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## HYDROSTATIC DRIVE OF THE FERRY APPROACH BANK

**Summary.** The operating problems of the ferry approach ramp have been presented in the paper. The incorrect idea of approach bank drive system and abnormal operator acting, have been both the reasons of break-down and damage of a ferry terminal. The evaluation of the run of events and finding the reasons of the failure, have been possible thanks to the analysis of drives and control systems.

## NAPĘD HYDROSTATYCZNY RAMPY PODJAZDOWEJ PROMU

**Streszczenie.** W artykule przedstawiono problemy eksploatacyjne pomostu ruchomego stacji promowej I rampy promu. Nieprawidłowa koncepcja układów napędowych podjazdowego pomostu ruchomego i nieprawidłowe działania operatora stały się przyczyną awarii i uszkodzeń stacji promowej. Wykonana analiza układów napędowych i sterowniczych umożliwiła odtworzenie przebiegu awarii i ustalenie jej przyczyn.

### 1. INTRODUCTION

The expertise, discovering the reasons of the ferry terminal approach bank in Gdynia has been done by the Chair of Working Machines, Drives and Control in 2006. The main objective of the expertise was the investigation of damage sequence and discovering the reasons of damages.

As the results of series of investigations and works, the inappropriate ferry station operating and weather conditions on the incident day, have been described. The geometrical analysis of the approach bank and ferry ramp positions and estimation of the approach bank drive and control systems have been done.

It was necessary to make the analysis of forces during the approach bank hoisting and the analysis of hydraulic drive operation. The final results of investigation were synthetic description of the damage running, estimation of station elements damage reasons and estimation of personal responsibility level for damages. The necessary construction and safety operation changes have been recommended as well.

### 2. OPERATING AND DAMAGE OF THE FERRY TERMINAL

The view of the terminal and ferry is presented in the fig. 1. The ferry has two decks: upper and lower. After mooring, the ferry lowers two ramps for cars' entrance. Cars can drive directly from the roadway on the lower ferry deck. For the boarding of the upper deck, the ramp ended with movable stage has been built. The stage is to be lowered on the upper ferry deck ramp.

After loading the ferry, the approach bank of the terminal is hoisted. It enables the hoisting of the upper ferry ramp and ferry can be unmoored and can steam away. There is a requirement in the technical and operational documentation that the upper deck ferry ramp can be hoisted only when the hoisting of the terminal approach bank has finally been ended.

In the fig. 1, which is one of the frames from the film presenting the terminal operation, it can be seen that the requirement mentioned above is not respected by the ferry operators. To reduce the time they started to hoist the upper ferry ramp before finishing the movement of the approach bank of the terminal. At the beginning of expertise works it has been assumed as the main reason of the damage. This assumption was done because during the incident, earlier hoisting of the ferry ramp hooked up the not finally hoisted approach bank.



Fig. 1. Dangerous close proximity of the ferry ramp with the approach bank  
Rys. 1. Niebezpieczne zbliżenie ramy promu do pomostu

On the basis of the operational film analysis it has been discovered that always in practice the hoisting of ferry ramp had begun before the ending of approach bank hoisting. It can be observed that the beginning of the ferry ramp hoisting took place when the position of the hoisted approach bank was about 40 – 56% comparing to its final destination. Usually it did not cause any failures however on the day of the accident when the ferry ramp came into collision with the being hoisted approach bank.

The accident resulted in damages of some construction elements and sliding surface of the hydraulic cylinders. For example fig. 2 and fig. 3 shows damages of the approach bank edge and lock support. It means that when being hoisted, the approach bank has been deformed (turned) in this way that the collision of the support placed on a fixed steel construction with the stay of the right hydraulic cylinder took place.

The initial analysis of damages led to the conclusion that the collision of the approach bank with the upper deck ferry ramp could not be the only reason of damages. It became necessary to make the geometrical analysis, which could determine the locations of the approach bank and the ferry ramp in critical positions.

The analysis was preceded by the determination of the weather conditions in the port, on the incident day. Particularly essential were data specifying port water level and ferry draught. After this, the essential geometrical collision positions: of the lock and hydraulic cylinder supports, approach

bank and ferry ramp, have been determined. The geometrical limitation of the hydraulic cylinder displacement in the plane of its axis limited by the axial play has been determined as well. It was done because the damages of the hydraulic cylinders piston rods' sliding surfaces showed that the cylinders had not been fixed correctly and had been bended during approach bank hoisting in the day of the incident.



Fig. 2. Damages of the approach bank strip and flap  
Rys. 2. Uszkodzenia listwy pomostu i kłapy obrotowej (flapa)



Fig. 3. Damages of the lock and cylinder support  
Rys. 3. Uszkodzenia podpór rygla i siłownika

### 3. THE ANALYSIS OF THE DRIVING SYSTEM

The essential part of the approach bank hydraulic drive scheme is shown in fig. 4.

