Oil- and water-based continuous control valve

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Abstract

Purpose – Environmental protection regulations are becoming increasingly strict. Using water instead of a hydraulic mineral or biodegradable oil in power-control hydraulic systems is a very positive step towards complying with these regulations. Since water hydraulics has many specifics, primarily related to lower viscosity and lubricity of water compared to oil, which greatly affects the leakage, and even more the friction and wear in these systems, a dedicated test rig is required for performing research with the real-scale components. The purpose of this paper is to present some preliminary representative results on dynamic responses of the two hydraulic circuits with and without a mass load.

Design/methodology/approach – The paper presents the newly developed dedicated test rig and its dynamic characteristics when used with water and oil as hydraulic fluid. Hydraulic pressures and motions of spool and piston in the two different fluids were of special interest.

Findings – The results clearly show their dependence on friction properties of selected materials in different hydraulic fluids. While the oil valve worked perfectly, water valve has some irregularity, 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.

Originality/value – The observed irregularity of the movement of the spool in the water hydraulic valve has almost no influence on the movement of the piston rod of the water cylinder, which is a very promising result for future research on water hydraulics.

Keywords Water, Oils, Hydraulic engineering, Valves (Fluids), Test equipment

Paper type Research paper

Nomenclature

I_A = input signal at solenoid A (per cent)
I_B = input signal at solenoid B (per cent)
p_A = pressure at port A (bar)
p_B = pressure at port B (bar)
p_P = pressure at port P (bar)
pT = pressure at port T (bar)
$s$spool = movement of the spool in the valve (per cent)
$s$cylinder = 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)

1. Introduction

Unexpected outflows of hydraulic liquids, i.e. mineral oils, from machinery into the ground and even into underground drinking-water supplies are frequent occurrence in mining, forestry, agriculture, and other similar industrial and agricultural disciplines. One of the today's major challenges to protect our environment from these accidents is to use alternative, natural sources of hydraulic fluid. In power-control hydraulics (PCH), there are two possible ways in which we can protect the environment through selection of the fluids. The first solution is to use a biodegradable oil (Bartz, 1998; Adhvaryu *et al.*, 2004; Kalin *et al.*, 2007; Vercammen *et al.*, 2004; Ramalho and Miranda, 2007; Kalin and Vižintin, 2006; Igartua *et al.*, 1998) instead of a mineral oil. But this is only a partial solution because biodegradable oils are not completely degradable and also 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, which is harmless to the environment, but is very difficult to realise (Backe, 1999; Trostmann, 1996; Kim *et al.*, 2005; Tan *et al.*, 2003). For water hydraulics, a relatively simple conventional control valve already exists on the market (Danfoss Nessie, 2008); 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 and are thus much more expensive then equivalent oil-hydraulic components.

Despite many years of water-hydraulics research there is still insufficient understanding of the mechanisms and performance of these parts, which seem to be one of the reasons for this slow increase in use of water hydraulics. There are several obvious technical questions that need to be solved related to use of water instead of oil. For example, much lower water viscosity may increase the leakage if the clearances are too high. On the other hand, reduced clearances increase the amount of asperity contacts, thus friction and wear. Furthermore, water is much poorer "lubricant" compared to oil and thus the protection against wear in such reduced clearance conditions is even worse. Accordingly, new component designs are needed, as well as new wear resistant material combinations, tailored for water and high frequency conditions. For example, ceramics and similar materials have high potential for use in the key components under these critical conditions (Lancaster *et al.*, 1992; Kalin *et al.*, 1996; Basu *et al.*, 2003; Kalin and Vižintin, 2000;

