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# Improving the output characteristics of planetary hydraulic machines

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**Abstract.** Current trends in expanding the field of application of mechatronic systems with a hydraulic drive of active working bodies of self-propelled vehicles necessitates the creation of new designs of hydraulic machines. For mechatronic systems with a hydraulic drive of the active working bodies of self-propelled vehicles, various types of hydraulic machines are used, but special attention is paid to orbital and planetary hydraulic motors. The crank in this hydraulics machines is a rotating hydraulic field formed by the distribution system of the planetary hydraulic motor. The distribution system of the considered hydraulic motor is one of the main mechanisms determining the stable operation of the planetary hydraulic motor. As a result of the research, design schemes, a mathematical apparatus, and a calculation algorithm have been developed that make it possible to justify the angular arrangement of the working and unloading windows of the moving distributor. The angular arrangement of the working and unloading windows of the moving distributor of the planetary hydraulic motor distribution system is substantiated. A technique has been developed for shifting the distribution window of the movable distributor, which allows to reduce fluctuations in the flow of the working fluid, and as a result, improve the functional parameters of the planetary hydraulic motor.

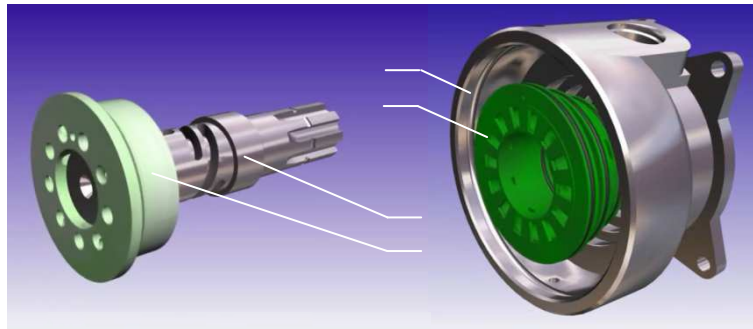
## 1. Introduction

Current trends in expanding the field of application of mechatronic systems with a hydraulic drive of active working bodies of self-propelled vehicles necessitates the creation of new designs of hydraulic machines. For mechatronic systems with a hydraulic drive of the active working bodies of self-propelled vehicles, various types of hydraulic machines are used [1, 2], but special attention is paid to planetary [3-7] and orbital [8-12] hydraulic motors. By plane tary hydraulic motors are meant hydraulic machines operating on the principle of a planetary gearbox. The crank in this hydraulic machine is a rotating hydraulic field formed by the end distribution system of the planetary hydraulic motor [3-7].

The distribution system of the planetary hydraulic motor consists of a front cover 1, a fixed 2 and a movable 3 distributors, as well as a shaft 4 of the hydraulic motor (figure 1). The fixed distributor 2 installed in the front cover 1 forms a node for supplying and plum discharging the working fluid of the hydraulic motor. A movable distributor 3 mounted on the shaft 4 of the hydraulic motor forms a distribution unit that supplies (discharges) the working fluid to the working chambers of the hydraulic



motor. When the distribution system is operating, the movable distributor 3 mounted on the hydraulic motor shaft 4 rotates relative to the stationary 2 installed in the front cover 1. The contacting of the end surfaces of the immobile 2 and movable 3 distributor having special windows [3, 6, 7] forms a zone of formation of a rotating hydraulic field.



**Figure 1.** Elements of the distribution system of the planetary hydraulic motor: 1 – front cover; 2 – immobile distributor; 3 – a movable distributor; 4 – a shaft of a hydraulic motor.

The distribution system under consideration is a source of complex nonharmonic pulsations that cause vibration of the hydraulic system elements leading to functional failures [1, 2, 4, 5]. The frequency and amplitude of the pulsations caused by the distribution system primarily depends on the kinematic scheme of the working fluid distribution system. The number of the kinematic diagram of the distribution system is determined by the ratio of the number of high pressure windows of the fixed distributor to the number of working windows of the movable distributor.

