CZESŁAW DYMARSKI, D.Sc.,M.E.
Technical University of Gdańsk
Faculty of Ocean Engineering
and Ship Technology

Theoretical investigation of pivoting mechanisms for boat davits

SUMMARY

This paper presents a theoretical investigation of the boat davit construction and pivoting mechanism designs which comply with current provisions of the International Convention for the Safety of Life at Sea - SOLAS.

The analysis is based on two main types of the mechanisms applied also in the davits produced by FAMA Marine Machinery Works, Gniew, Poland.

INTRODUCTION

Boat pivot davits are one of the oldest, but still widely used, types of the deck life-saving equipment. However, contemporary davits which comply with the current provisions of the SOLAS Convention are very complex devices and resemble former designs by the principle of work only.

Pivoting mechanism is one of the basic davit mechanisms which has been recently developing rapidly due to higher demands introduced into the above mentioned convention. Its working conditions are exceptionally hard, because the mechanism has to provide rotation of a davit from the rest position to the outboard position by using energy stored in it, loaded by a life boat with people embarked, in heavy sea conditions at ship's heel angle $\alpha = 20°$, ship's trim angle $\beta = 10°$, and ambient temperature from -30°C to +65°C.

Rotation control, consisting in starting and stopping the mechanism in an arbitrary angular position of the davit, should be possible both from a post close to the davit and, remotely, from the life boat. Moreover the davit should be stopped automatically in a given position if any failure of the davit drive occurs during davit rotation.

The specified requirements are the main assumptions used in determination of the basic design load conditions of the mechanism. Moreover, they influence substantially the ways of developing davit construction, drive and control systems.

BASIC LOAD CONDITIONS OF THE MECHANISM

Pivot boat davits are installed on a deck, at ship's side, as a rule, with their jib axis in rest position parallel, or close to parallel, in respect to the ship's plane of symmetry. Taking this into account and giving consideration to ship's heel and trim, values of line force components acting in the parallel (x-y) and perpendicular (y-z) plane to the davit axis of rotation can be determined in the function of its angle of rotation (θ).

In Fig. 1 a scheme of the davit is shown with the basic external loads and their components depicted in the rectangular coordinate system bound with the davit.

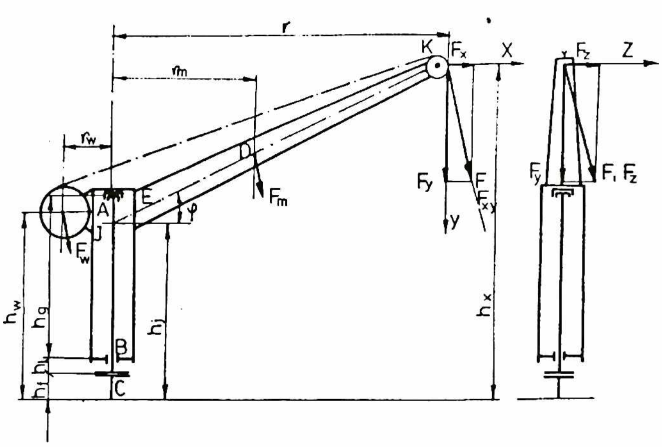

Fig. 1. Pivot davit scheme, its basic dimensions and loads

Variation ranges of the external loading components versus the ship's heel angle α and trim angle β is illustrated in Fig. 2 in the same coordinate system.

The most unfavourable working condition of the mechanism and its drive is the rotation of the davit, loaded by a boat, from the rest to the outboard position at the statical ship's heel to the oposite side by the angle α = -20° and the ship's trim in the jib's direction by the angle β = 10°. The highest mechanism loading occurs in this condition at the moment when the davit is pivoted by the angle θ_A defined as follows:

$$\theta_A = arc\ tg\left(\frac{tg\beta}{tg\alpha}\right) = 25{,}8^\circ \tag{1}$$

In this position the largest deviation angle of the line from y-axis appears in y-z plane, which is equal to:

$$\kappa = arc\ tg\sqrt{tg^2\alpha + tg^2\beta} = 22{,}02^\circ \tag{2}$$

and, due to this, the highest bending moment occurs in this plane, as well as twisting moment, loading davit structure.

