Analysis of structures, properties and basic indicators of two-row axial piston hydraulic machines with an inclined cylinders block

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Abstract. The article reviews the possibility of developing double-row axial-piston hydraulic machines with an inclined cylinder block by improving the block design. The block design is improved by placing a second pumping unit in it and also locating additional working chambers with smaller pistons in the inter-cylinder zones. It is shown that an increase in the outer diameter of the initial cylinders block by only 10% provides an increase in the operating volume, torque and power of the new hydraulic machine by 33%. Such design improvement of the block of a new hydraulic machine in comparison with the analogue such as a hydraulic machine with an inclined disk gives a greater result: an increase in the operating volume, torque and power in a hydraulic machine with an inclined block is 78% more compared to a hydraulic machine with an inclined block, all other things being equal. The possibility of developing a high-torque axial-piston hydraulic motor by pairing two double-row pumping units while simultaneously eliminating the overall dimension of the bearing unit by closing axial loads on the drive shaft of the machine and halving the ripple is additionally considered.

1. Introduction
Axial-piston hydraulic machines transmission of the same power differ from other rotary machines by the greatest compactness and the smallest mass, which provides the ability to quickly change the rotational speed due to the small moment of inertia [1]. High throttle response is one of the factors of their widespread use, therefore this research studies this type of machines, which vary significantly from each other in design: hydraulic machines with an inclined disk and an inclined cylinder block [1].

Despite of the seemingly developed flow, technical solutions and designs, the development of new, more and more unusual hydraulic machines continues in our time, although they have been widely used for a long in hydraulic systems of various machines and equipment, for example [2-6], but only radial piston hydraulic motors and pumps are made multi-row, where each row is an independent pumping unit [6-8]. Three or more sets of pistons with hydrostatic bearings or rollers sliding (rolling) along the surface of a single stator are placed in different sections of the rotor in this kind of hydraulic machines.
Axial-piston hydraulic machines with two pumping units and two rows of operating chambers in one block also exist, for example [9, 10], but only in theory and have not yet found application in real hydraulic drives of machines. Therefore, in this paper, we consider the possibility of improving the hydraulic machines of this type. The real point is to make the best use of the design of cylinder blocks of axial piston hydraulic machines with an inclined disk and an inclined block to increase the operating volume and power with no change in the size of the prototypes.

The aim of the research is to identify the design techniques that provide a significant increase in operating volumes and a comparative assessment of the modified axial piston hydraulic machines. Let’s consider the special features and capabilities of the machines designs of both varieties.

2. Two-row axial piston hydraulic machine with an inclined block

There is a drive shaft in it (Figure 1), which is made integral with the drive disk 1. The shaft is mounted in several bearings 2 located in the housing 3, since the axial forces 13 and 14 applied to the disk 1 strongly load the bearings and this is a disadvantage of this type of hydraulic machine [1]. At the same time, the cylinders block 4 is inclined to the axis of the shaft by an angle $\beta$ which is substantially larger than that of machines with an inclined disk.

![Figure 1. Axial piston hydraulic machine with an inclined cylinders block and additional pistons.](image)

It is mounted on the axis 5 with the possibility of the unit to self-adjust by a spherical end surface on the spherical surface of the distribution disk 6, which is mounted on the wall 7 of the housing and fixed by bolts 8. There are nine main cylinders 9 in the cylinder block around a circle with a diameter $D_c$. There are additional nine cylinders 10 in the cylinder sections of the main cylinders (Fig. 2, a) around a circle with a diameter $D_p$. The pistons 11 with elongated skirts are inserted into the main cylinders. The short additional pistons 12 are inserted into the additional cylinders 10.

The block axis with a spherical head is embedded in a joint-hinge in the center of disk 1 (Figure 1, 2, b) and the other end is inserted into the hole of the distribution disk 6. In the drive disk, the heads of the main thickened connecting rods 13 are sealed in the spherical joint-hinges, which are embedded with the other ends in the spherical joints of the pistons 11. In addition, in the drive disk (Figure 2, b) in the spherical joint-hinges which are made in places between the spherical joint-hinges of the main connecting rods and the edge of the drive disk 1, the heads of the additional connecting rods 14 are embedded. They are embedded by opposite ends in the spherical joints of the pistons 12.

