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Numerical simulation of the liquid distribution problem by an adaptive flow distributor

***Abstract**. The article presents a numerical modeling of the adaptive flow divider, which allows you to adjust the supply of the U-shaped frame according to the change in load acting on the mechanism for cutting and unloading the stem feed. The use of adaptive flow divider in the hydraulic drive system of the mechanism for cutting and unloading allows to stabilize energy consumption for separation of a portion of stem feed under the condition of change and fluctuation of parameters that significantly affect the process of separation and unloading of stem feed from monolith. On the basis of the carried out numerical modeling recommendations on a choice of constructive parameters of an adaptive flow divider are given.*

***Streszczenie.** W artykule przedstawiono modelowanie numeryczne adaptacyjnego dzielnika przepływu, który umożliwia regulację zasilania ramy w kształcie litery U w zależności od zmiany obciążenia działającego na mechanizm cięcia i odciążania posuwu łodygi. Zastosowanie adaptacyjnego rozdzielacza przepływu w hydraulicznym układzie napędowym mechanizmu cięcia i rozładunku pozwala ustabilizować zużycie energii na oddzielenie porcji podawczej łodygi pod warunkiem zmiany i wahań parametrów, które istotnie wpływają na proces rozdzielania i rozładunku pasza z łodygi z monolitu. Na podstawie przeprowadzonego modelowania numerycznego podano zalecenia dotyczące doboru parametrów konstrukcyjnych adaptacyjnego dzielnika przepływu. (**Symulacja numeryczna problemu dystrybucji cieczy z wykorzystaniemadaptacyjnego dystrybutora przepływu**)*

Keywords: mechanism for cutting stalk fodder, hydraulic drive, mathematical model, transients, flow divider, energy consumption.
Słowa kluczowe: mechanizm rozdrabniania paszy z łodyg, napęd hydrauliczny, model matematyczny, stany nieustalone.

Introduction

Today, in the context of the global economic and food crisis, the issue of agricultural production is one of the priorities [1, 2]. To achieve positive dynamics in the development of this industry, it is necessary to provide farms with energy efficient, mobile equipment that would automate the process of loading and unloading stalk fodder from trench storage, thereby saving time and money [3, 4].

Analysis of literary sources and problem statement

In the system of machines recommended for unloading stalk fodder from trench storage facilities, block-batch separators based on frontal (wheel) loaders have become widespread [5, 6, 7]. However, the recommended modes of operation of block-batch stalk feed separators provide fixed values of cutting speed and feed rate, in fact, without anticipating a possible significant increase in cutting forces when internodes of corn and other inclusions of high hardness fall under the knife. Therefore, total the power of the drive of the cutting mechanism and the drive of the U–shaped frame are increased [8]. Their total capacity in the machines produced by leading European companies is from 20 to 25 kW [9].

This fact of significant excess of the drive power of the separator of the block portion of stalk fodder over the theoretically and experimentally confirmed values of the required drive power indicates the need to improve the hydraulic drive system of the separator [9, 10]. The direction of improvement should include coordination of regulation of cutting speed and feed rate in order to stabilize the total power of these drives, which will provide a significant energy-saving effect [11].

Therefore, the development of a new generation of energy-efficient hydraulic drives based on hydraulic units with an adaptive control system which significantly increase the accuracy and efficiency of such machines is timely and important for the development of mechanical engineering.

Purpose and tasks of research

The purpose of the research is to increase the accuracy of the mechanism for cutting and unloading stalk fodder, reducing unproductive power losses and dynamic loads in the hydraulic drive of the mechanism for cutting and separation by creating a scientific basis for their development based on nonlinear mathematical models and adaptive hydraulic drive system.

To achieve this goal, it is necessary to study the transients in the adaptive system of hydraulic drives of the mechanism for cutting and unloading stem fodder depending on the parameters of the spool flow divider.

Materials and methods

To reduce the energy consumption of the hydraulic drive system for cutting and unloading stalk fodder, Vinnytsia National Agrarian University has developed a new structure and principle of building a hydraulic drive system (Fig. 1) which allows to significantly reduce the power of drive hydraulic motors by adapting their modes to the technological system [12, 13].

