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Research paper

Justification of the Kinematic Diagrams for the Distribution System of a Planetary Hydraulic Motor

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Abstract

The output characteristics of a planetary (orbital) hydraulic motor could be significantly improved if the kinematic diagrams for its working fluid distribution system are chosen correctly and substantiated. Fluctuations in the flow of the power fluid cause pulsation in the cavity of the input pressure of the hydraulic motor. This results to vibration of the hydraulic system elements. Thus, the hydraulic motor can be considered as a source of pulsation which leads to functional failures of the hydraulic system. As they run at low rotational speeds with high torque, planetary hydraulic motors are commonly applied for a hydraulic drive in active working tools of self-propelled machinery. It has been established that one of the main components of a planetary hydraulic motor, which causes pressure pulsations, is its distribution system. The frequency and amplitude of these pulsations depends on the kinematic diagram for the distribution system of the power fluid. Therefore, we studied how the kinematic diagram for the distribution system effects on the output characteristics of a planetary motor. Since the change in the capacity of a distribution system with various kinematic diagrams influences on the output characteristics of a planetary motor, the impact was investigated. The kinematic diagrams, which improve the output characteristics of planetary hydraulic motors, were justified.

Keywords: *distribution system; kinematic diagram; planetary hydraulic motor.*

1. Introduction

The most common hydraulic machines, which are used in hydraulic drives of active working tools, are planetary hydraulic motors [1] that operate at low rotational speeds with high torques and working pressure of 16 to 25 MPa. This feature of planetary hydraulic motors is especially important for self-propelled vehicles, where it is necessary to provide high starting moments when operating at a given power. We consider planetary hydraulic machines as hydraulic machines which operate on the principle of a planetary gearbox similar to orbital, gerotor, geroller, etc. [2]. A distinctive feature of the planetary motor is the need to create a rotating hydraulic field of the power fluid. A distribution system is used to form the hydraulic field. The hydraulic fluid distribution system for planetary hydraulic motors is presented (Figure 1) by the distributor 1, which is installed on the shaft 2 and the sleeve valve 3 put in the front cover 4 [1, 2]. Moreover, the sleeve valve 3 with the front cover 4 forms a valve device. The distributor 1 and the shaft 2 form a distribution block.
When the distribution system works, the slide valve (Figure 2, a), which is installed in the front cover, is stationary. The distributor (Figure 2, b), which is mounted on the shaft of the hydraulic motor, rotates relatively to the sleeve valve. The contact of the end faces of the distributor and the sleeve valve, which have special windows, makes a formation zone of the hydraulic field. It is necessary for the displacement system of a planetary motor operation.

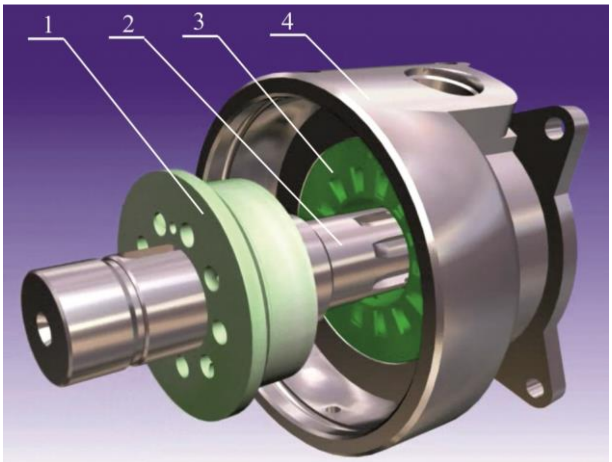

Fig. 1: The distribution system of power fluid in a planetary motor: 1 is a distributor; 2 is a shaft; 3 is a sleeve valve; 4 is a front cover.

The working windows 1 and the unloading windows are made on the end surface of the distributor (Figure 2, a). The injection 3 and discharge 4 windows were made on the end surface of the sleeve valve (Figure 2, b). The working windows of the distributor are the windows which participate in the operation of the power fluid distribution system. The unloading windows are the windows necessary for balancing the distributor [2].