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Novak *et al.*, 1999), but of course, primarily their high machining costs for required reduced roughness (Wong *et al.*, 1998; Kalin and Jahanmir, 2003; Agarwal and Rao, 2005) and brittleness (Adachi *et al.*, 1997; Suh *et al.*, 2008; Okada, 2008) are their negative points. Corrosion is an another parameter that reduces the available material selection, but again, with using the ceramic parts, this is nicely overcome, as some ceramic materials have excellent properties in water (Andersson, 1992; Zhou *et al.*, 2006; Novak *et al.*, 2001; Kalin *et al.*, 2003; Xu and Kato, 2000). On the other hand, different polymers are less expensive and sensitive to dynamic mechanical loads, but are less wear resistant and sometimes sensitive to water environment (Yamamoto and Hashimoto, 2004; Yamamoto and Takashima, 2002; Davim *et al.*, 2001). Further problems are also related to increased bulk and contact temperature (Kalin, 2004), which should with water remain at lower values than with oil due to water evaporation. This negative point, however, endorse potential for new low friction materials, which reduce contact temperature and frictional heating. For example, diamond-like carbon coatings are well-known low friction material (Donnet and Grill, 1997; Matthews *et al.*, 1998; Fontaine *et al.*, 2001; Kalin *et al.*, 2004, 2006, 2007; Neville and Matthews, 2007; Andersson *et al.*, 2003; Velkavrh *et al.*, 2008; Barriga *et al.*, 2006; Kano, 2006) and their use has already confirmed the effects of reduced temperatures in hydraulics and gears (Kalin *et al.*, 2008; Kalin and Vižintin, 2005). Nevertheless, there are also many issues related to change of design for optimisation of related dynamic effects.

As obvious from above, material selection and their tailoring for relevant conditions seems to be a crucial part of the innovation and optimisation in water hydraulics, especially in relation to necessary change of component design and understanding dynamic effects. Since water hydraulics has many specifics, a dedicated test rig is required for performing research with the real-scale components. Therefore, we have developed a test rig that allow experimental work in two separate circuits, using water and oil hydraulic systems with continuous control 3/4 valves as primary testing objects. Real scale tests are performed in this test rig using the selected material pairs that are first verified in our preliminary model tribological studies (Majdic *et al.*, 2008). However, prior to start with long-term tribological investigation of hydraulic components under real-scale conditions, dynamic differences in response from oil and water as hydraulic fluids need to be observed and understood. Based on this, some design parameters should be adjusted or modified for optimal test rig performance. Therefore, in this paper, we present newly developed and dedicated test rig with it's dynamic characteristics when used with water and oil as hydraulic fluid. A special interest is focused on hydraulic pressures and motions of spool and piston rod in the two different fluids.

2. Experimental

2.1 Test rig

A dedicated twin test rig for the study of water PCH was built for tests of a water and an oil proportional 4/3 directional control sliding type valve. Two types of tests are planned with this test rig: dynamic-transient tests and static-long-term life-time tests. The test rig allows simultaneous testing of both systems, and what is more important, it enables experiments under the same operational conditions in water and oil circuits. The water hydraulic part of the test rig 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 in our laboratory for PCH. 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 circuit of the hydraulic test rig 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 and was made in-house. It has the same design, the same dimensions and the same surface properties as the water cylinder. The power-control parts of the rig and the cylinders for water and oil circuits are shown in Figures 1 and 2, respectively.

