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DEVELOPMENT AND SUBSTANTIATION OF PARAMETERS OF THE MECHANISM WITH FLEXIBLE DRIVE FOR THE CUTTERBAR OF THE MOWER OF DOUBLE KNIFE STROKE

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This paper presents the results of experimental research on the development and substantiation of parameters and operating modes of the drive mechanism of the cutting apparatus in a mower with a double knife stroke.

A structural and technological scheme of the drive mechanism of the cutting device of the segment-finger type mower has been developed, in which a double stroke of the cutting device knife is provided. Analytical relationships were obtained to determine the knife stroke, speed and acceleration. Based on the results of theoretical and experimental studies, the main parameters of the mower drive mechanism were substantiated. Based on the condition of a high-quality cut of plants, at a minimum grass cutting speed, the minimum crank shaft speed was determined. By calculation, the feed area and the load area of the cutter for normal cutting with a double cut of the knife are determined. Analytical relationships were obtained to determine the power required to drive the cutterbar of a mower with a double knife stroke. Based on the research results, the main parameters of the mower with an improved drive are substantiated. An experimental sample was made and preliminary tests of the drive mechanism were carried out, agrotechnical and energy indicators of the mower operation were determined

Keywords: mower, drive, cutting device, toe bar, segment-finger mower, alfalfa, grass mowing, double stroke, knife, speed, crank

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1. Introduction

In the Republic of Kazakhstan, 5.0 million hectares of land are occupied by natural grasses with low yields, and it is planned to increase acreage areas for sown herbs by more than 3.4 million hectares [1].

In foreign countries for mowing grasses, rotary mowers are mainly used. They allow working at high forward speeds, limited only by the topography of the field and the capabilities of the tractor [2].

The disadvantages of rotary mowers are: high energy consumption (about 12...15 kW per meter of working width, high specific fuel consumption and high cost); risk of injury (significant acceleration of falling foreign objects) and soil contamination with grass when mowing grass on sandy and loose soils [3].

The most widespread in preparation of forage from natural and seeded grasses in practice is the technology of mowing grasses using mowers with segment-finger cutting devices with laying the mowed mass into a swath.

Mowers with segment-finger cutters are mainly manufactured in the CIS (Commonwealth of Independent States): «Berdyansk reapers» JSC (Ukraine) produces a single-bar mounted KPO-2.1 (single-bar finger mower) and KPN-2.1 (rotary mounted mower), «Bobruiskagromash» JSC (Open Joint Stock Company) (Republic of Belarus) – a segment-finger mounted KS-F-2.1B (segment-finger mounted mower) and mounted two-bar KDS-4.0 (mounted two-bar mower), «Urgenchkormmash» JSC (Uzbekistan) – single-bar mounted KOS-2.1 (single-bar mounted mower) and two-bar semi-mounted KDP-4.0 (two-bar semi-mounted mower). The eccentric shaft speed at a PTO speed of 540 rpm is 750–1100 rpm.

The advantages of these mowers are precise cutting, low energy consumption (about 2.0...2.5 kW per meter of working width), low fodder contamination and cost.

The disadvantage of mowers with segment-finger cutting devices is that when mowing grass on natural and seeded hayfields with uneven relief, frequent breakdowns of the knife and connecting rod occur. The reason is that a crank mechanism is used to drive the cutter bar in mowers. Rods, truss, and the connecting rod interacts with the knife head. Therefore, on uneven fields, when the outer shoe rises more than 0.2 m above the inner shoe, the angle of inclination of the connecting rod to the horizontal increases and the course of the segments changes. With an increase in the angle of inclination of the connecting rod, the vertical components of the forces acting on the knife and the elements of the finger bar grow, which increases the frictional forces in the cutting device and leads to pinching of the knife in the cutting device. As a result, frequent breakdowns of the knife and connecting rod occur, which requires additional time to troubleshoot [4, 5].

Also, the disadvantage of mowers is their low productivity (about 0.45 hectares per hour and meter of working width); high risk of clogging and frequent replacement of knives; high sensitivity to mechanical damage, high maintenance costs.

In the «Berdyansk reapers» KRN-2.1 mower, a knife drive mechanism with a short connecting rod is installed on the inner shoe. The advantage of this design is that the cutterbar can operate at any angle of inclination of the finger bursa with irregularities in the soil.

The mower performance can be enhanced both by increasing its working width, as well as the forward speed. Increasing the mower width leads to the creation of bulky, low-maneuverable and unreliable machines when used on the unevenness of hayfields.

One of the promising ways to increase the forward speed of mowers is to increase the crank shaft speed. This, in turn, leads to a sharp increase in alternating inertial loads, and hence to a decrease in the operational reliability and durability of the machine as a whole [6].

2. Literature review and problem statement

To implement the reciprocating motion of the knives of the cutting devices, various types of drive mechanisms are used. The most widespread is the crank mechanism. Due to the design features and operation conditions of the machines, the axis of the crank shaft is located above the line of knife motion by a certain amount, called displacement (disaxial).

In a mower with movable fingers (duplex cutterbar), the fingers are fixed on the back of the finger bar and reciprocate towards the segments driven by the crankshaft. At the same time, the bar and the knife of the cutting device oscillate in antiphase with the same speed and thereby self-balancing of the inertial forces in the cutting device is ensured. Such a device of the cutterbar allows you to double the cutting speed at the same speed on the driven pulley, which allows getting a cleaner cut of the grass stand. In addition, the reciprocating movement of the fingers provides the ability to mow lodged grasses even with wet grass stands. The disadvantage of this mower is the design complexity and the imbalance of the inertial forces of the finger bar and the cutting knife [7].

In the work «Physical and mechanical properties of plants and improvement of the cleaning apparatus of harvesting machines» [8], a detailed analysis of various knife drive mechanisms used in mass-produced machines, mowers and harvesters, also proposed in new inventions, copyright certificates and patents, is carried out. It analyzed all known drive mechanisms with an assessment of compliance with their requirements in terms of analysis and synthesis of drive mechanisms.

In mowers, the crank shaft with the box and the crank are located on the main frame, connected by means of a connecting rod to the head of the cutting device, which moves reciprocally. The toe bar is supported by the shoes on the field surface during operation. To copy the microrelief, the bar is pivotally connected with a drawbar to the machine frame. Due to the elastic deformations of the drawbar and the gaps in the hinges, the toe bar moves back. In order to ensure the operability of the mower, the field end of the finger bar is pushed forward along the course of the unit, and ball joints are used in the drive of the cutting device. This allows the links to move in different planes, the mechanism becomes spatial. Such a cutterbar drive is used in the KDP-4.0 double-bar mower, in the KS-2.1 mounted mower, etc. PTO rotational speed is 940...1024 min^{-1}.

Experiments have established that for a high-quality cut of plants, it is necessary to have a grass cutting speed of at least 2.15 m/s, and for cereals – 1.5 m/s [9].

Abroad, fingerless cutting devices with two active knives are used, equal in length to the width of the grip and vibrating in opposite directions. A fingerless cutter with two movable knives is used when harvesting tangled and lodged bread, rice, legumes, where usually cutters with fingers cannot work, as well as when switching to increased translational speeds of reaping machines. A cutterbar with two movable knives is used on mowers [10].

