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High flowrate digital hydraulic valve system

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ABSTRACT

This paper presents the design and properties of a digital hydraulic valve system for flowrates up to 400 l/min. The digital hydraulic independent metering valve system (D-IMV) presented in this paper is capable of replacing both traditional proportional valves and servo valves in many mobile and industrial applications. Paper presents the design of the valve system, the measured dynamic and static properties of the on/off-valve and the valve system, and the requirements for the power electronics of the control system.

The digital hydraulic valve package presented in this paper has 4x7 bidirectional seat-type single-stage solenoid on/off-valves from Bucher Hydraulics for controlling four independent metering edges. Compared to the proportional or servo valves, the D-IMV has the benefits of digital systems in general. The leak-free on/off-valve is always exactly open or closed, the on/off-valve is robust for environmental changes such as oil contamination or temperature variations and a failure in a single on/off-valve in system does not completely paralyze the metering edge, but only reduces the control resolution.

KEYWORDS: high flowrate valves, independent metering, digital hydraulic valves

1 INTRODUCTION

One of the biggest obstacles of digital hydraulics becoming more popular is the lack of suitable commercial components. The valve system designed in this paper is built with commercial components for a high flowrate mobile application consisting of four equal digital hydraulic valve packages. This paper presents one of these valve systems.

Key component for this valve system is a new directly controlled single-stage solenoid valve from Bucher hydraulics, the WS22GDA-10 that combines the good properties of previously available poppet and spool valves. The valve is capable of delivering relatively high flowrates with low pressure losses and the single-stage poppet structure makes it leak-free and more robust than spool-type valves or valves with a pilot-stage. Single-stage control makes it also dynamically highly repeatable in variable conditions. The valve can withstand also high pressure differences and it can be operated directly with standard mobile controllers operating at 24 VDC. Literature surveys done on digital hydraulic valves can be found on [1] and [2]

2 DIGITAL HYDRAULIC VALVE SYSTEM WITH PARALLEL CONNECTED VALVES

The designed digital hydraulic valve package for a single actuator, and its hydraulic schematics, is presented in figure 1. Dimensions of the valve package are 402x343x96 mm including the valves. It has two 28mm bore, and two 25mm bores through the block with one inch port connections.

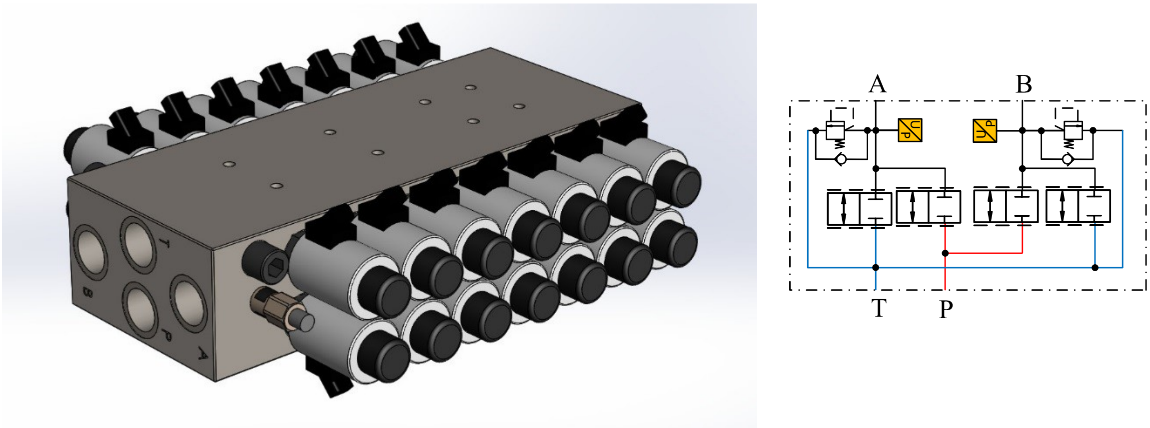

Figure 1. D-IMV for single actuators.

Valve package includes 4x7 Bucher WS22GDA-10 valves for controlling four metering edges independently, two Parker PLC182 shock pressure relief valves with anticavitation function for actuator ports and two Bosch Rexroth PR3 pressure sensors. Part of the valves have metering orifices with M12 threads in front of the valve as shown in Figure 2.

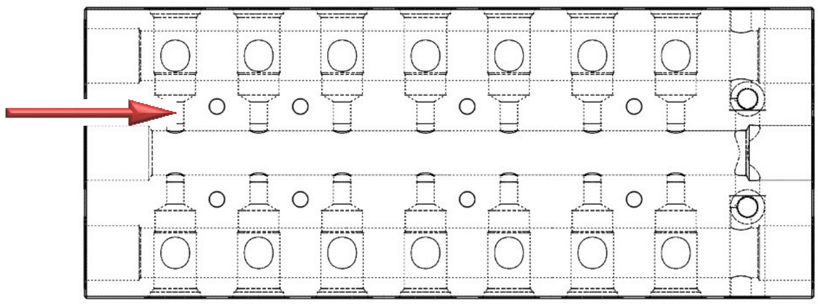

Figure 2. Cross-section of the block and place of metering orifices shown with the red arrow.

