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About Kinematics of the Axial Piston Hydraulic Machines with Motion Transmitting by Connecting Rods

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Abstract

Although the hydraulic machines with axial pistons and inclined block, without double cardan joint are used for a long time (from 60's of the past century), in the wide technical literature (technical books, university courses a.s.o.), which appeared in our country, is nothing spoken about the way in which the rotation motion from the driving shaft to the cylinder block is transmitted, and certainly about the consequences of this way. Also, no structural analysis of the mechanism of these machines is made. As a result, the present work enters upon a bibliographic study about the mechanism kinematics of the hydrostatic units with the rotation motion transmitting by connecting rods, with the purpose of carrying out a structural analysis and of the accurate kinematics approach of this mechanism in the frame of the following works.

Key words: *hydraulic machines with axial pistons, kinematics of driving by connecting rods.*

Introduction

The hydraulic machines with axial pistons (HMAP) are widely used in technics (inclusively in the oil equipment) in the frame of the driving groups, usually electro-hydrostatic ones, due to advantages proved by them (see [1]÷[4]).

At the present moment there is a constructive variety of HMAP (see [5], too) pointed out in the schema presented in Fig. 1. HMPA can work as hydrostatic pumps/generators, or as hydrostatic motors. Both of the kinds of machines are included in the making up of hydrostatic transmissions.

As a rule, if they work as pumps, these machines convert the mechanical energy in hydraulic energy, under its preponderant hydrostatic shape (due to volume variation occupied by liquid in cylinders), by converting the rotation motion of the driving shaft in the piston alternative translation motion. If it is the matter about motors, then the energetic and motion transformations above mentioned are in inversely development. The pistons aspiration/supply and discharge/draining out processes are succeeded as a result of passing each cylinder (due to the rotation motion of the cylinder block) near the low pressure window, and then near the high pressure window of the distribution plate/distributor block.

In this work a bibliographic analysis of the mechanism kinematics in case of hydrostatic machines with transmitting of the rotation motion by connecting rods with the purpose of realization a structural analysis and approach of this mechanism accurate kinematics in the frame of a next works.

