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AN ANALYSIS OF KINEMATIC PARAMETERS OF AXIAL PISTON HYDROMACHINE WITH CONICAL TYPE VARIABLE DISPLACEMENT

Summary. The variable displacement of axial piston hydromachines has wide application in hydraulic drives of mobile machinery in view of some advantages, such as small dimensions and weight at high values of working pressure. In this article a new design of conical type regulation of variable displacement axial piston hydromachines with bent axis is presented. Formulas for definition of cinematic parameters are given. Parameters are calculated and the results of calculations are analyzed. The results show that the offered way of regulation allows to essentially expand the functionalities of the hydromachine due to change of the adjusting characteristics to increase accuracy and sensitivity of regulation, to lower efforts of regulation, to provide overturn of working stream. This design of axial piston hydromachine with conical regulation also guarantees an increase of production adaptability because the surfaces of the socket contacting details are flat.

Keywords: hydraulic transmission, analysis kinematics, application in mobile machinery

INTRODUCTION

Application of hydraulic transmissions (HT) is one of the ways to improve characteristics of mobile machinery [1, 2 ,3]. The first attempt of usage of HT in mobile machinery was executed at the end of the XIXth century by Ch. Menly, USA [4]. In practice these systems (HT Jenny Williams) have been applied in tanks, automobiles and diesel locomotives since 1914. The main disadvantage of HT Jenny Williams is the big specific mass: 8,3 kg/kW. The long way of development of hydromachines was required before HT have received wide application in mobile machinery.

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STATEMENT OF A PROBLEM

The technological level of a modern hydraulic drive is determined by parameters of its basic power units – pumps and hydromotors. Now in HT for mobile engineering axial piston hydromachines (APH) have the widest application as pumps and as hydromotors aligned with step-down gears or reduction gears. Hydromachines of such type have small dimensions and weight, are approved for high pressure use (up to 60 – 70 MPa) and frequencies of rotation (5000 rev/min and are higher), have high efficiency and service life, and also an opportunity of change of displacement. There are two types of APH design: APH with raked disk and APH with raked block of cylinders (bent axis design). Operative displacement variation of bent axis APH is executed at the expense of variation of an angle between an axis of a shaft and an axis of the cylinder block, for example in designs of hydromachines A2V, A6V and A7V manufactured by Bosch Mannesmann Rexroth (Germany) [1]. Displacement variation of APH with raked disk is executed at the expense of variation of disk inclination angle comparatively to rotation axis of coaxial shaft and cylinder block, for example in pump A4V of the same manufacturer. Features of force interaction of APH elements provide the best pump characteristics to hydromachines with a raked disk – higher volumetric efficiency, and the best motor characteristics for hydromachines with the raked block because of higher hydromechanical efficiency. A distinctive feature of bent-axis APH is the lesser rigidity of requirements to working liquid clearing.

Adjustable APH with a raked disk have a range of regulation $D_{sp} = 2.5...2.8$, so the ratio of the maximum working volume to the minimum one is within the limits of minimum $\alpha_{sp\min} = 6...7^0$ and maximuml $\alpha_{sp\max} = 18...21^0$ disk inclination angle. For adjustable serially issued bent axis APH designs a range of regulation is somewhat higher; it is $D_{ba} = 3.5...3.7$ at the minimum block inclination angle $\alpha_{ba\min} = 6...7^0$ and the maximum one $\alpha_{ba\max} = 25...28^0$.

In HT for mobile machinery there are three possible variants of use of adjustable hydromachines:

– the variable displacement pump and the fixed displacement hydromotor;
– the fixed displacement pump and the variable displacement hydromotor;
– the variable displacement pump and the variable displacement hydromotor.

Application of the first circuit of pump design makes it possible to change feed at pump regulation, as a result the capacity fed in hydrosystem changes. Pressure in system raises in the process of hydromotor loading rise; the system starts working in a mode of throttle regulation.

