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Pressure pulsations in power hydraulics systems

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Abstract:

The paper discusses the problem of pressure pulsation in hydraulic systems. The most important causes of pressure disturbances were discussed, such as: instability of the pump performance, variability of the system load and transient states related to the control of the system. The next part presents the threats caused by pressure fluctuations. On the one hand, the effects of the occurrence of a water hammer are presented, as a temporary exceeding of the maximum operating pressure of the system. On the other hand, the problem of fatigue strength of the system was presented, which was illustrated on the example of tests and calculations of hydraulic cylinders and hydraulic hoses. In the last part, the author indicated further directions of literature, simulation and experimental research.

Streszczenie:

W pracy został omówiony problem występowania pulsacji ciśnienia w układach hydraulicznych. Poruszono najważniejsze przyczyny powstawania zaburzeń ciśnienia takie jak: niestabilność wydajności pompy, zmienność obciążenia układu oraz stany przejściowe związane z sterowaniem układem. W kolejnej części przedstawiono zagrożenia wywoływane przez fluktuacje ciśnienia. Z jednej strony zostały przedstawione skutki wystąpienia uderzenia hydraulicznego, jako doraźne przekroczenie maksymalnego ciśnienia roboczego układu. Z drugiej strony przytoczono problem wytrzymałości zmęczeniowej układu, który został zobrazowany na przykładzie badań i obliczeń siłowników hydraulicznych oraz węży hydraulicznych. W ostatniej części autor wskazał dalsze kierunki badań literaturowych, symulacyjnych i eksperymentalnych.

1. Introduction

The first hydraulic installations and devices were used to meliorate of farmland and provide drinking water to cities. Besides to using canals, pipelines and aqueducts to transport water from sources above the point of need, the ancients developed a series of water pumps that allowed water to be transported from lower levels to places above. In addition to simple structures for lifting water, e.g. the Archimedes screw, around 270 BCE a much more advanced piston pump design was developed by the Ctesibius of Alexandria (Fig. 1) [1].

A big leap towards modern power hydraulics took place in the period from the mid-17th century to the end of the 18th century. It began with the formulation of Pascal's law in 1648. The first hydraulic cylinder was patented by Joseph Bramah in 1795 [2]. Further development of power hydraulics was related to the use of hydraulic oils as working fluids, and the use of new structures and materials in hydraulic systems [3].

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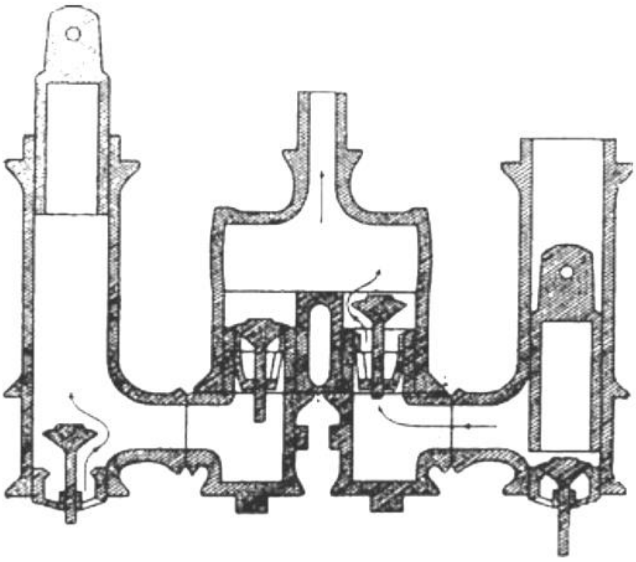

Fig. 1. Reconstruction of force pumps found at Bolsena, Italy [4]

Thanks to all these modifications, today's hydraulic systems generate tons of times greater forces from a unit of volume than electric or pneumatic systems. Unfortunately, such technological advancement has led to the occurrence of such phenomena as cavitation, water hammer and pressure pulsation in these systems. These lead to faster wear and failure of hydraulic systems. Mentioned harmful phenomena will be discussed in the following chapters.

