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OPTIMIZATION OF A LOADER DRIVE MECHANISMS ON THE BASIS OF THE CYCLE TIME CRITERION

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Abstract

The paper presents a mathematical model that defines the cycle time criterion as one of the possible criteria for optimizing the drive mechanisms of the loader manipulator. An analysis of the influence of drive system parameters and manipulator mechanisms on the duration of operations of the loader manipulation task is given. As an example, the results of the analysis of three different manipulator mechanisms of loader, which have in mass 15000 kg, are given.

Key words*: wheel loader, loader mechanisms optimization, cycle time*

1 INTRODUCTION

Loaders are mobile machines which basic function is cycle transport of bulk material. Loaders, as complex machine systems with their transfer function the input parameters of the environment, which include: subject, conditions, mode of operation and available energy of the drive system, transform into output performance parameters: capacity, range of work area and duration of manipulation task. For loaders with bucket-shaped manipulator tools, the capacity is the volume of the bucket and the reach of the working area: loading depth, reach and bucket angle of material unloading. The duration of the manipulation task is determined by the time of operations of loading, transport of loaded materila, unloading the material and returning it to the new position of loding.

2 LOADER CYCLE TIME

In general, for transport machines which have intermittent cycle, where loaders also belong, the technical performance is determined by equation [3]:

$$I = I_t \cdot k_I = 3600\frac{V}{t_c}k_I \qquad (1)$$

where: I_t - theoretical output [m^3/h], V - bucket volume [m^3] defined by standard [1], t - duration of manipulation task of intermittent transport of material [s], k_I - correction factor of theoretical output which takes into account: loading the bucket with material, looseness of the bulk material, conformity of unloading into another means of transport, and work conditions.

In the continuation of the paper, the influence of the parameters of the drive system and the mechanisms of the manipulator on the duration of the operations of the manipulation task of the loader is analyzed. Based on the results of the analysis, the time criterion for optimizing the mechanisms of manipulators is defined. The objectiv function is to determine the parameters of the mechanisms that enable the minimum time of operation of loading, transferring and unloading materials, i.e. the maximum loader performance.

2.1. Mathematical model of wheel loader

In paper general configuration of kinematic chain is observed, that is consists of: rear L_1 (Fig. 1) and front L_2 supporting-moving mechanism and the manipulator with arm L_3 and bucket L_4. With direct link of pairs of arm hydro-cylinders c_3 for the frame of moving mechanism L_2 and for arm L_3, is formed drive mechanism of arm.

The drive mechanism of bucket is consists of one or two hydro-cylinders c_4 which are on one side connected with direct link to the frame of moving mechanism L_2, and from other side is connected, via two-arm lever c_{41} and rod c_5, to bucket L_4, thus formed configuration in shape of letter "Z" by which the kinematics of the manipulator is named.

To analyze the influence of the parameters of the manipulator mechanisms on the duration of the manipulation task, a mathematical model of the loader was developed (Fig. 1), which includes: the kinematic chain of the loader, the drive mechanisms of the manipulator and the hydrostatic drive system of the manipulator with the assumptions:

• the hydraulic pump of the hydrostatic system of the manipulator drive is with flow regulation according to the criterion of constant hydraulic power,

• volumetric and mechanical efficiency of the hydraulic pump and hydraulic cylinder have a constant value,

• the pressure drop through the distribution valves, discharge and return lines of the hydrostatic system of the manipulator drive is neglected.

The analysis includes only the time tm duration of operations of the manipulation task performed by the executive members of the manipulator mechanisms, the sum of which is:

$$t_m = t_z + t_t + t_p \qquad (2)$$

where: t_z – duration time of loading operation by bucket rotation, t_t – duration time of transport operation by lifting full bucket L_4 with arm L_3, t_p - duration time of unloading operation by turning the L_4 bucket from the transport to the unloading position.

When performing the operations of the manipulation task, each executive member L_i of the mechanism, during the duration of t_{ij}, achieves the angle of the range of motion θ_{ijo}:

$$\theta_{ijo} = \theta_{ij4} - \theta_{ij1} \tag{3}$$

where: θ_{ij1}, θ_{ij4} - angles of the relative position of the executive member of the L_i mechanism at the beginning and end of the operation j.