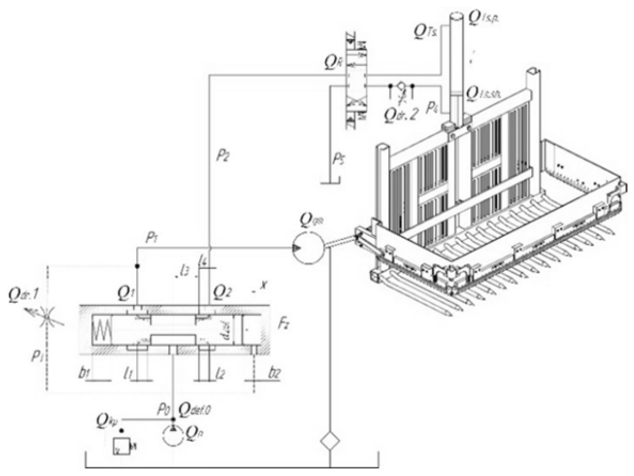

Fig.1. Calculation scheme of the hydraulic drive of the mechanism for cutting and unloading of stalk fodder

The adaptive system of hydraulic drives of the mechanism for cutting and unloading of stalk fodder provides regulation of speed of cutting and feed rate of the U–shaped frame. The result of this coordination of the speeds of the hydraulic drives of this system is to ensure constant total power of the drives when changing the conditions of separation of the feed unit from the monolith [13, 14].

A numerical experiment based on the mathematical model [15] was performed applying the software package "Mathcad 15.0", Microsoft Excel 2020.

Theoretical analysis of the processes that determine the characteristics and the quality of the block-portion separator hydraulic drives system was carried applying the mathematical modelling methods; using the fundamental laws of hydraulics, hydromechanics and theoretical mechanics with the use of differential calculus.

Research results

According to the calculation scheme of hydraulic drive systems (Fig. 1), in which is used an adaptive flow divider, a mathematical model that describes the working processes in the hydraulic drive was obtained [14].

The mathematical model of the hydraulic drive of the mechanism for cutting and unloading of a stem forage includes the equation of continuity of streams [5], and also the equation of the forces operating on control elements of the drive. The mathematical model represents a system of differential equations of the eleventh order, and also takes into account a number of nonlinear characteristics of the elements of the hydraulic drive system. For calculations and mathematical modeling of processes, research of dynamic characteristics of the system was used MathCad software product [16].

Implementation of a computational experiment using a system of differential equations [17, 18] in the environment of the software product Mathsad involves the transformation of this system of differential equations by recording equations in the form of Cauchy [15], developing an algorithm for solving a system of differential equations, and forming a sequence of power actions mechanism for separation and unloading of stem fodder, which adequately meet the operating conditions of the hydraulic drive system under consideration.

The system of differential equations [15] in the form of Cauchy has the following form.

(1) $$\frac{dp_0}{dt} = \frac{Q_n - Q_1 - Q_2 - Q_{k.p.} - Q_{ut.}}{K \cdot W_0}$$

(2) $$\frac{dp_1}{dt} = \frac{Q_1 - Q_M - Q_{dr1} - Q_{ym1} - Q_{per1}}{K \cdot W_1}$$

(3) $$\frac{dp_3}{dt} = \frac{Q_{dr1} - Q_{zol} + Q_{per2,3,}}{K \cdot W_3}$$

(4) $$\frac{dp_2}{dt} = \frac{Q_2 - Q_{ts.} - Q_{per.ts.} - Q_{vit.ts}}{K \cdot W_2}$$

(5) $$\frac{dp_4}{dt} = \frac{Q_{ts.s} + Q_{per,ts} - Q_{dr.2.} - Q_{vit.s}}{K \cdot W_4}$$

(6) $$\frac{d\vartheta_x}{dt} = \frac{F_З - F_{пр} - \beta \cdot \vartheta_x - (2 \cdot c_{gdi} \cdot x - K_{uнi} \cdot \vartheta_x, i = 1,2}{m_3}$$