2. Sources of pressure fluctuations

There are several terms in the literature relating to the types of non-stationary pressure. The most frequently used, and at the same time those that should be indisputably distinguished are: pulsating pressure and oscillating pressure. Pulsating pressure is a state in which the fluid pressure is the sum of two components (equation 1): the average pressure and the variable component of the pressure. Oscillating pressure is a special case of pulsating flow in which the average pressure of the medium is equal to zero [5].

$$P_{tot} = P_{avg} + P_f \tag{1}$$

where:

P_{tot} – Total pressure, Pa,
P_{avg} – Average pressure, Pa,
P_f – Variable component of the pressure, Pa.

An example of the transient pressure changes shown below (Fig. 2):

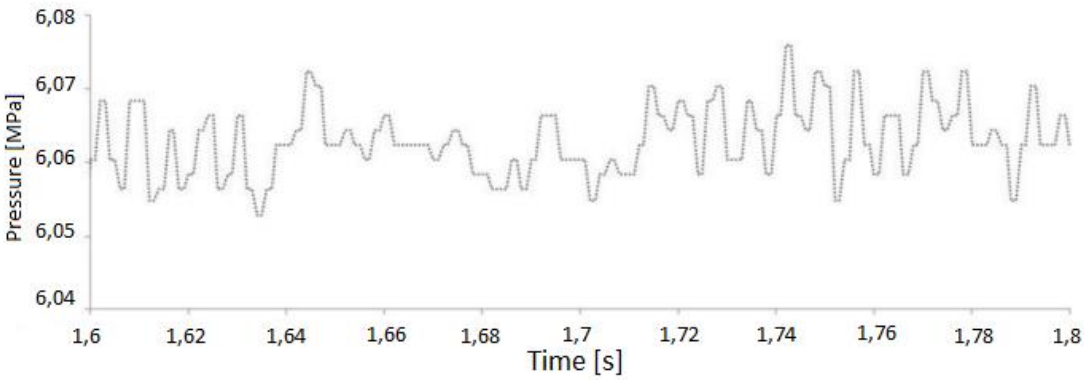

Fig. 2. Experimental pressure measurement results [6]

Fluid pressure fluctuations can have several causes, the most important of which are:

- periodic operation of hydraulic system components such as pumps and control valves,
- variability of the load on the executive elements of the hydraulic system, such as the hydraulic cylinder and hydraulic motors,
- unsteady states from shifting, starting and breaking the system,
- moving of the frame to which the system is attached,
- turbulent flow of the medium.

The following parts of the article discuss pressure changes caused by: uneven performance of the pumping device, variation of the system load and changes in the operating state.

2.1. Instabilities arising from pump operation

Unevenness of the displacement pumps operation results from the cyclic operation of a finite number of working elements. In the literature [7] to describe the temporary work variability of positive displacement pump, delivery fluctuation coefficient described by the equation (equation 2) is used.

$$\delta_p = \frac{Q_{max} - Q_{min}}{Q_{avg}} \tag{2}$$

where:

δ_p – delivery fluctuation coefficient,-,
Q_{max} – Maximum pump flow, m^3/s,
Q_{min} – Minimum pump flow, m^3/s,
Q_{avg} – Average pump flow, m^3/s.

The dependence of the delivery fluctuation coefficient on the number of working elements for selected types of pumps is presented in the diagram (Fig. 3).

