Improving resolution of digital hydraulic valve system by utilizing fast switching valves

IMPROVING RESOLUTION OF DIGITAL HYDRAULIC VALVE SYSTEM BY UTILIZING FAST SWITCHING VALVES

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ABSTRACT

A Digital flow control unit (DFCU) consists of a certain number of parallel connected on/off-valves, which are basically controlled by using pulse code modulation (PCM). In order to limit costs and installation space the number of valves in a DFCU has to be kept as low as possible. As a consequence the relative control resolution of such a system is limited especially for small flow rate of the DFCU. In the presented paper the use of fast switching valves for improvement of the control resolution of a cylinder drive is studied. Experimental measurements are presented and analyzed.

KEYWORDS: Digital flow control unit (DFCU), PWM, PCM, Control resolution

1. INTRODUCTION

Digital hydraulic valve system has been studied over several years in Tampere University of Technology at the Department of Intelligent Hydraulics and Automation. One of the key ideas of this technology is to transfer sophisticated properties of hydraulic servo and proportional valves into programmable controller logic which controls the on/off-valves. [1]

The research has shown numerous improvements in comparison to traditional technology. One of the benefits is the possibility of reducing energy losses in many applications, when a distributed valve system is used [2]. The system consisting of multiple, redundant, components is fault tolerant [3]. Furthermore, the valve system can be configured to different applications by changing the parameters of the controller or the controller itself.

There are also a few challenges involved in using a digital hydraulic valve system. In a typical binary coded DFCU, there is a possibility of temporary flow error resulting from slightly varying timing of the valves, which are simultaneously commanded open and closed. The timing errors lead into pressure peaks or jerky motion of the controlled device. Significant amount of research has been done on the subject and there are different ways to decrease the phenomenon. [4]

Another subject, which has not been studied very extensively yet, is the control of small flow rates. In the case of a cylinder drive, the challenges occur, when small velocities are to be controlled accurately. In order to achieve energy efficient control through multiple control modes, the digital hydraulic valve system has to be able to simultaneously control both velocity and the pressure level of the cylinder [2]. The theoretical ratio of minimum and maximum velocity of the cylinder drive is 2^n-1, where n is the number of parallel connected valves in a DFCU. This holds only if simultaneous pressure tracking is not needed [5]. Linjama et al. presented the use of simultaneous opening of three or four DFCUs in order to improve the velocity and pressure tracking at low velocities. The ratio of minimum and maximum velocity was raised to 50 instead of theoretical 15 for a four DFCU system utilizing four valves per DFCU.

One drawback related to the use of crossflow from supply line to tank line is the increased energy consumption. Therefore the use of crossflow is normally restricted to the control of small flow rates. Other downside mentioned by Linjama is the sensitivity to load force changes. One possibility to increase the resolution of a digital hydraulic valve system is to use PWM (Pulse Width Modulation) control in addition to PCM (Pulse code modulation) control.

The pulse width modulation control of a hydraulic on/off-valve has been studied as an economical replacement for proportional and servo valves. Winkler et al. studied the use of two on/off-switching valves in order to control a linear cylinder drive utilizing pulse width modulation. The rod side of the cylinder was connected to supply pressure and the two fast switching on/off-valves were controlling the inflow and outflow on piston side of the cylinder. An accumulator was connected to the piston side circuit to reduce pressure pulsation. [6]

Later Plöckinger et al. [7] presented a 3/2 way switching valve, which was used in so called digi-actuator. This combination of two switching valves is an actuator driving a flap for a huge stationary motor. The design criteria of the system were demanding and the digi-actuator was a good choice for such a system due to its fast dynamics. The system is stiff as it does not include accumulators in the actuator circuit. Due to the stiffness of the system and possibility to keep the flap in one position by two check valves, the energy consumption of the system is small. Also external loads are easily compensated. These are clear benefits when compared to electrical actuators.

Furthermore the switching control concept has been used in studies concerning the energy efficiency of hydraulic drives. Good examples are different switching type converters as the hydraulic buck converter [8]. In converter circuits the idea is to transform the energy of two supply lines efficiently into a form used by the actuator. In case of a hydraulic buck converter, this is realized by alternating the driving pressure of a hydraulic inductance between supply and tank line pressure so that the actuator is driven efficiently.

The combination of PWM and PCM control has been previously studied in pneumatics. Ferraresi [9] presented the idea of using one PWM-modulated valve together with binary coded PCM-valves to produce a pneumatic flow control valve. One disadvantage of the presented method was the limitation of the minimum flow due to a certain minimum duty cycle the switching valve is able to execute.

One method proposed by Belforte et al. [10] to improve the dynamics of a pneumatic servo system is to use two on/off-valves in parallel to control supply flow and similarly two valves to control outflow. In the case study presented, pressure level of a tank is controlled using the system of four valves. In this study the dynamics of the control are improved by utilizing the switching control of both valves.