(7) $$\frac{d\vartheta_x}{dt} = \vartheta_x$$

(8) $$\frac{d\vartheta_y}{dt} = \frac{F_{gts} - G_{pr} - \beta_{gts} \cdot \vartheta_y}{m_{pr}}$$

(9) $$\frac{d\vartheta_y}{dt} = \vartheta_y$$

(10) $$\left|\frac{dp_0}{dt} = \frac{Q_n - \mu \cdot f_1 \cdot \sqrt{\frac{2}{\rho}} \cdot \sqrt{|p_0 - p_1|} \cdot sign(p_0 - p_1) + \mu \cdot f_2 \cdot \sqrt{\frac{2}{\rho}} \cdot \sqrt{|p_0 - p_2|} \cdot sign(p_0 - p_2)}{K \cdot W_0} - \frac{\left| \begin{matrix} \mu \cdot f_{kl} \cdot \sqrt{\frac{2}{\rho}} \cdot \sqrt{|p_0|} \to p_0 \succ p_{n.kl} \\ 0 \to p_0 \le p_{n.kl} \end{matrix} \right. - Q_{ut.}}{K \cdot W_0}\right.$$

(11) $$\left|\frac{dp_1}{dt} = \frac{Q_1 - q_m \cdot \omega_{gm} - \mu \cdot f_{dr1} \cdot \sqrt{\frac{2}{\rho}} \cdot \sqrt{|p_1 - p_3|} \cdot sign(p_1 - p_3)}{K \cdot W_1} - \frac{\sigma_1 \cdot p_1 - \sigma_{1,2} \cdot (p_1 - p_{sl})}{K \cdot W_1}\right.$$

(12) $$\left|\frac{dp_3}{dt} = \frac{Q_{dr1} - S_{zol} \cdot \frac{dx}{dt} + \sigma_{2,3} \cdot (p_2 - p_3)}{K \cdot W_3}\right.$$

(13) $$\left|\frac{dp_2}{dt} = \frac{Q_2 - S_{p1} \cdot \frac{dy}{dt} - \sigma_{per.ts} \cdot (p_2 - p_4) - \sigma_{ts} \cdot p_2}{K \cdot W_2}\right.$$

(14) $$\left|\frac{dp_4}{dt} = \frac{S_{p2} \cdot \frac{dy}{dt} + Q_{per.ts} - \mu \cdot f_{dr2} \cdot \sqrt{\frac{2}{\rho}} \cdot \sqrt{|p_4 - p_5|} \cdot sign(p_4 - p_5) - \sigma_ш \cdot p_4}{K \cdot W_4}\right.$$

(15) $$\left|\frac{dx}{dt} = \vartheta_x\right.$$

(16) $$\left|\frac{d\phi_m}{dt} = \frac{q_m \cdot p_2 - M_{gm} - \beta_{tr} \cdot \phi_m}{I_{pr}}\right.$$

(17) $$\left|\frac{d\phi_m}{dt} = \phi_m\right.$$

(18) $$\left|\frac{d\vartheta_y}{dt} = \frac{S_{p1} \cdot p_2 - S_{p3} \cdot p_2 - G_{pr} - \beta_{gts} \cdot \vartheta_y}{m_{pr}}\right.$$

(19) $$\left|\frac{dy}{dt} = \vartheta_y\right.$$

As a result of the study of the mathematical model, the transients (Fig. 2-5) of the system of hydraulic drives of the mechanism for cutting and unloading for different ratios of parameters were obtained.

The transients shown in figures 3-6 are calculated at the following initial values of the parameters of the hydraulic drive system of the mechanism for cutting and unloading of stalk fodder: Q_n = 2,38·10^{-4} m^3/s; a = 1 mm; l_1 = 6 mm; l_2 = 2 mm; μ = 0.62; p_0 = 10,0 MPa; ρ = 850 kg/m^3; K = 0,6 · 10^{-9} m^2/N; d_{zol} = 25 mm; C_{pr} = 0,5 N/mm; m_{pr} = 45 kg; β = 2,5·10^3 N · s; D_{ts} = 63 mm; W_1 = W_2 = W_4 = 100 cm^3; W_3 = 25 cm^3; b_1 = 1 mm, b_2 = 2 mm; m_{zol} = 0,2 kg.