Two different orifice types were tested. Short distance between the nose of the valve and orifice due to block design, tends to create a jet stream that reduces the operation limits of the valve with flow direction from nose to the side of the valve. Improved orifice type had two parallel borings instead of a single boring, while keeping the flow area equal.

2.1 Components

The main component defining the properties of the D-IMV system is the digital bit, which in this case is the Bucher WS22GDA-10 on/off-valve (figure 3). Before of designing the D-IMV system, this on/off-valve was measured with methods that described in chapter 3.

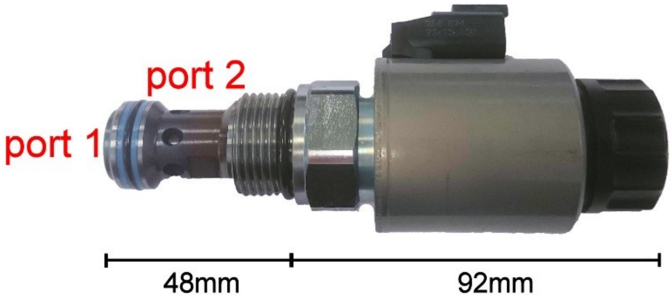

Figure 3. Bucher WS22GDA-10 dimensions and port identification.

Main parameters of the valve are described in Table 1. Nominal flow rate was measured to be 37 l/min @ 0.5 MPa and maximum flowrate over 140 l/min.

Table 1. Properties of the Bucher Bucher WS22GDA-10 with a 28.8 VDC boosting voltage

Nominal flow rate @ 0,5 MPa	~ 37 l/min	**Opening delay**	14 ms
Maximum flowrate	~ 140 l/min	**Opening time**	18-21 ms
Leakage (@20MPa)	< 0.1 cm^3/min	**Closing time**	14 ms
Coil	12 VDC; 7,4Ω; diam.45mm		

Valve was found to have very constant response times with different pressure levels. Closing time is around 6 ms faster than the opening witch needs to be compensated with controller output delay.

2.2 Valve control system requirements

For the target application of the designed valve system, a standard mobile controller is used with a 24 VDC supply system. In this case, the controller is Bosch Rexroth Bodas RC36-20/30, which has 36 proportional high-side outputs and 20 digital high-side outputs. It has a 32bit 150MHz Infineon Tricore processor and it is capable of running the main controller with a sample time of 20 ms and with the pressure filtering sample time of 2ms sample time. This controller is no more available and it is now replaced with model Bodas RC28-14/30.

For fast opening of the valve, voltage must be increased during the valve opening. This period is called a boosting period. For the Bucher WS22GDA-10, the boost phase is created by setting the duty cycle to 100 percent for a period of 20 ms when opening the valve. After the boost phase, duty cycle is lowered to around 40 percent as the nominal voltage of the coil is 12 VDC. To close the valve fast, voltage difference over the coil is reversed to to bring down the current going through the valve coil as fast as possible. In this case, the valve needs to be controlled with two outputs – the proportional PWM output for the high-side and digital output for the low-side of the coil. As the RC36/20 controller has only high-side outputs, an additional fet-circuit is required to control the low-side of the coil while the digital high-side output of the RC36 is used to control this fet-circuit. Figure 4 presents the connection between the RC36, low-side fet-circuit and the solenoid valve.

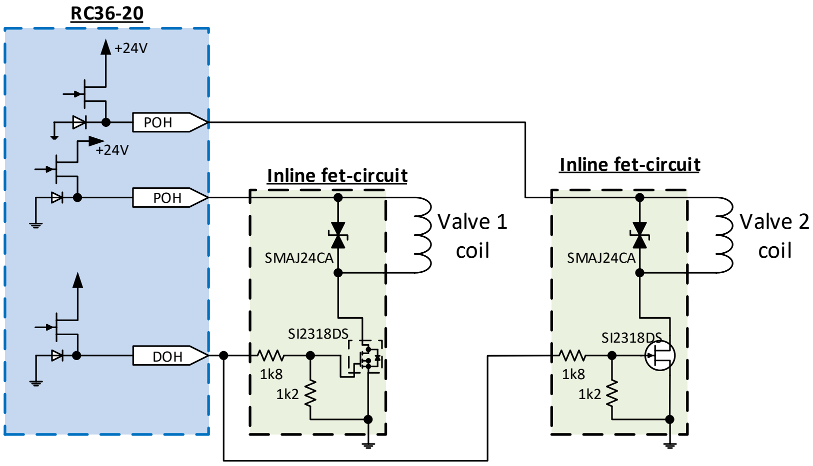

Figure 4. Inline fet-circuit for fast valve closing.

The fet-circuit includes also a bi-directional zener diode which is used to prevent too high voltage peaks over the valve coil. As there is only 20 digital outputs with RC36, digital outputs are shared with two valves from different metering edges that are not used simultaneously. Dimensions of the fet-circuit are 8x15mm and it is integrated to valve cables.

Power consumption of a single valve was measured to be 17.1 W with a duty cycle of 40%. Total power consumption of the valve controllers in operation can be estimated by assuming that half of the valves would be used by two metering edges. For the valve system presented in this paper, this leads to average power consumption of 120 W.

