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Reliability design of rotors for orbital hydraulic motors

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Abstract. The reliability of orbital hydraulic motors which are used in mechatronic systems with a hydraulic drive for active working tools on self-propelled machinery is a pressing engineering problem. To increase the reliability, a specific design method was proposed. It required development of a mathematical apparatus and a calculation algorithm. The mathematical tools allowed to realize the method for determination of hydraulic motor reliability by simulating changes in a technical state of the rotors in a hydraulic motor. A program, which has been developed, enabled modeling the conjugation of external and internal rotors. The program implemented an algorithm for the sequence of calculating the parameters for the external and internal rotors. The proposed program made it possible to obtain a three-dimensional image of zones with admissible interfaces which ensure the efficient and reliable operation of orbital motors. The modeling of working capacity change for an orbital motor has established some dependence. The changes in the number of teeth and overall dimensions of the rotor in the investigated range enabled to develop a standard size range for hydraulic machines, which operate in mechatronic drive systems for active working tools on self-propelled machinery.

1. Introduction

The reliability of hydraulic drives, which are applied in mechatronic systems on self-propelled machinery, decisively depends on the reliability design of hydraulic motors which are applied as the actuators in the active working tools drives. The analysis showed that orbital hydromotors were mostly used in the drives of mechatronic systems on self-propelled machines [1–5]. Orbital hydraulic motors have a high moving torque, operate steadily in the low range of rotational frequencies, allow forcing by pressure and provide high-efficiency operation modes in the entire range of regulation. The great advantage of these hydraulic motors is the ability to be installed directly into the drive mechanisms of conveyors, winches, tappers, wheel-hubs, etc.

Quite large experience in the production, testing and operation of gear and axial-piston hydraulic machines of volumetric action has been accumulated [6, 7]. However, that experience cannot be fully used in the production and maintenance of orbital hydraulic motors because of their specific design features.

An orbital hydraulic motor, like any hydraulic volumetric machine, is a rather complex mechanism with the parts which make up a precision joint formed by the outer and inner rotors. The movement of the working fluid between high and low pressure zones determines the interaction of the internal and



external rotors of the orbital hydraulic motor. The operational state of the hydraulic motors is determined by the reliability design of their rotors. Reliability design in this research is considered as the whole set of their geometric and kinematic parameters which provide necessary movement of the rotors when the working fluid moves.

2. Analysis of recent studies and publications

Currently, hydraulic drives of mechatronic systems often employ orbital hydraulic machines. In [8], a universal model of a mechatronic system with an orbital hydraulic motor was proposed, but the influence of its design features on functional parameters was not considered. The main units which limit the efficiency of orbital hydraulic motor operation are distribution and displacement systems. Existing computational model of the working processes which take place in the distribution system [9] allows to investigate the influence of its design parameters on the output characteristics of the hydraulic motor during operation. The kinematic diagrams for distribution systems of orbital hydraulic machines [10] and shape of distribution windows [11], which improved their output characteristics, were substantiated before. Mathematical expressions for estimating the working fluid flow in gerotor hydraulic machines were given [12]. Two dimensionless parameters were proposed to determine the performance of gerotor pumps. Cavitation processes, which occur in gerotor hydraulic machines, have been investigated [13]. A computational model [14] was proposed. It considers the pressure in the system, the commutation volume and the proportion of air entering the hydraulic fluid to vary on several levels. Experimental studies confirmed the simulation results [15]. However, that research did not touch the question of influence of the external and internal rotors geometrical parameters on the output characteristics of orbital hydraulic machines and their technical condition.

When designing orbital and gerotor hydraulic machines, we considered the forces acting in the gearing [2, 3] and compression state of the working fluid [4]. The software for gear surfaces design was offered [5]. The programs took into account the hydrodynamic equations for fluid motion in working chambers. The issues related to the design of rotors for gerotor hydraulic machines with the help of the upgraded application package Gero LAB [16] were considered. A technique for designing and manufacturing rotors of gerotor machines [17] has been developed. A technological process for rotors production has been suggested as well. The experimental studies which confirmed the results of the simulation were conducted. The recommendations [18] for the design of rotors of gerotor machines were proposed. However, the cited research did not deal with the change in the technical condition of the hydraulic motor during the operation of mechatronic drive systems as the parts of active working tools on self-propelled machinery.

