DIGITAL HYDRAULICS IN WORKBOAT PROPULSION CONTROL

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ABSTRACT

This paper introduces application of digital hydraulics in workboat propulsion control. The performance requirements of the propulsion control application can be considered to be moderate for hydraulics but because the application is safety critical robustness and reliability of the hydraulics are highly appreciated in harsh operating environments. Low cost and compact size are also preferred. Control method introduced in the paper is meter-out control of a hydraulic cylinder drive using a digital flow control unit. Performance of the digital propulsion control hydraulics is tested in test bench and a simple lifetime analysis is made and compared to requirements of standards concerning the application. Reliability and fault tolerance are also discussed.

KEYWORDS: Digital hydraulics, meter-out control, boat propulsion control, lifetime

1. INTRODUCTION

In marine applications propulsion control systems are used to control power and direction of propulsion of vessels. In high power applications where direct manual control (e.g. mechanical transmission) is not able to provide forces high enough to provide a reliable control of the propulsion, a power amplification system is needed. A common solution here is using hydraulic positioning system. Benefits of hydraulics in propulsion control application are robustness, large forces and good positioning accuracy achieved using compact actuators.

In addition to application specific requirements such as load forces and positioning accuracy, requirements for marine control systems are also set by international maritime regulations and standards. The international standards concerning vessels in boat class define test procedures for hydraulic propulsion control systems to ensure certain level of reliability before approving the design. In some cases certain level of redundancy is also required.

In this work control hydraulics of a water jet is used as a reference application which gives the performance requirements for the hydraulic system. In water jets the control hydraulics is used to operate nozzle and reversing deflector. The nozzle is used to control the direction of the propulsion on horizontal level and the reversing deflector is used to control the driving direction. Both the nozzle and the reversing deflector have their own control cylinder. Both cylinders are position controlled so that the position reference is proportional to position of control sticks used by the operator. Operation principle and structure of a water jet including the hydraulic control cylinders is shown in the following figure. The nozzle is marked with number 1 and the reversing deflector with number 2. Purple arrows in the figure show flow direction when reversing deflector is in up position and orange arrows show flow direction when reversing deflector is in reversing position (down). In the top view the reversing deflector components are transparent to highlight the nozzle operation.

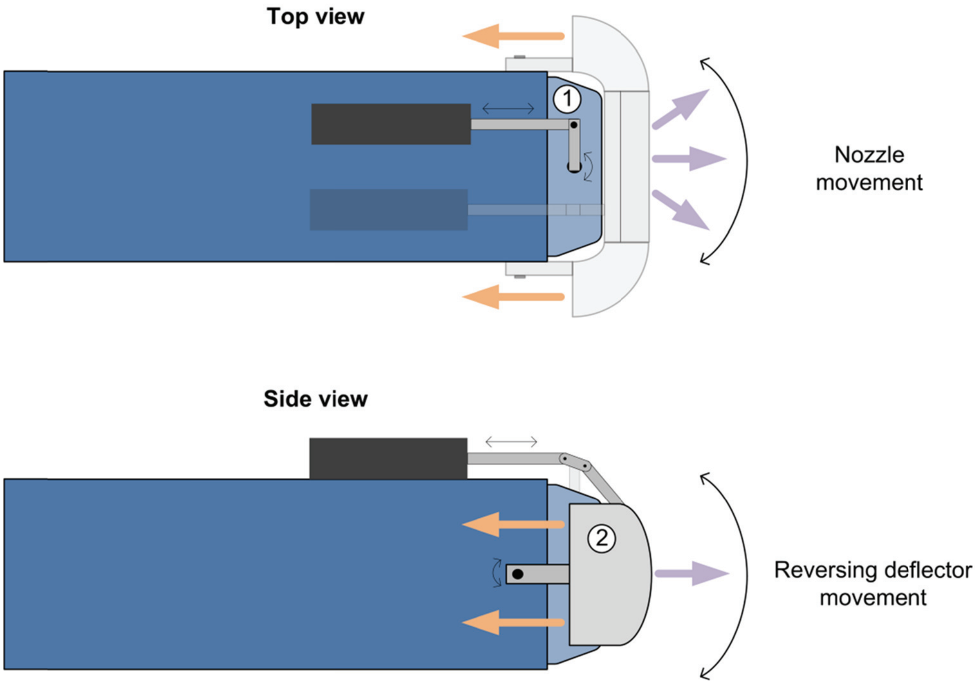

Figure 1. Operation principle of water jet control hydraulics

In this paper digital hydraulics applied in water jet control hydraulics is studied. Main focus of the work is in replacing traditional proportional control hydraulics with compact and cost effective digital hydraulic design. Meter-out control method for hydraulic cylinder drive using a single digital flow control unit (DFCU) is introduced and experimentally tested under different loading conditions.