Thus, the study of issues related to the calculation and design of distribution systems is an urgent task, the solution of which will improve the output characteristics of planetary hydraulic machines.

## 2. Analysis of recent studies and publications

When designing the orbital and gerotor hydraulic machines, the forces acting in the gearing were taken into account [13, 14], were justified the maximum deviations of the error the manufacturing contour of the gear of the rotors [11]. Developed universals models of mechatronic systems [12], mathematical models describing the change in loads [8] were taking into account the equations of hydrodynamics of fluid motion in the working chambers [9]. Tribological changes in the geometry of the working surfaces of the rotors [15] of these hydraulic machines and developed programs for designing gear surfaces [16] are investigated. However, in these works, the distribution systems of the working fluid, which are necessary for creating a rotating hydraulic field of the working fluid, are not considered.

The effect of additives in oils on the processes of friction and wear in movable joints was studied [17]. The results of laboratory studies of the effect of carbon nanoparticles on the antiwear and extreme pressure properties of industrial oil are presented [18]. The effect of an external magnetic field on the change in adhesion parameters upon contact of magnetized steel rolling elements was studied [19]. 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 [20]. The reasons for the occurrence of cavitation phenomena in the system of distribution [21] are substantiated, modeling of the flow of the working fluid through the channels of gerotor hydraulic motors [14]. Is considered Geometrical [22], mathematical [23], and hydrodynamic models [24, 25] are proposed that allow one to study the influence of the geometric parameters of flowing parts on the output characteristics of gerotor hydraulic machines. In a planetary hydraulic motor, an distribution system is used to create a rotating hydraulic field [3-7].

It was established [3] that the synchronization of rotation of the hydraulic field and the displacers of the hydraulic machine depends on the number of working chambers and is characterized by the kinematic diagram of the distribution system. Rational kinematic schemes of distribution systems are

substantiated [4]. A calculation scheme and a mathematical apparatus have been developed to study the performance of a distribution system with various windows made in the form of a segment [5], a circle [6] and a groove [7]. The issues related to the elimination of fluctuations in the flow area of the distribution system to ensure the constancy of the output characteristics of the planetary hydraulic motor are not considered.

Thus, ensuring the constancy of the output characteristics of the planetary hydraulic motor by eliminating fluctuations in the throughput of its distribution system is an important scientific problem.

### 3. Statement of the objective and tasks of the study

To study the effect of the number and angular location of the working and unloadings windows of the movable distributor on the output characteristics of the planetary hydraulic motor, it is necessary:

- to develop calculation schemes, a mathematical apparatus and a calculation algorithm to justify the angular location of the working and unloading windows of the moving distributor and to determine the influence of the location of the windows on the output characteristics of the planetary hydraulic motor;
- to develop a technique for bias the working and unloading windows of a movable distributor, which allows to reduce fluctuations in the flow of working fluid, and in order to improve the functional parameters of the planetary hydraulic motor;
- to justify the influence of the geometric parameters of the distribution system on the functional parameters of the planetary hydraulic motor.

### 4. The basic part of the study

The layout of the distribution windows in the zone of formation of the hydraulic field (figure2), formed by the distribution windows [5-7], located on the end surfaces of the fixed and movable distributors, clearly shows the formation of the high and low pressure zones when the working fluid is supplied (withdrawn) to the working chambers of the hydraulic motor.

On the end surface of the immobile distributor, discharge windows 3 and drain 4 are made (figure2). With these windows are in contact, the working 1 and unloading 2 windows of the movable distributor located on its end surface. The number of distribution windows of the immobile distributor is always two more than the movable [3, 5-7]. The superimposition of the windows of the movable distributor on the windows immobile distributor allows you to get a diagram of the instantaneous position of the phases of the distribution of the working fluid in the distribution system in question. Unloading windows 2 of the movable distributor do not take part in the distribution of the working fluid, but serve to balance the pressure force of the working fluid acting on the end surfaces of the fixed and movable distributors.