To analyze variation of the mechanism drive working parameters it is necessary to know the required values of the torque M_{so} related to the davit axis during the entire process of its outboard rotation. The values can be determined from the following relationship:

$$M_{so} = (Fr + F_m r_m - F_w r_w)[tg\alpha\ \cos(\theta-\theta_0) + tg\beta\sin(\theta-\theta_0)]\frac{\cos\kappa}{\eta_b} \tag{3}$$

where:

θ_0 - the angle between x-y plane in the davit rest position and ship's plane of symmetry, (usually equal to zero or somewhat greater than that)

η_b - efficiency of the davit pivoting column bearings

The remaining notations are given in Fig. 1

It is easy to determine the efficiency of bearings of the davits with pivoting column supported by rolling bearings. The problem is considerably more complicated when slide bearings are applied, because exact determination of their efficiency is very difficult especially in the phase of mechanism starting; as it requires to reliably estimate friction factor and to know bearing reactions.

Values of the reactions in the function of the pivot angle θ can be calculated from the following formulas:

$$R_{Axz} = \sqrt{(M_{Bxy})^2 + (M_{Byz})^2}\,\frac{1}{h_g} + (F + F_m + F_w)\sin\kappa \tag{4}$$

$$R_{Ay} = (F + G_0)\cos\kappa \tag{5}$$

$$R_{Bxz} = (F + F_m + F_w) - R_{Axz} \tag{6}$$

where:

G_0 - weight of pivoting column and all the davit units installed on it

M_{Bxy}, M_{Byz} - bending moments acting in x-y and y-z planes, respectively, in the fixing point of the lower bearing.

The moments can be calculated from the following formulas:

$$M_{Bxy} = \{Fr + F_m r_m - F_w r_w + [F(h_k - h_f - h_l) + F_m(h_j - h_f - h_l + r_m tg\varphi) + F_w(h_w - h_f - h_l)]\ [tg\beta\cos(\theta-\theta_0) + tg\alpha\sin(\theta-\theta_0)]\}\cos\kappa \tag{7}$$

$$M_{Byz} = [F(h_k - h_f - h_l) + F_m(h_j - h_f - h_l + r_m tg\varphi) + F_w(h_w - h_f - h_l)]\ [tg\alpha\cos(\theta-\theta_0) + tg\beta\sin(\theta-\theta_0)]\cos\kappa \tag{8}$$

The calculated values of the required pivoting moment and transverse reactions in bearings during outboard rotation of the ZO 1,0/3,2-90°davit of 10 kN lifting capacity and 3,2 m reach (see Fig. 4) are presented in Fig. 3 in function of the pivot angle θ.

DESIGN SOLUTIONS

The type of loading and motion to be performed by a pivoting mechanism are decisive for selection of the drive type and manner of storage of the energy required. A drive system comprising hydrostatic gear and hydropneumatic accumulator is suited relatively well to ensure slow rotation under high torque.

A drive of this type has the following advantages in comparison with an alternative, electric drive fitted with toothed gear and electric battery:

- easiness of rotative speed control and regulation
- possible application of a lower reduction ratio and in consequence, a smaller size reduction gear, or even elimination of the gear at all
- lower mass loading of the mechanism
- greater operational reliability of the accumulator over a wide variability range of the working conditions (of ambient temperature in particular)

Due to the advantages this type of drive is recently applied to the pivoting mechanisms of pivot boat davits almost exclusively.

Pivoting mechanisms can be divided into two basic categories, depending on a type of hydraulic motor, efficiency and working parameters of the driving system:

- ❐ with a linear piston motor (hydraulic cylinder),
- ❐ with a rotary motor.

