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IMPACT OF CUTTING UNITS' DESIGN ON BIOMASS CUTTING RESISTANCE

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Abstract: The paper presents mathematical models describing the moments of resistance to cutting on the cutting drum shafts in the biomass cutting process. The mathematical procedures described in the paper have been verified on a test stand developed and constructed by the authors, which reflects real conditions of the process of cutting plant material into pieces of specified lengths. Experimental verification proved that the developed mathematical models are adequate for drums of both cylindrical and conical constructions. The value of the average error did not exceed 13%. Following the mathematical elaboration and verification studies, the authors carried out calculations for machines currently available on the market that are equipped with drum cutting units. The calculations were carried out for the most commonly cut material, i.e. for maize, straw and green plant materials. The obtained results confirm the complexity of the problem arising from a wide range of numerical values of cutting resistance, which is contained in the range of 400–1,800 nm. The compiled database can be practically applied in the selection of machines for specific field works, and the mathematical models developed and verified in the study can be applied at the stage of designing new designs of cutting drums used in forage harvesters.

Key words: biomass cutting, drum cutting unit, plant material, mathematical modelling, cutting of fibrous materials

1. INTRODUCTION

The drum cutting unit is one of the basic work units of a forage harvester. Its purpose is to cut the plant material into pieces of specific lengths called chaff. The most common design, the so-called open drum, consists of a shaft on which discs with holes are mounted. Knives are screwed to the discs by means of tool posts. Depending on the construction of the drum, the knives may be straight or bent along a screw line. In addition, a distinction is made between solid and split knives. The cutting drum is supported on the side plates of the machine and makes a rotating movement that causes the knives to move. The moving knives cut the material layer into pieces at the contact line between the knife and the counter-cutting edge. The material is fed to the cutting line from the space of rotating intake and compression rollers, where the biomass is pre-formed and compressed.

The characteristics of the construction and functioning of the drum cutting unit result, among other things, from the fact, that the cutting process performed by it concerns biomass, i.e. plant materials whose structures are not homogeneous, and the physical and mechanical properties are not fully identified [1-7]. Due to the punctuality of the research conducted so far, it is not possible to unambiguously determine the features and design parameters of the drum cutting unit that have a decisive influence on the cutting efficiency and the load on the working unit.

The results obtained from these experimental studies are valuable for the purposes of designing new constructions of chopper cutting units. However, in order to accelerate and optimise the design stage of the mentioned working units, it is necessary to have a verified and adequate mathematical model describing the biomass layer cutting process [8-14].

In view of this, the authors of this paper have developed mathematical models of the moment of resistance to cutting on the shaft of a cutting drum of cylindrical and conical structure. Further, they carried out experimental verification of the developed models. The models developed have been formulated taking into consideration important features and design parameters of cutting drums and characteristic properties of the material being cut.

2. MATHEMATICAL MODEL OF CUTTING MOMENT

Figs.1 and 2 show photographs and diagrams of the analysed cutting drums. Based on observation and the analysis of the actual process of cutting a material layer with the use of a cutting drum knife of cylindrical type, the system of forces acting on the material layer and the reaction of the layer on the knife were determined (Fig. 3) [15].

By analysing the system of forces occurring in the process of cutting with a cylindrical drum (Fig. 3), it can be stated that the task of the peripheral force P is to overcome the resultant resistance to cutting P_c, equal in value to the reaction R, which consists of the normal force N and the friction force T, resulting from the interaction of the material with the knife. The normal force N depends on the unit cutting resistance p_c and the active length of the knife, which is expressed as

$$N = p_c \, \Delta l \quad (1)$$

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However, the friction force T depends on the friction angle φ and is represented as

