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Advances in Water Power-Control Hydraulics Experimental Research

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Environmental protection regulations are becoming increasingly strict. By using water instead of a hydraulic mineral oil in power-control hydraulic systems we can make a very positive step in complying with these regulations. However, introducing the water instead of oil in power control hydraulics is rather novel and difficult task. Moreover, due to several specifics of water that are also discussed in this paper, several requirements need to be fulfilled in every test rig and test specimen. In this paper we present a newly developed hydraulic test rig that is designed for these specific requirements of water as the hydraulic fluid in power control hydraulics. For direct comparison with oil system, the test rig is designed as a twin system with two equivalent circuits: one for water and one for oil tests. Some interesting results on dynamic response of both systems are presented. They show significant differences between the water and oil hydraulics. With these experiments, the test rig proved the suitability for the research in this new area and showed a good control of the parameters measured.

Keywords: water, mineral hydraulic oil, power-control hydraulics, proportional valve

0 INTRODUCTION

Unwanted leakages of hydraulic liquids, i.e., mineral oils, into the ground and even into the underground drinking-water supplies are a frequent occurrence. One of today's major challenges to prevent harmful consequences for the environment is to use alternative, natural and biodegradable sources of hydraulic fluid. In power-control hydraulics (PCH) there are two ways in which we can protect the environment. The first solution is to use a biodegradable oil [1] to [6] instead of a mineral oil, and the second – and more promising – solution is to use tap water instead of mineral oil. This solution is harmless to the environment, but is very difficult to realize [7] to [9]. Thus only some relatively simple conventional control valves exist on the market today. In spite of many years of water-hydraulics research there is still insufficient understanding of the mechanisms and performance and consequently the available component designs. Some of the reasons lie in many specifics that water has compared to oil in hydraulic systems, which affect already the developing and research phase, and later – in a long term – the performance of the water hydraulic system. Some of those are described below and some are listed in Table 1. For example, for any research of water hydraulics in real-scale components, home made components and test rigs are required, because they do not exist on the market, but this is associated with costs and technical problems. Much lower viscosity of water compared to oil causes high leakage with clearances typical for oil, while reduced clearances result in excessive wear and high friction. Higher working temperatures, which are still common for oil hydraulics, i.e. around 70 or 80 °C, are hardly acceptable for water in hydraulic systems because of the evaporation at local contact spots [10]. In water micro organisms develop with time. They cause several problems with chemical change of water and developing algae that result in sediments. Tribological properties of conventional materials (stainless steel) in water are unfavourable, while comparable material selection is poor, and their properties are unknown. For example, understanding and use of new class of highly potential diamond-like carbon

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Table1. *Properties, the main advantages and disadvantages of water*

Property	***Advantage***	***Disadvantage***
Low viscosity	Lower pressure losses	Higher leakage
High vapour pressure	-	Erosion during the cavitation
High compression modulus / high speed of sound	High / quick responses	Larger ''water-hammer effect''
Corrosion protection	-	Poor – special materials are needed
Lubrication, lubrication film	-	Weak, special materials are needed
Thermal conductivity	High – fast heat transmission	-
Relative cost	Low	-
Environmental impact	No negative impact	-
Temperature range	-	Narrow temperature area: 2 to 50°C
Flash / ignition point	No fire hazard	-

materials [11] to [21] that showed excellent properties in a variety of conditions that are in many ways comparable to those in water hydraulics have not been investigated in detail for this application yet. Furthermore, another class of materials that has already proved excellent properties suitable also for water [22] to [29], i.e. ceramics – are probably too brittle for required dynamic conditions in water hydraulics or are too expensive for precise manufacturing [30], but this was not investigated either. Corrosion and cavitation are other well-known problems related to tribological performance and life-time of the components. Therefore, understanding and research of chemical and tribological properties that affect life and performance, as well as dynamic characteristics of water hydraulics, are required for successful development of new components, which is necessary for wider use of water in power-control hydraulic.