2.3 Valve calibrations

For the D-IMV system designed, calibration measurements are required to determine the flow-characteristics of each valve as a function of inflow-side and outflow-side pressures. When PCM-coding, i.e. valves have different flowrates and the number of the flowrate combinations is 2^n-1, is used, the valve system controller needs to calculate the flowrate of each valve accurately based on inflow- and outflow-side pressures to avoid pressure peaks in state transitions [3]. For PNM-coded digital valves, where all valves have equal flow capacity, statistical estimations instead of measuring all valves can be used, as the state transitions do not generate pressure peaks.

For the calibrations, flowrate of each valve is measured with two pressure ramps to define the effect of cavitation choking when the pressure on the outflow-side is low. In the first ramp, the inflow-side is ramped up and down, while the outflow-side pressure is close to zero. In the second measuring ramp, the inflow-side is kept constant, while the outflow-side is ramped down to zero and back up to the level of the inflow-side pressure. If both flow-directions are used in the application, the valve needs to be measured in both directions.

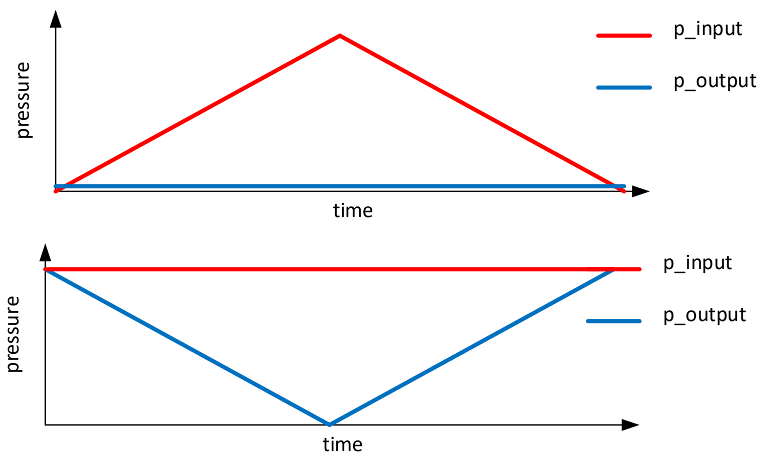

Figure 5. Pressure ramps for calibration measurements.

Flow calculations inside the controller algorithm can be done either by creating a look-up table from the measurements or by using a non-linear valve model. Standard square root equation is not accurate enough and one solution is to use the generalized exponent model:

$$Q_{valve}\ \ (p_1, p_2) = \begin{cases} K_{v1}(p_1 - p_2)^{x_1}, & b_1 p_1 < p_2 \le p_1 \\ K_{v1}[(1-b_1)p_1]^{x_1}, & p_2 \le b_1 p_1 \\ -K_{v2}(p_1 - p_2)^{x_2}, & b_2 p_2 < p_1 \le p_2 \\ -K_{v2}[(1-b_2)p_1]^{x_2}, & p_1 \le b_2 p_2 \end{cases} \qquad (12)$$

where p_1 is the inflow side pressure and p_2 is the outflow side pressure, K_v is the flow coefficient, b is the critical pressure ratio and x is the exponent. The subscript 1 describes the flow direction where p1>p2 and subscript 2 describes parameters for the opposite flow direction. Accuracy of this model is studied in [4] by Linjama et. al. Linjama et al. presented also an alternative, computationally light solution in [5]. In this application, the generalized exponent model can be used as the controller unit has enough calculation power.

3 MEASUREMENT SYSTEM

Measurements were done in a test bench shown in figure 6. This setup was used first to measure the single valve in separate block and later the designed D-IMV system. This test bench was too small to measure the maximum limits of the whole D-IMV system, but it was large enough to allow calibration of the system and to measure the operating limits of the single on/off-valves. Measurement system included flowrate and pressure measurements, temperature measurements, current and voltage measurements and a dSpace computer to log the measurements. Valves were controlled with Bodas RC36 – controller which was connected to the dSpace with CAN bus with 1ms transmit interval.

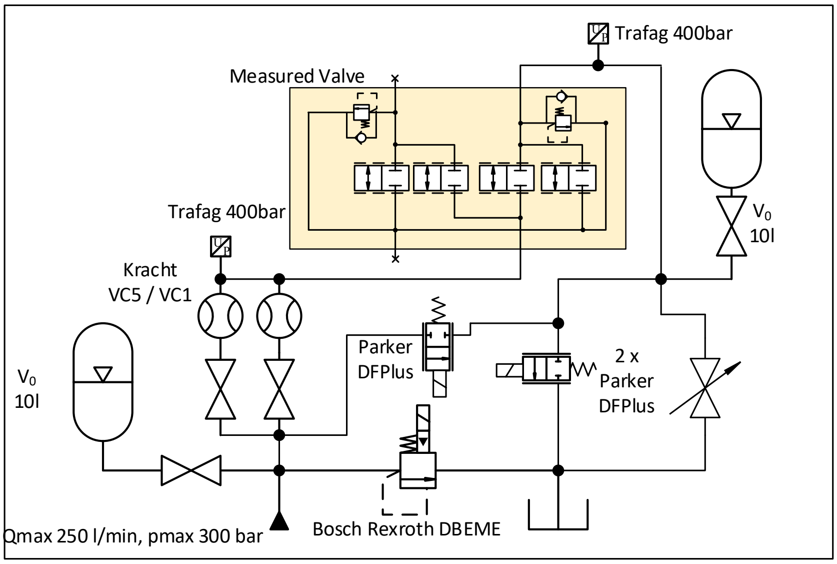

Figure 6. Test bench for valve calibrations.