The double-knife cutterbar allows the tractor speed to be increased up to 12 km/h, which significantly increases productivity with clean mowing quality and low power requirements (approx. 2.5 kW per meter of working width). The design of the double-knife cutterbar allows the inertial forces to be balanced. The cutting device is driven by a crank-rocker mechanism, the links of which are pivotally mounted on the silent blocks, which ensures the ease and noiselessness of the mower.

The disadvantages of a double-knife cutterbar include the difficulty of maintaining a constant gap between the segments of the upper and lower knives during operation. An increase in this gap leads to clogging of the apparatus. The knife drive mechanism is folded. In areas clogged with stones, the devices are not reliable in operation, due to the unprotected segments. When cutting low grass on uneven fields, the blade segments burrow into the ground, causing the segments to break [11].

In the drives of the cutting units of forage harvesters, crank-rocker mechanisms, which are spatial, are used. Their use is caused by the need to reduce the transverse dimensions of the headers. A distinctive feature of the crank-rocker mechanism is that there are additional links between the connecting rod and the knife of the cutting device: a two-armed lever and a small connecting rod.

The research of mechanisms with flexible connecting rods, connected in pre-stressed contour, is carried out in the works of [12], and his students [6, 7].

At the Kazakh Agricultural Institute under the leadership of [12] with his students, a wide-cut mower was developed, in which the transformation of the rotary motion of the hydraulic motor shaft into the reciprocating motion of the knives is carried out by a mechanism with flexible connecting rods.

Currently, the reapers of the German harvesting machines use a drive design using a planetary gearbox, improved by Schumacher. Due to the straight blade, beating and vibration acting on the header are eliminated. The number of knife strokes increases to 1,120...1,200 per minute. The specialists of the «Astarta-Technics» Limited Liability Company (Russia) provide services for the modernization of various types of reapers by replacing the standard drive and cutting mechanism with the Schumacher cutting system with a planetary gear.

Due to the high cost of the gearbox, which varies depending on the manufacturer from 700 to 1200 US dollars, mowers are not used.

An increase in mower performance with a decrease in the crank shaft speed is achieved when using a cutterbar with a double knife stroke.

When studying the operation of the cutting device with a double stroke of mower segments, the works of Russian scientists [13–15] were studied, devoted to the theory, design and calculation of agricultural machines, study of the process of cutting grasses and grain crops by cutting tools of harvesting machines. The advantage of a cutterbar with a double stroke of segments, in comparison with an apparatus with a single stroke of segments, is that the angular speed of the crank decreases by 1.5...2.0 times, the feed of the cutterbar can be increased by 1.6 times, the inertia force of the knife is reduced by 1.1...1.3 times.

But this device also has significant drawbacks:

– insufficient use of the maximum knife speed in the process of cutting the stems does not allow, with a radius increase of 2.0 times, reducing the rotational speed by the same amount;

– vibrations of the finger bar, the machine frame with a double knife stroke are much greater than with a single one;

– the power required to overcome the frictional forces of a cutterbar with a double knife stroke will be 25 % more than that of a cutterbar with a single stroke.

It should be noted that these results were obtained for a cutterbar with a double knife stroke driven by a deaxial crank mechanism. Double knife stroke is provided when the crank radius is 2 times larger than in normal cutting machines with a single stroke of segments. In this case, the angle of inclination of the connecting rod increases, which leads to an increase in the vertical components of the forces, causing an increase in the friction force against the guides.

3. The aim and objectives of the study

The aim of this study is develop the structural and technological scheme, parameters of a drive of a mowing machine of segment-manual type of dynamic loadings providing decrease and qualitative performance of the technological process.

To achieve the aim, the following objectives are set:

– to study the indicators of the test conditions, the characteristics of the grass stand that affect the mowing process;

– to conduct an analysis of the research carried out on various mechanisms for the drive of the cutting device, select the most appropriate structural and technological scheme;

– to conduct a kinematic analysis of the drive and the dynamics of the knife of the cutting device, to justify its main parameters that ensure the high-quality performance of the cutting process;

– to give a design solution and a method for calculating a mower with a segment-finger cutting device and with an improved drive mechanism;

– to make an experimental sample and conduct preliminary tests of the mower with a new drive.

4. Materials and methods

A methodology for conducting preliminary tests of a mower prototype with an improved drive was developed, which provided for determining: compliance of the manufactured sample with technical documentation; agrotechnical indicators; indicators of purpose; reliability, including a list of failures and malfunctions of the machine during the testing period; manufacturability, etc.

Factory tests of the manufactured prototype of the mower have established that it is operable, ensures the implementation of a given technological process, has the necessary protective covers and warning labels. According to the results of factory tests, an act was issued on the readiness of the KS-2.1M mower prototype for conducting its preliminary tests.

Preliminary tests of the KS-2.1M mower prototype were carried out in the OTBI LLP of the Talgar district of the Almaty region when mowing seeded, natural grasses and natural grasses with reeds. Tests were carried out for compliance of the KS-2.1M mower with the requirements of the technical specification for its development.

Methodology and calculation of the main parameters of mowers with segment-finger cutting devices of single and double knife strokes.

As a result of theoretical and experimental studies, a method for calculating the parameters of the KS-2.1. A mowers with segment-finger cutting devices with a single knife stroke and the developed KS-2.1M with a double knife stroke has been developed, which is shown in Table 1.

The table shows that in a cutting device with a double knife stroke, the crank speed can be reduced at least 2 times, from 840 min^{-1} to 420 min^{-1}, therefore, the knife inertia forces can be reduced 2 times, from 1468.25 N to 734.34 N, due to an increase in the feed 2.0 times from 0.071 m to 0.142 m, the machine speed increases.

The research was carried out using classical methods of theoretical and applied mechanics, theory of mechanisms and machines.

The kinematic study of the mechanism was carried out by the method of vector contours. According to this method, the diagram of a flat flexible mechanism, located in rectangular coordinate system xOy, is represented as a closed polygon, which, depending on the complexity of the mechanism, consists of one or more closed vector contours. Closure conditions are written in vector form or as a projection on the coordinate axis.

