756. Oscillations of cylinder piston rod – comparison of amplitudes and frequencies for the transient phenomena in tap water- and oil-based PCHS

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Abstract. Power-control hydraulic system (PCHS), as a part of a machine or production line, provides it with all or most of the necessary movements. Most of the movements in PCHS are carried out by means of hydraulic cylinders. In this case movements are mostly generated by cylinder piston rods. More or less obvious transient phenomena occur during these movements under conditions of acceleration and deceleration. As a consequence, oscillations are induced in the system. In our work we investigate the phenomena and parameters of such PCHS for two hydraulic fluids. Most of the PCHSs still use mineral oil as hydraulic fluid but it is environmentally very harmful. Ecological awareness during natural disasters and man-made pollution is the subject of much discussion. It is everybody's responsibility to take care of the natural environment and reduce the threats to our future existence. The preservation of drinking water and the prevention of its contamination by pollution are particularly important. Power-control hydraulics is one important area in which a positive step could be made to protect the resources of drinking water. The use of tap water instead of the conventional hydraulic fluids in power-control hydraulics is one of the most environmentally friendly changes that could be implemented. Therefore in this paper we show, based on dynamic-transient parameters, both the functionality and the usability of water hydraulics in comparison to the more familiar oil hydraulics. A comparison of the dynamic behavior between the conventional oil and the relatively new water hydraulics under the same conditions is described. Mineral hydraulic oil was used in the oil hydraulic test rig and distilled water was used in the water hydraulic test rig. The tests were conducted at different flow rates (11, 22 and 33 lpm) and system pressures (70, 110 and 160 bar) as well as applying different loading conditions (first, with a mass of 163 kg in the horizontal and vertical positions and, second, without the mass). The registered amplitudes of the cylinder piston rod oscillations were 20-30 % smaller in the water hydraulics with respect to the case of oil hydraulics, while the frequencies of the piston rod oscillations were 7-20 % higher.

Keywords: power-control hydraulics, piston rod oscillating amplitudes and frequencies, tap water, mineral oil.

1. Introduction

Despite being environmentally friendly, water hydraulic systems are not involved in many applications. When we talk about water hydraulics, we are referring to the use of tap water without any additives for the hydraulic fluid instead of conventional hydraulic fluids that can harm the environment.

Interestingly, it was water that was the first fluid used in industrial power-control hydraulics, more than two hundred years ago [1]. However, in the early years of water hydraulics there were many problems associated with both durability and functionality.

During the 19th century, after the oil industry began to develop [2, 3], there was no further use of water hydraulics. Oil-based hydraulic machines worked better and longer than the equivalent water hydraulic machines. The reasons for the replacement of water hydraulics were linked to the low volumetric and mechanical hydraulic efficiencies, corrosion and high wear for the materials known at that time.

However, mineral hydraulic oil is not the best solution. The main problem is related to polluting the natural environment and, in particular, to the contamination of the drinking water. One so-called "soft" solution is to use bio-degradable hydraulic oil [4-9], but the problem is with the additives, which tend not to be totally degradable. For this reason, in the early 1990s, many countries [2, 10, 11] started the research on the possibilities of using tap water as a hydraulic fluid.

The current situation on the market is that the available water hydraulic components do not persuade customers that they can replace oil-based systems and lead to a significant increase in use [10].

In this paper we would like to demonstrate that water hydraulics can function as well as the familiar oil hydraulics. For this purpose a combined oil and water hydraulic test rig was designed and constructed [12, 13, 14]. A new water proportional 4/3 directional control valve was designed and long-term tests were conducted [16, 17].

In terms of stationary behavior, the most important functional working characteristics were examined and compared with those of oil hydraulics [15]. Four stationary characteristics of both types of hydraulic systems were compared, and these characteristics show the basic functionalities of both the water and oil hydraulic systems.

The dynamic characteristics of water power-control hydraulics were examined and compared with the characteristics of oil hydraulics. In this paper we present different dynamic characteristics of water-based and similar oil-based power-control hydraulics.

The aim of the paper is also to determine the difference in the behavior between water and oil power-control hydraulics and to present a relatively simple mathematical model that enables prediction of some important parameters during the transient phenomena, using either water or mineral oil as the hydraulic fluid. It is important to establish critical parameters during the design phase of the hydraulic system for either water or oil.

