Influence of the Design Features of Orbital Hydraulic Motors on the Change in the Dynamic Characteristics of Hydraulic Drives

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Abstract. The operation of power hydraulic drives of self-propelled vehicles is accompanied by oscillatory processes associated with the technical imperfection of the actuating elements of the hydraulic drive. In this regard, the issue of stabilizing the dynamic characteristics of hydraulic drives is an urgent problem. As a result of the research, the initial data and conditions have been substantiated, making it possible to simulate the transient processes occurring in the hydraulic drives of self-propelled vehicles. A structural-functional diagram and a mathematical apparatus have been developed to reveal the dynamics of changes in the characteristics of a hydraulic drive of self-propelled equipment, considering the conditions of its operation. Changes in the stability of the dynamic characteristics of hydraulic drives of self-propelled vehicles, under the influence of the design features of orbital hydraulic motors, have been determined. The acceleration time of the hydraulic motor No. 2 is 12% less than that of the hydraulic motor No. 1, while the pressure and torque fluctuations during steady motion are less by 34% and 17%, respectively. Such changes are due to a decrease in the gap between the teeth of the rotors of the hydraulic motor No. 2 and the elimination of fluctuations in the flow area of its distribution system.

Keywords: Energy efficiency · Transient processes · Acceleration · Dynamic characteristics · Output parameters · Structural and functional diagram · Industrial growth

1 Introduction

The hydraulic drive is widely used in municipal, road, agricultural, construction, forestry, and other self-propelled machines. Recently, the hydraulic drive has been used as a drive for working equipment and mechanisms for the movement of self-propelled equipment. Such operation of hydraulic drives is accompanied by shock loads and oscillatory processes in hydraulic systems associated with both the occurrence of significant fluctuations

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in the pressure and flow of the working fluid [1–4] and as a result of technical imperfection of the actuating elements of the hydraulic drive. Oscillatory processes occurring in the hydraulic drive during acceleration and deceleration have a negative effect on the resource of the hydraulic drive, reduce the utilization factor of the drive's installed power and productivity, and reduce the reliability of the drive and the machine as a whole. Therefore, in designing hydraulic drives for self-propelled machines, one of the important tasks is to study the influence of structural elements of hydraulic machines on changing the characteristics of the entire hydraulic drive during transient processes.

One of the main elements causing the uneven change in the output characteristics of hydraulic drives is hydraulic motors. At present, orbital (gerotor) [5–8] hydraulic motors are widely used in hydraulic power drives of working equipment and mechanisms of movement of self-propelled machines. One of the disadvantages of the considered hydraulic machines is the unevenness of their output characteristics, which occurs during transient processes. The non-uniformity of the characteristics of this type of hydraulic motor is due to the error in the manufacture of the toothed surface of their rotors (fluctuation of the gap G_t between the teeth of the rotors) [8–10] and the pulsation of the working fluid flow in the distribution systems of these hydraulic machines [12–14].

In this regard, studying the influence of the design features of orbital hydraulic motors on the change in the dynamic characteristics of hydraulic drives to stabilize them is an urgent problem requiring an essential solution.

2 Literature Review

A semi-analytical method for analyzing the contact interaction of elements has been proposed [15], methods and models have been developed for studying the stress-strain state considering the contact interaction [16], and the fundamental laws of the stress-strain state of elements have been obtained [17]. A method is proposed for determining the magnitude of the interaction force between bodies and the distribution of contact pressure without limiting the shape of the initial gap between the bodies [18]. The proposed RANS approach using the corrected SST turbulence model allows one to determine the main characteristics [19] and optimal geometric parameters [20] of vortex-chamber pumps, as well as improve the output characteristics [21]. The characteristics of rational regulation of the composition of the fuel-air mixture were determined [22], the effect of the viscosity of Bingham fluids on the energy characteristics of vortex-chamber pumps [23] was investigated, a computational model of losses in the hydraulic circuit with an emphasis on losses caused by the compressibility of the liquid [24] was carried out, experimental studies were carried out showing the presence of pressure fluctuations [25], not provided by the model [24]. The flow of working fluid through the channels of hydraulic machines [26, 27] was considered, an approach to modeling a gerotor pump operating under cavitation conditions [28] was developed, and the occurrence of cavitation in the distribution zone was substantiated [29–32]. Modeling of the processes occurring in the distribution systems of orbital hydraulic machines has not been carried out.

