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JAMMED ON/OFF VALVE FAULT COMPENSATION WITH DISTRIBUTED DIGITAL VALVE SYSTEM

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Abstract

The digital valve system is an on/off valve based directional flow control valve capable of accurate control of hydraulic actuators. The presented system has good features concerning fault tolerance since it can detect, diagnose and compensate faults on-line. This paper concentrates on fault compensation when a valve has jammed in the open – position and the system has internal leakage. The system can adapt to the fault and continue operation with only a small degradation in performance. This feature is unique in the area of hydraulics since the system has no extra components added. The cost for this compensation is increased calculation in the controller and increased energy consumption if a fault occurs. If these downsides can be accepted the system can be considered fault-tolerant and it could be used even in critical applications where failing is not an option. Fault tolerance can also be introduced as standard in every modern hydraulic application where good performance and fault tolerance are needed.

Keywords: digital hydraulics, valve faults, compensation

1 Introduction

Hydraulic systems are used in applications where large forces must be mastered accurately, flexibly and fast. Modern machine systems also have high demands in terms of energy consumption and reliability. Traditionally, hydraulic systems do not always meet these challenges and therefore new innovative ideas are needed in order to compete with electrical and mechanical solutions.

Digital hydraulics is a somewhat new way to control hydraulic power. The system consists of on/off -valves connected in parallel. Figure 1 presents the hydraulic drawing symbol of one digital flow control unit, DFCU, and the connection of individual valves in it. Since all on/off valves have only two possible states, open or closed, the system is completely digital. The total number of different opening combinations or states in one DFCU in a binary based scheme is two powered by the number of valves in the DFCU. For example, with five valves, the total number of discrete opening combinations is 32, which also includes the state zero, which is closed.

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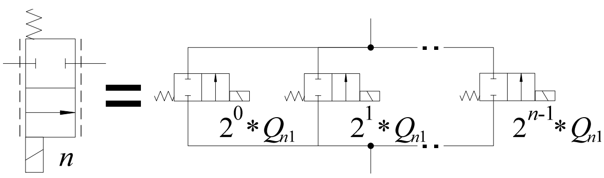

Fig. 1: *Digital Flow Control Unit, DFCU and flow rate through each valve with binary coding scheme*

A complete digital valve system usually consists of several DFCUs. For example, controlling a simple double-acting hydraulic cylinder accurately with variable load demands at least two DFCUs and one valve to control the flow direction, or four DFCUs. Other concepts have also been tested, but the four-DFCU solution has proved itself to be rather effective in several different tasks. Figure 2 presents a digital valve system with four DFCUs, pressure measurement sensors, and hydraulic cylinder.

The digital valve system has positive features with respect to both energy efficiency and fault tolerance. Linjama et al. (2008) compared digital and proportional valve system in hydraulic test bench with LS-pump, different kinds of loads and trajectories, and calculated up to 39 % less used energy with the digital system.

Basically, the efficiency is better when a differential connection, i.e. regenerative connection, can be used and when the load is varying. The digital valve system is capable of choosing the optimal control mode for each situation online. This online optimization and selection of optimal control out of millions of different combinations also enables the possibility of active fault compensation.

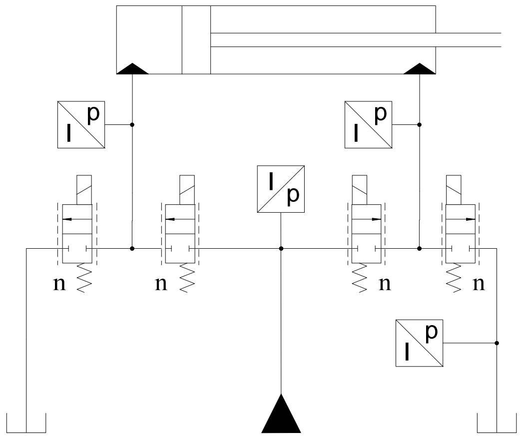

Fig. 2: *Digital valve system and double acting hydraulic cylinder*

1.1 Fault Tolerance

Fault tolerance is a wide concept. The term is not standardized in the area of hydraulics but Blanke et al. (2003) have defined it rather well in the area of process industry. The definitions can also be used in hydraulic systems since they are extensive and general.

- Fail-operational: The system is able to operate with no change in performance despite any single point failure.
- Fault-tolerant: A system is able to continue operation and degradation of performance may be accepted.
- Fail-safe: The system fails to a state that is considered safe in either a general or specific application.
- Passive Fault Accommodation: Robust design of the system covers certain faults.
- Active Fault Accommodation: Detection and isolation of a fault leads to a change in the system to accommodate a fault. It may include reconfiguration but is not limited into it.

Fault tolerance of hydraulic valves has been researched a lot during the last few decades. Especially the areas of fault-detection, condition monitoring, and fault-diagnosis have been studied in many different areas of technology (Hindman et al., 2002 and Isermann, 1997). The monitoring and condition diagnosis of hydraulic valves in industrial applications has been researched by Rinkinen et al. (1997) and Lurette and Lecoeuche (2003). Although some development has been done, no commercial proportional or servo valve is actually fault-tolerant. This is due to the fact that traditional systems always include single point of failure (SPoF) - items that can cripple the whole system. The only way to achieve fault tolerance is to double some vital components or even the whole system, as is often done e.g. in aerospace hydraulics (Persson and Fritz, 2001). Figure 3 presents a doubled valve system for aerospace applications. The system includes a back-up valve that can be used if the primary valve fails. If both valves fail, the cylinder can be set into free running mode so that it has no effect on, e.g. airplane wing aerodynamics. Commercial solutions in traditional valves are not fault-tolerant. The design might be robust and some emergency functions included, so fault tolerance is limited mainly to passive fault accommodations and fail-safety.

