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Characteristics of the stationary behaviour of water- and oil-based power-control hydraulics

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1. Introduction

When we talk about water hydraulics, we refer to the use of tap water – without any additives – for the hydraulic fluid, rather than the usual oils. Currently, water hydraulics are involved in very few applications, even though such systems have a decidedly low impact on 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], there was no further use of water hydraulics. Oil-based hydraulic machines worked better and for 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 oils are not the best solution. The problem is the risk of pollution to the environment and especially the spoiling of drinking water. One so-called “soft” solution is the use of biodegradable hydraulic oils [3-8], but here the problem is with the additives, which tend not to be totally degradable. For this reason, in the early 1990s, many countries [2, 9, 10] began with research into the possibilities of using tap water as a hydraulic fluid. The current situation on the market is that the available water hydraulic components are not persuading customers that they can replace oil-based systems and so lead to a significant increase in use [9]. In this paper we would like to show that water hydraulics can work as well as the familiar oil hydraulics. In order to do this a combined oil and water hydraulic test rig was designed and constructed [11, 12]. A new water proportional 4/3 directional control valve was designed and long-term tests were conducted [13]. The presented stationary measurement results for this new water valve are compared with accessible results from a commercially available oil hydraulic valve [14].

In terms of stationary behaviour, the most important functional working characteristics were examined and compared with those of oil hydraulics. The main aim of this paper is to show the functionality and usability of the newly developed water hydraulic system in comparison with a similar oil hydraulic system. 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.

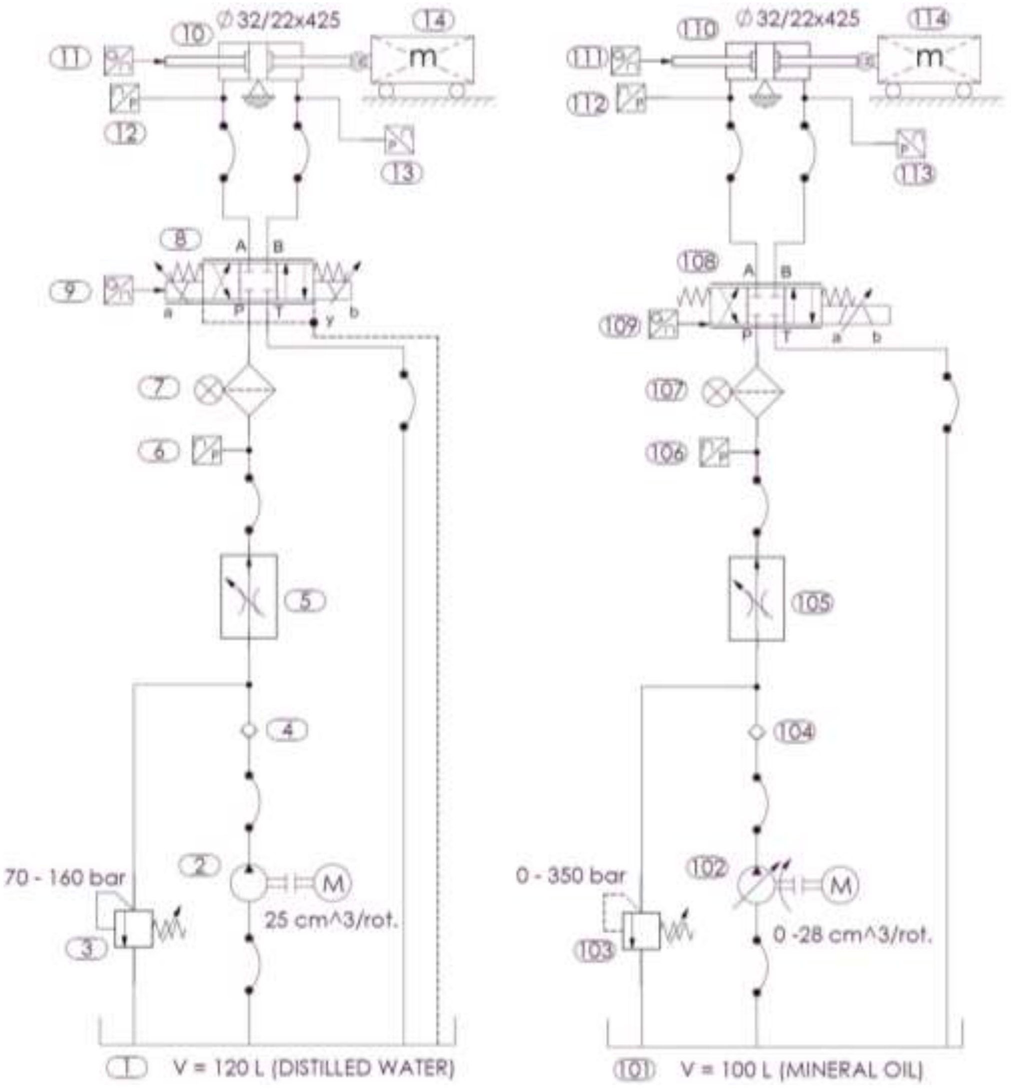
Further research on the dynamic and transient characteristics of water power-control hydraulics and a comparison with similar oil hydraulics are in progress [15].