There are channels of 15 main cylinders and additional channels of 16 additional cylinders in the end part of the block (Figure 1, 3, a). Through these channels the operating chambers of all the cylinders of the block are connected through the main and additional crescent-shaped windows 17 and 18 of the distribution disk (Figure 3) and the channels 16 are connected with additional crescent-shaped windows 18. Crescent-shaped windows 17 and 18 on the left side of the distribution disk 6 are connected by a
slot 19, which is connected with the inlet 20. Crescent-shaped windows 17 and 18 on the right side of the distribution disk 6 are connected by a slot 21, which is connected with the hole 22 for pumping fluid.

Figure 2. View of the cylinder block from the side of the drive disk (a) and view of the disk from the side of the block (b).

Figure 3. View of the end face of the block from the side of the distribution disk (a) and its cross section A-A (b).

When the shaft rotates simultaneously with the disk 1 and the block 4 around the axis 5, the main and additional pistons reciprocate sucking in and then displacing the operating fluid through channels 15 and 16. As the block rotates 360°, each piston, as main 11 and additional 12, first sucks the operating fluid through the corresponding crescent-shaped windows, slot 19 and hole 20, and then passes it through the jumpers separating the left and right crescent-shaped windows of the disk 6. When the unit rotates through the next 180° through the windows on the right side of the distribution disk (Figure 3) the fluid is displaced under the pressure through a slot 21 and hole 22.

3. Specifications of a two-row axial piston hydraulic machine with an inclined block
The simultaneous operation of eighteen pistons will increase the pump flow due to the larger operation volume. When the outer diameter of the cylinder block is increased by 10%, with the original outer diameter of the block (Figure 2, a) is equal to \( D = 125 \text{ mm} \), and altered diameter is (increased) \( D = 116.8 \text{ mm} \).
$D_1=137$ mm, the diameters of the additional cylinders $d_{ad}$ can be only two times smaller than the diameters of the main cylinders $d_m$, and their area will be only four times smaller. Then the operating volume of the new hydraulic machine can be calculated by the formula (m$^3$):

$$V_o = S \cdot D_e \cdot z \cdot \tan \beta + 0.25 \cdot S \cdot D_p \cdot z \cdot \tan \beta = S \cdot \tan \beta \cdot (D_e + 0.25 \cdot D_p)$$

(1)

where $S$ is the area of the main piston, m$^2$; $D_e$ is the diameter along the axes of the main cylinders of the block, m; $\beta$ is the angle of inclination of the axis of the block to the axis of the drive shaft; 0.25·$S$ is the area of the additional piston, m$^2$; $D_p$ is the diameter along the axes of the additional cylinders, m; $z$ is the number of cylinders in the block in each of the rows (or the number of pistons, which is usually 7 or 9).

When parameters are as the mentioned above and shown in Figure 2, the diameter of the main pistons is 25 mm, the diameter $D_e$ is 88.5 mm, the diameter $D_p$ is 116.8 mm, $z=9$, and the angle $\beta=30^\circ$. In this case, the operation volume of the original hydraulic machine will be equal to (cm$^3$):

$$V_o = S \cdot D_e \cdot z \cdot \tan \beta = 225.62.$$  

The operating volume of the new two-row hydraulic machine, calculated according to formula (1), will be equal to 300.1 cm$^3$, i.e., it will increase by 33%. Thus, the placement of additional cylinders of a smaller diameter in the inter-cylinder zones of the main cylinders leads to a significant increase in the operating volume of the hydraulic machine by 33% at a small increase in the outer diameter of the cylinders block.

The torque $T$ on the shaft of the hydraulic machine without taking into account the efficiency is determined by the formula (N·m):

$$T = \Delta P \cdot S \cdot z \cdot \tan \beta \cdot (D_e + 0.25 \cdot D_p)/2\pi.$$  

(2)

where $\Delta P$ is the pressure drop in the pressure and suction (in pump mode) and the supply and discharge (in motor mode) hydraulic lines.

The torque of the new hydraulic machine will increase by the same 33%, but its transmission from the drive shaft to the cylinders block will be performed only by specially thickened connecting rods of 13 main pistons (Figure 1).

The high throttle response of axial piston machines, as noted above, is one of their main features, which is responsible for the ability to quickly change the rate speed [1]. Let us compare the moments of inertia of the initial and modified cylinders block, and at least for them, without taking into account the influence of additional pistons 13 and the drive disk 1 that has increased in diameter (Figure 1).