The conditions of static equilibrium of a mobile ground-based robotic complex were established based on the analytical relationship in the form of the sum of the moments of gravitational processes [33]. A four-mass dynamic model has been constructed, consisting of equations of kinematic constraints and equations of dynamics [34]. Mathematical models have been compiled allow investigating the dynamics and oscillatory processes of multi-element aggregates [35, 36], a measuring system for the dynamics and energy of self-propelled machines has been proposed [37], a parametric model of the dynamics of a cantilever rotor [38], the characteristics of aero- and hydrostatic load-bearing elements are determined [39, 40], the possibility of carrying out hydrodynamic calculations using CFD software packages [41, 42] is considered. The dynamic processes occurring in the hydraulic drives of self-propelled vehicles were not considered.

A universal model of a mechatronic system with a hydraulic drive is considered, the initial conditions of modeling are substantiated [43], proposed mathematical and physical models [44–46], allowing to simulate the processes occurring in planetary hydraulic motors and their elements, hydrodynamic models are considered that will allow one to study the influence of the geometric parameters of the flow paths of a gerotor pump on its output characteristics [47, 48], the dynamics of change in the output characteristics of a mechatronic system with serial and modernized hydraulic motors is investigated, considering the influence of the error in the form of manufacturing elements of the rotor system [5, 49] and the flow area of the distribution system [9, 12]. The dynamics of changes in the output characteristics of hydraulic drives of self-propelled vehicles, considering the design features of orbital hydraulic machines in the conditions of their operation, have not been studied.

Analysis of literature sources related to the solution of the problem posed - stabilization of the output parameters of hydraulic drives, shows that the issues related to the influence of the design features of orbital hydraulic motors on the change in the dynamic characteristics of hydraulic drives have not been given due attention. Therefore, this work is devoted to solving issues related to studying the influence of structural elements of orbital hydraulic motors on the change in the dynamic characteristics of hydraulic drives during their operation on transient processes.

3 Research Methodology

Studies of the influence of the design features of orbital hydraulic motors on the change in the dynamic characteristics of hydraulic drives to stabilize their output parameters are carried out by modeling the transient processes arising during the operation of hydraulic drives of self-propelled equipment. To simulate changes in functional parameters and output characteristics of hydraulic drives of self-propelled vehicles in operating conditions, it is necessary:

– to substantiate the initial data allowing to simulate transient processes occurring in hydraulic drives of self-propelled equipment;
– to develop a structural and functional diagram and mathematical apparatus of a dynamic model of a hydraulic drive of self-propelled equipment, taking into account the conditions of its operation;
– to study the influence of the design features of the rotor system and the distribution system of the orbital hydraulic motor on the dynamics of changes in the functional

parameters and output characteristics of the hydraulic drive during the operation of self-propelled equipment.

The developed mathematical model and the results of the performed parametric studies [43] make it possible to study the change in the functional parameters and output characteristics of hydraulic drives of self-propelled vehicles during transient processes, depending on the difference in the geometric parameters of orbital hydraulic motors.

To simulate the change in the functional parameters and output characteristics of the hydraulic drive depending on the difference in the geometric parameters of the orbital hydraulic motors, when describing the pumping station of the hydraulic system (pump, safety valve, working fluid), the initial data outlined in [43] were taken.

The studies were carried out with two orbital hydraulic motors (No. 1 and No. 2) with a working volume of 160 cm^3. The design differences were as follows: the gap G_t between the teeth of the rotors (considering the error in the profile shape [5]) is 0.02…0.21 mm – for hydraulic motor No. 1, and 0.02…0.065 mm for hydraulic motor No. 2. The area cross-section of the distribution system of the hydraulic motor No. 1 fluctuates in the range of 200…226 mm^2, while for the hydraulic motor No. 2, it is constant and amounts to 226 mm^2. For both hydraulic motors, the moment of resistance is constant and is 365 N·m, the moment of inertia of the rotating masses is 3.6 N·m, the volumetric efficiency is 0.95, and the hydro-mechanical efficiency is 0.9 [9].