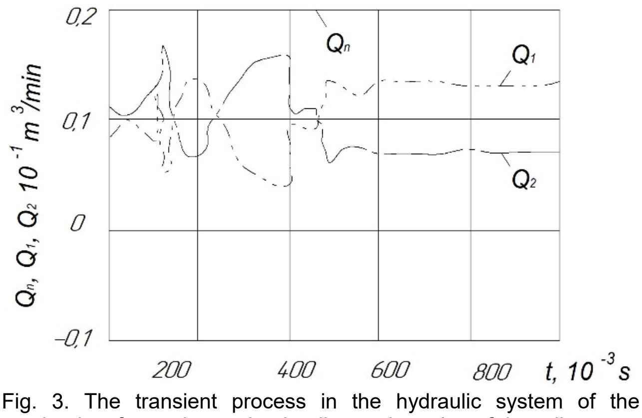

Fig. 3. The transient process in the hydraulic system of the mechanism for cutting and unloading at the value of the adjustment of the stop b_2 = 4 mm Q_n, Q_1, Q_2 10^{-1} m^3/min t, 10^{-3} s

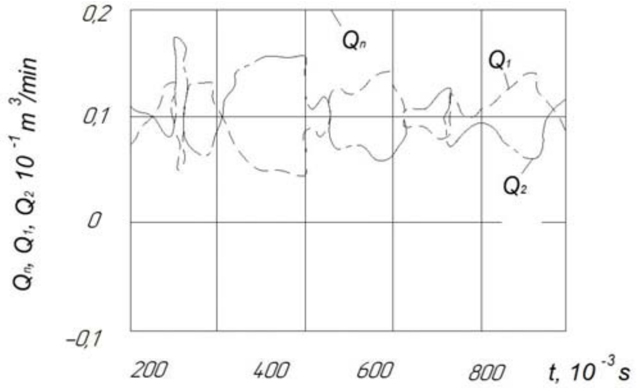

Fig. 3. The transient process in the system when adjusting the stop b_2 = 4 mm, the diameter of the spool d_{zol} = 19,5 mm, the spring stiffness C_{pr} = 0,3 N/mm

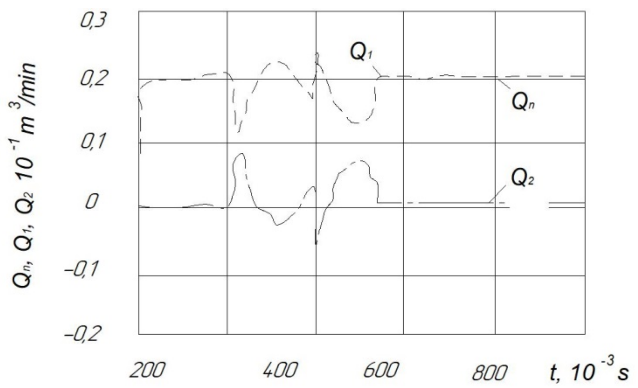

Fig.4. The transition process in the system when adjusting the stop b_1 = 3 mm, the diameter of the spool d_{zol} = 32 mm, the spring stiffness C_{pr} = 0,5 N/mm

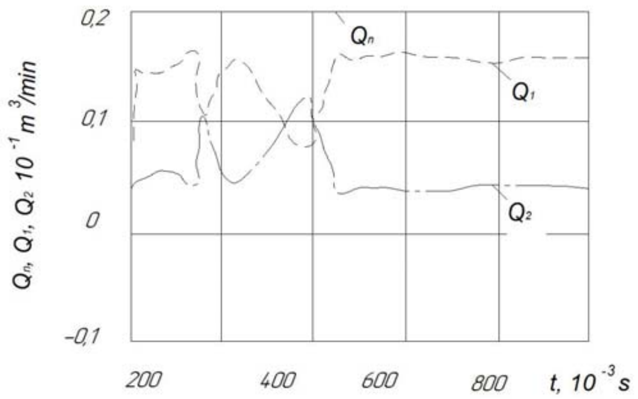

Fig.5. The transition process in the system when adjusting the stop b_1 = 1 mm, the diameter of the spool d_{zol} = 27 mm, the width of the working edge a = 0,5 mm, the spring stiffness C_{pr} = 0,5 N /mm