$$T = N\, tg\varphi \tag{2}$$

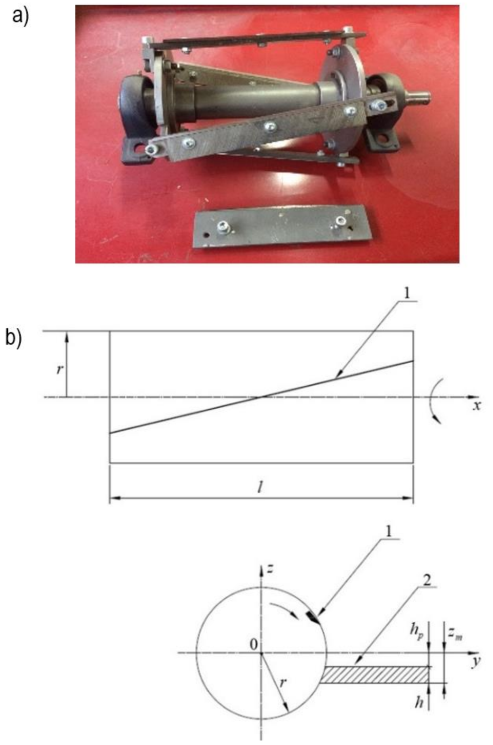

Fig. 1. Drum cutting unit of cylindrical type with straight knives. a) actual view of the drum being at the test stand equipment; and b, graphic diagram. 1 - cutting knife, 2 - the layer of material to be cut

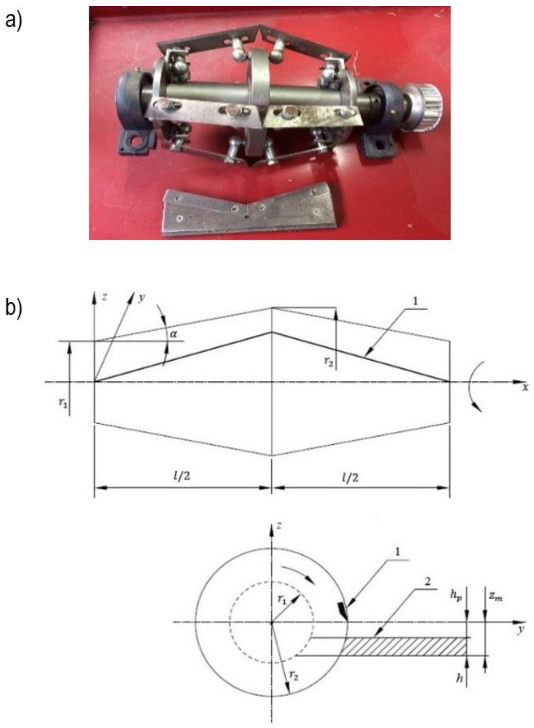

Fig. 2. Diagram of the drum cutting unit of conical type. a) actual view of the drum being at the test stand equipment; and b) graphic diagram. 1 - cutting knife, 2 - the layer of material to be cut

Therefore, the cutting resistance P_c, which is the resultant of the normal force N and the friction force T, is expressed as

$$P_c = \frac{p_c \Delta l}{cos\varphi} \tag{3}$$

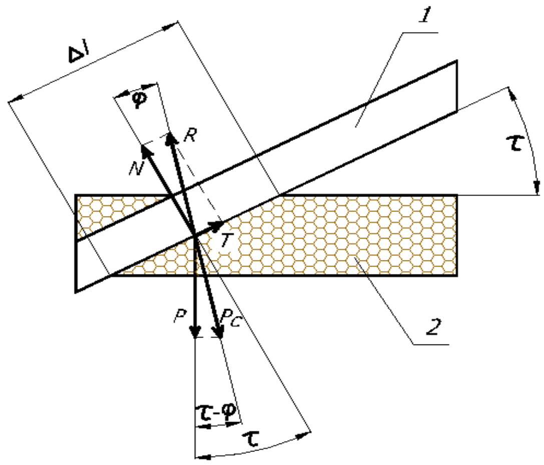

Fig. 3. The arrangement of forces occurring during the cutting of the biomass layer by the knife of a cylindrical type cutting drum. 1 - cutting knife, 2 - the layer of material

The circumferential force P is the vertical component of the cutting resistance P_c and is represented by the dependence

$$P = P_c \cos(\tau - \varphi) = \frac{p_c \Delta l}{cos\varphi} cos(\tau - \varphi) \tag{4}$$