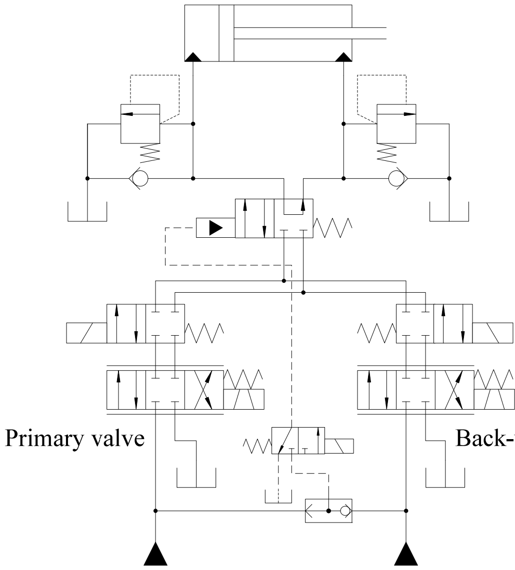

Fig. 3: *Fault-tolerant proportional valve system with doubled components*

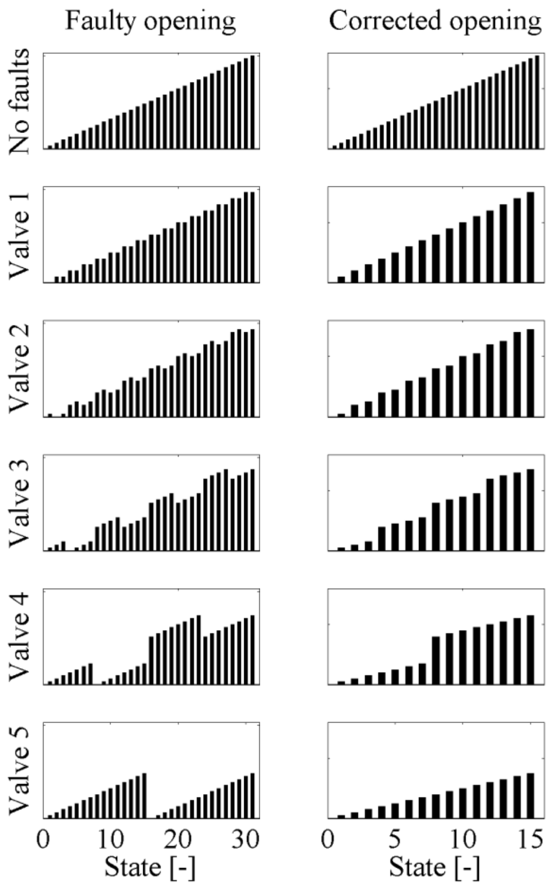

Fig. 4: *Opening versus control signal of DFCU with fault and with fault compensation*

A digital valve system has the ability to react to faults. Siivonen et al. (2005a) presented a system that can compensate the effect of certain faults by re-configuring the system parameters during normal operation. In further studies, compensation methods were towards better performance (Siivonen et al., 2006). The best way to handle an off-fault is to use all control edges simultaneously so that decreased accuracy of a single DFCU is compensated with other DFCUs. This creates a cross flow from pressure to tank but on the other hand accuracy is almost the same as with a correctly functioning system. Figure 4 presents graphically the theory behind fault compensation in faults where valves fail to open. The faulty acting valve is removed from the valve controller so that it is not used. The effect of the fault on system performance depends on nominal flow rate of the valve. Usually the fault either reduces the maximum flow rate or decreases the accuracy of the DFCU. In both cases the system is still usable.

1.2 Fault Detection and Diagnosis

Fault detection and diagnosis (FDD) is the key to fault tolerance of the hydraulic system. If something goes wrong, the fault must be detected and analyzed correctly so that it can be compensated. Faults can be searched for, both on- and off-line, during normal operation or during, for example, stoppages. The best possible case would be on-line FDD that could detect and analyze all possible faults without any extra sensors. In practice, this is usually not possible and some compromises must be made. In general, the system needs a sensor or multiple sensors to detect abnormalities in behavior. In the case of hydraulics, the characteristics of the studied valve must also be known relatively well. On-line fault detection is more efficient since a possible fault does not necessarily have time to influence the process itself.

This, however, is dependent on the application. In critical systems, such as aerospace or marine hydraulics, faulty behavior may cause severe damage, whereas in some other applications faulty acting does not necessarily affect the result significantly. Fault detection was introduced into digital valve systems by Siivonen et al. (2007a) and the first prototype detected electrical faults such as cable brakes etc. with relatively simple and low cost components. Figure 5 presents electrical measurement based FDD and reacting to a cable break fault with a digital valve system. The controller does not know about the fault before the faulty acting valve is used for the first time. The fault is detected, diagnosed and compensated in one calculation step time (approximately 20 ms). The fault does not affect system performance almost at all.

