Kinematics of motion of rotors of an orbital hydraulic machine

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Abstract. There is no “rigid” kinematic connection between the centers of the rotors of the orbital hydraulic motor, which leads to non-standard changes in its output characteristics. A kinematic diagram of the movement of the rotors of an orbital hydraulic motor was developed, which made it possible to substantiate the kinematics of movement of its rotors and analyze the change in output characteristics. Abnormal changes in the output characteristics of this type of hydraulic motors are changes in the overall efficiency and changes in the angular speed of rotation of its shaft. When the gap between the rotors changes in the range of 0 to 0.4 mm, the overall efficiency of the positive displacement hydraulic machine decreases 3.6 times, which is explained by the increasing pour over between its rotors. The high value (0.92) and constancy of the volumetric efficiency of the orbital hydraulic motor is explained by the property of its rotors “self-sealing” in the process of moving, eliminating overflows. A decrease in the angular speed of rotation of the shaft of an orbital hydraulic motor 35 to 27 rad/s, with an increase in the gap of 0 to 0.4 mm, is explained by additional displacements of its inner rotor.

1. Introduction
Various types of hydraulic machines [1–3] are used to drive the active working bodies of self-propelled vehicles, but special attention is paid to orbital [2, 4] hydraulic motors. Orbital motors are a new, little-studied hydraulic machine with high torque and low output shaft speed. These hydraulic machines are widely used in mechatronic systems with a gearless hydraulic drive of active working bodies and running systems of construction, railway, agricultural, drilling, municipal, logging and other self-propelled equipment.

A distinctive feature of these hydraulic motors is the presence of external and internal rotors with a special hypocycloidal tooth profile [4]. There is no “rigid” kinematic connection between the centers of the rotors of the orbital hydraulic motor, which leads to non-standard changes in its output characteristics [5]. The stability of the output characteristics of hydraulic drives of self-propelled vehicles is determined by the parameters of the hydraulic motors used in these drives.

Therefore, the study of changes in the output characteristics of an orbital hydraulic motor, by modeling the kinematics of the movement of its rotors, is an urgent direction in solving problems related to the design, manufacture and operation of orbital hydraulic motors. The solution of such problems will improve the output characteristics of hydraulic machines for mechatronic systems with a hydraulic drive of active working bodies and running systems of railway, agricultural, logging,
drilling, construction, municipal and other self-propelled equipment.

2. Analysis of recent studies and publications

A semi-analytical method for analyzing the contact interaction of structural elements along leveled surfaces [6] was proposed, the coefficients of friction, wear, roughness and hardness of contacting surfaces were determined [7]. Approaches have been developed that involve a combination of the advantages of analytical models and methods for analyzing the stress-strain state taking into account contact interaction [8]. Mathematical nonlinear models of the stress-strain state and approximation methods were used to construct functions that allow evaluating the characteristics of the object under study [9]. The approaches considered make it possible to develop more adequate models for analyzing the response of thin-walled structures to the action of the load [10]. A technique is proposed that takes into account the radial clearance and contact deformations of parts [11], as well as a technique for experimental studies and construction of control characteristics [12], is investigated the wear of the flow path of vortex-chamber blowers [13]. Prediction of aeration and cavitation in gerotor pumps [14] was considered, optimization of gerotor pumps was carried out [15], the values of pressure loss, flow rate and velocity distribution over the cross section of the pipeline were determined [16]. Comparison of the SST turbulence model is carried out taking into account the curvature of streamlines and flow rotation [17], the application of the corrected SST turbulence model is considered, which makes it possible to determine all the main characteristics of the vortex flow [18]. The results of tests of tribosystems with the use of liquid crystal additives [19] are presented, methods for the production and application of carbon nanoparticles in tribology are considered [20]. Experimental studies are considered, taking into account the effect of an electrostatic field on the working fluid of a volumetric hydraulic drive [21]. Issues related to the study of mechatronic systems with a hydraulic drive of active working bodies of self-propelled equipment were not considered.

