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FAST SWITCHING VALVE FOR LOW-PRESSURE WATER HYDRAULICS

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ABSTRACT

Pneumatics are widely used in low-pressure systems, especially in environments where cleanliness is presumed; however, efficiency of pneumatic systems can be considerably low due to leakages and compressibility of air. Hydraulic systems, instead, could provide better efficiency and control dynamics for low-pressure applications with even smaller components. A major disadvantage of traditional hydraulics, however, is pollution; oil cannot be used in clean environments. Unlike oil hydraulics, water hydraulics can be considered as clean technology. In addition to the environmental benefits, water-based fluids as a hydraulic medium are safer to use, but still they can become less expensive than oil-based liquids in process of time. A reason for lack of interest in water hydraulics is limited availability of modern components. In this paper, design and measured characteristics of a fast switching valve for low-pressure water hydraulics are presented. The seat valve is supposed to operate in pressures under 1 MPa. In addition, 12 VDC opening boost voltage will be used, whereas current is limited to 2.5 A, giving the preconditions for the design process. The magnetic circuit of the valve is dimensioned based on basic equations of electromagnetics and iterative simulations. Despite miniature size, the valve has flow capacity beyond 1 l/min at 0.5 MPa pressure difference but its switching energy and power consumption are very low. In addition, the developed valve has fast response time: the opening and closing takes well under 2 ms each.

KEYWORDS: On/off valves, water hydraulics

1 INTRODUCTION

1.1 Low-pressure applications

Low-pressure applications, such as light manipulators and robots used in material handling and packaging, for example, have traditionally been pneumatic. Rather new area of low-pressure applications is soft robotics, which researches actuators inspired by nature [1]. Fluidic soft-bodied robots are usually composed of compliant rubber materials allowing elongation, bending or twisting when pressurizing channels inside the actuator. According to the survey, soft robotics can be utilized in application areas such as locomotion and manipulation. In addition, medical and wearable applications can be developed by means of the new technology. For example, soft robotic rehabilitation devices or orthoses may replace the rigid ones in the future. So far, these systems have also been pneumatic rather than hydraulic.

A disadvantage of pneumatic systems is their low efficiency due to leakages and compressibility of air. Low-pressure water hydraulics can provide an alternative for pneumatics. In addition to enhanced energy efficiency, the size of an overall system is likely smaller when water hydraulics is used because pneumatics has poorer power-to-weight ratio. Stiffer fluid also provides better control dynamics. Nevertheless, like pneumatics, water hydraulics can be used in clean environments.

1.2 Water hydraulic valves

Water hydraulics has a considerable benefit over traditional oil hydraulics: water hydraulics is environmentally friendly technology. Furthermore, water is safer to use because, unlike oil-based hydraulic fluids, it is non-flammable. However, water sets higher demands on hydraulic components due to ineffective lubrication and its corrosive effect. In addition, low viscosity is challenging from leakage point of view, especially in valves design.

Several researches have focused on developing water hydraulic servo- and proportional valves [2–5], which are generally used for actuator flow control. The leakage, however, is a well-known disadvantage of the spool-type valves, and that is emphasized further when water is used. Digital hydraulics is an approach that uses parallel connected on/off valves, instead of proportional spool valves, for the flow control [6–7]. Seat-type valves are naturally almost leak tight, and thus, more suitable for water hydraulics. In addition, the on/off valves are more robust than servo- or proportional valves. The output of a digital valve is also possible to control using pulse-width modulation [8].

This paper presents development of a miniature on/off switching valve for low-pressure water hydraulic applications. Section 1 of the paper gives a short background and motivation for the research. Valve designing procedure is explained in detail in Section 2. Section 3 presents experimental results and they are summarized in Section 4. Finally, the study is concluded in Section 5 by evaluating relevance of the results.

2 VALVE DESIGN

2.1 Pre-conditions

The aim of this study is to design a fast, water hydraulic needle valve, which is suitable for pressure levels up to 1 MPa. A diameter of the flow orifice is 1 mm. The needle head has an angle of 90°, whereas the seat has a chamfer of maximum 0.15 mm. A closing compression spring is positioned inside the needle (plunger) that moves 0.5 mm between on- and off-states. The control electronics is supposed to provide 12 VDC boost voltage for the valve opening, while the maximum current is limited to 2.5 A.