Application of the first circuit of pump design the pump feeds hydrosystem with constant capacity which is determined by power engine. Employment of regulator with constant capacity permits to increase the moment on a shaft and to reduce frequency of rotation increasing pressure; that is similar to gear-box.

The best variant is the third circuit, it is introduced actively in the last years, as the pump they apply the adjustable pump with raked disk, and as the hydromotor they apply the adjustable pump with the raked block. Application of variable displacement hydromotors instead of fixed displacement also allows to increase frequency of pump rotation up to frequency of rotation of engine shaft without intermediate mechanical gears, which as a whole reduces dimensions and weight of transmission and raises its reliability.

For a long enough time variable displacement bent axis APH were spoiled by hydromachines with raked disk on weight and dimensions. The most known design adjustable APH with the raked block - cradle type, for example A2V, contained the case and a cradle in which swinging unit was placed. At a turn of a cradle the relation of an axis which passes through a point of crossing of axes of a shaft to the angle of an inclination of the block changes. The change of an angle of an inclination of the cylinder block occurs at a turn of a cradle.

In the middle of the 70-ties the constructive circuit bent axis APH TRIMOT with linse-type distributor was patented (type A6V, A7V). On the one hand the distributor contacted with face surface of the block, and on the other hand with the appropriate surface of the case. To the distributor the finger of the mechanism of regulation is fastened. At moving a regulator the angle of an inclination of the block changes. Designs of trimot-type hydromachines allowed to expand significally the sphere of application of APH with the raked block, especially as hydromotors, in 80-th and now [3].

The technical parameters of a bent axis APH with fixed displacement were increased also due to changes of design: application of one piece pistons with piston rings, hinge conducting of cylinder block (BC), increase of its discharge angle up to 40^{O}, use of special piston rings as sealings, and also bearing mount assemblies with roller taper bearings. Modernization of designs and the current technologies of manufacturing have permitted to reach in the most perfect samples of hydromachines of this type the specific weight - 0.1-0.2 kg/kW.

However, till nowadays the advantages of bent axis APH and fixed adjustment have not been realized because of different reasons.

The main design lacks of trimot-type APH are:

1. The big square of connected cylindrical surfaces of case and distributor that are necessary to provide chamber connection between hydrolines and pump unit at variable inclination angle. These surfaces form cylindrical slots through which there is an outflow of a working liquid.
2. Impossibility of stream reverse caused by complexity of performance of distribution unit, besides hydromotor stops working in regulation zone with minimal working volume (when it works in a range of friction angles).
3. Complexity of creation of big inclination angles for BC (up to 40^{O}) is also caused by design of distributor.
4. Nonlinearity of the adjusting pressure characteristic is connected with the necessity of the maintenance of a guaranteed clip between the distributor and case at various inclination angles of a cylinder block.
5. Presence of only one adjusting characteristic of the mechanism of regulation.
6. Weight and inertial force of swinging unit are perceived by a regulator with an increased force of regulation.

To eliminate these lacks an essentially new method of regulation of APH with the raked block was offered and patented, besides hydromachines with "conical" regulation have been designed and tested.

RESULTS OF RESEARCH

In known designs of adjustable APH with the raked cylinder block – of cradle- or trimot-type – the angle between shaft axis and block axis changes in the only one plane of shaft and block axes accommodation. The cinematic characteristic of change of displacement, for such type APH is described by the equations submitted in [1, 2]. One of the most important parameters of volumetric hydromachines is working volume. For adjustable bent axis APH the working volume is connected with inclination angle of swinging unit α (an angle between axes of a shaft and the block) by dependence:

$$q(\alpha) = q_{\min} \cdot \frac{\sin\alpha}{\sin\alpha_{\min}} \tag{1}$$

where $q_{\min}$ - working volume at the minimal angle of an inclination of the block $\alpha_{\min}$.