Table 1

Methodology and calculation of the main parameters of mowers with a cutting device

Indicators	KS-2.1 A – with a single knife stroke		KS-2.1 W – with a double knife stroke	
	formula	meaning	formula	meaning
Step between the fingers	t_0, mm	76.2	t_0, mm	76.2
Step between the knives	t, mm	76.2	t, mm	76.2
Knife stroke	$S_1=t=t_0$, mm	76.2	$S_2=2t=2t_0$, mm	152.4
Radius of the eccentric, crank	r_1, mm	38.1	r_2, mm	40
Shaft speed	n_1, min^{-1}	600÷1010	n_2, min^{-1}	300÷505
Average knife speed	$V_{1\ optim}$, m/s	1.52÷2.57	$V_{2\ optim}$, m/s	1.52÷2.57
Minimum grass cutting speed	$V_{\min}$, m/s	2.15	$V_{\min}$, m/s	2.15
Rational shaft speed	$n_1=\frac{V_{optim}\cdot 60}{2S}$, min^{-1}	840	$n_2=\frac{V_{optim}\cdot 60}{2S}$, min^{-1}	420
Angular velocity	$\omega_1=\frac{\pi\cdot n}{30}$, rad/s	87.92	$\omega_2=\frac{\pi\cdot n}{30}$, rad/s	43.96
Kinematic mode	$X_1=-r_1\cdot\cos\omega_1 t$, m	0.0381	$X_2=-2r_2\cdot K\cdot\cos\omega_2 t$, m	0.0762
Knife speed V=2.15 m/s	$V_x=r_1\cdot\omega_1\cdot\sin\omega_1 t_1$, m/s	3.34	$V_x=2r_2\cdot K\cdot\omega_2\cdot\sin\omega_2 t_2$, m/s	3.34
	$j_x=r_1\cdot\omega_1^2\cdot\cos\omega_1 t$, m/s^2	293.65	$j_x=r_2\cdot\omega_2^2\cdot\cos\omega_2 t$, m/s^2	146.8
Mower working speed, m/s	V_p, m	1.0...2.0	V_p, m	1.0...2.4
Knife feed	$h_1=\frac{V_m}{\omega_1}\pi$, m	0.071	$h_2=\frac{V_m}{\omega_1}\pi$, m	0.142
Cutting height factor	A_1	1.25	A_2	0.78
Cutting resistance	$P_{cp}=\frac{\varepsilon\cdot F_h\cdot Z}{X_p}$, N	1368	$P_{cp}=\frac{\varepsilon\cdot Z}{X_p}\left(F_{H_1}+F_{H_2}\right)$, N	716.34
Knife movement from the beginning to the end of cutting, cm	X_p, cm	2.8	X_p, cm	2.8
Work spent on the cut	ε, N cm/cm ^{2}	2÷3	ε, N cm/cm^2	2÷3
Number of segments	Z, pc	28	Z, pc	28
Load area	$F_H=Khs$, cm^2	45.6	$F_H=0.32hs$, cm^2	20.2
			$F_{H2}=0.18hs$	16.5
Knife friction force	$F_1=G_m\cdot f$, N	15	$F_2=G_m\cdot f$, N	15
Coefficient of friction	f	0.25...0.3	f	0.25...0.3
Friction force from the action of the connecting rod	$F_2=\frac{\left(P_{cp}+P_j+f\cdot G_m\right)\cdot \mathrm{tg}\,\alpha f}{1-f\cdot \mathrm{tg}\,\alpha}$	510	$F=0$	0
Knife inertia force	$P_j=\left(m_H+m_c\right)r\cdot\omega_1^2$, N	1468.25	$P_j=m_r\cdot 2r\cdot\omega_2^2$, N	734.34
Knife resistance to movement when mowing	$P_{aggre}=(P_{cp}+P_j+F_1+F_2)$, N	3401.45	$P_{aggre}=(P_{cp}+P_j+F)$, N	1465
Power required for idling	$A=\frac{P\cdot V}{1{,}000}$, kW	3.156	$N=2\Pr\cdot\sin\left(\varphi+\theta\right)\frac{\sin\beta}{2}$	1.31
Power required for mowing grasses	$A=\frac{P_{aggre}\cdot V}{1{,}000}$, kW	7.313	$N=2P_{aggre}r\cdot\sin\left(\varphi+\theta\right)\frac{\sin\beta}{2}$	4.89
Capture width	$B_1=Z\cdot t$, m	2.1	$B_2=Z\cdot t$, m	2.1
Mower performance	$W_1=0.36B_1\cdot V_p$	0.75...1.5	$W_2=B_2\cdot V_p\cdot 0.36$	0.75...1.8

The numerical analysis of the equation of motion of the knife drive of the mower cutter is carried out using standard Excel and Mathcad programs. When processing the results of experimental studies, the provisions of mathematical statistics were used.

5. Results of research on the operation of a mower with an improved drive mechanism

5. 1. Indicators of test conditions, characteristics of the grass stand that affect the mowing process

The Research Institute of Agricultural Engineering named after V. P. Goryachkin (JSC «VISKHOM») has established that for high-quality cutting of plants, a cutting speed of at least 2.15 m/s is required for grasses, and 1.5 m/s for cereals.

To determine the cutting speed of the stems for a cutting machine with double stroke, the contours of the anti-cutting plates, fingers are applied (Fig. 1), as well as the contours of the segment in one of its extreme positions. After that, we build a diagram of the speed of movement of any point of the knife according to the method of N. I. Kalinin, from the selected point A, we postpone the segment $AO=r$ and from the point O we draw a circle with a radius r.

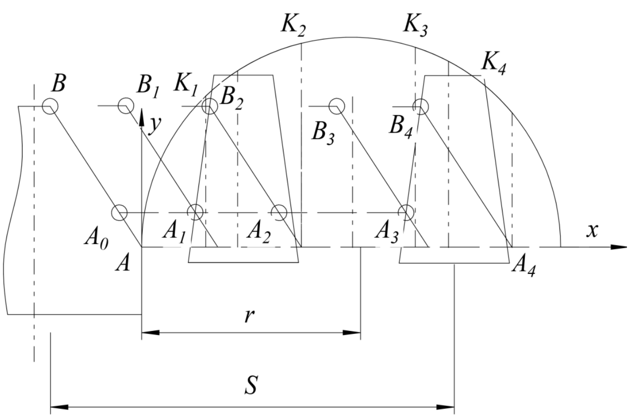

Fig. 1. Diagram of the cutting speed for a normal cutting machine with a double knife stroke

Fig. 1 shows a diagram of the cutting speed for a normal cutting machine with a double knife stroke. In this device, in one move, the segment cuts off the stems of the middle and extreme fingers, the speeds V'_{H_H} and V''_{H_H} of the cutting end at the middle and extreme fingers are respectively equal to:

$$V'_{H_H} = A_1K_1\mu;\ V''_{H_H} = A_3K_3\mu \quad (1)$$

and the speed of the cutting end:

$$V'_{H_K} = A_2K_2\mu;\ V''_{H_K} = A_4K_4\mu. \quad (2)$$

Cutting occurs at different speeds, i.e. the speeds at the beginning and at the end of cutting are not equal. The speed V''_{H_K} of the cutting end at the extreme finger is small. Due to the low speed, there may be an unsatisfactory cut and clogging of the cutting device. To ensure the necessary operability of these devices, careful adjustment of the gaps in the cutting pair is needed.

Based on the condition of a high-quality cut of plants, with a minimum cutting speed of herbs $V''_{H_K} = 2.15$ m/s, we determine the required crank shaft speed by the formula:

$$n = \frac{V''_{H_K} \cdot 30}{S}. \quad (3)$$

The minimum crank shaft speed for a mower with a double knife stroke for a high-quality cut of plants should be n_2=420 min^{-1}. Accordingly, the minimum rotation speed for a mower with a single knife stroke for a high-quality cut of plants is n_1=840 min^{-1}.

The performance indicators of the mower were taken at the following speeds: when mowing alfalfa – 1.56 m/s, when mowing various grasses –1.6 m/s. The rotation speed of the eccentric shaft was 400...420 min^{-1}.