From the trigonometric dependence, we obtain

$$cos(\tau - \varphi) = cos\tau\, cos\varphi(1 + tg\tau\, tg\varphi) \tag{5}$$

After considering that $tg\,\tau = \mu$, where μ is the coefficient of friction of the knife against the layer of the plant material to be cut, we obtain the equation for the circumferential force P:

$$P = \frac{p_c \Delta l}{cos\varphi} cos\tau\, cos\varphi(1 + \mu tg\tau) = p_c \Delta l cos\tau(1 + \mu tg\tau) \tag{6}$$

The cutting moment M_c is the product of the force P acting on the circumference of the drum and the radius of the drum r, on which the knives are mounted. Therefore, we have:

$$M_c = P\, r \tag{7}$$

Taking into account the dependencies in Eqs (6) and (7), the cutting moment equation M_c takes the form

$$M_c = p_c \Delta l r cos\tau(1 + \mu tg\tau) \tag{8}$$

Assuming that the expression $p_c\, r\, cos\tau\, (1 + \mu tg\tau)$ takes a constant value of C at the time of cutting, the moment M_c will be represented by the equation

$$M_c = C\, \Delta l \tag{9}$$

where C is a constant value and Δl is the active length of the knife.

Assuming that the number of knife lines of the cutting drum is z, with only one knife line crossing the layer each time, the equation for the mean moment $\overline{M}_c$, acting on the shaft of the cutting drum, is obtained as

$$\overline{M}_c = \frac{L_n\, z}{2\pi} \tag{10}$$

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where L_n is the work done by the chopper knife during one pass through a layer of plant material and z is the number of knife lines of the chopping drum.

However, operation L_n is expressed by the equation

$$L_n = \int_{\psi_p}^{\psi_k} M_c(\psi)d\psi \tag{11}$$

where $M_c(\psi)$ is cutting resistance moment dependent on the angle of rotation of the knife, ψ_p is angle of start of cut and ψ_k is angle of end of cut.

The following parameters were adopted as design features of the cutting unit: h – height of cut layer and b – width of cut layer.

The integral calculated over the angle $d\psi$ is replaced by the integral calculated over the arc length $dx = r\, d\psi$, where r is the drum radius. Then the work done by a single knife line during its passage through the biomass layer will be described by the equation

$$L_n = \frac{1}{r}\int_{\psi_p}^{\psi_k} M_c(\psi)rd\psi = \frac{1}{r}\int_{0}^{x_k} M_c(x)dx \tag{12}$$

When analysing the cutting of a rectangular layer of material, the process was divided into three phases under the following assumptions:
- each time the material layer is cut by only one line of knives;
- the height of the layer of material to be cut is equal to the path taken by a given point of the knife through this layer.

PHASE I: Penetration of the knife into the layer (the active length of the knife Δl increases)

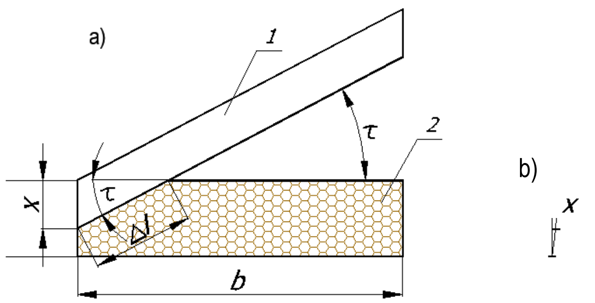

Fig. 4. Penetration of the knife into the layer (phase I). a, cross-section through the layer; b, comparison of the length of the arc drawn by the knife *x* and the height of the layer *h:* 1 - cutting knife and 2 - the layer of material

According to Fig. 4b, the difference between the length of the arc drawn by any point of the knife from the top to the bottom edge of the cut layer is approximately equal to the layer height *h*, which follows from the fact that we assume $h \approx h\frac{\psi}{\sin\psi}$ for small angles, because $sin\psi \approx \psi$.

By using the trigonometric dependence $\frac{x}{\Delta l} = sin\tau$, we get

$$\Delta l = \frac{x}{\sin\tau} \tag{13}$$

For $x = h$ the Eq. (13) takes the form: $\Delta l = \frac{h}{\sin\tau}$.

The cutting work L_{nI} in the phase I of the knife movement can be represented by the dependence:

$$L_{nI} = \frac{1}{r}\int_{0}^{h} M_c(x)dx \tag{14}$$

where $M_c(x)$ is the cutting moment dependent on knife position.