2. Testing device

2.1. Test rig

The combination test rig, realized in two parts, with one part intended to investigate the water power-control hydraulics (PCH) (Fig. 1, a) and the second part to investigate the oil PCH (Fig. 1, b) was constructed and used for the experimental investigations [11, 12]. 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. The same test rig was used to carry out comparative stationary (this paper), dynamic-transient [15] and static-long-term life-time tests [16] under the same, or at least analogous, working conditions. Fig. 1 shows a simplified hydraulic circuit of the water (Fig. 1, a) and oil parts (Fig. 1, b) of the test rig. The water hydraulic test rig uses a standard Danfoss axial piston pump, type PAH 25 (Fig. 1, pos. *2*), with a flow of 35 lpm [11, 12] at 1450 r/min at a volumetric efficiency of 97%. This pump delivers water through a pressure-compensated flow-control valve (Fig. 1, pos. *5*), which ensures a constant flow (in these series of experiments, 11, 22 or 33 lpm) through the newly designed water proportional directional control valve [11, 12] (Fig. 1, pos. *8*). A pressure-line water filter with a rating of 1 μm (Fig. 1, pos. *7*) was installed on the P line, close to the water proportional directional control valve. This valve was controlled from a PC in a closed loop. To the connection port A of the proportional valve we connected a stainless-steel tube, to which a pressure transmitter (Fig. 1, pos. *12*) and a double-acting hydraulic cylinder (Fig. 1, pos. *10*) were connected at the end. The second branch on the connection B was the same. A roller-guided load-mass of 163 kg (Fig. 1, pos. *14*) was connected to the rod of the hydraulic cylinder. The water relief valve (Fig. 1, pos. *3*) was set to different pressures (70, 110 and 160 bar). A centrifugal water pump, a temperature transmitter and an additional 1-μm by-pass filter were used to maintain a constant temperature and to ensure high-quality off-line filtering. The pressure on the P connection port of the water proportional valve was measured during the test using a pressure transmitter (Fig. 1, pos. *6*). The control of the proportional magnets (Fig. 1, pos. *9*), the data acquisition and the electro-motors was automated with a 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.



a b

Fig. 1 Simplified hydraulic circuit for the a) water and the b) oil hydraulic test rig

The water hydraulic test rig (Fig. 1, a) is assembled from standard, commercially available, water hydraulic components, except for the proportional directional 4/3 control valve and the hydraulic cylinder. These two components were designed in our LPCH. The tubes for the water and oil hydraulic cylinders were made from stainless steel and the 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 important parts used in the new water proportional 4/3 directional control valve – the specimen (Fig. 2) were a spool with an outer diameter of 12 mm and a sleeve. The oil part of the test rig (Fig. 1, b) is the same in terms of function. It is assembled from standard components, except for the hydraulic cylinder. The developed oil hydraulic cylinder is typical of that used 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 combination hydraulic test rig is shown in Fig. 3.

