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DEVELOPMENT OF THE POWER STEERING SYSTEM IN MOBILE MACHINES

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Abstract

This paper presents a mathematical model and program for synthesis and simulation of the drive mechanism for power steering system of dumpers. The program allows to simulate rotation of the front part of a supporting-moving mechanism in relation to the rear part of supporting-moving in a range from the minimum to the maximum turning mechanism angle. As an example, analysis results of the geometrical, kinematic and hydrostatic parameters of power steering system are given for dampers that have in mass 24000 kg.

Key words: dumpers, power steering system

1 INTRODUCTION

Steering of mobile machines and vehicles of large capacity requires great physical effort from the operator and there are large number of different types of mobile machines so the purely mechanical way of the steering system is unable to fully meet all the requirements that are placed in front of the steering system. One of the most important requirements of easily steering is the reduction of control effort and less transmission of shock loads from wheels to the steering wheel and therefore to the body of operator.
In order to enable easy steering of mobile machines in the steering system are included power systems with a particular source of energy whose main task is to reduce the force required on the steering wheel. Where by the energy parameters of power steering systems, controlled by the input signal, performs the activation of valve-regulating members of the hydrostatic system. The power steering systems, according to the nature of the energy source and character of boost signal are performed as electric, pneumatic, hydraulic, electric, or combined (hybrid) systems.

2 STEERING SYSTEMS OF MOBILE MACHINES

The mobile machines usually for the drive of steering mechanisms have hydrostatic systems, which are derived in several ways, but with the rotary control valve as a primary component.
Classically performance of these systems is with the rotary control valve 3 (Fig.1), hydraulic pump 2 which proportionally to the number of rotation of steering wheel 3.1 connected to the pillar 3.2, directed to the actuators 4 (hydrocylinders) of the steering mechanism.

2.1. Rotary control valves

At the hydrostatic steering system, rotary control valves has a dual function: a) as a rotary valve for the distribution of oil to the chamber of hydrocylinder of steering mechanism and b) as a hand pump in the case of failure of the main hydraulic pump, during spraying running lines or other malfunction of the steering system.
The rotary control valve is powered by the operator with the steering wheel of the machine by which, depending on the installation space, it can be directly connected with rotary valve, or via a rigid or an articulated steering pillar [1].