Coefficient of working volume change for adjustable bent axis APH:

$$K(\alpha) = \frac{q(\alpha)}{q_{\min}} = \frac{\sin\alpha}{\sin\alpha_{\min}} \tag{2}$$

Range of regulation of the hydromachine, that is the relation of the maximum working volume to the minimum one:

$$D = \frac{q(\alpha_{\max})}{q_{\min}} = \frac{\sin\alpha_{\max}}{\sin\alpha_{\min}} \tag{3}$$

where: $\alpha_{\max}$ - the maximal angle of an inclination of swinging unit.

At small inclination angles of the block $\alpha \le 6^0$ values $\sin\alpha \approx \alpha$, that is the characteristic of change working volume from change of an angle of an inclination of swinging unit α it is linear only in the following limits: $-6^0 \le \alpha \le 6^0$. But APH work at such angles of an inclination of the block is not effective. In a pump mode in view of the low value of volumetric efficiency the submission of the hydromachine is comparable to outflow of a working liquid. Besides capacity of hydromachine at motor mode is comparable to friction losses of capacity.

The new way of working volume change for adjustable bent axis APH is the conical regulation. It means the following: a distributor is executed with an opportunity of a relative turn of an axis that passes through a point of crossing axes of the block and a shaft of the hydromachine under sharp angle [5].

In Fig. 1 the axial section of a bent-axis APH design with conical regulation is shown. In such a way of regulation the axis of cylinder block describes spatially a conical surface when the working volume of the hydromachine changes. This kinematic circuit, in comparison with the known variable working volume of APH with the raked block of cylinders allows the following: to expand essential functionalities of the hydromachine due to change of adjusting characteristics, to increase accuracy and sensitivity of regulation, to lower efforts of regulation, to provide reverse of working stream, and also to raise adaptability to manufacture of a design because surfaces of a socket of contacting details are executed as flat surfaces.

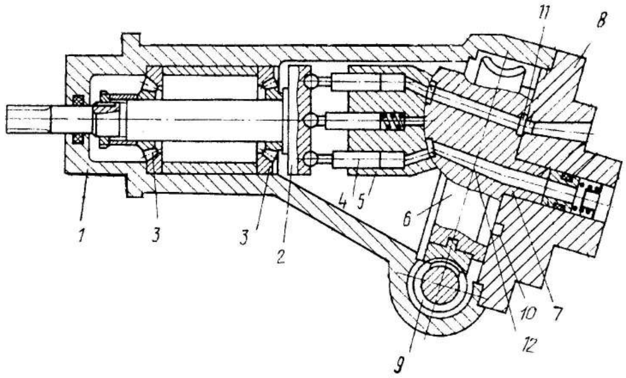

Fig 1. Axial section adjustable APH with conical regulation: 1 – case, 2 – a shaft, 3 – bearings of a shaft, 4 – the piston with a rod, 5 – the block of cylinders, 6 – the rotary distributor, 7 – a support of the distributor, 8 – a back cover, 9 – a worm of change of a angle of inclination block of the cylinders, 10 – the ring channel of low pressure in a cover of the case, 11 – the channel of low pressure of the rotary distributor, 12 – the axial channel of a high pressure

In a considered design the axis of the block of cylinders during regulation describes a conical surface, as shown in Fig 2. Therefore dependence between working volume of the hydromachine and parameters of the regulating device has some differences from traditional adjustable bent-axis APH. Let's establish dependence between an inclination angle of swinging unit and an turn angle of allocator.

In Fig.2 there are designated: 1 – an axis of a shaft, 2 – an axis of rotation block of cylinders, 3 – an axis of rotation of the allocator, α – an angle between axes of a shaft and the block of the cylinder, β – an angle of turn of the allocator in the regulating device, γ – an angle between an axis of rotation of the block of cylinders and an axis of rotation of the allocator (an angle of a cone), δ_0 – the minimal angle between an axis of rotation of the block of cylinders and an axis of a shaft, W – the conditional conical surface on which moves axis block of cylinders. We shall designate $L = SB$ – distance between a point of crossing of axes of a shaft and block of cylinders and the center of the distributor - a point B on a surface of a socket with block of cylinders.