2.2. Experimental procedure and testing parameters

The whole testing procedure was fully automated with PC software [12]. All the presented results were recorded with the same procedure, using the same controlling signal (Fig. 4) for the proportional 4/3 directional control valve.

Fig. 2 The specimen – prototype of the proportional 4/3 directional control valve for water hydraulic

After the start of an individual measurement the proportional valve was switched from the zero position (Fig. 5) to the cross-shaped position (solenoid a energized). As a consequence of this the piston rod of the cylinder starts to move forward. The electrical controlling signal increases from 0 to 100% in 0.01 s. The electrical signal then stays at the same level for 0.18 s and holds the spool in the valve in the cross-shaped position. After 0.01 s the solenoid A is de-energized and the solenoid B is energized at the same time, so that the spool in the valve moves from the cross-shaped to the parallel position in approximately 0.02 s and the cylinder rod starts to move backwards. Between switching from the cross-shaped to the parallel position of the directional valve, the cylinder rod stops moving for a brief moment. The electrical input signal for the parallel-shaped position remains at 100% for 0.18 s. In the final phase the input signal decreases from 100% to zero in 0.01 s and the cylinder rod stops moving. The total time needed for the measurement of one cycle was 0.5 s.

Fig. 3 Photograph of combination water (on left) and oil (on right) hydraulic test rig

The measurements were performed with and without the load mass of 163 kg. The load mass was positioned once in the horizontal (Fig. 3) and once in the vertical direction. The tests were made with three different flows (11, 22 and 33 lpm) and three different pressures (70, 110 and 160 bar).

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

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

The whole testing procedure was fully automated with the PC software (Fig. 4), NI Labview. After start of the measurement the proportional valve (specimen) was switched from zero position (see Fig. 1 – P, T, A and B blocked) to cross-shaped position (solenoid A energized). Consequently the piston rod of the cylinder starts to move up. The electrical controlling signal increases from 0 to 100% in 0.01 s. The electrical signal then stays at that level for 0.28 s and holds the spool in the valve in cross-shaped position. After 0.3 s solenoid A is deenergized and solenoid B energized at the same time, so that the spool in the valve moved from the cross-shaped to the parallel position in approx. 0.02 s and the cylinder rod starts to move down. Between switching from cross-shaped to parallel position of the directional valve, cylinder rod stops to move for a short moment. The electrical input signal for the parallel-shaped position stays at 100% for 0.28 s. In the final phase the input signal falls from 100% to 0% in 0.01 s and the cylinder rod stops to move. The total time of the measurement of one cycle was 2 s.

The same experimental procedure was used in the two hydraulic circuits, water and oil.

Fig. 4 Software front panel for automation of measurements and control of the system

