

*The object of research is the processes in hydraulic motors based on power cylinders, designed to drive the shaft of the working equipment in modern machines into rotational motion.*

*When using standard motors, a problem arises relating to the need to introduce additional devices into the structure of the mechanisms of modern machines. Such devices are aimed at matching the rotation frequency of the motor shaft with the rotation shaft of the working equipment of these machines. Such a device is a reducer, the use of which leads to the appearance of a number of disadvantages. Their elimination is achieved by using the results of this study.*

*The reported results differ from standard motors that are mass-produced, in that, based on research, motors with a rotation frequency of its shaft in the range from zero to two hundred and more revolutions per minute are proposed, which is not realized by known motors. This testifies to the construction of motors based on power cylinders, which make it possible to realize this range of rotation frequencies of its shaft.*

*The special and distinctive features of the results are based on the application of the principle of disintegration of motor elements into two functional components. One of them includes power cylinders with a crankshaft, and the second one includes the distribution system of the working fluid.*

*The motor implementation went through the stages of designing computer and physical models and devising schematic solutions. Calculation dependences were obtained to determine the main design parameters, according to which the motor was manufactured in the form of a full-scale sample.*

*The scope and conditions of practical use refer to machines with working equipment capable of functioning under a mode with a low rotation frequency and a significant torque on the motor shaft*

*Keywords: hydraulic drive, earthmoving and construction machines, low-speed motors, valve distributors, power cylinders*

# DESIGN OF HYDRAULIC MOTORS WITH ROTARY SHAFT MOVEMENT FOR DRIVING WORKING EQUIPMENT IN MODERN MACHINES

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## 1. Introduction

Machines with a continuous working cycle are the most loaded and, at the same time, the least reliable, which include rotary and chain excavators. Cyclic machines, which are also the most heavily loaded, include construction machines with their load-lifting mechanisms. The structure of the working equipment of such machines includes hydromechanical devices consisting of gearboxes and high-speed hydraulic motors (HM).

It is generally known that the frequency of revolutions of the working equipment of such machines, under the condition of ensuring high-quality execution of the work process, is in a narrow range from practically zero to two hundred or more revolutions per minute.

Thus, this is confirmed by study [1], in which it is reported that in order to match the frequency of rotation of the drum shaft of the cargo lifting mechanism with the frequency of rotation of HM shaft, multi-stage gearboxes should be used. On the basis of well-known sources, it is known that the modern machine-building industry produces serially, main-

ly, high-speed HMs of various designs with a frequency of 1000 revolutions per minute and more.

That is why, in the structure of the working equipment of the load lifting mechanism [1], a multi-stage gearbox is installed between the drum and the motor. Such a gearbox in the machine mechanism leads to additional power consumption and the appearance of other disadvantages, in particular, inefficient fuel consumption.

One of the directions for overcoming these shortcomings is the use of such mechanisms of serial low-speed high-torque HMs instead of gearboxes in the structure of the working equipment. Such HMs are characterized by the presence of internal losses of liquid between its moving joints; as a result, this leads to the process of lowering the cargo. To keep the cargo at any height during operation, the cargo lifting mechanism is equipped with a brake device. The inclusion of this device in operation leads to additional power consumption and a decrease in the performance of such machines. Construction of HM and its control system with the elimination of the shortcomings indicated above could improve the efficiency of the machines with the rotary movement of their working equipment.

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## 2. Literature review and problem statement

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In [2] it is stated that in low-speed high-torque HMs due to their design features aimed at ensuring the process of its operation, technological gaps form between the moving surfaces of the working elements of HM. The presence of such gaps, according to [3], leads to the appearance of constant internal flows of liquid that circulates in the body of HM, providing lubrication of its friction surfaces. In addition, the internal flow of liquid ensures maintenance of the internal liquid pressure in the HM housing at a given level due to its constant draining into the oil tank through a special drainage pipeline. Such fluid leaks in the HM housing do not allow fixing the stable position of the working equipment of modern machines, which leads to the need to use various special devices, for example, brakes. It also leads to a decrease in the operational productivity of such machines.

In study [4] it was shown that in the range of low rotation frequencies of the HM shaft due to internal fluid flow and the effect of high fluid pressure, an unstable mode of rotation of its shaft occurs. This mode of operation is characterized by the appearance of short-term stops and a sudden sharp increase in the speed of rotation of the HM shaft.

The reason for this is the conditions for the appearance of a phenomenon in the form of self-exciting vibration [5], and then for the appearance of resonance (a phenomenon in the form of a flutter). The vibration, which enters the resonance mode, can lead to the partial destruction of the HM components and the working equipment of such machines, the deterioration of the operator's work condition, and the reduction of the machine's performance. In general, this phenomenon has a negative effect on the reliability of other mechanisms of the above machines.