The study presented in this paper focuses on inflow-outflow control of a hydraulic cylinder. Two additional parallel connected fast switching valves are used in each DFCU and also the concept of crossflow is implemented to avoid problems with the minimum duty cycle of the valves. The algorithm of combining the PCM and PWM – control is presented as well as experimental results.

2. COMBINING PWM AND PCM CONTROL

In case of hydraulics, there are a number of challenges in using PWM-control, when compared to pneumatics. First of all, the stiffness of a typical cylinder drive require high switching frequencies, if smooth velocity tracking is required. As the pulse width modulated control of the valve results in flow rate pulsation in the actuator circuit, some pressure pulsation and noise is also to be expected. There have been advancements in hydraulic on/off-valve technology, which enables the use of high enough switching frequencies. The challenges in the design of fast switching hydraulic valve include the fact that pressure levels are higher compared to pneumatics and there is also the problem with oil sticking. That is the reason why fast switching valves with switching times around 2 ms and repeating frequencies up to 100 Hz are not commercially available on the market.

2.1. Different valve sizing schemes

In this study, the goal is to combine the advantages of both, PCM and PWM control methods. In order to achieve high enough velocities, DFCUs with big enough flow capacities should be used. In order to keep the number of valves relatively small, the PWM-control is used to fine tune the output of a DFCU. The pulsation of velocity and pressure is related to the amplitude of the flow pulsation of the PWM-controlled valve, thus it is beneficial to keep the flow capacity of the switching valve small if possible.

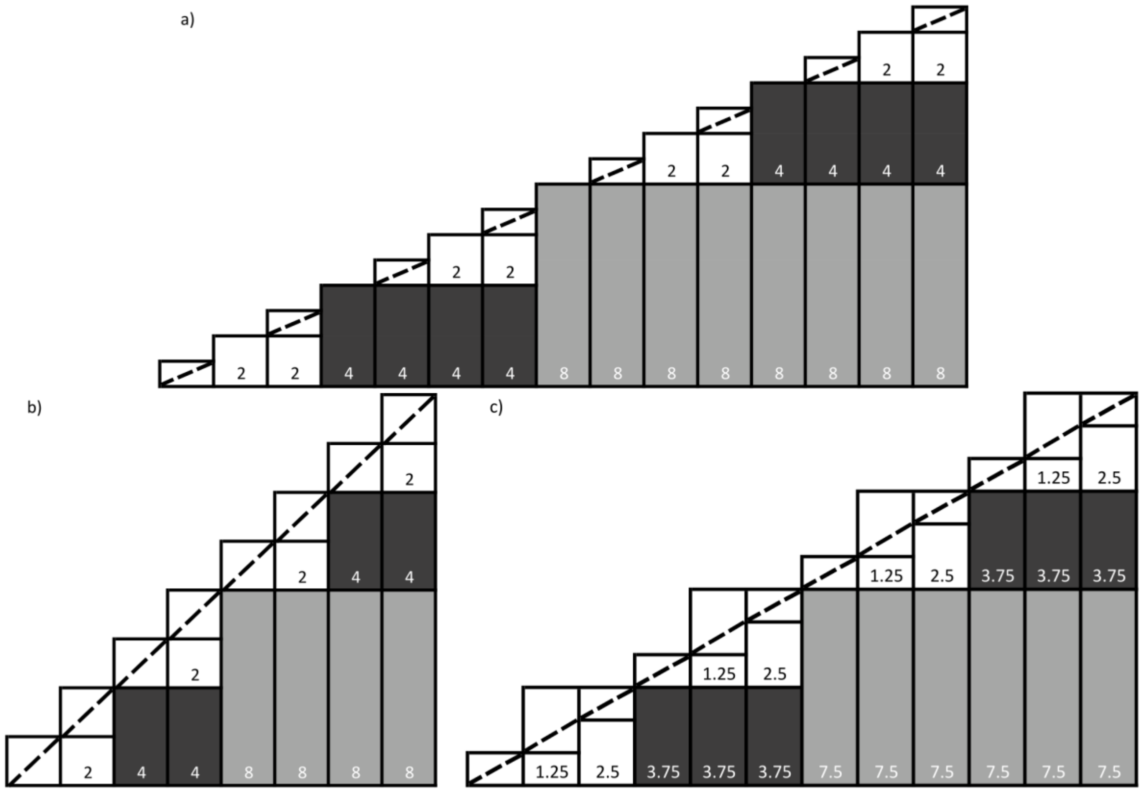

Figure 1. Different coding schemes.

Figure 1 presents flow series, which can be obtained by using different size valves in a four valve DFCU and different number of PWM-controlled valves. The dashed line shows all average flow rates, which are possible by using PWM-control. The case (a) is a typical binary coded valve series. The PWM-control is restricted to the control of the smallest valve in order to minimize the flow pulsation. The drawback of this approach is that the PWM-control of the smallest flow rate is restricted between zero flow rate and the flow rate of the smallest valve. When the second smallest valve is opened and the smallest valve is closed, there is a stepwise change in the flow rate.