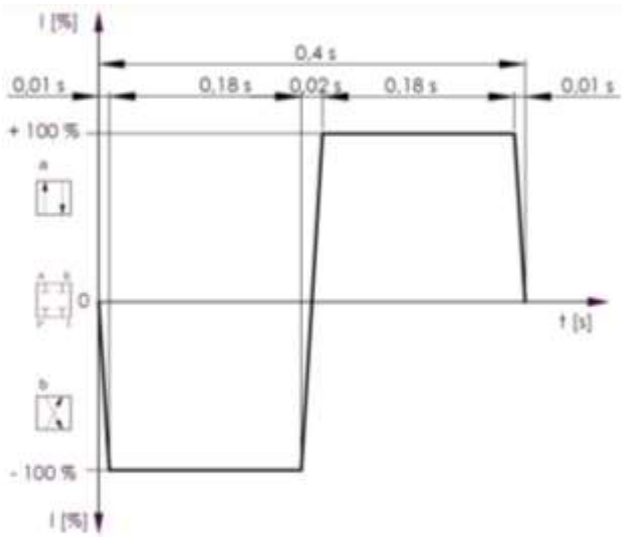


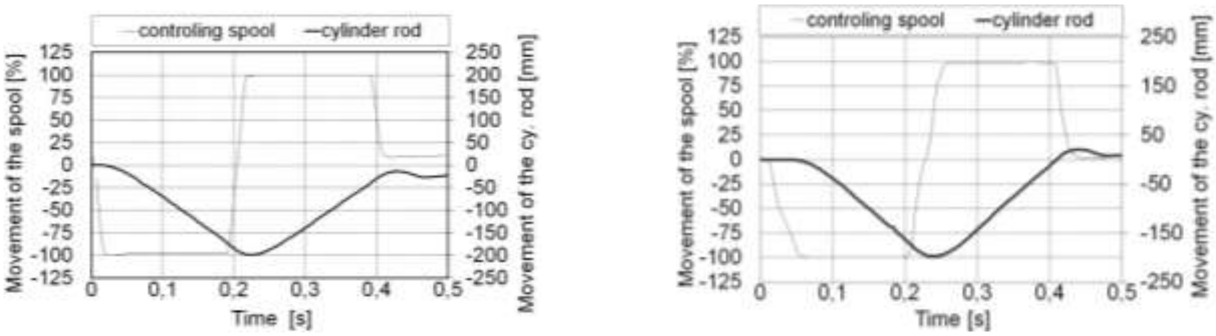
Fig. 5 Shape of the step-controlling signal for control of both the water and oil proportional 4/3 directional control valves (Fig. 1, a, pos. *9* and Fig. 1, b, pos. *109*)

3. Results

3.1. Movement of the rod of the hydraulic cylinder

Fig. 6 shows the results of two measurements. The first curve in each graph is for the movement of the controlling spool in the proportional 4/3 directional control valve and the second is for the response of the movement of the hydraulic cylinder rod with a loading mass of 163 kg in the horizontal position at an inlet pressure of 160 bar and a flow 33 lpm. Fig. 6, a shows a measurement with the oil hydraulic system. The loaded oil hydraulic cylinder rod has not returned during the symmetrical controlling signal to its start position. It is stopped at a position that is 23 mm away from the starting position of the cylinder rod. This amounts to approximately 12% of unsymmetrical movement of the oil hydraulic cylinder.

Fig. 6, b shows measurements of the movement of the controlling spool in the water proportional 4/3 directional control valve and its response to the movement of the rod in the water hydraulic cylinder. The loaded water hydraulic cylinder rod is stopped at a position that is 8 mm away from the starting position of the cylinder rod. This indicates approximately 4% of unsymmetrical movement of the water hydraulic cylinder.

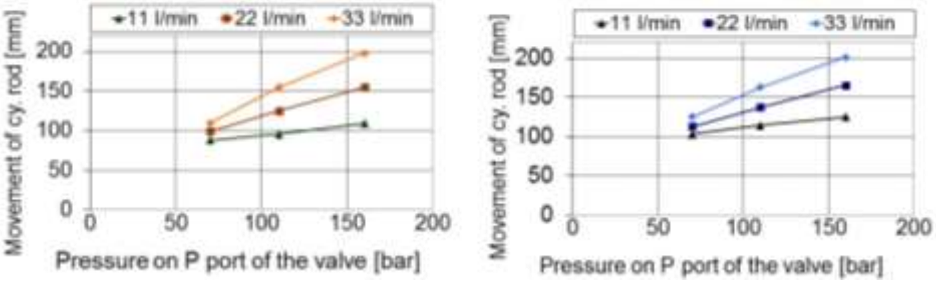


a

b

Fig. 6 Response of the rod of the hydraulic cylinder to a known controlling signal (Fig. 3); a) oil and b) water (flow = 33 lpm, pressure = 160 bar, loading mass = 163 kg in horizontal position)