Two hydraulic cylinders used for approach bank hoisting and lowering are individually supplied from the constant pressure hydraulic line, this supplied by two hydrostatic variable displacement pumps co-operated with constant pressure regulators.

Hydraulic cylinders are individually controlled by proportional directional valves, which keep constant pressure drop in the directional valves. Hydraulic cylinders are equipped with individual inductive displacement sensors for the synchronisation of their movement. The follow-up system has been used, where left cylinder piston rod keeps up with the right reaction to the deviation of the piston rods  $\Delta x_s = 10$  mm.

The incremental step of displacement sensors applied in the system, type BTL5, is  $\delta_x = 5$  mm. It means that the regulation system, in the range of displacement deviation, receives practically only one signal to compare the right and left side of approach bank positions. Usually the accuracy of sensors in regulation and measurement systems should be at least 6 or at best 10 times higher than the regulated or measured value.

The lack of pressure pump regulators at the high supply pressure (20 MPa) causes very low drive system energetic efficiency and brings up unnecessary losses of energy.

In fig. 5 schemes of both, used and correct conception of the approach bank driving systems are shown.

Applied solution conception of hydrostatic drive approach bank shown in fig. 5a has been recognised as incorrect for reasons as follows:

- forces  $S_1$  and  $S_p$  of hydraulic cylinders can be different in values resulting from the deviation of displacement and position sensors accuracy. Practically the approach stage will always be turned during the hoisting and lowering until the loosening of cylinder chambers after putting down of the approach bank on the ferry ramp,
- operation of ferry station requires very special operator's attention because the failure of regulation system can lead to serious damages of approach bank and hydraulic cylinders,
- individual supply of hydraulic cylinders with position regulation demands complicated control and regulation systems with many valves and sensors putting down to climatic stress and

pollution which causes decrease of operational reliability. The unnecessary problems had been involved which have to be solved in the next step by means of expensing elements and complicated system.

This kind of driving system can be use when the values of external forces acting on hydraulic cylinders are different and when there is no mechanical coupling or when the mechanical coupling is slightly rigid and the synchronisation of pistons' moving rods is demanded.

In case of sufficient torsional rigidity of the approach bank and of a small difference of external forces' values the conception shown in fig. 5b should be taken into the project of drive system hoisting.

This system is much simpler, cheaper and has bigger operational reliability and safety. The autonomous synchronisation of piston moving rods and loss of pressure after putting down the chamber bank on ferry ramp takes place in a simple way.