The lifetime of digital hydraulic control valve is studied based on the state transitions of on/off valves of the DFCU and results are compared to test procedures defined in the standards concerning the application field. Also the fault tolerance of digital hydraulic control valves is shortly discussed.

2. METER-OUT CONTROL OF HYDRAULIC CYLINDER DRIVE USING DIGITAL FLOW CONTROL UNIT

2.1. Steady state flow equations

Hydraulic diagram of meter-out control of a hydraulic cylinder drive for cylinder extraction is presented in Figure 2. Velocity of the cylinder is controlled by restricting return flow using a DFCU. Notations used in Figure 2 and steady state equations are:

p_S	Supply pressure	p_T	Tank line pressure
p_A	Cylinder piston side pressure	p_B	Cylinder rod side pressure
A_A	Cylinder piston side area	A_B	Cylinder rod side area
Q_B	Flow in return line	F_{load}	Load force
v	Cylinder velocity	u_{BT}	DFCU control vector
K_{v}	Flow coefficient		

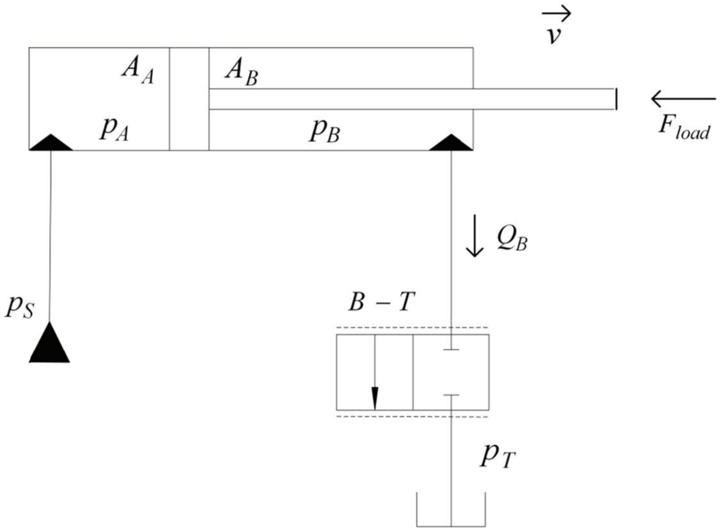

Figure 2. Meter-out control of a hydraulic cylinder drive

Steady state equations for the hydraulic system in Figure 2 are:

$$p_A = p_S \qquad (1)$$

$$F_{load} = A_A p_A - A_B p_B = A_A p_S - A_B p_B \qquad (2)$$

Steady state pressure $p_B$can be solved from equation (2):

$$p_B = \frac{A_A p_S - F_{load}}{A_B} \qquad (3)$$

Flow rate equation of turbulent flow of an ideal valve is:

$$Q = K_v \sqrt{\Delta p} \qquad (4)$$

The total flow in the return line according the equation (4) is:

$$\mathrm{Q_B} = sign(\mathrm{p_B} - \mathrm{p_T})\left(\sum_{i=1}^{N} \mathrm{u_{BTi}K_{v,BTi}}\right)\sqrt{|\mathrm{p_B} - \mathrm{p_T}|} \qquad (5)$$

The $sign()$ notation in (5) is used to define the direction of the flow. The DFCU control vector $\mathrm{u_{BT}} = [u_1\ u_2 \ldots u_N]$.

Velocity of the cylinder is:

$$v = \frac{Q_B}{A_B} \qquad (6)$$

Steady state equations for cylinder retraction can be solved in the same way.

2.2. Control principle

Control signal of DFCU is selected so that it minimizes a simple cost function (7) which consists of absolute value of velocity error and number of On/Off valve state transitions. Respectively gains $K_e$and K_s are used to set appropriate weight for the terms in the cost function. The velocity error is difference between reference velocity and velocity calculated using the steady state equations 1 – 6. Control principle using cost function has been described in details by Linjama et al. in [1] and [2].

$$J = K_e(|v_{ref} - v|) + K_s N_{switchings} \quad (7)$$

Occurrence of pressure peaks caused by variations in on/off valve switching times is eliminated by rejecting state transitions which could cause pressure peaks in case of varying switching times. Comprehensive research of the pressure peak phenomenon in digital hydraulics has been carried out by Laamanen et al. [3].