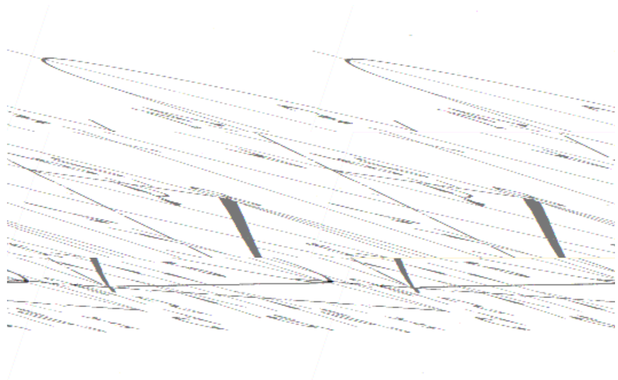

Fig. 2. The diagram of arrangement of axes APH with conical regulation

As a result of consideration of triangles in Fig. 2 we shall receive, that an angle between an axis of the block of cylinders and an axis of a shaft of the hydromachine at the conical regulation is given by:

$$\alpha = \arccos(A + B\cos\beta), \tag{4}$$

where: $A = \frac{1}{2}(\cos\varphi_{\max} + \cos\varphi_{\min})$,

$B = \frac{1}{2}(\sin\varphi_{\max} + \sin\varphi_{\min})$,

thus we shall designate $\varphi_{\min} = \delta_0$, $\varphi_{\max} = 2\gamma + \delta_0$.

From the submitted dependence (4) it is visible, that at conical regulation the characteristic APH depends on three parameters: β, γ, δ_0. In special cases when for the distributor $\beta = 0, \alpha_{\min} = \varphi_{\min}$ for the distributor with full turn at $\beta = \pi, \alpha_{\max} = \varphi_{\max}$, and for the distributor with half turn at $\beta = \pi/2, \alpha_{\max} = \arccos A$.

The basic kinematics parameters of APH with the raked block of cylinders, such as a stroke of the piston, speed of the piston and its acceleration depend on angle α. Therefore the working volume of APH with conical regulation is defined on the dependence:

$$q(\beta) = q_0 \frac{B\sqrt{E - 2C\cos\beta - \cos^2\beta}}{\sin\varphi_{\min}} \tag{5}$$

$$q(\beta) = q_0 \frac{B\sqrt{E - 2C\cos\beta - \cos^2\beta}}{\sin\varphi_{\min}} \tag{6}$$

where q_0 – working volume of the hydromachine at $\alpha = \varphi_{\min}$, $C = \frac{A}{B}, E = \frac{1}{B^2} - C$.

Factor of change of working volume at conical regulation

$$K(\beta) = \frac{B\sqrt{E - 2C\cos\beta - \cos^2\beta}}{\sin\varphi_{\min}} \tag{7}$$

Range of regulation

$$D = \frac{B \cdot \sqrt{E - 2C\cos\beta_{\max} - \cos^2\beta_{\max}}}{\sin\varphi_{\min}} \tag{8}$$

where $\beta_{\max}$ – the maximum angle of turn of the distributor.

At $\beta_{\max} = \pi$ – the full turn distributor according to the formula (8)

$$D_\pi = \frac{\sin\varphi_{\max}}{\sin\varphi_{\min}} \tag{9}$$

At $\beta_{\max} = \pi/2$ – the half turn distributor in view of the formulas (4) and (8)

