# AN ANALYTICAL COMPARISON OF HYDRAULIC SYSTEMS BASED ON WATER AND ON OIL

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**ABSTRACT**

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. In this paper we present some preliminary results on twin-type hydraulic experiments, employing equal parts containing water and oil. Our initial findings suggest the need for modifications to the test rig, and a comparison of the behaviour between two similar hydraulic test rigs is shown. The main parameters measured during the investigation were the pressures, the spool displacements and the responses of the piston in the double-acting hydraulic cylinder. However, transient phenomena in the water and oil hydraulic test rig were also analysed and compared. Experiments were performed on systems with and without an applied load. The results reveal very different behaviours for the oil and the water hydraulics.

**KEY WORDS**

Water, Mineral oil, Power control, Hydraulics, Proportional valve

## NOMENCLATURE

| | | |
|---|---|---|
| $I_A$ | : | input signal at solenoid A (%) |
| $I_B$ | : | input signal at solenoid B (%) |
| *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) |
| $t_{A,up}$ | : | rising time of the signal for solenoid A (s) |
| $t_{A,d}$ | : | falling time of the signal for solenoid A (s) |
| $t_A$ | : | total working time of the signal for solenoid A (s) |
| $t_{B,up}$ | : | rising time of the signal for solenoid B (s) |
| $t_{B,d}$ | : | falling time of the signal for solenoid B (s) |
| $t_B$ | : | total working time of the signal for solenoid B (s) |

## INTRODUCTION

Unexpected outflows of hydraulic liquids, i.e., mineral oils, into the ground and even into underground drinking-water supplies are a frequent occurrence. One of today's major challenges is to use alternative, natural sources of hydraulic fluid to protect our environment. 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 [1-6] instead of a mineral oil. But this is only a partial solution because biodegradable oil has to contain the necessary additives, which are sometimes detrimental to the environment. The second – and better – solution is to use tap water instead of mineral oil. This solution is harmless to the environment, but is very difficult to realise [7-8]. For water hydraulics a relatively simple conventional control valve already exists on the market; however, the continuous control of water hydraulic systems is needed for almost every hydraulic machine. Nowadays, the market for disposable water-hydraulics components for continuous control is very small. Even if they can be located, they are normally very complicated and with a lot of parts.

Despite many years of water-hydraulics research there is still insufficient understanding of the mechanisms and performance.

In this work we present some preliminary experiments on the design of a new, continuous control 4/3 directional control valve for use with water.

## EXPERIMENTAL

### Test rig

A dedicated twin test rig for the study of water power-control hydraulics (PCH) was built [9]. The test rig can be used for tests of a water and an oil proportional 4/3 directional control sliding type valve for dynamic-transient and static-long-term life-time tests under the same conditions.

The main parts of the water hydraulic half of the test rig are as shown in Figure 1:

a reservoir, an axial piston pump, a relief valve, a specimen-proportional directional 4/3 control valve, a double-acting hydraulic cylinder with a through rod, a loading mass of 162 kg, four pressure transducers and two linear variable differential transformers (LVDTs). One transformer is for measuring the spool movement and the other is for measuring the rod that moves in the hydraulic cylinder.

The high-pressure hydraulic pump delivers approximately 30 lpm of water flow to the P port of the specimen. It is controlled from a PC using special software.

We observed the pressures, the displacements and the temperatures of the fluid in the reservoir. The pressure relief valve was set to 160 bar.

The water hydraulic test rig (Fig. 2) is assembled from standard, on-market-disposable, water hydraulic components, except for the proportional directional 4/3 control valve and the hydraulic cylinder. These two components were designed and constructed in our laboratory for power-control hydraulics. 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 hydraulic test rig (Fig. 2) is the same in terms of function, but assembled from standard, on-market-disposable components, except for the hydraulic cylinder. The oil hydraulic cylinder is typical for oil hydraulic applications. It has the same construction, the same dimensions and the same surface properties as the water cylinder.