An option to overcome the above shortcomings can be achieved by creating conditions for the occurrence of a phenomenon in the form of liquid friction [6] in moving joints, which is capable of reducing the internal flow of liquid. This approach makes it possible to slightly shift the threshold for the appearance of vibration and resonance, provided that the frequency of rotation of the HM shaft is further reduced. In work [7] it is stated that the frequency mode of vibration depends on the operating conditions, rigidity of the structure, damping characteristics, and the frequency of rotation of the shaft. It was established in [8] that with an increase in the injection pressure of the liquid, the value of the resonance peak amplitude increases, but at the same time, the resonance frequency decreases. According to [8], to reveal the completeness of the process, it is necessary to conduct additional research. In general, the cited studies do not solve the issues related to the creation of conditions for ensuring a stable minimum frequency of rotation of the HM shaft with the simultaneous elimination of internal fluid flows and conditions for the occurrence of resonance at the indicated frequencies of its operation.

The elimination of internal fluid flows in the moving joints of HM can be achieved by applying the design of HM reported in study [9], which is based on the principle of disintegration into several main components. These components include two power cylinders (PC), a crankshaft, and a fluid distribution valve for adding fluid to the working cavities of PC.

This is exactly the approach to designing HM on the basis of two PCs, studied in work [10]. According to the results of the study, the regularities in the operation of HM designed on the basis of two PCs have been established. However, the solution to the problem according to [10] was not successful because it was established that such a HM has a new drawback, in the form of uneven rotational movement of its shaft.

Therefore, improving HM, according to known study [9], in the form of an invention, an attempt to eliminate this shortcoming is proposed through the use of three PCs in the composition of HM. However, in the materials of the invention, only a structural hinged connection of three PCs with a crank shaft is presented. Other issues remained unresolved, especially regarding the application of the PC control system and the establishment of dependences for calculating the structural parameters of PC when designing such a HM.

The statement of a scientific and practical problem follows from our review of the above literature. It implies solving the contradiction between the need to ensure low rotation frequencies of the HM shaft compatible with the working equipment of modern machines and eliminating internal fluid flows and resonant oscillations in the HM structure.

An attempt to solve this problem is presented in the invention [11] by performing HM as a complete system, also based on the application of the principle of disintegration in the form of its two structural components. The first component includes three PCs, which are connected to the crankshaft, and the second one includes valve distributors designed to supply the working fluid from the pump to the PC cavities. Also, in order to perform reciprocating movements with the same speed and the same effort, it is recommended, according to this invention, to observe a number of special conditions, which must be met in line with this invention. The simultaneous use of three PCs and non-return controlled valves in the structure of HM leads to the elimination of internal fluid losses and, accordingly, to the prevention of conditions for the occurrence of vibration and resonance.

However, according to this invention, this is only an attempt. And all this gives reason to assert that it is expedient to continue the process of conducting research into the design of HM on the basis of PC. At the same time, when designing similar HMs, one should take into account the number of PCs, their schematic connection with the crankshaft, the number of knees on the crankshaft, the circular or row arrangement of PCs, whether PCs work in one or more planes.

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## 3. The aim and objectives of the study

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The purpose of our work is to design low-speed, high-torque HMs with the use of PC and their valve control based on knowledge of the input and output parameters of the working equipment in modern machines. This will make it possible to increase the level of efficiency of operation of both modernized and new modern machines.

To achieve this goal, the following tasks must be solved:

- to conduct comprehensive studies based on the construction of computer and physical models and laboratory working samples of HM with the supply of pneumatic and hydraulic energy to the PC inlet;
- to present the hydraulic schemes of HM based on three and six PCs with the provision of their coordinated movement to generate the maximum torque on the crankshaft;
- to design modules with non-return control valves intended to control PC as part of HM based on the application of their butt connection;
- to derive theoretical dependences for determining the main parameters of PC, taking into account their number and the nature of their connection in the HM structure;
- to design an operational full-scale model of HM with a circular arrangement of PC.

#### 4. The study materials and methods

The object of our study is the processes in HM based on PC, intended to drive the shaft of the working equipment of modern machines into rotational motion.

The main hypothesis relates to the researched conditions for the construction of HM capable of operating under modes based on shaft rotation frequency and torque on its shaft where standard HMs are unable to function.

Achieving the set goal and accepted hypothesis is based on the use of the methodology for constructing computer and physical models and operating HM models, taking into account the nature of energy distribution for driving the PC rods.

During modeling, a number of assumptions and simplifications were adopted, which do not significantly affect the nature and mode of operation of the designed models and full-scale samples. This made it possible to most fully study the peculiarities of the flow of real processes in the HM, designed on the basis of PCs with a circular arrangement in the HM body.

Determination of the main parameters of HM based on the application of three and six PCs is based on consideration of their joint operation in the structure of the drive mechanism of the working equipment in modern machines. Moreover, a systematic approach is used to calculate the main parameters of PC, taking into account the process of converting the supplied power into usable power [12] and taking into account the internal state of HM.

