Changes in the dynamics of the output characteristics of mechatronic systems with planetary hydraulic motors

A Voloshina¹, A Panchenko¹, O Titova¹, I Panchenko¹

¹ Dmytro Motorny Tavria State Agrotechnological University,
18 B. Khmelnytsky Ave., Melitopol 72310, Ukraine

E-mail: voloshinaa2012@gmail.com

Abstract. A structural-functional diagram of a dynamic model of a mechatronic system with a planetary hydraulic motor is proposed. The initial conditions for the simulation of transients occurring in a mechatronic system with a planetary hydraulic motor are substantiated. The design parameters of the distribution system, which determine the unevenness of the output characteristics of the planetary hydraulic motor, are also substantiated. The influence of the design features of a serial and modernized hydraulic motors on the dynamic processes of the mechatronic system is investigated. It is established that fluctuations in the flow area of the distribution system of a serial hydraulic motor cause pulsations of torque on the hydraulic motor shaft and pressure in the discharge line of the mechatronic system. At the time of acceleration, significant pulsations of the flow of working fluid through the safety valve are observed, and as a result, pulsations of the flow of working fluid through the hydraulic motor. Elimination of fluctuations in the flow area of the distribution system of the upgraded hydraulic motor allows you to stabilize the values of pressure, torque and flow rate of the working fluid throughout the study of the acceleration process. Under steady-state operation, fluctuations in the area of the passage section of the distribution system do not affect the nature of the change in the shaft speed, either of the modernized or serial hydraulic motors.

1. Introduction

At present, gerotor [1–3], orbital [1, 4–9] and planetary [10–13] hydraulic machines are widely used in hydraulic drives of mechatronic systems of self-propelled machinery. From the point of view of self-propelled equipment, planetary hydraulic machines deserve the greatest attention, having the ability to install directly into the drive mechanisms conveyors, winches, motor wheels, etc. The main components of planetary hydraulic machines are rotor systems and distribution of the working fluid. The design of the rotor system is based on the principle of operation of a gear pair (movable and fixed rotors) with internal hypocycloidal gearing [7, 8]. The distribution system of planetary hydraulic machines is formed by movable and fixed distributors, which allows the formation of a rotating hydraulic field, necessary to obtain the planetary motion of the rotors [9–13]. One of the disadvantages of planetary hydraulic machines is the unevenness of the output characteristics due to the pulsation of the flow of the working fluid in the distribution systems [11].

The quality of the mechatronic system with a planetary hydraulic motor is largely determined by the stability of the output characteristics of the hydraulic motor. In order to improve the functioning of self-propelled equipment, by predicting the output characteristics of its mechatronic systems, it is
necessary to study the influence of design features of the planetary hydromotor distribution system on changes the dynamics of transients occurring in these systems.

2. Review of literary sources

The increasing performance requirements of mechatronic systems with a hydraulic drive of active working bodies of self-propelled vehicles require the use of new approaches in the process of their development and design [6]. The functional parameters of mechatronic systems depend on a rational choice of the operating modes of the hydraulic system and the structural design of mechatronic modules and their elements [5].

A significant part of the structures incorporates parts that are in contact interaction with each other. Therefore, an important aspect in the study of the stress-strain state of such structures is the determination of the dependence of the contact pressure on the external forces that act on them [14]. In order to ensure high technical characteristics of machines, contact interaction models have been developed that combine physical and structural nonlinearity [15]. The factors determining the stress-strain state of the systems studied are established: geometric nonlinearity, contact interaction, friction and slippage [16]. A nonlinear mathematical model is obtained that allows one to analytically determine hydraulic losses [17]. An approach has been developed involving a combination of analytical models and methods for analyzing the stress-strain state of elements taking into account contact interaction [18]. The developed approach is based on the use of a mathematical nonlinear model of the stress-strain state and approximation methods for constructing functions that describe the characteristics of the studied object [19]. Questions related to the study of working processes occurring in the elements of mechatronic systems with a hydraulic drive are not considered.

Geometrical, mathematical, and hydrodynamic models have been proposed [1, 2], which allow one to study the influence of the geometric parameters of the flowing parts of the gerotor pump on its output characteristics. However, for the functioning of the gerotor pump there is no need to create a rotating hydraulic field of the working fluid necessary for the operation of the rotors of the planetary hydraulic motor.