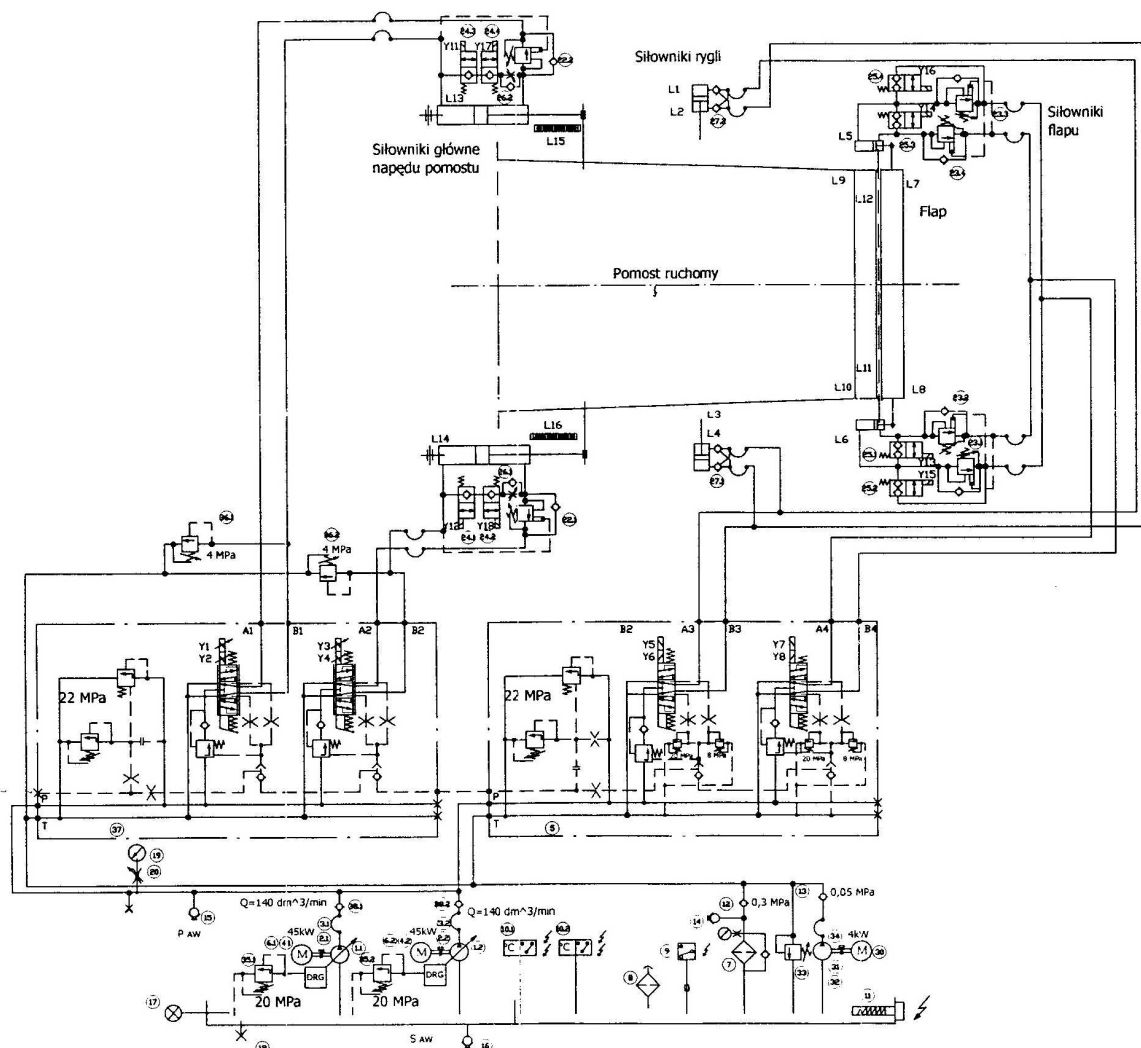


Fig. 4. Hydraulic scheme of the approach bank driving system

Rys. 4. Schemat układu napędowego pomostu

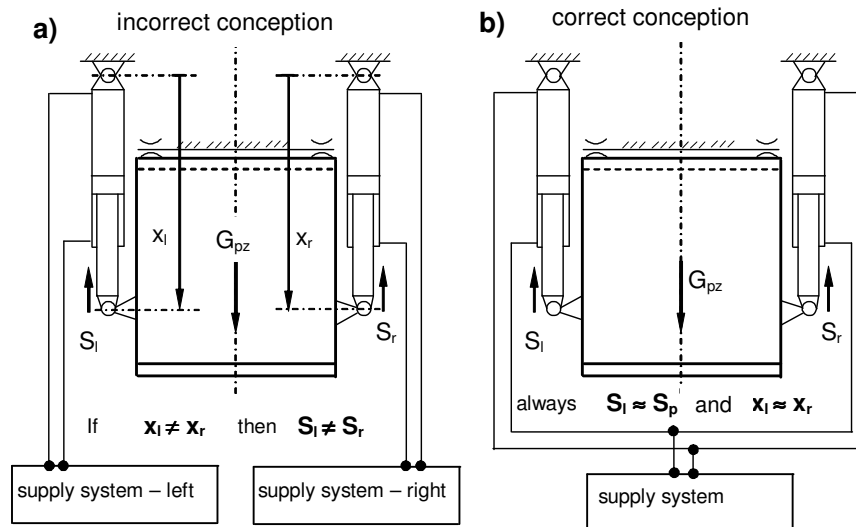


Fig. 5. Scheme of incorrect a) and correct b) conceptions of building approach bank driving system  
 Rys. 5. Schematy niewłaściwej a) i poprawnej b) koncepcji dla budowy układu napędowego pomostu stacji

After the moment  $t_{26}$  the hoisting of the approach bank has been continued next to the correct hoisting of both sides of the approach bank without bevelling, it means that the automatic control of displacement was active.

The diagrams of hydraulic cylinders' forces during the hoisting of the approach bank have been done by means of deformation analysis. For example, the system of forces acting on the approach bank at the moment when the right cylinder support collides with the lock support is shown in fig. 7.

#### 4. ANALYSIS OF APPROACH BANK DEFORMATION AND FORCES

The operational film recorded by industrial camera has been used for identification of incident running and for calculation of forces which turned the approach bank. The camera records cars driving onto the ferry and it has recorded the hoisting of approach bank after the ferry was loaded. Comparing appropriate film frames the running of approach bank hoisting has been reconstructed. The displacements of left and right approach bank edges during the hoisting have been particularly identified and the deformation of the stage has been calculated.

In the fig. 6 diagrams of left side -  $\varphi_l$  and right side -  $\varphi_p$  turn angles of the approach bank edge and bevel angle -  $\theta_k$ , of the its ending edge are presented. The collision position angle of the approach bank right side calculated on the basis of geometrical analysis is shown in this figure as well.

The hoisting of the approach bank has started only with the right side of the bank and next the movement has been stopped for about 11 second. Probably the automatic control system was not active and the operator switched to manual control. At this kind of control the left and right sides were non-uniformly hoisted and the bevel angle of the approach bank ending edge reached its maximal value in the moment  $t_7$ .