Figure 1

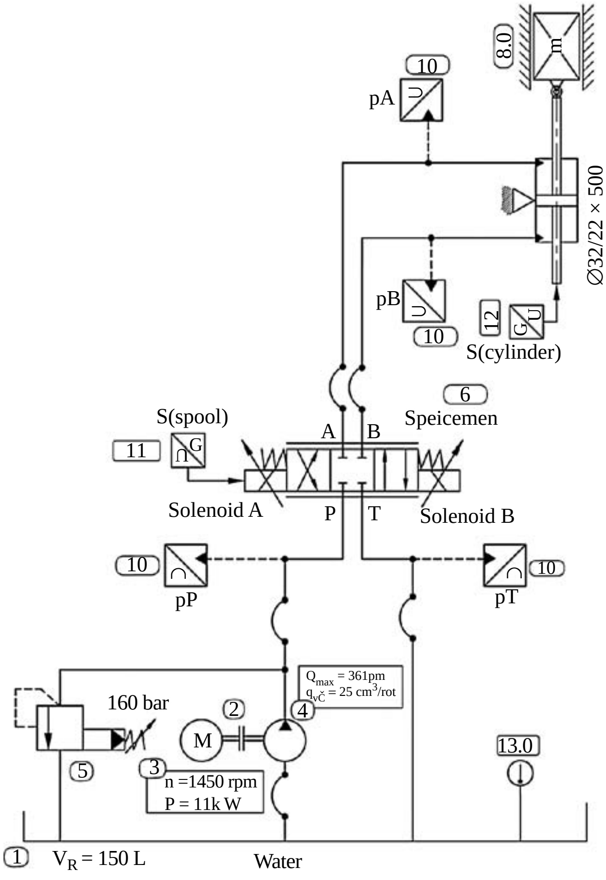
Figure 2

The main parts of the water hydraulic half of the test rig are as shown in detail in Figure 3: 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. One transformer is used 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 l/min of water flow to the pressure port of the specimen. The pressure relief valve was set to 160 bar, which is a maximum pressure allowed in the system. As mentioned above, the oil-circuit of the test rig contains equivalent parts that are, however, designed for oil hydraulic systems. The operational parameters are controlled from a PC using an in-house developed software. The testing data measured in the test rig were the pressures, the displacements of spools and pistons and the temperatures of the fluid in the reservoir. All these were continuously recorded using the acquisition system throughout the test. A short duration experiments for evaluating the "dynamic response" were performed in this work and representative spectra for water and oil system are reported.

2.2 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 work, the specimens were both made from stainless steel. This material combination, including some other material pairs, was tested in our previous tribological experiments (Majdic *et al.*, 2008) and fundamental tribological properties were assessed. The results indicate reasonably good wear performance – within acceptable limits and comparable to other well-performing couples. Friction, however, was higher than more advanced material couples. These results therefore suggest repeatable testing for assessment of dynamic properties without every-time dismounting to evaluate wear. Leakage that was measured during the tests confirmed appropriate and "no-wear" conditions. 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.

Figure 3



2.3 Testing procedure

Two types of the "dynamic-response" tests were performed: one with a load mass of 162 kg and one without the mass. This load mass was positioned in the vertical direction (Figure 2).

The same experimental procedure was used in both types of test, and the whole testing procedure was fully automated with the PC software. Figure 4 shows the loading cycle for each experiment, which is described in more detail in Table I. The table presents the times for the various stages of the cycle. As shown in Figure 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 per cent 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.

Figure 4

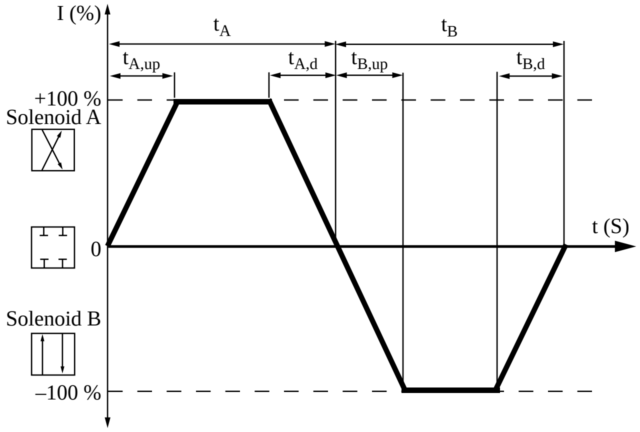


Table I Setting the time ramp for the water and oil proportional directional 4/3 control valve

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%

Increasing the signal from 0 to 100 per cent takes $t_{B,up}$ seconds. This input signal for the parallel-shaped position stays at 100 per cent for ($t_B - t_{B,up} - t_{B,d}$) seconds. In the final phase the input signal falls from 100 to 0 per cent in $t_{B,d}$ seconds. During the whole set of experiments, the signal was a maximum, i.e. 100 per cent for both proportional solenoids, for both the water and the oil proportional 4/3 directional control valve.