4 VALVE DESIGN

The application, for which the valve system is designed, sets quite demanding target values. Maximum flowrates are close to 400 l/min, actuator forces can be restrictive or over-running and the multi-actuator system has only a single supply line, which can cause high pressure differences over the valves to be inevitable.

Design target properties for the valve system were gathered by measuring and analysing the velocities and forces of the actuators of the target application with the original valve system. It was shown that the maximum flowrate through a single metering edge was around 400 l/min. By analysing typical work cycles in real work, it was shown that these maximum velocities were used only seldom and in most cycles two or more actuators were moved simultaneously and individual actuator flowrates were close to 200 l/min. With that information, the valve system was designed to have small pressure losses up to 250 l/min. Larger flowrates are possible by increasing the target pressure difference over the valve and thus increasing the losses over the valves. Maximum flowrates of different metering edges differ from 150 to 400 l/min with different actuators, but all valves were designed to have same number of valves and identical structure.

Number of valves was defined by the maximum flowrate and by desired controllability. Controllability was studied with a simulation model of the application. This lead to a valve series that has 7 valves with 2-4 equal sized valves without the metering orifices. Selected metering orifices and estimated flowrates for one of the actuators are presented in table 2.

Table 2. Selected metring orifice series and the nominal flowrates @ 0.5 MPa pressure difference.

DFCU PA	**Valve 1**	**Valve 2**	**Valve 3**	**Valve 4**	**Valve 5**	**Valve 6**	**Valve 7**
Orifice [mm]	1.4	2	2.8	4	-	-	-
QN [l/min]	1.9	3.9	7.6	15.5	37.3	37.3	37.3
DFCU PB							
Orifice [mm]	1.4	2	2.8	4	-	-	-
QN [l/min]	1.9	3.9	7.6	15.5	37.3	37.3	37.3
DFCU AT							
Orifice [mm]	1.1	1.6	2.2	3.1	4.4	-	-
QN [l/min]	1.2	2.5	4.7	9.3	18.8	37.3	37.3
DFCU BT							
Orifice [mm]	1.5	2.1	3.0	4.2	-	-	-
QN [l/min]	2.2	4.3	8.7	17.1	37.3	37.3	37.3

5 MEASUREMENTS

5.1 Flow characteristics of Bucher WS22GDA-10

Figure 8 shows the measured flowrates for both directions and with the inflow-side and outflow-side pressure ramps. The valve has some variance in the flow-capacity with different flow directions but the cavitation choking did not affect the flow much.

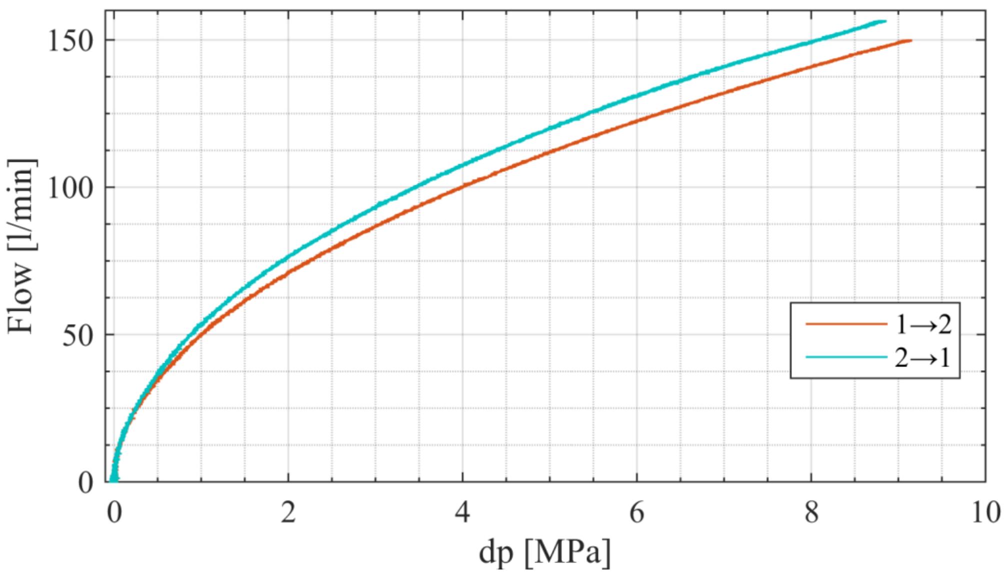

Figure 7. Flow-characteristics of the Bucher hydraulics WS22GDA-10.

Variance between different valves was small. Flowrates varied from 59 to 61.4 l/min in flow direction 1→2 and from 64.9 to 66 l/min in flow direction 2→1 with 1.5 MPa pressure difference. For the exponent valve model, the exponent parameter varied from 0.49 to 0.51.