A newly developed hydraulic test rig that is designed for specific requirements of water instead of oil as the hydraulic fluid is presented in this paper. For direct comparison with oil system, the test rig is designed as a twin system with two equivalent circuits: one for water and the other for oil tests. Some interesting results on dynamic response of both systems are presented. They show significant differences between the water and oil hydraulics, but appear optimistic for further research and development of water power-control hydraulics [31].

1 EXPERIMENTAL APPARATUS

1.1 Requirements for Water Hydraulics Test Rig

The purpose of the newly designed test rig was to study the tribological and dynamic properties of water hydraulic systems, with a special focus on a simple, but advanced hydraulic component. A 4/3 valve was selected as a testing specimen. There are several specifics that need to be taken into account, in particular related to properties of water, which significantly differ from those of oil. This relates to design of the rig, selection of sensors and development of measuring systems. Some of very important functions that the test rig should allow to perform are:

- measurement and control of pressure, flow and temperature at the inlet and outlet of the proportional directional control valve;
- sustaining a constant flow through the proportional directional control valve independently of a possible decrease in pump volumetric efficiency;
- simulating different loading conditions and controlling its response;
- easy change and variation of load;
- controlled (pre-defined) fluid temperature via cooling system;

- enabling full automatic life-cycling test with satisfactory safety measures;
- variation of the spools and sleeves (materials and design) for tribological and life-performance studies;
- measurement of the dynamic response of the proportional directional control valve and of the whole system;
- efficient and simple measurement of the leakage of the proportional directional control valve.

1.2 Test Rig

Fig. 1 shows hydraulic circuits of the twin test rig for study of water power-control hydraulics (PCH) that is used for tests of water and oil proportional 4/3 directional control sliding type valve for dynamic-transient and static-long-term life-time tests under the same conditions.

