The influence of the design parameters of the rotors of the planetary hydraulic motor on the change in the output characteristics of the mechatronic system

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Abstract. One of the main stages of research related to increasing the efficiency of planetary hydraulic motors operating as part of the mechatronic systems of self-propelled vehicles is the experimental research of real samples. Experimental studies of the influence of design features of the rotor system of serial and modernized hydraulic motors on the output characteristics of mechatronic systems were carried out by means of comparative bench tests. A technique has been developed for conducting comparative bench studies of planetary hydraulic motors. A test bench scheme is proposed for testing a family of unified series of high-torque, low-speed planetary-type hydraulic motors. The main factors determining the change in the output characteristics of the planetary hydraulic motor, taking into account the design features of the rotor system, are: pressure drop, flow rate of the working fluid and the error the manufacturing form of the gear profile of its rotors. Tests of planetary hydraulic motors with a serial and modernized rotor systems were carried out. The modernization of the rotor system was carried out by changing the design of the external and internal rotors in order to reduce the shape error of their gear profile. As a result of experimental studies, it was found that eliminating the error the manufacturing form of the rotors of the modernized hydraulic motor can significantly improve its output characteristics - increase the torque at specified rotation speeds, and as a result, increase the hydromechanical and overall efficiency of the mechatronic system as a whole.

1. Introduction

Actuators of hydraulic drives of mechatronic systems of self-propelled machinery are most often equipped with gerotor [1], orbital [2] and planetary [3] hydraulic motors. One of the advantages of these hydraulic motors is the possibility of installing directly in the drive mechanisms of the active working bodies of self-propelled equipment, which greatly simplifies the kinematic scheme of the self-propelled machine, improving its weight characteristics [4]. The main structural feature of the hydraulic machines under consideration, in particular planetary ones, is the rotor system (external and internal) that forms the working chambers necessary for filling and displacing the working fluid [5, 6]. The external rotor together with the internal one is a gear pair with internal gearing, which simultaneously performs two functions. The first function is the running-in of the internal rotor inside the external, and the second is the sealing of the working chambers of the planetary hydraulic motor. The working chambers are sealed with a hypocycloidal gear profile of the external and internal rotors of the planetary hydraulic motor with a minimum clearance between the rotors.
It should be noted that the inner surface of the hypocycloidal gearing of the outer rotor is an equi-
distant curve approximated by circular arcs made in the form of rollers [5, 6]. This design of the ex-
ternal rotor allows you to replace sliding friction with rolling friction, which can significantly reduce contact stresses in the gear pair and increase the mechanical efficiency of the rotor system (total mesh-
ing). The disadvantages of the presented system of rotors of planetary hydraulic machines, as well as many rotary hydraulic machines of hydrostatic action, are the presence of an error in the shape of the gear profile due to the accuracy of their manufacture, which leads to a decrease in the output character-
istics of these hydraulic machines. One way to address these shortcomings is to modernize the sys-

tem of rotors of planetary hydraulic machines by changing their design in order to reduce the shape error of the gear profile.

The output characteristics of the mechatronic system of self-propelled equipment is determined by
the parameters of the hydraulic motors used in the output links of the mechatronic devices. Therefore,
this work is devoted to research aimed at increasing the output parameters of planetary hydraulic mo-
tors by improving the design of their rotors in order to improve the output characteristics of mecha-
tronics systems of self-propelled vehicles.

2. Review of literary sources

It is known [7] that a significant part of the designs of machines, engines, machine tools, technolog-
ical equipment, etc. consists of parts in contact with each other. Today, much attention is paid to studies of
the stress-strain state of such structures, i.e. determination of the dependence of contact pressure on the
external forces that act on them [8]. The regularities of the distribution of contact pressure have been
established [9], a new method has been developed for studying the stress-strain state and ensuring the
strength of machine parts for various purposes [10, 11]. The stress-strain state of the contacting parts
of the gerotor, orbital and planetary hydraulic machines was not considered.