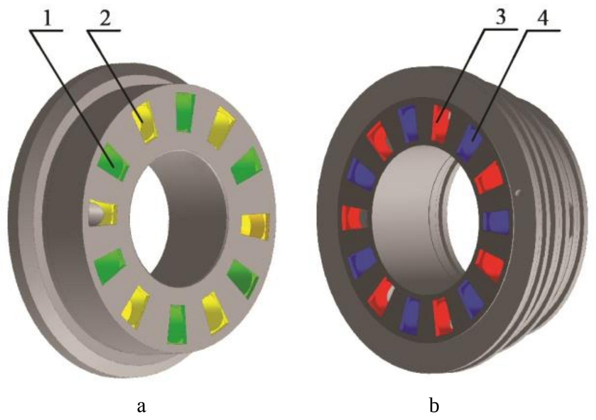

Fig. 2: Contacting end surfaces with distribution windows: a is sleeve windows; b is the distributor ones; 1 is an injection window; 2 is a discharge window; 3 is a working window; 4 is an unloading window.

The principle of operation of the end distribution system can be represented as follows (Figure 3) [3]. Hydraulic fluid is forced to the front cover 7 and moves along the annular channels 8 in the cover 7 and the sleeve valve 6. The power fluid goes from the annular channel 8 of the sleeve 6, enters the radial holes and then passes the end openings to the discharge windows 5 which are made on the end face of the sleeve valve 6.

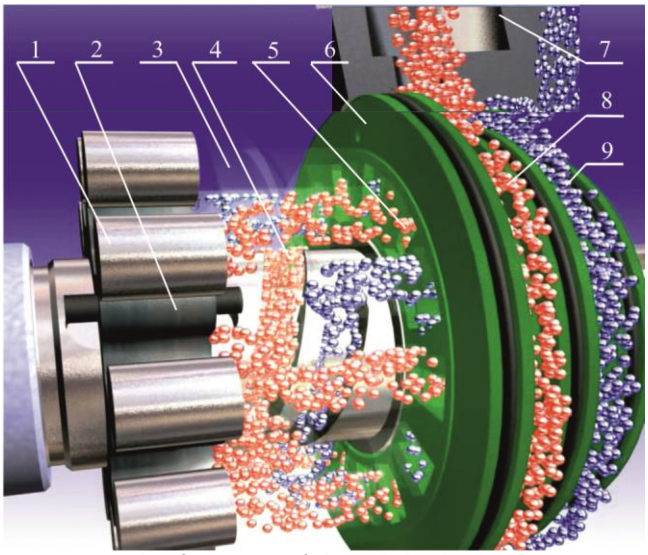

Fig. 3: Principle of operation of the end distribution system: 1 is a covering displacer; 2 is a covered displacer; 3 is the distributor; 4 are the channels made in the distributor; 5 are the injection windows of the sleeve valve; 6 is a sleeve valve; 7 is a cover; 8 is an annular channel; 9 is power fluid discharging.

The end face of the sleeve valve 6 (Figure 3) contacts the end face of the distributor 3. It contains working windows of the distributor. The windows are used when the power fluid passes through the channels 4 in the distributor 3 into the working chambers which are formed by the gearing surfaces of the covering distributor 1 and the covered distributor 2.

When the distributor rotates, the injection zone (red color) is replaced by the discharge zone (blue color), i.e. the hydraulic field starts to move and the power fluid enters the discharge falling into the channels which are made in the distributor 3. Along the channels it moves to the end windows of the distributor. The distribution windows are connected to the discharge windows of the sleeve valve 6. The power fluid flows through the discharge windows into the radial holes of the sleeve valve and discharged to the drain 9. The holes are connected to the annular grooves.