In these modes, the mower provides a good cut quality and uniformity. When setting the cutting height H_c=50 mm, the actual cutting height was H_f=55 mm (Fig. 2).

The Scientific and Production Center of Agroengineering has developed a mower drive mechanism in which the reciprocating movement of the cutting machine knife is carried out by curved-spike-roller and flexible links. The technical novelty of the invention is protected by innovative patents of the Republic of Kazakhstan No. 21946 [16], No. 26421 [17] and No. 29916 [18].

A diagram of the drive mechanism of the cutterbar of a mower with a double knife stroke is shown in Fig. 3.

The mechanism is mounted on the inner shoe and contains a rack plate 1, two supporting rollers 2 and 3, a drive shaft connected to it with a crank 4, on the finger 5 of which a roller 6 is mounted with the possibility of rotation, a driven element 7 and two flexible elements covering the roller on both sides, each of which interacts with one of the supporting rollers and is attached at one end to the rack plate 1, and the other to the driven element – knife 7. The flexible element is made in the form of chains 8, 9.

When designing and studying the operation of the mechanism, it is of great practical importance to determine the kinematic parameters of the mechanism: movement, speed and acceleration of the knife.

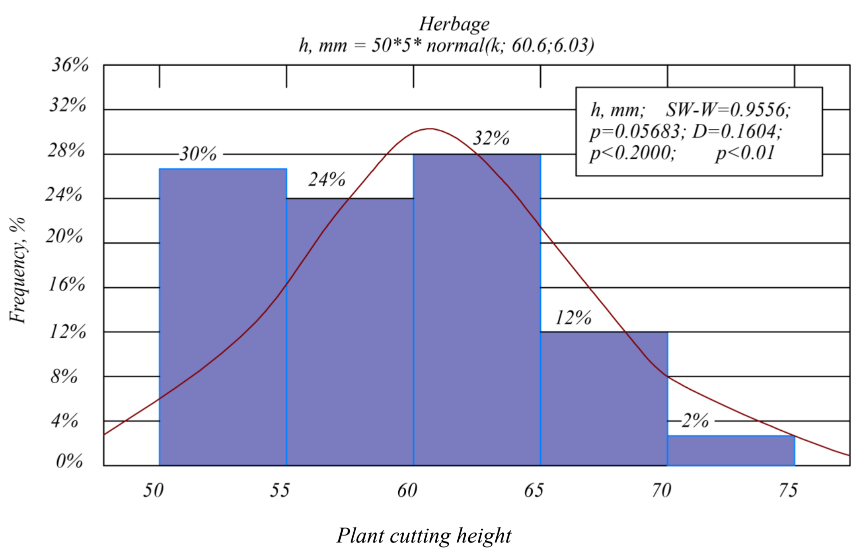

Fig. 2. Histogram and curve of the normal distribution of the plant cutting height

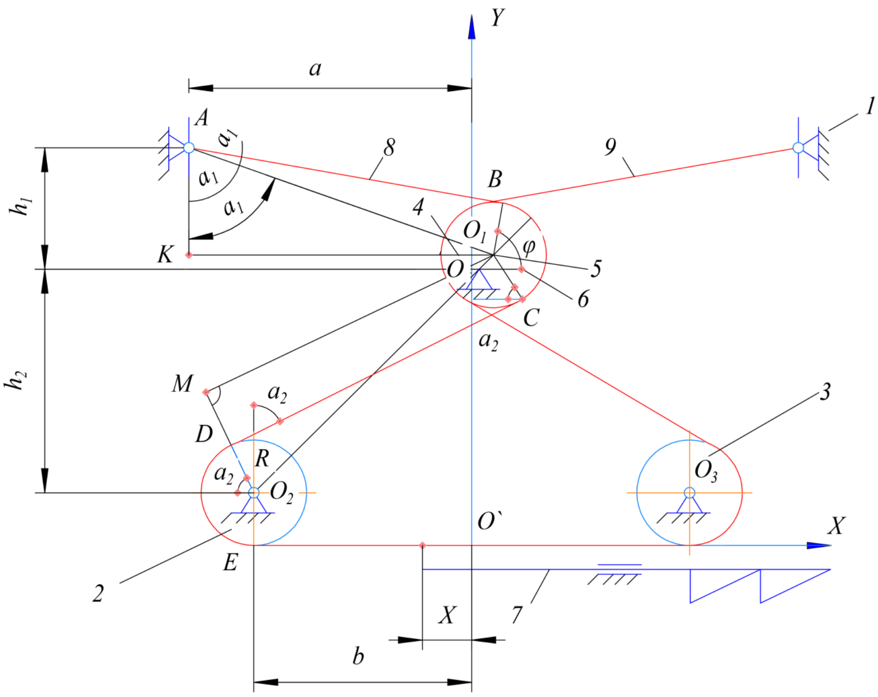

Fig. 3. Mechanism of the drive of the knife of the cutterbar of the segment-finger type mower

The area of the field from which the plants are cut by a segment in one knife stroke is called the feed area and is denoted as *F*.

The area of the field from which the plants are cut by a segment in one knife stroke at one finger is called the load area and is denoted as F_n. Determination of the feed area and load area for cutters for normal cutting with a single cut of the knife is described in detail by [14, 19].

To determine the feed area and the load area of the cutting device for normal cutting with a double knife stroke, the known technique is proposed [19].

The top of segment 1 (Fig. 4), when turning the crank by one turn, outlines the *ABCDE* curve. When moving from position II to position III, segment 1 cuts out plants with sites *Sun D* and DED_1C_1, respectively in fingers 2 and 3. From the ABC_1B_1 platform, the plant cuts off segment 2 at the middle finger 2 when the knife moves from position I to position II, and from the $B_1C_1D_1$ platform – at the extreme finger 3 during the reverse stroke of the knife.

5. 2. Analysis of the studies of various mechanisms for driving the cutting device, choosing the most appropriate structural and technological scheme

Indicators and values of the conversion of a cutterbar with a single stroke to a double stroke according to [14] are given in Table 2.

Table 2

Indicators and values of the conversion of the cutterbar with a single stroke to a double stroke

Indicators	Single stroke	Double stroke
Knife stroke, mm	$S_1=t=76.2$	$S_2=2t=152.4$
Angular crank speed	$\omega_1=\frac{\pi n_1}{30}$	$\omega_2=\frac{\pi n_2}{30}$, $\omega_2=0.5\omega_1$
Longitudinal bending of stems	A_1h_1	A_2h_2
Plant cutting height factor	$A_1=1.2$	$A_2=0.78$
Cutter feed	h_1	$h_2=1.6\,h_1$
Cutting width	L	$L_2=(1.12\div1.28)L_1$
Knife inertia force	$P_1=m_k\omega_1^2=\frac{S_1}{2}$	$P_2=m_k\omega_2^2S_2$, $P_2=0.5P_1$
Power to overcome friction forces	$S_1\,n_1$	$S_2\,n_2$

Thus, when converting the cutterbar from single to double stroke:

– the crank angular speed decreases $\omega_2=0.5\ \omega_1$;

– the cutter bar feed increases $h_2=1.6h_1$;

– the knife inertia force decreases $P_2=0.5P_1$ and the grip width can be increased to $L_2=(1.12\div1.28)L_1$.