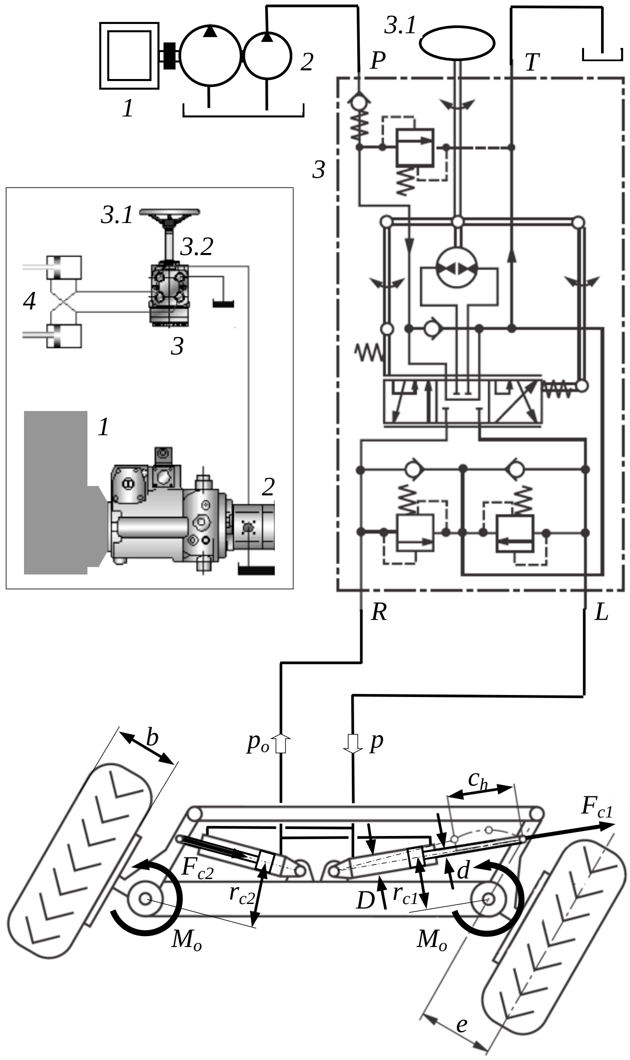

Fig. 1. *Hydrostatic drive systems of steering axles[1]*

The general power steering hydrostatic system of mobile machines build the following basic components: hydraulic pump 2 (Fig. 1 and Fig. 2), the rotary control valve 3 with a steering wheel 3.1 and steering pillar 3.2 and hydraulic cylinders 4. The system components are connected to an open hydraulic circuit. The drive of the rotary control valve is performed directly with a hydraulic pump 2 (Fig.1) or from the priority valve 2.1 (Fig.2), with a hydraulic pump 2 which is used to drive some other system of the machine, for example, the brake system or drive system of the manipulator.

It has been developed power steering systems with the closed and open center. The power steering system of open center with non reaction (OC/NR) has the hydraulic pump which is in the neutral position connected with a tank P-T. Wherein L and R lines of the power steering system blocked so that the external loads of wheels are transferred to the power steering system but the operator via the steering wheel does not feel.

The rotary control valve in power steering has working lines indicated with L (left) and R (right) and does not like the rest of control valves A and B. The power steering systems with the closed-center in hydrostatic control system mainly is driven by the hydraulic pump with the constant specific flow.

At the power steering system of the open center with reaction (OC/R) in the neutral position lines L-R are connected to hydraulic cylinders of the steering mechanism. External forces that are acting on the hydraulic cylinder, the operator feels as reaction forces on the steering wheel. If the operator lets go the steering wheel after the rotation of machine in a road curve, the wheels and steering wheel correct themselves and the machine continues to move in a linear trajectory.

A method of designing a power steering system of mobile machines include: the selection of the concept of the steering mechanism, defining the parameters of the function of rotation, the selection of the concept and the size of the rotary control valve, selection of hydraulic pump which drives power steering system.

The choice of the concept of rotation mechanism depends on functions (types) and the size of the machine. Also is necessary to define the number, type and size of the steering axles and hydraulic cylinders [2][3] .