The case (b) is a modified binary coding, where the two smallest valves have identical flow capacity. As the figure indicates, the PWM-control can be used together with every state of the DFCU to fine tune the flow rate. One downside is that the switching valve is twice the size of the switching valve in case (a). Also the resolution of the DFCU is only half of the original binary series, which is an issue, if the system is used with PCM-control only at some operating point.

The valve sizing used in this study is presented as case (c). By using two PWM-controlled valves, which are of nominal size 1.25 and 2.5, the PWM-control can be used again at any state of the DFCU. The benefit compared to case (b) is that the smallest flow rates are produced by a PWM-controlled valve, which has a nominal size of 1.25, only slightly bigger than the smallest valve of the original binary series. This reduces the pressure pulsation and possible velocity pulsation of a cylinder drive especially at the slowest velocities, when the most accurate control is required.

2.2. The steady-state model based controller

The controller is programmed based on the PCM-controller developed at IHA [2]. The controller uses steady-state equations of the valve-cylinder system to evaluate different opening combinations of the on/off-valves in order to find the optimal opening combination. The PCM-controller is based on four subsystems which realize the main functions of the controller:

The selection of the control mode determines, whether inflow-outflow control mode or differential control mode should be used, and into which movement direction. The selection of control mode produces also chamber pressure references as the pressure level of the cylinder is controllable simultaneously with the velocity of the piston. In the measurements presented later in this paper, the selection of control mode is restricted to inflow-outflow modes only and the pressure reference is set into a user-set constant value.

As there are a large number of different opening combinations to choose from in a digital hydraulic distributed valve system, the number of candidates has to be reduced in some way. For example a valve system with four valves in each four flow edge has over 60000 possible opening combinations. Therefore all of the combinations cannot be evaluated using the full steady-state equations. The evaluation of the opening combination candidates can be separated into evaluation of A-side and B-side valves. Then the number of studied candidates in the example case is reduced to 256 candidates per cylinder chamber. A user set number of best valve opening candidates is chosen to be evaluated using the full steady-state equations. The best valve opening candidates in this case are the ones with the smallest flow error.

In order to evaluate the quality of each chosen opening combination candidate, the steady-state values for chamber pressures and piston velocity are calculated. As the equations cannot be solved symbolically, Newton-Raphson method is used to find the desired values.

A cost function is used to find a compromise between different desired properties for the outputted control result. The opening combination candidates are evaluated based on the steady-state results. The compromise between following aspects is made: The velocity error, chamber pressure errors, energy consumption of each candidate and the number of valve switchings needed to achieve the new opening combination. When the value of cost function is calculated for the candidates, the candidate with the smallest cost value is chosen. Finally this valve opening combination is outputted, and fed to the valve control electronics.

2.3. Implementation of the PWM-controller into the model-based controller

As the PCM-controller operates using steady-state equations, it is not capable of PWM-control without modifications. The approach taken is to model different duty cycles as constant flow rates inside the PCM-controller and to handle the actual switching control of the PWM-valve outside the PCM-controller. This way the core components of the PCM-controller are not modified.

Different duty cycles are modeled as the openings of smaller artificial valves inside the PCM-controller. The valves share the same steady-state flow parameters as the real PWM-valve, expect for the reduced nominal flow rate. The first artificial valve has a flow rate of half of the real PWM-valve and the second artificial valve has one quarter of the real valve and the rest of the artificial valves are sized also according to binary series. Thus the PCM-controller handles the different duty cycles of the PWM-valves as an opening combination of the artificial valves. As the PCM-controller handles the PWM-controlled valves as they were producing a constant flow rate, it is important to have the switching frequency significantly higher than the natural frequency of the controlled cylinder-load system in order to avoid oscillatory response.

The PCM-controller calculates the optimal valve opening combination for each sample time. As the output of the PCM-controller includes the real valves and the artificial PWM-valves representing the different duty cycles of the PWM-controlled valves, an additional logic is required for realization of the actual PWM-control. The desired duty cycle is reconstructed from the openings of the artificial valves:

$\boldsymbol{u}_{\text{artificial\_valves}}$ x ***duty_cycles*,**

where $\boldsymbol{u}_{\text{artificial\_valves}}$ is a row vector defining the opened artificial valves, and ***duty_cycles*** is a column vector defining the corresponding duty cycle of each artificial valve. As an example, a PWM-valve is modelled with 5 artificial valves and PCM-controller is outputting following output vector: [1 0 0 1 0]. This results in a target duty cycle of [1 0 0 1 0] x [3.125 6.25 12.5 25 50]' = 28.125. The PWM-controller uses this target duty cycle for driving the PWM-valve during the next cycle.

2.4. Control of the crossflow

Crossflow between the supply and tank line can be used to increase the resolution of the PWM-control. As the PWM-controlled valve is not infinitely fast, there is a certain minimum duty cycle that it can produce consistently. The actual value of the minimum duty cycle depends of course on the switching frequency and the response time of the valve. If the repeatability of the valve is good even in ballistic mode, where the valve is not closed or opened completely during the cycle, the minimum duty cycle is much lower.