We determine the moment of inertia of the initial block $J$ at the above indicated and shown in Figure 2 parameters. According to the Steiner formula [11] it will be equal, (kg·m$^2$):

$$J = \frac{M \cdot R^2}{2} - 9m_m l_m^2.$$  

(3)

where $M$ is the mass of a full-bodied block without holes of the main cylinders, kg; $R$ is the radius of the initial block equaled to 0.0625 m; $m_m$ is the mass of the removed metal when cutting the main cylinder, kg; $l_m$ is the distance from the axis of the block to the axis of the main cylinder of 0.0443 m.

For a steel block with a length of 120 mm, calculation by formula (2) gives a value of 0.3581 kg·m$^2$.

For the modified block, formula (3) will take the form (kg·m$^2$):

$$J = \frac{M_1 \cdot R_{11}^2}{2} - 9m_m l_m^2 - 9m_{ad} l_{ad}^2,$$  

(4)

where $M_1$ is the mass of a full-bodied block increased by 10% in the outer diameter without holes of all cylinders, kg; $R_{11}$ is the radius of the changed block equaled to 0.0685 m; $m_{ad}$ is the mass of the removed metal when cutting an additional cylinder, kg; $l_{ad}$ is the distance from the axis of the block to the axis of additional cylinder 0.058 m.
The calculation by formula (4) for a steel block with a length of 120 mm, gives a value of 0.3247 kg·m² taking into account the above initial data. The ratio of 0.3247/0.3581 = 0.91 indicates a decrease in the moment of inertia of the modified cylinders block by 9% compared with the initial one, which is achieved by a greater distance of the additional cylinders from the axis of the block.

An empirical throttle response factor \( k \) is used [12] to assess the throttle response of hydraulic motors, which characterizes the ability to accelerate the inertial load:

\[
k = \frac{T}{\sqrt{J}}.
\]

To compare the throttle response of a new modified hydraulic machine \( k_2 \) with the throttle response of the original hydraulic machine \( k_1 \), we find the ratio:

\[
\frac{k_2}{k_1} = 1.33 \cdot \frac{0.3247}{0.3582} = 1.206,
\]

where 1.33 is the ratio of the torques \( M_k \) of the new and original hydraulic machines.

As it can be seen, the throttle response increases, but mainly due to an increase in torque and operating volume. But this value can be considered approximate, since the moments of inertia of the additional pistons and the increased moment of inertia of the drive disk of the modified hydraulic machine were not taken into account in the calculation.

4. Two-row axial piston hydraulic machine with an inclined disk

The axial piston hydraulic machine with an inclined disk can also have a two-row design and in our research [10] some of its features were already considered. To compare their capabilities with hydraulic machines with an inclined block, let us imagine one of these structures (Figure 4).

Externally, the hydraulic machine is distinguished by a straight housing 1, it contains a drive shaft 2 with splines 3 forming a spline connection with block 4. The shaft is installed in bearings 5 and transmits torque to the block, which provides reciprocating movement of the main 6 and additional 7 pistons. The cylinders block by its right Figure 4 spherical end is pressed tightly to the spherical surface of the distribution disk 8 by a spring 9 through a thrust ring 10 with a spherical end face, which provides the cylinders block 4 to self-adjust when rotating at an angular speed \( \omega \).

There are the main cylinders 11 with axes in diameter \( D_c \) and additional cylinders 12 with axes in diameter \( D_p \), (Figure 2, a; the splines in the central hole of the block are not shown) in the cylinders block with an outer diameter which was increased by 10% \( (D_1 = 137 \text{ mm}) \), in comparison with the initial diameter \( (D = 125 \text{ mm}) \). Moreover, the diameters of the additional cylinders are two times smaller than the diameters of the main cylinders and are 12.5 mm and 25 mm, respectively as well as in a machine with an inclined block.

In the cylinders block (Figure 4) branch channels 13 and 14 are drilled, extending from the main 6 and additional 7 cylinders, respectively. The same channels are shown in Figure 3 under the positions 15 and 16. The channels 13 and 14 in block 4, leading to the operating chambers formed by the main and additional cylinders and their pistons 6 and 7, respectively, have diameters equal to the width of the corresponding crescent-shaped windows and jumpers between them (Figure 3, b). The distribution disk device is fully conform to that shown in Figure 3, b distributor of axial piston hydraulic machine with an inclined block.