2. Testing device

2. 1. Test rig

A combined test rig, with one part of it for investigating water power-control hydraulics (PCH) and the second part - for investigating the comparison oil PCH, was constructed and used for the experimental study [12, 13, 15]. This combination test rig was also used to test and investigate the water and oil valves, with both valves being of the proportional 4/3 directional spool-sliding control type (Fig. 1). The same test rig was used to carry out comparative stationary [15], dynamic-transient (this paper) and static-long-term life-time tests [16, 17] under the same, or at least analogous, working conditions. Fig. 1 illustrates a simplified hydraulic circuit used for the dynamic tests of the oil (Fig. 1a) and water parts (Fig. 1b) of the test rig. The water hydraulic test rig contains a hydraulic power pack and a cooling-filtration unit (not shown in Fig. 1) [15], and a newly designed water proportional directional control valve [12, 13] (Fig. 1b, pos. 1) with a linear variable differential transformer (Fig. 1b, pos. 2). The proportional valve was controlled from a PC in a closed loop. To the connection port A of the proportional valve, we connected a 3-m stainless-steel tube (Ø12x1.5 mm) and a 3-m flexible tube, to which a pressure transmitter (Fig. 1, pos. 5) and a double-acting hydraulic cylinder (Fig. 1, pos. 3) were connected at the end. The second branch on the connection B was the same. A roller-guided load-mass of 163 kg (Fig. 2, Fig. 3b and Fig. 3d) was connected to the rod of the hydraulic cylinder in the vertical or horizontal position, depending on the type of measurement. A centrifugal water pump, a temperature transmitter and an additional 1-μm by-pass filter were used to maintain a constant temperature and to enable high-quality off-line filtering [12, 13]. The pressures on the A and B connection ports of the water proportional valve were measured during the test using a pressure transmitter (Fig. 1, pos. 5 and 6). The control of the proportional magnets (Fig. 1, pos. 1), the data acquisition and the electro-motors was automated with the PC.

The oil part of the hydraulic test rig is equivalent to the water test rig, in terms of function, but it is assembled using standard, commercially available components.

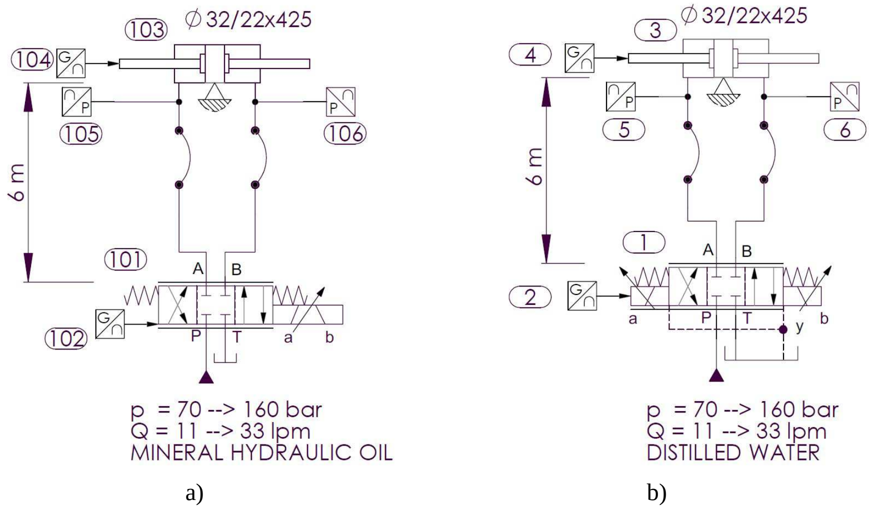

Fig. 1. Simplified hydraulic circuit for measurements of the dynamic characteristics of a) the oil and b) the water hydraulics

The water hydraulic test rig (Fig. 1b and Fig. 2) is assembled from standard, commercially available, water hydraulic components, except for the proportional 4/3 directional control valve (Fig. 1.b, pos. 1) and the hydraulic cylinder (Fig. 1b, pos. 3 and Fig. 2). These two components were designed in our Laboratory for power-control hydraulics (LPCH). The tubes for the water and the oil hydraulic cylinders were made from stainless steel and the piston rod was made from hard-chromium-plated steel. The seals and guide rings for both hydraulic cylinders are the same; they were made from nitrile rubber, polyurethane, and a fabric-based laminate. The oil part of the test rig (Fig. 1a) was the same in terms of function. It is assembled from standard components, except for the hydraulic cylinder. The developed oil hydraulic cylinder (Fig. 1a, pos.103 and Fig. 2) is typical for oil hydraulic applications. It has the same design, the same dimensions and the same surface properties as the water cylinder. A photograph of the water and oil hydraulic cylinder with loads in vertical position (mass of 163 kg) is shown in Fig. 2.