By substituting the Eq. (13) into the Eq. (9), we obtain

$$M_c = C\frac{x}{\sin\tau} \tag{15}$$

On the other hand, after substituting Eq. (15) into Eq. (14), the work of cutting in the interval $0 \le x \le h$ is described by the dependence:

$$L_{nI} = \frac{C}{r}\int_{0}^{h}\frac{x}{\sin\tau}dx = \frac{C}{r}\left[\frac{x^2}{2\sin\tau}\right]_{0}^{h} = \frac{C}{r}\frac{h^2}{2\sin\tau} \tag{16}$$

PHASE II: Cutting through the layer (the active length of the knife Δl remains constant)

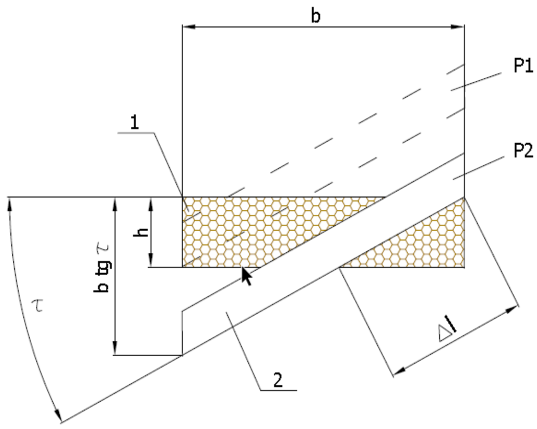

Fig. 5. Cutting through a layer (phase II).1 - the layer of material, 2 - cutting knife, P1 - initial position of the knife, P2 - final position of the knife

According to Fig. 5, the cutting in the second phase takes place in the interval $h \le x \le b\,tg\tau$. In the interval $h \le x \le b\,tg\tau$, the value Δl is invariant and is expressed by the equation $\Delta l = \frac{h}{\sin\tau}$. Therefore, the cutting work is described by the dependence

$$L_{nII} = \frac{C}{r}\int_{h}^{b\,tg\tau}\frac{h}{\sin\tau}dx = \frac{C}{r}\frac{h}{\sin\tau}(b\,tg\tau - h) \tag{17}$$

PHASE III: Withdrawal of the knife from the layer (the active length of the knife Δl decreases).

According to Fig. 6, the cutting in phase III takes place in a range $b\,tg\tau \le x \le h + b\,tg\tau$ i.e. over the same length as in phase I.

In the range $b\,tg\tau \le x \le h + b\,tg\tau$, the value of $\Delta l = \dfrac{x - b\,tg\tau}{\sin\tau}$.

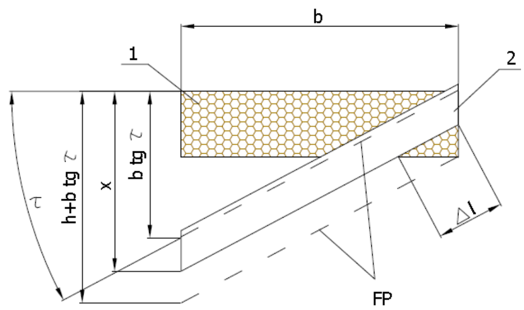

Fig. 6. Coming out of the knife from the layer (phase III). 1 - the layer of material, 2 - knife of the cutting drum, FP - extreme position of the cutting edge

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Therefore, the cutting work in phase III is described by the dependence

$$L_{nIII} = \frac{C}{r}\int_{b\,tg\tau}^{h+b\,tg\tau}\frac{(x-b\,tg\tau)}{\sin\tau}\,dx = L_{nI} = \frac{C}{r}\frac{h^2}{2\sin\tau} \tag{18}$$

Therefore, the overall work done by the knife during one passage through the layer of cut material will be expressed by the following equation:

$$L_n = L_{nI} + L_{nII} + L_{nIII}$$

$$L_n = \frac{C}{r}\left(\frac{h^2}{2\sin\tau} + \frac{hb\,tg\tau}{\sin\tau} - \frac{h^2}{\sin\tau} + \frac{h^2}{2\sin\tau}\right) = \frac{C}{r}\frac{hb}{\cos\tau} \tag{19}$$