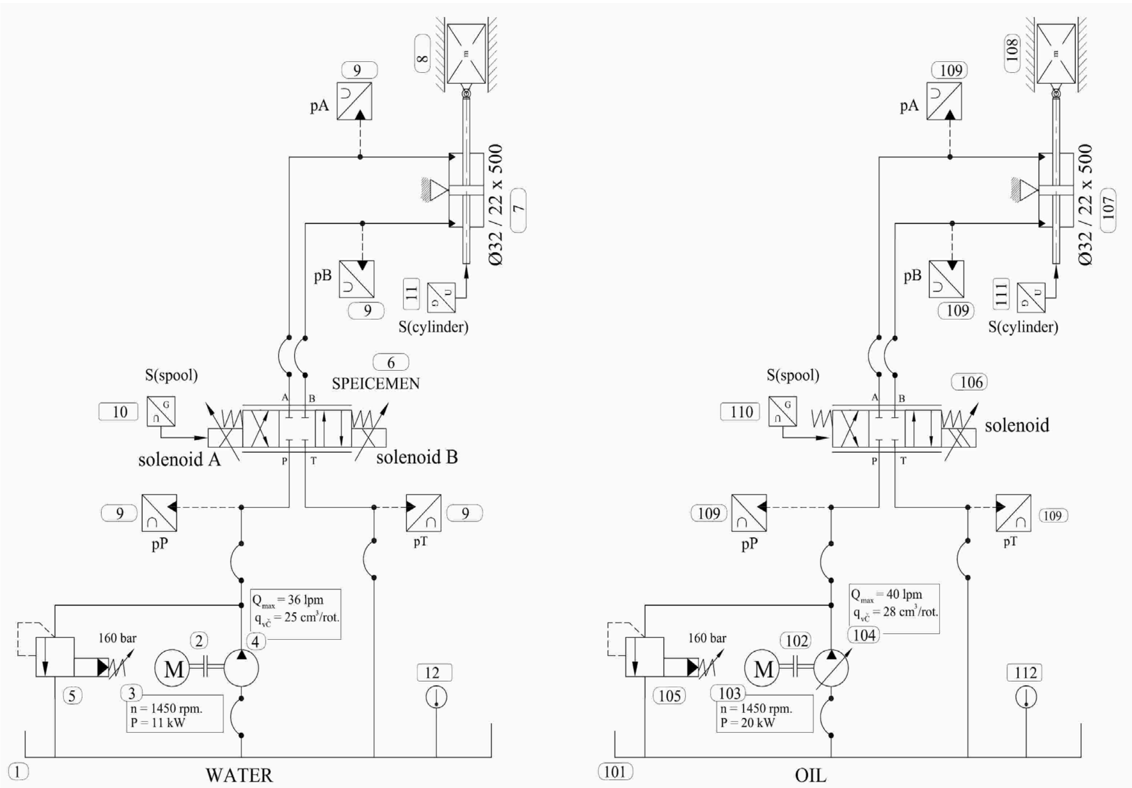

Fig. 1. *Hydraulic circuits of the test rig*

Legend:

Water (a) and Oil (b) PCH part of test rig:

1 and 101…reservoir
2 and 102…clutch
3 and 103…electric motor
4 and 104…axial piston pump
5 and 105…relief valve
6 and 106…4/3 directional control valve-a specimen
7 and 107…double-acting hydraulic cylinder
8 and 108…loading mass of 162 kg
9 and 109…pressure transducers
10 and 110…linear variable differential transformer
11 and 111…linear variable differential transformer
12 and 112…temperature sensor.

The maximum pressure, which is adjusted through the relief valve, was set to 160 bar. The pressures, the displacements and the temperatures of the fluid are set and/or monitored using an in-house developed software.

Fig. 2. *Water power-control part of the test rig*

The water hydraulic test rig (Fig. 2) is assembled from standard, on-market-available, water hydraulic components, except for the proportional directional 4/3 control valve and the hydraulic cylinder.

These two components were designed in LPCH. The tubes for the water and the oil hydraulic cylinders are made from stainless steel and the rod is made from hard-chromium-plated steel. The seals and guide rings for both hydraulic cylinders are the same; they are made from nitrile rubber, polyurethane, and a fabric-based laminate. The oil part of the test rig (Fig. 3) is the same in the term of function. It is assembled from standard components, except for the hydraulic cylinder. The developed oil hydraulic cylinder is typical for oil hydraulic applications. It has the same design, the same dimensions and the same surface properties as the water cylinder.

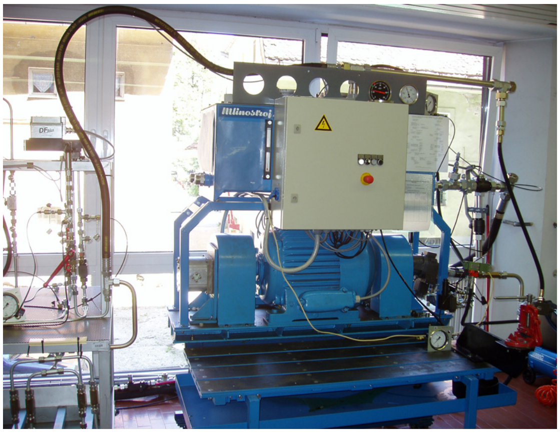

Fig. 3. *Oil power-control part of the test rig*

The important parts used in the new water proportional 4/3 directional control valve – the specimen (Fig. 4 and 5) were a spool with an outer diameter of 12 mm and a sleeve.