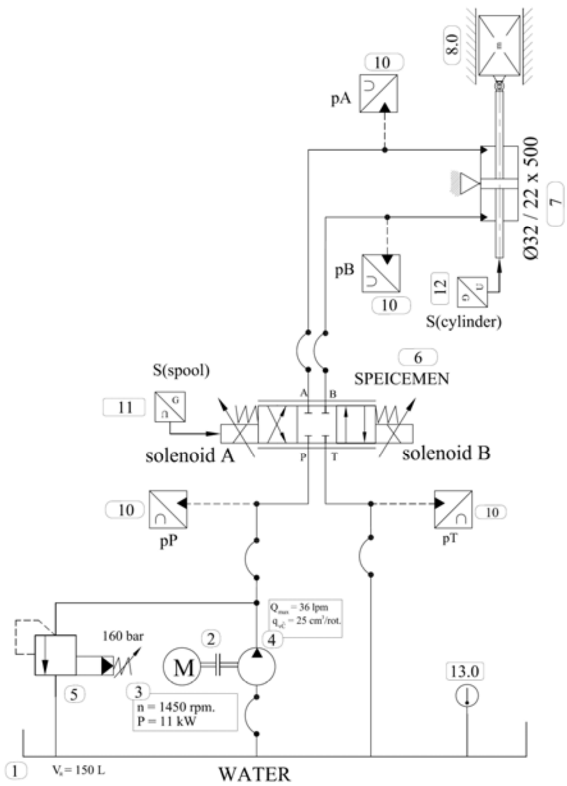


Figure 1 Water hydraulic test rig for dynamic tests

Figure 2 Water (on the left) / oil (on the right) power-control part of the test rig

**Samples**

The test specimens used in the new, water proportional 4/3 directional control valve were a spool with an outer diameter of 12 mm and a sleeve. The clearance between the spool and the sleeve was less than a few micrometers. In this test the specimens were both made from stainless steel. This material combination, including some other material pairs, was tested in previous tribological experiments [9]. 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.

**Testing procedure**

Two types of test were performed: one with a load mass of 162 kg and one without. This load mass was positioned in the vertical direction (Fig. 3).

Figure 3 Water (on the left) and oil (on the right) hydraulic cylinder with load masses

The same experimental procedure was used in both types of test, and the whole testing procedure was fully automated with the PC software.

Fig. 4 shows the loading cycle for each experiment, which is described in more detail in Table 1. The table presents the times for the various stages of the cycle. As shown in Fig. 4, the input signal consists of six phases.

The first phase includes the input signal for moving the spool in the cross-shaped position of the valve. As a consequence, the piston rod of the cylinder starts to move up. This signal increases from 0% to 100% in $t_{A,up}$ seconds. The signal then stays at that level for ($t_A$ - $t_{A,up}$ – $t_{A,d}$) seconds. After that, the third phase of the input signal begins. It lasts for $t_{A,d}$ seconds and causes the spool to return to the zero position. The piston rod in the cylinder then stops moving.

In the fourth phase is the input signal for moving the spool in the parallel-shaped position of the valve. As a consequence, the piston rod of the cylinder starts to move downwards. Increasing the signal from 0% to 100% takes $t_{B,up}$ seconds. This input signal for the parallel-shaped position stays at 100% for ($t_B$ – $t_{B,up}$ – $t_{B,d}$) seconds. In the final phase the input signal falls from 100% to 0% in $t_{B,d}$ seconds.

During the whole set of experiments the signal was a maximum, i.e., 100% for both proportional solenoids, for both the water and the oil proportional 4/3 directional control valve.

## RESULTS

**Experiments - without mass**

Fig. 5.a shows the movement of the spool and the piston rod of the cylinder during the loading cycle without the mass load in the oil PCH. The motion curve of the spool is smooth and without any visible mistakes. The second curve, which represents the response when moving the control spool, is similarly smooth and nearly symmetrical. The downward movement of the oil-cylinder piston rod was approximately 75% of the upward movement for the same, symmetrical input signal.

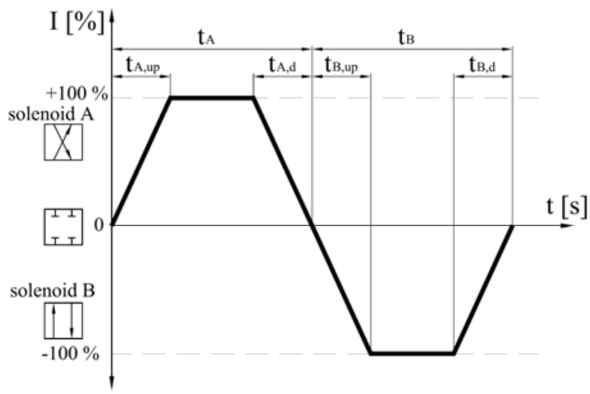


Figure 4 Input signal (time ramp) for specimen

Table 1 Setting the time ramp for the water and oil proportional directional 4/3 control valve

| $t_A$ | $t_{A,up}$ | $t_{A,d}$ | $I_A$ | $t_B$ | $t_{B,up}$ | $t_{B,d}$ | $I_B$ |
|---|---|---|---|---|---|---|---|
| 0,3 s | 0,01 s | 0,01 s | 100 % | 0,3 s | 0,01 s | 0,01 s | 100 % |