After substituting into Eq. (10) the expressions for L_n and C, we obtain, in conclusion, Eq. (20) for the mean moment of resistance to cutting on the drum shaft, which is given as

$$\overline{M}_c = \frac{p_c(1+\mu tg\tau)b\,h\,z}{2\pi} \tag{20}$$

Eq. (20) describes the average moment of resistance to cutting for a drum of cylindrical type. However, for a conical drum, according to Fig. 7, the material layer is not cut along the length b and height h but along the length $2a$ and height h. However, it follows from the geometrical analysis that we have

$$2a = \frac{b}{\cos\alpha} \tag{21}$$

where α is the cutting angle of the material layer in the case of a cutting drum of the conical type what is shown in Fig. 8..

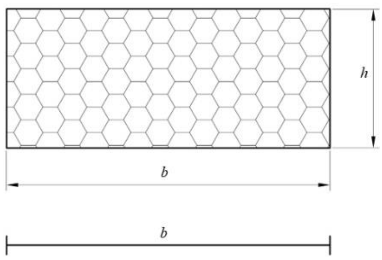

Fig. 7. Cross-section of a cut material layer using a cutting drum of cylindrical type

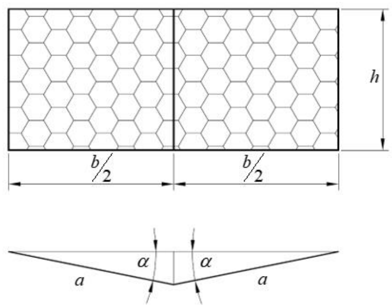

Fig. 8. Cross-section of a material layer being cut by a cutting drum of the conical type

Therefore, for a cutting drum of the conical type, the equation for the mean moment of resistance to cutting on the shaft assumes the following form:

$$\overline{M}_c = \frac{p_c(1+\mu tg\tau)\frac{b}{\cos\alpha}h\,z}{2\pi} \tag{22}$$

3. METHODOLOGY FOR EXPERIMENTAL STUDIES

In order to verify the mathematical models developed, a test stand was designed and constructed to test the biomass layer cutting process. The test stand allows the process of cutting a layer of material to be carried out with the use of cutting drums of cylindrical and conical construction. A schematic representation of the test stand construction is shown in Fig. 9.

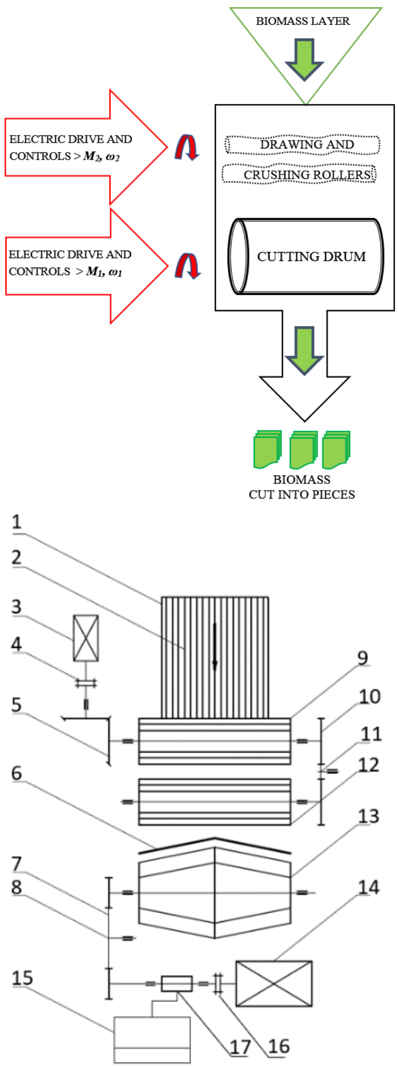

Fig. 9. Scheme of the test stand construction. 1 - trough of chaff cutter, 2 - material to be cut (biomass layer), 3 - electric motor, 4 - coupling, 5 - angular gearbox, 6 - cutting counter edge, 7 - belt transmission, 8 - tension roller, 9 - upper drawing-crushing roller, 10 - belt transmission, 11 - tensioning roller, 12 - lower drawing - crushing roller, 13 - cutting drum, 14 - electric motor, 15 - computer (recorder of measuring system), 16 - clutch, 17 - measuring system for moment and rotational speed on the drum shaft