It is known [1-5] that fluctuations in the flow of power fluid, which the distribution system of planetary hydraulic machines causes, adversely affect their output characteristics. Such fluctuations cause pressure pulsation in the input cavity of the hydraulic machine. Meanwhile, their amplitude can exceed the values of the safety valve operation. Thus, the distribution system of planetary hydraulic machines can be considered as a source of complex nonharmonic pulsations that causes vibration of hydraulic system elements. This vibration leads to functional failures. The frequency and amplitude of the pulsations, which are caused by the distribution system of a hydraulic machine, primarily depends on the kinematic diagram for the system of the power fluid distribution. The number (a kind of a serial number) of a kinematic diagram was determined by the ratio of the working windows number (quantity) for the sleeve valve and the distributor. Therefore, the study of the effect of the hydraulic motor distribution system on its output characteristics is an actual task.

1.1. Analysis of Recent Studies and Publications

The cross-sectional area of the distribution system depends on the design parameters of the distributor and the sleeve valve. It is determined by the sum which is made up of the areas of the overlapping when the injection (discharge) windows of the sleeve valve overlap the distributor windows [2]. The main influence on the change in the cross-sectional area is provided by the kinematic diagram of the distribution system [3, 6]. The change in the cross-sectional area of the distribution system occurs cyclically and depends on the angle of rotation of the distributor. In the literature [7–9] the questions connected with designing of working surfaces of rotors in gerotor machines are considered. The theoretical and practical aspects of the problem were studied, and the mathematical models, which described the design process, were developed. The limitation of the studies was the fact that they did not consider the influence of the distribution system capacity on the output characteristics of the gerotor hydraulic machines. The investigation of the processes caused by the unsteady motion of viscous incompressible fluid [10, 11] established the reasons for the appearance of cavitation phenomena in the distribution zone. However, the mutual arrangement of the distributor and sleeve valve windows is characterized by a periodic change in the capacity of the distribution system. And it has not been investigated.

1.2. Statement of the Objective and Tasks of the Study

The purpose of the study is to improve the output characteristics of a planetary motor by substantiating the kinematic diagram of its power fluid distribution system.

To achieve this objective, the following tasks were accomplished:

– determine the relationship between the throughput capacity of the distribution system and the output characteristics of a planetary motor;

– investigate how the change of the throughput capacity of the distribution system with various kinematic diagrams effects the output characteristics of a planetary motor;

– justify the kinematic diagrams of the distribution system that could improve the output characteristics of the planetary motor.

2. The Basic Part of the Study

The mechanism of fluctuations occurrence in the flow of power fluid in the distribution systems of planetary hydraulic machines is the same as in axial-piston hydraulic machines [2, 4]. At the moment when the distributor window connects the sleeve valve injection window, a reverse flow of liquid occurs. It is accompanied by a pressure drop (hydraulic shock). This burst (pulsation) of pressure is repeated at each subsequent cycle. The possibility of pressure pulsations can be eliminated (reduced) by a rational choice of operating modes for the power fluid distribution system, when designing the planetary hydraulic motors.

The throughput of the distribution system of a planetary motor is defined as the flow of power fluid through the gap [4, 5]:

$$Q_{hm} = \mu \cdot A_{p.s} \cdot \sqrt{\frac{2(p_{in} - p_{out})}{\rho}} \ , \qquad (1)$$

where μ is the flow coefficient; ρ is the density of the power fluid; p_{in} is the pressure at the input to the hydraulic motor; p_{out} is the pressure at the output of the hydraulic motor; $A_{p.s.}$ is the area of the passage section [2, 6] of the distribution system of a planetary motor.

The cross-sectional area depends on the mutual arrangement of the distributor and the sleeve valve windows and their overlap. The cross-sectional area can be expressed by the following dependence which describes the overlap of the *i-th* window of the distributor with the sleeve valve injection windows according to the operating time of the hydraulic motor [2, 6]:

$$A_{p.s_i}(t) = \sum_{i=1}^{Z} \left(\frac{\pi}{Z_2} - \left| \beta_i - \alpha_i(t) \right| \right) \cdot \frac{\left(R_2^2 - R_1^2\right)}{2} , \qquad (2)$$

where Z_2 is the number of the sleeve valve windows; α_i is the angle of the distribution window location; β_i is the angle of the sleeve valve windows location; R_1 and R_2 are the internal and external radiuses of the distribution windows location, respectively.