An analysis of literary sources showed [12] that there are currently very few published literature on
the methodology for the design and manufacture of gerotor, orbital and planetary hydraulic machines.
Modern approaches and new concepts of orbital and planetary hydraulic machines are formulated,
geometric [13], mathematical [3, 14] and dynamic [4, 15] models are developed that allow simulating
operating conditions. The modeling of the processes occurring in the rotor system [5, 6] and the distrib-
ution system [16, 17], aimed at studying the changes in their output characteristics, was carried out.
The analysis of productivity [2] and wear of mating elements [18] was carried out using numerical
modeling and experimental studies, as applied to orbital type hydraulic motors. Theoretical and expe-
imental studies of the characteristics of the steady-state regime of a low-speed hydraulic motor with a
small number of rotor revolutions have been performed [19]. A test setup with hydraulic components
and sensors [1] for testing a gerotor engine, which is very rarely described in the literature, is present-
ed. A comprehensive study of a hydrostatic installation with a low rotational speed of the orbital rotor
in a hydrostatic transmission system was carried out and some critical parameters were evaluated [20].
Not considered issues related to experimental studies of planetary hydraulic machines used in mecha-
tronics systems of self-propelled vehicles.

The characteristics of the parameters of hydraulic motors with cycloid transmission of the internal
and external rotor systems are considered [21]. Hydraulic machines with epicycloidal and hypocyc-
loidal gearing in a rotor system are compared. The parametric equations that determine the set of
gears with round teeth are obtained and implemented, an algorithm for generating a gerotor gear wheel
is developed [22]. The optimal tooth profile for cycloidal gears was substantiated [23], numerical
models of cycloidal gears using the finite element method [24] were developed. A model was devel-
oped that describes changes in the geometry of rotor working surfaces [25], forces acting in gearing
[26] are considered. A method is proposed for determining the load range for gear rotors [27], methods
for increasing the load limit for cycloidal gear rotors [28] are presented. A mathematical apparatus has
been developed that makes it possible to implement a method for determining the reliability of an or-
bital hydraulic motor by modeling changes in the technical condition of its gearing [5]. The marginal
deviations of the error in the manufacturing form of the gear surface of the internal and external rotors
are justified [6]. The influence of the error in the manufacturing form of the rotors of planetary hydraulic motors on the change in their output characteristics has not been studied.

The analysis of the performed studies shows that the influence of the manufacturing error of the gear surface of the external and internal rotors of planetary hydraulic machines on changes in the output characteristics of mechatronic systems has not been studied. In this regard, one of the urgent tasks associated with improving the output characteristics of the mechatronic systems of self-propelled vehicles is experimental research to determine changes in the output characteristics of planetary hydraulic machines during their modernization.

3. Research Methodology
To conduct studies determining the effects of improving the design of rotors of a planetary hydraulic motor on changing its output parameters in order to improve the output characteristics of mechatronic systems of self-propelled vehicles, it is necessary:

- develop a methodology for conducting experimental studies of the influence of design parameters of rotor systems of serial and modernized hydraulic motors on their output characteristics;
- to develop a basic hydraulic circuit of an experimental bench for comparative bench tests of high-torque low-speed hydraulic motors;
- to study the change in the output characteristics of the mechatronic system with serial and upgraded planetary hydraulic motors, taking into account the design features of their rotor system.

The main factors determining the changes in the output characteristics of the planetary hydraulic motor, taking into account the design features of the rotor system, are: pressure difference $\Delta p$, flow rate $Q_{\text{nom}}$ and the shape error of the gear profile of the rotors $E$. By the error in the shape of the gear profile of the rotors of the planetary hydraulic motor, we agree to understand the quantitative deviations of the real geometric dimensions of the elements of the gear surface determined by the manufacturing technology from the calculated ones.

The study of changes in the output parameters of an upgraded planetary hydraulic motor is evaluated according to the results of its comparative tests with a serial hydraulic motor.

The tests were carried out with planetary hydraulic motors with a working volume of 630 cm$^3$ (with a serial and modernized rotor system). In the modernized design of the hydraulic motor, in order to increase the comparability of the research results, all details of the serial hydraulic motor, except rotors, were used. The error in the manufacturing form of the rotors of the upgraded hydraulic motor was $E = 0.02...0.065$ mm, and the serial error was $E = 0.02...0.21$ mm.

The nominal (current) value of the flow rate was established by changing the flow of the working fluid when the hydraulic motor was idling (without load), respectively, equal to 50, 70, 90 and 110 l/min.

The pressure difference was set by the corresponding change in the load of the test bench in the range of 8, 16 and 20 MPa, respectively. The required load was set using the brake device of the test bench in the range of 100...1500 N·m in increments of 1000 N·m.

Previously performed theoretical studies (development of mathematical models [3, 4], parametric studies [5, 6], etc.) are associated with a number of assumptions and limitations. Therefore, in order to adjust the models, determine its adequacy, as well as determine the effectiveness of the theoretical results obtained, one of the main stages of comprehensive research is the comparative bench tests of serial and modernized planetary hydraulic motors.