The elementary angle $d\theta_{ij}$ of the range of relative motion of the executive member of the mechanism during operation j is determined by the equation:

$$d\theta_{ij} = \dot{\theta}_{ij} \cdot dt_{ij} \tag{4}$$

on the basis of which the duration of the operation is determined:

$$t_{ij} = \int_{\theta_{ij1}}^{\theta_{ij4}} \frac{1}{\dot{\theta}_{ij}} d\theta_{ij} = \int_{\theta_{ij1}}^{\theta_{ij4}} \frac{i_i}{v_{ci}} d\theta_{ij} \tag{5}$$

where: $\dot{\theta}_{ij}$ - angular velocity of the actuator L_i of the mechanism, v_{ci} - speed of the piston rod of the hydraulic cylinder, i_i - transfer function of the mechanism.

The speed v_{ci} of the piston rod of the hydrocylinder during the start of the executive member L_i of the mechanism during the manipulation task is determined by the equation:

$$v_{ci} = \begin{cases} v_{ci1} = \dfrac{4 \cdot Q_{ci}}{n_{ci} \cdot D_i^2 \cdot \pi} \eta_{cv} & \forall \quad \dot{\theta}_{ij} > 0 \\ v_{ci2} = \dfrac{4 \cdot Q_{ci}}{n_{ci} \cdot (D_i^2 - d_i^2) \cdot \pi} \eta_{cv} & \forall \quad \dot{\theta}_{ij} < 0 \end{cases} \tag{6}$$

where: v_{ci1}/v_{ci2} - speed of extraction / retraction of the piston rod of the hydraulic cylinder of the mechanism, Q_{ci} - flow of power supply of the hydraulic cylinder, i.e. flow of the hydraulic pump of the hydrostatic system of the manipulator drive, η_{cv} - volume efficiency of the hydraulic cylinder of the mechanism.

The previous equations 5 and 6 show that the duration time of the operation depends on the transfer function i_i of the mechanism and the flow Q_{ci} of the power supply of the hydraulic cylinder of the mechanism. During operations, the transfer functions of the mechanisms change depending on the relative position of the executive member of the mechanism. The flow of power supply of the hydraulic cylinder to the mechanisms depends on the concept of the hydrostatic system of the manipulator drive and during the operations of the manipulation task it can have a constant and variable value.

According to the conducted analysis, two conceptions of hydrostatic systems of manipulator drives are distinguished, which have open hydrostatic circuits, and fundamentally different hydraulic pumps. One conception is with hydraulic pumps of constant and the other with hydraulic pumps of variable specific flow.

The concept of hydrostatic systems with hydropumps of constant specific flow is used for smaller loaders, weighing up to 10000 kg.