The power required to overcome the friction forces of the device with a double stroke remains at the power level for the cutter bar with a single knife stroke $S_1n_1=S_2n_2$.

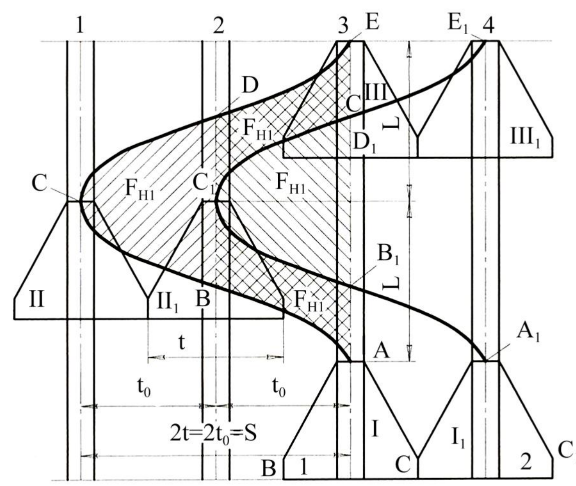

Fig. 4. Feed area and load area of the normal cutter with a double knife stroke

Fig. 4 shows that the areas of the sections are equal to the load area:

$$S_{BCD}=S_{B1C1D1}=F'_{H1},$$

$$S_{ABC1B1}=S_{C1DED1}=F'_{H2}.$$

The load area on the first finger:

$$F'=0.32Ls,\ \ k_1'=0.32, \tag{4}$$

on the second finger:

$$F'_{H_2}=\frac{Ls}{2}-F'_{H_1}=0.18Ls,\ \ k_2'=0.18, \tag{5}$$

The shear resistance force depends on the size of the load area. Table 3 shows the values of the load areas for different devices with a supply of L=6 cm. The table shows that the maximum load area corresponds to the normal cutting device with a single knife stroke, and the minimum – normal cutting knife with a double stroke.

Table 3

Load areas of cutting units of various types

Machine type	F_{H_1}, cm^2	F_{H_2}, cm^2
$t=t_0=s=76.2$	–	45.6
$2t_0=t_0=S=152.4$	20.2	16.5

Since the number of plant cut-offs by the blade of the segment at the counter plate is proportional to the load area, it can be seen from the table that the load of each centimeter of the blade working length is not the same for different devices. In the single-cut normal cutter, the segment cuts more stems at the same time than in other machines. The number of simultaneously cut stems affects the value of shear resistance forces and power needed for cutting.

The diagram of the forces applied to the drive mechanism of the mower cutterbar is shown in Fig. 5.

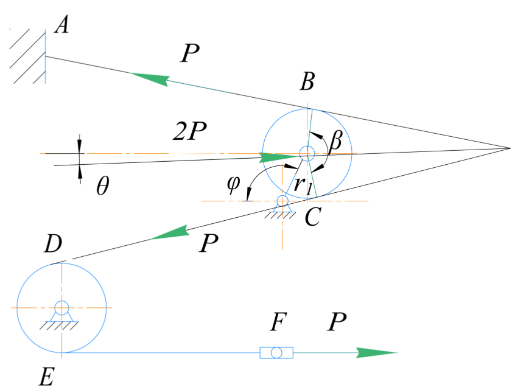

Fig. 5. Driving forces applied to the drive mechanism of the mower cutterbar

To determine the power required for the mower drive, the resistance force F is determined from the knife for mule:

$$P=P_{cp}+P_j+F, \qquad (6)$$

where P_{CP} – average value of the shear resistance force, N; P_j – knife inertia force N; F – knife friction force, N.

The force of inertia is determined and the cause of the mass m_H of the knife and the acceleration j_H:

$$P_j = m_H j_H = m_H 2Kr\omega_2^2\left(1-\frac{X}{2r}\right). \qquad (7)$$

Known mower knife friction force of the finger elements of mower finger bar are the sum of the frictional force F_1, caused by the knife gravity force, and force F_2 from the action of the connecting rod, i. e. $F=F_1+F_2$.

The strength of the blade friction directed the boiling is:

$$F_1=G_H \cdot f, \qquad (8)$$

where G_H – knife gravity, N; f – coefficient of friction.

The friction force acts on the rod anchor for the proposed mechanism of the mower F_2=0.

The power necessary to drive the mower mechanism is determined by the formula:

$$N=M_P \cdot \omega_2, \qquad (9)$$

where M_P – torque on the crank shaft, Nm:

$$M_P = 2P\cdot r\cdot \sin(j+q)\cdot \sin\frac{\beta}{2}, \qquad (10)$$

where θ – angle between the direction of the impact force F and the horizontal axis; β – chain sprocket angle; r – crank radius, m.

Substituting P into formula (10), we obtain the value of the average power required for the idling of the knife and the power required for mowing grass.

5. 3. Kinematic analysis of the drive and the dynamics of the knife of the cutting device, justification of the main parameters

The mechanism is mounted on an inner shoe and contains a rack plate 1, two supporting rollers 2 and 3, a drive shaft connected to it with a crank 4, on the pin 5 of which roller 6 is rotatably mounted, a driven element 7 and two flexible elements covering the roller with both sides, each of which interacts with one of the supporting rollers and is attached at one end to the rack plate 1, and the other to the driven element – knife 7. The flexible element is made in the form of chains 8, 9.

When designing and studying the operation of the mechanism, it is of great practical importance to determine the kinematic parameters of the mechanism: movement, speed and acceleration of the knife.

The geometric parameters of the mechanism are set (Fig. 3): r – crank radius, R – roller radius (radii of all rollers are the same), a – distance from the crank shaft axis to the point A of fixing the flexible link horizontally; B – distance from the crank shaft axis to the of roller axis horizontally; h_1 – distance from the point of attachment A of the flexible link to the crank axis vertically; h_2 – distance from the roller center to the vertical axis of crank shaft rotation; α_1 and α_2 – angles of inclination of the branches of the flexible draft to the vertical; φ – crank angle.

The initial position of the mechanism corresponds to the crank angle φ=0, while the knife is in the middle position.

The movement and stroke of the knife are determined through the length L of the flexible link from point A to point O':

$$L = AB + B\breve{C} + CD + D\breve{E} + EO', \qquad (11)$$

where: AB, CD, EO' – lengths of the straight parts of the flexible element; $B\breve{C}$, $D\breve{E}$ – lengths of the parts of the flexible element corresponding to the arcs.

From triangles ABO_1 and O_2MO_1, the lengths of the straight parts AB and CD are determined:

$$AB = \sqrt{AO_1^2 - BO_1^2} = \sqrt{(a+r\cdot\cos\varphi)^2 + (h_1 - r\cdot\sin\varphi)^2 - R^2},$$

$$CD = \sqrt{O_1O_2^2 - MO_2^2} = \sqrt{(b+r\cdot\cos\varphi)^2 + (h_2 + r\cdot\sin\varphi)^2 - 4R^2}. \qquad (12)$$

The lengths of the arcs BC and DE are equal to:

$$\breve{BC} = \frac{\pi R}{180} \cdot (\alpha_1 + \alpha_2); \; \breve{DE} = \frac{\pi R}{180} \cdot (\alpha_2 + 90°). \quad (13)$$

At the crank angle $\varphi=0$, the knife is in the extreme left position, and at $\varphi=180°$ – in the extreme right position.