5.2 Operation limits

Operation limit test was done with low and high input pressure levels. With higher pressures, the maximum flowrates are lower, so that will define maximum flowrate for the valve. Figure 9 shows the typical flowrate limits for the flow direction 1→2 for high pressure levels, and the figure 10 shows the operation limits for the flow direction 2→1 for high pressure levels. The maximum flowrate is around 140 l/min and lower curve shows, the maximum flowrate was around 160 l/min. Similar results were achieved with repeated measurements.

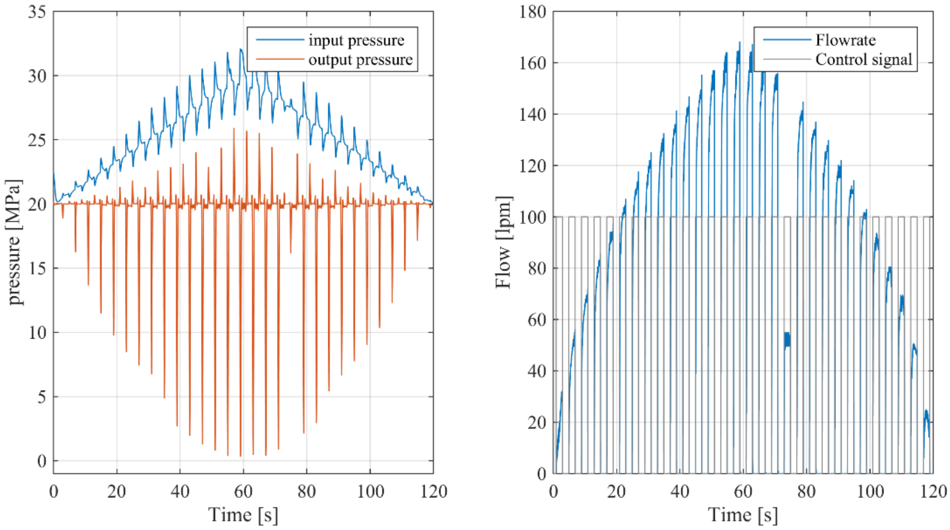

Figure 8. Operation limits for the Bucher hydraulics WS22GDA-10 in flow direction 1→2.

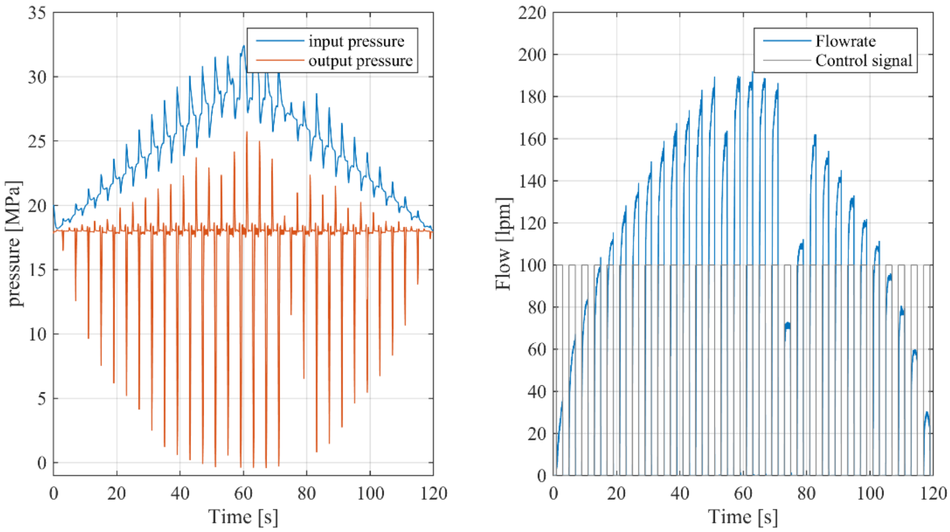

Figure 9. Operation limits for the Bucher hydraulics WS22GDA-10 in flow direction 2→1.

When the outflow-side pressure was kept to zero and the inflow-side pressure was increased from zero to upwards, valve was noticed to start closing after 180 l/min. These operation limits were tested with the booster circuit parameters presented in chapter 2.2.

5.3 Dynamics

Figure 11 shows the opening delay and the opening time for the valve with a supply pressure of 31 MPa and pressure difference of 1 MPa. Valve receives the control signal at time 0 s.

