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STRUCTURAL ANALYSIS OF THE MECHANISM IN CASE OF HYDRAULIC MACHINES WITH AXIAL PISTONS AND WITH ROTATING MOTION TRANSMITTING BY CONNECTING RODS

Simion Parepa
Petroleum-Gas University of Ploieşti, Department of Oilfield and Petrochemical Equipment
e-mail: sparepa@upg-ploiesti.ro

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Abstract: In the special technical literature a structural analysis of the mechanism in case of hydraulic machines with axial pistons and inclined block without double cardan joint, which to take into account the specific modality of driving in rotating motion of the cylinder block, cannot be found. That is way, in the present work such an analysis is presented with the aim to understand this complex mechanism, to make evident the functional and kinematical role of the component elements, and to realize in a next work an study of the accurate kinematics, and to estimate the running consequences which appear due to the transmitting of the rotating motion from the driving shaft to the cylinder block by means of connecting rods.

1. INTRODUCTION

The hydraulic machines with axial pistons and with transmitting of the rotating motion from the driving shaft to the cylinder block by means of the connecting rods, called simply by us hydraulic machines with the motion transmitting by connecting rods (HMMTCR), are not studied in the wide-spread technical literature (see e.g. [4], [7], [13], [14]) taking into account this specific modality of driving of the cylinder block.

As a matter of fact, the present practice uses an elementary kinematics (see e.g. [2], [9], [13], [14]), although it is not in another way called, in accordance with it the connecting rod length (l) is considered much greater than the crank radius (the radius of the circle of disposition of the spherical joints between the connecting rods and the driving flange) noted with R_f, so that the ratio R_f / l may be neglected. Therefore, theoretically it is considered that $l \to \infty$, a hypothesis which can not be accepted; e.g. for HMMTCR having the type F232 and F132 realized at the Mechanical Works Plopeni, R_f/l = 0,56. If $l \to \infty$, then the connecting rod axis remains always parallel to the piston axis, and the connecting rod will not be in connection with the inside wall of the piston cup; it means that the connecting rod does not take part to the driving of the cylinder block in rotating motion, contrary to reality.

In [3] the authors make a kinematical analysis of the mechanism in case of pump with axial pistons, with inclined block, with and without double universal joint between the driving shaft and the cylinder block, but without doing a difference of principle between the two types of mechanisms, concerning the rotating motion transmitting to the cylinder block. These authors will determine in a geometrically way the expression of the piston displacement, taking into account that the pump driving shaft and the cylinder block are in a synchronous motion, but this is true only in case of hydraulic machines with double universal joint between shaft and cylinder block.

Therefore, in the frame of this work the realization of a structural analysis of the HMMTCR complex spatial mechanism is imposed.

2. ABOUT THE KINEMATICS OF THE CYLINDER BLOCK DRIVING BY USING CONNECTING RODS

In the works [10] and [11], a bibliographic analysis regarding the treatment of the HMMTCR kinematics is made, and in [11] the kinematics, hydraulics and dynamics of these types of mechanisms in the frame of the accurate theory, presenting also the unfavorable consequences of the cylinder block driving by means of connecting rods on their running conditions, is studied.

HMMTCR are able to work both as pumps/hydraulic generators (P/HG), and as rotating hydraulic motors (RHM). In fig. 1 a longitudinal section through an HMMTCR with a fixed capacity is presented, where the component elements are made evident.