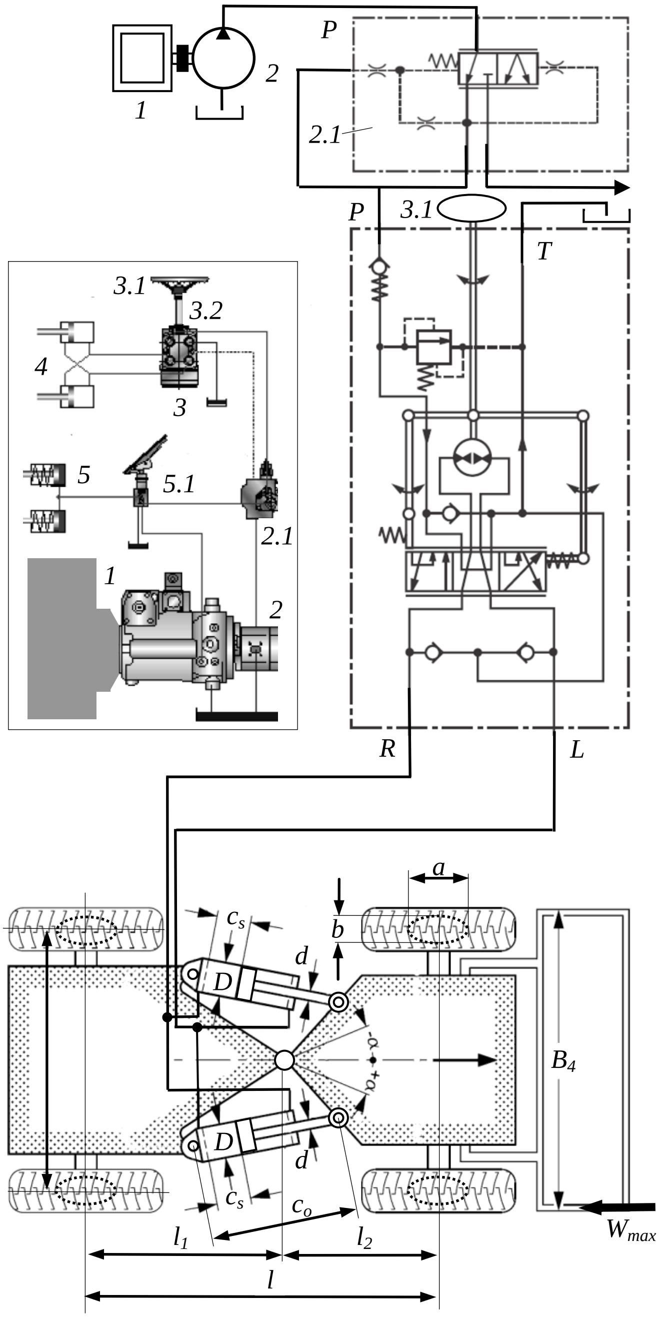

Fig. 2. *Hydrostatic steering system of articulated moving mechanism of mobile machines[1]*

3 DEFINING THE POWER STEERING SYSTEMS OF DUMPERS

Main (primary) function of the dumpers is a cyclic (non-contiguous) transport of the bulk material to a certain place for processing or to a place where it is unloaded. Generally, the basic function of damper consists of the following partial functions of loading, transport and unloading of materials, again going back to a new place of loading, thus completing the cycle of material transport.

Kinematic chain of moving mechanism of dumpers consists of a front part of L_1 (Fig. 3) and a rear part of the L_3 which are connected with vertical joint and with horizontal rotary joint via the two-arm lever L_2.

The two-arm lever L_2 is connected with the vertical rotary joint for the front part of the moving mechanism L_1 and for the rear part of moving mechanism L_3 with the horizontal rotary joint. Dumpers have a hydrodynamic transmission, the hydrostatic drive mechanism of basket unloading and hydrostatic steering system.

The hydrostatic steering system of dumper consists of the hydraulic pump 3 (Fig. 3a) which is driven by the diesel engine 1 via the pump circuit of the hydrodynamic (torque) converter 2, rotary control valve 4 and the hydraulic cylinder 5.

By rotation of steering wheel 6 the oil is led over the rotary control valve to hydraulic cylinders so that, depending on the direction of rotation of the steering wheel simultaneously retracts one hydro cylinder and at the same time second hydro cylinder extracts resulting in a relative rotation of the front and rear moving mechanism.

In the synthesis of power steering system of the dumper the next sizes are determined: hydraulic pump, rotary control valve and hydraulic cylinders on the basis of known parameters: size of the vehicle, the steering mechanism, hydrostatic system and the parameters damper rotation function.

The mathematical model of the dumper steering system is defined in the absolute coordinate system XOY (Fig.3).

Synthesis starts with a set of values that are related to the characteristics of the vehicle, steering drive mechanism and the hydrostatic system.

A set of variables that are related to the characteristics of the dumpers:

$$P_V = \{l_1, l_2, l_3, m, n_p, r_d\} \quad (19)$$

where: l_1, l_2, l_3 – wheelbase of the dumper (Fig.3), m - mass of the dumper, n_p - number of tires, r_d - dynamic radius.

A set of geometric parameters of the steering mechanism:

$$P_G = \{a_x, a_y, b_x, b_y, \theta_p, \theta_k\} \quad (20)$$

where: a_x, a_y - coordinates of joint connection of the two arm lever L_2 and front supporting-moving mechanism L_1, b_x, b_y - coordinates of joint connection of the two arm lever L_2 and rear supporting-moving mechanism L_3, θ_p- initial rotation angle, θ_k – final rotation angle.