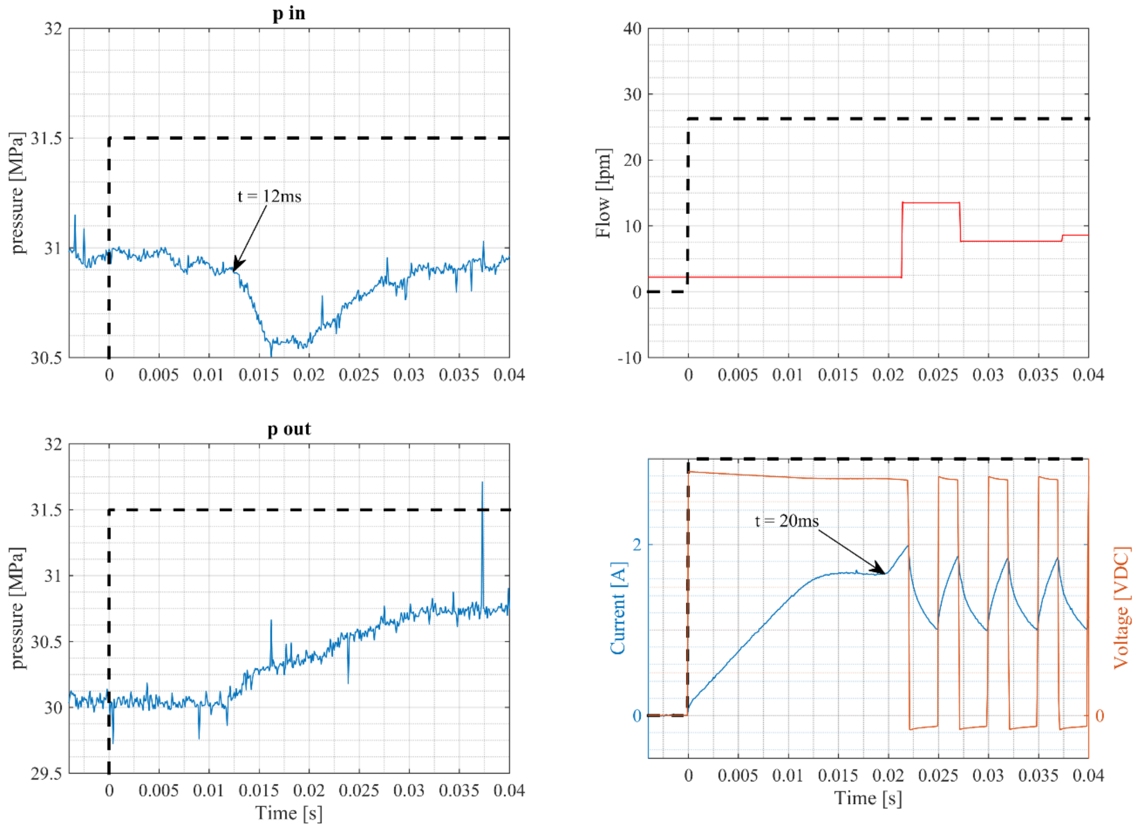

Figure 10. Opening delay and response time of the Bucher hydraulics WS22GDA-10.

Opening delay can be estimated from the time where pressures start to change at around 12ms. Full opening time can be estimated from the current graph in lower right corner. Current rises with constant gradient while the valve poppet is in closed position. Gradient starts to decline after 12 ms which implies that the poppet that is acting as a solenoid armature is moving and thus opposing the rise of the current. At around 20ms, the gradient of the current starts to rise again which implies that the poppet is reached the end of the valve housing. With different pressure levels, the response time was measured to vary 18-22 ms. It can be seen from figure above that the flow-meter dynamics are not fast enough to measure the delay or the response time of the valve.

Figure 12 shows the closing delay and estimated closing time of the valve. Control signal is set to zero at time zero.