The knife stroke is determined by the formula:

$$S = L_1 - L_2 = \sqrt{(a+r)^2 + h_1^2 - R^2} + \sqrt{(b+r)^2 + h_2^2 - 4R^2} + \frac{\pi R}{180°} \cdot (\alpha_1' + 2\alpha_2') - \sqrt{(a-r)^2 + h_1^2 - R^2} - \sqrt{(b-r)^2 + h_2^2 - 4R^2} - \frac{\pi R}{180°} \cdot (\alpha_1'' + 2\alpha_2''), \quad (14)$$

where L_1 – length of the flexible link at $\varphi=0$; L_2 – length of the flexible link at $\varphi=180$; α_1' and α_2' – angles of inclination of the branches of the flexible link at $\varphi=0$; α_1'' and α_2'' – angles of inclination of the branches of the flexible element at $\varphi=180°$.

To determine the movement and stroke of the knife with different geometric dimensions of the mechanism, a program was drawn up and, based on the analysis of the kinematic parameters, the optimal geometric parameters were determined: crank radius $r=42.3$ mm; roller radius $R=42.8$ mm; races standing $a=200$ mm; $b=150$ mm; $h_1=159$ mm; $h_2=150$ mm.

The knife stroke, calculated by (14), with a crank radius $r=42.3$ mm, is 152.4 mm.

(14) for determining the knife movement is too cumbersome and inconvenient for determining the knife speed and acceleration. For practical calculations and analysis of knife kinematics, expression (14) can be represented as:

$$X=-2r \cdot K \cdot \cos\varphi, \quad (15)$$

where K is the coefficient depending on the geometrical dimensions of the mechanism.

Fig. 6 shows the graphs of the knife displacements determined by (14) (curve 1) and by simplified (15) (curve 2). With a direct stroke, i. e. when the crank is turned from 0° to 180°, the displacements coincide, and during the reverse stroke of the knife, there is a slight mismatch of the curves and the phase shift is 5–6°.

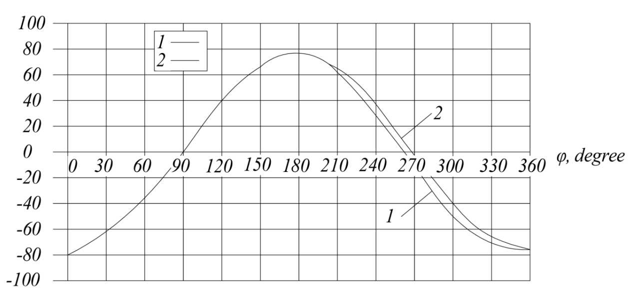

Fig. 6. Graph of knife movement depending on the crank angle

Based on this, it can be concluded that simplified (15) can be used to determine the displacement, speed, acceleration of the knife and to study the dynamics of the mechanism with sufficient accuracy [20].

The kinematic characteristics of the well-known single-stroke crank and the proposed double-stroke mechanism are as follows:

$$X_1 = -r\cos\varphi = -r_1 \cos\omega_1 t;$$
$$V_1 = \frac{dx}{dt} = r_1\omega_1 \sin\omega_1 t;$$
$$j_1 = \frac{dV_x}{dt} = r_1\omega_1 \cos\omega_1 t; \quad (16)$$
$$X_2 = -2r_2 K\cos\varphi = -2r_2 K\cos\omega_2 t;$$
$$V_2 = \frac{dx}{dt} = 2r_2 K\omega_2 \sin\omega_2 t;$$
$$j_2 = \frac{dV_x}{dt} = 2r_2 K\omega_2^2 \cos\omega_2 t; \quad (17)$$

r_1, r_2 are the crank radii and ω_1, ω_2 are the angular velocities of the cranks of the cutting devices, respectively, with a single and double cut of the knife.

Fig. 7 shows the graphs of displacement X, speed V and acceleration j of the cutter blade with single and double strokes, depending on the crank angle (1 – with a single knife stroke; 2 – with a double knife stroke).

With a crank speed $n_1=840$ min^{-1}, the maximum speed of the knife with one and the same stroke is equal to $V_1=3.34$ m/s, and the maximum acceleration $j_1=293.7$ m/s^2; and a cutting device for a dual stroke at the crank speed $n_2=423$ min^{-1}, the maximum knife speed $V_2=3.3$ m/s and the maximum acceleration $j_2=150.0$ m/s^2, inertial loads are reduced by almost 2 times.

It has been established by experiments that for a high-quality cut of plants, a cutting speed for grasses of at least 2.15 m/s is required. To determine the cutting speed of the stems for a cutterbar with doubled stroke, we apply the contours of the shearing plates, fingers, as well as the contours of the segment in one of its extreme positions. We build a diagram of the speed of movement of any point of the knife according to the method of [21].

In a normal cutter with double cut of the knife in one stroke, the segment cuts the stems at the middle and outer fingers.

Plants are cut at different speeds, i.e. the speeds at the beginning and at the end of cutting are not equal. The speed of the cutting end at the outer finger is low. Low speed may result in unsatisfactory cutting of plants and blockage of the cutter bar. To ensure the necessary performance of the cutting device, we take the minimum cutting speed of plants.

Based on the condition of a high-quality cut of plants, with a minimum cutting speed of grass=2.15 m/s, we determine the required crank shaft speed according to:

$$n = \frac{V_k \cdot 30}{S}. \quad (18)$$

The minimum crank shaft speed for a mower with a double knife stroke for a high-quality cut of plants should be $n_2=420$ min^{-1}.

The performance indicators of the mower were taken at the following speeds: when mowing alfalfa – 1.56 m/s, when mowing various grasses – 1.6 m/s. The speed of the eccentric shaft was 400...420 min^{-1}.

In these modes, the mower provides a good cut quality and uniformity. When setting the cutting height $H_c=50$ mm, the actual cutting height was $H_b=55$ mm.