In position control the velocity reference is proportional to control error. The block diagram of the controller is shown in Figure 3.

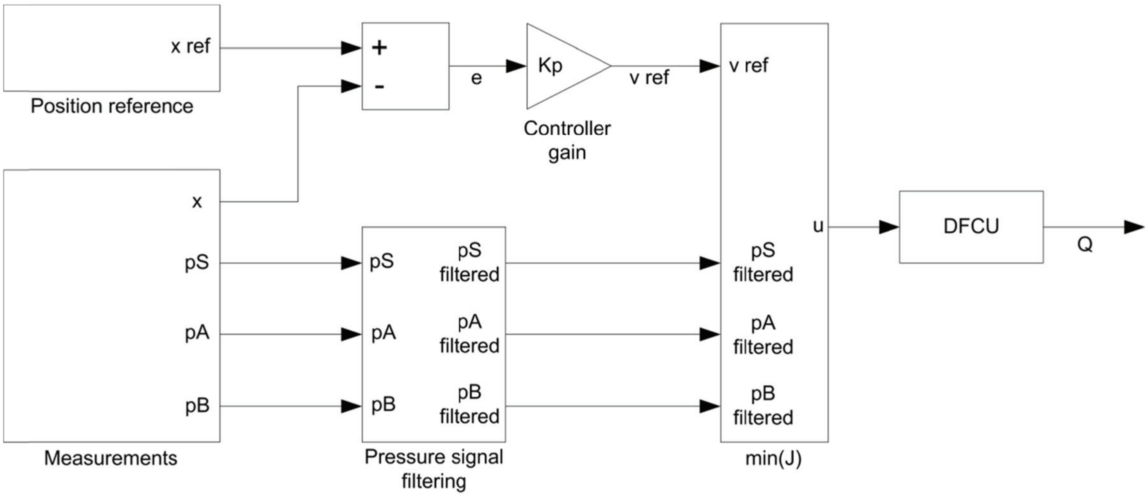

Figure 3. Controller block diagram

The implementation of the controller was done using a low cost MC56F8323 microcontroller which provides sufficient amount of calculating power for control algorithm and also necessary I/O interfaces for analogue signals and communication. Sample time of the controller is 50ms.

3. TEST SETUP

Meter-out control of propulsion hydraulics was tested in 1 degree-of-freedom (DOF) test bench shown in Figure 4. There are two cylinders in the test bench. One of the cylinders is used as control cylinder and the other one is used to generate load forces. Load mass can be attached to the boom above the control cylinder. Control cylinder position is measured using a resistive linear sensor.

Figure 4. Propulsion control test bench

Performance and lifetime requirements for the control hydraulics are presented in

Table **1**. Load forces shown in the table are estimated maximum forces affecting the control cylinders. The mass of inertia in the application is very low because it consists only of the mechanical parts used to direct the propulsion.

Lifetime requirement in the table is according the control system components duration tests defined in ISO standard concerning hydraulic steering systems of small crafts [4]. In the standard the test procedure is intended to hydraulic cylinders but here it is applied also for the control valve and it consists of 50 000 reversals of the control cylinder driven from one hard end to the other. In the experimental tests a working cycle consisting of driving the control cylinder from one hard end to the other one and back is used. This gives us lifetime requirement of at least 25 000 working cycles.

Table 1 Loading conditions and performance requirements for propulsion control hydraulics

Maximum load force on reversing deflector control cylinder [N]	Maximum load force on nozzle control cylinder [N]	Mass of inertia [kg]	Maximum velocity [mm/s]	Lifetime [Working sequences]
0 – 2400	-800 – 800	60kg	±50	25 000

Hydraulic diagram for meter-out control of the propulsion control cylinder is presented in Figure 5. The DFCU used for return flow control is connected to the tank line and between the DFCU and the cylinder there is a directional 4/3 logic valve which is used to select direction of the movement. The A and B side pressures of the cylinder and the supply pressure are measured. Tank pressure is assumed to be zero.

Control method of the DFCU is tribonacci coding and number of bits is five (N=5). Flow rates for five bits tribonacci sequence are 1:1:2:4:7. The tribonacci control method was selected because with tribonacci control method most of the net flows of the DFCU can be achieved at least with two different control signal values. This allows better properties in pressure peak elimination and also certain level of redundancy. Comparison between different DFCU pulse code modulation (PCM) control methods was done by Laamanen et al. [5]. Fault tolerant control of the DFCU is out of the scope of this paper.

Booster electronics was used to speed up switching times and decrease switching time variations of the on/off valves in the DFCU and the directional 4/3 valve.