The transients obtained at different combinations of parameters testified to the presence of different modes of operation of the hydraulic drive system of the mechanism for cutting and unloading of stalk fodder. Figure 2 shows the transient in the hydraulic system of the mechanism for cutting and unloading, which confirms the possibility of adjusting the range of changes in the speed of the hydraulic motor and the feed of the rod by appropriate choice of rational values of some system parameters. The start of the hydraulic drive system of the mechanism for cutting and unloading stalk fodder occurs at zero load on the executive hydraulic motors, which generally corresponds to the process of bringing the U–shaped frame to the surface of the preserved monolith, when the load on the output links of executive hydraulic motors is minimal or absent. At 400 ms from the beginning of the work, the load on the output links of the executive hydraulic motors is increased to a value that corresponds to the real value of the load moment on the hydraulic motor shaft M_{gm} = 100 N · m and the force F_{rez} = 1200 N on the hydraulic cylinder rod. The volumetric supply of the working fluid Q_1, which is consumed by the hydraulic motor, increases from 0,088 × 10^{-1} m^3/min to 0,136 × 10^{-1} m^3/min, which corresponds to an increase in the cutting speed of the silage monolith by 57 %. At the same time, the supply of working fluid Q_2 which is consumed by the hydraulic cylinder is reduced from 0,113 × 10^{-1} m^3/min to 0,075 × 10^{-1} m^3/min, which corresponds to a reduction in the feed rate of the U–shaped frame by 43 %.

In the process of studying the transient processes of the hydraulic drive system of the mechanism for cutting and unloading stalk fodder it was found that with certain combinations of system parameters there are unstable operating modes (Fig. 3). They are characterized by the occurrence of fluctuations in speed and pressure with an amplitude that reaches the limit values, in terms of system power [19], and the nature of these processes does not correspond to the specified control signals [20, 21]. This mode of operation is unacceptable from the point of view of the efficiency of the hydraulic drive system of the mechanism for cutting and unloading stalk fodder. In this regard, an important point of study of this system of hydraulic drives is to determine the range of values of parameters at which this system will work stably, which will allow further research to identify rational parameters that ensure high efficiency of the proposed hydraulic system [22, 23].

The results of the calculation of transients in the hydraulic drive system of the mechanism for cutting and unloading stalk fodder indicate that the stability condition significantly depends on the values of parameters as components of hydraulic units of the hydraulic drive mechanism for cutting and unloading (hydraulic motor, hydraulic cylinder, etc.), as well as the parameters of the spool flow divider. These include the following parameters: d_{zol} is the diameter of the spool of the flow divider, C_{pr} is the stiffness of the spring of the spool of the flow divider, a is the width of the working edge of the spool, f_{dr} is the area of the control throttle, W_3 is the volume of the control line cavity, l_1, l_2 are the initial opening of the working window of the flow divider and b_1, b_2 are the distance to the stops that limit the movement of the spool.

Determining the conditions of stability of the adaptive hydraulic system of the mechanism for cutting and unloading is necessary to ensure its efficiency in dynamic modes of operation. For this purpose, the area of stability of this hydraulic drive is determined in the plane of values of its parameters – diameter d_{zol} spool flow distributor and stiffness C_{pr} its springs which largely determine its design and functional characteristics (Fig. 6).

The stability limit divides the plane of parameters into the area of stability and instability of the hydraulic drive adaptable to changes in the load on the working bodies [24, 25]. In figures 7-12, the stability limit is shown by a solid line with hatching. The hatching is turned towards the area of stability.

It should be noted that the parameters of the structural elements of the spool flow divider have an ambiguous effect on the characteristics of the hydraulic system of the mechanism for cutting and unloading. Thus, increasing the diameter of the spool d_{zol} has a positive effect on the dynamic characteristics, while significantly expanding the area of stability, facilitating the task of developers of such a hydraulic drive when choosing the dimensions of hydraulic equipment and its mass.