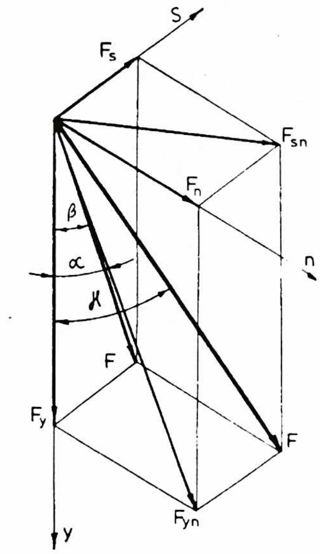

Fig.2.Davit external load components in the n-s-y coordinate system bound with a ship heeled by the angle α and trimmed by the angle β

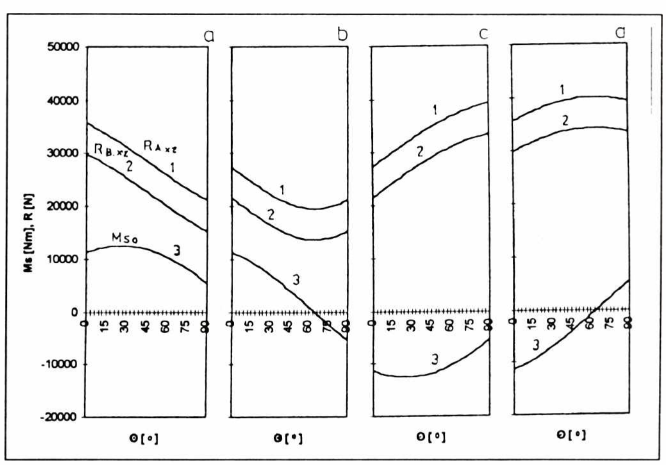

Fig. 3. The required pivoting moment (M_{so}) related to the davit axis and transverse reactions (R_{Axz}, R_{Bxz}) in bearings during outboard rotation of ZO 1,0/3,2-90° davit versus he pivot angle θ, at different statical ship's heel and trim angles: ***a)*** *α = - 20°, β = 10°;* ***b)*** *α = - 20°, β = - 10°;* ***c)*** *α = 20°, β = - 10°;* ***d)*** *α = 20°, β = 10°*

Pivot mechanisms of both categories can be found in many versions, but each of them maintains basic features of the category which it belongs to. In Fig. 4. two similar boat davits, but with different pivoting mechanisms, produced by FAMA Works, Gniew, Poland, are shown schematically to better illustrate the problem.

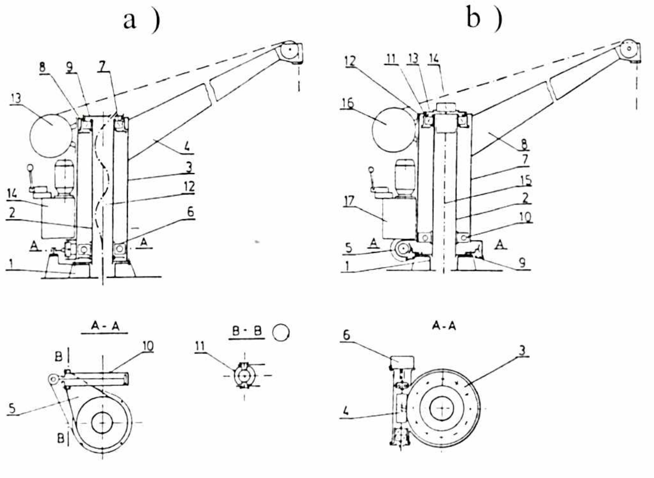

Fig. 4. Pivot davit schemes: a) ZO 1,0/3,2-90° type, b) ZOS 1,0/3,2-360° type

Notation:
a) *1 - foundation, 2 - post, 3 - pivoting column, 4 - jib, 5 - column arm, 6 - transverse bearing, 7 - angular bearing, 8 - angular bearing casing, 9 - cover with cable packing, 10 - hydraulic cylinder, 11 - hydraulic cylinder clamping ring, 12 - electric cable, 13 - line hoisting winch, 14 - hydraulic supply unit*
b) *1 - foundation, 2 - post, 3 - wormwheel, 4 - worm, 5 - gear casing, 6 - hydraulic motor, 7 - pivoting column, 8 - jib, 9 - bottom cover, 10 - transverse bearing, 11 - angular bearing, 12 - bearing casing, 13 - upper cover, 14 - cable rotary joint, 15 - electric cable, 16 - line hoisting gear, 17 - hydraulic supply unit*