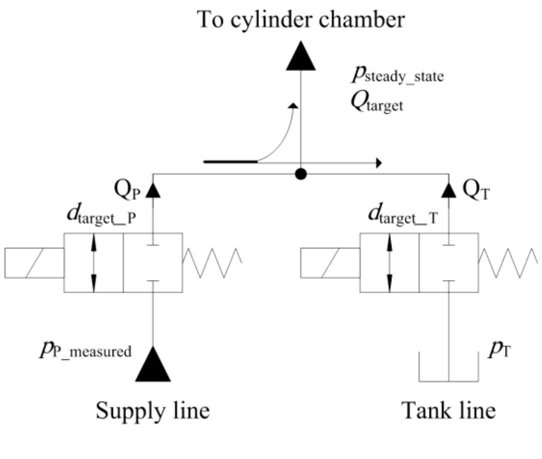

Figure 2. Use of cross-flow in order to obtain smaller duty cycles than the minimum duty cycle of the fast switching valves.

Figure 2 presents the hydraulic diagram of the control of one cylinder chamber. The target duty cycle can be obtained by calculating the suitable duty cycles for both, the supply side and tank side PWM-valves so that both operate with higher duty cycle than the minimum duty cycle.

Following algorithm is implemented for calculating the duty cycle for an inflow target:

1. Flow rate of opened PWM-valve of supply Q_P and tank side Q_T are calculated using the same steady-state valve model as the PCM-controller uses

2. Minimum flow rate is calculated for both sides using the user set minimum duty cycle and the calculated flow rates of the opened valves resulting in values Q_{P_min} and Q_{T_min}

3. Target flow rate Q_{target} is calculated from the flow rate of the opened supply side valve and the target duty cycle

4. If $Q_{target} - Q_{T\_min} < Q_{P\_min}$, then the supply side flow target Q_{P_target} is set to Q_{P_min} and the tank side flow target Q_{T_target} is set to $Q_{target} - Q_{P\_min}$, otherwise Q_{P_target} is $Q_{target} - Q_{T\_min}$, and Q_{T_target} is Q_{T_min}

5. The duty cycle references are calculated for both valves as a ratio of the reference flow rate and full opening of the valve: $d_{target\_P} = Q_{P\_target}/Q_P*100$ and $d_{target\_T} = Q_{T\_target}/Q_T*100$

For an outflow target, sections 3 and 4 are changed as follows:

3. Target flow rate Q_{target} is calculated from the flow rate of the opened tank side valve and the target duty cycle

4. If $Q_{target} – Q_{P\_min} > Q_{T\_min}$, then the tank side flow target Q_{T_target} is set to Q_{T_min} and supply side flow target Q_{P_target} is set to $Q_{target} - Q_{T\_min}$, otherwise Q_{T_target} is $Q_{target} – Q_{P\_min}$, and Q_{P_target} is Q_{P_min}

There is a possibility of achieving infinitely small flow rates just by adjusting the duty cycles of the valves. In practice the smallest achievable flow rate is limited due to uncertainty of valve switching time and also inaccuracies of the valve model and pressure measurement.

3. THE TEST APPLICATION

Figure 3 presents the hydraulic diagram of the test system, which is a horizontally positioned linear cylinder drive with a load mass of 500 kg. The valve blocks are located directly on top of the piston side port of the cylinder in order to minimize dead volumes and transmission lines between the switching valves and the cylinder (see figure 4). The rod side of the cylinder is connected to the valve block via 600 mm pipe.

3.1. The supply system

In order to decouple the transmission line between the accumulator of the supply system and the valve block, a small local accumulator is placed close to the valve block. The need for the local accumulator depends on the characteristics of the supply line. If the supply line is short and the cross section is big enough enabling small flow velocities, the system could be possibly used without the local accumulator. Supply pressure is set to 12 MPa and a zero-pressure tank line is used.