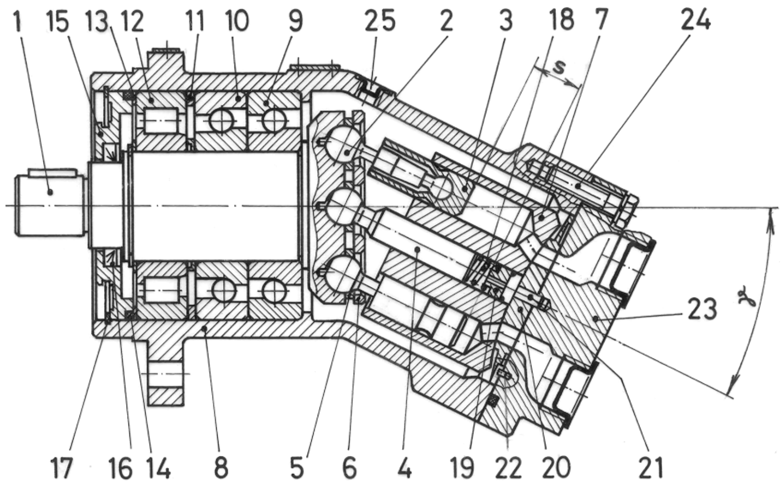


Fig. 1. Hydrostatic unit with axial pistons, without adjustment − longitudinal section: 1 – shaft with driving flange; 2 – connecting rod with double joint; 3 – piston; 4 – guiding axle with joint at the driving flange; 5 – holding ring; 6 – holding plate; 7 – cylinder block; 8 – carcass; 9, 10 – radial-axial ball bearing; 12 – cylindrical roller radial bearing; 15 – cover; 16 – cup „A"; 17 – elastic ring; 18 – arch; 19 – bush; 20 – distributing plate; 21 – bolt; 22 – bolt; 23 – distributor; 24 – clamping screw; γ – angle of inclination of the cylinder block; S – length of the piston stroke.

The kinematical chain (KC) by which the conversion of the rotating motion in alternative translation motion is carried out in case of HG or inversely in the situation of RHM, is the ensemble of elements (shaft+crank)-connecting rod-piston-cylinder, and cylinder-piston-connecting rod-(crank+shaft) respectively, the crank role being played by the driving flange (see fig 1).

If the hydraulic machine has *z* pistons, then in its structure will be *z* cylinders, realized as the cylinder block, and *z* double jointed connecting rods (in piston and driving flange). The cylinder block is guided by means of an axle jointed in the driving flange and it is relied on the distributing plate by a spherical surface, under the action of the elastic force of a spring set inside the axial hole of the cylinder block between a bush (fixed by the block) and the end of the guiding axle (see fig. 1).

In case of running as a pump, the cylinder block is driven from the driving flange, by means of pistons and their rods, especially realized − the connecting rods. The connecting rods (the piston rods) are set in pistons and in driving flange by means of spherical joints (with nut). In this way, each connecting rod turns around freely in the piston, being inclined in comparison with the respective cylinder axle, with an the angle δ (according to fig. 2), which is variable from a minimal value δ_m to a maximal one δ_M. The outline of the connecting rod and the inside surface of the piston cup are in a such a way realized (see fig. 4) that at δ_M will produce a linear contact, by which the connecting rod drives − by means of the piston − the cylinder block. In this way, the rotating moment to be transmitted is well taken over. This moment is represented by the pressure force moment, the dynamic moment due to acceleration of the element masses in translation motion − of the pistons and connecting rods − and rotating motion − of the cylinder block, pistons and connecting rods, due to moment of friction between the frontal surfaces of the cylinder block and the distributing plate, the moment of the friction forces between the pistons and cylinders, and the moment of the impulse forces realized by acceleration of the oil mass in motion.

The kinematical analysis of the driving mechanism shows that the driving flange, connecting rod and cylinder block will make up a spatial mechanism having five jointed elements (a pentajoint). As a result, in case of a hydraulic unit with axial pistons there are as spatially coupled pentajoints as many pistons there are in its composition. The cylinder block is driven by the pentajoint having as index *i* whose connecting rod has the momentary inclination angle (the angle of inclination against the respective cylinder axis) δ_i equal to δ_M (see [1], [8], [10], [12]).

If HMMTCR carries out the function of HG, then its driving/motor element is the shaft with driving flange. The rotating motion of the driving shaft/flange is transmitted to the connecting rods and by them due to inclination with angle γ of the cylinder block against to the shaft axis, the piston translation motion and the cylinder block rotating motion is carried out.