3. Results

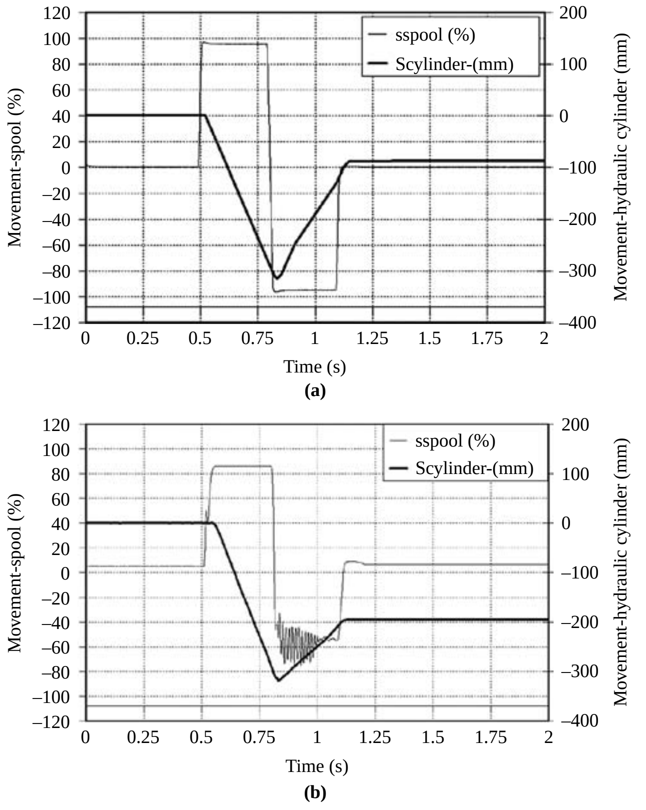
3.1 Experiments – without mass

Figure 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 per cent of the upward movement for the same, symmetrical input signal.

Figure 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 per cent 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 per cent of the negative signal and a time approximately 0.8 s 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 per cent of the upward movement for the same, symmetrical input signal.

Figure 6(a) shows the pressure response at port B of the valve (Figure 3) 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 eight-bar working pressure. At the end of this phase, we observe another, similar, pressure peak. Similar pressure

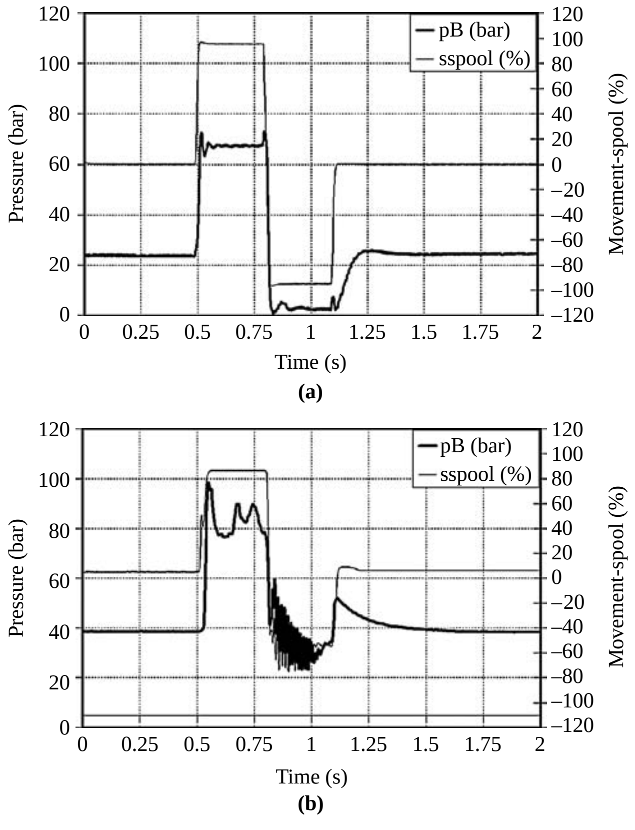
Figure 5



(a)

(b)

Figure 6



(a)

(b)

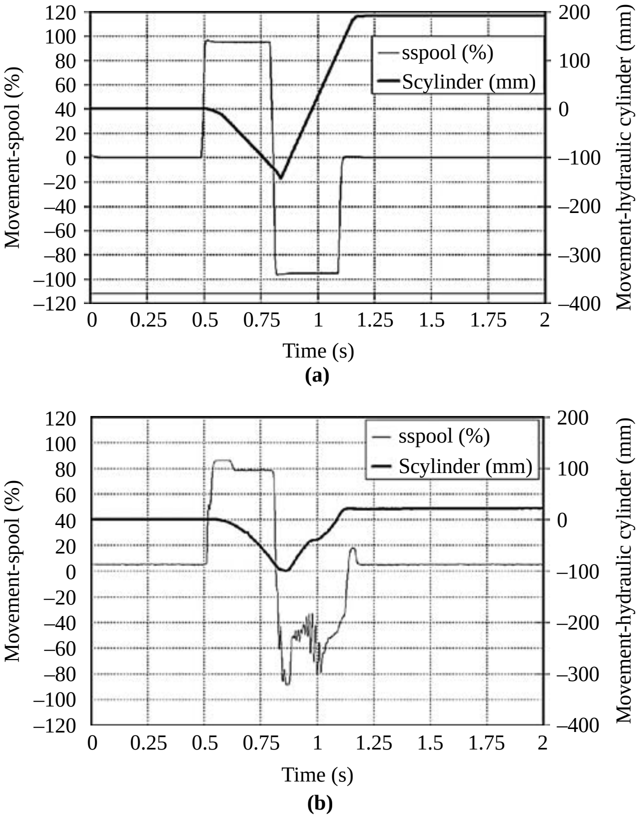
peaks were obtained for the reverse motion of spool (holding the spool in a parallel-shaped position); however, this is not so important, because they are at a very low-pressure level. The maximum pressure when moving the piston rod in the oil cylinder was close to 72 bar, at the start of the experiment.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