To determine the change in the output parameters of the planetary motor during operation, it is necessary to settle the magnitude of the fluctuations in the flow of the power fluid.
The amplitude of the output parameters fluctuations in a planetary motor:
– throughput of the distribution system

$$A_Q = \mu \cdot \sqrt{\frac{2(p_{in} - p_{out})}{\rho}} \cdot (A_{max} - A_{min}) , \qquad (3)$$

where A_{max}, A_{min} are the maximum and minimum values of the cross-section area, respectively;

– rotational speed of the motor shaft

$$A_n = \frac{\mu \cdot \sqrt{\frac{2(p_{in} - p_{out})}{\rho}} \cdot \eta_v}{V} \cdot (A_{max} - A_{min}) ; \qquad (4)$$

where V is the working volume of the planetary motor; η_v is the volumetric efficiency;

– power fluid pressure

$$A_p = \frac{Q_{гм}^2 \cdot \rho}{2\mu^2} \cdot \left(\frac{1}{A_{\min}^2} - \frac{1}{A_{\max}^2} \right) ; \qquad (5)$$

– torque on the motor shaft

$$A_M = \frac{V \cdot \eta_м}{2\pi} \cdot \frac{Q_{гм}^2 \cdot \rho}{2\mu^2} \cdot \left(\frac{1}{A_{\min}^2} - \frac{1}{A_{\max}^2} \right) , \qquad (6)$$

where η_m is the mechanical efficiency of a planetary motor.

The pulsation coefficient can be used to measure and evaluate the value of the pressure pulsation in the power fluid flow [2]:

– throughput of the distribution system

$$P_A = \frac{2 \cdot (A_{\max} - A_{\min})}{A_{\max} + A_{\min}} 100\% ; \qquad (7)$$

– rotational speed of the motor shaft

$$P_n = \frac{2 \cdot (A_{\max} - A_{\min})}{A_{\max} + A_{\min}} 100\% ; \qquad (8)$$

– power fluid pressure

$$P_p = \frac{2 \cdot \left(\frac{1}{A_{min}^2} - \frac{1}{A_{\max}^2} \right)}{\left(\frac{1}{A_{\max}^2} + \frac{1}{A_{min}^2} \right)} 100\% ; \qquad (9)$$

– torque on the motor shaft

$$P_M = \frac{2 \cdot \left(\frac{1}{A_{min}^2} - \frac{1}{A_{\max}^2} \right)}{\left(\frac{1}{A_{\max}^2} + \frac{1}{A_{min}^2} \right)} 100\% . \qquad (10)$$

The studies enabled to determine the interconnections between the capacity of the distribution system and the output characteristics of a planetary motor. It is established that the change in the flow area of the hydraulic motor distribution system has a significant effect on the variation in the capacity of the distribution system, the speed of the shaft, the pressure of the power fluid and the torque on the shaft of the planetary motor. Fluctuations in the cross-section area cause a pressure pulsation of the power fluid flow. This adversely affects the operation of the planetary motor.