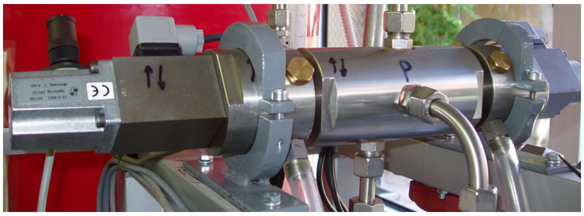

Fig. 4. *The specimen – prototype of the proportional 4/3 directional control valve for water hydraulic*

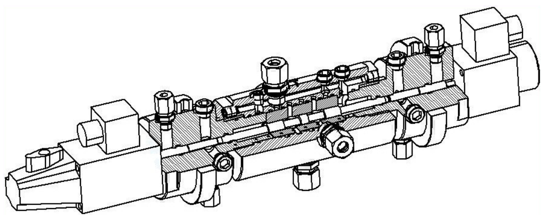

Fig. 5. *Cross section of the prototype proportional 4/3 directional sliding control valve*

The static clearance between the spool and the sleeve was in the range of spool sliding valves of high quality. For this test the spool and sleeve were both made from stainless steel. This material combination, including some other material couples, was previously verified and tested in tribological experiments [31]. For a stainless steel acceptable wear a high coefficient of friction, was obtained in this research. According to these findings, dynamic testing in terms of repeatability due to dimensional stability appears acceptable, but some dynamic transient phenomena can occur as a consequence of too high friction and consequently stick-slip phenomena. The liquid in the water PCH part of the test rig was distilled water, to ensure a neutral environment that does not reflect the water type from any particular part of the world. The liquid in the oil PCH part of the test rig was the mineral oil ISO VG 46.

1.3 Testing Procedure

Tests were performed with a load mass of 162 kg. The load mass was positioned in the vertical direction (Fig. 6).

Fig. 6. *Water (on the left) and oil (on the right) hydraulic cylinder with load masses*

The whole testing procedure was fully automated with the PC software (Fig. 7), 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 second. The electrical signal then stays at that level for 0.28 seconds and holds the spool in the valve in cross-shaped position. After 0.3 seconds 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 seconds 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 seconds. In the final phase the input signal falls from 100 % to zero in 0.01 seconds and the cylinder rod stops to move. The total time of the measurement of one cycle was 2 seconds.

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

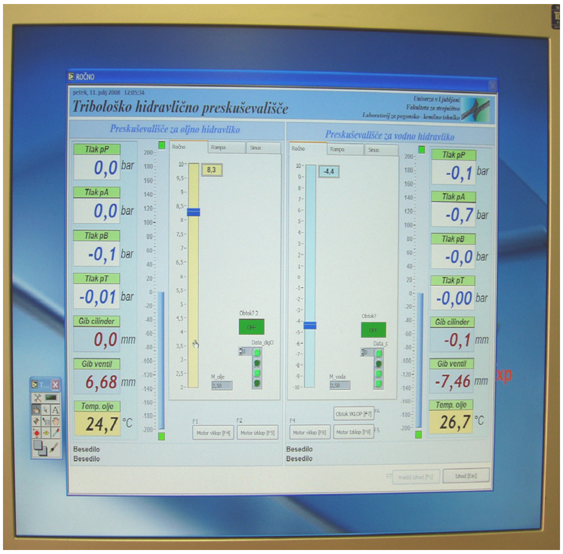

Fig. 7. S*oftware front panel for automation of measurements and control of the system*

2 EXPERIMENTAL RESULTS

Fig. 8 shows the movement of the oil spool and the piston rod of the oil cylinder during a loading cycle with the mass of 162 kg in the vertical position. It shows a regular, smooth curve when moving the spool. The curve representing the movement of the oil cylinder's rod is similarly smooth, as well. However, we could see a distinctive difference in the symmetry between the upward movements and downward movements of the piston rod. The upward movement of the piston rod is nearly 56% shorter than the downward movement. Fig. 9 shows the movement of the water valve spool and the piston rod of the water cylinder during the loading cycle with the mass of 162 kg in the vertical position. The curve of the movement of the spool in the direction of the cross-shape position (energizing solenoid A – Fig.1) of the proportional water valve was smooth.