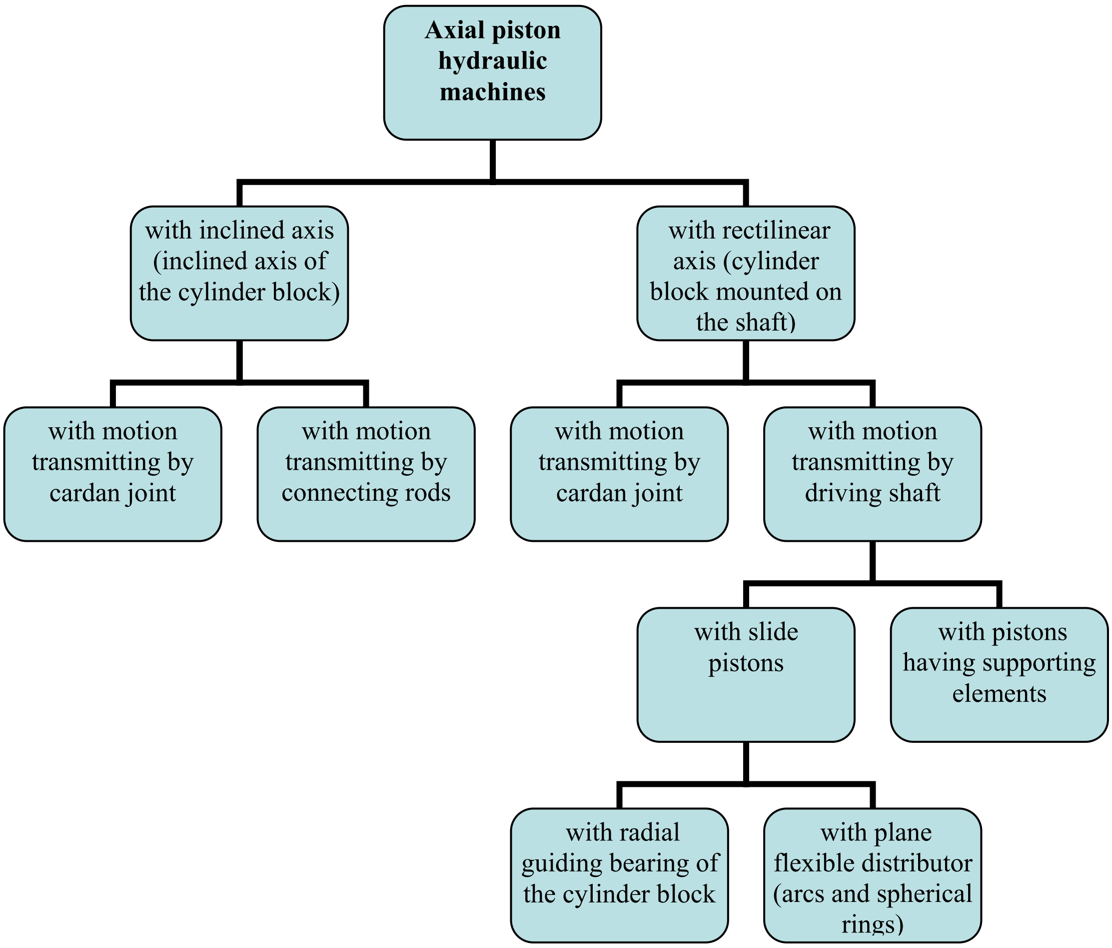

Fig. 1. Classification of the axial piston hydraulic machines.

These kinds of machines are called hydrostatic machines with transmitting of the motion by connecting rods (HMTMCR).

Bibliographical Analysis Regarding the Kinematics of the Hydrostatic Machines with Transmitting of the Motion by Connecting Rods

Although the hydraulic machines with axial pistons and inclined block, without double cardan joint (see Fig. 2), are used for a long time (from 60's of the past century), in the technical literature (technical books, university courses a.s.o.) which have appeared in our country (for example, [1] ÷ [4], it is nothing spoken about the way in which the rotation motion from the driving shaft to the cylinder block is transmitted and certainly about the consequences of this way. In [4] it is only noted that the motion transmitting from the disk/driving flange to the cylinder block, in the case of the pump with "inclined block", is made either by means of a propeller shaft or by the side contact between the connecting rods and the piston, or by a bevel gear, indicating (really!) the figures corresponding to each of the transmitting way.

Otherwise, in the present practice, the elementary kinematics is used (see, for examples, [3], [4], [5], [6]), though it is not so called, in accordance with the fact to which the connecting rod length (l) is considered longer than the crank radius (the disposition circle radius of the spherical joints of the connecting rods with the driving flange) noted R_f, so that the ratio R_f/l may be neglected. Therefore, theoretically, it is considered that $l \to \infty$. This is not true; for example, for HMPA having a kind of F232 and F132 built in the Mechanical Works Plopeni, $R_f/l = 0.56$. If

$l \to \infty$, then the connecting rod axis will always remain parallel to the piston axis and the connecting rod does not make contact with the piston inside wall, meaning that the connecting rod does not take part in driving the cylinder block, contrary to the reality.