The mechanism with the hydraulic cylinder does not require any toothed gear and therefore is very simple. The hinge, which fastens the cylinder rode eye to the foundation and the cylinder to the pivoting column arms, makes this kinematic system rather insensitive to workmanship and assembling accuracy and to some structural elastic deformations due to work condition variations. This improves reliability of the mechanism and simplifies its operation and maintenance.

However apart from the advantages the mechanism has an important drawback. This is its pivoting ability limited practically to 100° , and 110°at most, which makes the davit fitted with the mechanism not well suited for more universal applications. Some producers elaborated designs with the pivot angle up to 140°, but at the expense of a much more complicated construction. A design of SEZAMOR Works, Słupsk, Poland, in which a single rack reduction gear was applied additionally to make increasing pivot angle of a davit up to 200° possible, may serve as an example of that trend.

The second drawback of such mechanism, although less burdensome, is an angular change of the hydraulic cylinder position in respect to the pivoting column during davit rotation that makes elastic piping necessary. Motion trajectory of the hydraulic cylinder and change of its length should be carefully analyzed during design of the mechanism, because, in result of the motion, an instantaneous arm of the force, generated by the hydraulic cylinder, varies in respect to the davit rotation axis. This is illustrated in Fig. 5.

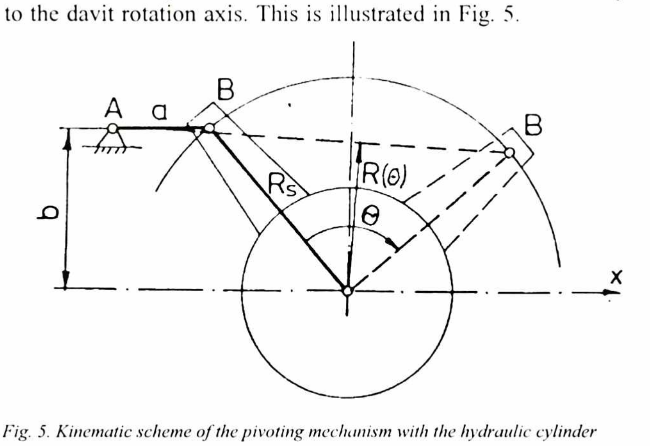

Fig. 5. Kinematic scheme of the pivoting mechanism with the hydraulic cylinder

A course of these changes can be controlled to some extent by selecting appropriate stroke of the cylinder, its location and mutual distance of its fixing points as well as their position in respect to davit axis. In this way, characteristics of the required pivoting moment and of that developed by the drive can be better matched, and thus, the stored energy better utilized .

A position of the hydraulic cylinder should be chosen such as not to block passage nearby or even make it difficult. Moreover, the position should provide such a direction of the force generated in the cylinder as to cause maximum mechanism loads, especially those in bearings, not rising, but dropping. In the davit version shown in Fig. 4. the hydraulic cylinder displaces in the unusable space between the davit and the boat bed. The maximum force, transmitted from the hydraulic cylinder to the pivoting column during outboard rotation of the davit, is almost parallel to x-y plane and directed against the force which is exerted on the lower bearing, and therefore it partly unloads the bearing .