2. 2. Experimental procedure and testing parameters

The whole testing procedure was fully automated with the PC software [13]. All the presented results were measured using the same procedure.

The parallel-shaped position of the proportional 4/3 directional control valve (Fig. 1a, pos. 101 and Fig. 1b, pos. 1) was first switched on and the hydraulic cylinder piston rod moved with constant velocity. The working pressures on ports A and B of the valve (Fig. 1a, pos. 105 and 106 and Fig. 1b, pos. 5 and 6) were therefore stable-constant, without any larger disturbances. After sometime with these constant circumstances the proportional directional valve instantaneously switched into the zero-blocked position. Whereupon the flows through all four ports of the valve were closed. The closing of the flow-gaps in the valve lasted only approximately 10 ms. Immediately after the closing of the valve the pressure-surge effect occurred.

The measurements were performed with and without the load mass of 163 kg. This load mass was differently positioned (Fig. 3), once in the horizontal (Fig. 3c and Fig. 3d) and once in the vertical direction (Fig. 3a and Fig. 3b). The tests were performed with three different flows (11, 22 and 33 lpm) and three different pressure settings of 70, 110 and 160 bar.

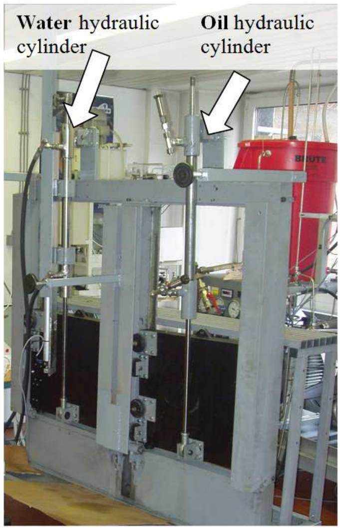

Fig. 2. Photograph of the water and oil hydraulic cylinder with a load of 163 kg in the vertical position

The same experimental procedure was used in both hydraulic circuits with the water and oil. In the water hydraulic test rig we used distilled water and in the oil hydraulic test rig we used ISO VG 46 mineral hydraulic oil. The working temperatures of the fluids in both test rigs were maintained, through cooling, at 40 °C +/- 2°C.

All of the presented measurements were repeated at least three times.

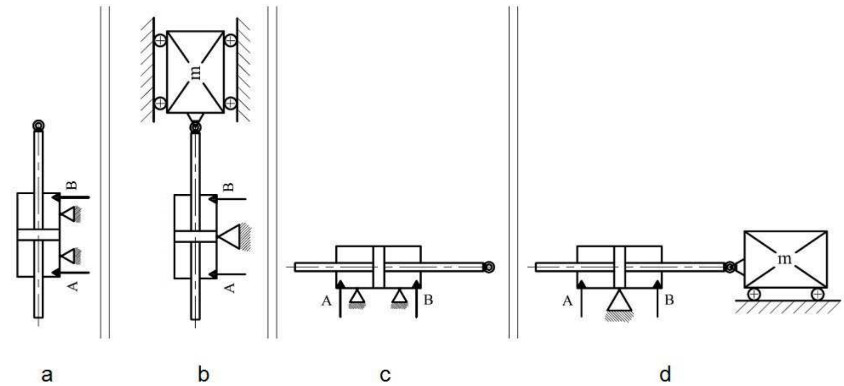

Fig. 3. Different positions and loads used during the measurements a) without vertical mass, b) with vertical mass, c) without horizontal mass and d) with horizontal mass

3. Mathematical validation

The change in the rate of motion of an energy-carrying hydraulic fluid and within it of the actuator, inside a given time interval, involves the acceleration or deceleration of that motion and of the moving masses, depending on that motion through the hydraulic fluid. The final applicable equations for the flow Q and the pressure changes Δp over time, at an instant, or for gradual changes of the fluid and the actuator's velocity can be derived from a basic equation (1) [18, 19]. This equation is identical for accelerations and decelerations. In our tests the piston rod without or with load was accelerated and decelerated. Yet in practice, for machines using hydrostatic drives, the decelerations are normally more problematic than the accelerations. Therefore, our experiments were focused mostly on decelerations. In particular, the instant stopping of movements can cause oscillations, as a result of which heavy damage to a machine's construction can occur because of the additional mass-inertia forces. Instant stopping of fluid flow through stopping the cylinder piston and piston rod, perhaps with the masses connected to it, causes the pressure surge effect.