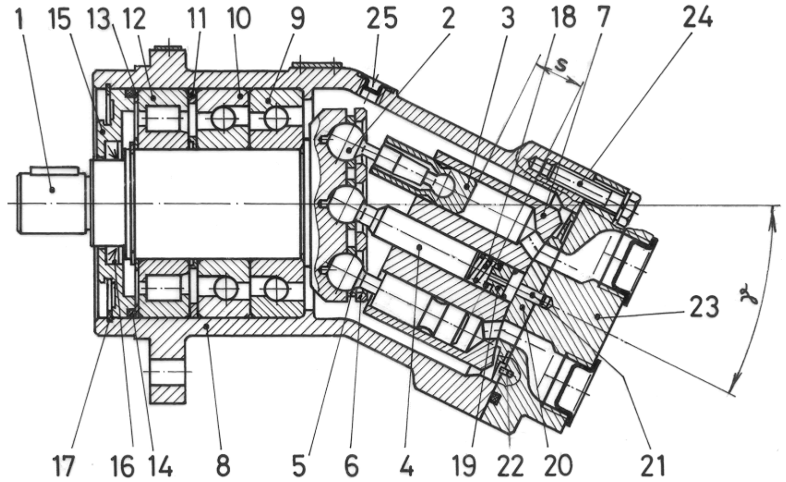

Fig. 2. Non-adjustable hydrostatic unit with axial pistons – longitudinal section: 1 – shaft with driving flange; 2 – connecting rod with double joint; 3 – piston; 4 – guiding axis with joint at the driving flange; 5 – retainer ring; 6 – retainer plate; 7 – cylinder block; 8 – carcass (frame); 9, 10 – radial-axial ball bearings; 11 – spacing ring; 12 – radial bearing with cylindrical rollers; 13 – spacing ring; 14 – "O" ring; 15 – bonnet; 16 – "A" cuff; 17 – elastic ring; 18 – arch; 19 – sleeve; 20 – distribution plate; 21 – bolt; 22 – cylindrical pin; 23 – distributor; 24 – fixing bolt; γ – angle of inclination of the cylinder block; S – length of the piston stroke.

In exchange, the author of the book [7] describes thoroughly the way of transmitting of the rotation motion from the driving flange to the cylinder block, through a couple of connecting rod-piston, in the moment when the angle of inclination (δ) of the connecting rod axis against the cylinder axis in which the respective piston is displaced becomes maximal, showing that there is a regular succession in running of the connecting rods, as leading elements, a difference ($\Delta\varphi$) between the angle of rotation of the driving shaft (φ_1) and of the cylinder block (φ_4) (in accordance with Fig. 3),

$$\Delta\varphi = \varphi_1 - \varphi_4 , \tag{1}$$

and a non-uniformity of the cylinder block motion as a result of the angle variation δ. But, the same author of the book [7] does not appoint an expression of the piston displacement which will take into account the connecting rod motion, the difference angle $\Delta\varphi$ respectively, being limited himself to the elementary kinematics theory.

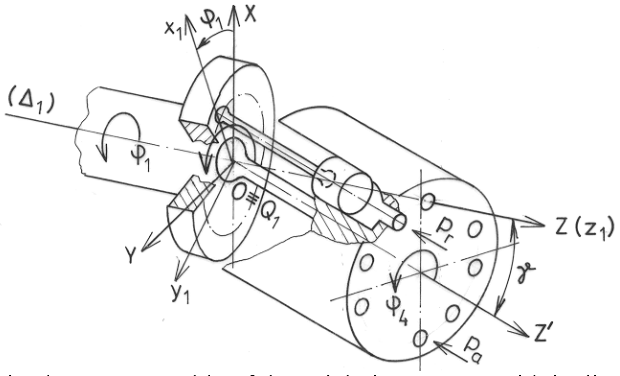

Fig. 3. The kinematic element ensemble of the axial piston pump with inclined cylinder block, with motion transmitting by connecting rods: γ – tipple angle of the cylinder block; φ_1 – rotating angle of the driving shaft flange; φ_4 – rotating angle of the cylinder block; p_a – aspiration pressure; p_r – discharge pressure.

The kinematics problem, regarding the axial piston pumps, is also solved in this way in the paper [8], though it is precisely stated that “the motion transmitting is by successive contacts carried out: driving flange-joint, connecting rods-pistons and pistons-cylinders”.