A method for designing hydraulic mechatronic systems with elements of multicriteria optimization has been developed, which makes it possible to design a mechatronic system with given output characteristics [22]. A dynamic model of the drive and methods for its simplification are proposed [23]. The dynamic processes of mechatronic systems with planetary hydraulic motors were investigated in order to predict changes in their output characteristics [24]. The functional characteristics of a hydraulically driven mechatronic system on a chassis, which consists of an axial piston variable pump and two mechatronic modules (wheel hubs) with orbital hydraulic motors, have been studied [2]. The influence of the design features of orbital hydraulic motors on their functional parameters has not been studied.

In recent years, there has been an intense search and improvement of the applied hydraulic machines in order to create the simplest and most technologically advanced designs at the lowest cost [1]. Particular attention is paid to the development of low-speed hydraulic motors, the working elements of which must have a low speed of movement and develop high torques [2, 24]. The parameters of variation that determine the change in the output characteristics of a planetary hydraulic motor depending on the design features of the system of its rotors [4, 5, 25] and the system of fluid distribution [3, 26] are substantiated. It has been established [27] that one of the main units in these hydraulic machines causing pressure pulsations is its distribution system. Geometric parameters of elements of distribution systems have been substantiated, the influence of geometric parameters and work processes within distribution systems of orbital hydraulic machines on the change in their output characteristics has been studied [3, 26, 27]. The forces acting in the cycloidal gearing [28] were considered, mathematical models were developed that describe the robot of the rotors [29], the change in the geometry of the working surfaces of the rotors [30] and the loads in the gearing [31]. Ways and methods of increasing the bearing capacity of cycloidal gears [32] are presented, an optimal tooth profile for cycloidal gears is proposed [33]. Mathematical models have been developed that describe the relationship between the design features of the rotors and the output characteristics of the orbital hydraulic motor [4]. A two-scale model is considered, which combines the effects of wear, leading to changes in the surface relief of orbital engines [34], a method for determining the reliability of a
hydraulic motor by modeling changes in the technical state of rotors [35] is proposed. The kinematics of the movement of the rotors of orbital hydraulic machines was not considered.

The analysis of the performed studies shows that the question of studying the kinematics of the movement of the rotors of an orbital hydraulic motor remains open, and this to a certain extent limits the work associated with the design of new types of orbital hydraulic machines, their manufacture and operation. Therefore, this work is devoted to the study of the kinematics of movement of the rotors of an orbital hydraulic motor, in order to predict changes in its output characteristics at the stages of design, manufacture and operation.

3. Statement of the objective and tasks of the study
To study the kinematics of the movement of the rotors of an orbital hydraulic motor, in order to predict changes in its output characteristics, it is necessary:
– to develop a kinematic diagram of the movement of the rotors of the orbital hydraulic motor;
– substantiate the kinematics of motion of the rotors of an orbital hydraulic motor and a change in its output characteristics;
– investigate the change in the output characteristics of an orbital hydraulic motor by modeling the kinematics of movement of its rotors.

4. The basic part of the study
The basis of an orbital hydraulic motor is a system of its rotors (Figure 1) consisting of an external stationary rotor 1 and an internal movable rotor 3. To reduce contact loads between the corresponding teeth of the rotors, the teeth 2 of the external rotor 1 are made in the form of plug-in rollers. When the hydraulic motor is operating, under the action of the pumping pressure \( p_{\text{in}} \) of the working fluid, the inner rotor 3 rotates by an angle of movement \( \phi \) relative to the outer rotor 1. When the inner rotor 3 moves, its center describes a circle with a radius \( e \) around the center of the outer rotor 1.

![Figure 1. The layout of the rotors of the orbital hydraulic motor: 1 – outer rotor; 2 – tooth (roller) of the outer rotor; 3 – inner rotor; \( e \) – eccentricity; \( \phi \) – the angle of movement of the inner rotor relative to the outer; \( p_{\text{in}} \) – pressure of the working fluid at the inlet to the hydraulic motor; \( p_{\text{out}} \) – pressure of the working fluid at the outlet of the hydraulic motor.](image)

Errors in the approximation of the hypocycloidal contour of the profile of the teeth of the outer 1 and inner 3 rotors, the tolerances for their manufacture lead to the presence of an initial diametrical gap \( G \) in the location of the rotors (Figure 2). During the operation of an orbital hydraulic motor, as a result of wear of the teeth of its rotors, the diametral clearance \( G \) is constantly increasing [4, 5]. Therefore, when studying the kinematics of the movement of the rotors of an orbital hydraulic motor, two cases of the arrangement of the rotors are distinguished: theoretical (Figure 2, a) and real (Figure 2, b).