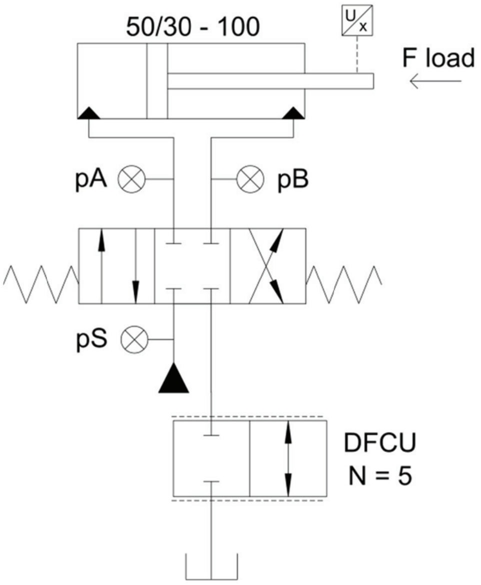

Figure 5. Test bench control cylinder hydraulics

DFCU tuning was done placing restriction elements with drilled holes into valve block to flow path of each on/off valve. Actual flow rates of on/off valves in DFCU as a function of pressure difference were measured and square root flow equation of turbulent flow of an ideal valve (4) was fitted in measured data to find out the actual flow coefficient values. Measured values with fitted curves are shown in Figure 6.

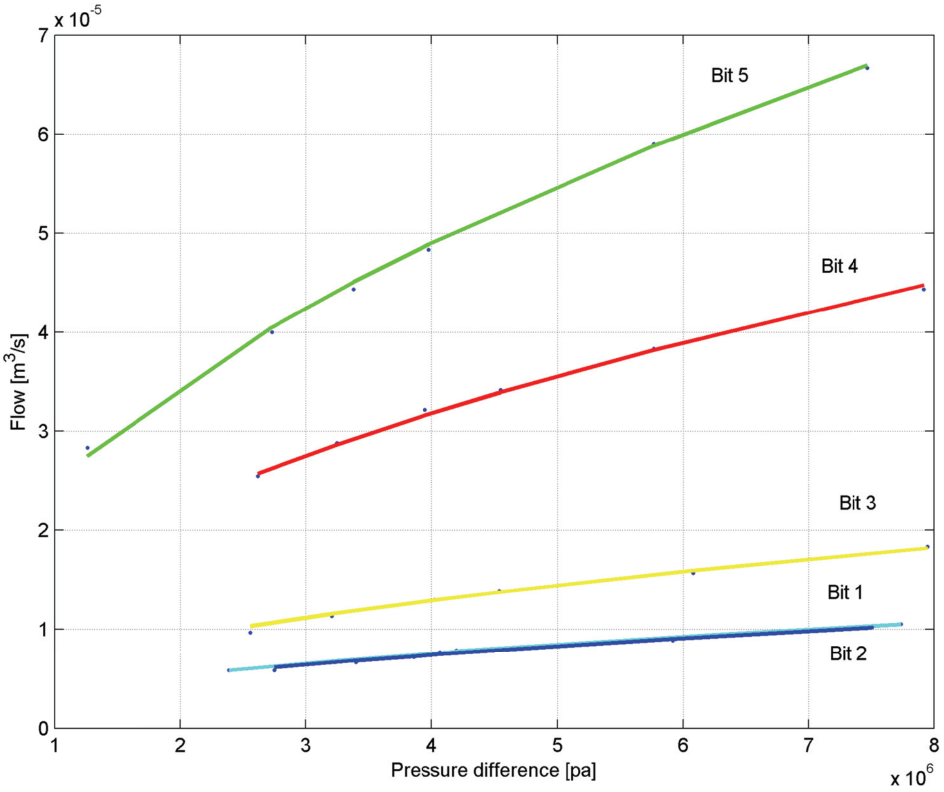

Figure 6. Measured ΔpQ values of the DCFU with fitted curves

The measured flow coefficient values of DFCU bits are listed in Table 2. In practice the tuning of the DFCU turned out to be difficult and in the worst case the measured flow coefficient value differs 12 percents from the target value. In the table the actual bit sizes are also compared to ideal tribonacci sequence flow rates so that the smallest measured size is scaled to 1Q.