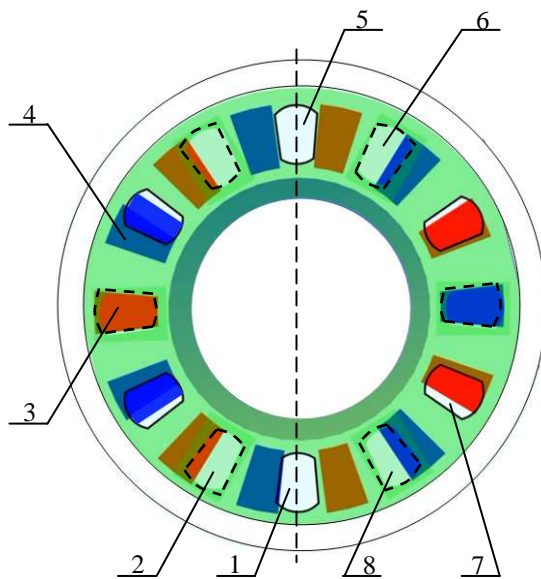
The main characteristic of the distribution system is its bandwidth (flow rate of the working fluid), determined by the area of the passage section of this system [4, 5]. An increase in the bandwidth of the distribution system can be achieved by using additional (unloading) windows of the movable distributor as workers.

It is known [4, 5] that the use of additional (unloading) windows leads to both an increase in throughput and a change in the pulsation of the flow of the working liquid.

In order to reduce the pulsation of the flow of the working fluid, a technique has been proposed that methodology to reduce fluctuations in the area of the flow by shifting the windows of the movable distributor.

1. Determined by position of the distribution windows of the movable and fixed distributors is determined.

In articles [3, 5-7] is described in detail the definition: of angles of location of the first working window  $\alpha_1$  and subsequent  $\alpha_i$  windows of the movable distributor; of first window high pressure  $\beta_1$  and subsequent  $\beta_i$  windows of the fixed distributor; of angles of restricting the geometric parameters of the distribution windows  $\varepsilon$ , angles  $\sigma_i$  between the centers of the windows of the movable and fixed distributors that are in the overlap; of angles of overlap  $\gamma$  distribution windows.



**Figure 2.** The layout of the distribution windows in the zone of formation of the hydraulic field: 1 – working windows of the movable distributor; 2 – unloading windows of the movable distributor; 3 – discharge windows of a immobile distributor; 4 – drain windows of a immobile distributor; 5 – an opening window for supplying fluid to the working chambers (opening phase); 6 – an opening window for draining liquid from the working chambers (opening phase); 7 – a window that closes when fluid is supplied to the working chambers (closing phase); 8 – a window that closes when draining the liquid from the working chambers (closing phase).

2. The range of opening and closing of each working and additional (unloading) windows of the movable distributor.

If the windows do not overlap  $|\beta_i - \alpha_i| > \varepsilon$ , then

$$\alpha_{open_i} = \beta_i - \varepsilon - \alpha_i, \quad \alpha_{closed_i} = \beta_i + \varepsilon - \alpha_i. \quad (1)$$

If  $\alpha_i > \beta_i + \varepsilon$ , then

$$\alpha_{open_i} = \beta_{i+1} - \varepsilon - \alpha_i, \quad \alpha_{closed_i} = \beta_{i+1} + \varepsilon - \alpha_i. \quad (2)$$

If the windows overlap  $|\beta_i - \alpha_i| \leq \varepsilon$ , then the calculation is performed according to the expressions (1, 2) until  $\alpha_{open_i} > 4\pi/Z_2$  and  $\alpha_{closed_i} > 4\pi/Z_2$ . If  $\alpha_{open_i} < 4\pi/Z_2$ ,  $\alpha_{closed_i} > 4\pi/Z_2$ , then  $\alpha_{closed_i} = 4\pi/Z_2$ , where  $Z_2$  – the number of windows of the immobile distributor (windows high pressure have odd numbers, and drain windows have even numbers).