#### 5. Research results of a low-speed high-torque motor based on power hydraulic cylinders

##### 5.1. Construction of computer and physical models and laboratory working samples of hydraulic motors

The computer and physical models built, with a circular arrangement of PCs, simulating the operation of HM, are shown in Fig. 1.

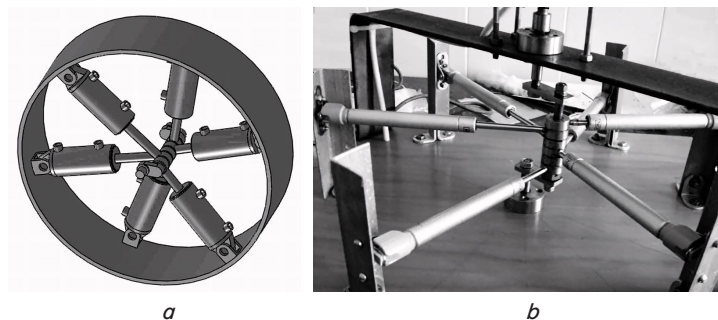


Fig. 1. Motor models: *a* – computer model; *b* – physical model

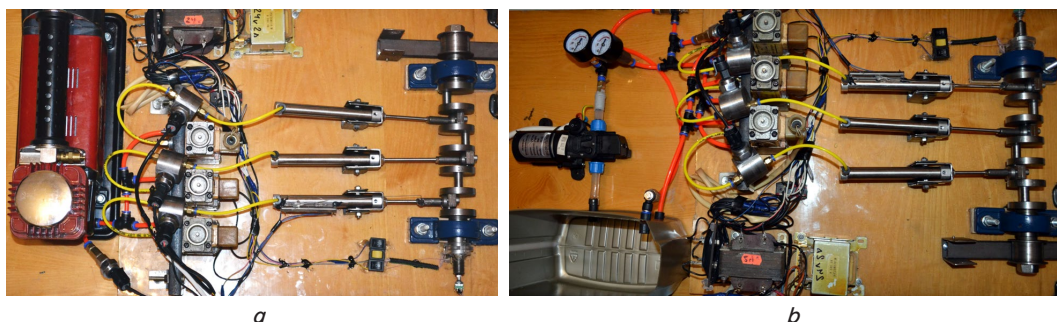


Fig. 2. Operating laboratory samples of motors with a series arrangement of three PCs when using energy: *a* – from the compressor; *b* – from the hydraulic pump

Based on the results of constructing computer and physical models of HMs, a property characteristic of them was established. This property is expressed in the ability to work under pump or HM mode. That is, they have the property of reversibility, depending on the particularity of the supply of energy to the input or to the output of these models. Considering this property, it can be stated that all the theoretical provisions known for pumps can be applied for HM as well.

Working models of motors with a series arrangement of PCs have been built, when energy is supplied to them from the compressor and pump, shown in Fig. 2.

The results of experimental studies established on the basis of the designed models (Fig. 1, 2) have made it possible to identify the need to comply with a number of conditions when designing HM based on the use of PC.

##### 5.2. Construction of hydraulic circuits of hydraulic motors based on power cylinders

The hydrokinetic scheme of HM with a circular arrangement of three PCs is shown in Fig. 3, *a*; the electrical circuit, which ensures the continuous movement of the PC rods, is shown in Fig. 3, *b*.

The electrical circuit is designed to control electromagnets E1...E7 of the corresponding distributors (Fig. 3, *a, b*), which provide fluid supply to the movement control units BCU of the PC rods. In turn, due to the programmed nature of the supply of liquid under pressure to the PC cavities, continuous rotation of the HM shaft is ensured, and if necessary, its reversal.

A single eccentric is installed on the output shaft, on the protrusions of which the limit switches LS1, LS2, LS3 are placed with the coordination of the PC operation, provided that they are placed evenly around the circle. To reverse the direction of rotation, a reversal block RB has been developed, which consists of logical «or» elements. Six logical elements are used to reverse the change in the sequence of operation of electromagnets. A change in the direction of movement of the crankshaft occurs when all logic elements are switched simultaneously.