Table 1: Static faults for an on/off valve

Valve fault	Control is OFF (0)	Control is ON (1)	Fault type
Normal	0	1	-
Jammed closed	0	0	I
Jammed open	1	1	II
Jammed in an intermediate position	x	x	III

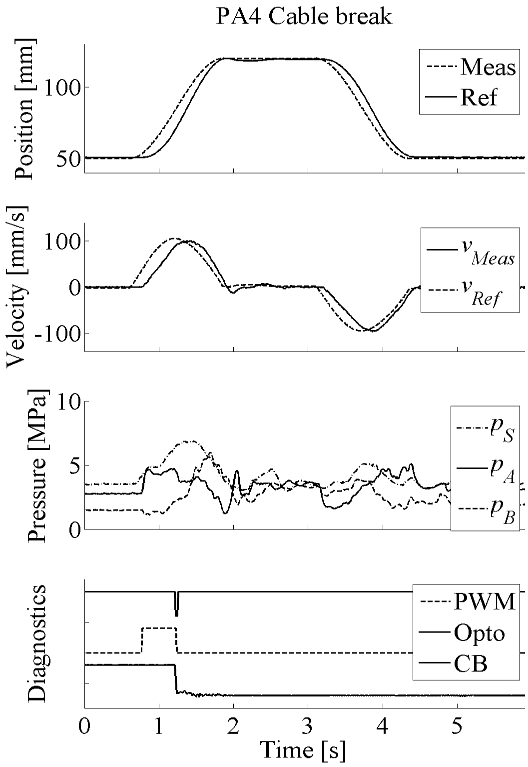

Fig. 5: *Fault detection, diagnosis and reaction with digital valve system (Siivonen et al., 2007a)*

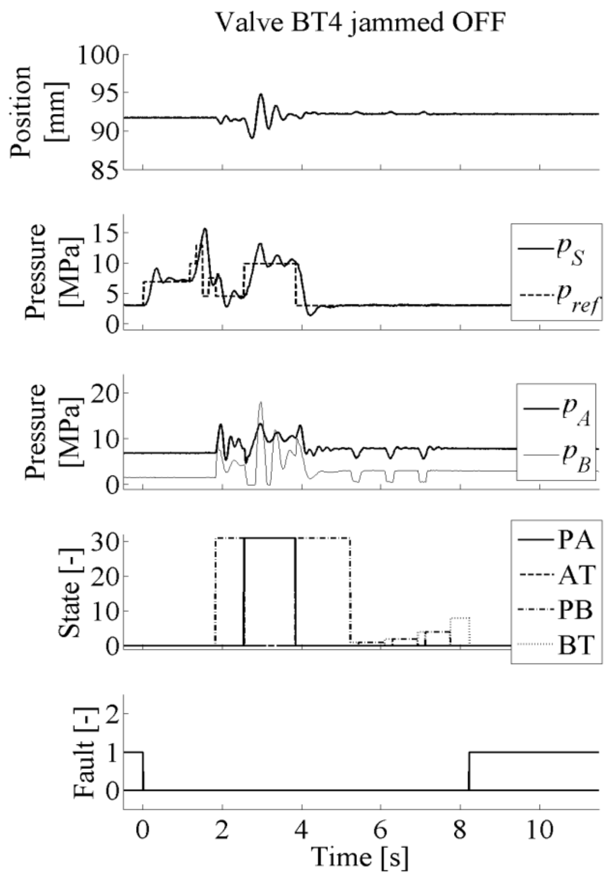

Fig. 6: *Off-line fault-detection cycle using digital valve system (Siivonen et al., 2007b)*

Siivonen et al. (2007b) developed an off-line fault detection cycle for digital valve system which uses pressure sensors to detect both on and off type faults (See Table 1).

Pressure sensor faults are also tested at the same time. The cycle takes less than 9 seconds to complete and was able to detect all faults that were generated in the system. Figure 6 presents the fault detection cycle when a valve fails to open.

2 On - Jammed Valve Fault Compensation

If an on/off valve jams into a fully open position, it causes a leak through the DFCU. This affects the system performance and pressure levels significantly. The fault can be detected, e.g. from electrical measurements or from pressure sensor based measurements depending on the details of how it is broken. If the fault is in electronics, it can be detected with a simple 1-bit current measurement. Also some electrical components can sense these kinds of faults by themselves. The main issue is that this fault can also be compensated so that total performance of the system does not reduce significantly. The presented fault compensation method is realized for the first time in this study.

2.1 Fault Compensation

The leakage flow must be either estimated or measured. If the characteristics of the faulty acting valve are well known, the flow can be calculated from the pressure difference. Since the flow depends on more than just one parameter, the calculation is not always correct. For example, the temperature of the fluid can cause changes in the static and dynamic characteristics of the on/off valve (Siivonen et al., 2005b). If the application demands more accurate control, the flow must be either measured or calculated, e.g. from the actuator movement.

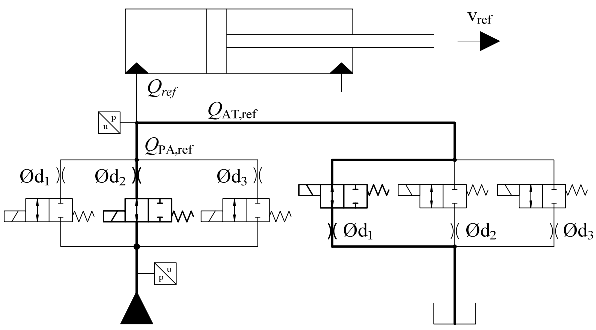

Fig. 7: *Valve jammed open into DFCU PA and compensation with DFCU AT*

This study focuses only on using the digital valve system with a hydraulic cylinder. If some other actuator, e.g. a hydraulic motor, is used, using these methods must be thought through carefully. Fault compensation depends on the fault itself, the pressures and direction of piston velocity reference. A fault in a tank side valve differs from a fault in a pressure side valve. The cylinder chamber side and load force on the other hand only affect the pressures, so the same compensation methods apply to both cylinder chambers. Figure 7 presents a double acting cylinder with fault in DFCU PA valve 2 and its compensation with DFCU AT valve 1. The basic idea is that the flow Q_{ref} to the cylinder port must remain in desired level. In ideal case without faults, the $Q_{AT,ref}$ would be zero since the cross flow to the tank causes increased energy consumption.