Table 2 Flow coefficient values

Bit	Measured flow coefficients	Measured flow rate	Ideal flow rate
1	3.8*10e-9	1.03Q	1Q
2	3.7*10e-9	1.00Q	1Q
3	6.5*10e-9	1.76Q	2Q
4	15.9*10e-9	4.30Q	4Q
5	24.5*10e-9	6.65Q	7Q

4. EXPERIMENTAL RESULTS

Meter-out control strategy using a single DFCU was tested in different operating situations. First stage of the tests was verification of the cylinder open loop velocity tracking using steady state equations presented in chapter 0. Position control accuracy and performance was measured under different loading conditions using approximated propulsion control cylinder load forces. For lifetime analyzes DFCU state transitions during a working cycle was studied.

In all figures where control signal of the 4/3 directional valve is shown the control signal value 1 means movement to positive moving direction and value 2 movement to negative moving direction. Control signal value zero means that the valve is closed.

4.1. Cylinder velocity tracking

Cylinder open loop velocity tracking accuracy was tested using sinusoidal velocity reference. Measured responses are presented in Figure 7. Amplitude and frequency of the reference signal on the left hand side are respectively 17mm/s and 0.5rad/s and 34mm/s and 1.0rad/s on the right hand side.

From Figure 7 it can be seen that the resolution of the velocity control is better when moving to negative direction. This is caused by asymmetry of the cylinder which yields to different flow rates and chamber pressures during negative and positive movements. The differences in resolution of velocity are more clearly visible in the left hand side curves where amplitude of the velocity is smaller.

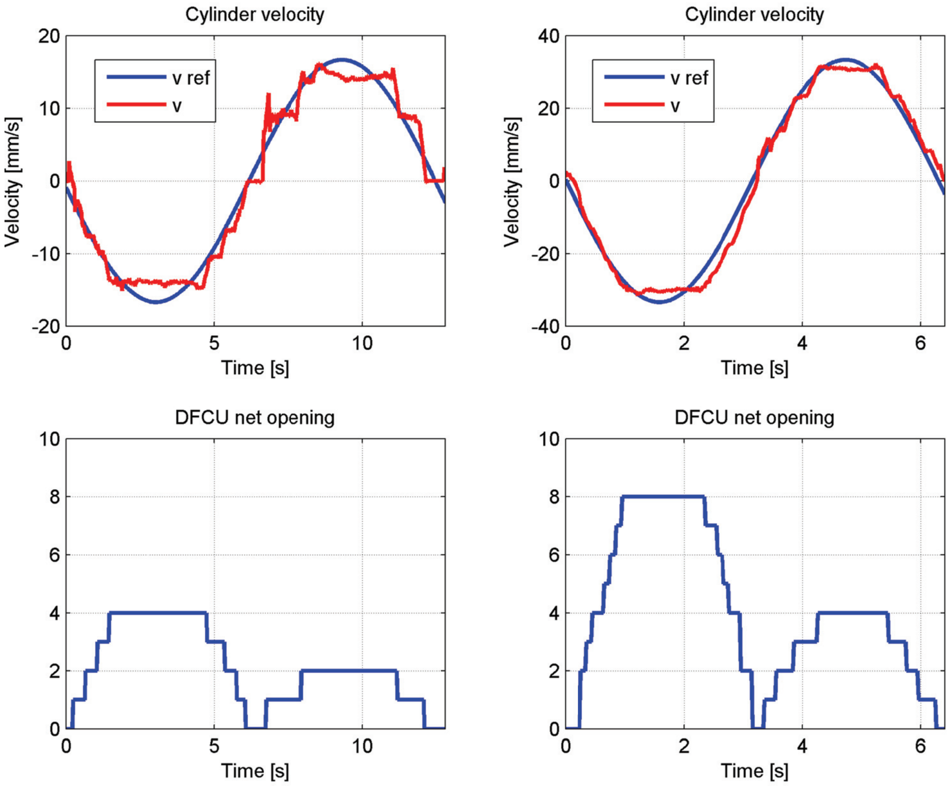

Figure 7. Cylinder velocity tracking

4.2. Position control accuracy under different loading conditions

Position control accuracy and performance of the digital hydraulic propulsion control hydraulics were studied under three different load forces. The load forces were generated using loading cylinder and taking gravity force of the load mass into consideration. The total load forces used were: -1000N, 1000N and 2500N. The maximum and minimum load forces were selected a bit larger than the estimated maximum loading conditions introduced in chapter 3. Load force 1000N was selected between the maximum and minimum.

Position control accuracies in different cases were measured using a test sequence. The results are shown in figures 8 – 10. Steady state control error is less than 0.8 millimetres in all cases.