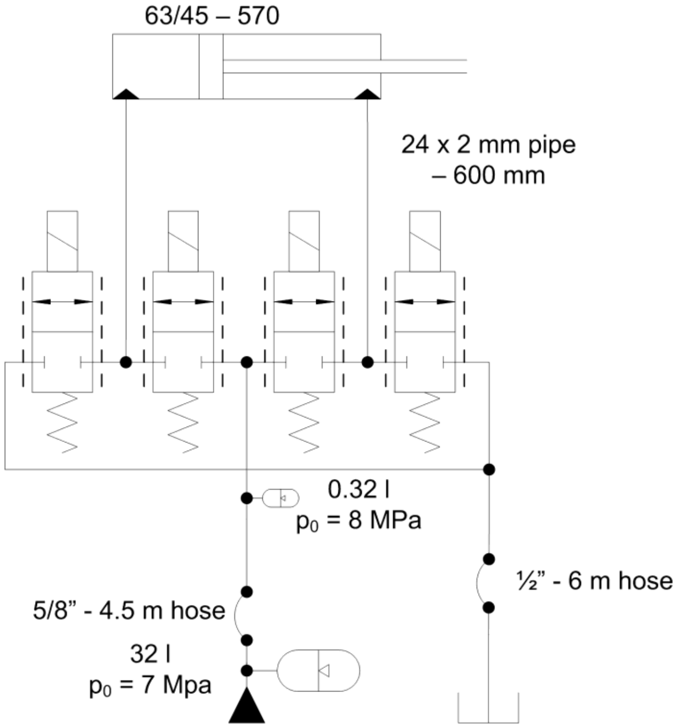

Figure 3. Hydraulic diagram of the test system

3.2. The switching valves

Each DFCU of the digital hydraulic valve system constitutes of two fast switching valves developed at LCM (Linz Center of Mechatronics GmbH.) and two commercially available Bosch Rexroth KSDE on/off-valves. The most significant difference between the performance of the two valves is the response time. The fast switching valve has an opening and closing time of about 2 ms, whereas the opening and closing time of the KSDE valve was measured to be 10-12 ms. According to manufacturers data the flow capacity of the KSDE valve is 10 l/min at 0.5 MPa similarly to the fast switching valve designed by LCM.

The orifices of the valves are sized in a certain way to obtain highest possible resolution and flow capacity: Biggest flow rate is produced by a KSDE valve without a throttle to maximize the flow capacity. The second KSDE valve has the orifice of diameter 2.4 mm and the two fast switching valves are equipped with 1.8 and 1.3 mm orifices.

The valve flow characteristics are measured in order to find out the flow capacity of each valve – orifice system. For example the valves of the DFCU PA are measured to have flow capacities of 2.86, 4.09, 6.23 and 13.68 l/min at 0.5 MPa pressure difference. Sizing of the orifices seem to agree quite well with the desired flow capacities given in chapter 2.

Modular block design was used for the fast switching valve block, which 3D model is shown in figure 5. A single valve block houses switching valve for each four metering edge. In this study two of these valve blocks were used together with earlier manufactured 4 x 4 KSDE valve block. As described earlier, two KSDE valves were used per DFCU, so the system was driven using a 4 x 4 digital valve system, where half of the valves were fast switching valves.

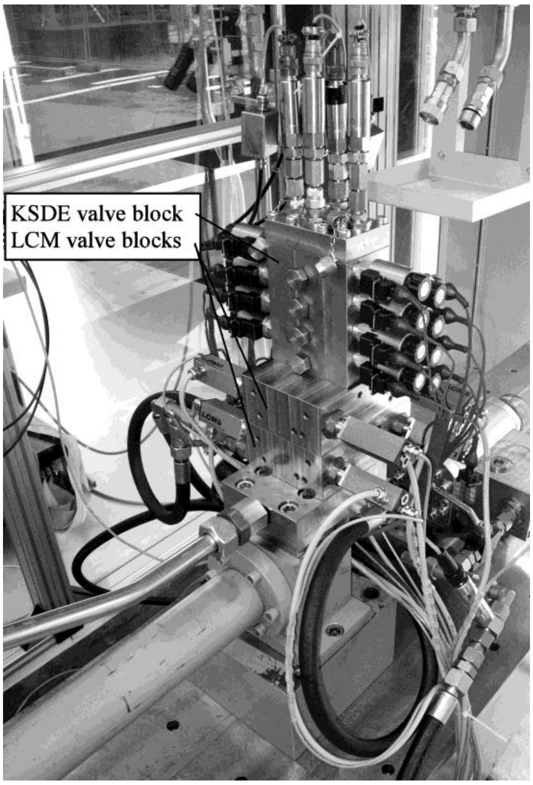

Figure 4. Valve blocks connected to the cylinder.

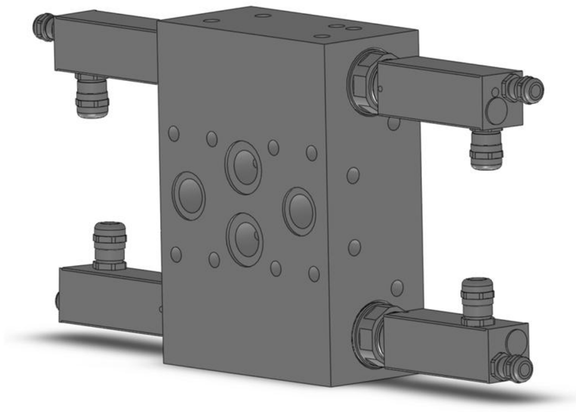

Figure 5. 3D model of the valve block including fast switching valves in four metering edges.

3.3. Controller configuration

The PCM-controller is set to operate at a sample time of 30 ms, in order to ensure long enough computing time as shown in table 1. The PWM frequency is set constant to 100 Hz and the sample time of the PWM-controller to 0.1 ms. Thus the PWM controller drives 3 cycles between the output updates of the PCM-controller.