In case when HMMTCR has a RHM function, then by one piston occurring in the high pressure zone of the distributing plate will represent the driving/motor element. By the force appearing due to pressure which acts on the motor/driving piston and by the inclination of the connecting rod which is coupled with this piston, a tangential component at the contact between the connecting rod and the piston cup is created. This tangential force will cause a rotating moment on the cylinder block which, in this way, is driven in a rotating motion determining both the translation motion of the piston (because the cylinder block inclination related to the driving shaft) and the rotating motion of the driving flange. It is ascertained that the cylinder block rotating motion is, in fact, from kinematical point of view, a driving motion for RHM.

Both the cylinder block rotating motion and the piston translation motion are necessary for carrying out the aspirating and upsetting processes of the pumps and the supplying and removal processes of the hydraulic motors, respectively.

The cylinder block, at a given moment, is driven only by only one connecting rod from those *z* the pump has. This connecting rod, called driving or active one, it is that being in contact with the piston cup, therefore, it has the maximal angle of inclination (δ_M) in comparison with the piston axis. In this time, the other connecting rods have smaller angles of inclination δ than δ_M.

Each connecting rod will become driving only in a domain of values of the driving shaft rotation angle (φ_1), being equal to π/z and called driving zone ([1], [8], [10], [12]). In case of a complete rotation, each of the connecting rods takes twice part in action: once in the course of upsetting of the corresponding piston and other time in its aspiration course ([1], [8], [10], [12]).

There is a well stated succession of the connecting rod running. In this way, the working order of the connecting rods in case of a pump having seven pistons is: 1– 4 – 7 – 3 – 6 – 2 – 5, that is it will alternate the connecting rod from a piston being set, let us say, in an upsetting phase with the connecting rod from a piston being in aspiration phase.

As a result of driving of the cylinder block by a single connecting rod, by variation of the angle δ, its rotating motion is not uniform, without taking into consideration the rotating motion character of the driving shaft and the asynchronism of the shaft and cylinder block motions is yielded with a lagging angle Δφ, the cylinder block remaining behind the shaft ([1], [8], [10], [12]).

3. STRUCTURAL ANALYSIS OF THE HYDRAULIC MACHINE MECHANISM WITH MOTION TRANSMITTING BY CONNECTING RODS

According to construction of the pumps with axial pistons, presented in fig. 1, a structural scheme of its mechanism, with a piston, shown in fig. 2, is carried out.

The kinematical elements of HMMTCR (the cylinders, pistons, connecting rods and the flange with driving shaft) are considered as tough.

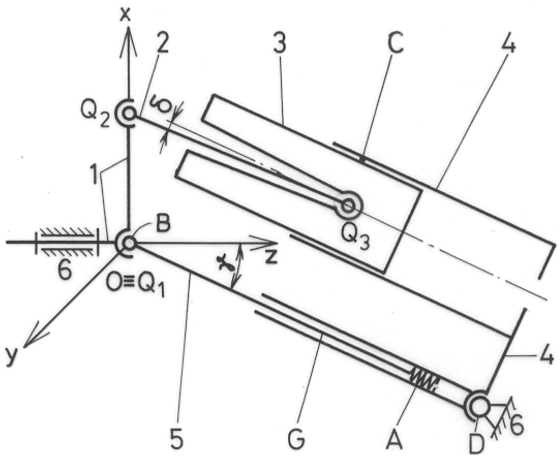


Fig. 2. Structural scheme of the mechanism with a piston, belonging to a pump with axial pistons, with the motion transmitting by connecting rods: 1 – shaft and driving flange/crank; 2 – connecting rod; 3 − piston; 4 – cylinder/cylinder block; 5 – guiding axle; 6 – fixed element; O≡Q_1 – rotating centre of the driving flange; Q_2 – joint between the connecting rod and the driving flange; Q_3 – joint between the connecting rod and the piston; C – piston in the cylinder; D – ensemble of spherical surfaces of the cylinder block and distributing plate; A– arch of pressing of the cylinder block on the distributing plate; G – guide of the cylinder block; B – joint between the driving flange and the guiding axle.