3. The number of additional (unloading) windows of the movable distributor is selected (from 2 to  $Z_1/4$ ) and determined their numbers, where  $Z_1$  – is the number of windows of the movable distributor (working windows have odd numbers, and unloading windows are even). If  $Z_1/4$  of additional (unloading) of the windows is used, then their numbers are always a multiple of 4.

4. Compared moment of closing of each window of the movable distributor with the opening of the windows is (taking into account additional (unloading) windows). That is, for each closed (or closing) window of the movable distributor there is such an open (or opening) window so that their difference does not exceed the order of the "opening-closing" windows of the movable distributor

$$\alpha_{period} = \alpha_{closed_i} - \alpha_{open_i}. \quad (3)$$

Closing additional (unloading) windows always correspond to opening working windows, and the number of the corresponding opening working window is  $i_{work} = i_{unload} + 1, i_{unload} + 4, i_{unload} + 8, \dots, Z_1$ .

However, if the number of the closing additional (unloading) window is  $i_{unload} = Z_1$ , then the number of the corresponding opening working window is determined  $i_{work} = 1$ .

Opening additional (unloading) windows always correspond to closing working windows, which will subsequently shift, and the number of the closing working window is  $i_{work(offset)} = i_{unload} - 1$ .

5. For each pair of windows, the overlap angle of the windows is determined ahead or behind

$$\gamma_{outrun_i} = \alpha_{closed_i} - \alpha_{open_i} > 0, \quad \gamma_{lag_i} = \alpha_{closed_i} - \alpha_{open_i} < 0. \quad (4)$$

If the difference between the closing and opening windows is positive, then the windows overlap ahead, and if the difference is negative, then the overlap is lagging.

For kinematic schemes 7/6 и 11/10 ( $Z_1 = 12; 20$ ): if the closing working window corresponds to the opening working window, then the overlap determined by 0; if the closing working window corresponds to the opening additional unloading window and vice versa, then the overlap is equal to  $i_{closedZ1}$ .

For kinematic schemes 5/4, 9/8 и 13/12 ( $Z_1 = 8; 16; 24$ ): if the closing working window corresponds to the opening working window, then the overlap determined by  $i_{period}$ ; if the closing working window corresponds to the opening additional unloading window and vice versa, then the overlap is equal to  $i_{closedZ1}$ .

6. The algebraic sum of the leading and lagging phases is determined

$$\sum \gamma = \sum \gamma_{outrun_i} - \sum \gamma_{lag_i}. \quad (5)$$

If all pairs of windows overlap ahead of time, then expression (5) will take the form:

$$\sum \gamma = \sum \gamma_{outrun_i}.$$

7. Is determined the average overlap value

$$\gamma_{mean} = \frac{\sum \gamma}{Z_{work} + Z_{unload}}. \quad (6)$$

8. Is determined the shift of the windows  $\tau$  of the movable distributor.

For kinematic schemes 7/6 и 11/10 ( $Z_1 = 12; 20$ ):

– for additional (unloading) windows involved in the work

$$\tau_{unload} = \gamma_{outrun,unload} - \gamma_{mean}; \quad (7)$$

– for working windows

$$\tau_{work} = \gamma_{mean} - \gamma_{lag}. \quad (8)$$

If the distributor and spool windows are located without a gap, then  $\tau_{work} = \tau_{mean}$ .

For kinematic schemes 5/4, 9/8 и 13/12 ( $Z_1 = 8; 16; 24$ ):