In 1963, a paper [9] is published by H. Heumann, where, in case of the cylinder block, the way of transmitting of the rotation motion by connecting rods which “come into lateral contact with the prolonged piston inside” is mentioned. He quotes Bloch [10], when he states that “there is always on the piston wale only a connecting rod, by which cannot be avoid the known non-uniformity of the motion transmitting”. But, as a follow, the expression of the piston travel is determined with the assumption that the cylinder block and the driving shaft turn synchronously, that is

$$\varphi_4 = \varphi_1 \equiv \varphi . \quad (2)$$

The HMTMCR kinematics problem and of the non-uniformity of the cylinder block rotation was approached in the Romanian specialized literature for the first time in 1964 by the I. Nan, in his paper [11]. Although, there are some contradictions and mistakes, however, the paper brings some important contributions to understanding the process of motion transmitting from the connecting rods to the cylinder block and its rotation motion character. I. Nan states the “accurate relation” of the piston travel, taking into account the connecting rod finite length and the connecting rod inclination against the cylinder axis, respectively, but considering that the pump driving shaft and the cylinder block rotate synchronously, but the cylinder block is not driven by connecting rods. The non-uniformity of the cylinder block rotation motion in case of its driving by means of connecting rods is studied, respectively of the piston kinematics, although the same formula for projection of the connecting rod length on the plane perpendicular on the block axis is used. I. Nan shows in this paper the way in which all the connecting rods take part in the cylinder block driving, presenting the two zones of driving of each of the connecting rods, in case of a complete rotation, and he presents the variation of the angle of rotation curve of the cylinder block, depending on φ_1, for a pump with seven pistons. In such a way, at a given moment, the cylinder block is driven by a single connecting rod, existent a well defined succession of setting in work of the connecting rods. In case of a pump having seven pistons, the connecting rod working succession is: 1– 4 – 7 – 3 – 6 – 2 – 5, that is, the connecting rod corresponding to a piston which is, to say, in a discharge phase with the connecting rod of a diametrically opposed piston which is in a aspirating phase alternates. In case of the cylinder block rotation, therefore, there are two driving zones, which do not change then position against the pump body. They are diametrically opposed and distanced against the reading origin of the shaft angle of rotation (φ_1) having an angle about of 135° for $\gamma = 25°$. At the same time with the decrease of the γ angle value, the distance of the driving zone center increases, so that for $\gamma = 12.5°$, this is about 157.5°. The cylinder block difference of phase in comparison with the pump shaft, when the angle γ is changed for the purpose of flow rate variation, will bring about a disturbance of the distribution phase. In such a way, in the case of the pump Hydromatik 14.25, the maximal error of phase distribution is 1°24' [11].

A complete work from point of view of accurate kinematics treatment of HMTMCR is presented in the paper [12]. In such a way, in this work are determined: the expression of the piston displacing, of the difference angle between the driving shaft and the cylinder block ($\Delta\varphi$) in the case when the connecting rod relies on the conical surface of the piston cup, the variation speed of the difference angle depending on φ_1, the connecting rod motion against the piston (the connecting rod hodograph), the two angular ranges of working of the driving connecting rod being defined, the angle φ_1, where $\Delta\varphi$ is minimal ($\Delta\varphi_m$), the shaft and cylinder block synchronism condition (“for which, each of the connecting rods is always relied on the conical surface of the corresponding piston cup and the hydraulic machine may be reversible”), the condition to avoid the machine blockage/sticking (the unregulated reversible hydraulic motor blockage, respectively), the character of simple harmonic of the piston motion in the cylinder, considered in practical purposes with enough accuracy, and the influence of the difference angle on the distribution process. In such a way, by using the vectorial algebra and drawing the vectorial diagram, the expression of the piston displacing is determined in the shape

$$s = s^{(e)} + \Delta s\,, \tag{3}$$

where $s^{(e)}$ and Δs are the piston displacing in the elementary kinematics theory, and the displacing correction for the accurate theory, respectively. These are given for the following relationships:

$$s^{(e)} = R_f \cdot \sin\gamma \cdot \cos\varphi_1\,; \tag{4}$$

$$\Delta s = \sqrt{l^2 - p^2}\,, \tag{5}$$

p being the projection of the connecting rod length on a perpendicular plane on the cylinder block axis (although this is not mentioned in the work) and having the expression