Modeling the flow of working fluid through the channels of gerotor motors [20, 21] substantiates the causes of cavitation phenomena in the distribution zone, an approach is proposed for predicting cavitation [22]. Based on modeling and experimental studies [4], a semi-empirical approach is proposed for evaluating interchamber leakage resistance. A mathematical apparatus is proposed for determining feed pulsation for machines with internal cycloid gearing [23]. A 3D model of gerotor hydraulic motors [24] and an energy loss model with an emphasis on losses created by the compressibility of the working fluid [25] are proposed. Experimental confirmation of the proposed model is presented [26]. Modeling of the distribution system of the planetary hydraulic motor was not considered.

Design constructive methods for expanding the feed channels in planetary hydraulic machines have been proposed [27], a systematization of planetary rotary-hydraulic machines with floating rollers has been presented [28]. The methods for distributing the working fluid necessary to create a rotating hydraulic field are not considered.

With a variety of designs, planetary hydraulic machines can be combined into three main nodes, which determine the effectiveness of these hydraulic machines. This is a force connection with a special cycloid profile of the external and internal rotors [7, 8], a mechanism that compensates for the planetary motion of the rotors [7, 10] and a distribution mechanism [9, 12, 13], which creates the hydraulic field [11] necessary for the rotors to work. The influence of the design features of planetary hydraulic machines on the dynamics of changes in their output characteristics and the mechatronic system as a whole has not been studied.

An analysis of the work performed showed that the influence of the design features of the distribution systems of planetary hydraulic motors on changes in the dynamics of the output characteristics of transients occurring in mechatronic systems has not been studied. Thus, one of the urgent tasks associated with improving the quality of functioning of self-propelled equipment is
predicting changes in the output characteristics of mechatronic systems by studying the influence of design features of the distribution systems of planetary hydraulic motors on the dynamic processes occurring in these systems.

3. Research methodology
To study the dynamic processes occurring in mechatronic systems with planetary hydraulic motors, in order to predict changes in the stability of their output characteristics, it is necessary:
- to develop a structural-functional diagram of a dynamic model of a mechatronic system with a planetary hydraulic motor, taking into account the design features of its distribution system;
- substantiate the initial data and initial conditions for the simulation of transients occurring in a mechatronic system with a planetary hydraulic motor, as well as the design parameters of the distribution system of the planetary hydraulic motor, affecting the change in its output characteristics;
- to study the dynamics of changes in the output characteristics of the mechatronic system with serial and upgraded hydraulic motors, taking into account the design features of their distribution systems.

4. Results
The developed mathematical models and the performed parametric studies [9–13] allow us to study the dynamic processes occurring in the mechatronic system with a planetary hydraulic motor. The studies were conducted on the basis of the developed universal model of the mechatronic system [6], taking into account the design features of the serial and modernized distribution systems of the planetary hydraulic motor.

Previous theoretical studies [10, 11] made it possible to identify the design features of the distribution system that affect the change in the output characteristics of the planetary hydraulic motor, as well as to justify the most rational geometric parameters of the working fluid distribution system. It was found that the most rational is a distribution system with a 7/6 kinematic scheme [10].

Studies of the dynamics of changes in the output characteristics of a mechatronic system with a planetary hydraulic motor were carried out using the Vissim simulation package.

In studies of the mechatronic system, the following initial data and initial conditions were adopted [6]:
- pump: the pump flow is constant and equal to \( Q_{n.g}(t) = 1770 \, \text{cm}^3/\text{s} \); the angular velocity of the pump shaft is equal to \( \omega_n = 125 \, \text{s}^{-1} \); for an unregulated pump, the control parameter is \( e = 1 \); pressure in the drain line is \( p_{sl} = 0 \);
- hydraulic motor: the working volume of the hydraulic motor is equal to \( V_{0gm} = 160 \, \text{cm}^3 \); the moment of resistance is constant and equal to \( M_r = 365 \, \text{N\cdotm} \); the moment of inertia of the rotating mass is \( J = 3.6 \, \text{N\cdotm} \); volumetric efficiency of the hydraulic motor - \( \eta_{ob} = 0.95 \); hydromechanical efficiency of the hydraulic motor - \( \eta_{gm} = 0.9 \); the change in the cross-sectional area of the distribution system with a kinematic scheme 6/7 of serial hydraulic motor is \( A = 222 \ldots 226 \, \text{mm}^2 \) (with the additional use of three discharge windows); for the distribution system of the modernized hydraulic motor, the passage area is constant and equal to \( A = 226 \, \text{mm}^2 \) (with the additional use of two discharge windows);
- safety valve: spring stiffness equal to \( C = 200 \, \text{kg/cm} \); spring pre-compression value \( x_0 = 0.125 \, \text{cm} \); positive gap overlap is \( x_z = 0.53 \, \text{cm} \);
- working fluid: the polytropic index is \( K = 1.2 \); the parameters of the working fluid, depending on the type of oil and the working temperature of the hydraulic system are \( A = 12.62 \) and \( B = 1740 \); the content of undissolved air in the working fluid in relative units is \( m_0 = 0.925 \).