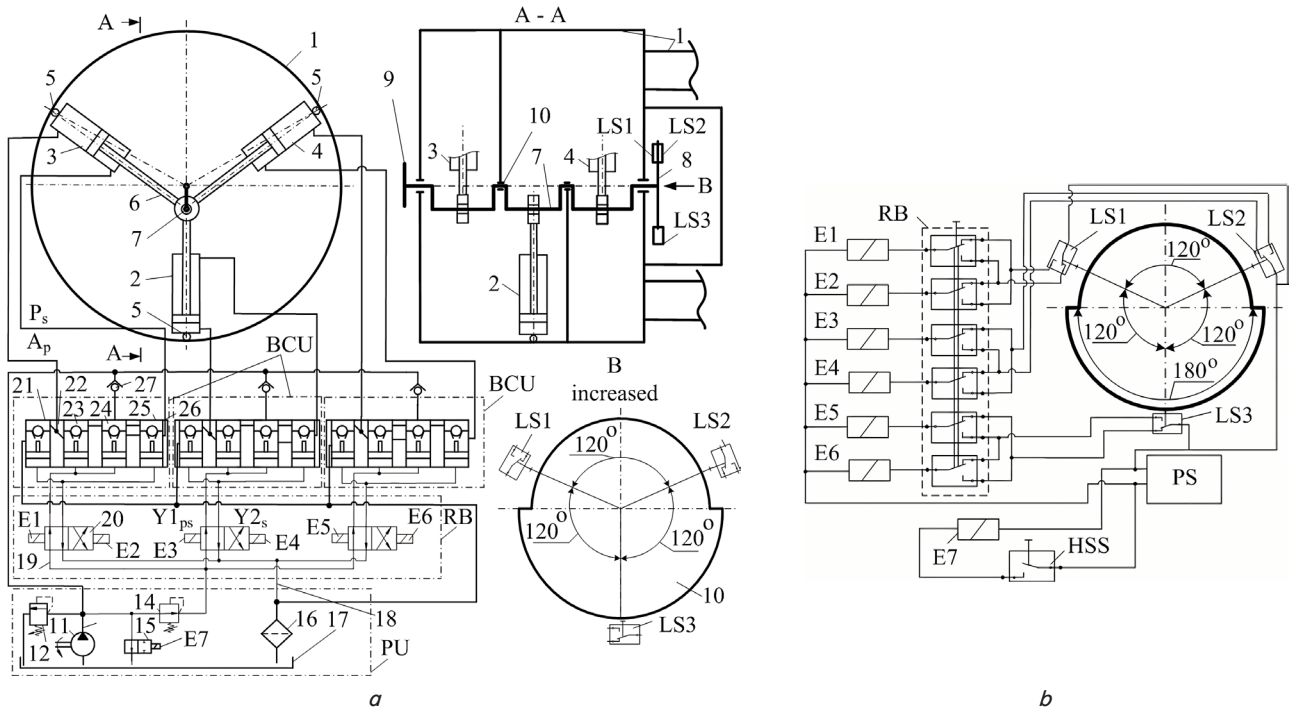


Fig. 3. Hydrokinematic diagram of HM with valve control of its shaft movement using three PCs:

- a* – hydrokinematic diagram of HM; 1 – HM housing; 2, 3, 4 – PC with one-sided stem; 5, – PC hinges; 6 – PC rod; 7 – crankshaft; 8 – eccentric; 9 – HM output shaft; 10 – crankshaft support; 11 – pump; 12, 14 – safety valves; 13 – pressure main; 15, 20 – hydraulic distributors; 16 – filter; 17 – oil tank; 18, 19 – pipelines of the control system; 21, 22, 23, 24, 25 – return controlled valves (hydraulic locks); 26 – intermediate insert between return controlled valves; 27 – non-return valve; LS1, LS2, LS3 – three limit switches; E1...E7 – electromagnets of distributors; RB – rotation reversal block; PU – pumping unit; BCU – control unit for supplying liquid to the PC cavities;  $A_p$  – hydraulic line for supplying fluid to the piston cavity of the PC;  $B_s$  – hydraulic line for supplying liquid to the stem cavity of PC;  $Y1_{ps}$  – hydraulic control line for opening the channels for feeding into the piston and rod cavities of PC;  $Y2_s$  – hydraulic control line for opening channels for feeding into the stem cavity of PC; *b* – electric control circuit of PC: RB – rotation reversal block; HSS – hydraulic system switch; PS – power source

The maximum possible uniformity of torque and rotation frequency of the HM crankshaft, which is shown in Fig. 3, is possible to ensure only under the condition that the ratio between the diameter of the rod and the diameter of the piston will be maintained at the level of 0.707. Failure to comply with this condition leads to the generation of different speeds of movement of the rod and the force that this rod transmits to the crankshaft of HM in the forward and reverse directions of their movement. This mode of operation of HM can negatively affect the performance of the HM and the working equipment of the machine.

The elimination of this shortcoming is achieved by constructing a HM in the structure of which three pairs of PCs are used, connected by rods to the crankshaft, as shown in Fig. 4.

Fig. 4 shows the hydrokinetic scheme of HM, using three pairs of PC cylinders connected by rods to its crankshaft. In the structure of the hydraulic scheme of HM, which is shown in Fig. 4, three valve control units BC1, BC2, BC3 are also presented. They provide the supply of liquid to convert its energy into an organized reciprocating motion of all six PCs located in a circle at the same time, with the possibility of converting the specified motion into the rotary motion of the HM shaft.