Corrosion resistant materials need to be employed because water is used as hydraulic liquid. Therefore, Böhler N360 IsoExtra is selected as material for all the valve parts, apart from a plastic (PEEK) coil frame. Böhler N360 IsoExtra has high hardness and its magnetic properties are good enough and for the purpose of a solenoid valve [9].

2.2 Effective forces

Initially, the smallest available compression spring is selected. The chosen spring has an outer diameter of 1.45 mm, unloaded length of 4.83 mm, and maximum force of 0.85 N. On the closed position of the valve, the spring is decided to have the length of 3.3 mm yielding the spring force of 0.49 N.

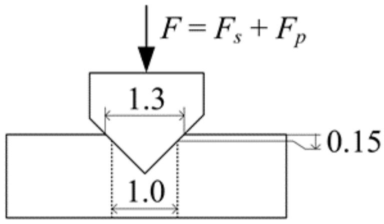


Fig. 1: Forces affecting the needle on the closed position.

Considering the orifice diameter and the maximum chamfer of the seat, the effective cross-sectional area creating pressure force on the needle has a diameter of 1.3 mm. Thus, 1.33 N active force is present at the rated pressure level. Adding up the spring force, the static overall force pushing the needle against the seat is 1.82 N, as depicted in Fig. 1. As the result, desirable force generated by the magnetic circuit is initially set to 3.0 N to provide sufficient acceleration for the plunger/needle while opening the flow path.

2.3 Magnetic circuit calculations

The magnetic core including a plunger and stator need to be driven close to the saturation during energization of the coil. As stated in [10], reluctance of the air gap is dominant when the needle is into contact with the seat; thus, the required magnetomotive force that can create saturation flux density B in air gap s can be calculated from the equation

$$F_m = B \frac{s}{\mu \mu_0} \tag{1}$$

where μ is the relative permeability (~1) and μ_0 the vacuum permeability. The saturation flux density is around 1.75 T for the stainless material yielding the magnetomotive force of about 700 A. Furhermore, the number of turns of wire in the coil can be calculated from the equation:

$$N = \frac{F_m}{I} \tag{2}$$

where I is the maximum coil current. Altogether 280 rounds of wire is needed as the current is limited to 2.5 A. Selecting a coil wire having a diameter of 0.15 mm leads into the current density of maximum 141 A/mm^2, which is acceptable considering short current peaks.

The length of the coil wire can be calculated from the equation:

$$l = \frac{R\pi d^2}{4\rho} \tag{3}$$

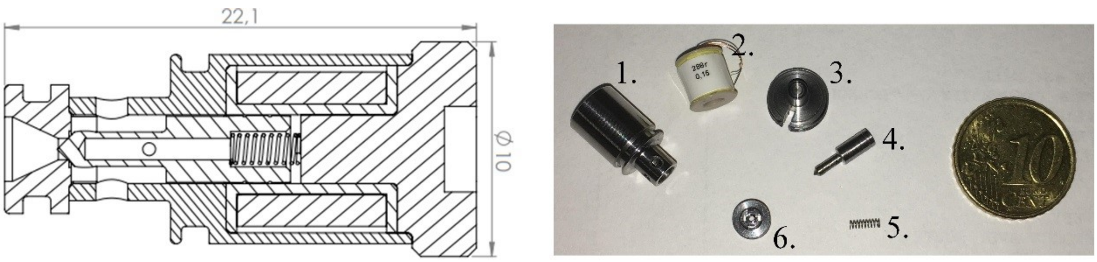
where R is the resistance that can be determined from the rated voltage (12 V) and current (2.5 A), d the diameter of the coil wire, and ρ the electrical resistivity of copper. Hence, the needed wire length is 5.05 m. Finally, a mean diameter of the coil can be determined from the equation:

$$D = \frac{l}{\pi N} \tag{4}$$

giving 5.7 mm considering the previously calculated wire length and number of the wire turns.