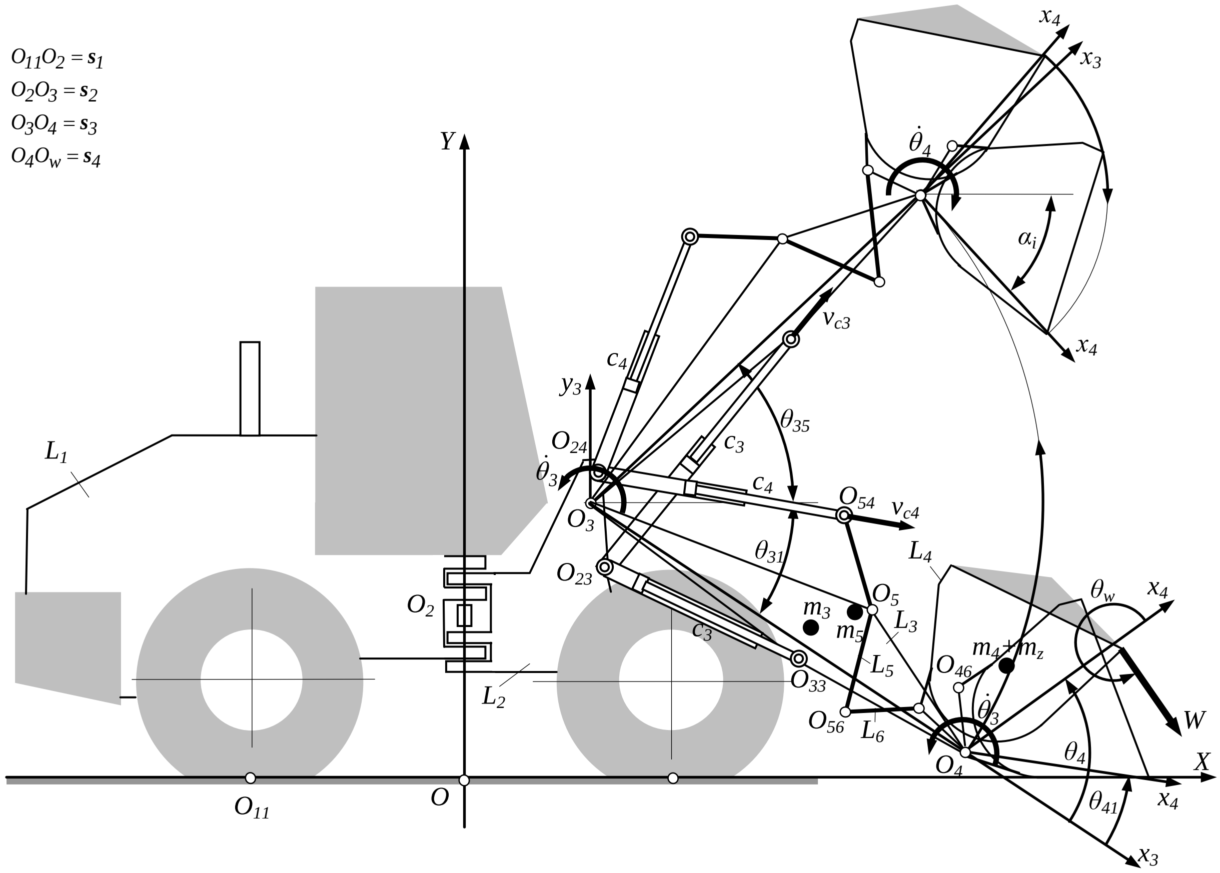

***Fig.1**. Mathematical model of the loader and the range of motion of the manipulator members during operations: loading, transfer and unloading of material*

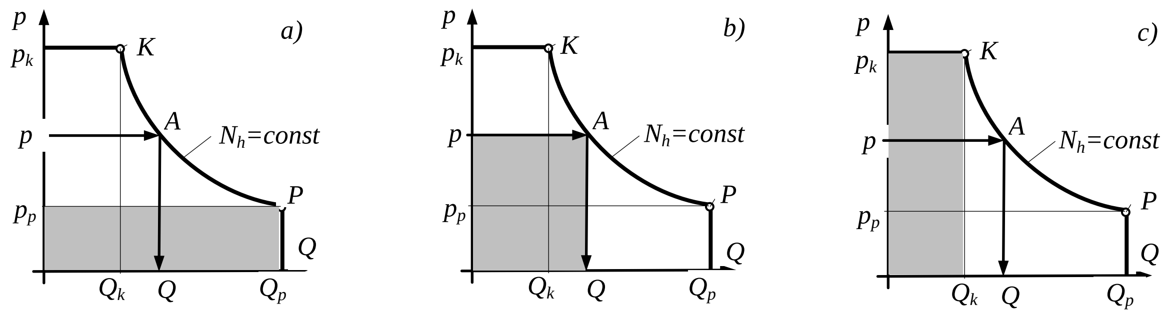

Fig. 2. *Regulation of the change of the flow Q of the hydraulic pump according to the criterion of constant hydraulic power: a) at the beginning, b) in the range and c) at the end of the regulation [3]*

The concept of hydrostatic systems with hydraulic pumps with constant specific flow is used for smaller loaders, weighing up to 10000 kg, on all other sizes of loaders for the manipulator drive are used hydrostatic systems with hydraulic pumps of variable specific flow.