Table 1: Controller parameters

T_s = 0.01 ms	K_{ff} = 0.75
$T_{s\_controller}$ = 30 ms	v_{tres_1} = 0.6 mm/s
f_{PWM} = 100 Hz	v_{tres_2} = 0.4 mm/s
ω_F = 10 rad/s	t_{delay} = 8 ms
ω_{pP} = 20 rad/s	$t_{delay\_closing}$ = 4 ms
K_p = 3.2	d_{min} = 25 %

The upper-level position controller is a P-controller together with a velocity feedforward. The gains are presented in the table 1. The system uses low pass filtered load force estimate, which is based on measured pressures of the cylinder chambers and the measured and low pass filtered supply pressure. The break frequencies of these low pass filters are shown in the table. Relatively low frequencies are used to ensure, that no oscillations in the controller output are caused because of these measurements. Velocity thresholds are used to avoid repeated starting and stopping of movement. The control signals to the fast switching valves are delayed by 8 ms in order to match their response time with the response time of the KSDE valves. Additional delay is placed on closing of KSDE valves in order to better match the dynamics of opening and closing of the KSDE valve. Minimum duty cycle is set to 25 % to ensure very linear behavior of the fast switching valve above the minimum duty cycle.

4. EXPERIMENTAL RESULTS

The behavior of the PWM-PCM controlled system is studied with four different kinds of responses in order to see the benefits and drawbacks of the control method in real experimental setup. The trajectory response shown in figure 6 shows the behavior of the system at high velocities. The smaller movement has a peak velocity of 175 mm/s and the bigger movement 350 mm/s. The maximum velocity of the system is about 350 mm/s in retracting direction with the used pressure differentials and slightly higher in extending direction.

Switching control is enabled throughout the opening of the DFCU in order to achieve smooth velocity control. The control signal of each DFCU is shown in the lowest diagrams. Black curve represents the opening of the supply side DFCU while the grey curve represents the opening of the tank side DFCU, value 15 being the maximum opening. Position signal is shown without filtering. The velocity signal is calculated from a low pass filtered position signal. The filtering of the data is done using a fourth order low pass filter with cut-off frequency of 20 Hz. Velocity response shows some measurement noise as well as real oscillation of the velocity of the mass. Figure 7 shows similar movement despite the smaller amplitude.

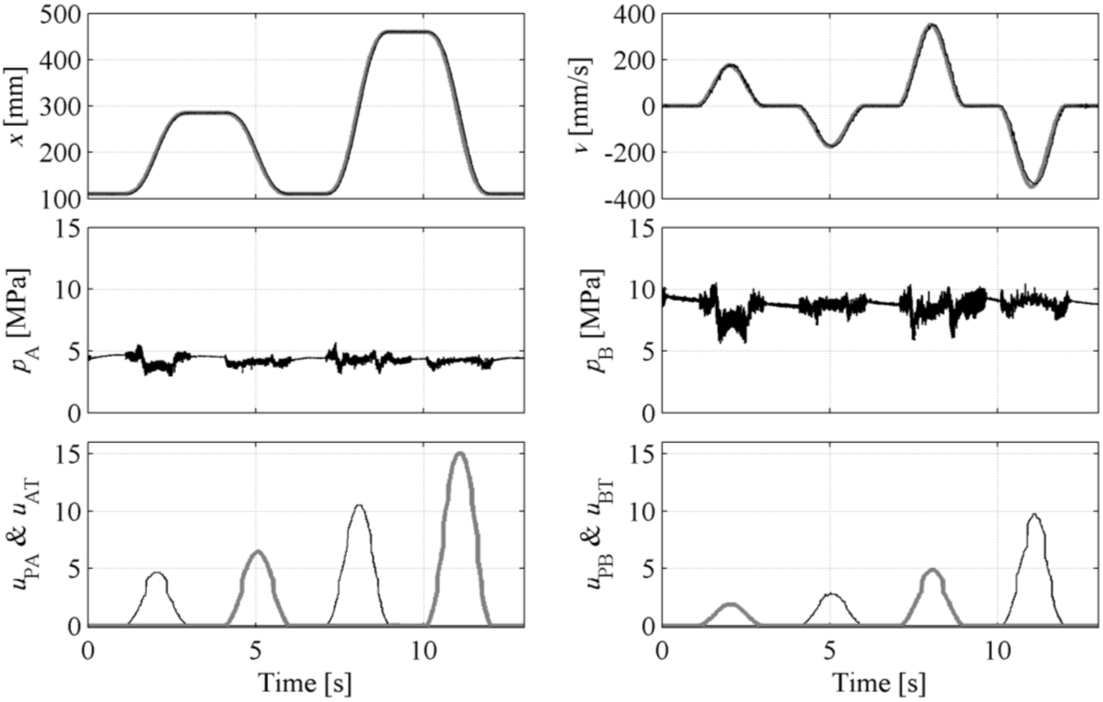

Figure 6. Measured fast trajectory.