Fig. 10 presents an example of the construction of a cutting drum of the conical type mounted in a chaff cutter. Therefore, the constructional form of the test stand, according to the assumptions of the authors of this paper, allows for experimental research on the process of cutting a layer of material with a cylindrical drum – cross cutting of a layer of material $(\alpha = 0^o)$ and with a conical drum – cutting a layer of material at an angle $(\alpha = 20^o)$.

Fig. 10. Mounted design of the cutting drum of the conical type in the chaff cutter

For the measurement of torque and revolutions on the cutting drum shaft during its idling and working runs, a torque meter with a tachometer type MT200Nm was used, which was directly coupled to a two-channel meter MW2006-3. During the tests, a computer system with a data recording program and the author's calculation program RB01 were used. It was assumed that the cutting speed of the knife would be 3.00 m · s–1. The aforementioned cutting speed ensures proper cutting of the material layer and corresponds to the actual value of the cutting speed in the known designs of chaff cutters. The cutting speed v_c is the resultant speed of the peripheral speed of the cutting blade v_b and the feed speed of the crop v_m intake and compression rollers. The dependence between these speeds is described by the following equation:

$$v_c = \sqrt{v_m^2 + v_b^2 + 2v_m v_b cos\varphi} \qquad (23)$$

where φ is the angle contained between the speed vectors $v_m$and v_b.

For a cutting drum of the conical type, the cutting speed was determined at the midpoint of the cutting edge of the knives. The degree of compaction of the material was assumed as the ratio of the height of the layer of plant material after compaction h to the height of the material before compaction h_o. In the course of the tests, the degree of material compaction $h \cdot h_o^{-1} = 0.5$ was used. The value of the degree of material compaction adopted in the test programme corresponds to the values recommended in the professional literature [16].

The experimental tests were conducted for the width of the cut layer $b = 0.25m$ and the height h=0,012; 0,016; 0,020; 0,024; 0,028; 0,032 i 0,036 m.

In order to experimentally determine the cutting resistance on the shaft of the cutting drum, a layer of rye straw was cut, from which test samples were prepared. During the experimental tests, the ears were cut and the individual stalks tied together to form so-called sheaves with an average length of l=855 mm. Each sample was then weighed using an electronic balance (ELDOM, model EK3130) with an accuracy of 2 g. The estimated number of stalks per sample was 280. In addition, the diameter of the stalks was measured with an electronic slide calliper with an accuracy of up to 0.01 mm. The diameter of the stalks ranged from 2.5 mm to 6.3 mm. The plant material was stored in a dry room before testing and the humidity on the day of testing was 12%. Moisture content of the material was determined based on randomly selected samples using the dryer method. The prepared samples, in the form of sheaves, were placed in the feeding chute of the test stand, the bindings were cut and the cutting was carried out. The degree of material compaction $h \cdot h_o^{-1}$ was determined based on measurement of layer height before and after compaction. Implementation of the plant material compaction was carried out by means of sets of pulling and compacting rollers and pressure elements that maintain a constant value of the material compaction level $h \cdot h_o^{-1}$ while moving the material towards the cutting drum (Figs. 9 and 10). The desired values of plant material v_m feeding were obtained by a proper selection of the rotational speed of the lower roller. The rotational speed of the roller was accurately measured on its shaft using an LCD contact tachometer. At the stage of determining the value v_m, the slippage of plant material in relation to the surface of pulling and crushing rollers was taken into consideration. The slip value was assumed as 10%, which was confirmed by experimental tests.

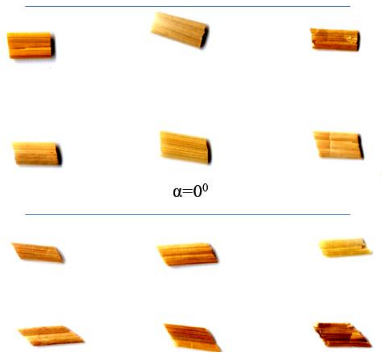

Fig. 11. Exemplary chopped pieces for cutting angles. α = 20° (two upper rows); α = 20° (two lower rows)

4. VERIFICATION OF MATHEMATICAL MODELS

In order to verify the mathematical models developed in Section 2 of this work, the results obtained from calculations of the models were compared with the results of experimental tests. The comparison was carried out individually for the moments of resistance to cutting $\overline{M}_c$, with the same systems of independent variables.