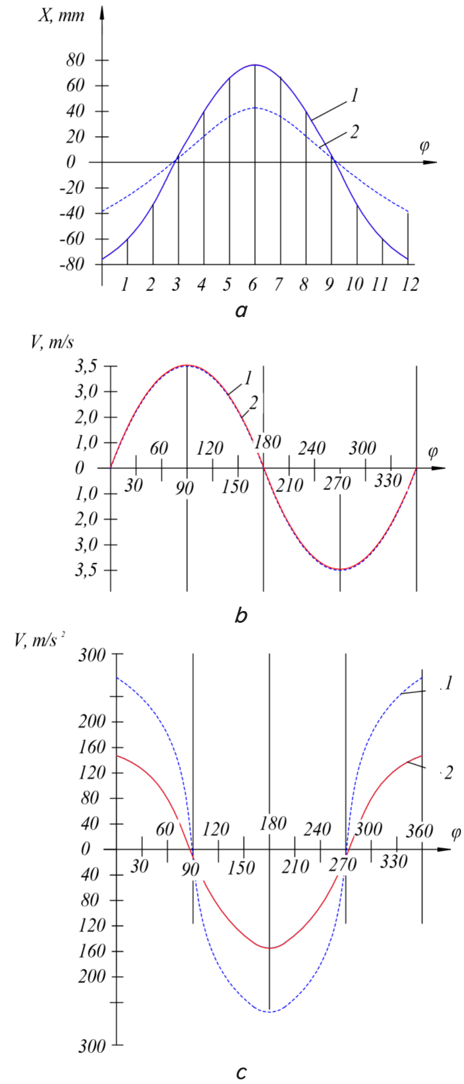

Fig. 7. Graphs of displacement *X*, speed *V* and acceleration *j* of the knife depending on the crank angle: *a* – displacement *X*; *b* – speed *V*; *c* – acceleration *j*

The energy parameters of the KS-2.1M mower were determined in the field by the method of strain measurement of the torque and speed of the tractor PTO. The power required for mowing grass at a speed of 2.0 m/h is 1.9...2.8 kW, and at idle – 0.8...1.22 kW. As a result of the tests, it was found that the technological processes of mowing grasses with laying in the slope are performed reliably and efficiently on uneven haymaking terrain. The mower has the ability to work in conditions of uneven terrain, natural and seeded hayfields, as well as on small areas of seeded and natural grasses.

5. 4. Calculation method of a mower with a segment-finger cutting device and with a new drive mechanism

5. 4. 1. Methods of laboratory tests

A laboratory installation has been developed for carrying out laboratory studies of a mower with an improved drive (Fig. 8). Laboratory and bench tests of an experimental sample of the KS-2.1 M mower were carried out in the laboratory of the Scientific and Production Center of Agroengineering LLP. The purpose of the bench tests was to determine the reliability and durability of the flexible link of the mower drive at idle.

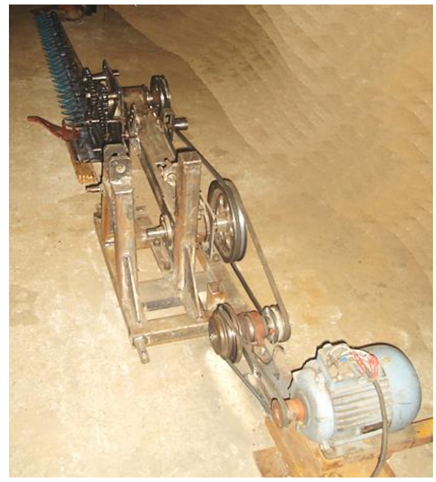

Fig. 8. Laboratory installation of a mower with an improved drive

The laboratory installation consisted of a mower and a gearbox with V-belt gears. The cutting device is driven by an electric motor using a mower drive mechanism made in the form of a chain transmission.

The speed of the eccentric shaft was changed within 300, 330, 360 and 460 min^{-1} using replaceable V-belt pulleys. The power required to drive the mower at idle was determined by the K-505 measuring kit (Fig. 9), and the speed of the eccentric shaft – using the PM-10-P tachometer.

Fig. 9. K-505 measuring kit

The power to drive the cutting device of the mower at idle was determined by the formula (drive from an electric motor):

$$P_p = P_n \frac{\xi}{100}, \text{ kW}, \tag{19}$$

where P_p is the power on the motor shaft at idle (kW); P_n – rated power of the electric motor according to the passport data (kW); ξ – degree of use of the electric motor power during the working stroke (%).

The value of ξ was determined by the value of the power factor cosφ from the catalog data. The value of cosφ during the working stroke was determined from the formula:

$$\cos\varphi = \frac{P_{a.p}}{P}, \tag{20}$$

where $P_{a.p}$ – active power at the working stroke (kW), determined by the wattmeter; P – apparent power at the working stroke (kW), determined by the formula:

$$P = \frac{\sqrt{3}\ U_P I_P}{1{,}000},\ \text{kW}, \qquad (21)$$

where U_P, I_P – line voltage (V) and current (A) at the operating stroke, respectively.

5. 4. 2. Determination of the torque required to drive the cutting device of the mower

The assessment of energy indicators was carried out in the optimal agrotechnical terms for this zone on funds corresponding to the technical task (TT) and technical conditions (TC) for the tested machine.

The power required to drive the mower was determined by the formula:

$$N = M_{cr} \cdot \omega = \frac{M_{cr} \cdot \pi n}{30},\ \text{W}, \qquad (22)$$

where M_{cr} – torque on the drive shaft, N·m; $\omega=\pi n/30$ – shaft angular speed, s^{-1}; n – shaft speed, min^{-1}.

The determination of the torque transmitted to the mower drive was carried out in the field. For this purpose, mowing of various grasses, alfalfa, natural grasses was carried out at different grass stand density, mower speed and PTO revolutions.

5. 5. Experimental sample of the KS-2.1M mower

An experimental sample of a KS-2.1M single-bar mounted mower with a flexible drive has been developed at the «Scientific and Production Center of Agroengineering» LLP («SPCAE» LLP, Almaty, Kazakhstan) plant, an experimental model of a KS-2.1M single-bar mounted mower with an improved drive (Fig. 10) has been developed. Its compliance with the technical task and efficiency were confirmed, the agrotechnical and energy indicators of the mower operation were determined.

Fig. 10. KS-2.1M mower (modified high-speed mower) in operation, mowing forbs

The agrotechnical assessment of the KS-2.1M mower was carried out when mowing vegetation on three backgrounds: mowing alfalfa, natural grasses and various grasses with reeds. The operating time for the entire test period was 200 hours, including mowing grass for 40 hours (26 ha) and imitation of the mower operation for 160 hours.

On all mowing backgrounds, the losses for the KC-2.1M mower (0.85 and 2 %) meet the agrotechnical requirements and the technical task (up to 2 %). The performance indicators of the mower were taken at the following speeds: when mowing natural grasses – 1.56...1.79 m/s; when mowing alfalfa – 1.56...1.92 m/s and when mowing mixed grasses with reeds – 1.6...2.17 m/s. In all the tested modes, the mower showed good cut quality and ~~a~~ uniformity.

6. Discussion of the results of research on the operation of a mower with an improved drive mechanism

Based on the results of the literature review, theoretical and experimental studies, the initial requirements for a mower with an improved drive are justified.

Employees of the laboratory of forage harvesting machines have developed a technical specification for the KS-2.1M mower.

The design department of the Scientific and Production Center of Agroengineering developed working drawings of the mower and experimental and prototype models of the mower were manufactured at the experimental and mechanical plant.

Laboratory and bench tests of the experimental model of the KS-2.1M mower were carried out in the laboratory workshop (Fig. 8, 9). The purpose of the bench tests was to determine the reliability and durability of the chain transmission of the mower drive at idle.