Fig. 5.b shows the movement of the spool and the piston rod of the cylinder during the loading cycle without any mass load in the water PCH. If we look carefully at the motion curve of the spool we can see the first irregularity, i.e., a peak near to 50% of the signal of the spool moving to the cross-shaped position of the proportional valve. This occurred approximately 0.55 s after the start of the measurement. However, there might

be a stick-slip effect or a key-effect because of the small gap, the shape irregularity and the surface roughness. During the de-energizing of the first solenoid for lifting the mass, the movement of the spool from the cross-shaped position of the proportional valve to the zero position showed no irregularity. This part of the curve is smooth. A larger irregularity in the spool's motion occurred at approximately 50% of the negative signal and a time approximately 0.8s after the start of the measurement. Here we were able to see the momentary key-effect of the spool. After that the electrical, closed regulation loop increased the signal to put the spool in the desired position. The spool jumped and the regulation loop subsequently decreased the signal. So there was a strengthening oscillatory movement of the spool using electrical regulation. The cylinder rod's motion curve shows the response of the hydraulic cylinder during the movement of the spool. This curve is quite smooth, but unsymmetrical. The reason for the unsymmetrical shape might lie in the unsymmetrical and irregular input signal, the unsymmetrical movement of the spool or the different friction in the valve and the hydraulic cylinder when moving up and down the piston rod. In the case of the experiment without any applied mass there was a larger unsymmetrical displacement of the water cylinder in comparison with the oil cylinder. The downward movement of the water cylinder's piston rod was only approximately 33% of the upward movement for the same, symmetrical input signal.

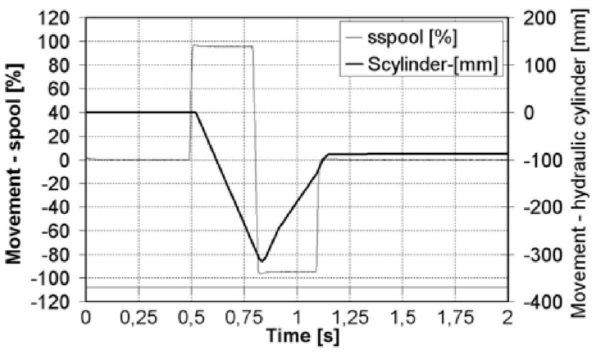


Figure 5.a Movement of the spool and the piston rod of the cylinder without any mass during the loading cycle in the **oil** PCH

Fig. 6.a shows the pressure response at port B when moving the control spool in the oil PCH part of the test rig without any loading mass. Port B is on the pressure side of the cylinder piston for lifting the rod up. The pressure curve at the port B shows a pressure peak at the start of the movement of the rod of the cylinder at about 8-bar working pressure. At the end of this phase we observe another, similar, pressure peak. Similar pressure peaks were obtained for the reverse motion of spool

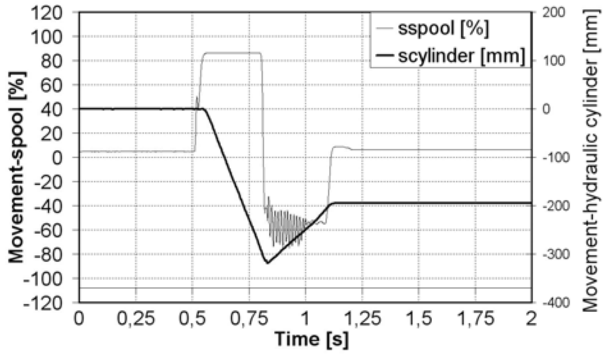


Figure 5.b Movement of the spool and the piston rod of the cylinder without any mass during the loading cycle in the **water** PCH

(holding the spool in a parallel-shaped position); however, this is not so important, because they are at a very low pressure level. The maximum pressure when moving the piston rod in the oil cylinder was close to 72 bar, at the start of the experiment. Additionally, we observed a water-hammer effect approximately 1.2 s after the start. The effect corresponded to approximately 8% over the static pressure.