A set of hydrostatic system parameters:

$$P_H = \{p, p_o, \eta_{cm}, \eta_{cv}\} \quad (21)$$

where: p - working pressure, p_o - back-pressure, η_{cm},η_{cv} – mass and volumetric efficiency of hydraulic cylinder.

The position of the kinematic chain of dumper. - Depending on the rotation angle θ (Fig. 3) position of the front moving mechanism L_1 is determined in relation to the rear part of moving mechanism L_3 of the dumper.

The angle of rotation θ correspond to the current kinematic lengths c_1, c_2 of hydraulic cylinder, determined with equations:

$$c_1 = \sqrt{a^2 + b^2 - 2ab\cos\gamma_1} \quad (1)$$

$$c_2 = \sqrt{a^2 + b^2 - 2ab\cos\gamma_2} \quad (2)$$

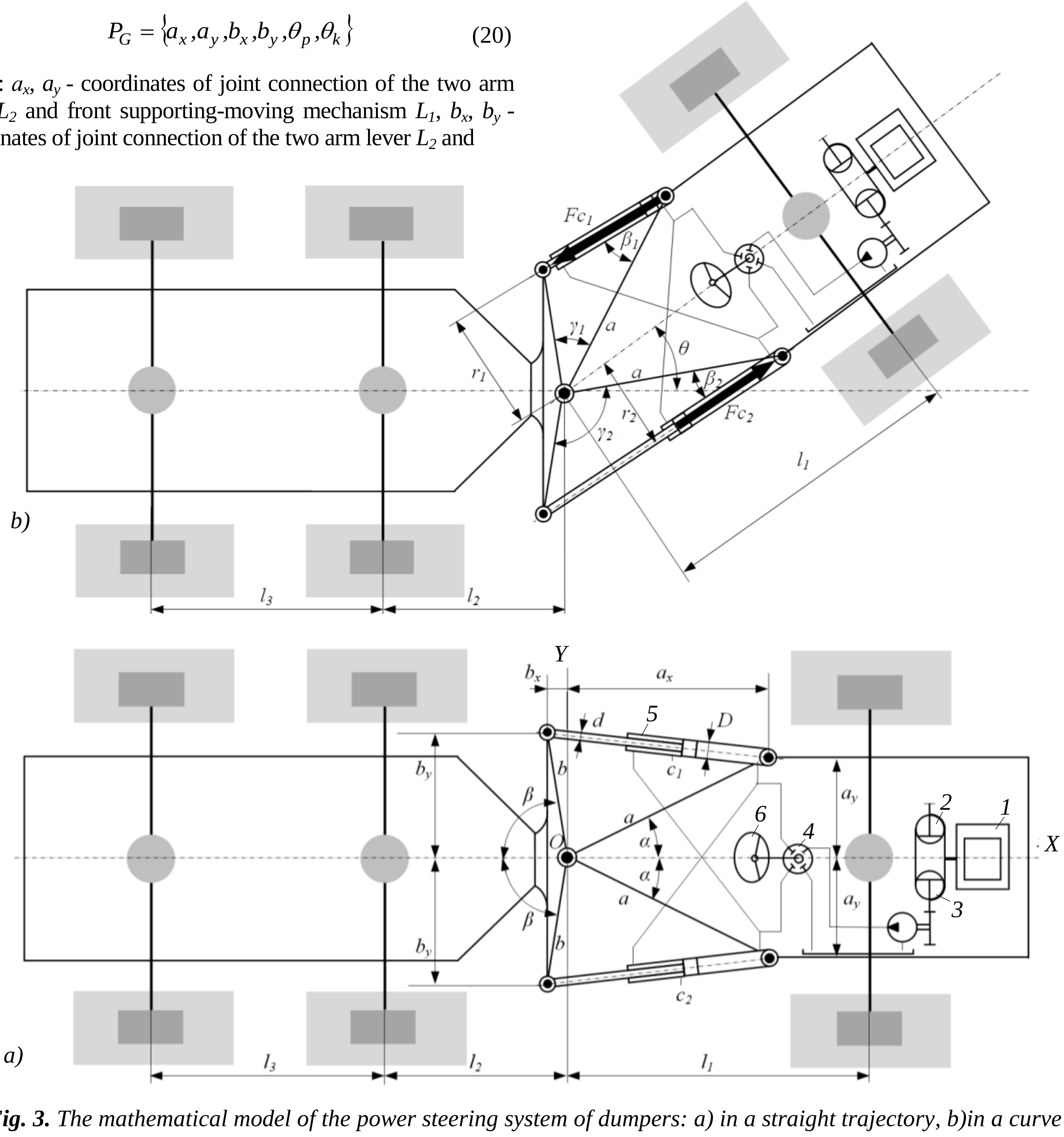

Fig. 3. *The mathematical model of the power steering system of dumpers: a) in a straight trajectory, b)in a curve trajectory[9]*

where:

$$a=\sqrt{a_x^2+a_y^2}\,;\ \ b=\sqrt{b_x^2+b_y^2} \quad (3)$$

$$\gamma_1=180^\circ-\theta-(\alpha+\beta);\ \ \gamma_2=180^\circ+\theta-(\alpha+\beta) \quad (4)$$

$$\alpha=arctg\,\frac{a_y}{a_x}\ \ \beta=arctg\,\frac{b_y}{b_x} \quad (5)$$

Transmission lenghts r_1, r_2 of the hydraulic cylinders c_1, c_2 in relation to the vertical axis of the rotation joint are determined by the equations:

$$r_1=a\cdot sin\beta_1=a\cdot\frac{b}{c_1}\cdot sin\gamma_1 \quad (6)$$

$$r_2=a\cdot sin\beta_2=a\cdot\frac{b}{c_2}\cdot sin\gamma_2 \quad (7)$$

Rotation resistance torque. - For articulated moving mechanism of the dumper rotation resistance torque is determined by the equation:

$$M_o=\frac{F_t\cdot\mu}{4}\left(\sqrt{a_r^2+b_r^2}+\sqrt{a_r^2+4b_r^2}\right)+F_t\cdot f\cdot(L_1+L_2+L_3) \quad (8)$$

where: F_t - force acting on one tire, a_r,b_r - reduced length of the contact area of the tire and reliance surface (fig. 3), f - the coefficient of rolling resistance.
The force acting on one tire is determined by the equation:

$$F_t=\frac{g\cdot m}{n_t} \quad (9)$$

where: m- mass of vehicle with load, n_t - number of tires of moving mechanism.

Drive rotation torque. - For a given position of the steering mechanism system of dumpers drive rotation torque is determined by the equation:

$$M_p=F_{c1}\cdot r_1+F_{c2}\cdot r_2 \quad (10)$$

where:

$$F_{c1}=\left[\frac{D^2-d^2}{4}\pi\cdot p-\frac{D^2}{4}\pi\cdot p_o\right]\eta_{cm} \quad (11)$$

$$F_{c2}=\left[\frac{D^2\pi}{4}p-\frac{D^2-d^2}{4}\pi\cdot p_o\right]\eta_{cm} \quad (12)$$

where: F_{c1} - the retraction force of hydraulic cylinder, F_{c2} - the extraction force of hydraulic cylinder, D, d - diameter of the piston and the piston rod of hydraulic cylinder, p, p_o- pressure in the main and return lines of the hydraulic cylinder, η_{cm} - mechanical efficiency of hydraulic cylinder [4].
By introduction of the relationship ψ = d/D in above equation (11) and (12) and equalizing rotation resistance torque M_o and drive rotation torque M_p, diameter of the piston of hydraulic cylinder are determined

$$D=\sqrt{\frac{4\cdot M_o}{\pi\cdot\eta_{cm}\cdot\left\{\left[p-(1-\psi^2)\cdot p_o\right]\cdot r_1+\left[(1-\psi^2)\cdot p-p_o\right]\cdot r_2\right\}}} \quad (13)$$