Because each connecting rod performs an oscillation motion by variable inclination with the angle δ in comparison with the piston axle until the contact with its cup, when it becomes a driving one, therefore it performs a motion which does not occur in the same plane with the piston and the respective cylinder, and because the driving flange and also the cylinder block yield rotating motions in different planes and, at the same time others than the planes where the piston motions are developed, KC represented by the ensemble of the elements cylinder-piston-connecting rod-crank (drive flange) is a spatial KC.

Being an ensemble of tough elements (in interaction by kinematical couples) whose motions and loadings have any orientations in the space, HMMTCR is a mechanical spatial system (MSS) [5].

The joints between the elements which make up the MSS are inside joints and the joints between these elements and the outside bodies, represented by a carcass and the distributing plate-distributing block (which are joined together with the carcass) are outside joints. The inside joints as the outside ones of this MSS are passive, mobile, and continuous, on surfaces, realized in the shape of some kinematical spatial couples.

Defining, according to [6] and [15], the rank of an element, noted by *j*, the number of the mobile joints (the number of the kinematical couples) that it has with the neighbor elements, the elements used in the frame of MSS having the type HMMTCR are simple or binary (with *j* = 2) and complex elements (of rank *j* > 2). In this way, the connecting rods and pistons are binary elements and the driving shaft-flange and the cylinder block are elements of the rank (*z* +1) (the driving flange having an outside couple and *z* inside couples, by them being realized the joints with *z* connecting rods, and the cylinder block having *z* inside couples for joints with the *z* pistons and an outside couple, as a joint with the distributing plate-distributing block-carcass).

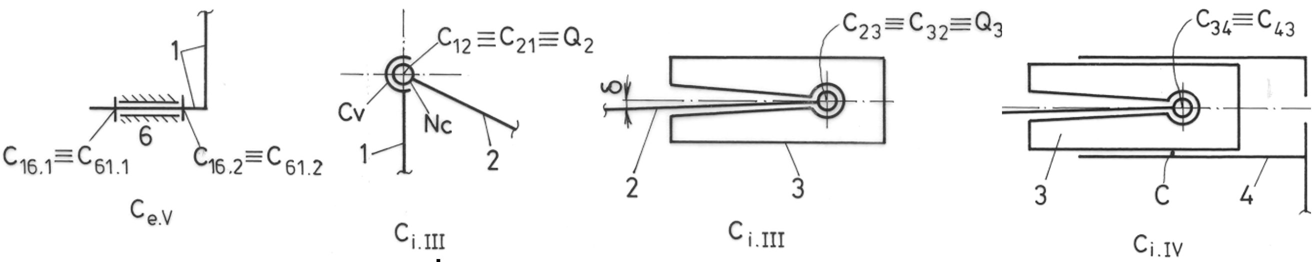
Axle (5) is a passive element [15] having only a guiding role of the cylinder block. This axle must not be taken into account in the calculation of the mobility degree [6].

The kinematical couple represented by the contact on the spherical surface between the cylinder block and the distributing plate, carried out by the elastic force of the arch (A) (placed in the cylindrical seat, in the centre of the cylinder block, between the guiding axis and the bush placed in this seat) and by a part from the weight of the ensemble cylinder block-pistons-connecting rods-guiding axle, it is an open couple (cf [6]).

The other kinematical couples occurring in HMMTCR are closed couples ([6], [15]), the contact between the respective elements being carried out by a permanent guiding.

The kinematical couples, represented by spherical joints, which connect the connecting rods to the driving flange and pistons are spatial ones ([6], [15]), because they allow of the component elements (namely of the driving flange and connecting rods, and of the connecting rods and pistons, respectively), relative space motions. The cylindrical couples made up by the cylindrical contact between the pistons and the respective cylinders of the cylinder block are defined as plane couples ([6], [15]), because they allow of the component elements relative motions in parallel planes. Because the contact between the component elements of the kinematical couples of MSS having the type HMMTCR is made on (spherical or cylindrical) surfaces, the couples are characterized as lower couples ([6], [15]).