– for additional (unloading) windows involved in the work

$$\tau_{unload} = \gamma_{mean} - \gamma_{outrun,unload}; \quad (9)$$

– for working windows

$$\tau_{work} = \gamma_{outrun,work} - \gamma_{mean}. \quad (10)$$

9. Are determined the numbers of windows that will be shifted.

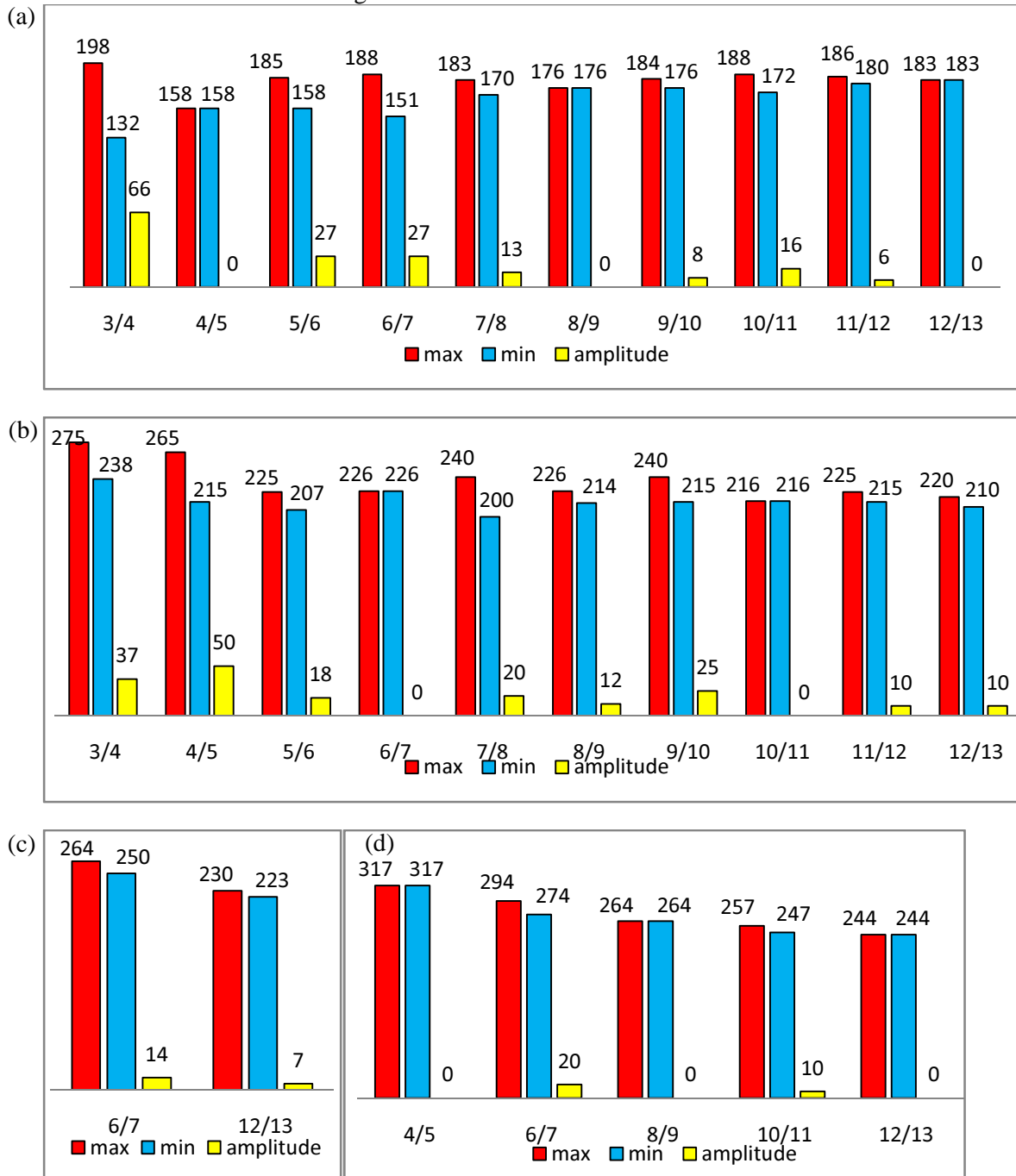
The numbers of working windows that will be shifted are determined:  $i_{work} = i_{unload} - 1$ .