Connection of hydraulic control units BC1, BC2 and BC3 and the pumping unit PU with the designed motor (Fig. 4) is ensured by the use of special connecting devices a, a', b, b', d, d'. The transformation of hydraulic

energy from pump 29 into the mechanical energy of the rotary movement of drum 8 is enabled by supplying the working fluid simultaneously to the piston and to the rod cavity of each pair of PCs 2, 2', 3, 3', 4, 4' during a half-turn of crankshaft 6. The next half-turn of crankshaft 6, and accordingly drum 8, is ensured by changing the supply of the working fluid simultaneously in the piston and rod cavities of the same PCs 2, 2', 3, 3', 4, 4'. Moreover, the working fluid is sent to the piston cavities of PCs 2, 3 and 4 and they work under the pushing mode, and the working fluid that is directed to the rod cavities of PCs 2', 3' and 4' they work in the pulling mode. This mode of operation of PC 2, 2', 3, 3', 4, 4' is provided due to the inclusion of distributors 23 and, accordingly, their electromagnets 23 or 24 and activation of limit switches 11, 11', 14, 14', 15, 15'.

Such schematic execution of HM provides for the maximum possible uniformity of the torque and the frequency of rotation of its crankshaft when executing any ratio between the diameter of the rod and the diameter of the piston other than 0.707. It should be noted that this ratio can be reduced to 0.3 or less. The admissibility of the decrease is based on compliance with the flexibility of the rods from the condition of their strength when compressing the PC rods. At the same time, reducing the ratio of the diameter of the rod to the diameter of the piston to a value of 0.3 or less makes it possible to slightly increase the level of torque on the shaft of such a HM.

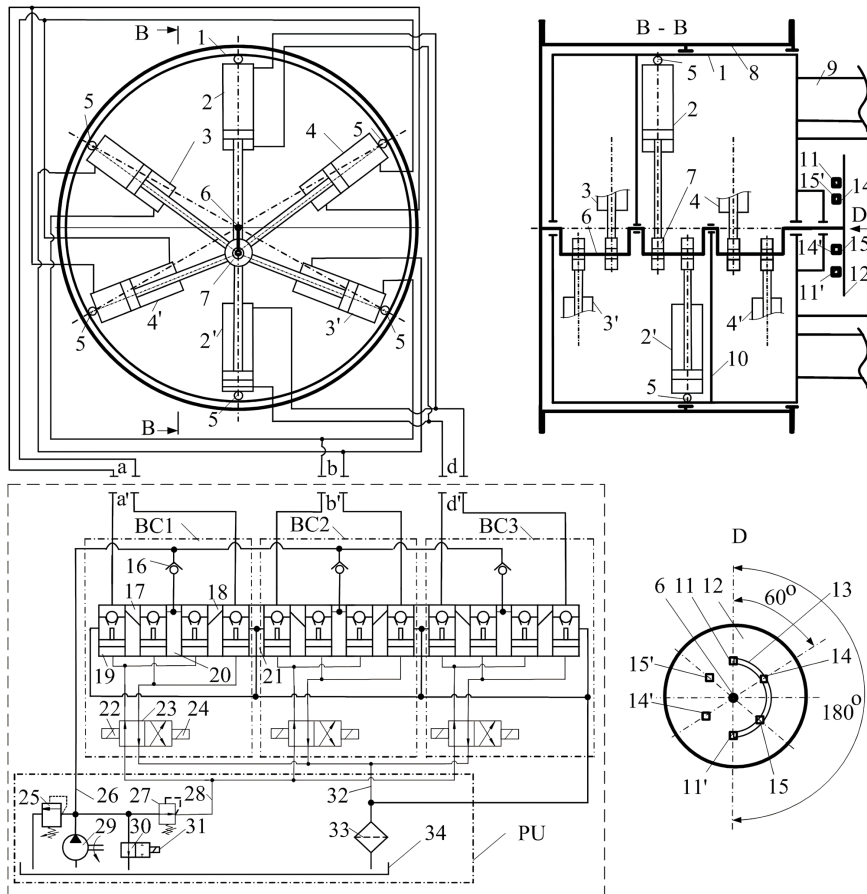


Fig. 4. Hidrokinematic diagram of HM with valve control of its shaft movement using three pairs (six) of PCs: 1 – HM body; 2, 2', 3, 3', 4, 4' – PC with one-sided rod; 5, 7 – PC hinges; 6 – crankshaft; 8 – load-lifting drum; 9 – the body of the mechanism; 10 – crankshaft support; 11, 11', 14, 14', 15, 15' – limit switches; 12 – disk; 13 – ring cut 180° long; 16 – non-return valve; 17, 18, 20 – intermediate inserts between controlled non-return valves; 19 – controlled non-return valve; 21 – intermediate inserts between control units BC1, BC2, BC3; 22, 24, 31 – distributor electromagnets; 23, 30 – distributors of four and two linear; 25 – safety valve; 26 – pressure main; 27 – reduction valve; 28 – control line of controlled non-return valves; 29 – pump; 32 – drainage main; 33 – filter; 34 – oil tank

### 5.3. Development of a control unit for non-return controlled valves

To reduce energy losses in the HM hydraulic system, taking into account the appropriate connection of PC cavities, three independent units for controlling the movement of the working fluid have been designed. The basis of the structure of these modules is the principle of connecting non-return controlled valves in a joint, which leads to a reduction in the length of the channels for moving the working fluid to the cavities of PC.