3. Results and Discussion

The simulation of the operation of the planetary hydraulic motors distribution systems with various kinematic diagrams [6] showed that the character of the change in the area of the passage section is described by three dependences:
– for diagrams 4/3; 6/5; 8/7; 10/9; 12/11, it is the dependence expressed by the unsynchronized cyclic curve, where the changes in the passage area of the injection and discharge windows are in antiphase;
– for diagrams 7/6; 11/10, the dependence is expressed by the synchronous cyclic curve. The changes in the passage section area of the injection and discharge windows are in the same phase;
– for diagrams 5/4; 9/8; 13/12, the dependence is a straight line.
The change in the cross-sectional area as a function of the kinematic diagram is shown in Table 1.
The change in the throughput of the distribution system effects on the planetary motor output parameters during its operation. The change was determined by modeling in the *Vissim* package (Figures 3-5). The simulation was performed for a planetary hydraulic motor of the PRG-22 series with a working volume of 160 cm^3. For the simulation, the following initial data were accepted: the pump supply, which provides the flow of power fluid through the hydraulic motor, was 70 l/min and the moment of resistance which provides working pressure of 14 MPa. It should be noted that in all planetary motors of the PRG series, the distribution systems are structurally the same. Therefore, the results of the research can be applied to the entire series of these motors, regardless of their size.

Figure 4 shows the dependence of the variation in the output characteristics of the PRG-22 planetary motor for 4/3; 6/5; 8/7; 10/9 and 12/11 kinematic diagrams of the distribution system.

Table 1: The change in the cross-sectional area as a function of the kinematic diagram for the distribution system

Kinematic diagram	Cross-sectional area, mm				
	Working windows number	max	min	mean	Fluctuation amplitude
4/3	3	198	132	150	66
5/4	4	158	158	158	0
6/5	5	185	158	165	27
7/6	6	188	151	169	37
8/7	7	170	183	173	13
9/8	8	176	176	176	0
10/9	9	184	176	178	8
11/10	10	188	172	180	16
12/11	11	186	180	182	6
13/12	12	183	183	183	0

Analysis of simulation results (Figure 4, a) showed that fluctuations in the cross-section area of the distribution system cause pulsations of the power fluid flow. The fluctuations amplitude for the flow rate of the power fluid is 24, 12, 6, 4 and 2 l/min, in accordance with the kinematic diagram (curves 1–5).

The change in the rotational speed of the shaft of the hydraulic motor (Figure 4, b) is expressed by the dependences similar to the flow rate of the power fluid. The amplitude of the fluctuations in the shaft rotation frequency is 160, 60, 30, 20 and 10 min^{-1} (curves 1–5), in accordance with the kinematic diagram of the distribution system.

Dependences of the change in the pressure of the power fluid are caused by the flow fluctuations (Figure 4, c) and expressed by the dependences of the reverse changes in the flow rate. The amplitude of variations in the pressure of the power fluid is 14, 4.5, 2.5, 1.5 and 0.75 MPa, for the corresponding kinematic diagrams (curves 1–5).

The dependence of the change in the torque on the hydraulic motor shaft (Figure 4, d) was analyzed. The analysis showed that the nature of its change is analogous to the change in pressure. The amplitude of the fluctuations of the torque is 250, 100, 50, 25 and 12.5 N·m, according to the kinematic diagram (curves 1–5) of its distribution system.

It should be pointed out that as the number (serial number) of a kinematic diagram increases (because of increasing of the working windows quantity), the throughput of the distribution system of the planetary motor increases, and the amplitude of the fluctuations of the modeled parameters decreases. The change in the speed of rotation of the hydraulic motor shaft (Figure 4, b) is provided by a variation in the flow rate of the power fluid (Figure 4, a). The variation in the pressure of the power fluid (Figure 4, c) is caused by the change in the (Figure 1, d) planetary motor torque.

Figure 5 shows the dependences of the variation in the output characteristics of the PRG-22 planetary motor for the 7/6 and 11/10 kinematic diagrams of the distribution system.

The studies established that the fluctuations in the flow rate of the power fluid for the 7/6 and 11/10 kinematic diagrams of the distribution system are 14 and 5 liters per minute, and the pressure fluctuations of the power fluid are 7 and 2.5 MPa, respectively. The analysis of the change in the rotational speed of the motor shaft (Figure 5, a) showed that the fluctuations of the rotational speed were caused by the change in the flow rate of the power fluid. They were 75 min^{-1} for the 7/6 kinematic diagram and 30 min^{-1} for the 11/10 diagram (curves 1, 2 respectively).