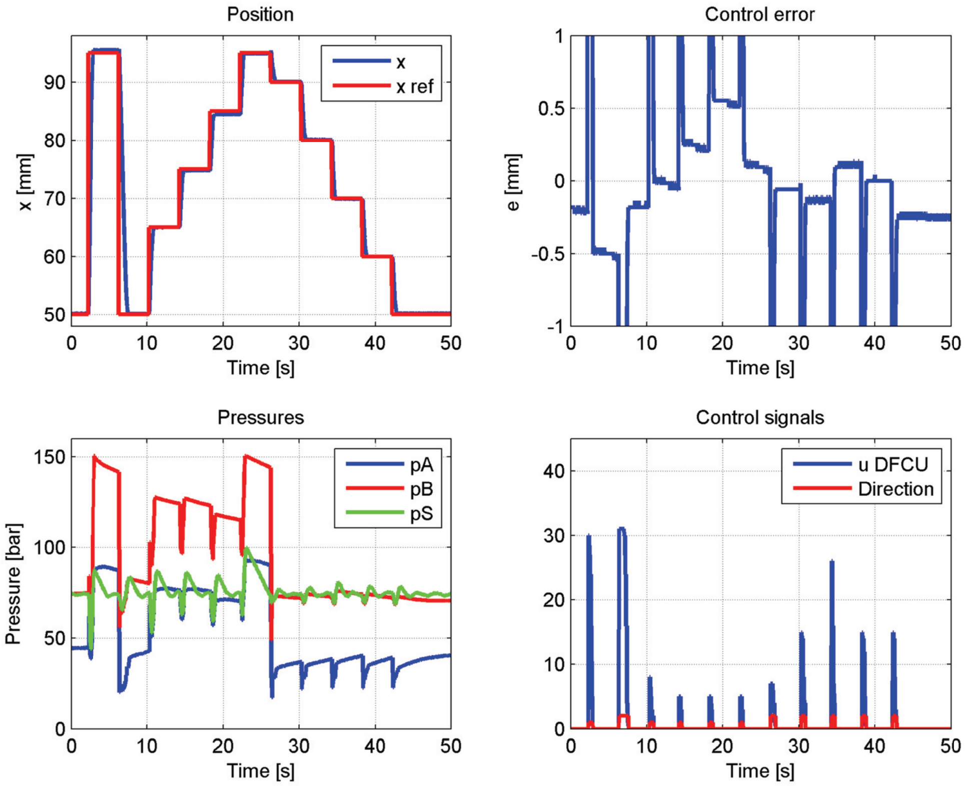

Figure 8. Test sequence. Load force -1000N

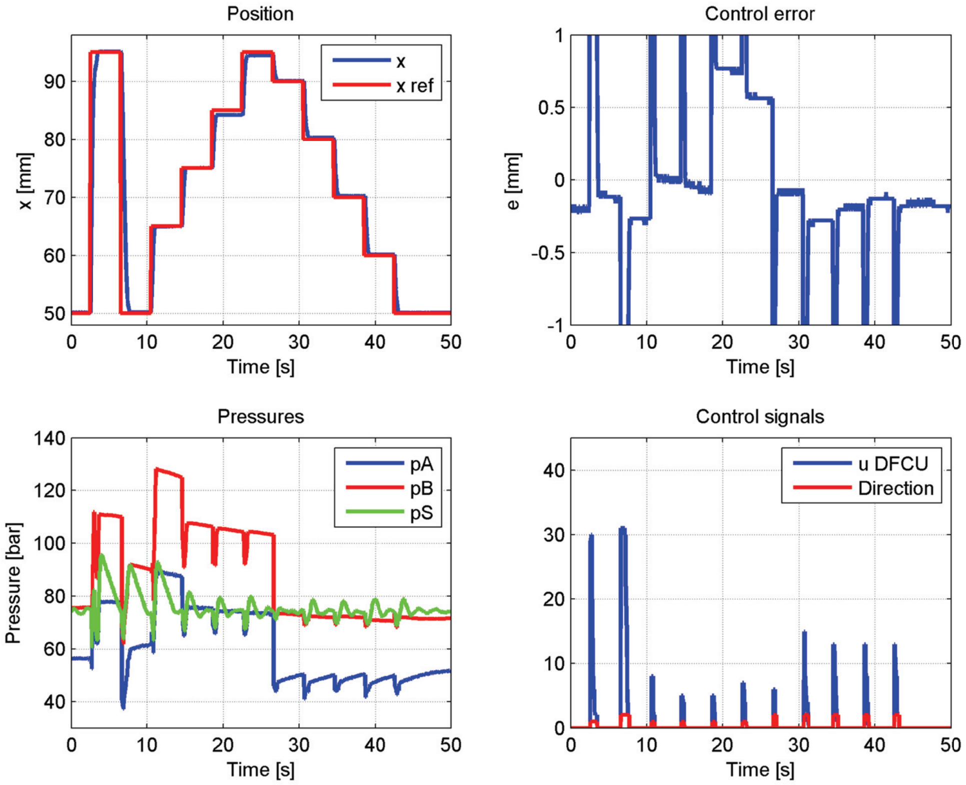

Figure 9. Test sequence. Load force +1000N

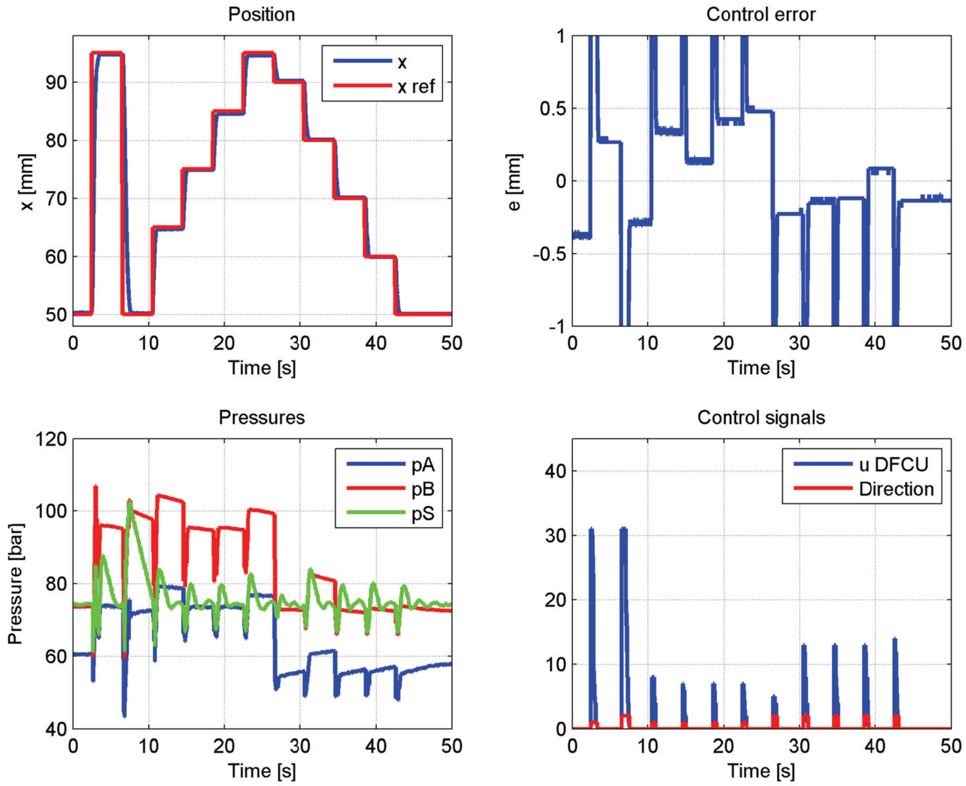

Figure 10. Test sequence. Load force +2500N

Maximum velocities during the test sequences under different loading conditions were measured and the results are shown in Table 3. The maximum velocities to the negative moving direction change under different loading conditions because of saturation of the DFCU.

Table 3 Cylinder maximum velocities under different loading conditions

Load force [N]	Max. velocity positive direction [mm/s]	Max. velocity negative direction [mm/s]
-1000N	105	48
+1000N	110	56
+2500N	110	65

4.3. DFCU state transitions during working cycle

DFCU state transitions were observed from control cylinder full stroke step response to find out what is the estimated lifetime of the DFCU in the application measured in working cycles. The response is shown in Figure 11.