2.4 Component design

A suitable plunger diameter is find iteratively using COMSOL Multiphysics software. According to simulations, the plunger diameter of 3.2 mm provides 3.4 N electromagnetic force; hence, that diameter is selected as it satisfies the original force requirement. In the final design, the coil frame is dimensioned such that the coil has eight full layers of wire (288 rounds), and thus, having slightly higher resistance (5.2 Ω) than calculated initially from the power supply specifications. The rest of components are designed round the coil frame and plunger.



(a) (b)

Fig. 2: Valve design: CAD-drawing (a) and manufactured components (b).

Graph (a) in Fig. 2 shows a CAD drawing of the valve assembly, whereas the valve parts are photographed in graph (b) in Fig. 2 with a 10-cent euro coin to demonstrate the scale. The valve consists of six parts: 1. Sleeve, 2. Coil, 3. Stator/cover, 4. Plunger/needle, 5. Return spring, and 6. Seat. The assembled valve has length of 22.1 mm and its largest diameter is 10 mm. Thus, the machined parts were able to be manufactured from a steel bar having a diameter of 10 mm. The stationary valve parts was put together using two-component epoxy adhesive.

3 MEASURED CHARACTERISTICS

3.1 Test setup

The used test setup, including a flow meter (1.) and pressure transducers (2. and 3.) in addition to the studied valve, is shown in Fig. 3. A type of the ultrasonic flow meter is Titan Atrato 760-V20-RA, and the pressure transducers are Variohm Eurosensor EPT1400-K-01600-B-4-E. A dSPACE DS4004 Digital I/O Board is used for controlling the valve, whereas Valmet Technologies provided the valve booster electronics.

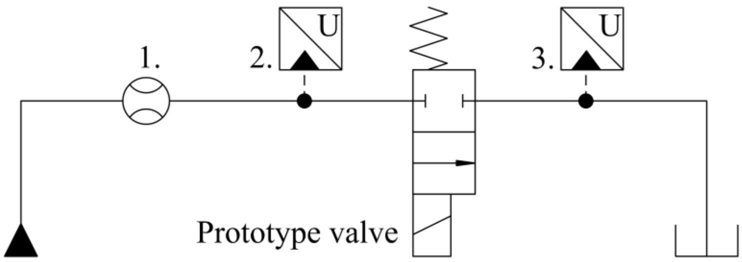


Fig. 3: Hydraulic circuit drawing of the measurement setup.

The coil current is measured using Fluke i30, and Lem LV 25-P is used to measure the coil voltage. The measurement data is captured using DS2003 A/D board. The sampling frequency is 20 kHz for the measurements. Municipal water supply network is used as the pressure source providing about 0.5 MPa. Thus, a limitation of the measurement setup is the constant pressure source. Therefore, extensive tests cannot be performed.

3.2 Initialization and modifications of the design

First tests showed that the designed valve would not close after it was opened. The reason was unexpectedly high remanent magnetization causing the needle to stick. As a solution, the compression spring was replaced by 1.8-times stiffer spring having the same outer diameter and unloaded length. However, even with the stiffer spring the valve could not be closed.

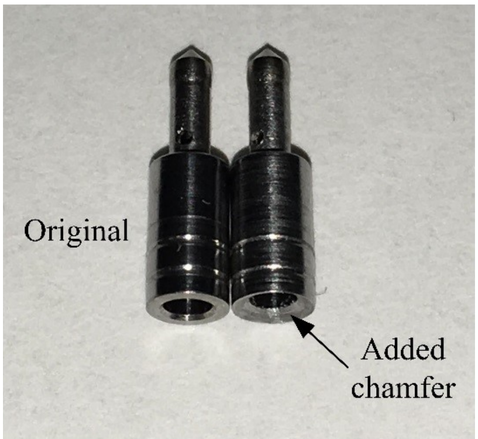


Fig. 4: Original and modified plungers.

The solution was to add a chamfer to a cavity of the spring in order to minimize the contacting area. Fig. 4 shows the original plunger on the left and the modified one on the right. With the stiffer spring and added chamfer, the valve started function properly.