Considering resistance to acceleration (H), resistance to deformation (D) and resistance to motion (R) we can write the equation (1) in following form:

$$H \cdot \frac{d^2Q}{dt^2} + H \cdot \kappa \cdot \frac{dQ}{dt} + D \cdot Q = 0 \tag{1}$$

In equation (1) Q is the fluid flow (changing in time) and κ represents the coefficient of the resistance to motion.

Final applicable equations for flow Q through time at instant or gradual changes of fluid flow and actuators velocity can be derived from basic equation (1). When the resistance to motion is low enough, the actuator with masses has oscillatory damped movements.

Solving eq. (1) for underdamped conditions we get the equation (2), which describes the temporal change of fluid flow Q at the instant of flow stopping:

$$Q = e^{-\frac{1}{2}\kappa . t}\, Q_0\, (\cos \omega\, t + \frac{\kappa}{2\omega} \sin \omega t) \tag{2}$$

Q_0 in eq. (2) represents the fluid flow just before stopping the flow by switching the directional valve from crossed or parallel into zero position (see Fig. 1). At the moment the ports A and B of the directional valve are blocked in a short time or instantly. That way we stop the movement of the piston and piston rod of the hydraulic cylinder. Eventually, masses connected to piston rod are stopped too. The oscillating movement of the piston rod follows the changing of the fluid flow Q through time.

4. Experimental results

4. 1. Amplitude of the oscillating cylinder piston rod during the pressure-surge effect

Figure 4a shows a measurement of the movement of the oil hydraulic cylinder rod with a load (mass of 163 kg) in the horizontal position at a flow of 33 lpm and inlet pressure of 160 bar. The piston rod of the oil hydraulic cylinder oscillated for 13.5 mm. The water hydraulic cylinder piston rod was also oscillating (Fig. 9b), but by 0.6 mm less than the oil cylinder piston rod under the same conditions. The second curve of the diagrams in Fig. 4a and Fig. 4b indicates the movement of the controlling spool in the proportional directional control valve. Oscillations of the cylinder piston rod started at the moment when the flow-gap in the valve was closed.

Figure 5a presents variation of oscillation amplitude of the cylinder rod for different inlet-system pressures in the oil and water hydraulic cylinders at an inlet flow of 33 lpm. The highest amplitude of the hydraulic cylinder piston rod in the oil hydraulics was 13.5 mm at 160 bar, and the lowest - 7.4 mm at inlet pressure of 70 bar. The highest oscillation amplitude of the hydraulic cylinder piston rod in the water hydraulics was 12.9 mm at 160 bar, and the lowest - 5.8 mm at inlet pressure of 70 bar.

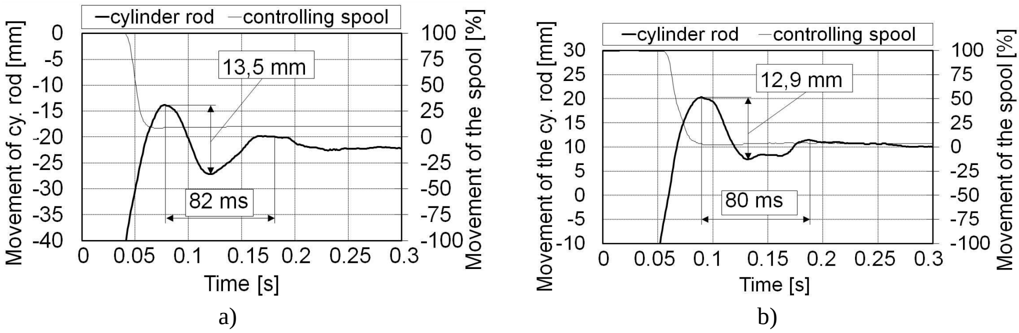

Fig. 4. Results of measuring the piston rod of the hydraulic cylinder in response to an instantaneously closed valve: a) oil, and b) water (*flow* = 33 lpm, *pressure* = 160 bar, *loading mass* = 163 kg in horizontal position)

Figure 5b presents variation of oscillation amplitude of the cylinder rod for different inlet fluid flows in the oil and water hydraulic cylinders at a system pressure of 160 bar. The highest amplitude in the oil hydraulics was 13.5 mm at inlet flow of 33 lpm, and the lowest - 5.3 mm at a flow of 11 lpm. The highest oscillation amplitude of the cylinder piston rod in the water hydraulics was 12.9 mm at 33 lpm and the lowest - 4.6 mm at a flow of 11 lpm.