To carry out bench tests of serial and upgraded planetary hydraulic motors, a basic hydraulic diagram of the bench (Fig. 1) was developed, which shows the location, relationship and operation of its main elements.

The working fluid required for testing is in tank 12 with a volume of 250 liters. When testing hydraulic motors, the working fluid from tank 12 is supplied to an adjustable axial piston pump 1.1 ($Q = 220$ l/min, $p = 30$ MPa) using a recharge pump 1.2 ($Q = 20$ l/min, $p = 1.5$ MPa).

To prevent overloads that occur during testing of the hydraulic motor 2.1, a safety valve 4.1 is installed in parallel with the pump 1.1. The pressure of the working fluid at the outlet of the pump 1.1 is controlled by a pressure gauge 9.1.
In order to ensure the necessary flow rate of the working fluid at the inlet to the pump 1.1, an overflow valve 4.2 is installed in parallel with the feed pump 1.2. The liquid pressure in the make-up line (at the outlet of the pump 1.1) is controlled by a pressure gauge 9.2.

**Figure 1.** Schematic diagram of the hydraulic experimental setup for testing a family of unified high-torque hydraulic motors:

1.1 – adjustable axial piston pump; 1.2 – vane feed pump; 2.1 – test planetary hydraulic motor; 2.2 – calibrated axial piston hydraulic motor; 3 – switch; 4.1 – safety valve; 4.2 – overflow valve; 5.1, 5.2 – fine filters; 6 – heat exchanger; 7.1, 7.2 – drive electric motors; 8 – powder brake; 9.1–9.4 – pressure gauges; 10.1, 10.2 – tachometers; 11 – thermometer; 12 – tank.

The pumps 1.1 and 1.2 are driven by drive electric motors 7.1 and 7.2, respectively. Further, from the axial piston pump, the fluid flows to the switch 3 and from it to the tested high-torque low-speed hydraulic motor 2.1. After passing through the control hydraulic motor 2.1, the working fluid returns to the commutator 3 and then through the fine filter 5.1, it is fed to a calibrated axial piston hydraulic motor 2.2. After the hydraulic motor 2.2, the working fluid through the fine filter 5.2 and the heat exchanger 6 is returned to the tank 12.

When testing as a load (to create the necessary braking torque), a powder brake 8 works. The reversing direction of rotation of the tested hydraulic motor 2.1 is provided by commutator 3.

The pressure at the inlet and outlet of the tested hydraulic motor 2.1 is controlled using gauges 9.3 and 9.4. The rotational speed of the hydraulic motor shaft is determined using a tachometer 10.1 with a pulse sensor and a disk mounted on the powder brake shaft 8. The flow rate of the working fluid passing through the tested hydraulic motor 2.1 is determined indirectly by the rotational speed of the shaft, the calibrated axial piston motor 2.2, the rotational speed which is determined by the tachometer 10.2.

Filtration of the working fluid is carried out using fine filters 5.1 and 5.2. The required temperature of the working fluid in the tank 12 is provided by a heat exchanger 6 with forced cooling with running water and is controlled by a thermometer 11.

According to the results of measuring the pressure drop and torque, the mechanical efficiency of the tested hydraulic motor is determined, and the results of measurements of the frequency of rotation
of the hydraulic motor shaft and the flow rate of the working fluid make it possible to determine the volumetric efficiency. The remaining characteristics of the tested hydraulic motor are determined by calculation by well-known methods.

4. Results

As a result of the studies, it was found (Fig. 2, Fig. 3) that for all pressure differences ($\Delta p = 8 \, MPa, \Delta p = 16 \, MPa, \Delta p = 20 \, MPa$) and intervals of change in rotational speeds ($n = 35...200 \, min^{-1}$) volumetric efficiency as serial (Fig. 2a – curve 1), and of the modernized (Fig. 2a – curve 2) hydraulic motors practically does not change and is close to unity. A slight decrease in volumetric efficiency to 0.87 (Fig. 2a – curve 2) is observed at low rotational speeds of the shaft of the upgraded hydraulic motor ($n = 40...70 \, min^{-1}$). High stability of volumetric efficiency in a wide range of rotational speeds indicates that the self-sealing of the modernized rotor system and serial are similar.