The pivoting mechanism with a rotary motor requires a reduction gear to be applied. Selection of a gear type and its reduction ratio is the crucial problem and depends on many factors and conditions; the most important of them are the following:

- a way in which davit angular position is blocked in the case of drive pressure loss
- limitations imposed on davit dimensions and position
- costs

Nominal speeds of rotation of hydraulic motors,even those of low-speed, are over a hundred times greater than these of davits. The mechanism designer has to decide whether to use a smaller, but high-speed motor and to increase reduction ratio, or a bigger one of low-speed, but usually more expensive, with a smaller reduction gear. Choice of a more advantageous solution is not always easy and unique. It should be based on an analysis of the remaining above mentioned factors, especially of the way of position blocking. There are several possible ways of that, which consist in application of one of the following alternatives in the mechanism:

- a self-locking wheeled gear
- a friction brake with a hydraulic release
- a pawl mechanism with a hydraulic release
- a motor hydraulic cut-off by the valves controlled aproppriately, or by a directional control valve

The first of the ways, which is characterized by the lowest efficiency, is the most popular therefore it can be found in many design versions. Differences among them consist mainly in the number and value of reduction steps, type of toothing, position of the gear and of its elements.

The davit shown in Fig. 4b has a pivoting mechanism with the one-step, self-locking, high reduction ratio worm gear. The wormwheel is rigidly connected with the fixed post and davit foundation, but the worm is supported in the pivoting column. Owing to this, the davit construction is very simple, but the drive motor must be of low-speed type, taking into account the limitation imposed by the reduction ratio of the one-step gear. A drawback of the solution is an unavoidable displacement of the worm axis in respect to the wormwheel which can occur in operation under different loads and cause lower gear meshing quality. In the discussed design a relatively large module pitch and a simple way of the mutual position regulation of the worm and wormwheel were chosen as a remedy.

Another popular design solution is a mechanism fitted with the two-step gear the first step of which is a self-locking worm gear, but the second one - a spur cylindrical gear. This system provides better working conditions of the worm gear because it is possible to close the gear in a single stiff casing which ensures that mutual position of the matched wheels is fixed regardless of the transmitted load, as well as because of somewhat lower loads and, in consequence, higher speeds of the matched teeth. The application of the spur cylindrical gear as the second gear step makes the system less prone to workmanship and assembling accuracy as well as to elastic structural deformations under variable loads. The advantages are at the expense of a higher complexity, cost and dimensions of the mechanism which may impair marketability of that davit type. Therefore, a not very high value of the total reduction ratio and the mechanism fitted with a low-speed drive motor is usually selected . Application of a high-speed motor requires either adding one reduction step more or using a two-step worm gear with one,self-locking step.

Pivoting mechanisms with the highly efficient gear and friction brake fitted with a hydraulic release are characterized by large gabarites and complicated design. Therefore such brakes are designed usually as multi-disk ones to limit their dimensions and placed between the drive motor and the gear.

A mechanism fitted with a hydraulically released pawl blocking are similar to the above described as far as its construction and features are concerned. A basic difference consists in that the pawl is placed behind the gear, instead of preceding it, or at its last step where wheel speeds are the lowest.

Mechanisms with the position blockage based on motor hydraulic cut-off require motors of high volumetric efficiency, e.g. multi-plunger ones, and additional, appropriately controlled valves or a directional control valve. The mechanisms are fitted, like the two types already described, with the highly efficient gears which are smaller and simpler due to lack of any brake or spawl.

All the discussed pivoting mechanisms , especially those driven by high-speed motors, require careful design analysis of their mass loading which can occur mainly when starting and stopping such a mechanism in heavy sea conditions.

DRIVING SYSTEMS AND THEIR WORKING PARAMETERS

The type of the motor applied in a given mechanism influences also hydraulic driving system structure as well as the type and size of the elements used in it.

In Fig. 6 block diagrams are presented of the hydraulic driving systems applied in the pivoting mechanisms of the davits shown earlier in Fig. 4. They are of similar structure but differ from each other by different means of maximum pivot angle limiting and position blocking, apart from the motors applied.