Moreover, for kinematic schemes 7/6 и 11/10 ( $Z_1 = 12; 20$ ) working and additional (unloading) windows are shifted clockwise, and for kinematic schemes 5/4, 9/8 и 13/12 ( $Z_1 = 8; 16; 24$ ) working and additional (unloading) windows are shifted counterclockwise.

10. The location angles of the workings and additional (unloading) windows of the movable distributor after the displacement are determined

$$\alpha'_{work_i} = \alpha_{work_i} \pm \tau_{work}, \quad \alpha'_{unload_i} = \alpha_{unload_i} \pm \tau_{unload}, \quad (11)$$

if the windows are shifted clockwise, then  $\tau_{work}$  и  $\tau_{unload}$  taken with a sign “+”, if the windows are shifted counterclockwise - with a sign “-”.



**Figure3.**Dependence of the passage area on the kinematic scheme: a – without the use of additional (unloading) windows (without window displacement); b – with the use of two; c– three; d – four additional (unloading) windows (after the displacement of the windows).

11. Is determined bandwidth of the distribution system [3, 5-7] using additional discharge windows.

Methodology of smoothing the pulsation of the flow of the working fluid when using two additional discharge windows is similar.

For kinematic schem 7/6 ( $Z_1 = 12$ ): opening working windows corresponding to closing additional unloading windows are shifted clockwise by an amount  $\tau_{unload}$ ; closing working windows, which correspond to opening additional unloading windows, are shifted counterclockwise by an amount  $\tau_{unload}$ .

For kinematic schemes 9/8; 11/10; 13/12 ( $Z_1 = 16; 20; 24$ ) except windows shifted similarly to the kinematic scheme 7/6 ( $Z_1 = 12$ ), the working windows are also shifted by  $\tau_{work}$  – for kinematic scheme 11/10 ( $Z_1 = 20$ ) on  $(\tau_{unload} - \tau_{work})$ .

For kinematic schemes 9/8 и 13/12 ( $Z_1 = 16; 24$ ): the opening working windows corresponding to the closing working windows that are shifted clockwise; the closing working windows, to which the opening working windows correspond, are shifted counterclockwise.

Based on the developed methodology, the possible options for using additional (unloading) windows of the movable distributor and changing the area of the passage section of the distribution system depending on the kinematic scheme are justified (figure 3).

The analysis of figure 3 shows that the use of additional (unloading) windows of the movable distributor allows you to increase the average passage area from 150...183 mm<sup>2</sup> to 215...317 mm<sup>2</sup>. The angular displacement of the distribution windows of the movable distributor to reduce the amplitude of the oscillations of the passage area to 0...50 mm<sup>2</sup> depending on the kinematic scheme.

The most rational kinematic schemes of a planetary hydraulic motor are: 5/4, 9/8 и 13/12 without the use of additional unloading windows of the movable distributor (without their displacement); 5/4 и 9/8 when using 4 additional (unloading) windows of the movable distributor (without their displacement); 7/6 и 11/10 when using 2 additional (unloading) windows of the movable distributor (with offset); 13/12 when using 4 additional (unloading) windows of the movable distributor (with offset).

Using these kinematic schemes will ensure the constancy of the output characteristics of the planetary hydraulic motor.

## 5. Conclusions

As a result of the research, design schemes, a mathematical apparatus, and a calculation algorithm have been developed that make it possible to justify the angular location of the working and unloading windows of the movable distributor and to determine the effect of the location of the windows on the functional parameters of the planetary hydraulic motor.

The angular arrangement of the working and unloading windows of the mobile distributor of the distribution system is substantiated, which allows to increase the throughput of the planetary hydraulic motor by almost 2 times. A technique has been developed for shifting the distribution windows of the movable distributor, which allows to reduce fluctuations in the flow of the working fluid.

The most rational kinematic schemes are substantiated: 5/4, 9/8 and 13/12 without using additional windows, as well as 5/4, 7/6, 9/8, 11/10 and 13/12 when using additional windows. In these kinematic schemes, there are no fluctuations in the flow area of the distribution system, which ensures the stability of the output characteristics of the planetary hydraulic motor.

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