3.1. The selection of the components of steering system

Selection of the rotary control valve. - Basic components of hydrostatic steering system for motion control of mobile machines are pre-built modules that produce specialized manufacturers. In their selection it is started from the parameters of the controllable functions of the machine and the set of ergonomic demands. Taking into account the limitations of components allowed by border parameters prescribed by their manufacturers.
Selection of rotary valve control starts from the ergonomic requirement that the full rotation of the wheels, respectively articulated moving mechanism, from one end to the other, opposite end position, provide for: a) the optimal number i=3 ÷ 5 of full turns of the steering wheel, and b) for the duration of a full rotation around $t=3\text{-}4\ s$.
All manufacturers of the power steering system proposed ergonomic requirements of the optimum number of revolutions of the steering wheel: $n_u = (60 \div 100)\ min^{-1}$.
The required ergonomic number of full revolutions steering presents the ratio:

$$i=\frac{V_c}{q_u} \quad (14)$$

based whome is determined the specific flow rate q_u of the power steering system.
Where: V_c – displacement of hydraulic cylinder for full rotation of the wheels, apropos articuled moving mechanism, from one end position to another end position.
On the basis of the calculated specific flow q_u from the catalog of specialized manufacturer size of rotary control valve is selected [5][6][7].
If the calculated specific flow of the power steering system considerably larger than the size of available models, it is selected steering units with additional components (enhancers) which enable increase of the specific flow of the power steering several times.
At steering axles with differential hydraulic cylinder and at articulated moving mechanism displacement of hydraulic cylinder is:

$$V_c=\frac{\pi}{4}(2D^2-d^2)(c_k-c_p) \quad (15)$$

where: c_k,c_p- initial and final length of hydraulic cylinder.
At steering axles with double acting hydraulic cylinder, displacement is:

$$V_c=\frac{\pi}{4}(D^2-d^2)c_h \quad (16)$$

where: c_h- stroke of hydraulic cylinder.
Selection of hydraulic pump. - Hydraulic pump that supply power steering system is selected according to the required displacement, or according to required flow of power steering system.
The required flow of power steering system is equal to the flow of hydraulic pump:

$$Q_u = \frac{q_u \cdot n_u}{1000 \cdot \eta_{uv}} = Q_p = \frac{q_p \cdot n_p}{1000} \eta_{pv} \qquad (17)$$

where: q_p – displacement of hydraulic pump, η_{uv}, η_{pv} - volumetric efficiency of rotary valve and hydraulic pump, n_u,n_p – number of revolution of rotary valve and pump.
From the last equation it can be determined the required displacement of hydraulic pump:

$$q_p = \frac{q_u \cdot n_u}{n_p \cdot \eta_{uv} \cdot \eta_{pv}} \qquad (18)$$

On which basis it can be selected size of hydraulic pump.
Power steering system for drive use separated hydraulic that can be gear, vane and screw pump.

4 EXAMPLE

On the basis of predefined mathematical model it has been developed program for synthesis and simulation of the power steering drive mechanism for dumpers [9].
The input of the program contains sizes of sets that determine the characteristics of the vehicle steering drive mechanism and hydrostatic system. Also, input of the program contains a data file of standard double acting hydraulic cylinders.
The program allows to simulate rotation of the front part of a supporting-moving mechanism in relation to the rear part of supporting-moving mechanism in a range from the minimum rotation angle (θ_{min}= -45˚) to a maximum rotation angle (θ_{max}=45˚) wherein is given the trapezoidal shape of the angular speed with the duration of acceleration and deceleration time.
For selected sizes of hydraulic cylinder, rotary valve and hydraulic pump, analysis of geometrical, kinematic and hydrostatic parameters of system, have been done for power steering system of dumper.
Using the developed program, the synthesis and analysis of power steering mechanism have been done for dumper which have in mass 24000 kg and basket volume 15 m^3.
By a synthesis method it has been determined the size of hydraulic cylinders for steering drive mechanism of dumper which diameter of the piston/piston rod, D/d = 80/56 mm with the initial stroke c_p = *956 mm* and final stroke c_k=*1520 mm*, then the size of the rotary control valve with displacement q_u = *1260 cm*^{3} and pump which determined displacement is q_p=*28,5 cm*^{3}.
For defined and adopted components results of the analysis show parameters (Fig. 4.5) of the steering drive mechanism of the dumper depending on the duration of the entire range of rotation of the front part in relation to the back part of the moving dumper mechanism.
For the geometric parameters it is given an angle of rotation θ (Fig.4a), the change of the hydraulic cylinder stroke c_1, c_2 (Fig.4b) and their transmission lenght r_1,r_2 in relation to the axis of rotation.
Kinematic sizes represents a change in angular speed ω (Fig.4c) and velocity v_1 and v_2 of hydraulic cylinders c_1 and c_2 (Fig.4d).
On picture 5a there are shown force F_{c1} of hydraulic cylinder c_2 retraction (Fig.6) and force of extraction F_{c2} of hydraulic cylinder c_1, as well as their individual and summary drive torques (M_{p1},M_{p2} M_p) (Fig.5б).