In the case of a hydrostatic system for manipulator drive with a variable flow hydraulic pump, the diesel engine 1 (Fig. 3) drives the main 3.1 and the auxiliary 3.2 hydraulic pump via the elastic coupling 2. The main hydraulic pump feeds the hydraulic cylinders of the arm c_3 and the hydraulic cylinder of the bucket c_4 of the manipulator mechanisms via the priority valve 3.3 and the manifold 4. The priority valve allows the main hydraulic pump, in addition to supplying the hydraulic cylinders of the manipulator, to supply the hydraulic cylinders of the loader movement control system.

With the auxiliary hydraulic pump 3.2, the sections of the distributor 4 are hydraulically activated via the manifold 4.1, whereby the working lines of the hydraulic cylinder are connected to the discharge and return line of the hydraulic pump.

The main hydraulic pumps are piston-axial with flow control Q, according to the criterion of constant hydraulic power N_h, determined by the equation (Fig. 2) [2]:

$$N_h = \frac{Q_p \cdot p_p}{\eta_{pv} \cdot \eta_{pm}} = \frac{Q_k \cdot p_k}{\eta_{pv} \cdot \eta_{pm}} = \frac{Q \cdot p}{\eta_{pv} \cdot \eta_{pm}} = const \quad (7)$$

according to which the flow Q of the hydropump depends on the pressure p, i.e. the load of the system, and has the values:

$$Q = \begin{cases} \dfrac{N_h}{p_p} \eta_{pv} \cdot \eta_{pm} & \forall \quad p < p_p \\ \dfrac{N_h}{p} \eta_{pv} \cdot \eta_{pm} & \forall \quad p_p < p < p_k \\ \dfrac{N_h}{p_k} \eta_{pv} \cdot \eta_{pm} & \forall \quad p = p_k \end{cases} \quad (8)$$