The maximum deviations for the error shape of the rotors tooth surfaces were substantiated in [19], the effect of additives in oils on the processes of friction and wear in moving joints was studied [20], The results of laboratory studies of the effect of carbon nano-additives on the antiwear and extreme pressure properties of industrial oil are presented [21], but those works did not consider reliability of the rotors.

The influence of an external magnetic field on the change in adhesion parameters in the contact of magnetized steel rolling elements is studied [22]. Theoretical and experimental studies [23, 24] have shown strong correlation between the nature and amount of wear on the working surfaces of rotors in orbital hydraulic motors. The coefficients of the regression equations are obtained that describe the dependence of the wear rate on the contact surface treatment parameters under real operating conditions [25]. Although the issues of structural reliability improvement which increases the performance of orbital hydraulic motors remain unstudied.

3. Statement of the objective and tasks of the study

To solve the problem of the orbital hydraulic motor performance improvement by changing the reliability design of its rotors it is necessary:

- to develop a mathematical apparatus and a calculation algorithm which allow to implement a design method for the improvement of reliability of orbital hydraulic motor rotors;

- to determine the range of changes in the geometric and kinematic parameters of the orbital hydraulic motor rotors ensuring its working state during operation.

4. The basic part of the study

The study of the reasons for the loss of performance of orbital hydraulic motors has been established [23, 24] that the main elements limiting their reliable and efficient operation are the external and internal rotors.

The kinematic analysis of an external rotor movement and characteristics of its contact interaction with an internal rotor revealed the main ways of upgrading the external rotor of the orbital hydraulic motor to improve the reliability of the motor's design. Based on this, we proposed a modernized design of the external rotor (figure 1) which is formed by an iron ring 4, which is a hollow cylinder indeed, and rollers 3 (teeth) inserted into it. The main feature of the design was rollers (3) placement. The rollers were installed without any gaps, touched each other in the ring 4. This arrangement of the rollers was provided by the geometric relationship between the radius of the rollers centers R_2 and the radius of the roller r_2 . The formed gear pair was a roller gearing.

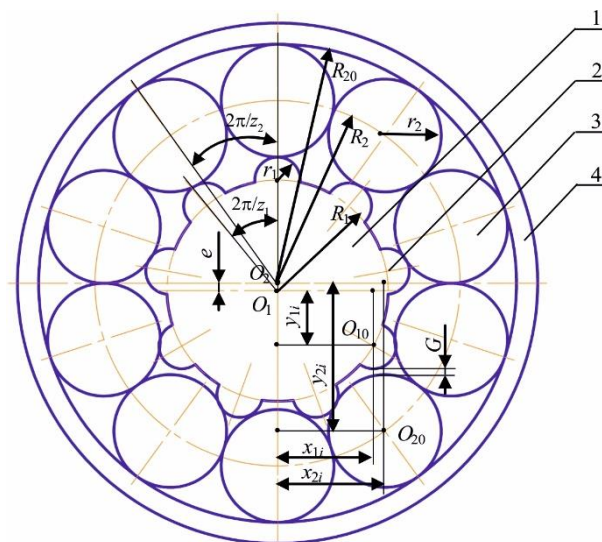


Figure 1. The design diagram of the relationship between geometric parameters of the external and internal rotors: 1 – internal rotor; 2 – internal rotor teeth; 3 – rollers (teeth) of the external rotor; 4 – iron ring.

In roller engagement, the change in the gaps G between the mating tooth pairs differs significantly from the serial design of the external and internal rotors engagement [19].

Radii R_2 or r_2 are related to each other according to:

$$r_2 = R_2 \cdot \sin(\pi / z_2), \quad (1)$$

where z_2 is the number of external rotor teeth (rollers).

The inner radius of the ring R_{20} which contains the rollers is determined by the sum of the rollers R_2 centers radii and the radius of the roller r_2 : $R_{20} = R_2 + r_2$.

The found radius is the basis for the development of external and internal rotors. In this, one of the gear radii is determined for the formation of a working pair. It is the radius of the teeth centers arrangement R_1 or the tooth radius r_1 (when the second radius is set).

The determination of the unknown R_1 or r_1 values is carried out by the method of successive approximations in the following algorithmic sequence:

1. Some starting (initial) values of the radii are specified taking into account that the starting gap G is provided:

– for given R_1 :

$$R_2 \geq R_1, R_1 = R_2 - r_1; \quad (2)$$

– for given r_1 :

$$R_2 - R_1 \geq r_1, r_1 = \frac{\pi \cdot R_1}{z_1}, \quad (3)$$

where z_1 is the number of the inner rotor teeth.