For pressure differences ($\Delta p = 8, 16$ and $20 \, MPa$) and intervals of change in rotational speeds ($n = 35...200 \, min^{-1}$), the nature of the change in the hydromechanical efficiency of serial and modernized hydraulic motors practically does not change. Some nonlinearity is observed in changes in hydromechanical efficiency depending on the frequency of rotation of the motor shaft with a pressure difference $\Delta p = 20 \, MPa$ (Fig. 2b). It was found that the hydromechanical efficiency of the modernized hydraulic motor is 0.95 (Fig. 2b – curve 2), which is 7...10% higher than the serial (Fig. 2b – curve 1). With an increase in the rotational speed of the hydro-motor shaft to $200 \, min^{-1}$, both the modernized and serial hydro-motors are characterized by a decrease in hydromechanical efficiency. Such a decrease in hydromechanical efficiency is associated with an increase in losses in the distribution system at a rotational speed of the hydraulic motor shaft exceeding the nominal value ($150 \, min^{-1}$).

Considering that the nature of the change in the values of volumetric and hydromechanical efficiency, over the entire range of changes in the rotational speed of the motor shaft for the pressure difference $\Delta p = 8$ and $16 \, MPa$, does not practically change, the nature of the change in the overall efficiency at these pressure drops also does not change. Distinctive are only changes in the overall efficiency for the pressure difference $\Delta p = 20 \, MPa$ (Fig. 2c). This phenomenon is explained by the fact that at low rotational speeds of the shaft of the modernized hydraulic motor, a decrease in volumetric efficiency is observed (Fig. 2a – curve 2), and the hydromechanical efficiency of the modernized hydraulic motor is 7...10% higher than the serial (Fig. 2b – curve 2).

![Figure 2](image_url)

**Figure 2.** The dependence of the efficiency on the frequency of rotation of the output shaft of the hydraulic motor with a pressure drop $\Delta p = 20 \, MPa$: a – volumetric; b – hydromechanical; c – overall; 1 – serial hydraulic motor; 2 – modernized hydraulic motor.
Figure 3. Changing the output characteristics of a planetary hydraulic motor operating as part of a mechatronic system: a – dependence of torque on the frequency of rotation of the output shaft of the hydraulic motor; b – dependence of the rotational speed of the output shaft of the hydraulic motor on the flow rate of the working fluid; 1 – serial hydraulic motor; 2 – modernized hydraulic motor.

Studies of the dependence of the torque on the rotation frequency have established that the nature of their change is identical (Fig. 3a). The difference between the torque values of the modernized and serial motors increases with increasing pressure drop. It was found that at a pressure difference of \( \Delta p = 20 \, MPa \), the torque developed by the modernized hydraulic motor is 1900 N·m (Fig. 3a – curve 2), and serial – 1600 N·m (Fig. 3a – curve 1), which is 16% below. This is explained by a decrease in mechanical losses due to an increase in the hydromechanical efficiency characteristic of the developed design of the rotor system of the modernized hydraulic motor.

Investigations of the influence of the shaft speed of the upgraded hydraulic motor on the flow rate of the working fluid at various pressure drops (Fig. 3b – curve 2) established a linear proportional relationship between these parameters. Similar data were established for a serial hydraulic motor (Fig. 3b – curve 1), which are identical to the flow curve of the working fluid of the upgraded hydraulic motor.

Thus, studies of the influence of the design features of the rotor system of planetary hydraulic motors on the change in their output characteristics have established that eliminating the manufacturing form error of the rotors allows increasing the hydromechanical and overall efficiency of the modernized hydraulic motor by 7...10%. The reduction of the shape error of the gear profile of the external and internal rotors also allowed to increase the torque on the planetary hydraulic motor shaft by 16% with the remaining output parameters being identical.

5. Conclusions
To conduct studies determining the effects of improving the design of the rotors of a planetary hydraulic motor on changing its output parameters in order to improve the output characteristics of the mechatronic systems of self-propelled vehicles, a methodology for conducting experimental studies of planetary hydraulic motors has been developed. A basic hydraulic circuit of an experimental bench for comparative bench tests of a family of high-torque low-speed planetary hydraulic motors has been developed.

As a result of the studies, it was found that eliminating the error in the manufacturing form of the rotors can increase the hydromechanical and overall efficiency of the modernized hydraulic motor by 7...10%. As a result of the modernization, it was possible to increase the torque by 16% at the given rotation frequencies, which makes it possible to increase the efficiency of the output links of the mechatronic systems of self-propelled vehicles.

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