This process proceeded for about 48 s. Next, during about 154 s, some changes of the approach bank ending edge bevel angle can be observed till the moment  $t_{22}$  and in the moment  $t_{16}$  this angle had reached the maximal value. Nearly after this moment the collision of the right cylinder support with lock support had taken place and the approach bank movement was stopped for about 1,5 minute till the moment  $t_{22}$ . After the moment  $t_{22}$  during about 18 s the levelling of the approach bank left and right side positions took place by means of left side lowering at the stopped movement of the right side.

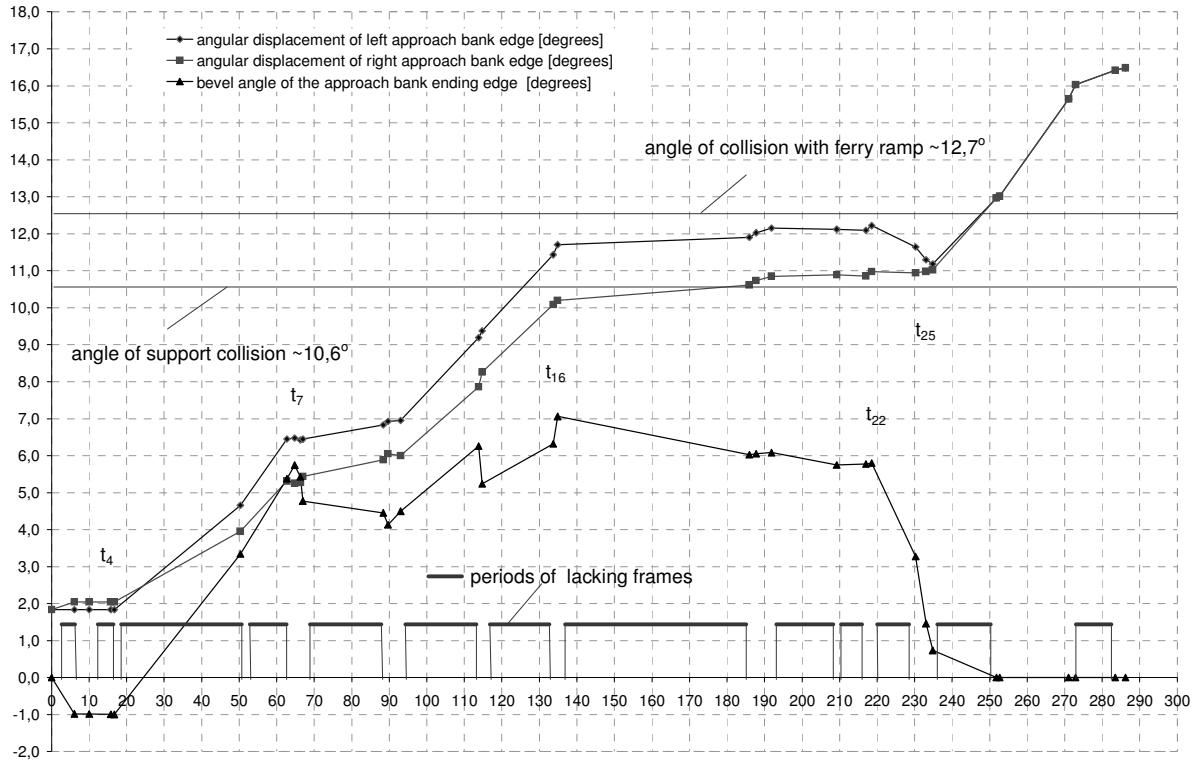


Fig. 6. The diagrams of the approach bank left and right side turn angles and bevel angle of the approach bank ending edge

Rys. 6. Przebiegi kątów obrotu podnoszenia lewej i prawej strony pomostu oraz kąta zukosowania jego krawędzi końcowej

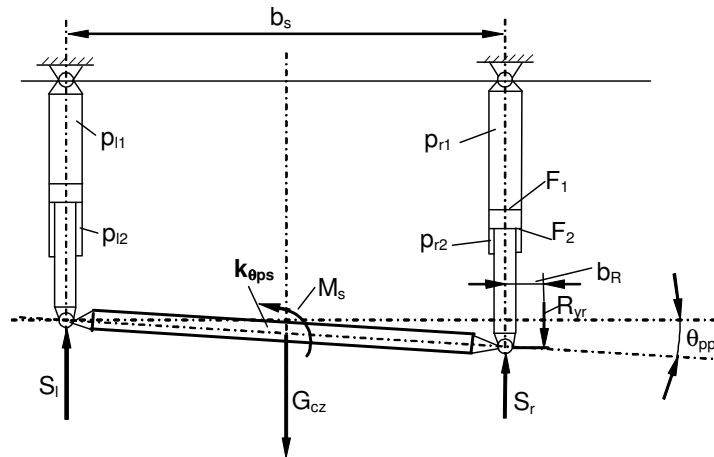


Fig. 7. Forces acting on the approach bank in the moment of supports collision

Rys. 7. Siły działające na pomost w czasie kolizji podpór

Forces  $S_l$  of left and  $S_r$  of right cylinder are determined by the equations as follow:

$$S_l = \frac{G_{cz} \cdot 0,5b_s \cdot \cos[0,5 \cdot (\varphi_{pl} + \varphi_{pp})] - R_{yr} \cdot (0,5b_s + b_r) + k_{\theta ps} \cdot \theta_{pp}}{b_s} \quad (1)$$

$$S_r = G_{cz} \cdot \cos[0,5 \cdot (\varphi_{pl} + \varphi_{pp})] - R_{yr} - S_l \quad (2)$$

where:  $G_{cz}$  – force of gravity reduced to the plane of cylinders acting,  $b_R$  – distance between the support reaction force and the cylinder axis,  $R_{yr}$  – support reaction force calculated on the basis of the metal plate plastic strain deformation,  $\varphi_{pl}$ ,  $\varphi_{pp}$  – position angles of approach bank left and right sides,  $\theta_p$  – bevel angle of approach bank in the cylinder plane,  $b_s$  – cylinders distance,  $k_{\theta ps}$  – torsion rigidity of the approach bank in the cylinder plane.

The diagrams of forces acted on the approach bank by hydraulic cylinders are presented in fig. 8.

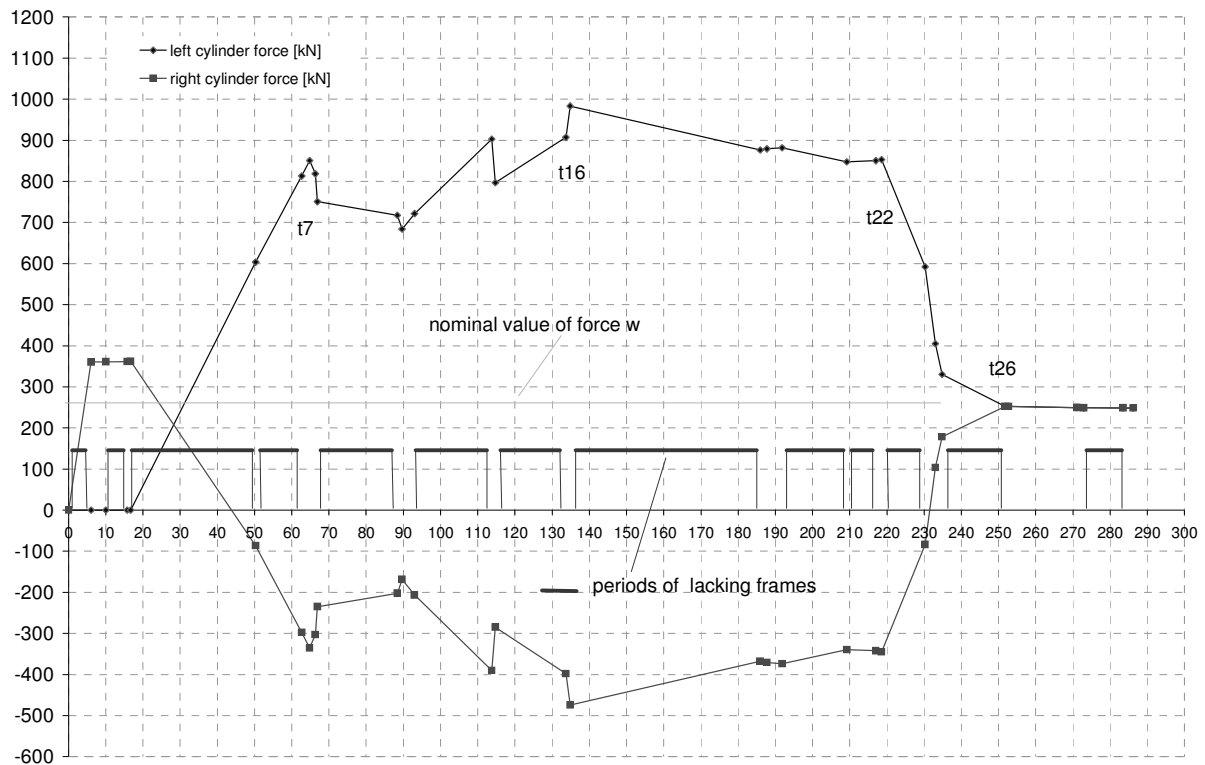


Fig. 8. The diagrams of hydraulic cylinders forces  
Rys. 8. Przebiegi sił siłowników hydraulicznych

Big differences between forces in the left and right cylinders as a result of their non-uniform movement causing approach bank steel construction torsion are seen in this figure. About the moment  $t_{16}$  the left cylinder force reached the value close to maximal as a result of supply line pump pressure.

In the long period of hoisting, the force of the right cylinder takes opposite sense in comparison with the sense of the left cylinder force. It shows the approach bank had being turned by the drive system. Forces in cylinders equalize at the ending of the analysed period taking nominal values.