During the calculations carried out on the models developed, the unit resistance of straw cutting$p_c = 8.5 \cdot 10^3 Nm^{-1}$ was assumed. However, the coefficient of friction of the knife against the cut material layer $\mu = 0.7$ was assumed in the calculations.

In mathematical statistics there are no unambiguously described methods of comparing the results of experimental tests with the results obtained from mathematical models derived a priori. Therefore, the criterion of adequacy of the mathematical model to the results of experimental tests was assumed to be the value λ, which is the ratio of the value obtained from the tests $\overline{M}_{cE}$ to the value obtained from the model $\overline{M}_{cM}$:

$$\lambda = \frac{\overline{M}_{cE}}{\overline{M}_{cM}} \qquad (24)$$

Furthermore, the average calculation error $\overline{\lambda}$ was calculated at the stage of comparing the results. A synthetic summary of the compared values of the cutting resistance moment on the shaft for the cylindrical and conical drum types is presented in Tables 1 and 2, respectively.

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Based on the comparison results, it can be confirmed that there exists a good conformity of the trend of the changes of the cutting resistance moment determined from the model and the experimental tests for the cutting drum of cylindrical and conical types. The average values of $\overline{\lambda}$ amount to 1.12 and 1.13, respectively, with the experimental test results, which clearly indicates that the developed models of the cutting resistance moment on the drum shaft give lower cutting resistance values by about 12%–13% from the simulation calculations. This may indicate that during the experimental tests a higher unit cutting resistance p_c of the rye straw layer occurred than that reported in the literature [17].

The authors of the study were not able to directly compare the results of their studies with the ones presented in the literature by other researchers. This is because the results of the studies presented in this article mainly concern a new design on the drum cutting assembly, which is covered by legal protection. In the specialised literature, there are no data that would describe the process of cutting rye straw into chopped straw with the use of a chaff cutter drum of the double truncated cone shape. The first proposal of the cutting drum's design of that shape, which realised diagonal cutting in both directions, has been presented by Bochat [15]. Other studies presented only the data connected with the commonly functioning design constructions of cutting drums realising lateral cutting. The results presented in the present study concerning the classic design of the drum cutting assembly are comparable with the data presented in the literature from within that scope [3,12,13,19,20].

The authors also carried out simulation calculations for the developed mathematical model, which showed good conformity with the trend of changes in cutting resistance moment, for real designs of drum cutting units found in leading manufacturers of chaff cutters. Structural solutions and parameters of cutting units of chaff cutters of the following manufacturers were analysed: John Deere, Fendt, Krone, New Holland, Claas and Rostselmash. The results of the analysis are presented in Table 2.

Tab. 1. Summary of the compared values of the cutting resistance moments on the shaft $\overline{M}_{cM}$ and $\overline{M}_{cE}$ for the cutting drum of cylindrical type $(\alpha = 0^o)$ and conical type $(\alpha = 20^o)$

	No.	$\alpha[...^o]$	$h[m]$	$\overline{M}_{cM}[Nm]$	$\overline{M}_{cE}[Nm]$	λ	$\overline{\lambda}$
$z = 4; \mu = 0.7;$ $\tau = 20^o; b = 0.25m;$ $h \cdot h_o^{-1} = 0.5$	1	0	0.012	20.33	22.56	1.11	1.12
	2		0.016	27.11	29.34	1.11	
	3		0.020	33.89	38.12	1.12	
	4		0.024	40.67	45.82	1.13	
	5		0.028	47.45	53.78	1.13	
	6		0.032	54.23	61.32	1.13	
	7		0.036	61.01	69.21	1.13	
	8	20	0.012	21.96	24.63	1.12	1.13
	9		0.016	29.28	32.98	1.13	
	10		0.020	36.60	41.20	1.13	
	11		0.024	43.92	49.03	1.12	
	12		0.028	51.24	58.33	1.14	
	13		0.032	58.56	67.68	1.14	
	14		0.036	65.88	75.12	1.14	