Fig. 7, a shows the response of the oil hydraulic cylinder to different inlet pressures and different flows through the oil proportional 4/3 directional control hydraulic valve. The smallest movement of the rod in the oil hydraulic cylinder was around 80 mm at 70 bars of inlet pressure and a flow 11 lpm. The largest movement of the rod in the oil cylinder was observed to be 200 mm, as was to be expected at an inlet pressure of 160 bars and a flow of 33 lpm. Fig. 7, b shows a similar effect as in Fig. 5, a for the oil hydraulics, i.e., the response of the water hydraulic cylinder to the different inlet pressures and different flows through the new water proportional 4/3 directional control hydraulic valve. The lowest movement of the rod in the water hydraulic cylinder was approximately 100 mm at 70 bar of inlet pressure and a flow of 11 lpm. The largest movement of the rod in the oil cylinder was observed to be 200 mm at an inlet pressure of 160 bars and a flow of 33 lpm.



a

b

Fig. 7 Movement of the rod of the hydraulic cylinder as a response to a known controlling signal (Fig. 3) for a known flow and inlet pressure a) oil and b) water (loading mass = 163 kg in horizontal position)

Fig. 8 shows the response of oil and water hydraulic cylinders at different positions and for different loads on the cylinder at an inlet pressure of 160 bar and a flow of 33 lpm through the oil/water proportional 4/3 directional control hydraulic valve. The smallest movement of the rod in the oil hydraulic cylinder was approximately 200 mm for the horizontal position of the loading mass of 163 kg. The smallest movement of the water cylinder rod was also observed for the the horizontal position with a load 163 kg and was also close to 200 mm. The largest observed movement of the rod in the oil cylinder was approximately 275 mm in the vertical position with a loading mass of 163 kg. The largest observed movement of the water cylinder rod was approximately 258 mm with the load (163 kg) in the vertical position.

3.2. Working pressures

Fig. 9, a shows the working pressures on both ports of the oil hydraulic cylinder for a known signal (Fig. 3), an inlet-system pressure of 160 bar and a loading mass of 163 kg in the horizontal position. The pressure difference between the A and B ports of the oil cylinder was, just to start moving the cylinder rod, 110.1 bar, and just 22.7 bar to move the oil cylinder rod with a constant velocity.

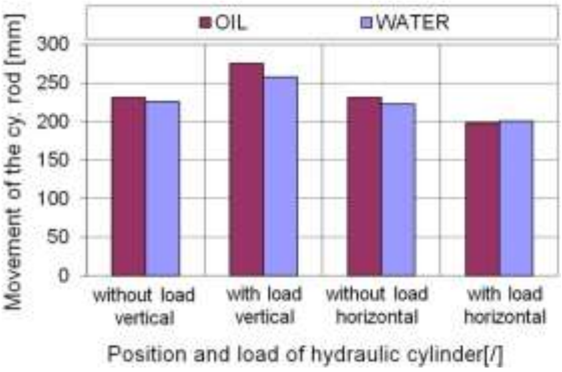
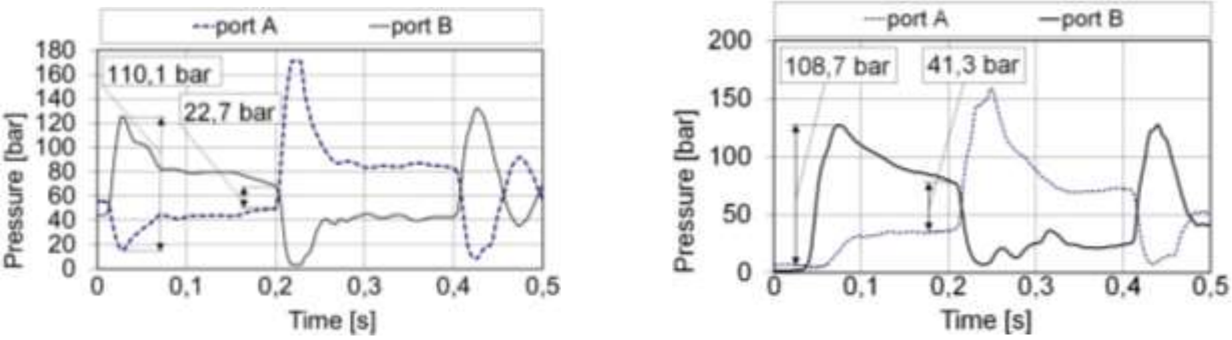