Further, the kinematical couples belonging to HMMTCR are studied according to the geometrical joint conditions imposed by the relative motions of the component elements, that is the number of suppressed liberties or the number of dependence relations between two or more motion liberties from the six ones which a free body may have in the space (cf [5], [6], [15]).



a b c d

Fig. 3. Representation of the kinematical couples between the shaft (1) and the carcass (6) ($C_{e.V}$), between the driving flange (1) and the connecting rod (2) ($C_{i.III}$), between the connecting rod (2) and the piston (3) ($C_{i.III}$) and between the piston (3) and the cylinder (4) ($C_{i.IV}$), specifying the coupling theoretical points: Nc – spherical joint nut; Cv – spherical cavity.

In this way, the outside joint between the driving shaft and carcass, which is the driving shaft bearing made up (practically) by two radial-axial ball bearings (which take over the combined loads, axial and radial ones) and a radial roller bearing (see fig. 1), it is a rotating couple, that is a kinematical couple belonging to the V class ($C_{e.V}$) − with five joint conditions − of type 1 ([6], [15]), 3 translation and 2 rotations being suppressed, therefore allowing only one rotation, the rotating axis being the driving shaft/flange axis, and the theoretical coupling points being the centers of the two bearings (from the left and the right, according to fig. 3.a): $C_{(6.1).1}$ and $C_{(6.1).2}$ in the element 6, and $C_{(1.6).1}$ and $C_{(1.6).2}$ in the element 1 (cf [5]).

The joints (Q_2 and Q_3) between the connecting rod and the driving flange (see fig. 3.b) and between the connecting rod and the piston (see fig. 3.c) are inside couples, belonging to the III class ($C_{i.III}$) – with 3 joint conditions − of type 1, that is spherical joints (cf [6], [15]), represented by the connecting rod nuts and by the spherical cavities in the driving flange and also in the piston cup. The theoretical points of coupling for each of the spherical joints are the nut center ($C_{1.2}$, and $C_{2.3}$ respectively) and the center of the spherical cavity ($C_{2.1}$, and $C_{3.2}$ respectively). The coupling condition is represented by the permanent coincidence of the theoretical points of coupling ($C_{1.2} \equiv C_{2.1} \equiv Q_2$, and $C_{2.3} \equiv C_{3.2} \equiv Q_3$ respectively).

The piston length is sufficiently long and the clearance between cylinder and piston is sufficiently small, so that the piston carries out only a rotation motion round its axis (which belongs to the cylinder too) and an independent translation motion along its axis. As a result, the piston inside the cylinder is an inside couple belonging to the IV class ($C_{i.IV}$) – with 4 joint conditions – of type 2, that is a cylindrical couple ([6], [15]). The theoretical point of coupling is considered to be the center of the piston joint spherical cavity: $C_{3.4} \equiv C_{4.3} \equiv C_{2.3} \equiv C_{3.2} \equiv Q_3$ (see fig. 3.d).

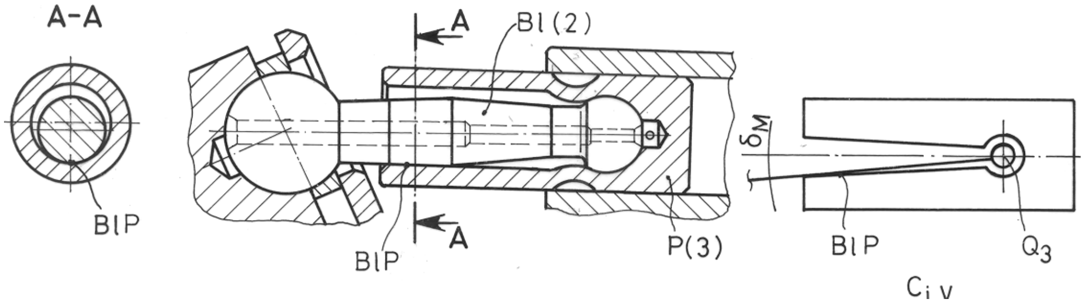


Fig. 4. The ensemble connecting rod-piston in case where the connecting rod is driving (it leans on the piston cup) (a) and the representation of the corresponding kinematical couple (b): BI (2) – connecting rod; P (3) – piston; BIP – cylindrical couple ($C_{i.IV}$), due to the contact between the connecting rod and the piston; BIP+Q_3 – rotating couple ($C_{i.V}$) between the connecting rod and the piston.