The amplitude of the fluctuations in the torque on the hydraulic motor shaft (Figure 5, b) for the 7/6 and 11/10 kinematic diagrams of the distribution system is 160 and 50 N·m, respectively (curves 1, 2).

Figure 6 presents the dependence of the variation in the output characteristics of the PRG-22 planetary motor for the 5/4; 9/8 and 13/12 kinematic diagrams of the distribution system.

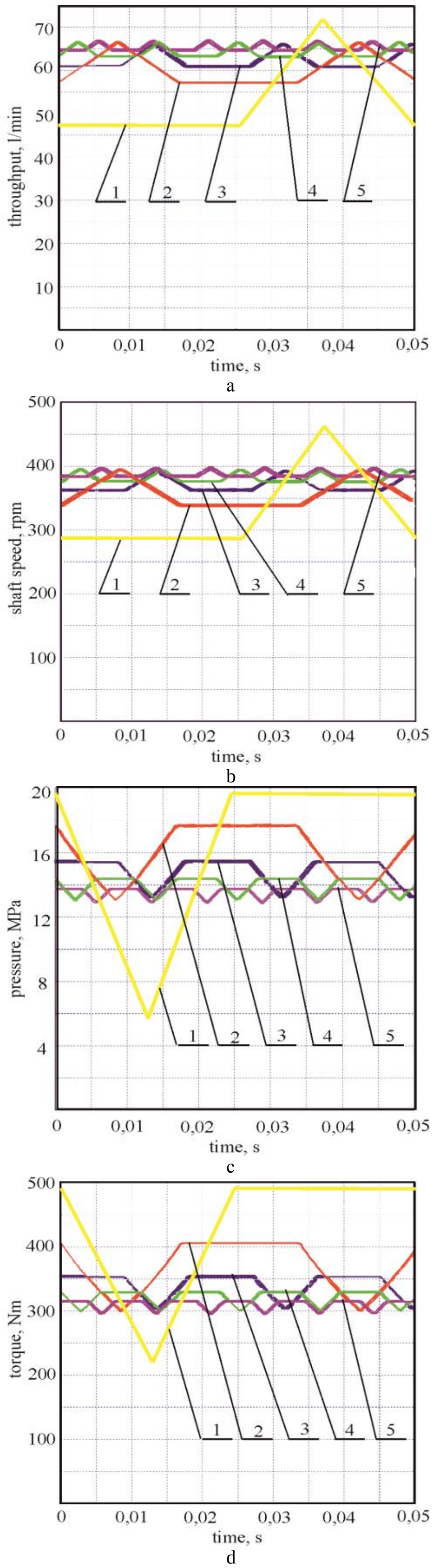

Fig. 4: The change in the characteristics of the PRG-22 planetary hydraulic motor for various kinematic diagrams of the distribution system: 1 – 4/3; 2 – 6/5; 3 – 8/7; 4 to 10/9; 5 – 12/11; a – power fluid flow rate; b – rotational speed of the motor shaft; c – pressure; d – the torque.