$$\begin{aligned} p^2 &= \left(R_f - R_c\right)^2 \cdot \sin^2\varphi_1 + \left(R_c - R_f \cdot \cos\gamma\right)^2 \cdot \cos^2\varphi_1 + \\ &+ 2 \cdot R_f \cdot R_c \cdot \left[\left(\cos^2\varphi_1 \cdot \cos\gamma + \sin^2\varphi_1\right) \cdot \left(1 - \cos\Delta\varphi\right) + \frac{1-\cos\gamma}{2} \cdot \sin 2\varphi_1 \cdot \sin\Delta\varphi\right]. \end{aligned} \tag{6}$$

If δ is the angle of inclination of the connecting rod against the piston/cylinder axis (see Fig. 4), then it is true the relationship

$$\sin\delta = \frac{p}{l} \tag{7}$$

and the displacing correction is written as

$$\Delta s = l \cdot \cos\delta\,, \tag{8}$$

and the piston displacing expression becomes

$$s = l \cdot \left(\frac{R_f}{l} \cdot \sin\gamma \cdot \cos\varphi_1 + \cos\delta\right). \tag{9}$$

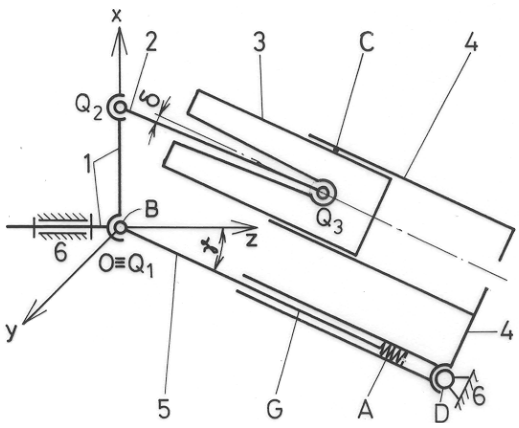

Fig. 4. Structural schema of a mechanism with a piston, of an axial piston pump, with the motion transmitting by connecting rods: 1 – driving shaft and flange/crank; 2 – connecting rod; 3 – piston; 4 – cylinder/cylinder block; 5 – guiding axis; 6 – fixed element; L – bearing of the driving shaft; $O \equiv Q_1$ – rotating centre of the driving flange; Q_2 – the joint between the connecting rod and the driving flange; Q_3 – the joint between the connecting rod and the piston; C – the piston inside the cylinder; D – the spherical surface ensemble of the cylinder block and of the distribution plate; A – the pressing arch of the cylinder block on the distribution plate; G – the cylinder block guiding; B – the joint between the driving shaft/flange and the guiding axis.

Because δ is very small, then may be given the approximation (accordingly to [12]):

$$cos\,\delta \cong 1 \tag{10}$$

and it will result

$$\Delta s \cong l\,, \tag{11}$$

and (9) becomes

$$s \cong l \cdot \left(\frac{R_f}{l} \cdot \sin\gamma \cdot \cos\varphi_1 + 1 \right), \quad (12)$$

this expression being taken into consideration (in [12]) as accurate enough for practical calculations.

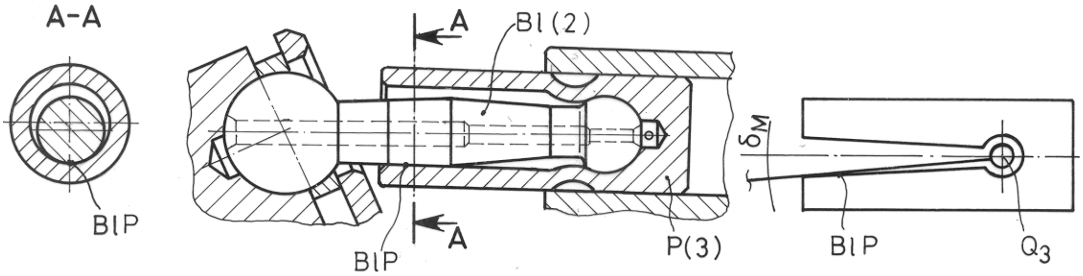

Fig. 5. The ensemble connecting rod-piston in the state when the connecting rod is lieding/driving (it relies on the piston cup), and its schematic representation: Bl (2) – the connecting rod; P (3) – the piston; BlP – the contact zone between the connecting rod and the inside wall of the piston cup; δ_M – the maximal angle between the connecting rod axis and the piston/cylinder axis.