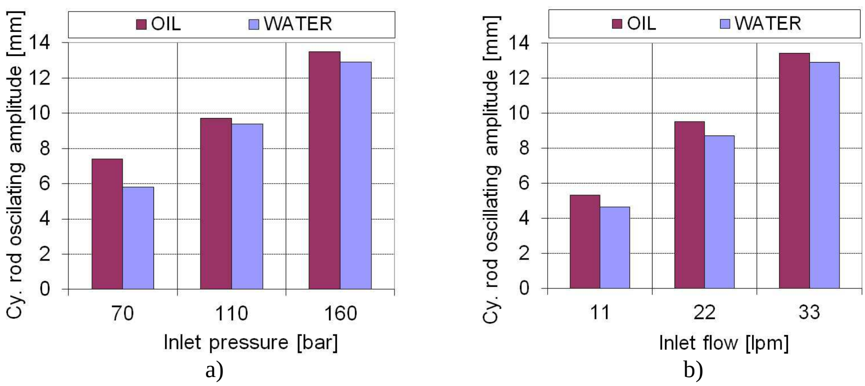

Fig. 5. Oscillation amplitude of the cylinder piston rod for the oil and water hydraulics during the pressure-surge effect in response to an instantaneously closed valve with a loaded hydraulic cylinder (163 kg in horizontal position) for a) different inlet pressures (*flow* = 33 lpm) and b) different flows (*pressure* = 160 bar)

The oscillation amplitude of the loaded (mass of 163 kg) oil and water hydraulic cylinder rod increased with an increasing inlet pressure (Fig. 5a). The differences between the amplitudes in the water and oil hydraulics depend on the inlet pressure. The amplitude of the loaded (mass of 163 kg) oil and water hydraulic cylinder piston rod increases with the higher inlet flow (Fig. 5b), just like it increased by raising inlet pressure. The average difference between the oil and water oscillation amplitudes of the cylinder piston rod at an inlet pressure of 160 bar and different flows (from 11 to 33 lpm) was 8 %. For this value the average amplitudes of the oil hydraulic cylinder piston rod were higher than the amplitudes in the water hydraulic cylinder under similar conditions.

The results of the measured oscillation amplitudes of the cylinder piston rod (Fig. 5) reveal lower amplitudes in the water hydraulics in comparison to the oil hydraulics (between 0.5 and 0.8 mm).

Fig. 6 provides the variation of oscillation amplitude of the cylinder rod for different positions and different loads of the water and oil hydraulic cylinders during the pressure-surge effect. The inlet flow was 33 lpm and the system pressure was 160 bar. The results of the measurements indicate that the oscillation amplitude of the oil hydraulic cylinder piston rod, in all positions and for all loads, was higher in comparison to the case of water hydraulics.

The lowest rod amplitudes in the oil hydraulic system, 4.8 mm, were registered for the case of the unloaded oil hydraulic cylinder in the vertical position. The largest oscillation amplitudes of the rod in the oil hydraulic system, 13.5 mm, were obtained for the case of the loaded oil hydraulic cylinder (with a mass of 163 kg) in the horizontal position.

The lowest amplitude of the water hydraulic cylinder piston rod, 3.5 mm, was measured for the case of the unloaded water hydraulic cylinder in the vertical position, while the largest amplitude of 13 mm was obtained for the case of the loaded water hydraulic cylinder (with a mass of 163 kg) in the horizontal position.

The largest difference in the oscillation amplitude of the hydraulic cylinder rod between the oil and water hydraulics (Fig. 6) was 2.2 mm, in the vertical position with a load. This means a 17 % larger amplitude of the oil hydraulic cylinder rod in comparison to a similar water cylinder. The smallest difference in the amplitude of the hydraulic cylinder rod between the oil and water hydraulics (Fig. 6) was 0.5 mm in the horizontal position with a load. In this case the amplitude of the oil hydraulic cylinder piston rod was approximately 4 % higher than the amplitude of the water hydraulic cylinder piston rod under similar conditions.