3.3 Steady-state response

With the properly functioning valve, the boost voltage is set to 12 V and the holding voltage is adjusted to a value as small as possible. Tests show that the holding voltage of about 0.27 V is sufficient to keep the valve open. The measured current is around 52 mA in this case, yielding the power consumption of 14 mW.

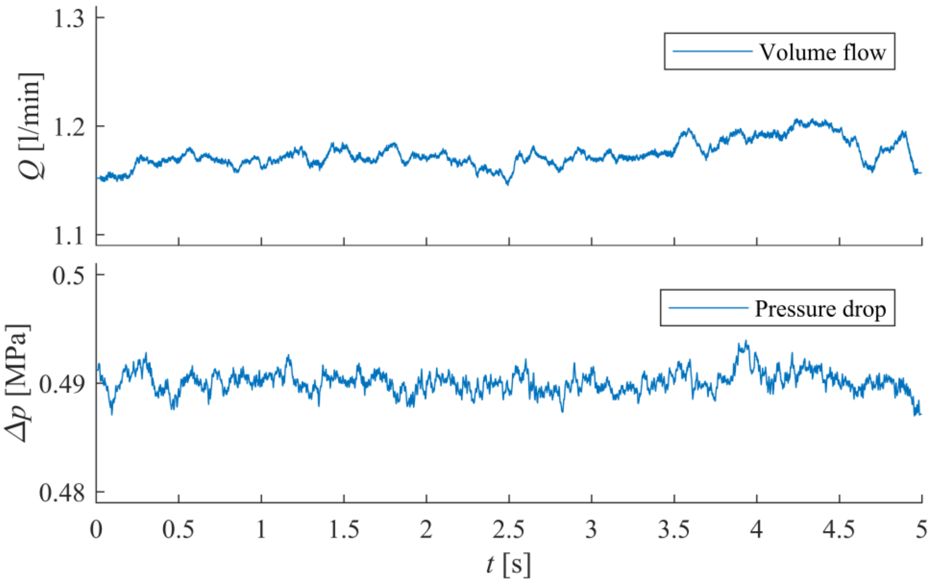


Fig. 5: Steady-state volume flow and pressure drop.

After setting the voltage levels, flow capacity of the valve was measured. Fig. 5 shows the measured volume flow and pressure drop over the valve. It can be seen that the pressure differential is around 0.49 MPa producing the flow of about 1.18 l/min through the orifice. The measurement shows slight variation in the water supply network pressure, which also affects the flow volume.

3.4 Dynamic response

Dynamic properties of the valve were tested applying a square wave input having the frequency of 5 Hz with 20% duty to guarantee that the coil current have time to stabilize. Fig. 6 shows the coil voltage and current during the valve opening. Altogether 25 cycles are plotted into the same axis. The voltage rises up to 12 V in the beginning of the opening boost that continues 3 ms until the voltage drops to the set holding level. The coil current reaches its maximum after 0.7 ms and is around 2.3 A. Hence, the switching energy is about 72 mJ. It can be predicted that the valve is fully open after 1.6 ms as an anomaly can be seen in the current curvature.