Fig. 8 Movement of the rod of the oil and water hydraulic cylinders in response to a known controlling signal (Fig. 3) for different positions of the cylinder and different loads (flow = 33 lpm, pressure = 160 bar)

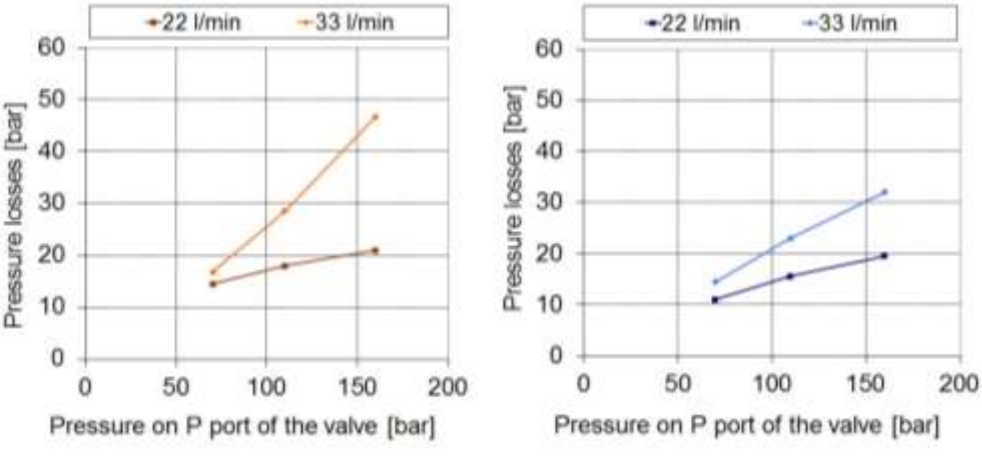
Fig. 9, b shows the working pressures on both ports of the water hydraulic cylinder for a known signal (Fig. 3), an inlet-system pressure of 160 bar and a loading mass of 163 kg in the horizontal position. The pressure difference between the A and B ports of the water cylinder was, just to start moving the cylinder rod, 108.7 bar, and 41.3 bar to move the cylinder rod with a constant velocity.



a

b

Fig. 9 Measuring the working pressures as a response to a known controlling signal (Fig. 3); a) oil and b) water (flow = 33 lpm, pressure = 160 bar, loading mass = 163 kg in horizontal position)



a

b

Fig. 10 Linear and local pressure losses between the inlet port P before the proportional valve and the B port near the hydraulic cylinder (Fig. 1) for an inlet pressure and flow for a) oil and b) water (loading mass = 163 kg in horizontal position, controlling signal as in Fig. 3)