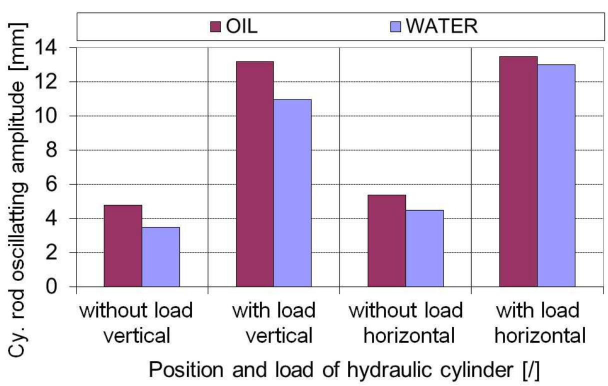

Fig. 6. Oscillation amplitude of the hydraulic cylinder piston rod for the oil and water hydraulics during the pressure-surge effect in response to an instantaneously closed directional valve for different positions of the cylinder and different loads (*flow* = 33 lpm, *pressure* = 160 bar)

4. 2. Frequency of the oscillating cylinder piston rod during the pressure-surge effect

Figure 7a provides the variation of oscillation frequency of the cylinder rod for different inlet-system pressures in the oil and water hydraulic cylinders at an inlet flow of 33 lpm. The highest oscillation frequency of the oil hydraulic cylinder piston rod was 11.9 Hz at 160 bar, while the lowest - 9.8 Hz at inlet pressure of 70 bar. The highest oscillation frequency of the water hydraulic cylinder piston rod was 12.8 Hz at 160 bar and the lowest - 11.6 Hz at inlet pressure of 70 bar.

Figure 7b shows the variation of oscillation frequency of the cylinder rod for different inlet fluid flows in the oil and water hydraulic cylinders at a system pressure of 160 bar. The highest oscillation frequency of the oil hydraulic cylinder piston rod was 11.9 Hz at inlet flow of 33 lpm and the lowest - 8.3 Hz at a flow of 11 lpm. The highest oscillating frequency of the water hydraulic cylinder piston rod was 13.5 Hz at 11 lpm and the lowest - 12.8 Hz at 33 lpm.

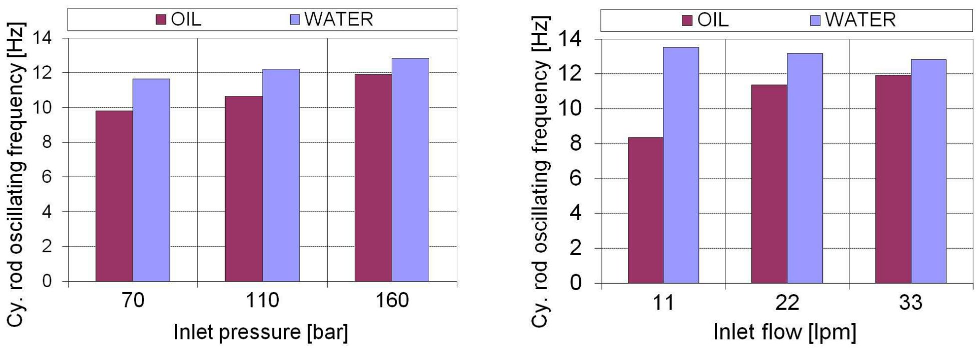

Fig. 7. Oscillating frequency of the hydraulic cylinder piston rod for the oil and water hydraulics during the pressure-surge effect in response to an instantaneously closed directional valve on a loaded hydraulic cylinder (163 kg in horizontal position) for a) different inlet pressures (*flow* = 33 lpm) and b) for different flows (*pressure* = 160 bar)

Figure 8 presents the variation of oscillation frequency of the cylinder rod at different positions and for different loads on the water and oil hydraulic cylinders during the pressure-surge effect. The inlet flow was 33 lpm and the system pressure was 160 bar. The lowest oscillation frequency of the oil hydraulic cylinder piston rod, 10.6 Hz, was registered for the case of a loaded oil hydraulic cylinder (mass 163 kg) in the vertical position. The largest oscillation frequency of the oil hydraulic cylinder piston rod, 35.7 Hz, was generated in the case of the unloaded oil hydraulic cylinder in the horizontal position.