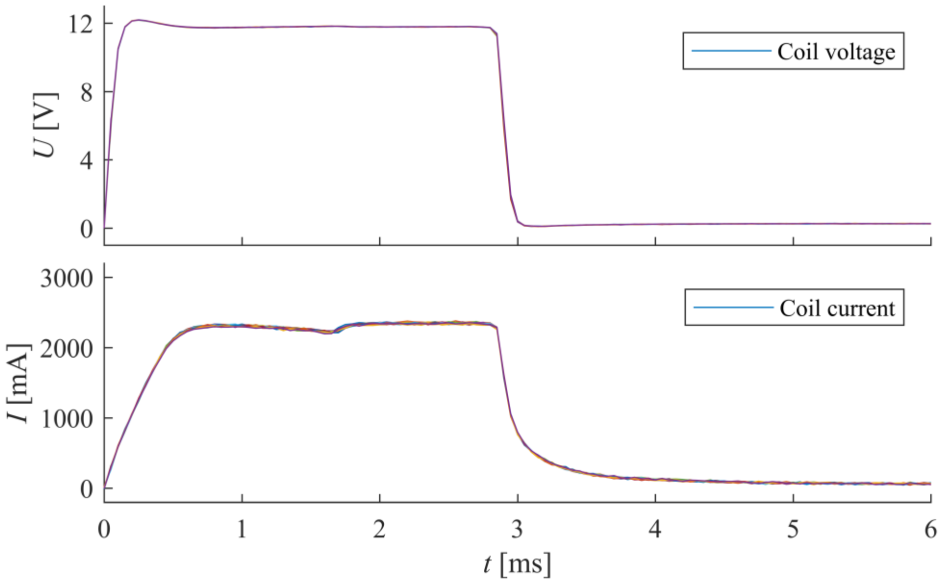


Fig. 6: Coil voltage and current during valve opening (@ 0.49 MPa).

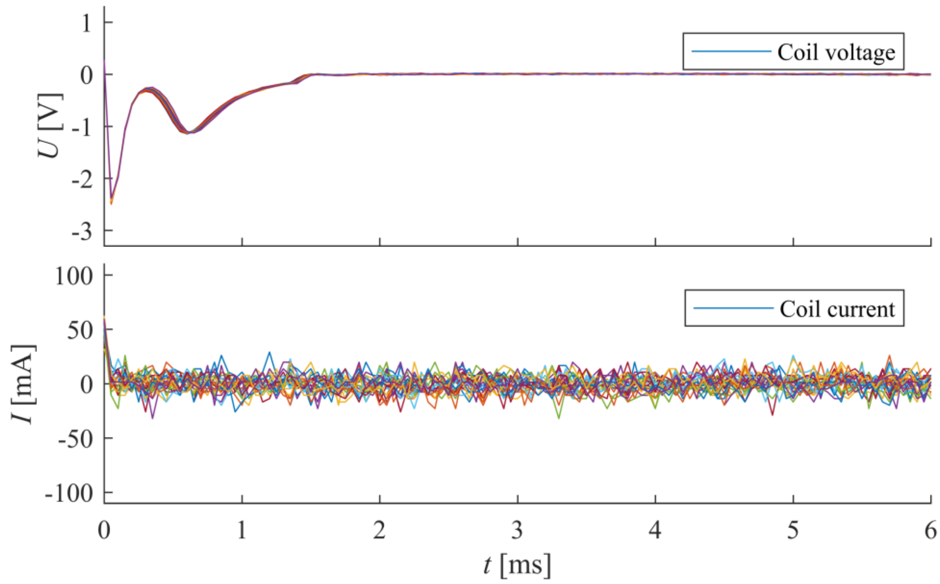


Fig. 7: Coil voltage and current during valve closing (@ 0.49 MPa).

The coil voltage and current during the valve closing are presented in Fig. 7. The voltage curvature shows that the booster electronics accelerates the valve closing by changing the polarity of coil voltage, and thus, allows the energy to be discharged faster. The coil current drops to zero in under 0.1 ms. The closing time of the valve can be predicted by investigating behavior of the coil voltage. However, determination of that exact moment is somewhat difficult because there exists two clearly visible anomalies in the voltage curvature. The first drop in the voltage takes place 0.6 ms after the valve is commanded off, and the second anomaly can be seen 0.8 ms later. It is plausible that the plunger (needle) oscillates during 0.6–1.4 ms, and the needle stabilizes into the closed-position after that.

4 SUMMARY OF FINDINGS

The study shows that a magnetic circuit of a solenoid valve can be dimensioned using simple equations of electromagnetism. The premise was that the magnetic core needed to be driven close to the saturation during energization of the coil. Considering the boost voltage and current, a mean diameter of the coil could be calculated. Magnitude of remanent magnetism after de-energizing the coil, however, was unpredictable. Therefore, the design needed to be slightly modified concerning the plunger and compression spring. Luckily, the generated force of the magnetic circuit was overdimensioned and could provide sufficient force for the valve opening despite the modifications.

Table 1: Measured properties of the designed valve.