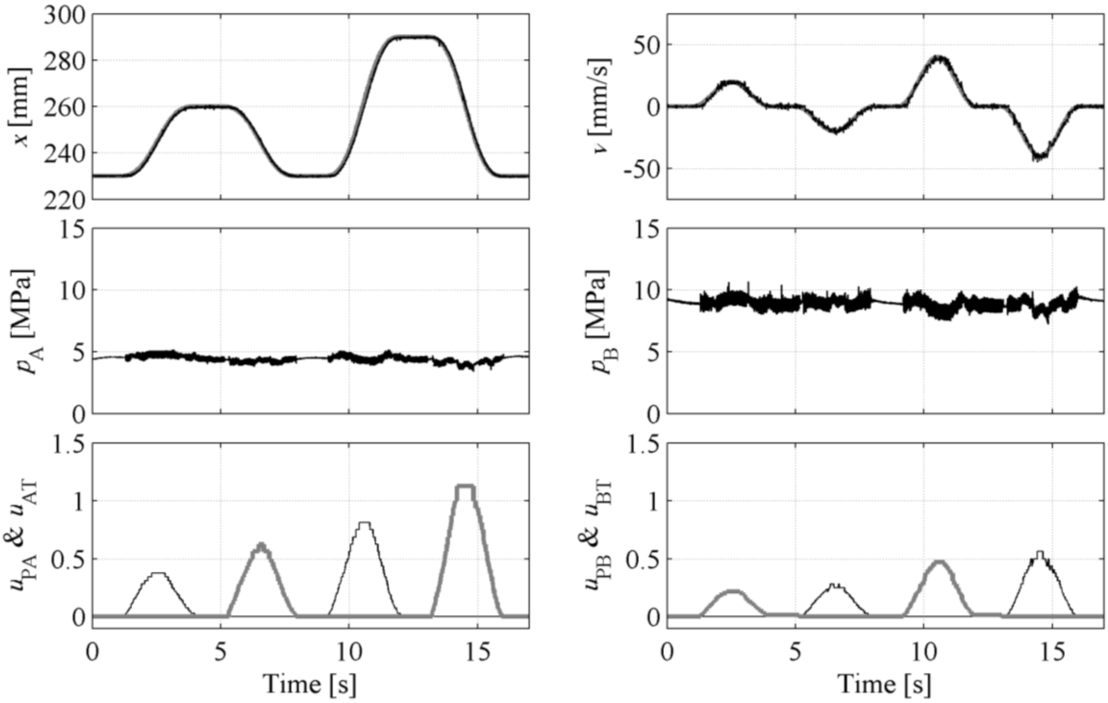

Figure 7. Measured slow trajectory.

Figures 8 and 9 show slow velocity ramp responses to positive and negative direction. The lowest diagrams present the use of crossflow, when the smallest velocities are driven.

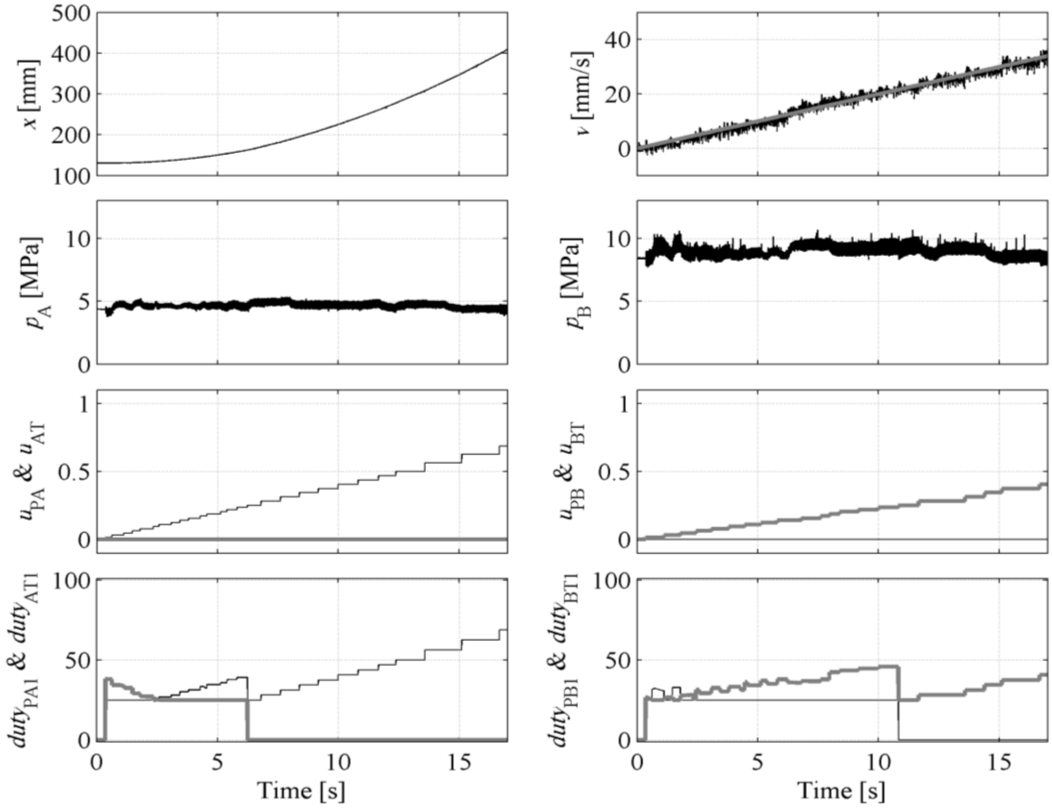

Figure 8. Slow ramp response to positive direction.