Increasing the stiffness of the spring C_{pr} also significantly affects the dynamic characteristics of this hydraulic drive, reducing the area of stability. Thus, to ensure the stability of the spool flow divider when using a spring with high rigidity it is necessary to increase the diameter of the spool, which can lead to an undesirable increase in the dimensions of the flow divider.

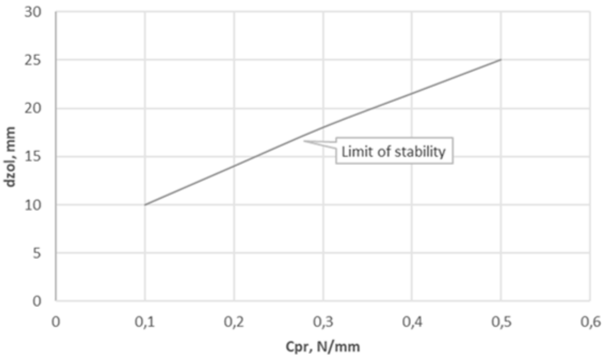

Fig. 6. Area of stability of the hydraulic drive system of the mechanism for cutting and unloading of stem forages

In a further study of the influence of the parameters of the hydraulic drive system of the mechanism for cutting and unloading on its stability, the results of calculations of the stability limit were compared with the calculation results, which are shown in Fig. 6.

Fig. 7 shows the areas of stability defined in the plane of the parameters "diameter of the spool of the flow divider d_{zol}, the stiffness of the spring C_{pr}" at different values of the width of the edges *a* of the spool of the flow divider.

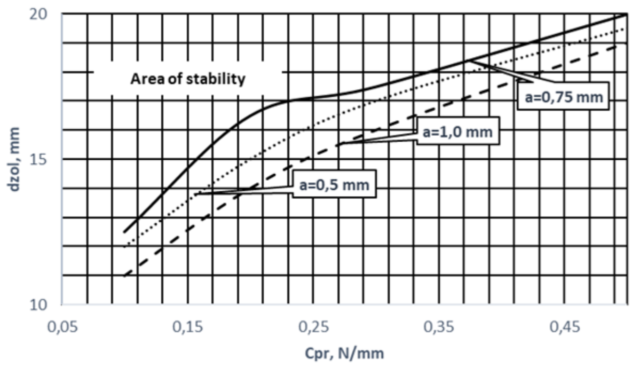

Fig. 7. Influence on the position of the stability limit of the width a of the flow divider edges

The limits of stability, which are shown in fig. 7 are calculated for the following values of the width of the working edges of the spool of the flow divider - *a* = 0,5; 0,75; 1,0 mm. Increasing the width of the working edges of the flow divider shifts the stability limit to reduce the allowable values of the diameter of the spool d_{zol} and increase the allowable values of the stiffness spring C_{pr} flow divider, thus expanding the range of values d_{zol} and C_{pr}, which provides a stable mode of operation unloading of stalk fodder. It should be noted that increasing the width of the edges of the spool of the flow divider does not significantly expand the range of values of the diameter of the spool d_{zol} and the stiffness of the spring C_{pr}, which provides a stable mode of operation of this hydraulic system.

Fig. 8 shows the limits of the stability of the hydraulic drive system of the mechanism for cutting and unloading calculated at different values of the cross-sectional area of the control throttle installed at the entrance of the right end-to-end cavity of the flow divider.

The limits of stability which are shown in fig. 8 are calculated at the following values of the throttle area f_{dr} = 1,5; 1,0; 0,5 mm^2.

Reducing the cross-sectional area of the throttle slightly increases the area of stability due to the shift of the stability limit towards smaller values of the diameters of the spool.

This usually reduces the oscillation of the control process, but reduces the speed of the spool flow divider. Therefore, in this case, it is advisable to recommend a value of the cross-sectional area of the throttle which is equal to f_{dr} = 1,0 mm^2. Based on the considerations of manufacturability of the throttle hole of small diameter and taking into account the limited influence of this parameter on the position of the stability limit, it is permissible to increase the cross-sectional area to f_{dr} = 2,0 mm^2 [24, 25].