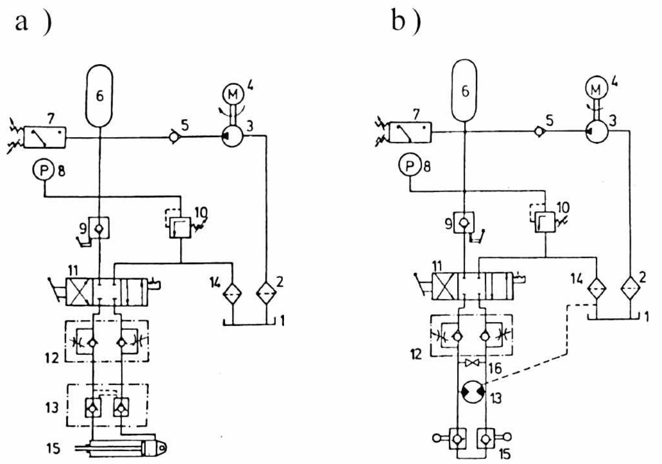

*Fig. 6. Block diagrams of the hydraulic driving systems of the davits: **a)** of ZO 1,0/3,2-90° type, **b)** of ZOS 1,0/3,2-360° type*

Notation:
1 - tank, 2 - suction filter, 3 - pump, 4 - electric motor, 5 - check valve, 6 - hydropneumatic accumulator, 7 - pressure switch, 8 - pressure gauge, 9 and 15b - pilot operated check valve, 10 - pressure relief valve, 11 - directional control valve, 12 - double throttle/check valve, 13a - double pilot operated check valve, 13b - hydraulic motor, 14 - return line filter, 15a - hydraulic cylinder, 16 - cut-off valve

In the driving system design with the hydraulic cylinder, davit's pivot angle is limited by cylinder stroke, but position blocking is ensured by a pilot operated double check valve which hydraulically cuts off cylinder supply pipes in the case of pressure loss in the system.

In the design with the rotary motor it is necessary to limit davit extreme pivot angles which is ensured in this case by applying two additional, roller-cam controlled check valves which serve as limit switches. If a roller of one of the valves tracks on a cam nose the valve opens and connects both motor supply pipes, thus causing pressure in them equal and the mechanism to be stopped. In the solution, position blocking is ensured by a self-locking worm gear. Therefore no pilot operated double check valve was needed. The cut off valve applied fulfills an auxiliary function. Usually it is closed. but opened only in emergency when the davit is to be pivoted by the use of a hand-crank installed in the worm shaft neck. Sub-assemblies used in that system, especially the accumulator, must be greater due to a low total efficiency of the mechanism. The total efficiency which comprises that of a hydraulic motor, worm gear and pivoting column bearings does not even reach the value of 0,4. Moreover, its value is substantially lower while starting the mechanism and can vary somewhat due to unfavourable working conditions of the gear under high loads and at low speeds, linked with various external influences.

The total efficiency of a mechanism with the hydraulic cylinder is more stable and of the value over twice higher than that given above, i.e. about 0,92.

This substantial difference of the total efficiency value of the two mechanisms highly influences the amount of energy required to rotate the davit outboard. That amount can be calculated from the following relationship:

$$E = \int_{\theta_1=0}^{\theta_2=90} p(\theta)V_g(\theta)\frac{1}{\eta_c(\theta)}d\theta \qquad (9)$$

where:

$p(\theta)$ - the required oil pressure at motor inlet
$V_g(\theta)$ - the absorbing capacity of the motor related to unit pivot angle of the davit

Amount of the accumulated energy can be controlled by changing oil volume in the accumulator, taking into account that working pressures in both systems should be similar to make unification of their elements possible. It means that the accumulator applied in the low efficient mechanism should be much greater, and that other elements of the system should be also greater, but to a lesser extent.

In Fig. 7 the curves are exemplified of the energy, the oil pressure and volume, the required and that available in the accumulator respectively, calculated for the two davits, loaded by a boat, during outboard rotation in similar working conditions and constant temperature.