If the leaking valve is in pressure side DFCU PA, the system leaks fluid from supply line to cylinder A-chamber. When velocity reference is below zero, the cylinder is retracting and the correction is done with DFCU AT. Excessive flow $Q_{leak,PA}$ is passed into tank according to Eq. 1. The total amount of flow passed in to the tank $Q_{AT,ref,comp}$ is therefore the sum of leakage and the flow that should be passed into the tank normally $Q_{AT,ref}$. This equation presumes that leakage flow from supply line to cylinder chamber $Q_{leak,PA}$ is positive and flow from tank to cylinder chamber Q_{AT} is also positive. If the velocity reference is above zero, the cylinder is extracting. The compensations depend on the magnitude of the leakage. If the leakage is smaller than the reference, no compensation is actually needed. The valve is always open and some other valves are opened also to achieve correct total flow. If the leakage is bigger than the flow reference, something must be done. The compensation is made with DFCU AT. Equation 2 presents the compensation in extending movement and the assumptions are the same as with Eq. 1. The flow Q_{ref} is sum of flows Q_{PA} and Q_{AT}. The symbols and hydraulic diagram can be seen also in Fig. 7.

$$Q_{AT,ref,comp} = Q_{AT,ref} - Q_{leak,PA} \quad (1)$$

$$Q_{AT,ref,comp} = Q_{AT,ref} + (Q_{ref} - Q_{leak,PA}) \quad (2)$$

If the fault is in the tank side DFCU AT, the fluid leaks from the cylinder chamber to tank. The compensation depends on the direction of the velocity reference. In extracting movement, the compensation is done with DFCU PA. Equation 3 presents this compensation. The assumptions for this equation are the same as for Eq. 1 and Eq. 2 presented previously. In retracting movement the compensation depends on the magnitude of the leakage, likewise with a fault in DFCU AT. If the leakage is smaller than the reference flow for DFCU AT, no extra compensations are needed. The valve is kept open and other valves control the flow as well as possible. If the faulty flow is greater than the reference flow, the compensations must be done with DFCU PA as presented in Eq. 4. The symbols and hydraulic diagram can also be seen in Fig. 7.

$$Q_{AT,ref,comp} = Q_{PA,ref} - Q_{leak,AT} \quad (3)$$

$$Q_{PA,ref,comp} = Q_{PA,ref} - (Q_{leak,AT} - Q_{ref}) \quad (4)$$

The load force affects only the pressures and pressure effect on flows. The fault situations presented above do not apply to loads directly and they can therefore be used in different conditions. Faults in B-side DFCUs can be compensated in the same way as A-side faults. The cylinder geometry does not affect fault compensation.

One issue that must be taken into account is the magnitude of the fault. If the faulty acting DFCU has a relatively big pressure difference compared to the compensating DFCU, the correction may consume a lot of energy. For example, the tank side DFCU can have even a ten times bigger pressure difference than the supply line side DFCU. The accuracy of flow control also suffers more because of this and the maximum flow rate reduces. The limit between a controllable and uncontrollable system is rather fuzzy since it depends on the application. Even if the system can be controlled, the power loss caused by the correction can be too big to handle.

2.2 Stopping the Cylinder

Stopping the cylinder piston is not always simple. The structure of the on/off valves and the complete hydraulic system must be well-known. For example, if the on/off valve is not actually on/off but instead has an internal check valve or pressure relief function, some faults may cause movement, even if all other valves are closed. Even in cases where the fault creates movement while all valves are closed, the system can be stopped by using the active pressure control of the cylinder chamber. This creates a cross-flow through the valve system, but all pressures and velocity remain within the reference values. In the case of a pressure side fault, the leakage flow is passed into the tank and in a tank side fault, the extra flow is passed from the supply line to cylinder. In practice, not all faults can be compensated optimally. The leakage decreases the stiffness of the system and causes instability. The compensation may also require a large amount of energy and, in some cases, this is not acceptable. In such applications, the system should be designed so that one leakage does not allow the system to move.

2.3 Digital Valve Controller

The valve controller is a model based system that uses a cost-function to select the optimal control for each situation. The fault tolerant controller developed in this study is based on the four-DFCU controller designed by Linjama and Vilenius (2005). The basic structure is presented in Fig. 8. The model includes functions for measuring analogue signals and filtering them, calculation of the load force, defining of references, calculating the cost function and outputting the control signals for the control electronics.

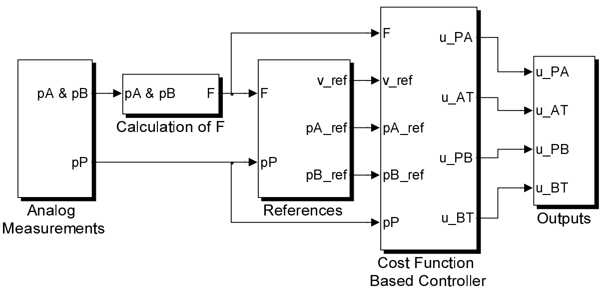

Fig. 8: *Digital hydraulic valve controller structure*

The controller first limits the search space by analyzing flow balances separately. Then these opening combinations are solved with a steady-state model by using Newton-Raphson iterations. The cost function is used to choose the best possible candidate for each situation. The mathematical theory is explained more deeply by Linjama and Vilenius (Linjama and Vilenius, 2005). In case of a fault, the search space limitation module is only given such opening combinations where the faulty acting valve is always either open or closed. Therefore, the end result is also such that the broken valve is not controlled wrongly.

3 Test System and Tested Faults

The fault tolerance of the digital valve system is tested with a hydraulic boom. The system mimics a medium-sized mobile machine. Different kinds of loads and cylinder velocities can be applied to the system.