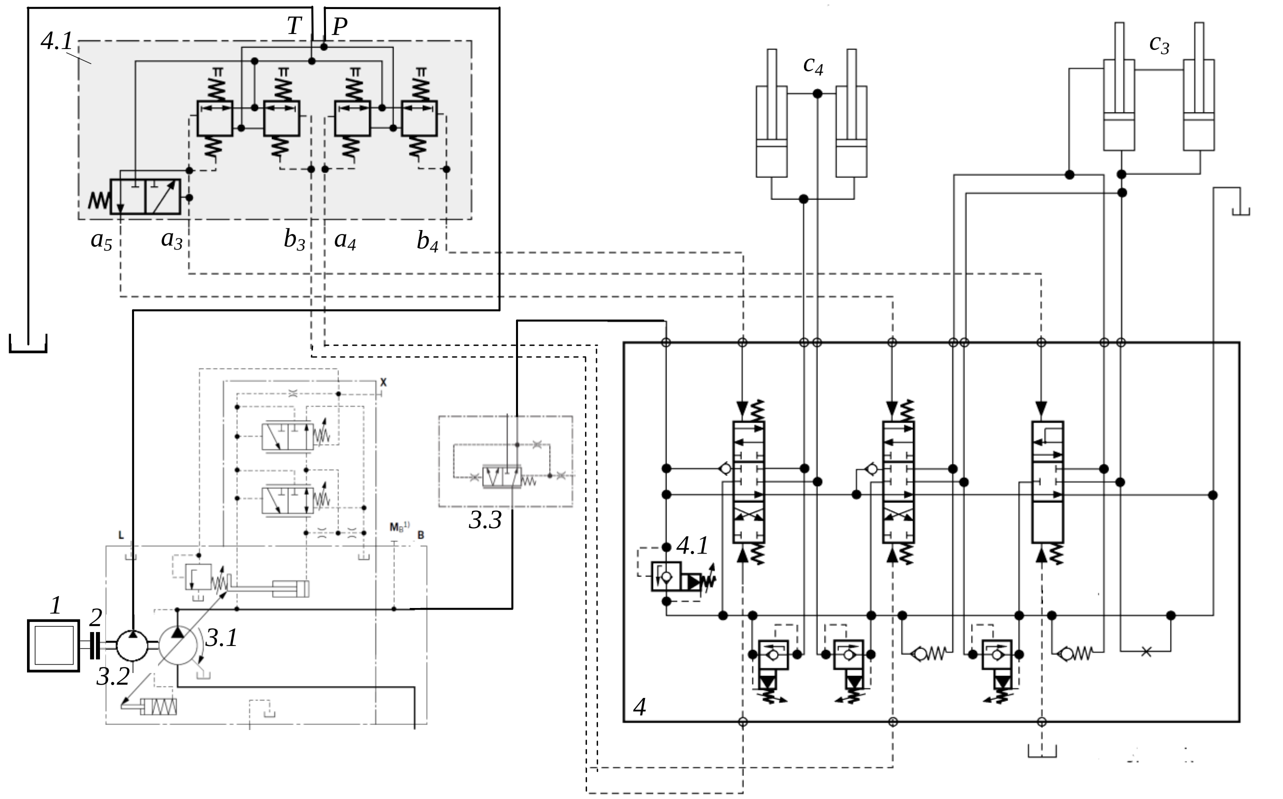

Fig.3. *Functional diagram of the drive hydrostatic system of the loader manipulator*

where: Q_p, p_p - flow and pressure at the beginning of regulation, Q_k, p_k - flow and pressure at the end of regulation, Q, p - flow and pressure in the control range of the hydraulic pump, η_{pv}/η_{pm} - volume/mechanical efficiency of hydraulic pumps.

According to the last equation and equation 5, the duration of the operation of manipulation tasks indirectly depends on the pressure in the hydraulic cylinders, i.e. on the load of the executive members of the mechanisms that the hydraulic cylinders drive.

3 PRESSURE ANALYSIS OF THE HYDROSTATIC SYSTEM

Based on the mathematical model of the loader and the generated variants solution of the mechanisms of manipulators *V.001*, *V.108* and *V.135* [3], the change of pressures p_3 of the hydraulic cylinder of the arm mechanism was analyzed by the numerical simulation procedure, using the MSC Adams software (Fig. 4a) and the change in pressure p_4 of the bucket mechanism hydraulic cylinder (Fig. 4b) during the manipulation task with loading operations with a straight (I), stepwise (II) and parabolic (III) penetration path of the bucket edge into the bulk material. The components of force and moments of loading resistance of materials are determined using the discrete element method.

The obtained analysis results show that in variants *V.001* and *V.108* with different transformation parameters (*V.001*: D_3/d_3*=125/90 mm*, D_4/d_4 = *150/100 mm* and *V.108*: D_3/d_3*= 150/100 mm*, D_4/d_4*=180/125* mm) and with a similar character of the change of the transfer function, the change of pressures in the hydraulic cylinders of the arm mechanism (Fig. 4a) and the hydraulic cylinders of the bucket mechanism (Fig. 4b) differ slightly during manipulation tasks, especially during operations of loading and transferring material. On the other hand, the comparative analysis shows that, in variants *V.001* and *V.135* with the same transformation parameters (*V.135*: D_3/d_3*=125/90* mm, D_4/d_4=150/100) and with different character of the change of transmission function, the pressures in the hydraulic cylinders of the arm mechanism (Fig. Fig. 4a) and the bucket (Fig. 4b) differ significantly in all operations of simulated manipulation tasks.