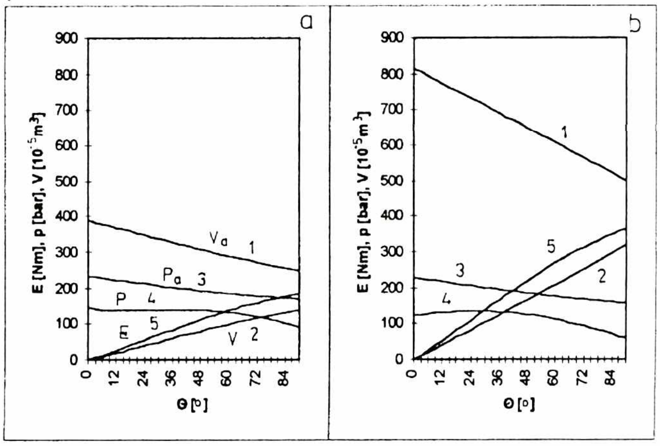

*Fig. 7. Curves of the required oil energy (E), pressure (p) and volume (V) and the available in the accumulator pressure (p_a) and volume (V_a) , in the same working conditions (see Fig. 3) and constant temperature, for: **a)** - ZO 1,0/3,2-90° davit, **b)** - ZOS 1,0/3,2-360° davit*

Selection of working parameters of a system and its elements should be preceded by a thorough analysis. Oil work pressure value, possibly high if size minimization is aimed at, is limited by the demand of a sufficient pressure margin (excess) in the accumulator, and thus, of a sufficient moment margin throughout the davit outboard rotation. It is not easy to determine this margin because account has to be taken of dynamic loads due to ship's motion in waves and unfavourable changes of working temperature, as well as of the influence of gas temperature and pressure while filling the accumulator. The course of the required pressures and volumes and the available ones in the accumulator during operation of ZO 1,0/3,2-90° davit in three characteristic temperatures and at three values of the accumulator filling pressure is presented in Fig. 8 to better illustrate the problem.

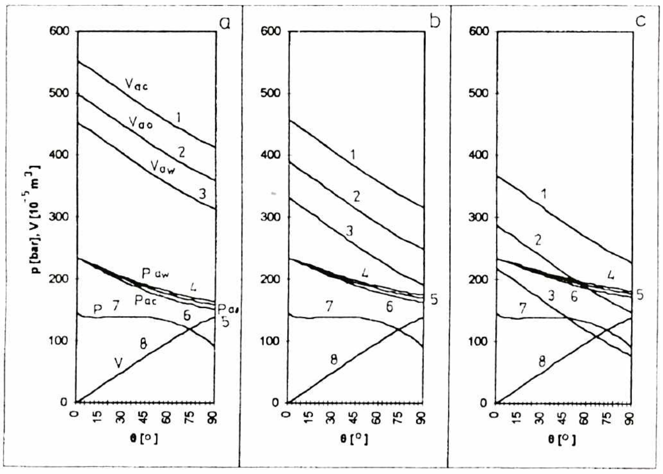

Fig. 8. Course of the required oil pressure (p) and volume (V), pressure (p_a) and volume (V_a) available in the accumulator of 10 litre capacity, in the same working conditions as given in Fig. 3 for ZO 1,0/3,2-90°davit, at three different values of gas filling pressure: ***a)*** *8 MPa,* ***b)*** *11 MPa,* ***c)*** *14 MPa and three work temperature values denoted on the diagrams as follows: (w) 65°C, (o) 20°C (accumulator filling), (c) -30°C*

It can be observed that the higher accumulator filling pressure the higher available pressure margin. This is achieved however at the expense of a lower margin of the available oil volume.

When selecting the accumulator size and its gas filling pressure the operational reliability assurance of the mechanism in different heavy sea conditions, stated in the rules generally, as well as cost of the mechanism, to some extent, must be first of all taken into account.

In the case of the presented design, it was justified necessary to provide 35% pressure margin , at least, due to not taking into account the dynamic loads from waves and gust impacts, as well as various additional static loads (e.g. due to icing).

Starting and stopping pressure in the pressure switch of the oil pump driving motor is the next important parameter. The pump stopping pressure should be chosen mainly on the basis of the permissible working pressure of the pump and other hydraulic system elements, but the starting pressure depends first of all on the stopping pressure and of the pressure switch type and its characteristics.

The course of pressure and volume parameters versus davit pivot angle for the following three values of the pump starting pressure: p_z = 20, 22 and 23,5 MPa is given in Fig. 9.