Flow capacity at Δp = 0.5 MPa	1.2 l/min
Opening response time	1.6 ms
Closing response time	1.4 ms
Switching energy	72 mJ
Holding power	14 mW

The measurements showed that the valve has flow capacity of about 1.2 l/min at 0.5 MPa pressure differential. Both the valve opening (0…100%) and closing (100…0%) takes less than 2 ms. Switching energy of the valve, calculated based on the measured coil voltage and current, was 72 mJ, whereas the holding power was as small as 14 mW. The valve properties are also presented in Table 1.

5 CONCLUSIONS

Low-pressure water hydraulics is an alternative for pneumatics, having better efficiency with compact size components. Hydraulic flow control is traditionally performed using proportional or servo valves. Due to low viscosity of water, however, leakage becomes a problem when the spool-type valves are in question. In addition, corrosive effect of water brings its own challenge to the component design. Considering these limitations, seat-type on/off valves are more robust solution than the spool valves. Moreover, on/off valves are also suitable for “proportional” flow control; a discrete flow control unit can be composed of parallel connected digital valves, or the flow can be controlled by using pulse width modulation of an on/off valve. The water hydraulic switching valve designed in this study is suitable for the both flow control methods. The valve is miniature in size and it has fast response time. In addition, its switching energy as well as holding power are small. Thus, the developed valve could be applicable in conventional low-pressure systems utilizing water hydraulics, but also novel applications areas such as soft robotics could benefit from the presented valve design. Overall, the achieved results are promising, and hopefully, they encourage other research groups and companies to further develop water hydraulic components for cleaner hydraulic systems.

ACKNOWLEDGEMENT
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REFERENCES

[1] D. Rus and M. Tolley, “Design, fabrication and control of soft robots”, *Nature*, vol. 521, pp. 467–475, 2015.

[2] E. Urata, S. Miyakawa, C. Yamashina, Y. Nakao, Y. Usami and M. Shinoda. ”Development of Water Hydraulic Servo Valve”, *JSME International Journal, Series B: Fluids and Thermal Engineering*, vol. 41, no. 2, pp 286–293, 1998.

[3] T. Takashi, C. Yamashina and S. Miyakawa. ”Development of Water Hydraulic Proportional Control Valve”, in *Proceedings of the JFPS International Symposium on Fluid Power*, vol. 1999, The Japan Fluid Power System Society, pp. 549–554, 1999.

[4] T. Watanabe, T. Inayama and T. Oomichi. “Development of the Small Flow Rate Water Hydraulic Servo Valve”, *Journal of Robotics and Mechatronics*, vol. 22, no. 3, 2010.

[5] K. Suzuki, S. Akazawa and Y. Nakao. “Development of Cam-Drive type Proportional Valve for Water Hydraulics”, *International Journal of Automation Technology*, vol. 6, no. 4, pp 450–456, 2012.

[6] M. Linjama, S. Oshima, K.T. Koskinen and M. Vilenius. ”High Precision On/Off Control of Low-Pressure Water Hydraulic Cylinder”, in *Proceedings of the Seventh Scandinavian Conference on Fluid Power, SICFP’01*, Linköping, Sweden, 2001.

[7] A. Laamanen, M. Linjama, J. Tammisto, K.T. Koskinen and M. Vilenius. ”Velocity Control of Water Hydraulic Motor”, in *Proceedings of the JFPS International Symposium on Fluid Power*, vol. 2002, pp. 167–172, 2002.

[8] S-H. Park. “Design and Performance Characteristic Analysis of Servo Valve-Type Water Hydraulic Poppet Valve”, *Journal of Mechanical Science and Technology*, vol. 23, no. 9, pp. 2468–2478, 2009.

[9] Böhler N360 IsoExtra – Stainless Steel (2003). Kapfenberg. Retrieved from http://www.bucorp.com/media/bohler_n360.pdf

[10] M. Paloniitty and M. Linjama. ”A Miniature On/Off Valve Concept for High Performance Water Hydraulics”, will be published in *Proceedings of Bath/Asme 2017 Symposium on Fluid Power and Motion Control, FPMC 2017*, Sarasota, Florida USA, 2017.