## 5. ANALYSIS OF HYDRAULIC SYSTEM OPERATION

The analysis of deformation and forces discovering that the force of the right cylinder in the first period of hoisting had opposite sense in comparison with the sense of the left cylinder force shows that after short time of hoisting the directional valve of the left cylinder has been directed to hoisting and the directional valve of the right cylinder has had the neutral position or has not been sufficiently directed to hoisting. Determined values of cylinder forces has enabled the creation of pressure diagrams in the cylinder chambers and hydraulic lines.

The computational scheme shown in fig. 9 was taken into the analysis of hydraulic system operation.

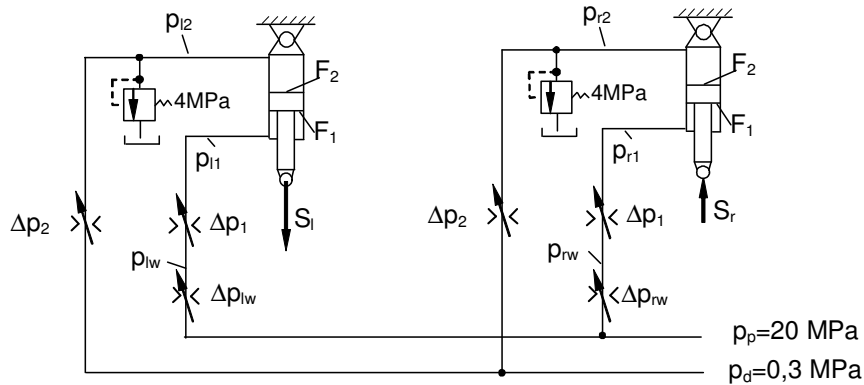


Fig. 9. Computational scheme of hydraulic system  
Rys. 9. Obliczeniowy schemat hydrauliczny układu

It was assumed for calculation that the pressure in the line of the pump – directional valve is  $p_p = 20$  MPa and the pressure in the opposite line  $p_d = 0,3$  MPa. It was assumed as well that the directional valve opens the same gap for pump – cylinder line as for the cylinder – tank line, hence:

$$\Delta p_1 \cdot F_2^2 = \Delta p_2 \cdot F_1^2 \quad (3)$$

where:  $\Delta p_1 \approx 1,0$  MPa – pressure drop in directional valve with the flow from the pump to the cylinder, controlled by hydraulic balance,  $\Delta p_2 \approx 1,778$  MPa - pressure drop in directional valve at the flow from the cylinder into the tank,  $F_1, F_2$  – active hydraulic cylinder areas in the chambers of piston rod and of the piston.

Limitations of calculation are pressure in the line of cylinder piston chamber – directional valve  $p_{l(p)2} \leq 4$  MPa and negative pressure in piston rod chamber in case of suction of oil  $p_{l(p)1} = -0,1$  MPa. The pressure lost in other elements have not been taken into account.

The pressures in cylinder chambers in case of left cylinder hoisting work have been calculated as follows:

$$p_{l2} = p_{ld} + \Delta p_{l2} \leq 4 \text{ MPa} \quad (4)$$

$$p_{l1} = \frac{S_l}{F_1} + (p_d + \Delta p_{l2}) \cdot \frac{F_2}{F_1} \quad (5)$$

The pressures at the directional valve inlet and pressure drop in the hydraulic balance have been calculated as follows:

$$p_{lw} = p_{l1} + \Delta p_{l1} \quad (6)$$

$$\Delta p_{lw} = p_p - p_{lw} \quad (7)$$

These hydraulic losses have had basic influence on the energy losses and it is the result of incorrect conception of the drive system. There are similar dependences for hoisting work of the right cylinder.

In the case which took place during the incident when the right cylinder had developed the negative direction force giving additional resistance for the left cylinder working then for hoisting, the value of the pressure in left and right cylinders' chambers can be calculated as follows:

$$p_{r2} = -\frac{S_p}{F_2} + p_{r1} \cdot \frac{F_1}{F_2} \leq 4 \text{ MPa} \quad (8)$$



$$p_{r1} = -0,1\text{MPa} \quad (9)$$

Similar dependencies are obligatory for the left cylinder, in case of its activity with the opposite force in comparison to the force of hoisting.