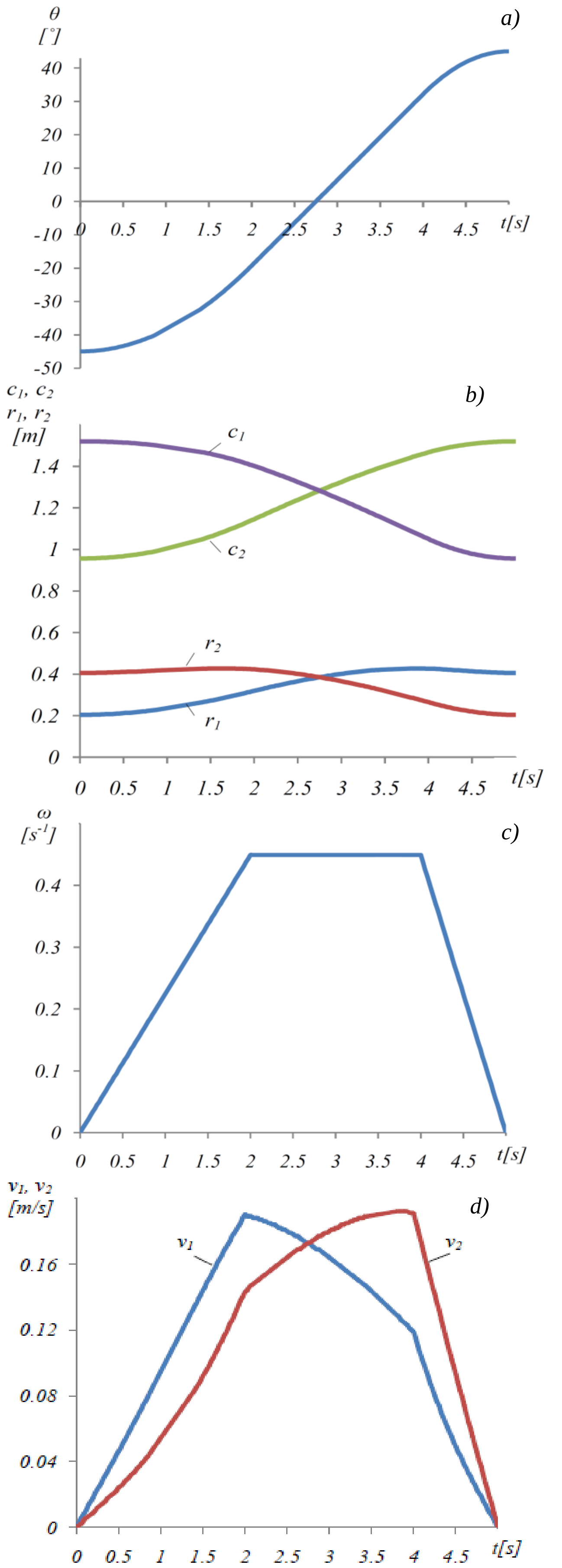

Fig.4. *Change of the geometric and kinematic parameters of steering system: a) the angle of rotation, b) transmission lenght and strokes of hydraulic cylindars, c) angular velocity of rotation of dumper, d) linear velocity of hydraulic cylinder[9]*