2. Then we determine the number of the pair, which requires a check by the condition of possible teeth contact:

– when z_2 is even:

$$i = \frac{z_2}{2} + 1; \quad (4)$$

– when z_2 is odd:

$$i = \frac{z_2 - 1}{2}. \quad (5)$$

3. The coordinates x_{2i}, y_{2i} of the tooth (roller' tooth) center (fig. 1) of the external rotor in the i -th pair are determined:

$$\begin{aligned} x_{2i} &= \cos\left(\frac{\pi \cdot (2 \cdot i + 1)}{z_2}\right) \cdot R_2; \\ y_{2i} &= \sin\left(\frac{\pi \cdot (2 \cdot i + 1)}{z_2}\right) \cdot R_2. \end{aligned} \quad (6)$$

4. The e eccentricity is calculated:

$$e = R_2 \cdot \cos \frac{\pi}{z_2} - R_1 - \sqrt{(r_1 + r_2)^2 - R_2 \cdot \sin \frac{\pi}{z_2}}. \quad (7)$$

5. The coordinates x_{1i}, y_{1i} of the gear tooth center (fig. 1) in the i -th pair are determined:

$$\begin{aligned} x_{1i} &= R_1 \cdot \cos\left(\frac{2 \cdot \pi \cdot i}{z_1}\right) + e; \\ y_{1i} &= R_1 \cdot \sin\left(\frac{2 \cdot \pi \cdot i}{z_1}\right). \end{aligned} \quad (8)$$

7. The actual clearance G_i (Fig. 1) in the considered working pair is calculated as

$$G_i = \sqrt{(x_{1i} - x_{2i})^2 + (y_{1i} - y_{2i})^2} - r_1 - r_2 - G_t, \quad (9)$$

where G_t is a technological (diametrical) [19] gap in the gearing.

As a result of the research, a mathematical apparatus has been developed and the algorithm for the roller engagement calculating was proposed. They could be used as the basis for the development and design of more reliable and efficient orbital hydraulic motors.

To simulate the process of interfacing between external and internal rotors, a program has been developed. It implements an algorithm for calculating the parameters of external and internal rotors. The program allows to obtain a three-dimensional image of the zones of admissible mates which ensure effective and reliable operation of rotors in orbital hydraulic motors.

The following initial conditions were accepted for modeling: the parameters affecting the overall dimensions of the orbital hydraulic motor were taken as variation parameters. They are the radius R_2 of the arrangement of the teeth (rollers teeth) centers or the rollers radius r_2 ; the number the external rotor teeth z_2 is constant; the radius of the teeth centers R_1 and the radius of the internal rotor tooth r_1 are constant.

To build the zones of acceptable rotors mates in coordinates (along the axes) i , r_1 , G , we determined the R_1 radius of the teeth centers for the internal rotor from the expression (2). The array of gap G values was determined from the expression (9). The tooth radius r_1 was changed stepwise in the 0.5...5.0 mm value interval with the step of 0.1 mm.

We carried out some studies on the operability of the roller gearing in the coordinates r_1 , R_{20} , e at a stage of orbital hydraulic motors design. The R_1 radius of the teeth centers for the internal rotor was determined for that. The e eccentricity was determined from the expression (7).

To determine the current value of R_2 , which was obtained from the expression (1), the ring inner radius R_{20} for the rollers was specified. The changes of the radius R_{20} were performed in the range of 30 to 200 mm with a step of 5 mm. The radius r_1 was changed discretely in the range of 0.5 to 5 mm with a step of 0.5 mm.

Simulating the interaction process between the external and internal rotors of a hydraulic motor (figure 2-4) enabled to established that the increase of the ring radius in the range of $R_{20} = 41...200$ mm resulted 11.5...16 times growth of the minimum tooth radius of the internal rotor r_1 . At the same time, the increase in the number of rollers for the external rotor z_2 from 5 to 30 was accompanied by 2.8...4 times decrease of the radius r_1 . The working area of the roller gearing was highlighted by a darker color. The initially inoperative rotor condition was marked by a lighter color.