With the theoretical arrangement of the rotors (figure 2, a) there is no diametrical clearance \( G \) (\( G = 0 \)). One of the teeth of the inner rotor 3 always touches two teeth 2 of the outer rotor 1 at points A and B, and the diametrically opposite teeth of the inner rotor 3 contact the teeth 2 of the outer rotor 1 at points C and D.

The points of contact of teeth A, D and B, C are always located on opposite sides of the line of
centers of the considered rotors, which makes it possible to separate the high-pressure area $p_{in}$ from the low-pressure area $p_{out}$ without additional structural elements. It should be noted that between the remaining pairs of rotor teeth located in the range of contact points $A$, $D$ and $B$, $C$, respectively, the gap $G > 0$.

Such contacting of the rotors is due only to the geometry of the mating profiles of their teeth and provides a kinematic connection between the centers of the rotors $O_1$ and $O_2$, located at a distance equal to the eccentricity $e$. The internal rotor 3 is affected by: the resulting force $P$ from the discharge pressure $p_{in}$ of the working fluid and the moment $M_r$ of the load resistance applied at point $O_1$. Under the action of the resulting force $P$, the inner rotor 3 with the number of teeth $z_1$, moving flat-parallel, turns through an angle $\phi$, rolling around the inner rotor 1, transmitting the torque $M_{tor}$. With the actual arrangement of the rotors (Figure 2, b), there is always a diametrical gap $G > 0$, associated with the technological features of manufacturing and necessary to compensate for the thermal expansion of the rotors. In the initial position, the inner rotor 3 with one of its teeth touches two teeth 2 of the outer rotor 1 at points $A$ and $B$. Similar points $C$ and $D$ of two diametrically opposite teeth of the rotor 3 are located at a distance $G$ from the corresponding teeth 2 of the rotor 1. Since the location of the rotors there is no "rigid" kinematic connection between the centers of the rotors $O_1$ and $O_2$, the distance between them changes and is equal to $e' = e + G/2$. The high-pressure zone $p_{in}$ with the actual arrangement of the rotors is hydraulically closed through a double slot of height $G$ (at points $D$ and $C$) with the low-pressure zone $p_{out}$, causing overflows that reduce the volumetric efficiency of the orbital hydraulic motor. We will call this position of the rotors (Figure 2, b) position I.

In position I (Figure 2, b) the same forces act on rotor 3 as in the theoretical position of the rotors, therefore, to further study the movement of the rotors of the orbital hydraulic motor, we will use the diagram shown in Figure 3.

Under the action of the resulting force $P$, the inner rotor 3 will move from position I to position II (Figure 3, a) until the diametrically opposite tooth of the rotor 3 touches the corresponding tooth of the rotor 1 at point $C$. Moving in position II, the inner rotor 3 moves progressively upward, moving along the normal applied at point $B$, similar to the movement of the hydraulic cylinder piston. When moving from position I to position II, the inner rotor 3 cannot turn through the angle of movement $\phi$, under the influence of the moment of load resistance $M_r$. Moving to position II, the rotor 3 “floats up” by the size of the diametrical clearance $G$, changing the distance between the centers $O_1$ and $O_2$ of the rotors, making it equal to $e'' = e - G/2$. This “floating” of the rotor 3 of the orbital hydraulic motor is caused...
by the absence of a "rigid" kinematic connection between their centers $O_1$ and $O_2$, which allows the rotors to occupy different positions in the diametrical clearance range $G$. zones of high $p_{in}$ and low $p_{out}$ pressure, eliminating overflows.

After "floating", under the action of the resulting force $P$, the inner rotor 3, transmitting the torque $M_{tor}$, rotates through the angle $\varphi$ taking position III (Figure 3, b). In position III, “self-sealing” of the rotors also occurs, since their touching points $B$ and $C$ separate the zones of high $p_{in}$ and low $p_{out}$ pressures, eliminating spill over.