The lowest oscillation frequency of the water hydraulic cylinder piston rod, 10.4 Hz, was measured in the case of a loaded water hydraulic cylinder (with mass of 163 kg) in the vertical position, while the highest rod oscillation frequency of 33.3 Hz was generated in the case of the unloaded water hydraulic cylinder in the horizontal position.

Increasing the inlet pressure in the oil hydraulics (Fig. 7a) has a greater influence on increasing the oscillation frequency of the hydraulic cylinder piston rod with respect to the case of water hydraulics under similar conditions. It is clear that different flows through the proportional directional control valve did not have a major influence on the oscillation frequency of the water hydraulic cylinder piston rod, while we observed a larger influence of the flow on the frequency in oil hydraulics under similar conditions. It is also clear that the main influence on the rod oscillation frequency (Fig. 8) was the load of the piston rod. In contrast, the position of the hydraulic cylinder had a smaller influence on the rod oscillation frequency in both the oil and water hydraulics.

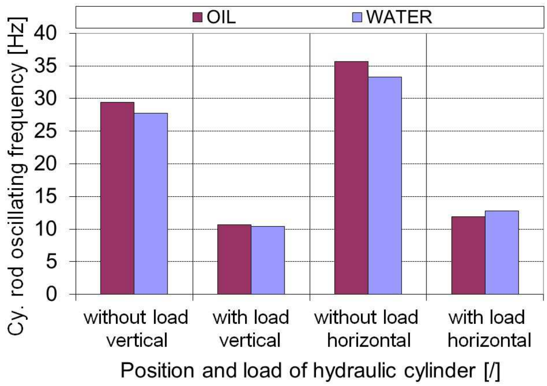

Fig. 8. Oscillation frequency of the hydraulic cylinder piston rod for oil and water hydraulics during the pressure-surge effect in response to an instantaneously closed directional valve for different positions of the cylinder and different loads (*flow* = 33 lpm, *pressure* = 160 bar)

5. Discussion

The mathematical model yields a higher flow and piston rod oscillation frequency for the water hydraulics than for the oil hydraulics with similar parameters. The reason for this difference probably lies in the very large internal damping of the water hydraulic cylinder. The high friction of the standard seals inside the water hydraulic cylinder on the piston and piston rod had an influence on the higher internal damping. In fact the internal damping in the water hydraulic cylinder was so high that aperiodical oscillations of the water cylinder piston rod almost occurred. An increased pressure damping tends to decrease the flow oscillation frequency.

The measured amplitudes of the oscillating cylinder piston rod during the pressure-surge effect were 4-17 % lower in the water hydraulics with respect to the similar oil hydraulics. The reason for the lower oscillation amplitude of the water cylinder piston rod is the lower compressibility of the water in comparison to the hydraulic mineral oil. The amplitude of the oscillating cylinder piston rod mainly depends on the pressure oscillations and the damping inside the hydraulic cylinder.

The results of the measured frequency of the oscillating cylinder piston rod during the pressure-surge effect indicate 7-20 % higher oscillating frequency in the water hydraulic test rig in comparison to the oil hydraulic test rig. The reasons for this difference were described above. Table 1 provides a summary of the dynamic-transient hydraulic parameters for the oil and water hydraulics.

6. Conclusions

The results of the measurements of dynamic characteristic and the mathematical model for the oil and water hydraulics indicate differences and similarities between the two hydraulic systems.

Table 1. Summary of differences in the dynamic-transient parameters of the oil and water hydraulics

No.	Dynamic-transient parameter	Test rig		Comment (response of the water hydraulics compared to the oil hydraulics)
		oil	**water** (in comparison with oil)	
1.	Amplitude of the oscillating cylinder piston rod during the pressure-surge effect	100 %	**-14 % → -7 %**	Smaller oscillations – acceptable
2.	Frequency of oscillating piston rod during the pressure-surge effect	100 %	**+7 % → +20 %** (+ 60 %)	Faster oscillation – acceptable

The amplitudes of the oscillating cylinder piston rod during the pressure-surge effect were 4-17 % lower in the case of water hydraulics with respect to the oil hydraulics for the same parameters.

The frequencies of the oscillating cylinder rod during the pressure-surge effect were on average 7-20 % higher in the water hydraulics than in the oil hydraulics for the same parameters.

These results make us optimistic about the possibility of using water hydraulics and will lead us to conduct future research and to develop water-based power-control hydraulics.

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