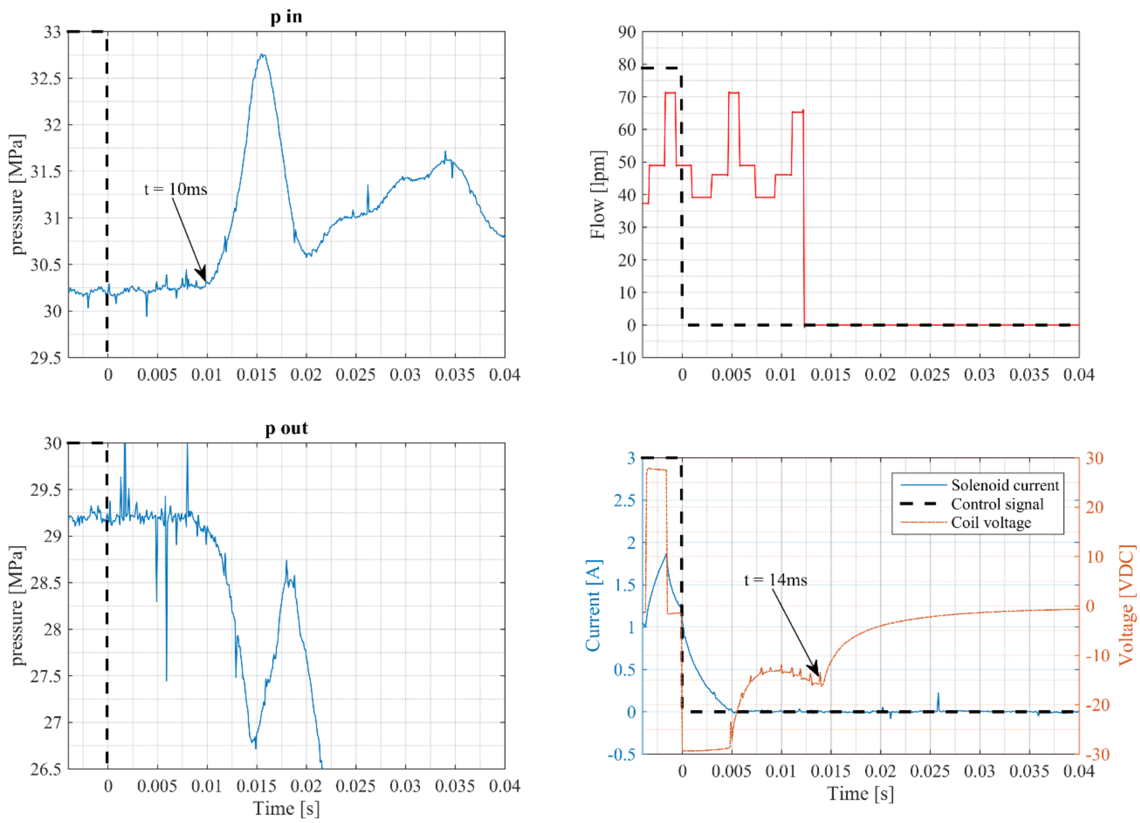

Figure 11. Closing of the Bucher hydraulics WS22GDA-10.

Closing of the valve generates a back-voltage that forces the current to zero in 5 ms. Pressure change can be seen at 10 ms which indicated the closing delay. Valve closing can be assumed to happen at 14 ms where the voltage gradient changes suddenly from negative to positive that occurs because of the solenoid armature hitting the end of the solenoid.

5.4 Steady state properties of the DFCUs

Figure 13 presents the individual flow-curves of a single DFCU. Only one DFCU is presented more thoroughly due to the very similar properties of the DFCUs.

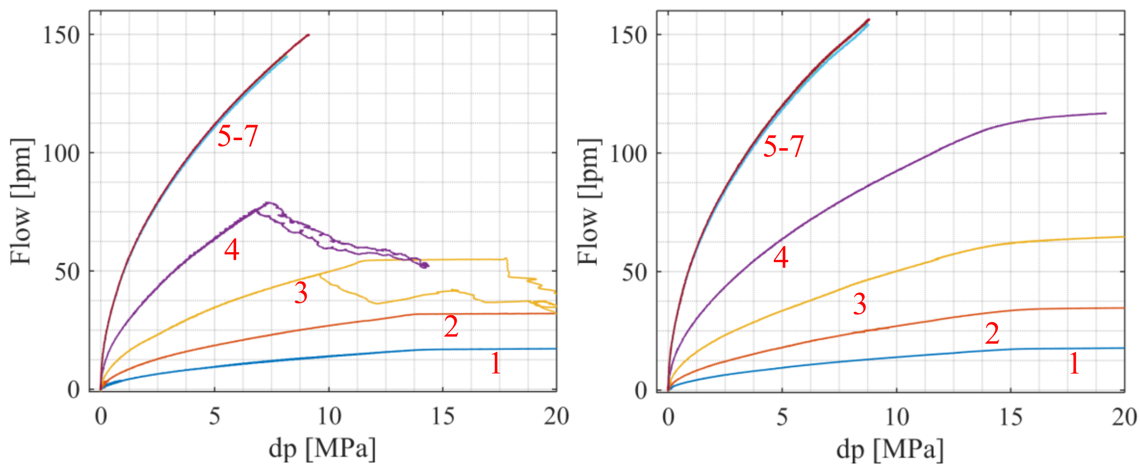

Figure 12. Flow-pressure difference curves for the seven on/off-valves of PB-DCFU. Flow direction P→B (1→2) left and flow direction B→P (2→1) right.

Flowrates of the three biggest valves are almost identical and curves are drawn on top of each other. Left figure above shows how the metering orifice actually lowers the maximum pressure difference with flow direction 1→2 due to the flow forces disturbing the valve operation. Valve 4 valve closes after 7 MPa even when the valves 5-7 work up to 10 MPa pressure difference. Right-side figure shows pQ-curves with opposite flow direction 2→1. In this direction valves 1-4 operate close to 20 MPa pressure differences. Orifice series used in this DFCU was [1.4, 2.0, 2.8, 4.0, -, -, -] mm.

Figure 14 presents the measured flowrate combinations of the PB-DFCU metering edge with a pressure difference of 1.5 MPa. Upper curve shows the measurements in flow direction 2→1 (B→P) and the lower curve shows the measurements in flow direction 1→2 (P→B).