In the figures 10 and 11 appropriate diagrams of pressures in the cylinders chambers for work period of the ferry station are presented:

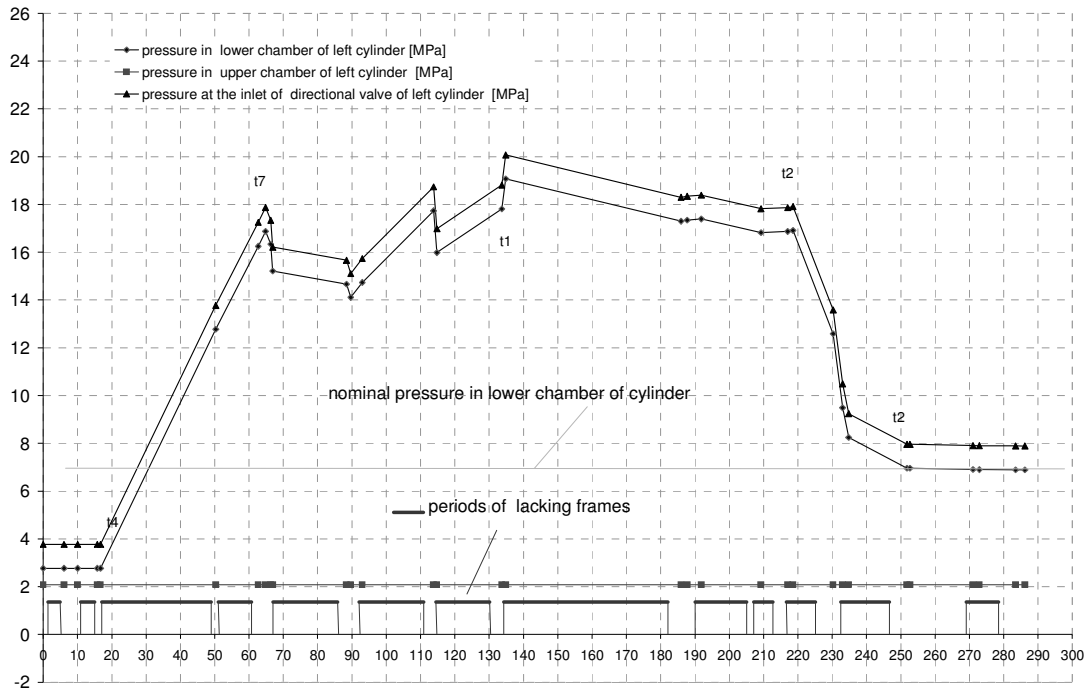


Fig. 10. The diagrams of pressures in chambers of the left cylinder  
 Rys. 10. Przebiegi ciśnień w komorach lewego siłownika

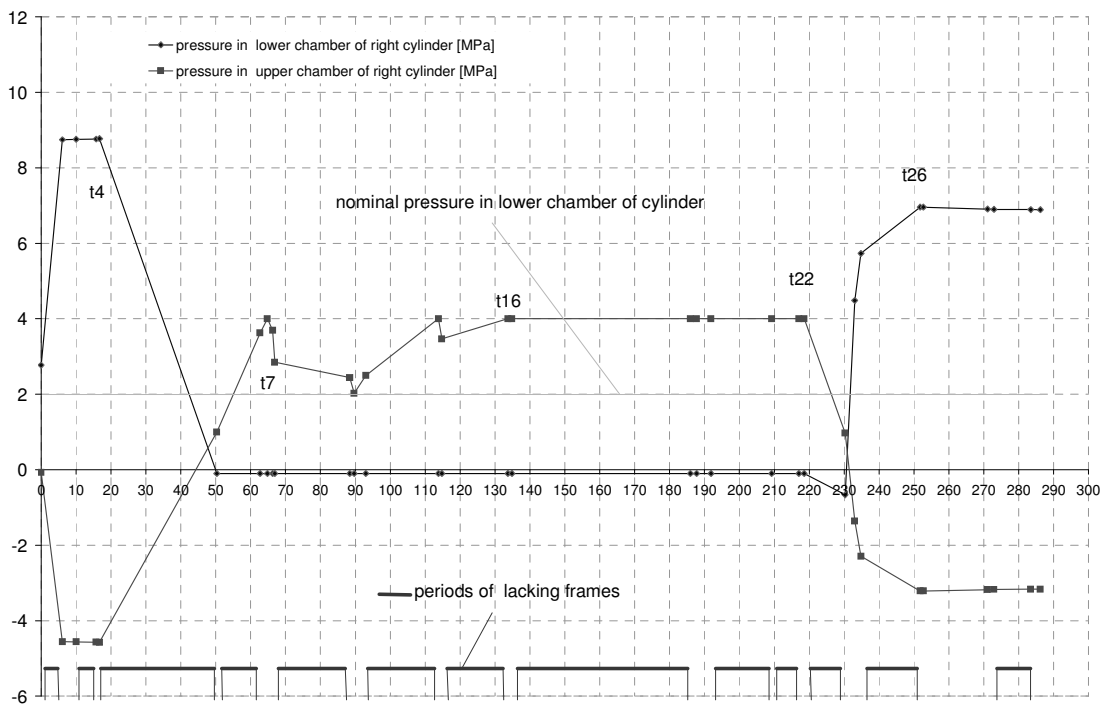


Fig. 11. Diagrams of pressures in chambers of right cylinder  
 Rys. 11. Przebiegi ciśnień w komorach prawego siłownika

The diagram of pressure presented in fig. 10 shows that its value is considerably higher than the nominal value which take place at the correct activity of automation control system. It is the result of approach bank bevelling by means of hydraulic cylinders. The pressure at the inlet of directional valve of the left cylinder obtains more than two times higher value in comparison with nominal value in about of the moment  $t_{16}$ .