Consequently, the presence of a diametrical clearance $G$, in the actual arrangement of the rotors, does not cause leakage in the radial direction, since the absence of a “rigid” kinematic connection between the rotors allows them to occupy a position at which “self-sealing” occurs. Therefore, it can be argued that an increase in the diametrical clearance $G$ in the process of wear of the rotors will not affect the decrease in the value of the volumetric efficiency of the orbital hydraulic motor. Attention is drawn to the “forced” movement of the inner rotor 3, in which it takes an additional intermediate position II (Figure 3, a). This movement takes additional time, which in turn affects the decrease in the angular speed of rotation of the inner rotor 3 and, as a consequence, the shaft of the orbital hydraulic motor.

Analysis of the movement kinematics of the rotors of orbital hydraulic machines allows us to conclude that the presence of a diametrical gap $G$ and the absence of a "rigid" kinematic connection between the rotors causes additional movements of the rotors, changing the kinematics of their movement. The phenomenon of "self-sealing" of the rotors of an orbital hydraulic motor, caused by their additional displacements, causes a non-standard change in some of the output characteristics of this type of hydraulic motors. Non-standard changes in the output characteristics of an orbital hydraulic motor include: no leakage rate, which is inevitable in the presence of a gap between the rotors, and, as a consequence, stabilization of volumetric efficiency; decrease in the angular speed of rotation of the hydraulic motor shaft as a result of additional displacements of the rotor 3. Therefore, to predict the change in the rotation frequency of the orbital hydraulic motor shaft depending on the diametrical clearance $G$, it is necessary to determine the dependence of the change in the steady-state angular speed of rotation at the theoretical and real position of its rotors.

The steady-state angular velocity $\omega_T$ of the inner rotor 3 for the theoretical arrangement of the rotors (Figure 2, a) is equal to $\omega_T = (\pi n)/30$, where $n$ is the frequency of rotation of the shaft (inner rotor 3) of the orbital hydraulic motor [4, 5]. It is known that $n = Q/V_0$, where $Q$ is the flow rate of the
fluid passed through the hydraulic motor; $V_0$ is the working volume of the hydraulic motor. After transformations, we have a model of the change in the value of the steady-state angular velocity for the theoretical position of the rotors

$$\omega_r = \frac{\pi \cdot Q}{30 \cdot V_0}. \quad (1)$$

The model for determining the value of the angular velocity $\omega_p$ of the inner rotor 3 with a real arrangement of the rotors (Figure 2, b) is described in detail in [4, 5] and is represented by the dependence

$$\omega_p = \frac{\omega_r \cdot (t - 2t_1)}{t}. \quad (2)$$

where $t$ is the time characterizing the steady rate of rotation $t_1$ is the time taken to move the inner rotor to the intermediate position II.

The time characterizing the steady-state speed of rotation of the hydraulic motor shaft is determined by the dependence

$$t = \frac{2\pi}{\omega_r \cdot z_1 \cdot z_2 - 2t_1}. \quad (3)$$

where $z_1$ and $z_2$ are the number of teeth of the inner and outer rotors, respectively.

The translational movement of the inner rotor from position I to position II (Figure 2, b) is similar to the movement of the hydraulic cylinder piston. Therefore, the additional time spent by the inner rotor on this movement can be determined by the known expressions, and, taking into account substitutions and transformations, can be described by the dependence

$$t_1 = \frac{G \cdot D \cdot b}{4Q \cdot \cos \delta}. \quad (4)$$

where $G$ is the path, displacement of the inner rotor from position I to position II (Figure 2), numerically equal to the diametrical clearance $G$; $D$ is the diameter of the rotor 3; $b$ is the width of the inner rotor.

Thus, by solving successively equations (1), (3), (4) and (2), the values of the angular velocity $\omega_p$ of the inner rotor are determined for the actual arrangement of the rotors of the orbital hydraulic motor, taking into account the diametrical gap.

The study of the processes of changing the output characteristics of the orbital hydraulic motor by modeling the kinematics of the movement of the rotors, depending on the change in the gap between them, was carried out according to the data of an orbital hydraulic motor GMP-22 with a working volume of 250 cm$^3$. The study of the change in the overall efficiency for a volumetric operating principle hydraulic machine was carried out according to the data of an MFS90 axial piston motor with a working volume of 89 cm$^3$.