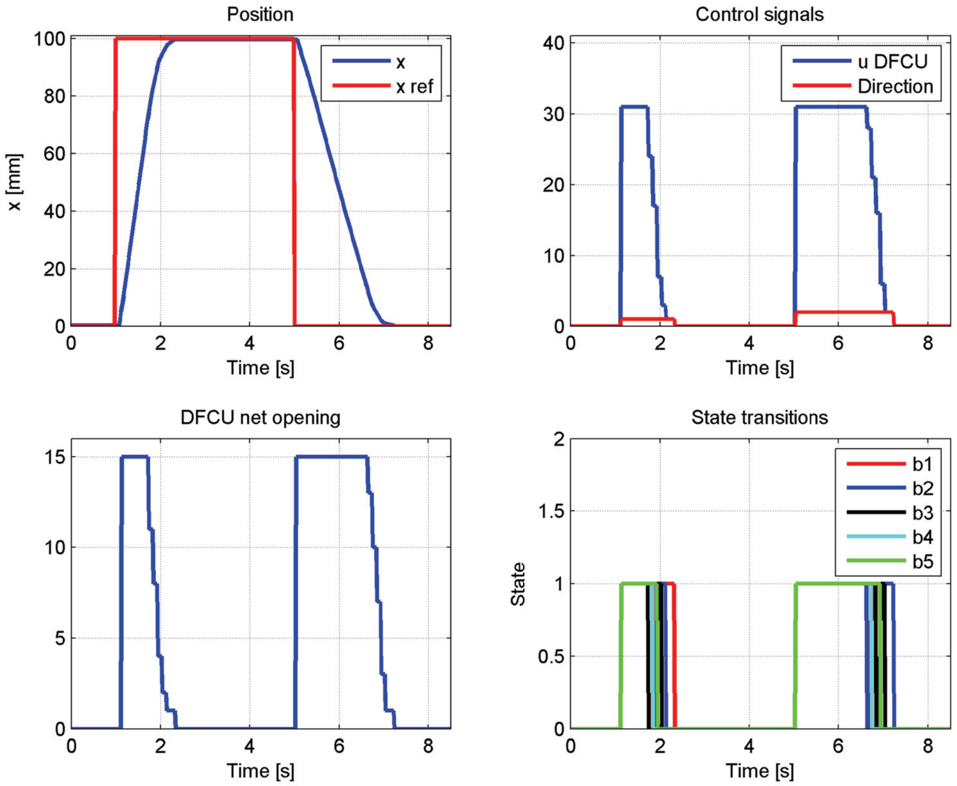

Figure 11. Control cylinder working cycle

State transitions in DFCU during one working cycle are shown in Table 4. State transitions are shown in load cycles. One load cycle consists of two state transitions meaning opening and closing the valve, or with binary states, the state transitions 0 → 1 → 0.

Table 4 DFCU load cycles during one working cycle

Bit	1	2	3	4	5
Number of load cycles	4	4	4	3	2

According the manufacturer information the 2/2 seat valves used in the DFCU have lifetime of 10 million load cycles [6]. Based on this information and the measured state transitions during one working cycle the lifetime of the most heavily loaded 2/2 seat valves of the DFCU in the application would be around 2.5 million working cycles.

5. CONCLUSIONS AND DISCUSSION

Meter-out control method of hydraulic cylinder drive using a single DFCU was introduced and experimentally tested in test bench under approximated maximum loading conditions of the propulsion control hydraulics used as reference application.

According the experimental results in the test bench the overall performance and control accuracy of the control system can be expected to meet the requirements of the application. The maximum velocity of the cylinder to the negative moving direction under largest negative load force was 48mm/s which is a little bit below the desired 50mm/s but this can be overcome by a slight increase of maximum flow of the DFCU. Estimating the real forces affecting the water jet control cylinders during operation of the craft is very difficult and that is why only estimated maximum loading conditions were studied and more realistic tests in the actual application under real loading conditions are recommended but these tests are left for future.

Downside of the control method is that using asymmetric cylinder causes different flow resolution when moving different directions. This is most visible in velocity tracking measurements and maximum velocities under different loading conditions. On the other hand, low cost of the system is achieved using low cost control electronics and low resolution DFCU with small number of on/off valves. This makes the design more attractive choice for applications where the resolution and performance criteria are only moderate but other benefits of digital hydraulics, such as reliability, are appreciated.

The lifetime of the DFCU was studied based on a working cycle and state transitions of the DFCU during the cycle. Expected lifetime of the DFCU according the experimental results is around 2.5 million working cycles. This exceeds greatly the minimum requirement of the ISO standard which was only 25 000 working cycles [4]. If the 4/3 directional valve is replaced using appropriate bridge connection and similar 2/2 valves as in the DFCU it can also be included in the lifetime analyzes.

In generally the fault tolerance of on/off valves is considered to be good because of relatively large tolerances and high actuator forces compared to proportional control valves. With digital hydraulic valves fault tolerant control is also possible. Research of fault tolerance of digital hydraulics has been carried out by Siivonen et al. and the results are very promising [7][8]. More detailed studies of fault tolerance and fault tolerant control of the propulsion control hydraulics presented in the paper are left for future work but with the insight of reliable nature of the components and possibility of fault tolerant control, the digital hydraulics can be expected to bring enhancements to reliability of the propulsion control hydraulics.

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