An inclined washer 15 is pivotally mounted in the housing 1 of the machine in question, which in the unregulated design of the hydraulic machine is stationary, and in the adjustable-movable and capable of changing the angle of inclination \( \beta \) to control its operating volume and feed.

In the simplest hydraulic machines of this type, operating under low pressure, the main and additional pistons have spherical heads that are supported and sliding during operation along the surface of the inclined washer 15.
5. Specifications of a two-row axial piston hydraulic machine with an inclined disk.

Let us calculate the operating volume of the original hydraulic machine with an outer diameter of \( D = 125 \) mm for the same block sizes as shown in Figure 2, \( a \) and \( \beta = 18^\circ \), (cm³):

\[
V_0 = S \cdot D_p \cdot z \cdot \tan \beta = 127.
\]

For a modified hydraulic machine with an outer diameter of the block \( D_1 = 137 \) mm with the same block sizes and angle \( \beta = 18^\circ \), we obtain the value, (cm³):

\[
V_0 = S \cdot z \cdot \tan \beta \cdot (D_c + 0,25D_p) = 168.9.
\]

The operating volume ratio of 168.9/127.0 is 1.33. This means that the use of additional second-row pistons in the cylinders block gives the same increase as that of axial piston hydraulic machines with an inclined block – by 33%. But if you compare different types of axial-piston hydraulic machines, then for a hydraulic machine with an inclined block, the operating volume at an angle \( \beta = 30^\circ \) is 300.1 cm³, and for a hydraulic machine with an inclined disk at \( \beta = 18^\circ \) and the same block parameters, the operating volume is 168.9 cm³. The ratio of the operating volumes of 300.1/168.9 gives a value of 1.78, that is, the efficiency of using of two-row cylinder blocks in axial piston hydraulic machines with an inclined block is 78% more.

6. High-torque axial piston hydraulic motor based on a two-row hydraulic machine.

Despite of the advantages shown above, axial piston hydraulic machines with an inclined block have a significant drawback [1]. The spherical heads of the connecting rods 13 and 14 are supported by the drive disk 1 (Figure 1), which is the cantilever end of the drive shaft. The forces exerted on the disk by the connecting rods perform not only tangential components that form a useful torque, but also axial components that load the bearings 2 heavily, which makes the entire bearing assembly cumbersome and consists of at least three bearings. Therefore, if you pair two such hydraulic machines, as shown in Figure 5, it is possible to close the axial components on themselves through two drive disks on a common drive shaft.
Figure 5 shows a structural diagram of two halves of a high-torque axial piston hydraulic motor coupled from two shortened ones due to sub-bearing units. There is a collapsible shaft 3 in the housing 1 in the bearings 2. It consists of the left and the right parts connected by a fixed spline connection with high centering accuracy. Using a spline connection, a drive gear 4 is fastened to the shaft. It extends into the slot a of the housing 1 for connecting with the driven gear of any mechanism. The docking unit of mechanism must ensure the tightness of the hydraulic motor housing and withstand a pressure of at least 0.15 MPa (not shown in Figure 5).

Since the design is symmetrical, the axial components of the forces $F_{a1}$ and $F_{a2}$ in the spherical joint-hinges of the main and additional connecting rods on the left and on the right are the same and are perceived by the drive shaft 3. It nullifies the axial loads acting on the pair of bearings 2, which now serve to install the shaft of the hydraulic machine. The force diagram illustrating this effect is shown in Figure 6. The tangential components $F_{\tau1}$ and $F_{\tau2}$ produce a torque on the shaft 3.

Since there are two identical cylinder blocks 5 in the hydraulic motor. They are located on the axles 6 with a small clearance, allowing the rotating blocks to be self-mounted on the spherical surfaces of the distribution discs 7 (Figure 3, b). There are the main pistons 8 with connecting rods in the cylinders of
the blocks. The connecting rods are fixed in spherical joints 9 of the driving disks of hydraulic machine, and additional pistons 10 with their own small connecting rods fixed in spherical bearings 11.