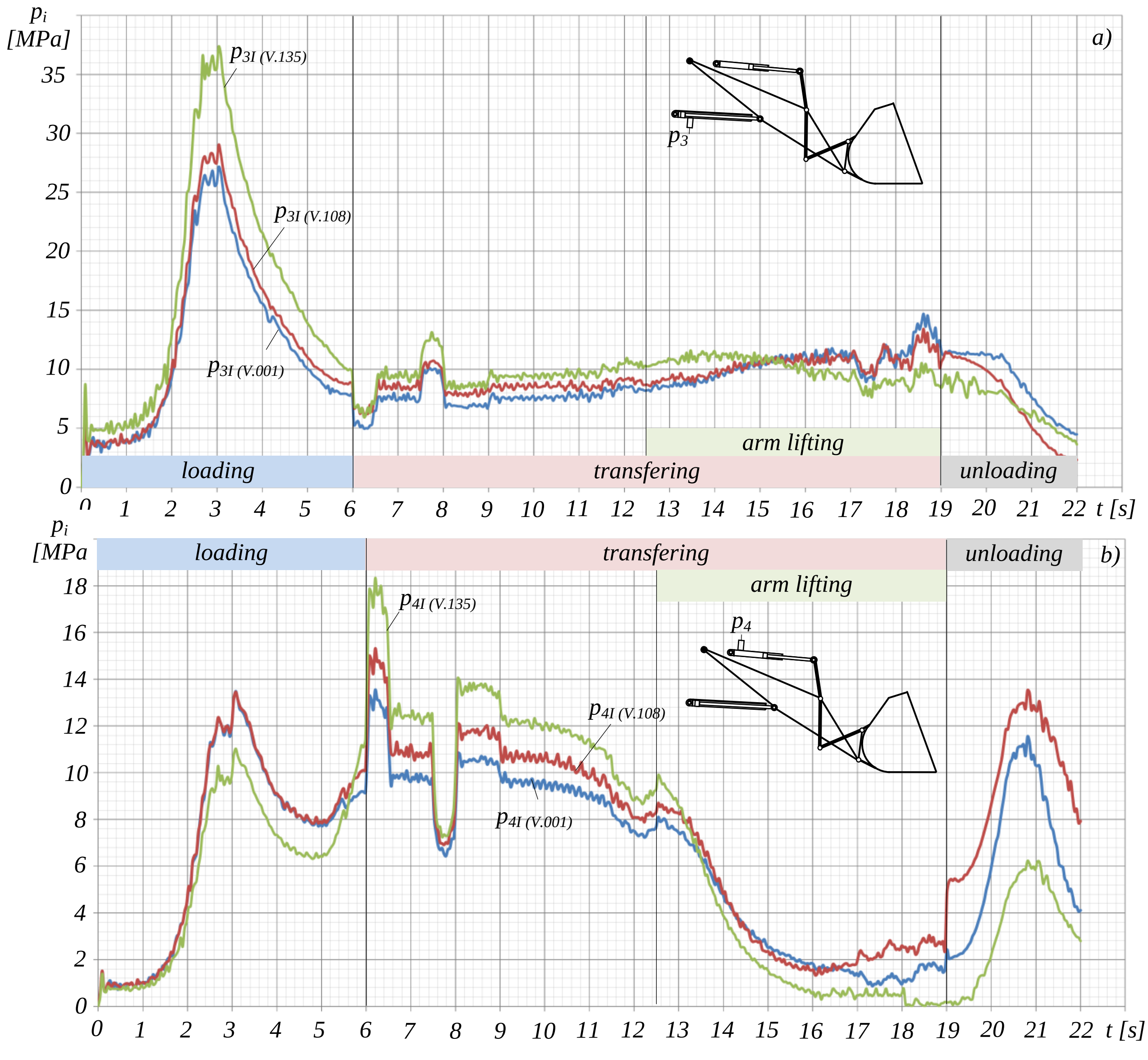

***Fig. 4** Change of hydraulic cylinder pressures: a) booms, b) buckets, variants of mechanisms in the manipulation task with: a) rectilinear I, b) step II and c) arc III way of capturing material*

The analysis shows that due to the difference in the parameters of the variant solutions of the manipulator mechanisms, under the same given conditions of manipulation tasks, in the hydraulic cylinders of the mechanisms there is a difference in pressure and flow (regulation of the hydraulic pump).

4 OBJECTIVE FUNCTION OF TIME CRITERION

Based on the results of the previous analysis, the time criterion for optimizing the mechanisms of the loader manipulator was determined, with the aim of determining the parameters of the mechanisms that enable the minimum duration of the manipulation task during the synthesis.
The objective function of the time criterion is deter-mined by the equation:

$$f_t = min t_m = min(t_z + t_t + t_p) \quad (9)$$

where: $t_m=t_z+t_t+t_p$ - the duration of the manipulation task with operations of loading (t_z), transfer (t_t) and unloading (t_p) of material performed by the executive members of the manipulator drive mechanisms.