3.1 Test System

The digital valve system used in this test is based on Sterling Hydraulics GS02 05 internal pilot controlled poppet valves and Sterling Hydraulics GS02 70 directly controlled poppet valves. The system has four DFCUs, all containing five parallel connected valves and more than one million different opening combinations. The valves are bi-directional when the control signals are on. When the valves are off, the flow is stopped from the main flow direction. In the other flow direction, e.g. from tank to cylinder chamber and from cylinder chamber to pressure line, the flow is restricted with an internal check valve.

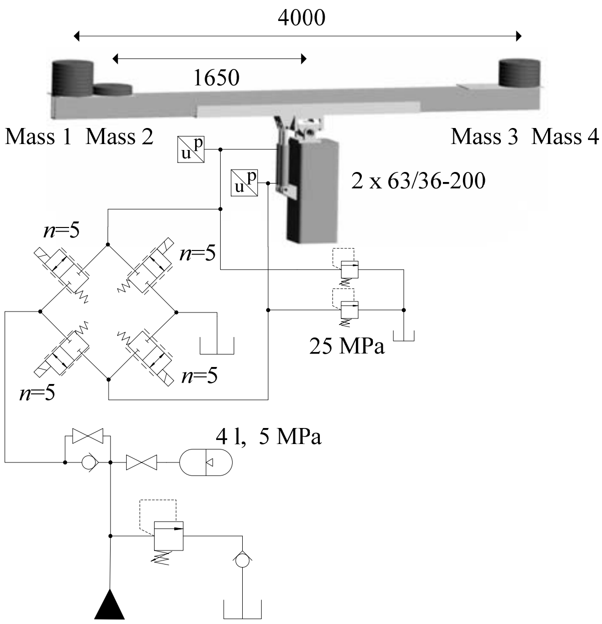

Fig. 9: *Hydraulic connection diagram for digital valve system test bench and test boom*

The electronic part is kept simple by using IPS0151 SmartFETs for controlling the solenoids. The controller is tested with a dSpace 1006 microcontroller system. The system has two parallel connected 63/36 hydraulic cylinders and emergency port pressure relief valves set to 25 MPa. The hydraulic power source is a Bosch-Rexroth pump system that provides constant flow. Supply pressure is set by using a proportional pressure relief valve. The load for the boom is set to 250 kg and 150 kg, as presented in Fig. 9. The load is restricting when the cylinder is extending. Figure 9 also presents the hydraulic connection diagram of the test boom. The hydraulic accumulator was not used during these tests.

3.2 Measured Faults

The system is driven with open-loop control and at first the system is tested without faults. The parameters are not optimized for any particular load, fault or e.g. energy saving. The system measures pressures from both cylinder chambers and supply pressure. This information is used as feedback in the controller for selecting optimal control of the system. The position of the cylinder joint is measured with a linear position sensor and the velocity is calculated from this information but this is not used for control.

The system is tested by forcing the on/off valves into a fully open position. All the valves are tested in situation where the controller does not know about the fault and also where the controller knows about the fault. The FDD is done off-line so that faults are not searched for during the movement in order to keep the system simple and see the effects correctly.

Energy consumption is also measured in order to compare the fully functional and faulty system

4 Experimental Results

Some of the results on the fault tolerance of the digital valve system are presented in Fig. 10 to 15. All the figures include position, velocity and velocity references, supply and port pressures and control signals for each DFCU. The expression PA3 refers to the third smallest valve in the DFCU between pressure line and cylinder A-chamber. All the faults are named in a similar way.

The system was first tested without faults as a reference. The parameters for the controller were set so that the system functioned normally and without any significant problems. The accuracy was good enough, pressures did not exceed limits, and the controller worked without problems. The reference run is presented in Fig. 10.

Figure 11 presents the system with a broken PA3 valve. The fault was not known by the controller and since it was open-loop, the opening of the faulty acting DFCU was always too big. In this case, the movement started immediately after the fault was injected. The B-chamber pressure rose above the supply pressure and therefore the cylinder piston started to move. When the piston moved to the other end of the cylinder the movement stopped and the pressure in the A-chamber rose to the supply pressure. In retracting movement the system leaked again and fell behind the reference velocity. After stopping, the drift started again until the piston reached the other end of the cylinder. When the fault was compensated, controllability was regained. This can be seen in Fig. 12. The control signals showed that some valves were kept open at all times to compensate the leak though the DFCU. The position did not drift at all and the pressures were relatively good considering the situation. The velocity error was almost as small in the reference run with no faults. The PA was the most critical control edge with the valves used in these tests. Leakage caused movement even when all other valves were closed.