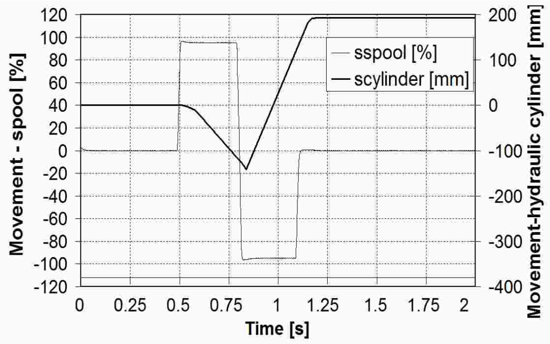

Fig. 8. *Movement of the spool and the piston rod of the cylinder with the mass during the loading cycle in the oil part of PCH*

However, the downward movement of the cylinder rod and the mass has a high irregularity. The spool first moved regularly to its maximum position, but soon it started to oscillate with a low frequency of about 6 Hz. The reason for this could be the stick-slip effect or the key effect and uncontrolled amplification of the input signal during the regulation of the valve. The water cylinder rod and mass have the expected regular response during the movement of the valve spool.

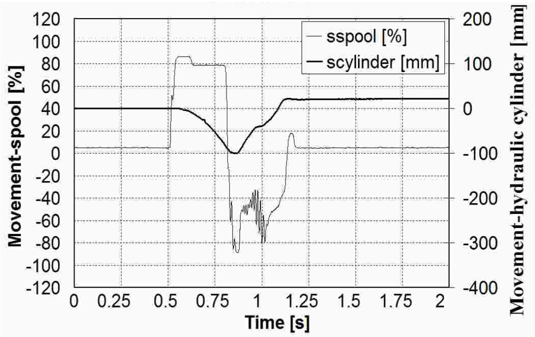

Fig. 9. *Movement of the spool and the piston rod of the cylinder with the mass during the loading cycle in the water part of PCH*

Fig. 10 shows pressure variation at port B of the specimen during the movement of the control spool in the valve of the oil circuit of the test rig. The pressure curve at port B shows a pressure peak up to 82 bars at the start of the movement of the cylinder rod. It is almost 10 bars (Fig. 10-A). Approximately 1.2 s after the start of the measurement we could see a pressure peak of about 20% (Fig. 10-B) more than the static

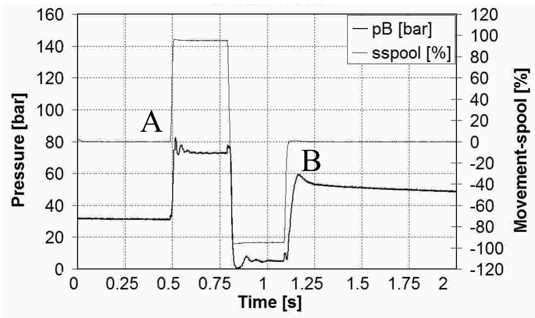

Fig. 10. *Movement of the spool and the pressure changes during the experiment with mass – cycle in the oil part of PCH*

pressure, which could be a consequence of the water-hammer effect.

Fig. 11 shows the pressure variation at port B during the movement of the control spool of the valve in the water circuit of the test rig with the load mass of 162 kg on the cylinder rod. Approximately 20 milliseconds after switching off the solenoid A, the pressure at port B increased up to 160 bar (Fig. 11-A). After this increase the pressure decreased and oscillated with the amplitude up to 125 bar. That is almost 80 bar higher than at the equivalent test in the oil part of the system. The pressure difference from the start to the end of lifting up the cylinder rod and the mass was 35 bar. During the oscillation of the valve spool, the pressure also oscillated with the frequency of approx. 6 Hz and amplitude of approx. 100 bar. In addition, we observed the water-hammer effect approximately 1.2 s after the start of the measurement. The effect amounted up to approximately 190% (Fig. 11-B) over the static pressure.