The unevenness of the pump flow $Q_p(t)$ and the change in the load on the working element (expressed by the moment of resistance $M_r(t)$) can be represented [43]:

$$\begin{cases} Q_p(t) = Q_\omega \cdot \sin\omega(t) + Q_\omega \cdot \sin\omega(t-\tau), \\ M_r(t) = M_t(t) \cdot \left(1 - e^{-\frac{t}{T}}\right) + M_\omega \cdot \sin\omega(t). \end{cases} \tag{1}$$

Modeling of changes in functional parameters (pressure $p\ (t)$, flow rate $Q_{h.m}\ (t)$ through the hydraulic motor and flow rate $Q_{vol}\ (t)$ through the safety valve) under operating conditions during acceleration of the hydraulic drive of self-propelled vehicles was carried out according to the dependencies

$$\begin{cases} p(t) = f(M_t(t)), \\ Q_{h.m}(t) = \mu \cdot \sum_{i=1}^{Z} \left[\left(\frac{\pi}{z_2} - \Delta \right) - |\beta_i - \alpha_i(t)| \right] \cdot \frac{\left(R_2^2 - R_1^2\right)}{2} \cdot \sqrt{\frac{2p(t)}{\rho}}, \\ Q_{vol}(t) = \mu \cdot \pi \cdot d_{pl} \cdot x(t) \cdot \sqrt{\frac{2p(t)}{\rho}}, \end{cases} \tag{2}$$

where μ and ρ are the flow rate and density of the working fluid; z_2, α_i, β_i, Δ and R_1, R_2 – kinematic, angular and dimensional parameters [9, 12] of the movable and fixed distributors; p_{pl} and $x\ (t)$ are geometrical parameters of the valve.

Modeling of changes in output characteristics (torque M_t (t) and speed n (t) on the shaft of the hydraulic motor) under operating conditions during acceleration of the hydraulic drive of self-propelled vehicles was carried out according to the dependencies

$$\begin{cases} M_t(t) = 2\left(e \pm \frac{G_t}{2}\right) \cdot p(t) \cdot b \cdot (z_1 + 1) \cdot h_i, \\ n(t) = f(Q_{h.m}(t)), \end{cases} \tag{3}$$

where e, b, z_1 and h_i are the kinematic parameters of the hydraulic motor rotors [5].

4 Results

The study of the dynamics of change in the output parameters of a hydraulic drive with an orbital hydraulic motor was carried out using the VisSim dynamic modeling system. The developed structural and functional diagram of the dynamic model of the hydraulic drive of self-propelled vehicles (Fig. 1) allows simulating the transient processes occurring in hydraulic drives under operating conditions, depending on the design features of the rotor system and the distribution system of the orbital hydraulic motor.

The simulation of the unevenness of the pump flow Q_p (t) and the change in the load on the working element, described by expressions (1), was carried out by block A (Fig. 1). Expressions (2), implemented in block B, allow simulating the change in the flow rate of the working fluid through the hydraulic motor and the safety valve, taking into account the design features of the distribution system of the hydraulic motor. The change in torque depending on the gap G_t between the teeth of the rotors, determined by expression (3), is implemented by block C. Block D provides a graphical visualization of the simulation process at each moment of the time.

As a result of the research carried out, dependencies were obtained that characterize the changes in pressure and flow in the hydraulic system (Fig. 2) and changes in the torque and speed on the shaft of the hydraulic motor (Fig. 3). The analysis of the presented dependences shows that the investigated moment of acceleration of the hydraulic drive can be divided into three stages: starting of the hydraulic motor shaft, direct acceleration, and steady motion.

The duration of the first stage, the movement of the hydraulic motor shaft for both hydraulic motors is 0…0.02 s (Fig. 2 – curves 1). The period of the second stage - direct acceleration is 0.02…0.85 s – for hydraulic motor No. 1 and 0.02…0.75 s – for hydraulic motor No. 2. Accordingly, the third stage – steady motion for the hydraulic motor starts from 0.85 s, and for the hydraulic motor 2 – from 0.75 s, which is 12% less.

Analysis of the dependence of the pressure change in the hydraulic system shows that at the first stage, there is a significant pressure jump of 90 MPa and 85 MPa for hydraulic motors No. 1 and No. 2, respectively (Fig. 2a, Fig. 2b – curve 1). Pressure surges are more than 5 times their nominal value. At the second stage, the pressure in the hydraulic system sharply decreases and stabilizes at a value from 29 MPa to 27 MPa, 1.8 times exceeding its nominal value. At the same time, the pressure in the hydraulic motor No. 1 has insignificant pulsations with an amplitude of 3…4 MPa, caused by fluctuations in the flow area of its distribution system and pump flow pulsations (Fig. 2a – curve 1).