Laboratory and field studies of the experimental sample of the KS-2.1M mower with an improved drive and a cutting device with a double stroke were carried out in the economic conditions of OTBI LLP of the Talgar district of the Almaty region when mowing natural grasses, alfalfa, various grasses with reeds (Fig. 10). The height of the alfalfa plants was 62.0...67.0 cm, deadness – 40...50 %, grass moisture – 82.8 %, yield – 5.4 t/ha, the height of the plants of various grasses – 72.0...130 cm, deadness – 60...70 %, yield – 5.9 t/ha, grass moisture – 60.2 %.

The translational speed of the mower when mowing alfalfa was 1.56 m/s, when mowing various grasses – 1.6 m/s. The rotation speed of the eccentric shaft was 400...460 min^{-1}. In these modes, the mower provided a good cut quality and uniformity (Table 1).

With the set cutting height H=50 mm, the actual average height of cutting plants by the KS-2.1M cutting device with a double knife stroke was 55 mm (Fig. 2).

The operating time for the entire test period was 200 hours, including mowing grass for 40 hours (26 ha) and imitation of the mower operation for 160 hours. The performance indicators of the mower were taken at the following speeds: when mowing natural grasses – 1.56...1.79 m/s; when mowing alfalfa – 1.56 and 1.92 m/s and when mowing mixed grasses with reeds – 1.6...2.17 m/s. In all tested modes, the mower provides a good cut quality and ~~a~~ uniformity. The losses for the mower are 0.85...2 %, which meets the agrotechnical requirements and technical specifications.

When mowing alfalfa, the productivity per hour of the main time of the mower is 1.14 ha, and the grass is 0.92 ha (Table 1). The quality of the plant cut is good, the cutting height of plants is uniform.

According to the test results, a protocol of preliminary tests of the KS-2.1M mower prototype was issued, which gives a detailed description of the test sample and the technological process performed by the KS-2.1M mower; reflects the test conditions and agrotechnical indicators of the mower; provides operational, technological and energy assessment, indicators of reliability, safety and ergonomics of the mower design; economic indicators; indicators of the technical level; conclusions and suggestions.

During the initial examination of the KS-2.1M mower, no non-compliance with the requirements of the technical specification (TOR) was found.

The advantages of the mower design (KS-2.1M) are: the exclusion of a rigid connecting rod with wear-resistant connections from the design, such as «connecting rod-head of the eccentric finger» (Fig. 3); a decrease in the speed of the eccentric shaft by 1.5–2.0 times, which reduces inertial loads; the double stroke of the knife allows increasing the feed by 1.56 times, i.e. increase the machine speed (Table 1).

Therefore, the development and justification of the parameters of the drive of the cutting device of a mower with a double knife stroke is an urgent task.

This mower drive has no analogs in the world, so with a deep study of the work and proper funding, the drive mechanism can be used in machines with reciprocating motion and there are no restrictions in the research of this work.

The advantages of the machine design are:

– the exclusion of a rigid connecting rod with wear-resistant connections from the design, such as «connecting rod-head of the eccentric finger»;

– the double stroke of the knife allows increasing the feed by 1.5 times, i.e. increase the machine speed;

– the speed of the eccentric shaft decreased by 1.5 times, which reduces inertial loads.

The disadvantages of the machine design are:

1. The material of the eccentric pin does not provide adequate strength during operation and a fracture occurs at the attachment point to the eccentric. This disadvantage can be eliminated by replacing this material with the most durable (for example, knee metal, etc.).

2. Daily adjustment of the chain tension of the drive mechanism is required. To solve this problem, you can conduct experiments with various flexible materials (for example, a flexible cable or belt).

The testing laboratory of the Scientific and Production Center of Agroengineering recommends making a prototype for conducting acceptance tests, provided that the noted shortcomings are eliminated.

7. Conclusions

1. Increasing the productivity of the mower by increasing the crank shaft speed or the crank radius leads to an increase in inertial loads. Therefore, it is necessary to improve their drive mechanisms, allowing to increase the mower productivity without increasing inertial loads. The characteristics of the herbage that affect the mowing process were studied: the height of the alfalfa plants was 620...670 mm, deadness – 40...50 %; humidity – 82.8 %; yield – 5.4 t/ha; the height of the plants – 720...1300 mm; deadness – 60...70 %; humidity – 60.2 %; yield – 5.9 t/ha. Based on the condition of a high-quality cut of plants, with a minimum grass cutting speed V=2.15 m/s, the minimum crank shaft speed n=423 min^{-1} is determined. The feed areas and load areas of the cutting device for normal cutting with a double knife stroke are determined. A diagram of the bending of the stems and the height of the stubble when mowing with a normal cutting device with a double knife stroke is compiled.

2. By the method of vector contours, analytical equations are obtained for determining the analogs of knife movement, speed and acceleration of movement with a single and double stroke. The structural and technological scheme of the drive mechanism of the cutting device of the segment-finger type mower is developed, in which there is no rigid connecting rod and the double stroke of the knife of the cutting device is provided.

3. Analytical dependences for determining the movement and stroke of the knife are obtained and as a result of kinematic analysis, the main geometric parameters of the mechanism are justified: crank radius r=42.3 mm; roller radius R=42.8 mm; distance from the crank shaft axis to the point A of fixing the flexible link horizontally a=200 mm; distance from the crank shaft axis to the roller axis horizontally b=150 mm; distance from the point of fixing A of the flexible link to the crank axis vertically h_1=159 mm; distance from the roller center to the vertical axis of crank shaft rotation h_2=150 mm. Analytical dependencies have been developed to determine the power required to drive the cutting device of a mower with a double knife stroke. The power required to drive the working bodies of the mower at idle is 0.8...1.22 kW, and when mowing grass – 1.9...2.8 kW. Based on the results of theoretical and experimental studies, the main parameters of the mower with an improved drive are justified: grip width is 2.1 m; knife stroke – 152.4 mm; step between the fingers – 76.2 mm; crank shaft speed – 423...460 min^{-1}; working speed – up to 9 km/h. The productivity of the mower per hour of the main time is 0.92...1.6 hectares.

4. A method for calculating the parameters of a mower with a segment-finger cutting device with a single and double knife stroke has been developed. It is established that in a cutting device with a double knife stroke, the crank speed can be reduced by at least 2 times, therefore, the knife inertia forces are reduced by 2 times, due to an increase in the feed, the machine speed increases by 1.6 times.

5. In the Scientific and Production Center of Agroengineering LLP, an experimental sample was made and preliminary tests of the KS-2.1 mower were carried out, its compliance with the technical task and efficiency were confirmed, agrotechnical and energy indicators of the mower were determined. The operating time for the entire test period was 200 hours, including mowing grass for 40 hours (26 ha) and imitation of the mower operation for 160 hours. The performance indicators of the mower were taken at the following speeds: when mowing natural grasses – 1.56...1.79 m/s; when mowing alfalfa – 1.56 and 1.92 m/s and when mowing mixed grasses with reeds – 1.6...2.17 m/s. In all tested modes, the mower provides a good cut quality and uniformity. The losses for the mower are 0.85...2 %, which meets the agrotechnical requirements and technical specifications. According to the results of preliminary tests of the experimental sample, it is recommended to produce a prototype of the KS-2.1 mower for submission to acceptance tests.

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