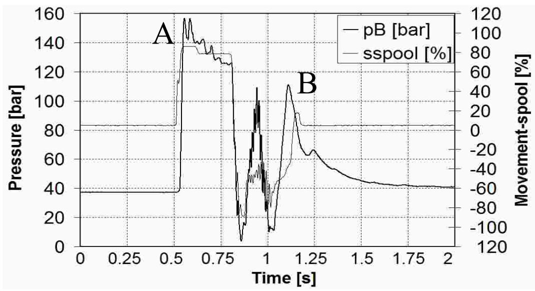

Fig. 11. *Movement of the spool and the pressure changes during the experiment with the mass – cycle in the water PCH*

3 DISCUSSION

A new testing device for the study of water hydraulics has been developed. This device enables studies with oil and water in separate, but equivalent, systems under the same conditions. In this paper we described the apparatus and requirements for the test rig design, and we present some of interesting results.

Generally if we compared the behaviour of the proportional 4/3 directional control valve for water (LPCH design – specimen) with the standard proportional valve for oil with a similar gap between the spool and the sleeve, we could see that the oil valve worked perfectly, as the would have expected, but the water valve has some irregularity in the specific direction of the movement of the spool. The motion of the water spool was very uncertain and irregular. Namely, the spool of the water valve was obviously even blocked in some short period of time during the movement of the spool in cross-shaped position, and most of the time in a parallel-shaped position (downwards moving piston rod). Typically, it is blocked at the side of solenoid B, after approx. 1 s of testing (Figs. 9 and 11). These problems are probably linked with the small gap, the shape irregularity, the surface roughness and the poorer lubrication conditions in the water hydraulics compared to these of the oil system. These problems were anticipated already from tribological investigations of the stainless steel in water under model test conditions [31]. Namely, although the wear was reasonable and comparable to other materials, the friction was very high, what indicates that smooth running is questionable. This was indeed found in the real-scale experiments in this research.

However, the observed irregularity of the movement of the spool in the water hydraulic valve had almost no influence on the movement of the piston rod of the water cylinder, where the curves are similarly smooth as in the case with the oil. Reasons for unsymmetrical movement of the cylinder rod are probably in different friction in the valve and in the cylinder when moving the cylinder rod up and down. However these phenomena need to be further investigated. It is suggested that part of the problems are caused due to the vertical position of the cylinder, which causes asymmetrical motion, as seen in our tests. Future experiments will be focused on better control of the water valve spool and cylinder motion and investigating reasons for the irregularity and uncertainties in behaviour. A new set of experiments will focus on tribological and life-time behaviour of different material combinations in our real-scale conditions. Primarily, various polymers and ceramics are planned for these tests.

Despite of some unfavourable results for the valve spool motion and pressure variation in these experiments, the results appear quite optimistic, especially as it seems that most of the problems relates to the position of the cylinder and too high friction of the stainless steel, which can be replaced, or better optimized for selected application. On the other hand, the test rig proved good control of parameters and suitability for future research of water PCH hydraulics.

4 CONCLUSIONS

1. The test rig proved good control of parameters and suitability for research of water PCH hydraulics.
2. The motion of the valve spool is regular for oil, but unstable for water, probably due to stick-slip and/or grab, caused by high friction of stainless steel in water.
3. The unstable motion of the valve spool in the water system does not result in the unstable motion of the cylinder, which remains similarly smooth and regular as in the case with the oil.
4. The pressure in the water system is, however, affected by the irregular motion of the spool, which seems to be influenced through the electric inputs, as well.
5. As expected, the water-hammer effect was much more obvious with water than with oil.
6. We observed a difference in the motion of the valve spool towards the cross-shaped position compared to the motion towards the parallel-shaped position. The reason is most probably in the small irregularities of the mechanical parts and position of the cylinder, rather than with the physical background, what will be investigated in the future.

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6 NOMENCLATURE

pA	pressure at port A (bar)
pB	pressure at port B (bar)
pP	pressure at port P (bar)
pT	pressure at port T (bar)
sspool	movement of the spool in the valve (%)
scylinder	movement of the piston rod in the hydraulic cylinder (mm)

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