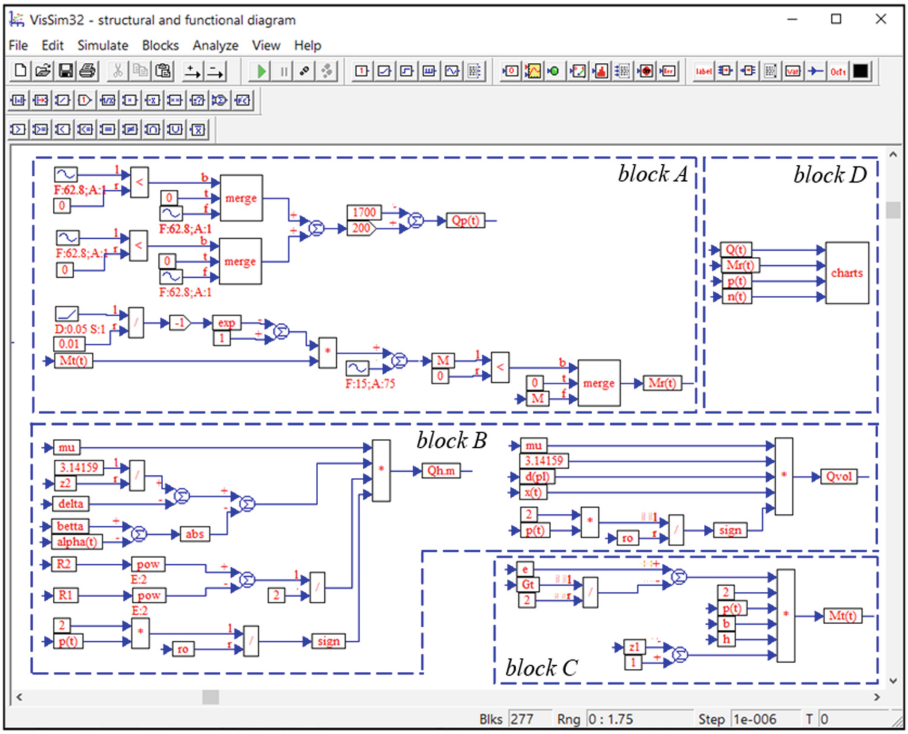

Fig. 1. Structural and functional diagram of a dynamic model of a hydraulic drive of self-propelled vehicles under operating conditions.

There are practically no pressure pulsations in hydraulic motor No. 2 (Fig. 2b – curve 1). Analysis of the pressure change dependence at the third stage shows that the pressure in the hydraulic system decreases, reaching its nominal value. However, in the area under consideration, there are significant pressure fluctuations caused by the pump flow pulsation and fluctuations in the moment of resistance with an amplitude of 15 MPa – for hydraulic motor No. 1 and 10 MPa – for hydraulic motor No. 2, which is 34% less.

An analysis of the dependences of the change in the flow rate of the working fluid through the hydraulic motor, considering the design features of its distribution system, shows that at the first and second stages, the flow rate increases uniformly for both hydraulic motors (Fig. 2 – curves 2). It should be noted that for hydraulic motor No. 1, during this period, there are significant flow rate pulsations caused by the imperfect design of its distribution system and pump flow pulsation, the amplitudes of which are 20…30 l/min (Fig. 2a – curve 2). There is no flow pulsation for hydraulic motor No. 2 at the first and second stages (Fig. 2b – curve 2). For both hydraulic motors, the third stage is characterized by insignificant flow rate pulsations of up to 3 l/min for hydraulic motor No. 1 and up to 2 l/min for hydraulic motor No. 2, caused by pump flow pulsations.

Analysis of the dependences of the change in the flow through the safety valve (Fig. 2 – curves 3) shows that for both hydraulic motors at the first stage, the flow has its maximum value of 98 l/min [43] since the safety valve is fully open. The second

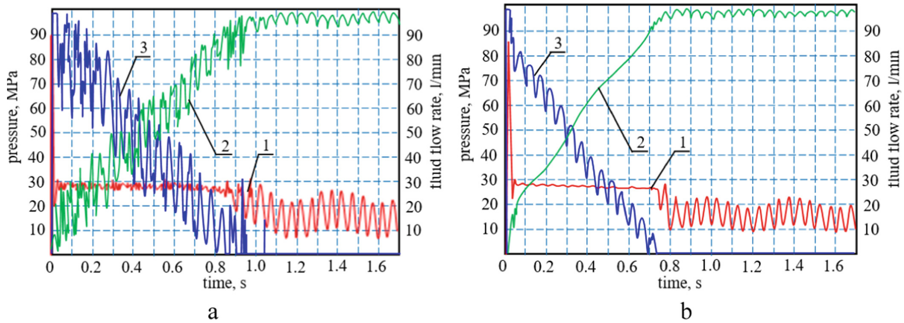

Fig. 2. Changes in the functional parameters of the hydraulic drive in operating conditions during acceleration: a – hydraulic motor No.1; b – hydraulic motor No. 2; 1 – hydraulic pressure; 2 – flow across hydraulic motor; 3 – flow across through safety valve.

stage for both hydraulic motors is characterized by a uniform decrease in flow to zero, which means that the safety valve is completely closed. This period is characterized by significant flow rate pulsations caused by pump flow pulsations - for hydraulic motor No. 1, the amplitude of which is up to 30 l/min, and for hydraulic motor No. 2 – up to 10 l/min, which is 3 times less. In the third stage, there is no flow through the safety valve.