$$D_{\frac{\pi}{2}} = \frac{\sqrt{1 - A^2}}{\sin\varphi_{\min}} \tag{10}$$

For the analysis of the received settlement dependences and estimations of influence of angles γ and δ_0 on an angle of an inclination of the block of cylinders there are executed calculations for 6 variants of a design:
1st variant – at $\gamma = 9^0$, $\delta_0 = 7^0$, 2nd variant – at $\gamma = 10^0$, $\delta_0 = 5^0$, 3rd variant – at $\gamma = 14^0$, $\delta_0 = 7^0$ 4th variant – at $\gamma = 15^0$, $\delta_0 = 5^0$, 5th variant – at $\gamma = 16.5^0$, $\delta_0 = 7^0$ and 6th variant – at $\gamma = 17.5^0$, $\delta_0 = 5^0$. Variants 1 and 2 for maintenance of the maximum angle between axes of the block and a shaft $\alpha_{\max} = 25^0$ at the full turn distributor $\beta_{\max} = 180^0$. Variants 3 and 4 for the maximum angle between axes of the block and a shaft $\alpha_{\max} = 25^0$ at the half turn distributor $\beta_{\max} = 90^0$, variant 5, 6 for maintenance of the maximum angle between axes of the block and a shaft $\alpha_{\max} = 40^0$ at the full turn distributor $\beta_{\max} = 180^0$.

In Fig. 3 dependencies of an angle between axes of the block and shaft APH from a angle of turn of the distributor β for variants of a design which are considered are submitted.

From the submitted dependences it is visible, that at conical regulation in APH with raked of the block it is possible to provide various characteristics of regulation. Number of characteristics indefinitely and they are determined by a choice of parameters β, γ, δ_0

In Fig. 4 the dependence of the factor of change of working volume on an angle of turn of the distributor β is shown at conical regulation. The advantage of such regulation is the opportunity of reception of various adjusting characteristics. Depending on the requirements of the system of regulation where APH is established, the linear part of the characteristic or its nonlinear part can be used.

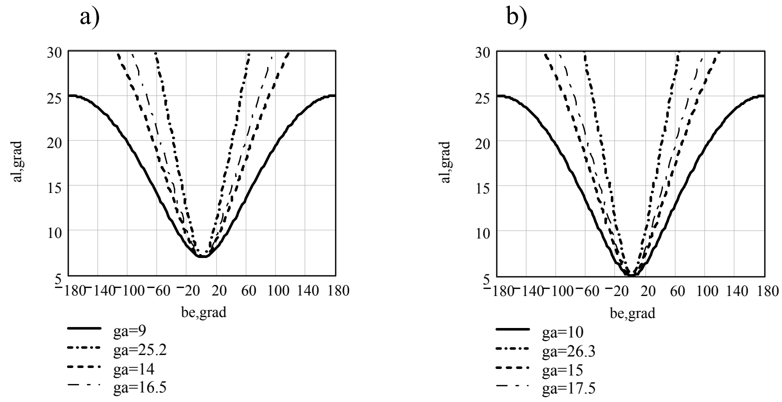

Fig 3. Dependence of an angle of turn of the distributor on an angle of inclination BC
a) $\delta_0 = 7^0$ variants 1, 3, 5; b) $\delta_0 = 5^0$ variants 2, 4, 6

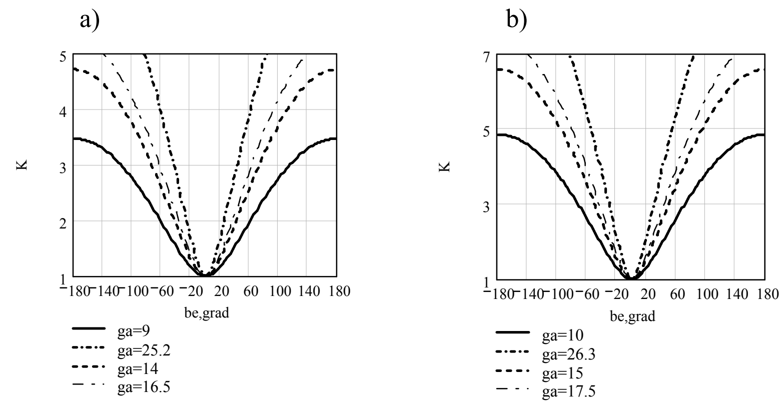

Fig. 4. Dependence of the factor of change of working volume
an an angle of turn of the distributor for variants:
a) $\delta_0 = 7^0$ variants 1, 3, 5; b) $\delta_0 = 5^0$ variants 2, 4, 6