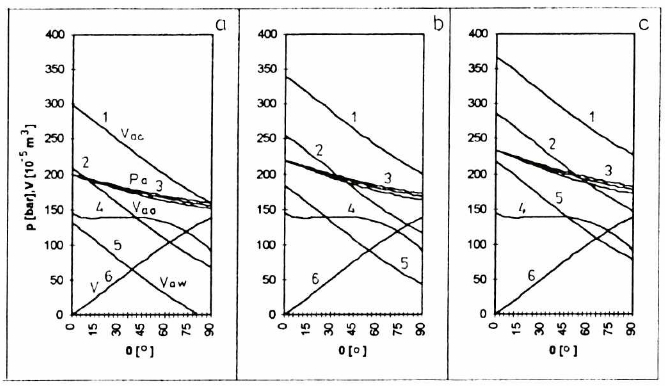

Fig. 9. Course of the pressure and volume parameters (the same as denoted in Fig. 8), for the same davit type and its working conditions, but at three different values of pump starting pressure: ***a)*** *20 MPa,* ***b)*** *22 MPa,* ***c)*** *23,5 MPa*

An important problem in designing of a mechanism with the hydraulic cylinder is to choose properly the geometrical parameters of its kinematic system. Influence of the distance b (see Fig. 5) on the mechanism performance is shown in Fig. 10. The parameter is decisive, to a large extent, for magnitude and form of changes of both:

- the distance R measured from the vector of the hydraulic cylinder rod force to the davit pivot axis, and
- the required oil working pressure

The presented analysis was elaborated with the use of the computer program prepared specially for this purpose. The software is very useful in the early design stage when proper values of different geometrical and working parameters of the mechanism designed have to be chosen and its hydraulic system elements selected.

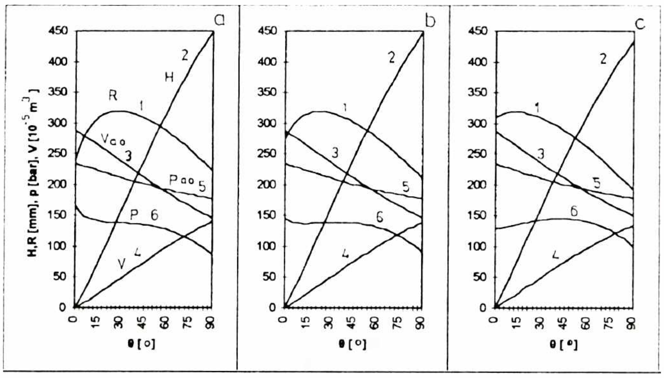

Fig. 10. Course of the pressure and volume parameters, the hydraulic cylinder stroke H and the distance R of hydraulic cylinder rod axis from davit pivot axis, in the same conditions as given in Fig. 8c, for the following three values of the parameter b (see Fig. 5): ***a)*** *240 mm,* ***b)*** *275 mm,* ***c)*** *310 mm.*

CONCLUDING REMARKS

Both pivoting mechanisms presented in this paper are widely used in new boat davits. Davits of the pivot angle θ >180° , fitted with the more expensive and less efficient mechanism with rotary motor, are, according to FAMA Works, Gniew, still in a higher demand. To improve the situation, in the end of 1994 a novel design of the boat-raft davit with the pivoting mechanism driven by two plunger cylinders through one-step rack gear was developed by Technical University of Gdańsk on the request of the FAMA Works. The new solution comprises the basic advantages of both earlier designs.

A prototype of the new davit, of 21 kN lifting capacity and 5 m reach, was installed on board a ship built in Northern Shipyard, Gdańsk, which entered into service in the end of September 1995.

BIBLIOGRAPHY

1. International Maritime Organization: „Amendments to the International Convention for the Safety of Life at Sea ". IMO, London, 1974
2. Polish Register of Shipping: „ Rules for the Convention Equipment of Sea-Going Ships ". PRS, Gdańsk, 1990

Appraised by Tadeusz Gerlach, Assoc.Prof.,D.Sc.