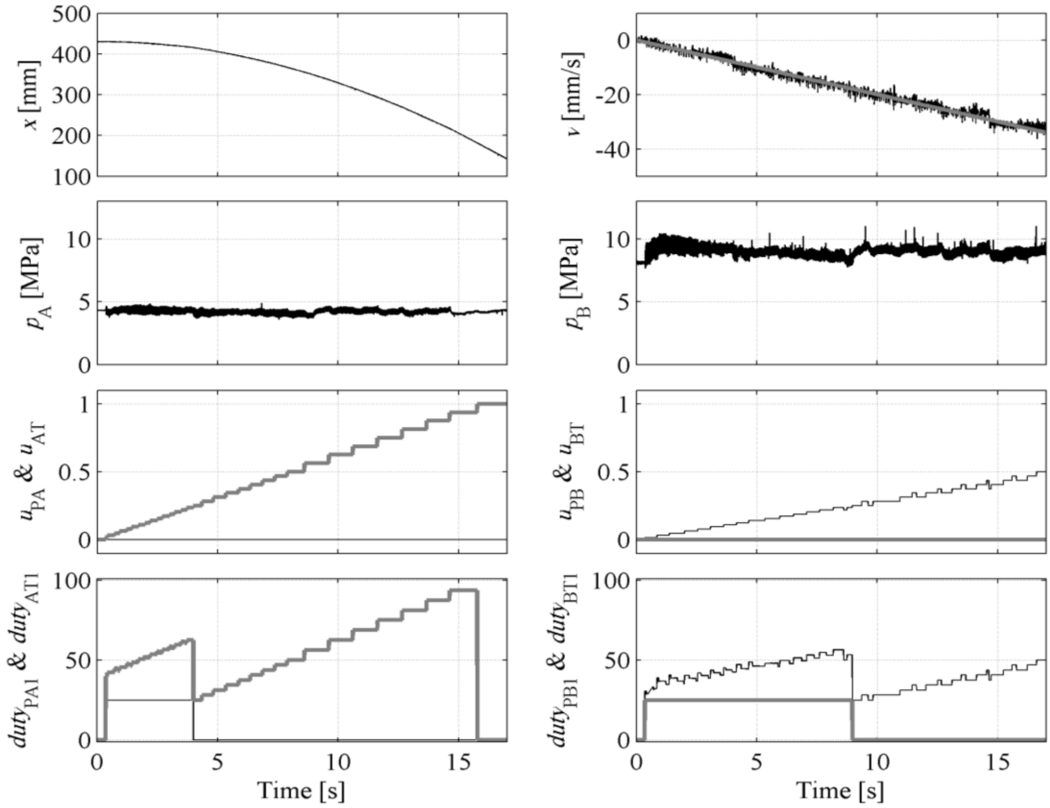

Figure 9. Slow ramp response to negative direction.

In addition to low pass filtered velocity signal shown in figures, an acceleration sensor was used to study the velocity oscillation at the switching frequency. Integrated signal of the acceleration sensor shows that the oscillation is the most pronounced, when the duty cycle of the piston side valve is near 50 %. The peak-to-peak value of the oscillation is about 8 mm/s. At the smallest velocities, the oscillation is below 2 mm/s. Typical value of the peak-to-peak chamber pressure ripple is 0.5 and 0.8 MPa for piston and rod side chamber respectively.

5. DISCUSSION AND FUTURE WORK

This paper presents a method to combine PWM-control of on/off-valves to a steady-state model based controller of digital hydraulic valve system. An algorithm for enabling crossflow is also presented. The use of crossflow enables significantly smaller flow rates than the flow rate at the minimum duty cycle. The minimum achievable velocity was measured to be about 1 mm/s while the maximum was 350 mm/s. This gives the ratio of maximum and minimum velocity of 350. In previous work with 4 x 4 valve system, the achieved value was reported to be about 50 [5]. The amount of pressure and piston velocity ripple is influenced heavily by the sizing of the system and the driven load. Combination of PCM and PWM control methods is a promising way to increase the control resolution of a digital hydraulic valve system.

In future work the number of switchings needed should be reduced. As the control resolution of the digital hydraulic valve system is sufficient at higher velocities, the switching control could be restricted to the smallest velocities only. Also the synchronization of the switching control of both sides of the cylinder should be further investigated to possibly allow smaller velocity and pressure ripple.

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