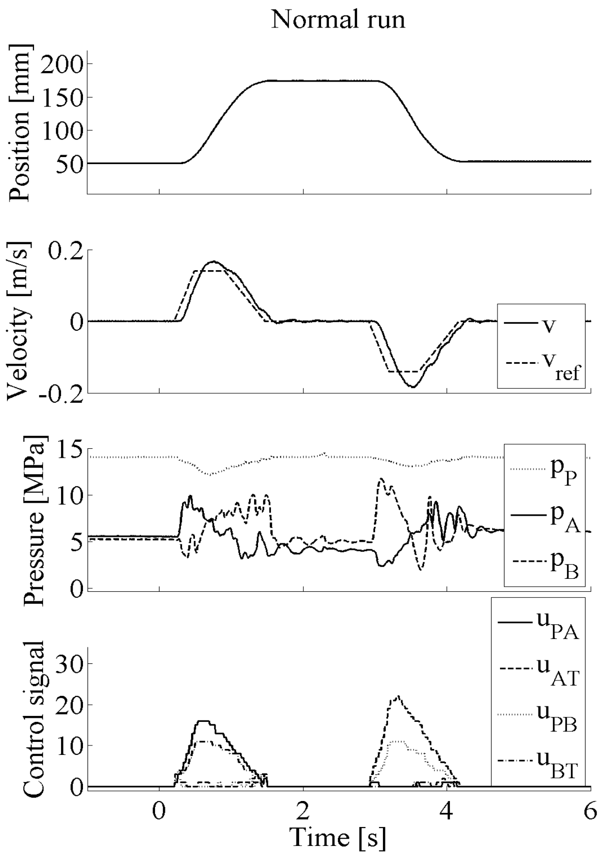

Fig. 10: *Normal run without faults*

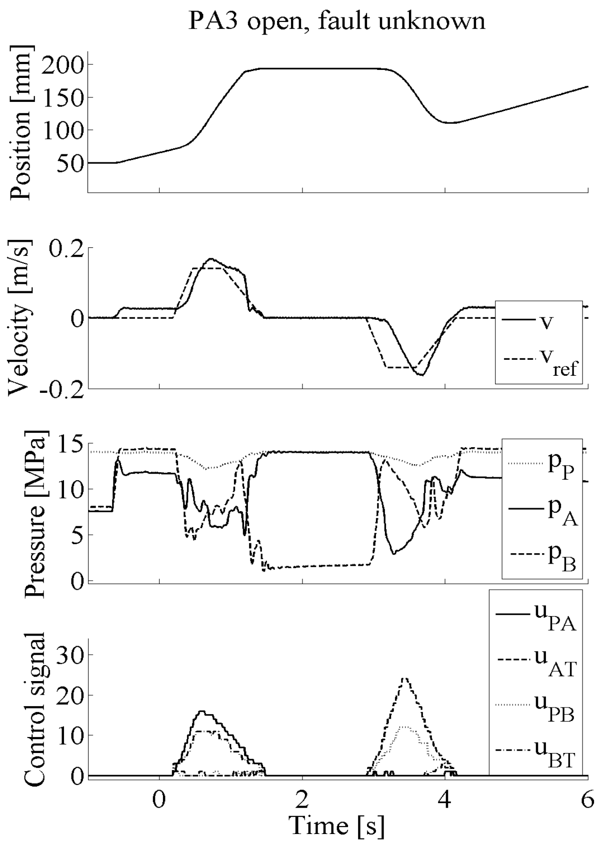

Fig. 11: *Valve 3 jammed open in DFCU PA. The fault was not known and the controller tried to control the boom normally*

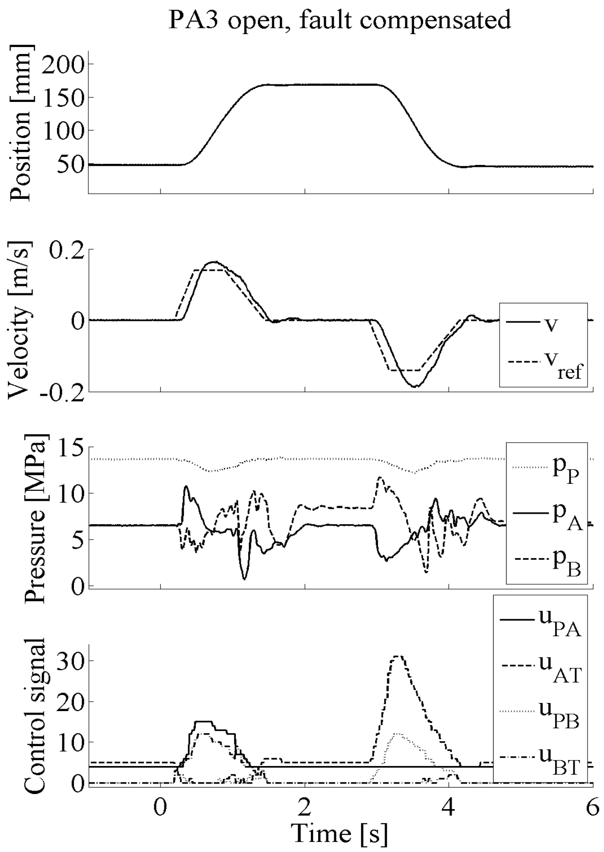

Fig. 12: *Valve 3 jammed open in DFCU PA. The fault was known and the digital valve controller compensated it by using other DFCUs*

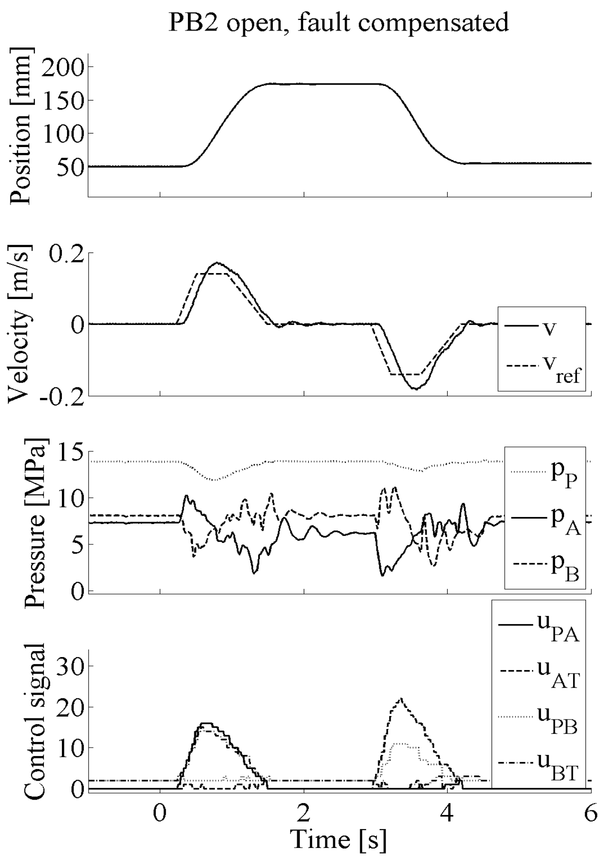

Fig. 13: *Valve 2 jammed open in DFCU PB. Fault was known and the digital valve controller compensated it by using other DFCUs*

The DFCU PB with fault was the best one in terms of fault tolerance. The system did not drift at all when stopped and although the movement was inaccurate, the system was controllable. The pressure in the B-chamber rose to the supply pressure but this did not cause big problems with the smaller valves. The reason for relatively good controllability was the restricting load force. Faults in the bigger valves caused the piston to hit the end of the cylinder chamber too early and no good measurements could be made. Figure 13 presents a B-side broken PB2 valve with compensated fault. The effect of the fault was smaller and the controllability good even with low speeds.