Analysis of the results of studies of the change in torque depending on the gap G_t between the teeth of the rotors shows that for both hydraulic motors at the first stage, there is a rather large jump up to 2100 N·m – for hydraulic motor No. 1 and 1900 N·m – for hydraulic motor No. 2 (Fig. 3 – curves 1). This jump is more than 5 times the rated torque. At the second stage, for both hydraulic motors, there is a sharp decrease in the torque value to 640…620 N·m, 1.8 times exceeding its nominal value. In this section, the torque of the hydraulic motor No. 1 has significant pulsations with an amplitude of 140…150 N·m, caused by the presence of an excessive gap G_t between the teeth of the rotors (Fig. 3a – curve 1). Fluctuations of the torque on the shaft of the hydraulic motor No. 2 in this section are practically absent (Fig. 3b – curve 1). The third stage is characterized by significant fluctuations in torque caused by fluctuations in the moment of resistance M_r with an amplitude of 300 N·m for hydraulic motor No. 1 and 250 N·m for hydraulic motor No. 2, which is 17% less.

The analysis of changes in the speed of the hydraulic motor shaft, taking into account the design features of its distribution system, shows that for both hydraulic motors at the first and second stages, the speed values increase, which is due to the gradual closing of the safety valve (Fig. 3 – curves 2). At the third stage, the speed values having reached their nominal value of 600 min^{-1} [43] are stabilized. However, there are slight pulsations caused by the pump flow pulsation Q_p and sinusoidal disturbances caused by fluctuations in the moment of resistance M_r.

The performed studies have shown that the design features of orbital hydraulic motors significantly impact the change in the dynamic characteristics of hydraulic drives of self-propelled equipment, ensuring their stabilization. Such changes are due to a decrease in the gap G_t between the teeth of the rotors of the hydraulic motor No. 2 and the elimination of fluctuations in the flow area of its distribution system.

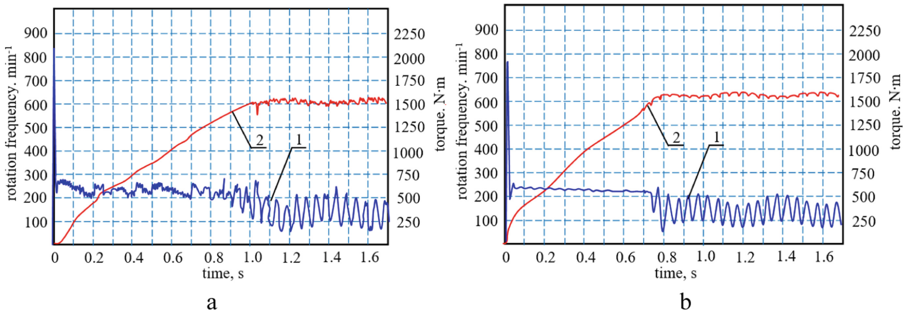

Fig. 3. Changes in the output characteristics of the hydraulic drive under operating conditions during acceleration: a – hydraulic motor No. 1; b – hydraulic motor No. 2; 1 – torque on the shaft of the hydraulic motor; 2 – speed of rotation of a shaft of a hydraulic motor.

5 Conclusions

As a result of the research, the initial data and conditions were substantiated, making it possible to simulate transient processes occurring in the hydraulic drives of self-propelled vehicles.

A structural-functional diagram and a mathematical apparatus have been developed, making it possible to study changes in the dynamic characteristics of a hydraulic drive of self-propelled equipment, taking into account the conditions of its operation.

Changes in the stability of the dynamic characteristics of hydraulic drives of self-propelled vehicles, under the influence of the design features of orbital hydraulic motors, have been determined. It was found that the acceleration time of the hydraulic motor No. 2 is 12% less than that of hydraulic motor No. 1. In comparison, the pressure and torque fluctuations are less at steady-state motion by 34% and 17%, respectively. Such changes are due to a decrease in the gap G_t between the teeth of the rotors of the hydraulic motor No. 2 and the elimination of fluctuations in the flow area of its distribution system.

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