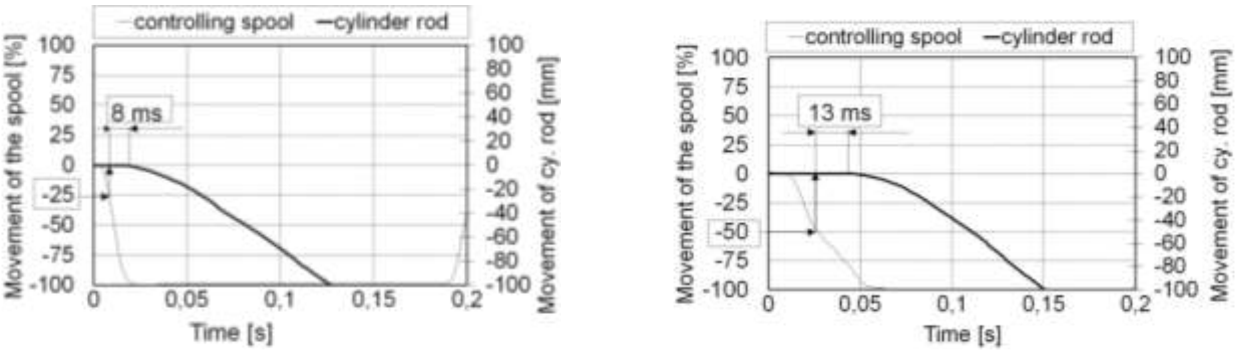
3.3. Pressure losses

Fig. 10, a shows the pressure losses in the oil hydraulic test rig from the inlet P port near the oil proportional directional control valve to the inlet B port near to the oil hydraulic cylinder. The lowest pressure loss of approximately 15 bar occurred at 22 lpm and an inlet pressure of 70 bar. The highest pressure loss of approximately 56 bar occurred at a flow of 33 lpm and an inlet pressure of 160 bar.

Fig. 10, b shows the pressure losses in the water hydraulic test rig from the inlet P port near the water proportional directional control valve to the inlet B port near to the water hydraulic cylinder. The lowest pressure loss of approximately 8 bar occurred at 22 lpm and an inlet pressure of 70 bar. The highest pressure loss of approximately 24 bar occurred at a flow of 33 lpm and an inlet pressure of 160 bar.

3.4. Delay of the movement of the hydraulic cylinder

Fig. 11 show zoomed details of the complete measurement for the response of the hydraulic valve to a known input controlling signal (Fig. 3). Fig. 11, a shows the time delay of the rod of the oil hydraulic cylinder. The oil proportional 4/3 directional control valve has an overlap of 25% in the zero position. The rod of the oil hydraulic cylinder started moving after 8 ms, when the flow gap was opened. Fig. 11, b shows the time delay of the rod of the water hydraulic cylinder. The water proportional 4/3 directional control valve has an overlap of 50% in the zero position. The rod of the water hydraulic cylinder started moving after 13 ms, when the flow gap was opened.



a

b

Fig. 11 Detailed view of measurements of the rod of the hydraulic cylinder after opening the flow gap in the valve a) oil, and b) water (flow = 33 lpm, pressure = 160 bar, loading mass = 163 kg in horizontal position, controlling signal as in Fig. 3)

4. Discussion

The main purpose of the paper was to examine the basic stationary-working parameters of the water hydraulic system and compare it with a similar, well-known oil hydraulic system.

The four following stationary hydraulic parameters were obtained.

A comparison of the cylinder rod movement between the oil and water hydraulics shows very small differences. The largest difference in the movement of the rod between the oil and water hydraulic cylinders was in the vertical position with the load. The rod of the oil hydraulic cylinder moved 17 mm further than the rod of the water cylinder. In general, the movements of the water cylinder rod differed from the movements of the oil cylinder rod by 2 to 6%, which has no significant influence on the functionality of the water hydraulics. The main reason for the differences is the approximately 70% lower compressibility of the water compared to the mineral oil.

Working pressures: Generally, we needed an approximately 20% higher pressure to start the movement of the water hydraulic cylinder rod than for the oil hydraulic cylinder under similar conditions (working parameters, design and materials of the hydraulic cylinders). This is acceptable if we consider the markedly higher coefficient of friction in the water hydraulic cylinder compared to the friction in the oil hydraulic cylinder when used with the same materials (sealing, guidance, cylinder rod and tube) and sliding-surface parameters (hardness and roughness).

Pressure losses: The measurements show from 45 up to 65% lower pressure losses in the water hydraulics than in the oil hydraulics for the same working parameters (tube diameters, working flows, etc.). Besides the ecology-friendly nature of the system this is one of the greatest advantages of water hydraulics. Lower pressure losses lead to a lower energy consumption, a factor that is becoming increasingly important.

Delay of the movement of the hydraulic cylinder: In the water hydraulic test rig we observed longer delays than with the oil hydraulics. For our configuration we observed from 2- to 5-ms-longer delay in the water hydraulics than in the oil hydraulics under similar conditions. The reason for the differences is closely connected with the higher friction inside the water hydraulic cylinder, as was previously described.

Table shows a summary of the stationary-working hydraulic parameters as a comparison between the oil and water hydraulics.