The important advantage of conical regulation APH is that in reversive hydromachines the passage of a range of the minimal submissions can be executed at the optimal parameters. For adjustable bent-axis APH trimot type reverse of a stream of a working liquid it is impossible in connection with features of a design. In adjustable bent-axis APH cradle type at reverse swinging unit there passes a range of angles between axis of a shaft and axis BC $-\alpha_{\min} \le \alpha \le \alpha_{\min}$ which cause the minimal efficiency of the hydromachine.

One of the basic requirements as to mechanisms of regulation are accuracy and sensitivity. They characterize an ability of the mechanism of regulation to reproduce with the minimum time error and coordinate the movement of an entrance link and target link.

Sensitivity of the kinematic circuit of a regulator of the considered design depends on angular coordinate

$$\psi(\beta) = \frac{d\alpha}{d\beta} . \tag{11}$$

We shall receive the differential of the expression (5)

$$d\alpha \cdot \sin\alpha = \sin\gamma \cdot \sin(\gamma + \delta_0) \cdot \sin\beta \cdot d\beta ,$$

In view of the dependence (5) we shall find sensitivity of the kinematics circuit of a regulator

$$\psi(\beta) = \sqrt{\frac{\sin^2\gamma \cdot \sin^2(\gamma + \delta_0) \cdot \sin^2\beta}{1 - (\cos\gamma \cdot \cos(\gamma + \delta_0) + \sin\gamma \cdot \sin(\gamma + \delta_0) \cdot \cos\beta)^2}} \tag{12}$$

Hence, the considered kinematics circuit of conical regulation at rotation of the allocator provides sensitivity

$$0 \le \psi(\beta) \le \frac{\sin\gamma \cdot \sin(\gamma + \delta_0)}{\sqrt{1 - \cos^2\gamma \cdot \cos^2(\gamma + \delta_0)}} \tag{13}$$

In Fig. 5 dependencies of sensitivity of the kinematic circuit are shown at conic regulation from a corner of turn of the allocator at conic regulation for 4 variants of parameters of the swinging unit considered above at $\delta_0 = 7^0$.

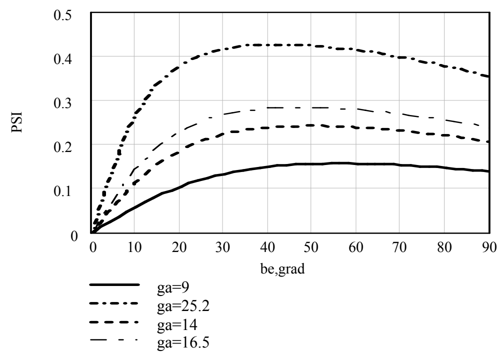

Fig 5. Dependence of sensitivity of the kinematic circuit on a corner of turn of the allocator at $\delta_0 = 7^0$, variants 1,3,5,7.

The analysis of the dependence (12) shows that the sensitivity of the kinematic circuit parameters of swinging unit β, γ, δ_0 which provide a corner of inclination БЦ

$\alpha \leq 40^0$ makes $\psi(\beta) \leq 0.5$. Apparently from the dependencies in Fig. 5 with an increase of the corner of the cone γ the sensitivity of the regulation mechanism grows. Thus for each variant of the parameters of the swinging unit there is the maximum value $\psi(\beta)_{\max}$.

CONCLUSION

In the present article the basic advantages of adjustable bent-axis APH are considered. Kinematics circuit APH with conical regulation on the basis of which the basic characteristics of hydromachines of such type are designed is submitted. Results of calculation of parameters for some sample designs APH with conical regulation are analyzed.

These results show, that the application of APH with conic regulation allows to expand a range of change of the transfer relation of transmission at 1.27 – 1.88 times. It allows to expand the sphere of application of hydrovolumetric transmissions in modern mobile engineering.

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