Based on the implementation of the butt connection of each of the non-return valves, a single control unit BC was designed, which is shown in Fig. 5, *a*; it is intended for the motor shown in Fig. 3. The control unit BC, which is shown in Fig. 5, *b*, is intended for the motor shown in Fig. 4. The butt connection of non-return controlled valves makes it possible, as indicated above, to reduce the length of hydraulic lines for the simultaneous execution of their inherent functions. This approach makes it possible to reduce hydromechanical and internal hydraulic power losses during the operation of the designed HMs.

Butt connection of non-return valves in the HM structure (Fig. 5) also makes it possible to significantly reduce the overall dimensions of the control units for supplying the working fluid to the piston and rod cavities of PC.

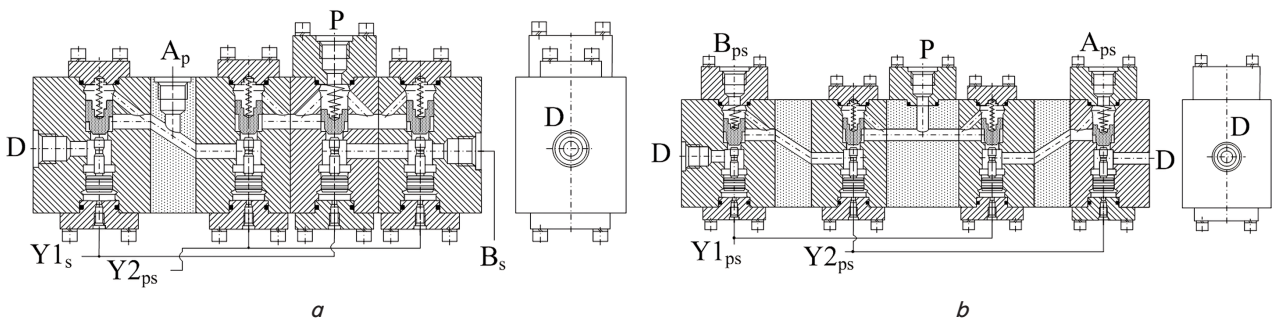


Fig. 5. Modules of valve distributors for controlling the movement of PC rods as part of HM:

*a* – a control unit for HM consisting of six PCs;  $A_p$  – channel of the piston cavity of the cylinder;

$B_s$  – channel of the cylinder rod cavity;  $Y1_s$  – a valve control channel for supplying liquid to the piston and rod cavity with the opposite connection of the PC rods with the crankshaft for the cylinders to perform the first half-turn of the motor shaft;  $Y2_{pi}$  – a valve control channel for supplying liquid to the piston and rod cavity with a counter connection of the PC rods with the crankshaft to complete the rotation of the HM shaft with the cylinders; P – pressure channel; D – drain channel; *b* – control unit for HM as part of three PCs;  $A_{ps}$  – the channel of the piston cavity in PC;  $B_{ps}$  – channel of the stem cavity of PC;  $Y1_{ps}$  – valve control channel for supplying liquid to the stem cavity of PC;  $Y2_{ps}$  – valve control channels for supplying fluid to the piston and rod cavities of PC

**5. 4. Theoretical dependences for determining the main parameters of the power cylinders in the structure of the hydraulic motor**

Based on the application of the theory of system analysis [12], taking into account knowledge about the usable power of the working equipment in the machine and the internal state of HM, a dependence was established for determining the main parameters of PC. Then, the value of the diameter of the piston  $D_p$  (mm) of PC, under the condition of the differential scheme of the connection of its cavities in the composition of HM (Fig. 3), will be determined from the formula:

$$D_p = \sqrt[3]{\frac{120 \cdot 10^6 \cdot N_m}{\pi \cdot (1 - \varepsilon^2) \cdot p_{mn} \cdot n_m \cdot Z_p \cdot k_r \cdot \eta_{gm}}}, \tag{1}$$

where  $N_m$  is the usable power on the HM shaft, kW;  $\varepsilon$  is the coefficient of the ratio of the diameter of the rod to the diameter of the PC piston;  $p_{mn}$  – working fluid pressure, MPa;  $n_m$  – frequency of rotation of the HM output shaft, rpm;  $Z_p$  – the number of PCs;  $k_r$  is the coefficient of change in the value of the knee at the crank shaft;  $\eta_{gm}$  is the hydromechanical efficiency factor of HM.