When studying the processes of changing the output characteristics of the orbital hydraulic motor depending on the change in the diametral clearance $G$ (Figure 4), the mathematical apparatus given in the works [4, 5] was used. When determining the overall efficiency of an axial piston motor, well-known mathematical relationships were used.

The study (Figure 4) of the dependence of the change in the functional characteristics of the orbital hydraulic motor on the diametral clearance $G$, taking into account the kinematics of the movement of its rotors, shows that they differ from the characteristics of hydraulic machine of volumetric of operating principle. Attention is drawn to the nature of curve 1 (Figure 4) characterizing the dependence of the change in the overall efficiency of a standard of a volumetric operating principle of a hydraulic machine on the change in the gap between the rotors. When this gap changes in the
range of 0 to 0.4 mm, the overall efficiency of a volumetric operating principle of the machine decreases by 3.6 times (0.75 to 0.21), which is explained by the increasing leaks between its rotors. The overall efficiency of the orbital hydraulic motor (curve 4) with similar changes in the diametral clearance \( G \) remains practically unchanged, since the hydromechanical and volumetric efficiency of this hydraulic machine does not change their values.

![Figure 4. Dependences of changes in the functional characteristics of the orbital hydraulic motor on the diametral clearance: 1 – overall efficiency of a hydraulic machine of a volumetric operating principle; 2 – volumetric efficiency; 3 – hydromechanical efficiency; 4 – overall efficiency; 5 – torque \( M_t \); 6 – angular velocity.](image)

The high value (0.92) and constancy of the volumetric efficiency (curve 2) of the orbital hydraulic motor is explained by the property of its rotors “self-sealing” in the process of movement, eliminating leaks in the diametrical direction.

A constant value of hydromechanical efficiency (curve 3) and torque (curve 5) with a change in the gap between the rotors of displacement hydraulic machines is a normal phenomenon for all hydraulic machines of this type.

Special attention should be paid to the change in the angular speed of rotation of the shaft of the orbital hydraulic motor (curve 6), the values of which decrease from 35 to 27 rad/s with an increase in the gap from 0 to 0.4 mm. Such a change in the angular velocity of the shaft of an orbital hydraulic motor is explained by additional displacements of its inner rotor, which arose in the presence of a diametrical gap and the absence of a “rigid” kinematic connection between the centers of its rotors.

5. Conclusions
As a result of the research carried out, a kinematic diagram of the movement of the rotors of the orbital hydraulic motor was developed, which made it possible to substantiate the kinematics of the movement of the rotors of the orbital hydraulic motor and analyze the change in its output characteristics.

It was found that in the absence of a “rigid” kinematic connection between the rotors of the orbital hydraulic motor, they occupy a position at which “self-sealing” of these rotors occurs. Additional movement of the inner rotor, in which it occupies an intermediate position, which in turn affects the decrease in the angular velocity of rotation of the shaft of the orbital hydraulic motor.

Analysis of the research on the change in the output characteristics of an orbital hydraulic motor, by modeling the kinematics of the movement of its rotors, shows that non-standard changes in the output characteristics of hydraulic motors of this type include changes in the overall efficiency and changes in the angular speed of rotation of its shaft. When the gap between the rotors changes in the range of 0 to 0.4 mm, the overall efficiency of the positive displacement hydraulic machine decreases 3.6 times (0.75 to 0.21), which is explained by the increasing spill over between its rotors. The overall efficiency of the orbital hydraulic motor with similar changes in the diametrical clearance \( G \) remains practically unchanged.

The high value (0.92) and the constancy of the volumetric efficiency of the orbital hydraulic motor is explained by “self-sealing” of its rotors in the process of moving, eliminating leakage in the diametrical direction.

A decrease in the angular speed of rotation of the shaft of an orbital hydraulic motor from 35 to 27 rad/s, with an increase in the gap from 0 to 0.4 mm, is explained by additional displacements of its
inner rotor, which arose in the presence of a diametral gap and the absence of a “rigid” kinematic connection between the centers of its rotors.

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