Fig. 6.b shows the pressure response at port B when moving the control spool in the water PCH part of the test rig without any loading mass. The pressure curve of port B shows a pressure peak of around 25 bar above the working pressure, for upward movements of the piston in the water cylinder. The maximum pressure when moving the piston rod in the water cylinder was close to 100 bar at the start of the experiment. This is almost 30 bar more than in the case of the oil. During this transient period the shape of the pressure curve for a constantly increasing pressure was smooth. After obtaining a parallel position of the valve the pressure started to oscillate according to the oscillations of the spool in the proportional 4/3 directional valve. Approximately 1.2 s from the start of the measurement we could see a pressure peak of about 30% over the static pressure, which could be a consequence of the water-hammer effect.

**Experiments – with mass in the vertical position**

Fig. 7.a shows the movement of the oil spool and the piston rod of the 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. Similar to this curve is the curve for moving the oil cylinder's rod. During the smooth movement of the curve of the piston rod of the oil cylinder we could see distinctive differences in the symmetry between the upward movements and downward movements of the piston rod. Here we obtained an inverted unsymmetrical curve, in contrast to the case without mass (Fig. 5.a).

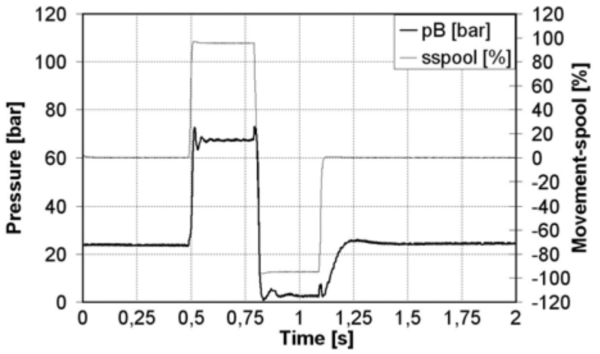


Figure 6.a Movement of the spool and pressure changes during the experiment without any mass – cycle in the **oil** PCH

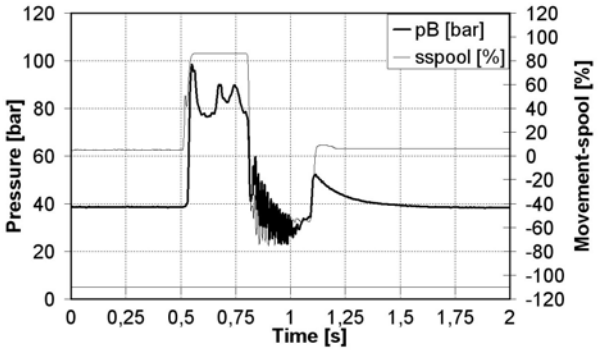


Figure 6.b Movement of the spool and the pressure changes during the experiment without any mass – cycle in the **water** PCH

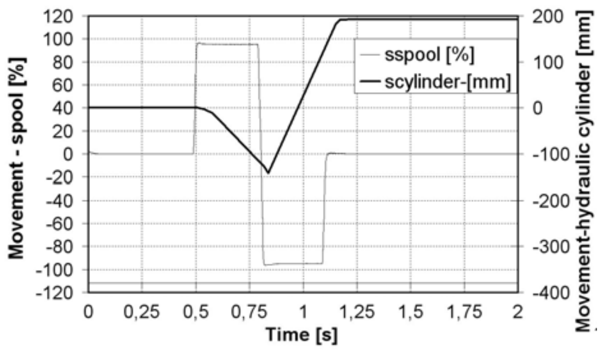


Figure 7.a Movement of the spool and the piston rod of the cylinder with the mass during the loading cycle in the **oil** PCH

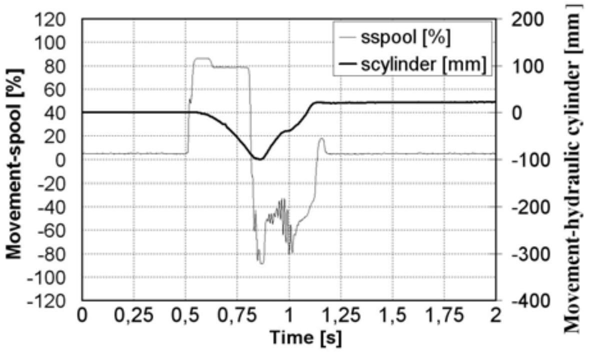


Figure 7.b Movement of the spool and the piston rod of the cylinder with the mass during the loading cycle in the **water** PCH

The upward movement of the piston rod is nearly 56% less than the downward movement.