Tab. 2. Summary of design parameters of actual cutting units

	John Deere	Fendt	Krone	New Holand	Rostselmash
Drum diameter [mm]	670	720	660	630, 700	630
Drum width [mm]	670, 850	800	630, 800	750, 880	703
Number of cutting knife sections [pcs.]	10, 12, 14, 16	10, 14, 20	10, 14, 18, 20	10, 12, 14, 18, 20	12

For the simulation calculations, the material most frequently cut in this type of machines was adopted, i.e. for straw of cereals, maize and green fodder. Following Dmitrewski, the following unit values of energy consumption were assumed: straw, $p_c = 8.5 \cdot 10^3 Nm^{-1}$; maize, $p_c = 16 \cdot 10^3 Nm^{-1}$; and green fodder, $p_c = 6 \cdot 10^3 Nm^{-1}$.

The results obtained were illustrated in the form of graphs. Fig. 12 shows the cutting moment as a function of the cutting drum width for three types of material: green forage, straw and maize.

On the other hand, Fig. 13 shows the plot of cutting moment as a function of the number of knife lines used to cut the biomass into pieces of a given length and as a function of the drum width.

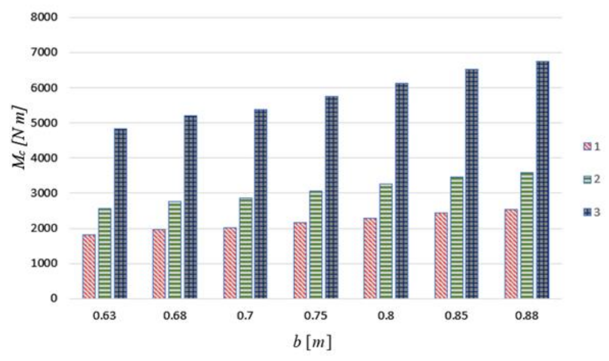

Fig. 12. Cutting moment as a function of drum width for three types of material. 1 - green material, 2 - straw, 3 - maize

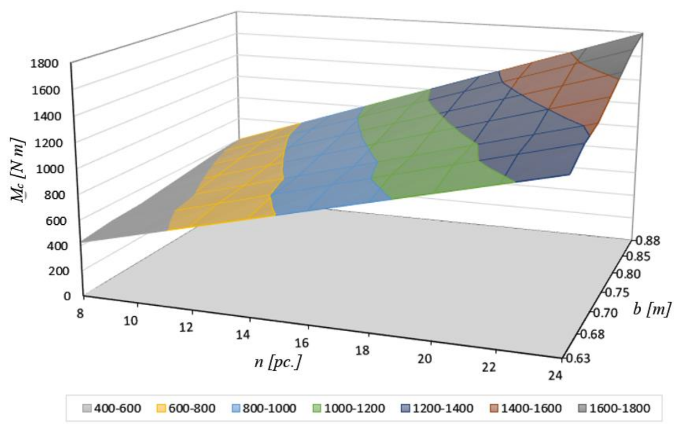

Fig. 13. Cutting moment M_c as function of the drum width b and the number of knife lines on the circumference of the drum for straw type material

5. CONCLUSION

The developed mathematical models, representing the average moment of resistance to cutting a layer of material on the rolls of cutting drums of cylindrical and conical types, can be considered adequate.

Adequate mathematical models of mean cutting resistance moment are of significant importance to speed up the design process of new cutting drum designs of this type.

The developed mathematical models can be applied with the use of computer simulation in the research of the cutting process of the plant material layer and in the optimisation of the design of cutting drums.

The development of mathematical models of the moment of resistance to cutting on the cutting drum shaft is significant due to the seasonality of work in agriculture, which means that, despite sometimes many years of experimental research, it might not be possible to generate a corpus of information sufficient for the rapid design of such working units.

The developed database of cutting resistance moment results for actual design solutions of drum cutting units gives the possibility to assess energy efficiency in terms of selection of the cutting drum design for the type of material to be cut.

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