4.1. Program

To determine the value of objective function f_t - time criterion, of loader variants with different parameters of manipulator mechanisms, a program was developed based on: set mathematical model of loader, defined duration of manipulation task, mechanism parameters and characteristics of hydrostatic system of manipulator drive.
On input of the program is given the parameters of the kinematic chain and drive mechanisms and the parameters of the hydraulic pump of the hydrostatic system of the manipulator drive (table 1): hydraulic power N_h, start/end of pressure regulation p_p/p_k, volume/mechanical efficiency of the hydraulic pump η_{pm}/η_{pv}. The duration of the operations is determined for the simulated parameters of the manipulation task which in terms of angles and range of movement of the arm and bucket (eq. 3). By iteratively changing the given number n_m of the manipulator position, the program determines: velocities v_{ci}, forces F_{ci}, pressures p_{ci}, flows Q_{ci} of the hydraulic cylinder mechanisms and the duration t_m of the manipulation task.

4.2. Example

Using the developed program, the values of the objective function f_t and indicators p_t of the time criterion (table 2) for the model of loader with the same parameters of kinematic chain members and generated variants of manipulator mechanisms were determined. with the same set parameters of the manipulation task and the hydrostatic system of the manipulator drive (table 1).
The obtained results show (table 2) that the generated variants of manipulator mechanisms have different values of objective function f_t and indicator p_t of the optimization time criterion under the same given conditions of the manipulation task and characteristics of the hydrostatic drive system of the manipulator. The differences are due to different parameters, i.e. different transfer functions of the manipulator mechanisms.
The duration of the manipulation task is more influenced by the transfer than transformation parameters of the mechanisms. This is indicated, for example, by the comparison of the variant of the mechanisms of the manipulator *V.001* with the higher value of the target function $f_{t1}=8.50435s$, (tabel 2, Fig.5), i.e. with the smaller indication $p_{t1}=0.89108$ and the variant mechanisms of manipulator *V.295* with a smaller value of the target function $f_{t2}=7.83184$ s, or a higher indicator p4 = 0.96759, which have a different character of change of transmission functions during the movement of the executive members of the mechanisms and the same transformation parameters ($D_3/d_3=125/90$ mm, $D_4/d_4=150/100$ mm).

Table 1 Parameters of the manipulation task and the hydrostatic drive system of the manipulator

Parameter name	Mark-dimension
Angle position of the arm when loading/unloading material	θ_{31}/θ_{35}=-40,9º/48,1º
Bucket position angle at the beginning/end of the loading operation	θ_{41}/θ_{43}=23,3/68,3º
Bucket angle when material is unloading	$\alpha_{i=}$-45º
Hydraulic power	N_h=37,5 kW
Pressure at start/end regulation	p_p/p_k=15/40 MPa
Volumetric/mechanical efficiency of the hydraulic pump	η_{pm}/η_{pv}=0,93/0,92
Angle of direction of action of possible loading resistance force	θ_w=270º

Table 2 Objective functions and time criterion indicators of manipulator mechanism variants

Manipulator variant E_v	Arm mechanism n_{m3}	D_3 [mm]	d_3 [mm]	Bucket mechanism n_{m4}	D_4 [mm]	d_4 [mm]	Time criterion: Objective function f_t (s)	Indicator $p_t=f_{4min}/f_{4i}$
V.001[1)]	3.001	125	90	4.001	150	100	8,50435	0,89108
V.108	3.108	150	100	4.108	180	125	7,83184	0,96759
V.135	3.135	125	90	4.135	150	100	8,10467	0,93502

[1)] *Parameters of Komatsu WA320 loader arm and bucket drive mechanisms*

5 CONCLUSION

The paper presents a mathematical model of a loader on the basis of which a time criterion is defined. The objective function of time criterion is to determine the parameters of the mechanisms that enable the minimum time of operation of loading, transferring and unloading materials.

It is determined that the duration of the operation of manipulation tasks indirectly depends on the pressure in the hydraulic cylinders, i.e. on the load of the executive members of the mechanisms that the hydraulic cylinders drive. Based on the results of the pressure analysis, the time criterion for optimizing the mechanisms of the loader manipulator was determined, with the aim of determining the parameters of the mechanisms that enable the minimum duration of the manipulation task during the synthesis. As an example, the results of the analysis of three different manipulator mechanisms of loader, which have in mass 15000 kg, are given. The example shows that the duration of the manipulation task is more influenced by the transfer than transformation parameters of the mechanisms.

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