The fault in control edge AT caused the pressure in the A-chamber to drop to tank pressure. This caused drifting since the pressure in the B-Chamber also dropped and the cylinder chamber sucked fluid from the tank line. Valve AT2 was the biggest that could be measured reasonably without the piston hitting the end of the cylinder chamber too early. Figure 14 presents a compensated system when the biggest valve was broken. The AT5 caused the system to leak heavily into the tank. The controllability with the compensated system was rather good, but as can be seen in control signals, the correction was rather heavy. The supply pressure dropped when flow was needed during the movement and all reactions became a little slow. The velocity oscillated a little when the velocity reference was set to zero and the controller tried to stop the movement. The system was still controllable.

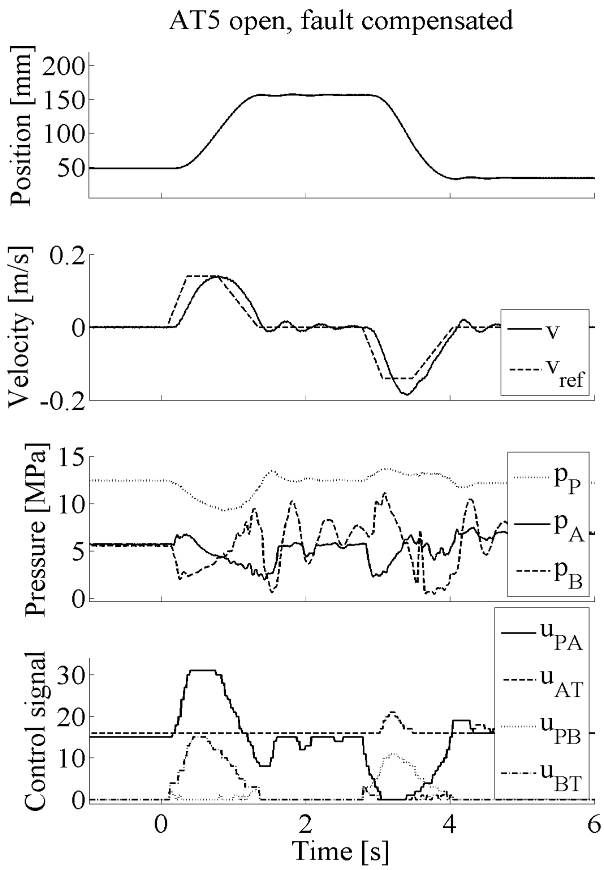

Fig. 14: *Valve 5 jammed open in DFCU AT. Fault was known and the digital valve controller compensated it by using other DFCUs*

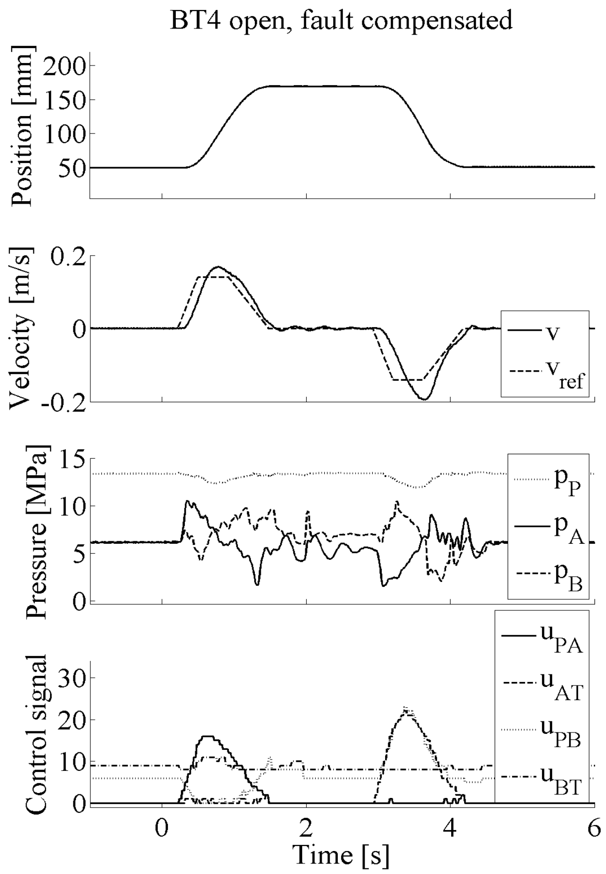

Fig. 15: *Valve 4 jammed open in DFCU BT. Fault was known and the digital valve controller compensated it by using other DFCUs*