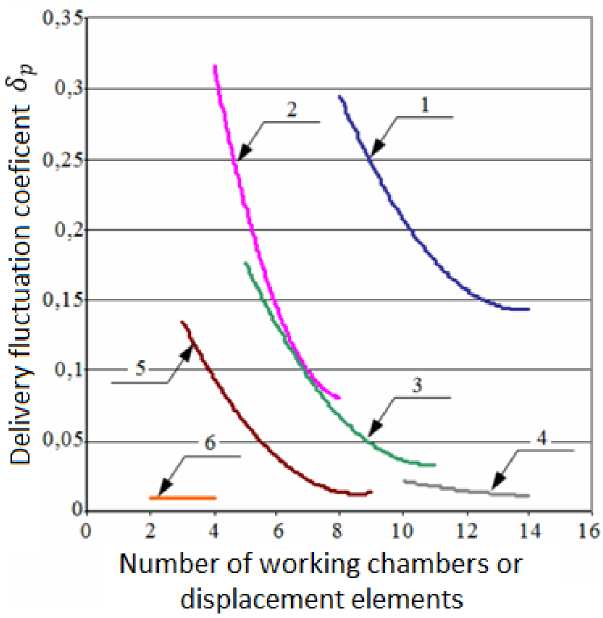

Fig. 3. Comparing the delivery fluctuation coefficient of positive displacement pumps: 1 - external gear, 2 - piston with an even number of pistons, 3 - single action vane, 4 - internal gear, 5 - piston with an odd number of pistons, 6 - screw [8]

On the basis of the graphs it can be seen that the coefficient takes the highest values for pumps with a small number of working elements. An exemplary pump, outside the range presented in the chart, of the Duplex type, working at 70 rpm and a nominal flow of 0,0057 m^3/s (340 l/min), generates the actual flow in the range from 0,007 m^3/s (420 l/min) to 0,0042 m^3/s (250 l/min) [9], which gives the delivery fluctuation coefficient equal to 0,5.

2.2. Pressure fluctuations related to working load of the device

Another factor that can generate pressure pulsation in the hydraulic system is the change in working load. As an example, a screw-type cutting head can be cited (Fig. 4). Machine load variations can be caused by the following factors:

- periodicity plugging knives in mined material.
- uneven breakout of the brittle raw material
- stochastic course of the friction forces between the tool and the material being cut.

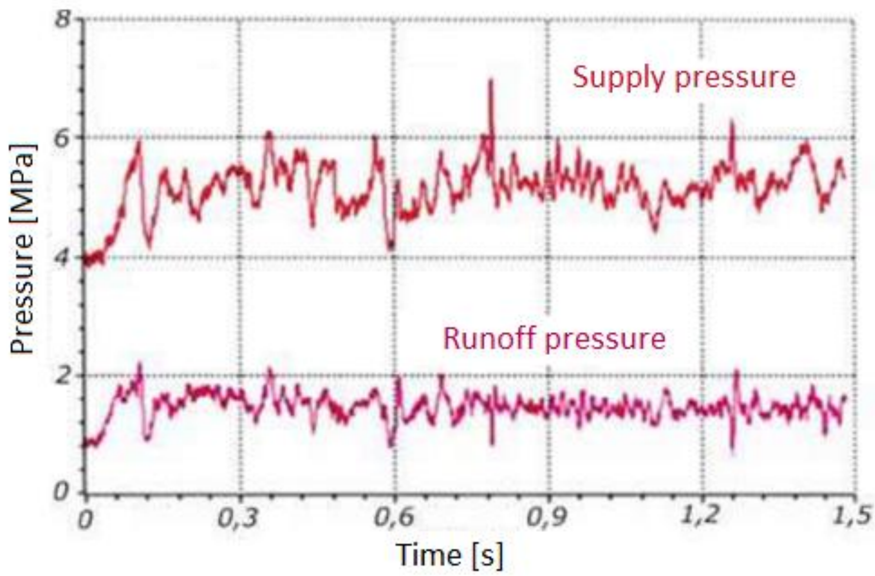

Fig. 4. Measurement signals during coal cutting [10]

2.3. Adjusting the hydraulic system as a source of pressure instability

Hydraulic fluid pressure changes in the system may also be caused by sudden system adjustment, e.g. starting / stopping the pump (Fig. 5), closing / opening the valve [11]. This phenomenon in the literature is called water hammer, and its prevention is the subject of many scientific studies. These changes are mainly caused by the inertia of the fluid in the operating system. These effects are more noticeable the longer the hydraulic line is, and the faster the changes to the system shifting.