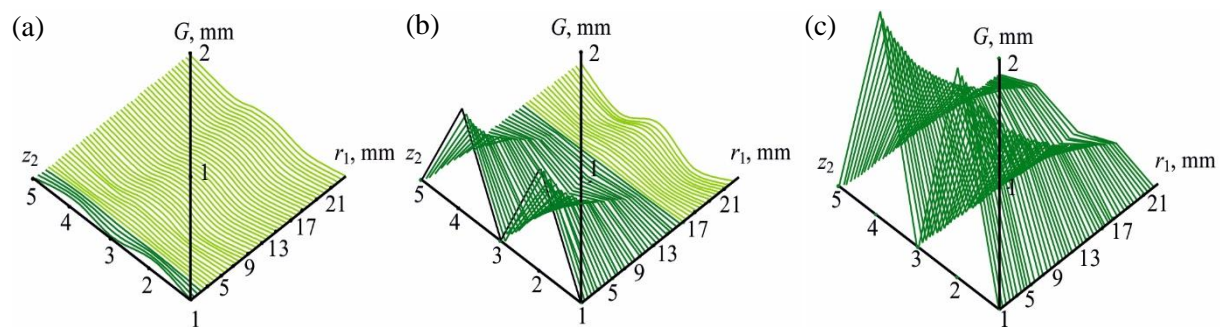


Figure 2. The change in the diametrical gap G between the rotors according to their geometrical and kinematic parameters with $z_2=5$: a – for $R_{20}=41$; b – for $R_{20}=118$; c – for $R_{20}=200$.

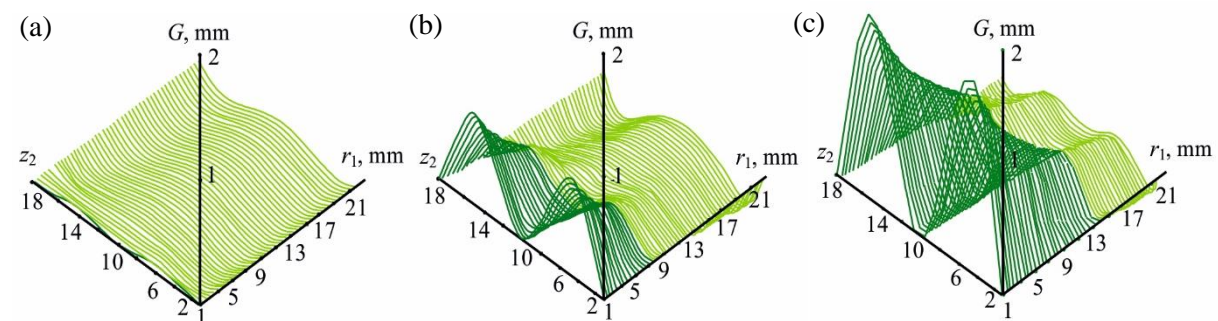


Figure 3. The change in the G diametrical gap between the rotors according to the geometric and kinematic parameters with $z_2=18$: a – for $R_{20}=41$; b – for $R_{20}=118$; c – for $R_{20}=200$.

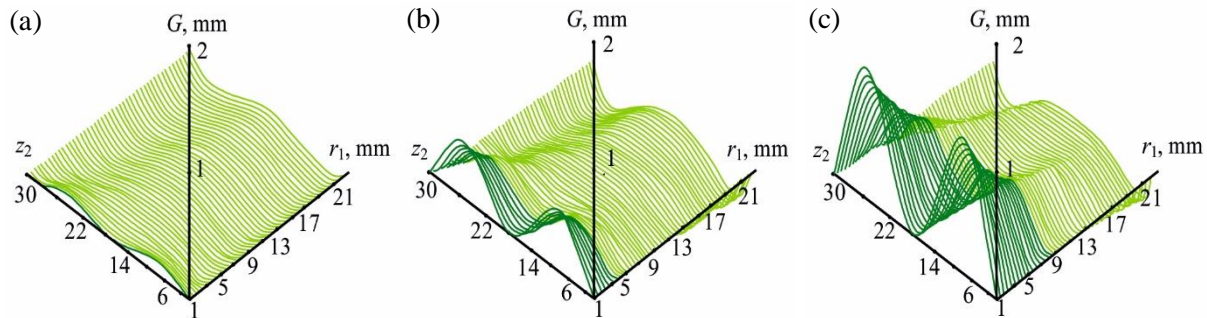


Figure 4. The change of the diametrical gap G between the rotors according to their geometric and kinematic parameters with $z_2=30$: a – for $R_{20}=41$; b – for $R_{20}=118$; c – for $R_{20}=200$.