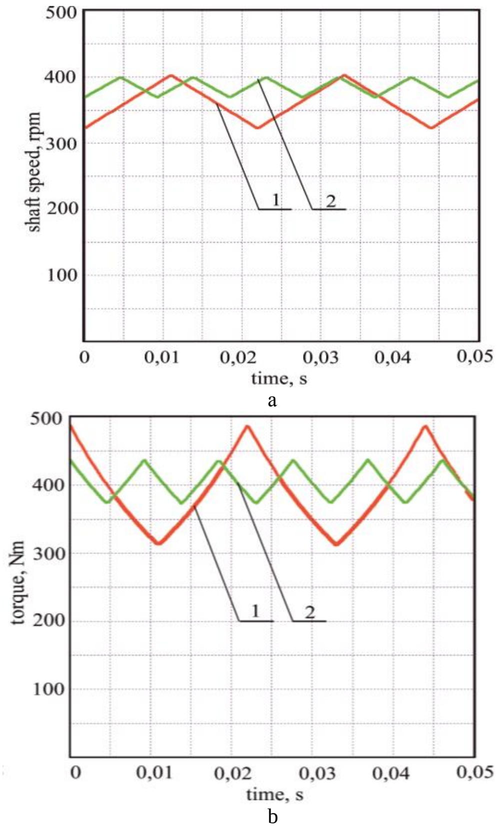

Fig. 5: The variation in the output characteristics of the PRG-22 planetary hydraulic motor for various kinematic diagrams of the distribution system: 1 – 7/6; 2 – 11/10; a – frequency of rotation of the motor shaft; b – the torque.

The findings revealed the situation when there were no any fluctuations in the in the passage area and, as a consequence, were no any fluctuations in the flow and pressure of the power fluid. That was true for the 5/4; 9/8 and 13/12 kinematic diagrams of the distribution system of the planetary motor.

Analysis of the change in the rotational speed (Figure 6, a) and torque on the motor shaft (Figure 6, b) displayed the absence of flow and pressure fluctuations of the power fluid, and as a result the absence of the fluctuations in the rotational speed and torque (curves 1-3 respectively).

Thus, the absence of fluctuation in the cross-sectional area for the 5/4; 9/8 and 13/12 kinematic diagrams for the distribution system of the planetary motor allows to ensure the constancy of its output characteristics.

The increase in the cross-sectional area of the distribution system can be achieved by using additional (unloading) distributor windows as the working ones. It is known [2] that the increase in the number of additional distributor windows results the growth of the cross-sectional area in the distribution system of the power fluid. However, the length of the distributor is limited, so no more than 4 screw grooves can be made on the shaft section corresponding to the length of the distributor. Thus, it is recommended to use no more than 4 additional distributor windows.

Moreover, in distribution systems with 4/3, 6/5, 8/7, 10/9, 12/11 kinematic diagrams, only 2 additional distributor windows can be used.

Possible options for the application of additional distributor windows and changes in the flow area depending on the kinematic diagram are shown in Table 2.

Analysis of Table 2 shows that for the 5/4 and 9/8 kinematic diagrams, when 4 additional distributor windows are used, there are no any fluctuations in the cross-sectional area of the distribution system. This will ensure the consistency of the output characteristics for the planetary motor.

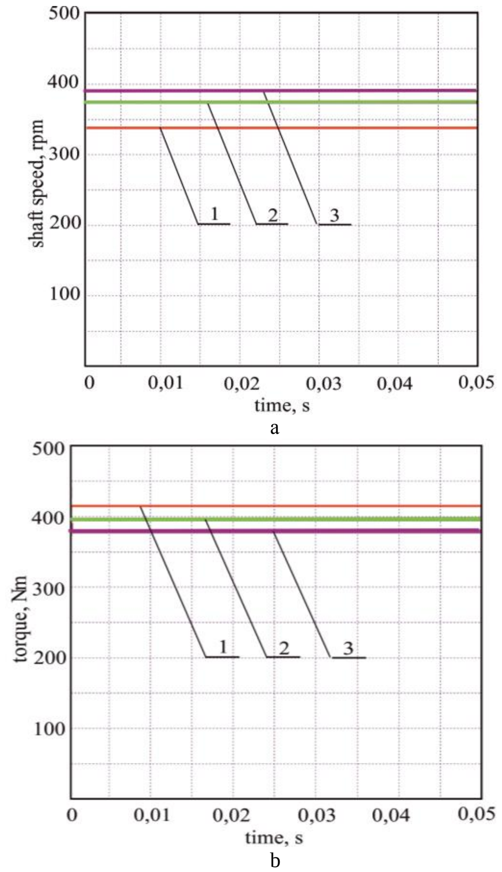

Fig. 6: The change in the output characteristics of the PRG-22 planetary hydraulic motor with various kinematic diagrams of the distribution system: 1 – 5/4; 2 – 9/8; 3 – 13/12; a – frequency of rotation of the motor shaft; b – the torque.