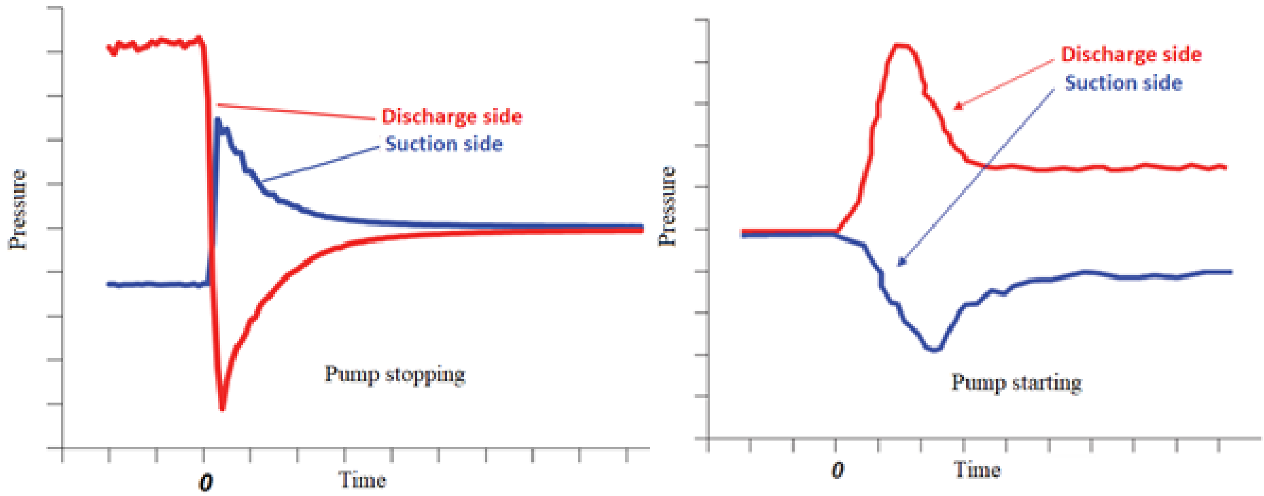

Fig. 5. An example of the pressure changes on the suction and discharge side after the rotor stop (left) and start (right) of the centrifugal pump. 0 – time of the rotor stop/start moment [11]

For example, if in a pipeline 300m long, with an internal diameter of 2.5" and an output of 680l/min, at a pressure of 1.7MPa, the water flow is stopped by a valve closed for 0.3 seconds, the dynamic pressure of water will increase to 6.7MPa [12]. Which gives almost 4 times increase in fluid pressure.

3. Propagation and amplification of the pressure disorders

Correct determination of the pressure wave propagation velocity in the hydraulic line is very important because of its influence on the accuracy of analytical and numerical calculations, both in terms of amplitude and frequency of their changes. This parameter is determined from the formula described in the literature (equation 3) [7, 13].

$$c_o = \sqrt{\frac{\beta_c}{\rho_o(1+\frac{\beta_c D}{E g_p}c_1)}} \tag{3}$$

where:

c_o – Pressure wave propagation speed, m/s,
β_c – Liquid bulk modulus, Pa,
ρ_o – Liquid density, kg/m^3,
D – Internal pipe diameter, m,
E – Young's modulus of the material the pipe, Pa,
g_p – Wall thickness of the pipe, m,
c_1 – Constant depends on the mounting of the pipe, -,

The constant c_1 is conditioned by the method of mounting the pipe and can be determined by one of the following equations (equations 4, 5, 6) [13]:

- for monolithic pipe with one-side fasten

$$c_1 = 1 - 0{,}5\nu_p \tag{4}$$

- for a pipe fixed on both sides (no axial displacement)

$$c_1 = 1 - {\nu_p}^2 \tag{5}$$

- for a pipe with longitudinal compensation (expansion joints)

$$c_1 = 1 \tag{6}$$

where:

c_1 – Constant depends on the mounting of the hydraulic line, -,
ν_p – Poison's modulus of the material the hydraulic line,-.