Simulation of transients occurring in the mechatronic system was performed for both serial and modernized planetary hydraulic motors. When modeling, the initial data are set by block 1 of the structural-functional diagram of the dynamic model of the mechatronic system with a planetary hydraulic motor (Fig. 1). Block 2 allows you to determine the angular location of the windows of the movable and fixed distributors. The change in the cross-sectional area of the distribution system of a
serial and upgraded hydraulic motors is described in block 3, and the change in volumetric losses, taking into account the design features of the distribution system of a serial and upgraded hydraulic motors, is described in block 4. The change in pressure in the mechatronic system, taking into account the change in the cross-sectional area of the distribution system of a serial and modernized hydraulic motors, is described unit 5. Change the flow rate of the working fluid, taking into account the design features of the distribution the system is represented by block 6.

**Figure 1.** Structural and functional diagram of a dynamic model of a mechatronic system with a planetary hydraulic motor.
Block 7 describes the change in torque, and the change in angular velocity is described by block 8. Block 9 allows you to display graphical dependencies of the pressure in the mechatronic system, torque, speed, as well as the flow rate through the safety valve and planetary hydraulic motor with taking into account the design features of the distribution system under various operating conditions and at any time.

The simulation results are represented by the corresponding dependencies:
- the dynamics of pressure changes in the discharge line of the mechatronic system and the flow rate of the working fluid through the hydraulic motor and safety valve (Fig. 2);
- dynamics of changes in torque and frequency of rotation of the motor shaft (Fig. 3).

An analysis of the pressure change in a mechatronic system with a serial hydraulic motor shows that during acceleration ($t = 0...0.007 \, \text{s}$) there is a rather large pressure surge up to 88 MPa (Fig. 2a – curve 1) 5.5 times higher than its value at steady motion. Further, the pressure is stabilized and with significant pulsations up to 18%, the amplitude of which is 2 ... 2.5 MPa, gradually decreases from 29 MPa to 26.5 MPa.

Pressure fluctuations in the mechatronic system during this period of time ($t = 0.007...0.8 \, \text{s}$) are caused by fluctuations in the flow area of the distribution system of a serial hydraulic motor. With further acceleration ($0.8 < t < 0.9 \, \text{s}$), the pressure decreases quite sharply and reaches its nominal value. Further, at $t > 0.9 \, \text{s}$, a steady motion of the shaft of the hydraulic motor operating as part of the mechatronic system is observed. In this case, pressure fluctuations caused by the design features of the distribution system are reduced and amount to 9...10% with an oscillation amplitude of 1.5MPa. It should be noted that there are no pressure fluctuations in the mechatronic system with the modernized hydraulic motor (Fig. 2b – curve 1) due to the absence of fluctuations in the passage area of the modernized distribution system.

![Figure 2](image1.png)

**Figure 2.** Dependences of pressure and flow rate in the acceleration mode of the mechatronic system:

- a – serial hydraulic motor; b – a modernized hydraulic motor;
- 1 – pressure curve; 2 – curve of the flow of the working fluid through the hydraulic motor;
- 3 – curve of the flow of working fluid through the safety valve.

An analysis of the change in the flow rate of the working fluid passing through the hydraulic motor during acceleration ($0 < t < 0.08 \, \text{s}$) shows that the flow values have quite significant pulsations up to 40 l/min (Fig. 2a – curve 2), caused by the design features distribution system of the serial hydraulic motor. Further ($0.08 < t < 0.9 \, \text{s}$), the flow rate of the working fluid increases uniformly with a significant reduction in pulsations. With further acceleration ($t > 0.9 \, \text{s}$), the flow rate reaches its nominal value with small ripples of up to 2 l/min. It should be noted that there are no fluctuations in the flow rate of the working fluid in the upgraded hydraulic motor (Fig. 2b – curve 2) due to the absence of fluctuations in the passage area of the upgraded distribution system.

An analysis of the change in the flow rate of the working fluid through the safety valve during acceleration ($0 < t < 0.08 \, \text{s}$) shows that the flow rate reaches its maximum value of 98 l/min (Fig. 2a –
curve 3) and has quite significant pulsations up to 40 l/min caused by the irrational design of a serial hydraulic motor. Further (0.08 < t < 0.75 s), the flow rate of the working fluid through the safety valve is uniformly reduced. At the same time, the magnitude of the ripple also decreases. Upon further acceleration (t > 0.75 s), the valve closes completely, characterizing the steady-state movement of the motor shaft operating as part of the mechatronic system. When studying the dynamics of changes in the flow rate of a working fluid through a safety valve in a mechatronic system with a modernized hydraulic motor, there are no flow pulsations (Fig. 2b – curve 3).