When the connecting rod becomes as driver, it leans on the piston cup, having a maximal inclination in comparison with the piston axis. Due to conical shape of the connecting rod in the respective contact zone, or due to the cavity having the same shape of the cup, a linear contact between the connecting rod and the cup is yielded (see fig. 4), appearing a contact force as a result of the resisting moment, opposed to the cylinder block, and due to the rotating angle lagging of the driving flange and cylindrical block (due to the delayed motion of the cylinder block in comparison with the driving flange). By the linear contact between the connecting rod and the piston cup, a quadruple joint (a cylinder pressed into another cylinder), an inside open couple of IV class ($C_{i.IV}$), of type 2 (a cylindrical couple) ([6], [15]), noted as BIP in fig. 4.b, is realized. If the spherical couples being between the connecting rod and the driving flange and the piston were detached, then the connecting rod could carry out only a translation motion along its axis and a rotating motion around it. As the spherical joint suppresses the translation motions of the connecting rod, is result that the existence of the Q_3 joint and the BIP couple will allow of the connecting rod only rotating motion around its own axis. As a result, the ensemble shaped from the spherical joint Q_3 and the cylindrical couple BIP will make up a rotating couple, that is an inside couple of V class ($C_{i.V}$), of type 1 [6].

In fig. 2, D is the joint between the cylinder block (4) and the plate-distributing block-carcass (6) represented (according to fig. 5.a) by the spherical surface ensemble of the cylinder block (BC) and of the distributing plate (PD), and A is the arch which presses (by means of the guiding axle 5) BC on PD. The role of the arch A is to press BC on PD, taking over the pushing force of BC, exerted by the pressure from the high pressure window of PD. The ensemble A+D will make up an open kinematical couple [6] (the contact being ensured by the arch elastic force), that is a spherical joint (see fig. 5.b), an outside kinematical couple of III class ($C_{e.III}$). The notation G in fig. 2 is the joint between the cylinder block (4) and the axle (5). The role of the axle (5) is to guide the cylinder block at its pushing towards the pressure being in the high pressure window of the distributing plate. That is why G represents a cylindrical couple (see fig. 5.c), that is an inside kinematical couple of IV class $C_{i.IV}$). In fig. 2, B represents the joint between the driving shaft/flange (1) and the guiding axle (5), which is a spherical joint (according to fig. 5.d), that is an inside kinematical couple of III class ($C_{i.III}$). The guiding axle (5) being a passive element, the ensemble of kinematical couples (A+D)+G+B in fact represent a rotating couple (see fig. 5.e), that is an outside couple of V class ($C_{e.V}$).