3.1. Construction of hydraulic hoses

Hydraulic hoses used today are most often of a layered structure. They differ in the number of layers of cord, their arrangement and the material from which the reinforcement is made. For this reason, it is very difficult to unequivocally determine their Young's modulus and Poison's coefficient, which are necessary to determine the velocity of the pressure wave in the medium. The problem is described in the literature [8] where the dependencies of the wave propagation velocity depending on the structure of the pipeline and the pressure in the system have been developed (Fig. 6).

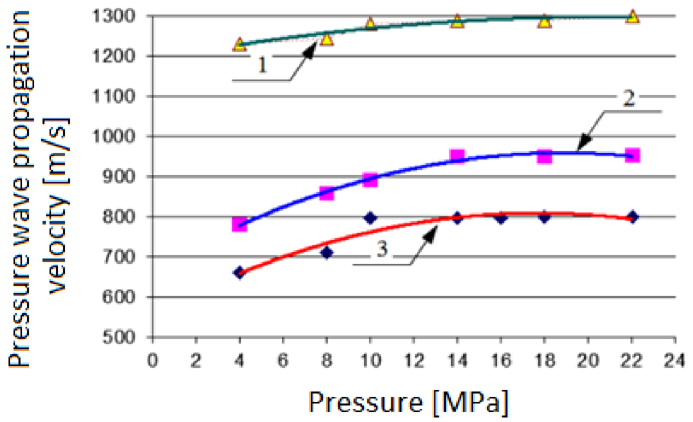

Fig. 6. The dependence of the velocity of propagation of the pressure wave on the mean pressure along the length of the pipeline for different pipe materials: 1 - rigid pipe, 2 - hose with two layers of steel cord, 3 - hose with one layer of steel cord [8]

We can see here that the speed of wave propagation depends not only on the design of the hose, which determines the coefficients needed for calculations (equation 3), but also on the pressure in the system.

3.2. Length of the hydraulic line

When testing pulsating flows, particular attention should be paid to the case where we are dealing with a long hydraulic line, i.e. when the length of the hose is on the order of the length of the pressure wave propagated in it or is greater than it [8]. Then it should be taken into account that the changes in pressure and flow rate propagate along the axis of the pipes with a finite speed in the form of current and reflected waves [14, 15, 16].

In the literature, two fundamentally different methods of describing transient (quasi-steady) waveforms in systems with a long hydraulic line are commonly used: the frequency waveform study method and the method of studying transient processes as a function of time. A hydraulic line is treated as a two-way element of a system with two inputs and two outputs: pressure p and flow rate q. Fluctuations in the efficiency of positive displacement pumps in systems with a long hydraulic line can be described using the so-called a hydraulic four terminal network (Fig. 7) [8].

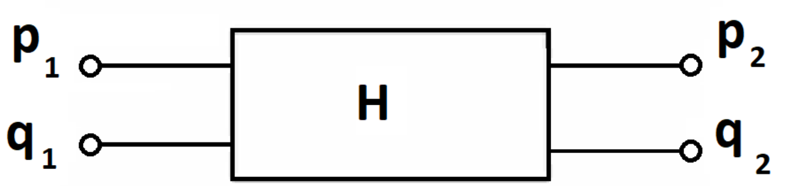

Fig. 7. Hydraulic four-terminal network

The results of sample calculations using the frequency waveform study method are presented below (Fig. 8). We can observe that for a flexible hose, the vibration amplitude gain is much higher than for rigid line.