An analysis of the change in the torque of the shafts of a serial hydraulic motor shows that during acceleration (t = 0...0.007 s) a rather large torque is observed up to 2000 N·m (Fig. 3a – curve 1), above face value 5.7 times. With further acceleration (t > 0.04 s), the torque values decrease and have a ripple frequency of up to 17%, which amounts to 65...70 N·m, due to the design parameters of serial distribution system. Further (0.04 < t <0.8 s), the torque values gradually decrease from 670 to 610 N·m, exceeding 1.7 times their nominal value and at t > 0.9 s reach the nominal value with slight ripple up to 35 N·m. In all studies of the acceleration process of the modernized hydraulic motor, torque pulsations are absent (Fig. 3b – curve 1).

An analysis of the change in the rotational speed of the hydraulic motor shaft during its acceleration (0 < t <0.9 s) shows that the changes in the rotational speed of the shaft of both serial and modernized hydraulic motors are linear (Fig. 3, a, b – curve 2). The values of the rotational speed gradually increase, reach the nominal value, and at t > 0.9 s there is a steady motion of the shaft of serial and modernized hydraulic motors. It should be noted that the design features of the serial and upgraded distribution systems do not affect the dynamics of the rotation frequency of the hydraulic motor shaft.

**5. Conclusions**

As a result of the studies, a structural-functional diagram of a dynamic model of a mechatronic system with a planetary hydraulic motor was developed, taking into account the design features of its distribution system. The initial data and initial conditions for the simulation of transients occurring in a mechatronic system with a planetary hydraulic motor are substantiated. The design parameters of the distribution system of the upgraded planetary hydraulic motor, which affect the change in its output characteristics, are substantiated. The dynamics of changes in the output characteristics of the mechatronic system with serial and modernized hydraulic motors is studied, taking into account the design features of their distribution systems.

It has been established that insignificant fluctuations in the cross-sectional area of the serial distribution system (222...226 mm²) of the planetary hydraulic motor cause significant pressure pulsations of up to 10%, flow rate of the working fluid up to 3% and torque up to 17%. Moreover, the elimination of fluctuations in the flow area of the modernized distribution system (226 mm²) allows you to stabilize the values of pressure, torque and
flow rate of the working fluid throughout the study of the acceleration process.
Under steady-state operation, fluctuations in the flow area of the distribution system do not affect the nature of the change in the shaft speed, either of the upgraded or serial motors.

The conducted studies of the dynamic processes occurring in the drives of mechatronic systems with planetary hydraulic motors make it possible to improve the functioning of self-propelled equipment by predicting the output characteristics of these systems at the stages of design, manufacture and operation.