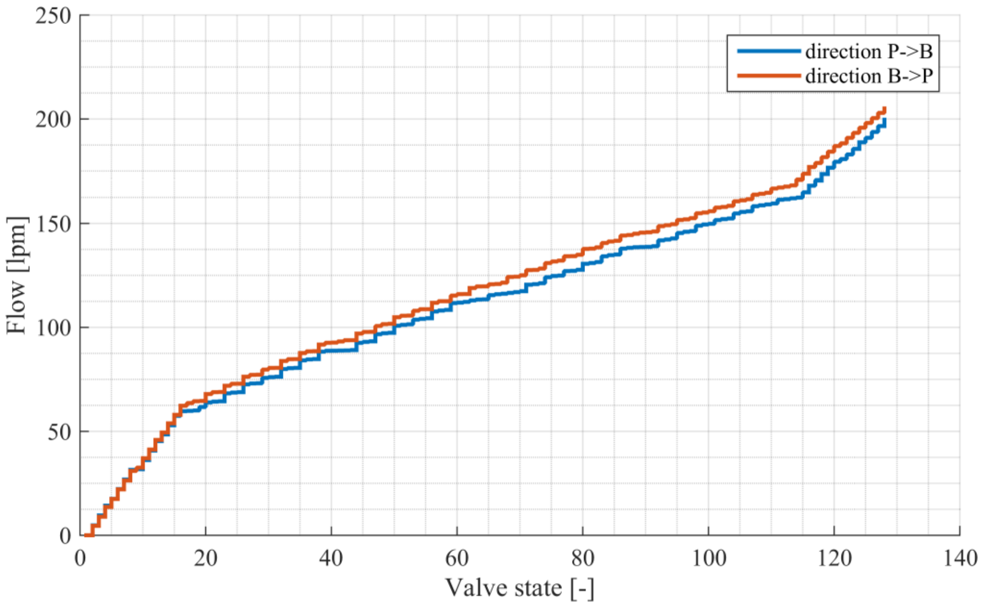

Figure 13. Flowrates with all possible valve combinations @ 1.5 MPa, sorted by the flowrate.

Because three of the largest valves have almost equal flow rates, valve system has states with almost equal flowrates. Total number of flowrate step is 127. Resolution of a DFCU is determined as ratio between the maximum flowrate and the largest step between two consecutive flow-steps. In this DFCU, resolution was around 51. For different DFCUs, the resolution varied from 43 to 71 depending on the metering orifice series used.

Figure 14 shows the difference between the designed flowrate, the measured flowrate and flowrate calculated from the calibrated valve models.

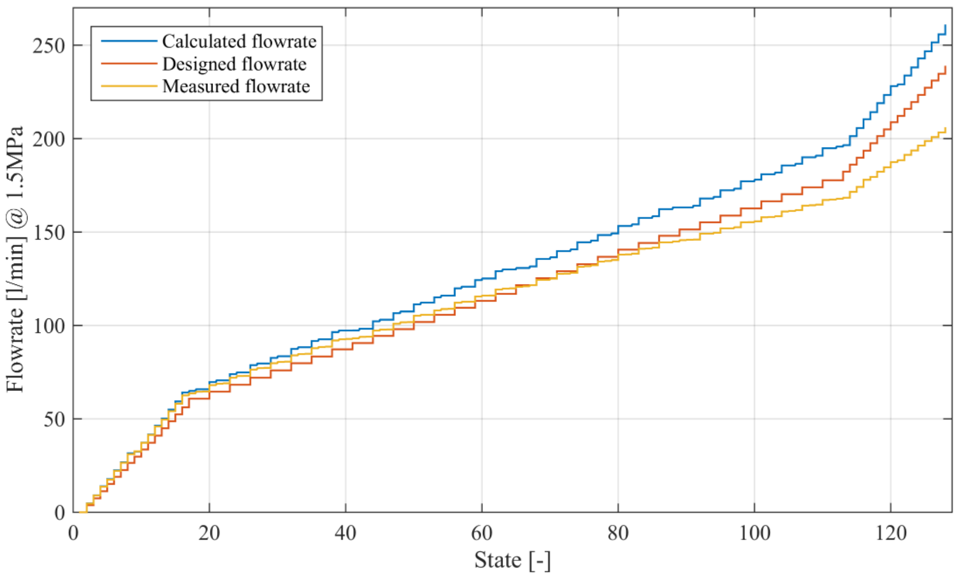

Figure 14. Differences between designed, calculated and measured flowrates.

The designed flowrate is lower than the calculated flowrate because of higher flowrates of the metering orifices than what was estimated. Flowrates of the valves with metering orifices were estimated with a square root equation for a standard short orifice with a discharging coefficient of 0.6. Actual flowrates turned out to be larger. Measured flowrates are smaller than the calculated flowrates due to the manifold restriction.

The restriction is roughly the same for each flow passage of the D-IMV manifold. At 200 l/min, the pressure loss in the manifold was around 0,5 MPa while with 100 l/min, the pressure loss is around 0.07 MPa. In case, accurate flow control is required, the manifold restriction needs to be taken into account on the controller algorithm.

6 CONCLUSION

The valve package presented in this paper opens new possibilities for utilizing digital hydraulics in different industrial and mobile implementations. With smart control, it can offer a fault tolerant and energy efficient solution to control hydraulic actuators in range up to 400 l/min and pressures up to 35 MPa depending on the design parameters of the valve system. Flowrate of a single valve was around 60 l/min @ 1.5MPa, which can be multiplied with number of the valves per DFCU to get the maximum flowrate. This paper presented the design of the valve package, the required control power electronics, and how the valve system performed compared to the desired design properties.

This design was based on an application were high pressure differences can occur due to multiple actuators with unpredictable force levels and only a single supply line. This led to a valve package with seven valves to ensure good control resolution and high enough flowrate. For this application manifold size was minimized which led to quite large pressure losses with high flowrates. Larger bores would have reduced the losses and allow bigger connectors.

In near future, this valve system will be fitted to the test machine, and the operation in actual system will be studied and compared to the traditional proportional valve system.

ACKNOWLEDGMENT
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ABBREVIATIONS

DFCU	Digital Flow Control Unit
D-IMV	Digital hydraulic Independent Metering Valve
PCM	Pulse Code Modulation
PNM	Pulse Number Modulation

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