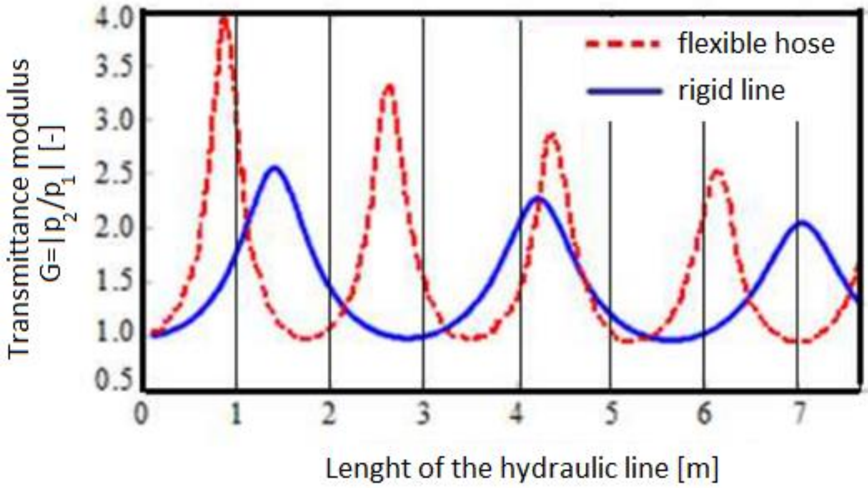

Fig. 8. Transmittance modulus as a function of the hydraulic line length [17]

4. The effects of the occurrence of pressure pulsations

The effects of pressure pulsation may be visible immediately or appear over time. The most immediate effects are water hammer or a combination of corrosion and pressure peaks. The latter issue is dealt with in detail by Tribo-Fatigue - a sub-discipline of mechanics that combines elements of tribology and fatigue wear. The types of wear that develop over time include fatigue wear on hydraulic components, especially joints. In addition, under the influence of pressure pulsation, displacement of hydraulic lines may occur, which, if insufficiently fastened, may be damaged or slowly abraded.

4.1. Exceeding allowable system operating pressures

During sudden pressure fluctuations caused by e.g. water hammer, the system components may burst, fail and blow out of the seals or implode some components (Fig. 9). An additional factor increasing the risk of sudden exceeding of the pressure resistance of the elements may be corrosive wear resulting from the flow of the medium through the system, e.g. corrosion or cavitation.

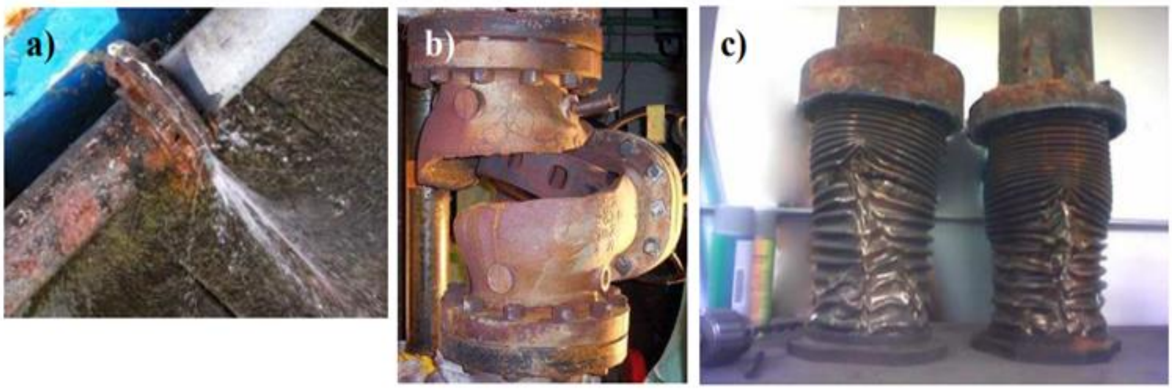

Fig. 9. Effects of a water hammer: a) failure of a seal, b) destruction of the valve casing, c) collapsing of expansion joints [18]

4.2. Fatigue wear of system elements

In the literature [2] we can find studies dealing with the fatigue strength of the hydraulic cylinder body. Out of the entire structure, the weakest elements were the welded joints of the structure (Fig. 10). The comparison of the results of analytical calculations and experimental tests is presented in the table (Table 1).