The difference angle between the pump shaft and the cylinder block is obtained in [12] from the condition that the connecting rod relies on the piston inside surface (that is $\delta = \delta_M$) and has the formula

$$\mathrm{tg}\frac{\Delta\varphi}{2} = \frac{-b + \sqrt{b^2 - a \cdot c}}{a}, \quad (13)$$

where a, b and c have the following expression

$$a = (R_f + R_c)^2 \cdot \sin^2\varphi_1 + (R_c + R_f \cdot \cos\gamma)^2 \cdot \cos^2\varphi_1 - l^2 \cdot \sin^2\delta_M; \quad (14)$$

$$b = R_f \cdot R_c \cdot (1 - \cos\gamma) \cdot \sin 2\varphi_1; \quad (15)$$

$$c = (R_f - R_c)^2 \cdot \sin^2\varphi_1 + (R_c - R_f \cdot \cos\gamma)^2 \cdot \cos^2\varphi_1 - l^2 \cdot \sin^2\delta_M. \quad (16)$$

From the representation of the variation law $\Delta\varphi = f(\varphi_1)$, will result the ranges of angle φ_1, where each of the connecting rods is driving one; for the connecting rod 1 these ranges are

$$\left[\frac{\pi}{4} - \frac{\pi}{2 \cdot z}, \frac{\pi}{4} + \frac{\pi}{2 \cdot z}\right] \text{ and } \left[\frac{5 \cdot \pi}{4} - \frac{\pi}{2 \cdot z}, \frac{5 \cdot \pi}{4} + \frac{\pi}{2 \cdot z}\right],$$

if the piston number z is odd. The smaller $\Delta\varphi$ is, the less marked the asynchronous character of the driving shaft and cylinder block rotation motion is. If for the angle of inclination of the cylinder block $\gamma = \gamma_*$, to which will correspond δ_{M*}, the mechanism is built in such a way that the following condition to be respected (accordingly to [12]):

$$\frac{R_f - R_c}{l} = \frac{R_c - R_f \cdot \cos\gamma_*}{l} = \sin\delta_{M*}, \quad (17)$$

then $\Delta\varphi = 0$ (because $c = 0$), this meaning that the cylinder block rotates synchronously with the driving shaft. Therefore, in this situation, all the connecting rods are leading ones at the same time, and as a result, there is the possibility of mechanism wedging. For that reason, in order to avoid the blockage, the joints must be made with some allowable clearances, and however a little enough lagging of the cylinder block must be realized, that is, for the purpose of ensuring an allowable asynchronous character for rotation motions of the two mechanism elements (accordingly to [12]). The lagging angle existence $\Delta\varphi$, which is changed in case of adjustment (when the angle γ is changed) has unfavourable influences on the distribution process development (accordingly to [12]). Therefore, in case of adjusted pumps it is necessary the distribution plate rotation at an angle of Δφ [12], choosing a mean value of the rotation angle corresponding to the adjustment range. If the pump working area needs a sufficiently great covering, then the use of a mean value of the distribution plate rotation angle can produce an increase and, also, a great decrease of pressure inside the closed cylinder passing through the bridges which divide the distribution windows (accordingly to [12]), making worse the distribution process and creating undesirable consequences as vibrations and noises. That is why, for obtaining a great guaranteed coverings, special narrowing slots are made in the separating bridges, through which a slow decrease and increase of the pressure inside the cylinder is created.