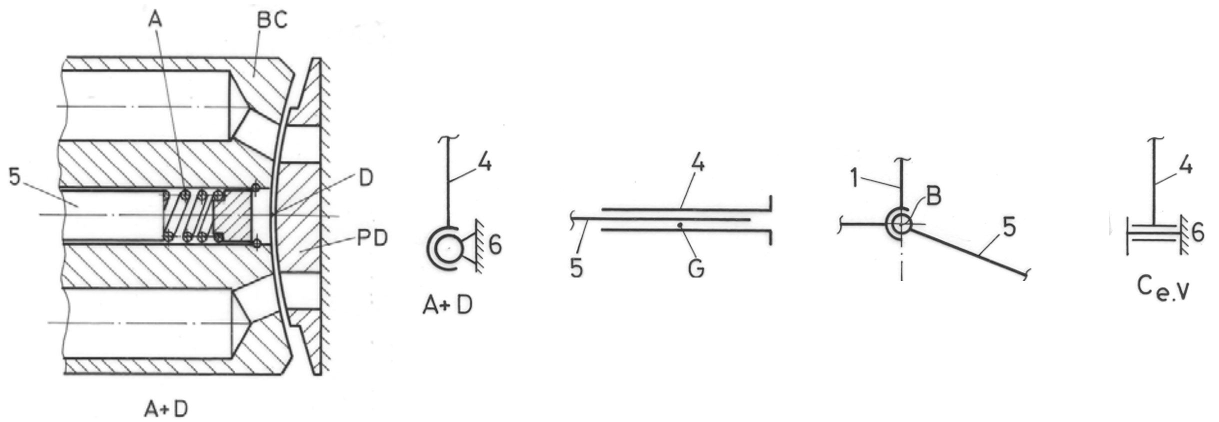


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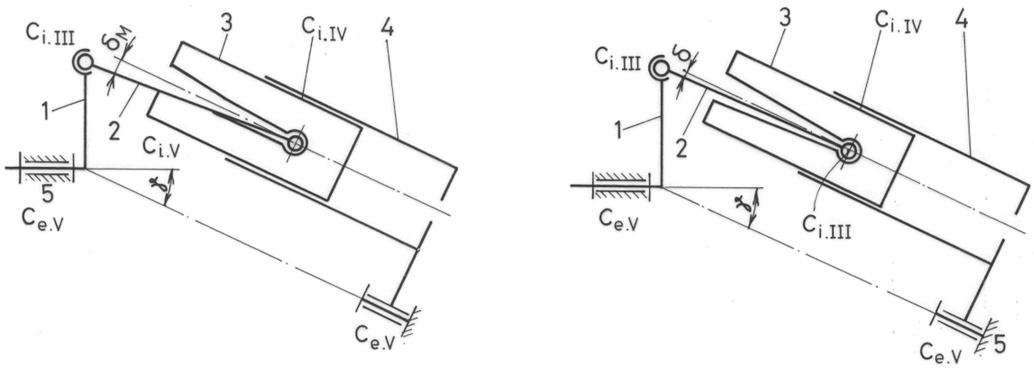
Fig. 5. Ensemble of cylinder block (BC)-distributing plate (PD)-arch (A)-guiding axle (5) (a) and representation of the kinematical couple made of D (the ensemble of the spherical surfaces of BC (4) and PD (6)) and A (b), of the joint (G) between BC (4) and the guiding axle (5) (c) of the spherical joint (B) between the driving shaft (1) and axle (5) (d), and of the rotating kinematical couple, made from (A+D), G and B (e).



a b

Fig. 6. Structural scheme of the HMMTCR mechanism, having a piston: a) in case where the connecting rod is in contact with the piston cup; b) in case where the connecting rod is not in contact with the piston cup; δ – inclination angle between the connecting rod axis and the piston axis, δ_M – maximal inclination angle, $\delta < \delta_M$.

All these above analyzed couples are considered as stationary [5], because they do not deform in a long running.

By using the above mentioned considerations, in fig. 6.a the structural scheme of the HMMTCR mechanism with an piston is represented in the case where the connecting rod comes in contact with the piston cup, and in fig. 6.b the structural scheme of the same mechanism when the connecting rod does not comes in contact with the piston cup.

Therefore, the mechanism has 5 elements from which one (the carcass, noted by 5) is fixed, joined between them by 5 kinematical couples, two of them being outside ones. All the kinematical elements of the mechanism are simple, having the rank 2 (because they have two joints with the neighbor elements). According to [3], the mechanism is spatial, having the family zero ($f = 0$).

4. CONCLUSIONS

In the paper a structural analysis of the HMMTCR mechanism, taking into account its particularity, and namely, the driving of the cylinder block in rotating motion by means of the connecting rods, is presented.

For this analysis realization, the driving process in rotating motion of the cylinder block and its consequences were necessary to be resumed on the basis of the specialty literature.

It is studied each element of the mechanism from constructive and running point of view and the joints between the kinematical elements; these elements and couples are characterized; the complexity of this spatial mechanism with *z* pentajoints, *z* being the number of the axial piston, is made evident, and then the structural schemes equivalent to the constructive scheme for the two situations where the connecting rod comes in contact or does not come in contact with piston cup are realized.

This study was really necessary for better understanding the HMMTCR mechanism from structural and running point of view and for approaching its kinematical analysis in another paper.

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