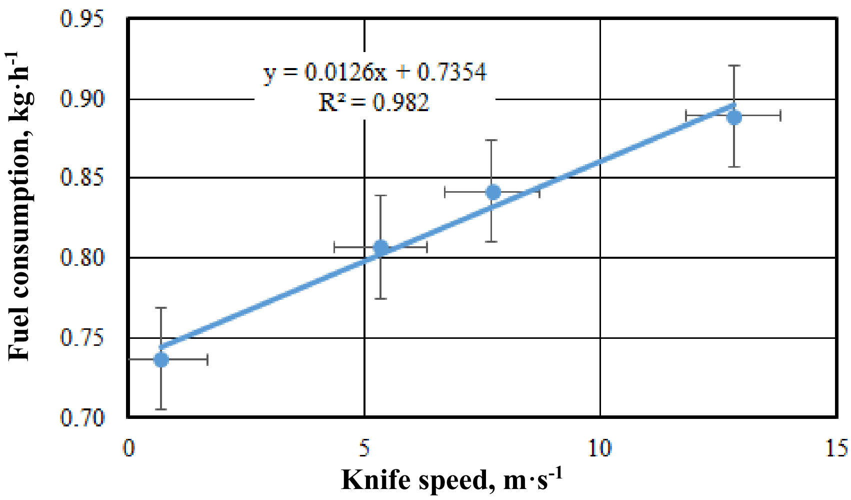

Fig. 4. **Dependence of fuel consumption for the process of picking up, feeding and cutting mass depending on the circular speed of the cutting edge of a circular knife**

This arrangement is formed by the tines of the rake, which push the raw material through. However, the arrangement of the stalks in the swath should also be taken into account. The latter depends on the operations performed on the swath: whether it is only mowing with simultaneous swath formation or moving the swath at the same time as raking. The pick-up operating parameters also affect the way the stalks are arranged.

Conclusions

1. The dimensions of the beater of the cutting machine correspond to the design features of the machine on which it is installed and vary within the following limits: length – 1120-2000 mm, diameter – 415-880 mm. The pitch of the beater pins along its length corresponds to the maximum possible number of knives to be installed to ensure backup cutting. In modern designs, the pitch of the pins around the circumference of the drum of the beater reaches the minimum value for uniform feeding to the knife in small portions. The minimum cutting length is determined by the distance between the knives and has reached 22-25 mm.
2. The circular blade reliably performs the cutting process while minimizing energy losses due to

friction on the blade side surfaces. Thanks to the circular shape of the cutting edge, its sharpness can be maintained with a sharpening mechanism with minimal time spent.

3. Minimum fuel consumption of 0.74 $kg \cdot h^{-1}$ for picking up, cutting, and feeding alfalfa using disk knives is achieved at a circular speed close to the speed of alfalfa transportation in the canal.

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