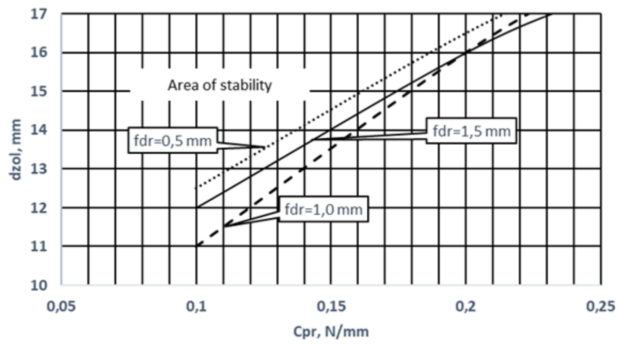

Fig. 8. Influence on the position of the stability limit of the throttle area f_{dr}

Studying the influence of the parameters of the hydraulic drive system of the mechanism for cutting and unloading stem fodder on the stability of its work revealed a significant impact on the stability of the values of the initial openings of the working windows of the distributor spool through which the working fluid enters the hydraulic motor and the distributor of the hydraulic cylinder. Fig. 9 shows the limits of stability of this hydraulic drive calculated at different values of the initial opening l_1 of the left working window. The magnitude of the opening l_1 varied from 2 mm to 6 mm.

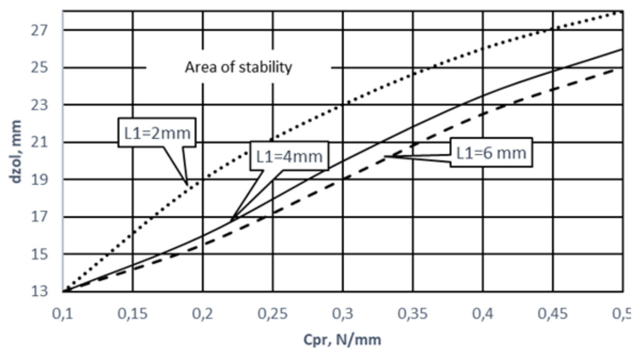

Fig. 9. Influence on the position of the stability limit of the value of the initial opening l_1 of the first working window of the spool of the flow divider

The smallest size of the stability area for this case was obtained at l_1 = 2 mm. The limit of stability is shifted towards larger values of the diameter of the spool of the divider. Increasing the initial opening of this working window to l_1 = 4 mm leads to a significant decrease (≈ 20 %) of the critical value of the spool diameter, at which there is an unstable mode of operation.

A further increase in the value of the initial opening of this working window to the value l_1 = 6 mm moves the limit of stability also in the direction of smaller values of the diameter of the spool, but the effect of increasing the area of stability in this case is much smaller.

To a lesser extent, the position of the limit of stability of the hydraulic drive of the mechanism for cutting and unloading (Fig. 10) is influenced by the initial opening of the right working window of the spool flow divider.

Only with increasing spring stiffness $C_{pr.}$ (up to 0,5 N/mm) increasing the initial opening of this working window to the value l_2 = 6 mm significantly reduces the critical value of the spool diameter (≈10 %), which corresponds to the limit of stability.

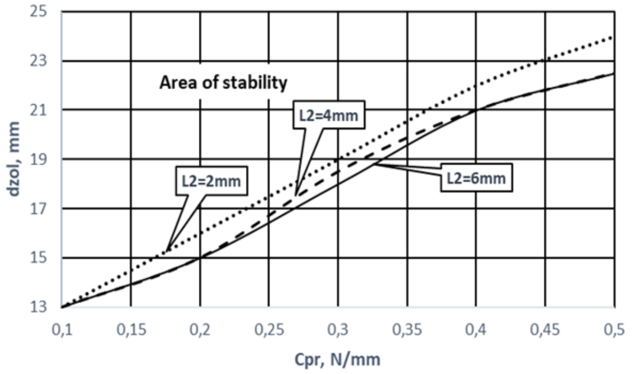

Fig. 10. Influence on the position of the stability limit of the value of the initial opening l_2 of the second working window of the spool of the flow divider

The distances b_1 and b_2 to the stops which limit the movement of the spool of the flow divider have a significant influence on the stability of the hydraulic drive system of the mechanism for cutting and unloading. Fig. 11 shows the boundaries of the stability area determined by changing the distance b_1 to the stop, which limits the movement of the spool when moving it to the left, in the range from 1 to 5 mm.