Table 2: Possible options for application of additional distributor windows depending on the kinematic diagram of the distribution system

Kinematic diagram	Cross-sectional area, mm					
	Working windows number	Additional windows number	max	min	mean	Fluctuation amplitude
4/3	3	2	387	132	250	255
5/4	4	2	317	157	240	160
		4	317	317	317	0
6/5	5	2	288	145	213	143
7/6	6	2	264	188	226	76
		3	264	236	255	28
		4	338	236	284	102
8/7	7	2	281	173	220	108
9/8	8	2	264	174	220	90
		4	264	264	264	0
10/9	9	2	265	175	218	90
11/10	10	2	246	186	216	60
		4	275	229	252	46
12/11	11	2	230	180	217	50
13/12	12	2	240	190	215	50
		3	245	220	225	25
		4	264	224	244	40

The reduction of the pulsation of the power fluid flow is achieved by the angular displacement of the distributor windows according to the developed procedure [2]. The change in the cross-sectional area, depending on the kinematic diagram after the distribution windows shift, is shown in Table 3.

The analysis of Table 3 shows that the angular displacement of the distributor windows allows reducing the fluctuations in the power fluid flow of the distribution system of the planetary motor significantly. If before the shift of the distribution windows the area fluctuations ranged from 25 to 250 mm^2, depending on the kinematic diagram (Table 2), so after the displacement it became 7 to 50 mm^2 (Table 3). That is 4 to 5 times lower.

Table 3: The cross-sectional area change according to the kinematic diagram of the distribution system after the shift of the distributor windows

Kinematic diagram	Cross-sectional area, mm					
	Working windows number	Additional windows number	max	min	mean	Fluctuation amplitude
4/3	3	2	275	238	250	37
5/4	4	2	265	215	240	50
		4	windows shift is not needed			
6/5	5	2	225	207	213	18
7/6	6	2	236	236	236	0
		3	264	250	255	14
		4	294	274	284	20
8/7	7	2	240	200	220	20
9/8	8	2	226	214	200	12
		4	windows shift is not needed			
10/9	9	2	240	215	218	25
11/10	10	2	216	216	216	0
		4	257	247	252	10
12/11	11	2	225	215	217	10
13/12	12	2	220	210	215	10
		3	230	223	225	7
		4	244	244	244	0

It should be noted that for the 7/6 and 11/10 kinematic diagrams, when 2 additional distribution windows are used, as well as for the 13/12 diagrams, when 4 additional windows are used, there are no any oscillations in the cross-section area of the distribution system. This phenomenon positively affects the output characteristics of the planetary motor.

4. Conclusion

There is interrelation between the capacity of the distribution system and the output characteristics of a planetary motor. The findings proved and established the relation under various kinematic diagrams of the distribution system.

The change in the capacity of the distribution system with various kinematic diagrams effects on the output characteristics of the orbital hydraulic motor. The investigation ascertained that fluctuations in the passage area cause a pulsation of the pressure of the power fluid flow. This adversely influences the operation of the planetary hydraulic motor. The change in the cross-section area of the distribution system of a planetary motor has a significant effect on the change of its speed, the pressure of the power fluid and the torque.

The operation of the distribution system of a planetary hydraulic motor was modeled according to various kinematic diagrams and it enabled to justify that the kinematic diagrams ofthe output characteristics are improving. The analysis of the performed studies showed that the most rational kinematic diagrams for the distribution systems of the power fluid are:

- 5/4; 9/8; 13/12 without additional distribution windows;
- 5/4; 9/8 when 4 additional distribution windows are used and the system does not require angular displacement of the distributor windows;
- 7/6; 11/10 when 2 windows are used and 13/12 - 4 additional distribution windows are applied followed by the angular shift of the distributor windows.

The application of the proposed diagrams provides absence of fluctuation in the cross-section area of the distribution system and, as a result, ensures the constancy of the output characteristics of the planetary motor.

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