The main research data required for the orbital hydraulic motors design are presented in table 1.

Table 1. The results of the geometrical parameters calculations for the updated hydraulic motor.

z_2	$R_{20} = 41 \text{ mm}$		$R_{20} = 118 \text{ mm}$		$R_{20} = 200 \text{ mm}$	
	$r_1, \text{ mm}$	$G, \text{ mm}$	$r_1, \text{ mm}$	$G, \text{ mm}$	$r_1, \text{ mm}$	$G, \text{ mm}$
5	2.0	0.076	15.0	0.911	23.0	1.838
18	1.0	0.084	7.0	0.751	14.0	1.761
30	0.5	0.094	3.5	0.525	8.0	1.141

The analysis of the obtained results showed that the operability of the roller gearing of the orbital hydraulic motor was ensured throughout the entire range of the rollers (teeth) number for the external rotor $z_2 = 5 \dots 30$ when the overall dimensions R_{20} of the ring were changed from 41 to 200 mm. Therefore, the proposed design of the external rotor could be used for the orbital hydraulic machines design.

The kinematics of the interaction between the external and internal rotors is characterized by the eccentricity e changes in the coordinates R_{20} , e , r_1 (figure 5, a, b, c).

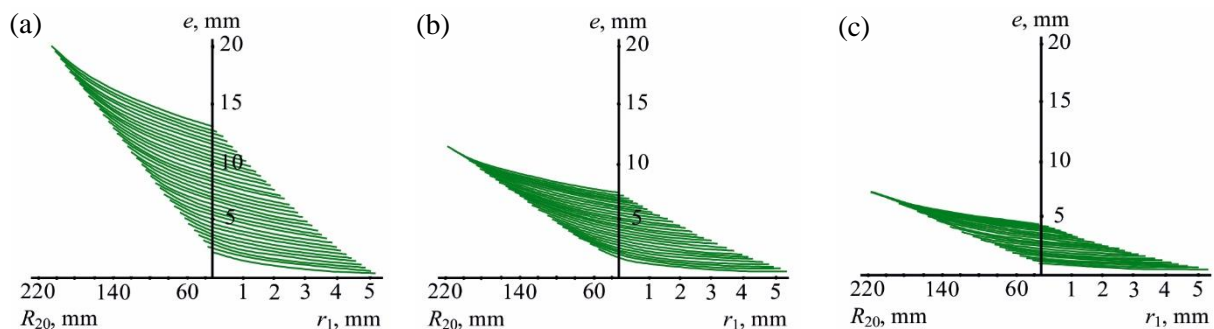


Figure 5. The eccentricity e change between the external and internal rotors: a – for $z_2 = 5$; b – for $z_2 = 18$; c – for $z_2 = 30$.

The simulation results have been analyzed. It was revealed that when the overall parameters of the external rotor ring were changed in the range of $R_{20}=41 \dots 200$ mm, the minimum value of the gear tooth radius 11.5...16 times increased and the eccentricity e remained almost unchanged.

The research result established that the increase in the number of rollers (teeth) of the external rotor from 5 to 30 was accompanied by a 2.8...4 times decrease in the minimum value of the radius r_1 . That had a significant effect (3 times) on the change in eccentricity e from 7 to 20 mm.

Thus, it can be stated that the eccentricity e of the orbital hydraulic motor is determined by the kinematics of the gearing and the number of teeth of the external and internal rotors.

5. Conclusions

The paper presents a constructive method for the improvement of design reliability of orbital hydraulic motors, which are used in mechatronic systems with hydraulic drive for active working tools on self-propelled machinery. A mathematical apparatus and a calculation algorithm were developed. That allowed to implement the method and determine the level of design reliability by simulating changes in the technical state of the orbital hydraulic motor during operation of the mechatronic system.

Theoretical studies on the orbital hydraulic motor performance were carried out by simulating the process of changing the rotors geometric and kinematic parameters. It has been established that when in the ring radius of the external rotor is increased in the range 41...200 mm, the minimum tooth radius of the internal rotor increases 11.5...16 times, and the eccentricity between the rotors remains almost unchanged. The increase in the number of rollers (teeth) of the external rotor in the range of 5...30 is accompanied by the 2.8...4 times decrease in the minimum teeth radius of the internal rotor and by the 3 times increase of the eccentricity. The completed studies have opened up the possibility of standard series development for orbital hydraulic motors which operate in mechatronic drive systems of active working tools on self-propelled machinery.

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