Under the condition of the compatible connection of the interchangeable cavities of two PCs in the HM system with the compatible connection of the rods of six PCs to the crankshaft from their location evenly around the circle, as shown in Fig. 4, the diameter of the PC piston will be determined from the formula:

$$D_p = \sqrt[3]{\frac{120 \cdot 10^6 \cdot N_m}{\pi \cdot (2 - \varepsilon^2) \cdot p_{mn} \cdot n_m \cdot Z_p \cdot k_r \cdot \eta_{gm}}}. \tag{2}$$

Cylinder rod diameter,  $d$  (mm):

$$d = D_p \cdot \varepsilon. \tag{3}$$

Cylinder piston stroke,  $S$ , mm:

$$S = D_p \cdot k_r. \tag{4}$$

The above dependences make it possible to determine the main parameters of PC, taking into account their number and the size of the piston stroke (the size of the knee of the crankshaft), as the main element in the HM structure.

**5. 5. Construction of a full-scale model of a motor with a circular arrangement of power cylinders**

Based on the above dependences, it is possible to enable the process of designing HM with a circular arrangement of PCs with different number of them and different execution of control units with non-return controlled valves.

Based on our studies, which, in particular, are represented in the form of dependences (2) to (4), taking into account the schematic connection of PC in the HM structure, its structure was built, which is shown in Fig. 6, *a-c*.

In this HM design, the supply of working fluid is provided only to the piston cavities of all six PCs, which allows reducing the number and length of hydraulic lines, as shown in Fig. 6.

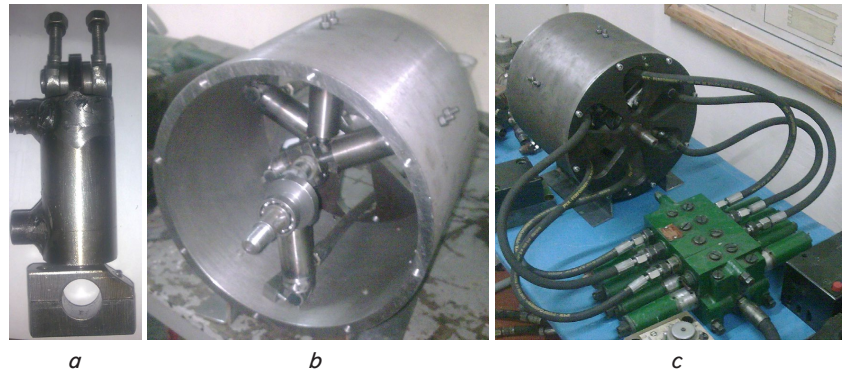


Fig. 6. Implementation of a full-scale model of HM: *a* – design of PC with a one-sided rod; *b* – placement PCs in a circle in the HM housing; *c* – connection of PC to the distributor and pump

Cylindrical execution of the HM housing with a circular arrangement of PC and the control unit for supplying the working fluid, as shown in Fig. 6, makes it possible to confirm the implementation of HM with the provision of the principle of its disintegration into two structural components. Such execution of HM makes it possible to eliminate the internal consumption of the working fluid, provide for the minimum frequency of rotation of the HM shaft and access to all its components.

**6. Discussion of research results related to motors designed on the basis of power cylinders with valve distribution of working fluid to their cavities**

The results of our study can be explained by the introduction into the HM structure of PCs with their two-way translational movement of the rod in comparison with the one-way movement of pistons in standard (factory) HMs, this is the first. Secondly, it is the provision of maximum sealing of both PC cavities of the designed HM in relation to standard HMs in which gaps and internal fluid losses are allowed to ensure their functioning, which is their disadvantage. Thirdly, the disintegration of the components of the designed HM makes it possible to eliminate the failure of its individual components by replacing them, compared to standard HMs. In addition, the designed HM closes the niche of low revolutions of the drive shaft connected to the working equipment in machines, compared to standard HMs, in which it is not operational.

Our solutions resolve the problem through the following findings:

1. The study of computer and physical models and laboratory working samples of HM shown in Fig. 1, 2, was carried out to identify a number of requirements and comply with them at the stage of HM design based on the application of PC. These requirements are aimed at reducing the unevenness of the rotational movement of the HM shaft. These include the requirements to enable the same force and speed of movement of the PC rods and their uniform location around the circle.

2. Depending on the specificity of the load on the working equipment in specific machines and the minimization of costs for the manufacture of HM, hydraulic systems have been designed, based on three and six PCs, which are shown in Fig. 3, 4. Schematic implementation of HM hydraulic systems shown in Fig. 3, 4, are significantly different from each other. The result of the construction of such hydraulic systems is influenced by the number of PCs in the HM struc-



ture, the nature of the location of PCs around the circle, and their connection to the crankshaft.