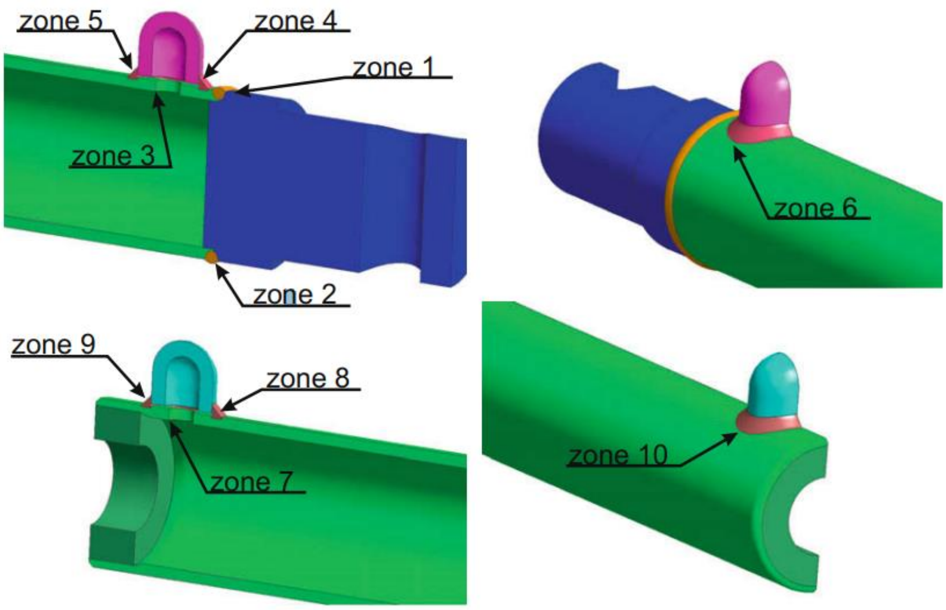

Fig. 10. Critical zones of the hydraulic cylinder: 1 and 2 correspond to the weld between cylinder tube and the end cap, 3–6 correspond to oil port (near end cap), 7–10 correspond to rod oil port [19]

Table 1. Comparison of calculated and real fatigue resistance of hydraulic cylinder [19]

Critical zone	Stress value [MPa]	Fatigue resistance, calculation [number of cycles]	Fatigue resistance, experiment [number of cycles] [20]
1	387,2	309 719	384 000
2	321,2	1 774 879	352 249 / 350 395
3	366,9	520 395	436 887
4	243,5	> 5 000 000	598 798
5	221,4	> 5 000 000	347 427
6	372,3	452 944	358 947
7	357,0	672 740	675 891
8	208,5	> 5 000 000	581 900
9	248,3	> 5 000 000	740 698
10	245,5	911 011	763 187

Another element of the system that is exposed to fatigue wear is the hydraulic hoses. The fatigue strength of a hydraulic hose can be checked by a hydraulic test with pulsating pressure without bending or with simultaneous bending (test methods are defined in ISO 6803, ISO 6802 and ISO 8032). The required resistance to pulsating pressure is the number of pressure pulsation cycles (pulses) that the hose should withstand (it is specified in the standard for a given type of hose). Pressure pulsations are characterized by a high frequency of changes, the test pressure is from 100% to 133% of the maximum working pressure, and the test temperature is increased (100 °C) [21].

5. Summary

The effects of damage to hydraulic systems presented in the previous chapter confirm the validity of research on methods of securing hydraulic systems against both cyclic pressure changes and sudden peaks of its value. In the near future, the author intends to conduct literature research on current methods of securing hydraulic systems against pressure pulsations. The next steps will be to develop a new structure, perform numerical calculations of its effectiveness, and validate model studies through experimental studies.

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