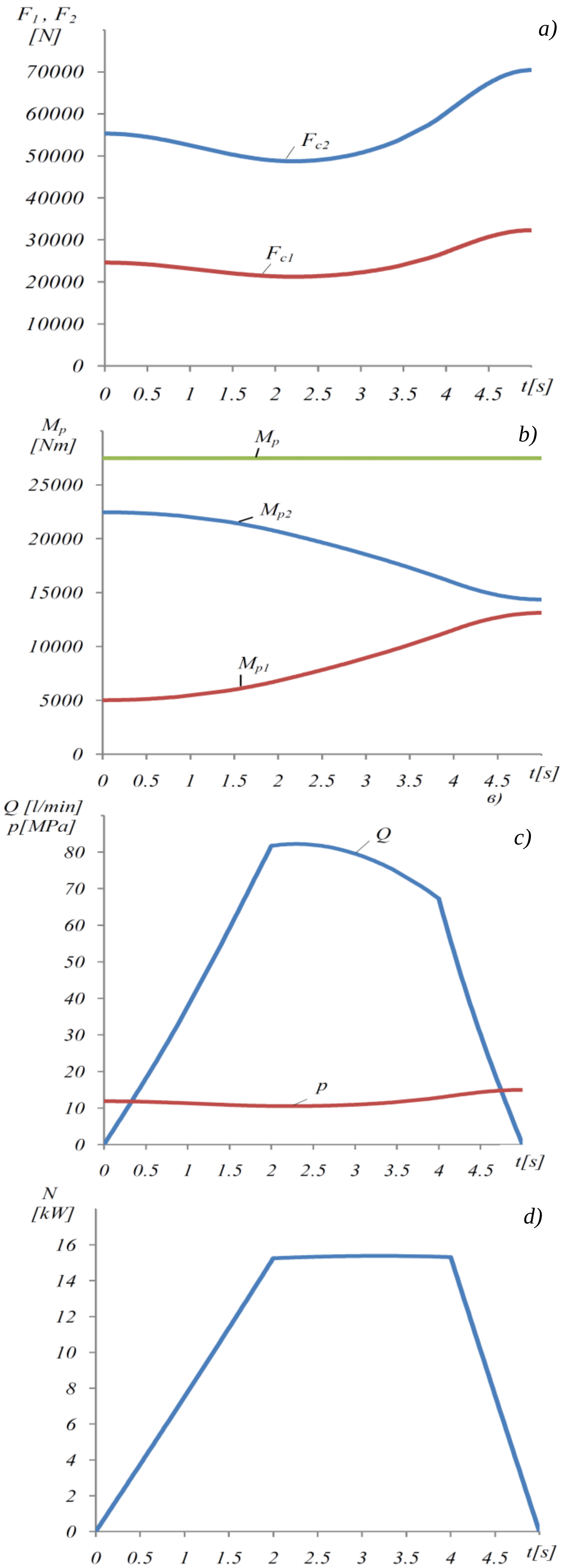

Fig. 5. *Mechanical and hydrostatic function of parameters: a) the forces in the hydraulic cylinders, b) the drive torque, c) change of the flow and pressure, g) the required power*

Parameters of the hydrostatic pressure *p* change are given on pivture 5c and flow *Q* as well as change of total required output power *N* (fig.5d) of power steering system.

4 CONCLUSION

Conducted analysis shows that the hydrostatic drive system of power steering in mobile machines consist of components (hydraulic cylinder, rotary control valve and hydraulic pump) that are produced as separate modules by specialized manufacturers.

The paper defines a general method for the synthesis of the hydrostatic system of power steering of articulated dumpers. It has been developed mathematical model and program for selection of the size of the components and analysis of geometrical, kinematic, dynamic and hydrostatic system of power steering system of articulated dumper.

Modern vehicles and mobile machines still use hydrostatic power steering systems regulated by mechatronic systems.

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