3. To enable consistent movement of the rods by each PC in the structure of the HM, modules of non-return controlled valves have been designed, which are shown in Fig. 5. These modules were designed by using butt connection of non-return controlled valves. The designed module provides the above-mentioned function, and also ensures the closure of the working fluid volume between the PC cavities and the non-return valve. This structural solution enables reliable fixation of the HM shaft without the need to apply a brake in the structure of the working equipment in the machines.

4. The basis of HM design is the process of determining the structural parameters of the PC and crankshaft of HM, taking into account a number of factors affecting these parameters. The calculation of the design parameters of HM is based on the derived dependences (1) to (5). These dependences take into account the amount of usable power that the HM is able to transmit to the shaft of the machine's working equipment with a given frequency of rotation of the shaft of this equipment. At the same time, the number of PC, the ratio of the diameter of the rod to the diameter of the piston of PC, and other factors were also taken into account. In general, the main differences between dependences (1) and (2) are the structure of the HM, the number of PCs, and the amount of usable power that this HM can transmit.

5. The results of HM calculation according to dependence (2) under the condition of using six PCs and on this basis its manufacture are shown in Fig. 6. Based on the result shown in Fig. 6, the advantages were confirmed, and shortcomings were identified in the design and manufacture of HM based on PC.

Limitations for the use of this study are the level of rotation frequency of the HM shaft and working equipment. The range of effective application of the designed HM at high rotation frequencies of its shaft is subject to additional research. After conducting such studies, it is possible to apply them in practice.

The shortcomings of the study include the difficulty in ensuring high accuracy in measuring the distance between the hinged connections of PC with the crankshaft and the location of the bearing assemblies for the HM shaft. The design of HM should include the need to enable a clear setting of the control system by turning on the valves of the solenoid-controlled distributors for the coordinated operation of all PCs in the structure of HM. All of them can be eliminated at the stage of manufacturing experimental HM samples.

The development of this study consists in its continuation during the construction of HM based on PC, taking into account the change in their number, the connection scheme with the crankshaft, the number of knees on the crankshaft, and other operating conditions.

The construction of the proposed HM will make it possible to reduce the production cost of modern machines, to increase the reliability of their operation on the basis of improving the repair conditions of individual components of this HM. This applies, in particular, to each separate PC or distributor of the working fluid, which may fail during the operation of the specified machines when working in industrial construction.

To confirm the advantages of the designed HM compared to standard HM, it is necessary to carry out comparative operational tests, which should be attributed to the issues of further research in this area.

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## 7. Conclusions

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1. The computer and physical HM models built have made it possible to identify the need to observe two conditions when designing them based on the use of PC. The first is compliance with the condition of equality of the speed of movement of the rods in both forward and reverse directions of movement. The second is to ensure the same forces that will be received by PC and transmit it to the crankshaft for the directions of movement of their rods indicated above. The third is the location of PC evenly around the circle.

The designed operating HM models with a drive from a compressor and a hydraulic pump have made it possible to confirm the need to comply with the above conditions.

2. We have developed hydraulic schemes of HM with three and six PCs. For a HM with three PCs, the direct direction of the rod movement is ensured with the simultaneous supply of the working fluid into the piston and rod cavity of each of the PCs. With the reverse direction of movement of the PC rod, the working fluid is directed only into its rod cavity. Moreover, in order to ensure the same movement speeds and forces on the PC rods, it is necessary to observe the ratio between the diameter of the rod and the diameter of the piston at the level of 0.707.

For a six-PC motor, it is necessary to observe two conditions, the equality of movement speeds and forces on the crank. To meet these conditions, it is necessary to simultaneously ensure the supply of the working fluid to the rod cavity of one of the PC and the piston cavity of the other PC, and vice versa.

With this supply of the working fluid to PCs, their mode of operation is executed in the form of «push and pull». This makes it possible to use the ratio of the diameter of the rod to the diameter of the piston to the minimum possible level, for example, 0.3 and less. The limiting value is the condition for ensuring sufficient compressive strength of the PC rods. According to this, following this approach creates an opportunity to obtain maximum efficiency from the construction of such HM.

3. The application of the principle of aggregation in the process of designing check valve control units with a butt connection of each of them achieves a reduction in energy losses in the cylinder control system in the motor.

4. We have obtained theoretical dependences for determining the PC parameters and the value of the knee on the crankshaft for HM when using three and six PCs. The use of six PCs in HM compared to HM with three PCs, all other factors being equal, allows for a proportional increase in the power on the shaft of such HM.

5. The implementation of HM in the form of a full-scale sample has made it possible to reveal its advantages in relation to standard HM in the first approximation. However, this requires further research.

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## Conflicts of interest

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The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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**Data availability**

All data are available, either in numerical or graphical form, in the main text of the manuscript.

**Use of artificial intelligence**

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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