The same way of solving a HMTMCR kinematics presented in the paper [12] is taken over by K. B. Frolova in the book [13] being not included the determinations and considerations regarding the non-uniformity of the cylinder block motion and its consequences on the process of distribution.

Analysing the noise sources in an axial piston pump, the author of the work [14] makes evident the cylinder block non-uniform motion in case of its driving by means of the connecting rods and states that the driving transmission among the connecting rods is accompanied by the shock between the connecting rod which becomes active and the respective piston cup, from which will result a pump excitation as an impulse. The radial shock speed of the connecting rod, which makes contact with the piston cup, has the maximal size almost 0.1m/s at the pump with seven pistons, having the piston diameter of 25 mm, and running at 1 500 rot/min. The measurements have shown that the apart noise of this source is with 20 to 25 dB (*A*) smaller than the pump normal noise, this fact meaning that it has a smaller importance in comparison with the totality of other sources.

Only in the book [15], authors make a kinematical analysis of the axial piston pump mechanisms, having or not having double cardan joint between the driving shaft and the cylinder block, but without making a principle distinction between the two mechanisms regarding the rotation motion transmitting to the cylinder block. After that, they determine geometrically the piston displacing expression, under the form of that obtained by I. Nan, therefore, taking into account that the pump driving shaft and the cylinder block rotate synchronously, but the connecting rod projection length on the plane perpendicular on the cylinder block axis is expressed under the form given by H. Heumann in [9].

Conclusions

From the bibliographical analysis realized above, may be stated the following: the scientific literature which has a wide diffusion in our country does not mention anything about the transmitting of the rotation motion by connecting rods from the driving shaft to the cylinder block, in case of the running analysis of the pumps of this kind, and solves the kinematics problem of these hydraulic machines, admitting that the connecting rod length is infinitely, which is in a total discordance with the reality; in the great majority of works regarding the accurate kinematics study of HMTMCR appeared abroad there is a contradiction between the way of approaching this kinematics and the considered synchronous character of the rotation motion transmitting from the driving shaft to the cylinder block; in the work [12] a complete study of the accurate kinematics of this kind of hydraulic machines is realized; the works studying the accurate kinematics of the hydraulic machines, about which it is talking here, in accordance with the way of driving in rotation motion of the cylinder block by connecting rods, they do not make a structural analysis of this mechanism; then when make a structural analysis of the axial piston pump mechanisms having or not having double cardan joint between the driving shaft and the cylinder block it is not made the principle distinction between the two kinds of mechanisms regarding the rotation motion transmitting to the cylinder block; the way of driving by connecting rods of the cylinder block has non-favourable running consequences; constructive measures can be taken for the purpose of ensuring an admissible asynchronous character to the rotation motions of the two mechanism elements with decrease of the mentioned non-favourable effects.

This study is useful to understand the HMTMCR kinematics, and the non-favourable running influences of the cylinder block driving by connecting rods, and also for carrying out the mechanism structural analysis of these machines, and approaching an accurate kinematics in an improved shape, this one being the intention of the author in his next work.

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Despre cinematica maşinilor hidraulice cu pistoane axiale, cu transmiterea mişcării prin biele

Rezumat

Deşi maşinile hidraulice cu pistoane axiale, cu bloc înclinat, fără articulaţie cardanică dublă, sunt utilizate de multă vreme (de prin anii '60 ai secolului trecut), în literatura tehnică de largă circulaţie (cărţi de specialitate, manuale universitare etc.), apărută la noi, nu se vorbeşte despre modul în care se transmite mişcarea de rotaţie de la arborele de antrenare la blocul cilindrilor şi, bineînţeles, despre consecinţele acestui mod. De asemenea, nu se întreprinde vreo analiză structurală a mecanismului acestor maşini. Ca urmare, lucrarea de faţă întreprinde un studiu bibliografic despre cinematica mecanismului unităţilor hidrostatice cu transmiterea mişcării de rotaţie prin biele, în scopul realizării unei analize structurale şi al abordării cinematicii exacte a acestui mecanism, în cadrul unor lucrări viitoare.