Fig. 7.b shows the movement of the water spool and the piston rod of the 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 of the proportional water valve was smooth. The second curve, which represents the downward movement of the cylinder rod and the mass, has a major 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. 8.a shows the pressure response at port B on the movement of the control spool in the oil PCH part of the test rig with the loading mass of 162 kg. The pressure curve at port B shows a pressure peak at the start of moving the rod of the cylinder by about 10 bar around the working pressure. The maximum pressure when moving the piston rod in the oil cylinder with the mass was close to 82 bar at start of the experiment. Approximately 1.2 s after the start of the measurement we could see a pressure peak of about 20% more than the static pressure, which could be a consequence of the water-hammer effect. This effect was 12% higher than in the case without any mass.

Fig. 8.b shows the pressure response at port B when moving the control spool in the water PCH part of the test rig with a loading mass of 162 kg. Approximately 20 milliseconds after switching off the solenoid A, the pressure at port B increased up to 160 bar (absolute). After this the pressure decreased and oscillated up to 125 bar. This is almost 80 bar higher than in the similar case with oil. The pressure difference from the start to the end of lifting up the cylinder rod and the mass was 35 bar. In parallel with the oscillating of the movement of the spool was an oscillating pressure with a frequency of approximately 6 Hz and an amplitude of approximately 100 bar. In addition, we observed the water-hammer effect approximately 1.2 s after the start of the measurement. The effect amounted to approximately 190% over the static pressure.

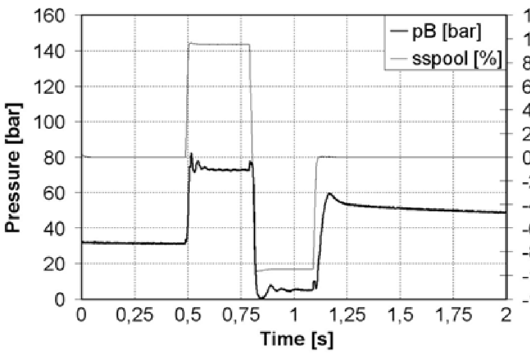


Figure 8.a Movement of the spool and the pressure changes during the experiment with mass – cycle in the **oil** PCH

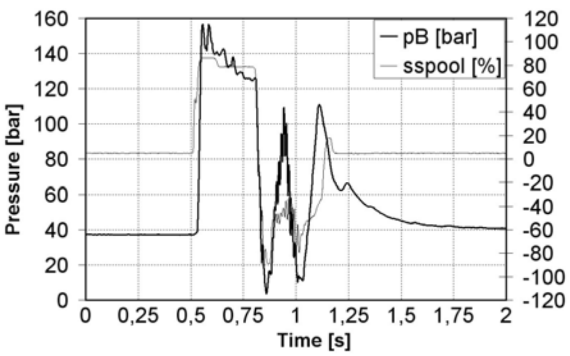


Figure 8.b Movement of the spool and the pressure changes during the experiment with the mass – cycle in the **water** PCH

## DISCUSSION

A new testing device for the study of water hydraulics was developed; this device enables studies with oil and water in separate, but equivalent, systems under the same conditions. In this work we present some of our preliminary results.

In general, if we compare the behaviour of the proportional 4/3 directional control valve for water (our 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 we would expect, but the water valve has some irregularity in the specific direction of the movement of the spool.

If we compare Fig. 5.a and Fig. 5.b we see that the motion curve for the oil spool is smooth and similar to the input electrical signal (Fig. 4 and Tab. 1). Meanwhile, the motion of the water spool is coincidental. The spool for the water valve obviously blocked in a short time, 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 approximately 1 second of testing (Fig. 5.b, 6.b, 7.b and 8.b).

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 the oil system. 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 to the case with the oil.

## CONCLUSIONS

1. The motion of the spool is regular for oil, but unstable, probably due to stick-slip and/or grab, for water.
2. The unstable motion of the spool in the water system does not result in the unstable motion of the cylinder, which remains similarly smooth and regular to the case with the oil.
3. 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.
4. In the experiments with the mass, the irregularity of the water-spool motion remains, and is even more pronounced than when there is no mass.
5. As expected, the water-hammer effect was much more pronounced with water than with oil.
6. We observed a difference in the motion of the 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, rather than with the physical background, which will be investigated in the future.

## ACKNOWLEDGEMENTS

The authors wish to acknowledge the Slovenian Research Agency ARRS (Proj. Nr.: L2-9407 from 2006) for partial funding of the work. The authors are sincerely grateful to the company Tajfun Planina d.o.o. (Planina pri Sevnici, Slovenia), for financial and technical support. The majority of the components of the oil test rig were donated by the Kladivar Žiri d.d. (Žiri, Slovenia). The authors are very grateful for this support.

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