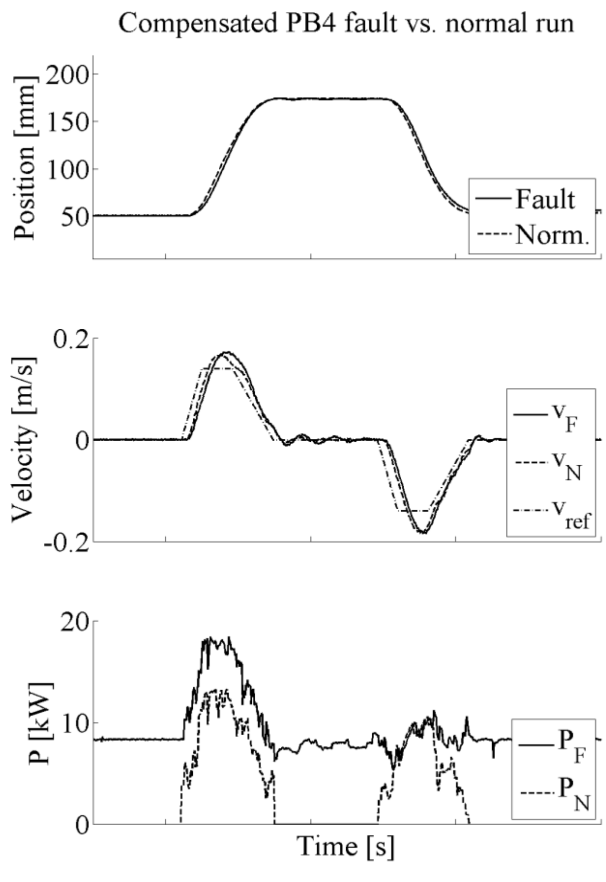

Fig. 16: *Comparison between normal run without faults and compensated run with valve PB4 jammed open*

In DFCU BT faults, the system leaked to the tank from the B-chamber. When the system was stopped, the chamber pressure dropped to tank pressure and when moving the piston, the system leaked to the tank. This caused drift during the movement and especially when reducing velocity. Figure 15 presents the system with a B-side to tank DFCU fault in the second biggest valve. The correction was not as big as with the AT5 fault and controllability was also much better. The pressures behaved relatively well and velocity followed the reference with almost the same accuracy as with the system without any faults.

Figure 16 shows a comparison between the system with PB4 fault and normal run without faults. The position and velocity are almost equal but the fault can be seen in increased power consumption.

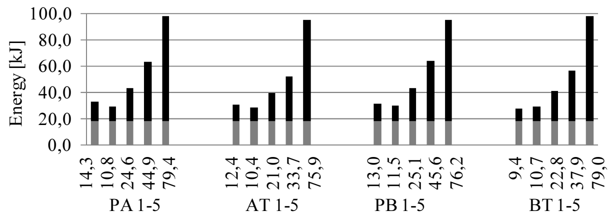

Fig. 17: *Energy consumption during the test sequence. Normal consumption is in gray (18.6 kJ) and extra consumption in black (extra consumption also as numbers below the bars)*

The normal and total energy consumption with different faults can be seen in Fig. 17. Smaller corrections consume less energy than larger ones. Leakage caused increased energy losses. Controllability can be obtained even with the worst faults but it depends strongly on the application as to whether such losses can be accepted. For example, the energy loss caused by the fault in valve PA5 was more than 4 times higher than the energy loss for system without faults. If the system is vital, such losses can be accepted if the energy source is big enough.

Conclusions

The digital valve system is a hydraulic flow control valve that uses on/off valves to achieve accurate control, good performance, and better energy efficiency. One of its features is fault tolerance without any extra components. The system can detect, diagnose and react to different kinds of faults in valves, electronics or in electrical wires. So far only faults that close some valves have been studied and the aim of this paper was to develop compensation methods for open-jammed valve faults.

The system can adapt to a fault where the valve has jammed in an open position by compensating the leakage with other valves in the system. If the fault is detected and analyzed correctly the correct control can be calculated and applied. This allows the system to continue normal operation with slightly decreased performance. The system was tested by injecting faults and all the tests were completed successfully. The energy consumption increased when a fault was injected, but the system remained controllable, even with the worst possible faults. This allows the system to operate until it can be repaired in a controllable environment instead of resulting in the stoppage of factory, airplane crash or towing a tractor out of the forest. In most cases, increased energy consumption is a small price to pay for what could happen. However, not everything can be done since with some faults, a limited power source can prevent the compensation being applied.

The structure of the hydraulic system and characteristics of all hydraulic and electronic components must be well-known in order to achieve good results in fault tolerance. The characteristics of on/off valves used in this study were not the best possible if only fault tolerance is considered and, therefore, components should be carefully selected if the best possible fault-tolerant system is desired. Especially energy consumption can be decreased by using valves without internal check valves. The mechanical structure of the cylinder and load also affect the complete system and they must be taken to account when designing a system. Although better results in energy consumption could be achieved by optimizing the system, in certain loads this is usually not acceptable since hydraulic systems have typically varying loads.

The digital valve system proved itself to be fault-tolerant, which is a unique feature in the area of hydraulics. The control code that is used to calculate the optimal opening of on/off valves is also the heart of fault tolerance. In this paper the compensation of faults was applied to a previously developed valve controller. The results encourage the developing of fault tolerance further as part of normal control code. In this way, fault tolerance would be one main advantage of hydraulic systems compared to rival technologies.

Nomenclature

DFCU	Digital flow control unit	
FDD	Fault detection and diagnosis	
AT	Valve between A-chamber and tank	
BT	Valve between B-chamber and tank	
PA	Valve between supply line and A-chamber	
PB	Valve between supply line and A-chamber	
SPoF	Single point of failure	
p_A	Pressure in cylinder A-chamber	[Pa]
p_B	Pressure in cylinder B-chamber	[Pa]
p_P	Pressure in supply line	[Pa]
p_S	Pressure in supply line (Used in reference)	[Pa]
p_T	Pressure in tank line	[Pa]
Q	Flow	[m^3/s]

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