Figure 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 per cent over the static pressure, which could be a consequence of the water-hammer effect.

3.2 Experiments – with mass in the vertical position

Figure 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 (Figure 5(a)). The upward movement of the piston rod is nearly 56 per cent less than the downward movement.

Figure 7



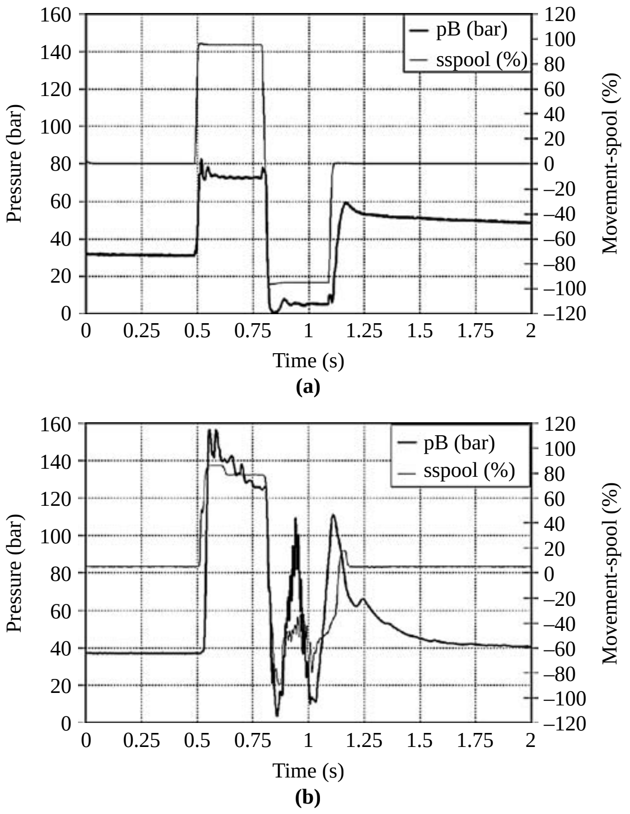
(a)

(b)

Figure 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.

Figure 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 per cent more than the static pressure, which could be

Figure 8



(a)

(b)

a consequence of the water-hammer effect. This effect was 12 per cent higher than in the case without any mass.

Figure 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 ms 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 per cent over the static pressure.

4. 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 representative results on dynamic responses of the two hydraulic circuits with and without a mass load.

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 Figure 5(a) and (b), we see that the motion curve for the oil spool is smooth and similar to the input electrical signal (Figure 4 and Table I). 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 s of testing (Figures 5(b), 6(b), 7(b) and 8(b)). These irregularities 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. Therefore, it is clear that high friction of the steel/steel couple, which was measured significantly higher compared to better tribological pairs, such as those with ceramic materials (Majdic *et al.*, 2007), have a negative effect on the spool motion in water circuit, supporting the initial hypothesis that new tailored material pairs need to be used for the water hydraulic systems. This motion is a major drawback of the water system compared to oil in present experiments. Namely, 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.

Another observation is that the water-hammer effect was more pronounced with water than with oil, however, this need to be treated through optimised design principles, which will be critical at the final valve development stage, rather than at this experimental-valve design.

5. Conclusions

- The motion of the spool is regular for oil, but unstable, probably due to stick-slip and/or grab, for water system, caused by non-optimal valve material combination (steel/steel) in water-lubricated conditions. This is a major drawback of water hydraulic system compared to oil observed in our experiments, clearly indicating that new tailored tribological conditions need to be established between the spool and the sleeve in water systems.
- 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.
- 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.
- 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.
- As expected, the water-hammer effect was much more pronounced with water than with oil.
- 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 further investigated in the future.

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