Rotation is provided by two cylinder blocks when an operating fluid is supplied to their distribution disks 5 and then is transmitted to a coupled drive disk and gear 4, which transmits torque and power to one or another actuator through an attached mechanism:

- the torque on the gear of the hydraulic motor doubles (2) (N·m):

\[ T = \Delta P \cdot S \cdot z \cdot \tan \beta \cdot (D_c + 0.25 D_p) / \pi. \]  

(6)

where \( \Delta P \) is the pressure drop in the supply and discharge hydraulic lines, N;

- the output of the hydraulic motor will be determined by the formula, W:

\[ N_{hm} = \Delta P \cdot S \cdot z \cdot \tan \beta \cdot (D_c + 0.25 D_p) \cdot \omega / \pi. \]  

(7)

The operating volume (m³) and fluid flow rate \( Q_{hm} \) (m³/s) passing through the hydraulic motor correspond to the angular frequency of rotation of the gear \( \omega \) and will be determined by the expressions:

\[ V_o = 2 \cdot S \cdot z \cdot \tan \beta \cdot (D_c + 0.25 D_p); \]  

(8)

\[ Q_{hm} = 2 \cdot S \cdot z \cdot \tan \beta \cdot (D_c + 0.25 D_p) \cdot n; \]  

(9)

where \( n \) is the gear rotation speed, rev/s; \( S \) is the area of the main pistons, m²; \( D_c \) is the diameter along the axes of the main cylinders of the blocks, m; \( \beta \) is the angle of inclination of the axes of the blocks to the axis of the drive disc, 0.25·S is the area of the additional pistons, m²; \( D_p \) is the diameter along the axes of additional cylinders, m; \( z \) – the number of cylinders in the block in each of the rows.

The design of the considered coupled two-row hydraulic machine is reversible and can be used as an unregulated pump in hydraulic systems of machines and equipment. In this case, flows from each pair of pumping units can be summed up or split into different parts of the hydraulic system. However, the considered two-row axial-piston hydraulic machines with an inclined block (Figure 1, 5) may have an adjustable design.

Let's see how the coupledness of the pumping units will affect the pulsation of the flow rate of the operating fluid passing through the hydraulic motor and the angular velocity of its shaft.

The pulsation in rotary machines is estimated by the feed non-uniformity coefficient \( \sigma_Q \), which for an odd number of pistons is determined by the expression [1, 8]:

\[ \sigma_Q = 2 \tan \gamma \left(0.25 \pi / z\right), \]

where \( z \) is the number of cylinders. For a single-row nine-cylinder hydraulic machine, it is 0.0154.

In a coupled high-torque hydraulic motor with thirty-six cylinders, the coefficient non-uniformity will be determined by another formula [1, 8]:

\[ \sigma_Q = 2 \tan \gamma \left(0.5 \pi / z\right), \]

which gives the same value of 0.0154, but this is if the blocks of the left and right parts are installed as shown in Figure 5. But if you install one of the blocks with a rotation of 20° relative to the other, the non-uniformity coefficient of flow and the angular velocity of rotation of the shaft will decrease by half and become equal to 0.0077 [1, 8]. And this is a unique indicator for all types of reciprocating hydraulic machines.

7. Conclusion
The study of the design features, properties and main indicators of two-row axial-piston hydraulic machines with an inclined cylinder block discovered a number of advantages over typical axial-piston machines.
An increase in the outer diameter of the initial block by only 10% makes it possible to place additional operating chambers with pistons smaller by half the diameter in the cylinder sections of the main cylinders of the block. Now the hydraulic machine becomes two-row and is characterized by such a parameter as row, previously peculiar only to radial-piston hydraulic machines. The total number of pistons becomes not nine, but eighteen. It makes possible without changing the dimensions of the machine to increase the operating volume, torque, feed and power by 33%. In this case, although the number of pistons becomes even, the feed pulsation coefficient (for the pump) does not change.

In comparison with axial piston hydraulic machines with an inclined disk, where the angle of inclination, as a rule, does not exceed 18° due to increasing contact loads, the operating volume and other indicators of hydraulic machines with an inclined block are approximately 78% larger, and therefore the development of machines with inclined unit is much more efficient.

Due to the cantilever end of the drive shaft in the form of a drive disk in hydraulic machines with an inclined block, the forces applied to the disk from the connecting rods side perform significant axial components that load the bearings heavily, which makes the entire bearing assembly bulky. However, if you pair two such hydraulic machines and close axial forces by yourself through two drive disks to a common drive shaft, then the bearing assembly will be compact and lightweight, and it makes possible to develop two-row high-torque hydraulic motors that can operate like pumps.

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