Table

Summary of the differences of the stationary-working parameters between the oil and water hydraulics

No.	Stationary-working parameter	Test rig		Comment (response of water hydraulic compared to oil hydraulic)
		Oil	Water (in comparison with oil)	
1.	Movement of the rod of the hydraulic cylinder	100 %	–2% → + 6%	Equivalent movement
2.1.	Working pressure at the start of movement of the cylinder rod	100 %	–3% → + 21%	Highest pressure, acceptable differences
2.2.	Working pressure at a const. velocity of the cylinder rod	$p_{d,o}$	$p_{W,water} = p_{W,oil} + \sim 20$ bar	Higher pressure is needed; acceptable; further research is required
3.	Liner and local pressure losses	100%	–65% → –45%	High difference – evident advantage of water
4.	Delay time of movement of hydraulic cylinder rod	Δt_o	$\Delta t_{water} = \Delta t_{oil} + (2 \rightarrow 5)$ ms	Acceptable, further research is required

5. Conclusions

The movement of the cylinder rod, being the first obtained response in terms of a hydraulic parameter, was acceptable and comparable in the water hydraulic system relative to the oil hydraulic cylinder rod. The working pressures in the water hydraulics are higher than in the oil hydraulics, but with further development and research, especially with regard to sealing and guidance in the water hydraulic cylinder, it is possible to achieve better, acceptable characteristics and make the performance similar to that of oil hydraulics. This is also linked with a longer delay time in the water hydraulic cylinder.

One of the great advantages of water hydraulics, apart from it being ecologically friendly, is clearly the lower pressure losses. This is very important now, because it is linked to better efficiency and a lower energy consumption. The presented results give us optimism about the possibility of using water hydraulics in the future. In our future research we will look at a comparison of the dynamical parameters of oil and water hydraulics [15].

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HIDRAULINĖS SISTEMOS SU VANDENIU IR ALYVA VEIKIMO CHARAKTERISTIKOS

Reziumė

Šiame straipsnyje pateikiami hidraulinės sistemos su vandeniu ir alyva veikimo charakteristikos. Vandens hidrocilindro judėjimas nuo alyvos hidrocilindro judėjimo skiriasi nuo 2 iki 6%. Vandens hidraulikoje hidrocilindro judėjimui reikalingas slėgis 21% didesnis negu alyvos hidraulikoje. Darbinis slėgis reikalingas hidrocilindro stūmoklio perstūmimui pastoviu greičiu 20 barų didesnis vandens hidraulikoje nei alyvos. Vandens hidraulikos pagrindinis privalumas – mažesni slėgio nuostoliai (nuo 45% iki 65%) lyginant su alyvos hidraulika. Paskutinis hidrocilindro stūmoklio judėjimo nustatytas (įvertintas) stacionarus (pastovus, nesikeičiantis) parametras yra laikas. Vandens hidraulikoje hidrocilindro stūmoklio judėjimas nuo 2 iki 5 ms lėtesnis lyginant su judėjimu alyvos hidraulikoje.

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CHARACTERISTICS OF THE STATIONARY BEHAVIOUR OF WATER- AND OIL-BASED POWER-CONTROL HYDRAULICS

Summary

In this paper we demonstrate with stationary parameters the functionality of water hydraulics in comparison to the usual oil hydraulics. The movements of the water hydraulics’ cylinder rod differed from the movements of the oil hydraulic cylinder by 2 to 6%. The pressures required to start the movement of the cylinder rod were up to 21% higher in the water hydraulics than in the oil hydraulics. The working pressures required to move the cylinder rod with a constant velocity were 20 bar higher in the water hydraulics than in similar oil hydraulics. The great advantage of water hydraulics is the clear 45% to 65% lower pressure losses than in the oil hydraulic. The last stationary parameter that we evaluated was the time delay of the movement of the hydraulic cylinder rod. In water hydraulics this delay was 2 to 5 ms longer than in oil hydraulics.

Keywords: distilled water, mineral oil, hydraulics, proportional directional valve, stationary characteristics.

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