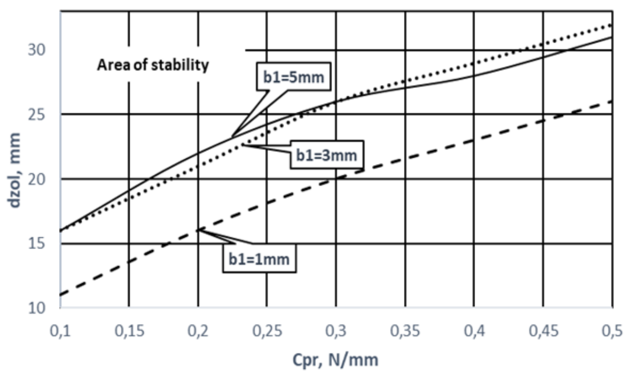

Fig. 11. Influence on the position of the boundary of the stability area of the distance b1 to the stop which limits the movement of the spool when it moves to the left

According to the calculation, the best result is possible at the minimum of the specified values, b_1 = 1,0 mm.

When increasing the value of the spool stroke in the specified direction (b_1 = 3 mm, 5 mm), the critical value of the spool diameter increases significantly - up to 40 %, which worsens the possible operating conditions of this hydraulic drive and significantly increases the dimensions of hydraulic equipment.

To a much lesser extent, the stability of the hydraulic system of the mechanism for cutting and unloading is affected by the setting b_2 of the second stop which limits the movement of the spool to the right. The boundaries of the area of stability, which are shown in Fig. 12, calculated by changing the specified distance from 2 to 8 mm, show that the size of the stability area and the position of the stability limit changes insignificantly.

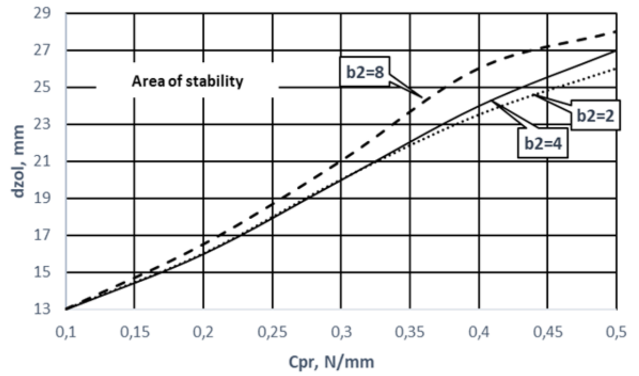

Fig. 12. Influence on the position of the boundary of the stability area of the distance b_2 to the stop, which limits the movement of the spool when it moves to the right

As a result of the analysis of transients in the adaptive system of hydraulic drives of the mechanism for cutting and unloading stem fodder the design and technological parameters of the spool flow divider were substantiated, which allows to monitor and respond to changes in load on the hydraulic motor by changing the flow rate of the working fluid through the throttle slots.

Conclusions

As a result of theoretical research of the system of hydraulic drives of the mechanism for cutting and unloading of stalk forages its rational parameters are substantiated: diameter of a spool of a flow divider d_{zol} = 22 mm, rigidity of a spring of a spool of a flow divider C_{pr} = 0,2-0,3 N / mm, working width spool edges a = 0.5 mm, control throttle area f_{dr} = 1 mm^2, control line cavity volume W_3 = 50 cm^3, initial opening value of first spool working window l_1 = 6 mm, initial opening of second working window spool l_2 = 2 mm, the setting value of the left stop of the spool b_1 = 1 mm, the right stop - b_2 = 2 mm, the moment of loading on the shaft of the hydraulic motor within M_{gm} = 150 N·m.

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