References
[1] Gamez-Montero P J, Codina E, Castilla R A 2019 Review of gerotor technology in hydraulic machines Energies 12 2423
[2] Altare G, Rundo M 2016 Computational fluid dynamics analysis of gerotor lubricating pumps at high-speed: geometric features influencing the filling capability Journal of Fluids Engineering 138 (11) FE-15-1757
[3] Chiu-Fan H Flow 2015 Characteristics of gerotor pumps with novel variable clearance designs Journal of Fluids Engineering 137 (4) FE-14-1137
[4] Dasgupta K, Mukherjee A, Maiti R 1999 Estimation of critical system parameters that affect orbit motor performance-combining simulation and experiments J. of Manuf. Sc. and Eng.- Trans. of the ASME 121 (2) 300-306
[5] Panchenko A, Voloshina A, Milaeva I and Luzan P 2019 Operating conditions’ influence on the change of functional characteristics for mechatronic systems with orbital hydraulic motors Modern Development Paths of Agricultural Production 169-176
[6] Panchenko A, Voloshina A, Kiurchev S et al 2018 Development of the universal model of mechatronic system with a hydraulic drive East.-Eur. J. of Enterpr. Tech. 4 (7(94)), 51–60
[7] Panchenko A, Voloshina A, Milaeva I, Panchenko I, Titova O 2018 The Influence of the form error after rotor manufacturing on the output characteristics of an orbital hydraulic motor. Int. J. of Eng. and Tech. 7 (4.3) 1-5
[8] Panchenko A, Voloshina A, Panchenko I, Titova O, Pastushenko A 2019 Reliability design of rotors for orbital hydraulic motors IOP Conf. Ser.: Mater. Sci. Eng. 708 (1) 012017
[9] Voloshina A, Panchenko A, Panchenko I and Zasiadko A 2019 Geometrical parameters for distribution systems of hydraulic machines Modern Development Paths of Agricultural Production 323-336
[10] Panchenko A, Voloshina A, Boltiansky O et al 2018 Designing the flow-through parts of distribution systems for the PRG series planetary hydraulic motors East.-Eur. J. of Enterpr. Tech. 3 (1(93)) 67–77
[11] Voloshina A, Panchenko A, Boltiansky O, Panchenko I, Titova O 2018 Justification of the kinematic diagrams for the distribution system of a planetary hydraulic motor Int. J. of Eng. and Tech. 7 (4.3) 6–11
[12] Voloshina A, Panchenko A, Panchenko I, Titova O, Zasiadko A 2019 Improving the output characteristics of planetary hydraulic machines IOP Conf. Ser.: Mater. Sci. Eng. 708 (1) 012038
[13] Voloshina A, Panchenko A, Boltiansky O, Titova O 2020 Improvement of manufacture workability for distribution systems of planetary hydraulic machines In: Ivanov V et al (eds) Advances in Design, Simulation and Manufacturing II DSMIE 2019 Lecture Notes in Mechanical Engineering 732-741
[14] Tkachuk M M, Grabovskiy A, Tkachuk M A, Saverska M, Hrechka I 2020 A semi-analytical method for analysis of contact interaction between structural elements along aligned surfaces East.-Eur. J. of Enterpr. Tech. 1/7 (103) 16–25
[15] Tkachuk M M, Skripchenko N, Tkachuk M A, Grabovskiy A 2018 Numerical methods for contact analysis of complex-shaped bodies with account for non-linear interface layers East.-Eur. J. of Enterpr. Tech. 5/7 (95) 22–31
[16] Atroshenko O, Tkachuk M, Martynenko O, Tkachuk M, Saverska M, Hrechka I, Khovanskyi S
2019 The study of multicomponent loading effect on thin-walled structures with bolted connections East.-Eur. J. of Enterpr. Tech. 1/7 (97) 15-25

[17] Khovanskyi S, Pavlenko I, Pitel J, Mizakova J, Ochowiak M, Grechka I 2019 Solving the coupled aerodynamic and thermal problem for modeling the air distribution devices with perforated plates Energies 12 (18) 3488

[18] Tkachuk M M, Grabovskiy A, Tkachuk M A, Hrechka I, Ishchenko O, Domina N 2019 Investigation of multiple contact interaction of elements of shearing dies East.-Eur. J. of Enterpr. Tech. 4/7 (100) 6–15

[19] Bondarenko M, Tkachuk M, Grabovskiy A, Hrechka I 2019 Substantiation of thin-walled structures parameters using nonlinear models and method of response surface analysis Int. J. of Eng. Research in Africa 44 32–43

[20] Velev E 2016 Study cavitation gerotor motors using computer simulation Proc. XV International Scientific Conference: Renewable Energies and Innovative Technologies 64-66

[21] Marcu I L, Pop I I 2004 Interconnection possibilities for the working volumes of the alternating hydraulic motors Scientific Bulletin of the Politehnica University of Timisoara: Transactions on Mechanics: The 6th International Conference on Hydraulic Machinery and Hydrodynamics 365–370

[22] Shah Y G, Vacca A, Dabiri S 2018 A fast lumped parameter approach for the prediction of both aeration and cavitation in Gerotor pumps Meccanica 53 (1-2) 175-191

[23] Yang D, Yan J, Tong S 2010 Flowrate Formulation of Deviation Function Based Gerotor Pumps Journal of Mechanical Design 132 (6) 064503-5

[24] Ding H, Lu X J, Jiang B 2012 A CFD model for orbital gerotor motor IOP Conf. Ser.: Earth Environ. Sci. 15 (6) 062006

[25] Van de Ven J D 2012 On Fluid Compressibility in Switch-Mode Hydraulic Circuits – Part I: Modeling and Analysis J. of Dyn. Syst., Measur., and Contr. 135 (2) 021013-021013-13

[26] Van de Ven J D 2012 On Fluid Compressibility in Switch-Mode Hydraulic Circuits – Part II: Modeling and Analysis J. of Dyn. Syst., Measur., and Contr. 135 (2) 021014-021014-7

[27] Smirnov V V, Volkov G U 2019 Computation and structural methods to expand feed channels in planetary hydraulic machines J. Phys.: Conf. Ser. 1210 012131

[28] Smirnov V V, Volkov G U 2018 Systematization and comparative scheme analysis of mechanisms of planetary rotary hydraulic machines MATEC Web of Conferences 224 02083