Diagrams of pressures show very low energetic efficiency of the system which is seen in the ending phase of analysed period of the movement when the system was normally working as well. The pressure drop obtains the value 12 MPa. The efficiency of the system excluding the pressure drop in hydraulic lines and volumetric loses in the case of the correct work of the system, can be approximately calculated as follow:

$$\eta = \frac{p_{s1} \cdot Q_s}{p_{lp} \cdot Q_p} = \frac{G_{cz} \cdot Q_s}{2 \cdot F_1 \cdot Q_p} \approx \frac{G_{cz}}{2 \cdot F_1 \cdot p_{lp}} = \frac{0,518326}{2 \cdot 0,6032 \cdot 20} = 0,21 \quad (10)$$

where:  $G_{cz}$  [MN] – gravity force reduced onto the cylinder axis,  $F_1$  [m<sup>2</sup>] – active area in the chamber of piston rod,  $p_{lp}$  [MPa] – pressure in the pump line,  $Q_s \approx Q_p$  [m<sup>3</sup>/s] – intensity of charge into the cylinders approximately equal the capacity of the pump.

The result of calculation covering only loses being the results of the conception of the system shows that 80% of power is lost and converted to heat during the ordinary undisturbed hoisting of the approach bank.

## 6. SUMMARY

Analysis which was carried out and calculations show that after the start during about 6 s only, the right side of the approach bank was being hoisted with the stopped left side. At that time the piston rod of the right cylinder realised the displacement about 33 mm and the automation control system did not set in motion the left cylinder piston rod and there was not the equalisation of the approach bank sides. Probably the operator noticed the signalised error of the approach stage sides displacement and had stopped the movement. During the time of about 11s the operator had made the decision for the next activity and at the end he had switched to the manual control mode.

After this break the hoisting of the approach bank in manual mode had been continued. The left side of the bank had been hoisted faster than the right one and during the first 5 s previous bevelling of the approach bank has been stopped but the continuation of this kind of movement without cylinders speed balance, caused the bevelling of the bank in the opposite direction. This bevelling had caused the hydraulic cylinders bending and it had happened because there was no sufficient side shakes on supports.

The approach bank had been bevelled in this way that the support of the right cylinder hooked up with the right support of the lock. The collision of supports had to be noticed by the operator and the move of the approach bank had been stopped for about 80 s. That time has been probably used to recognize the situation and for taking decisions concerning next procedures.

The decision about balancing of the approach bank had been taken and the operator started the approach bank left side lowering with the stopped right side. This process had been taken about 30 s and the positions of bank sides were balanced. After balancing the bank sides positions the hoisting of the approach bank had been restarted probably with active automatic control system. It had been found because both sides of the approach bank had being hoisted with the same speed without bevelling.

During the restarted hoisting of the approach bank the collision with too early hoisted ferry ramp had taken place. This collision did not disturb the hoisting process which had not been stopped.

The general responsibility for the existent damage carries the person, or the institution, which have accepted using the incorrect conception of the approach bank drives and control construction. Using this kind of solution for hoisting of the approach bank was taken as contradictory in engineering art.

The responsibility for cylinder damages was the responsibility of the operator and constructor of cylinders' supports who unnecessarily limited the range of their joined support. The responsibility for damages of cylinder and lock support was the operator who did not behaved rightly with attention and care during the manual controlling of the approach bank hoisting. The responsibility for the approach bank support's strip damages takes the ferry ramp operator who has started the ferry ramp hoisting too early, ignoring the technical and operational instructions of the ferry terminal documentation.

It was temporarily recommended to lower the limit of supply pressure in the pumps line and the usage of more extensive signalling concerning incorrect position of cylinders piston rods during manual control. The suggestion of drive and control system change to the system which has been presented in fig. 11b has been recommended into recognition as well. It guarantees higher simplicity and reliability and immunity of driving system against operators' mistakes.

It was also recommended to use the close proximity sensors on the ferry ramp in case of the ferry ramp hoisting before ending the approach bank hoisting (which reduces the time of ferry loading of about 1 minute).

## Literature

1. Cink J., Tomczyk J., Wolski T.: *Hydrostatyczne układy napędowe maszyn roboczych*. WPL, Łódź 1993.
2. Kaczorek T.: *Teoria sterowania*. PWN, Warszawa 1981.
3. Stryczek S.: *Napęd hydrostatyczny*. WNT, Warszawa 1984.
4. Tomczyk J., Cink J., Kosucki A.: *Metody rozwiązywania problemów automatyzacji sterowania dźwignicami*. Przegląd Mechaniczny, nr 1, 2003, s. 9-16.
5. Tomczyk J.: *Modele dynamiczne elementów i układów napędów hydrostatycznych*. WNT, Warszawa 1999.

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