PROPORTIONAL VELOCITY CONTROL OF LOW-PRESSURE WATER HYDRAULIC CYLINDER DRIVE

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ABSTRACT

This paper studies velocity control of a low-pressure water hydraulic cylinder drive. Two different systems are used, one with a proportional 4/3-way directional control valve and one with a proportional flow control valve. Experimental results with the proportional directional valve show that good control results can be achieved with closed-loop control system. Compensation of system nonlinearities allows also open-loop velocity control, which gives quite good accuracy in constant conditions. However external load force increases the velocity error and when good accuracy is needed in varying load conditions, the closed-loop control system has to be used. The results with the flow control valve are not as good but on the other hand the price of the valve is lower, which supports the use of this valve if the accuracy demand is not so high.

KEYWORDS

Water hydraulics, Proportional velocity control

INTRODUCTION

A lot of research has been carried out in the field of Low-pressure water hydraulics (LPWH) over the last decade. The aim is to develop a fluid power technology that combines good characteristics of water hydraulics and pneumatics. The pressure medium is pure tap water, which ensures environmental safety and good controllability of water hydraulics. On the other hand aim is to achieve low price level of pneumatics. The pressure level is between 10 and 40 bar, which allows the use of low-cost materials such as plastics. [1]

In oil hydraulics proportional valves are basic components in controlling actuators but in LPWH the problem is the lack of suitable valves. The demand for low price level sets strong limits for valves used in controlling LPWH systems. The most cost-effective solution is the use of on/off valves. These valves are reliable, cheap and they already exist on the market [2]. A lot of research has been carried out lately on this area and the results show that on/off control gives quite good position control results. [3], [4], [5]

Smooth movements, continuously controllable velocity or accurate path following can be quite difficult to realize with on/off technology and therefore proportional control is needed. The biggest problem in the proportional technology in LPWH is the lack of suitable valves. A few proportional valves exist for high-pressure water hydraulics and previous studies show that at least some of these can be used in LPWH. [6], [7]

In this paper velocity control of LPWH cylinder drive with two different type proportional valves is discussed. The other valve is a proportional 4/3-way directional valve and the other is pressure compensated flow control valve. In this study open-loop control and closed-loop control are used. Closed-loop controller consists of open-loop controller and integrating controller.

TEST SYSTEM

The hydraulic test system with the flow control valve is shown in figure 1. The cylinder is SSH Stainless Ltd., AQUA 70 series water hydraulic cylinder loaded by inertial load. The size of the cylinder is 32/16-500 and the load mass is 200 kg. The 500 N load force is achieved by tilting cylinder bench 15°. The piston position is measured with pulse encoder. The supply pressure is 30 bar.

Figure 1. The hydraulic circuit of the test system.

The test system with the 4/3-way directional proportional valve is similar to the figure 1 except the flow control valve and the on/off-valve are replaced with the directional proportional valve.

A difficulty in using a flow control valve in controlling a bi-directional actuator is that the flow control valve can only control the flow rate through the valve and not the direction. That is why the system has a 4/2-way on/off valve to change the direction and only the velocity is controlled with the flow control valve. The flow control valve is installed to control the flow from the cylinder.

VELOCITY CONTROLLERS

The velocity control was done with both open and closed-loop control. Open-loop velocity control is very simple and doesn't need velocity feedback. Open-loop velocity control is realized simply by measuring the cylinder velocities with different valve controls. Measured velocities with both valves are presented in figure 2.

Measured velocities with proportional directional valve are presented with stars in figure 2. The maximum velocity in extending movement is 460 mm/s and in retracting movement 410 mm/s. The curve is smooth and quite linear except around zero velocity where there is a dead band of about 2 V. The velocity values are also precise when measured several times since the hysteresis of the valve is low [6].

Measured velocities with flow control valve are presented with circles in figure 2. The maximum velocity in extending movement is 710 mm/s and in retracting movement 570 mm/s. The velocities are different to different directions because the maximum flow rate through the valve is 30 l/min. The flow rate from the unsymmetrical actuator to tank is larger in retracting movement and hence the maximum velocity in this direction is smaller. The shape of the curve with this valve is also quite good. However the valve has quite high hysteresis, which creates variation to the measurements.

From these curves it can be seen what kind of valve opening is needed to achieve a certain velocity. A drawback in this open-loop control is that the relation between the valve control and the piston velocity has to be known accurately. If conditions are not constant, for example if a load force is changing, the accuracy of velocity decreases since there is no feedback.

Figure 2. Velocities of the test systems as a function of control voltage with both valves.

In closed-loop velocity control the open-loop controller is used as a feedforward signal and an integral controller is used to reduce velocity error. Figure 3 shows a block diagram of the velocity controller. In the open-loop velocity control the integral gain is set to zero and hence the integrating term has no effect to the control. In the closed-loop control the feedforward gain, which is less than 1, is needed to reduce the effect of feedforward term. The reduction of feedforward term is needed to reduce overshoot.

Figure 3. Block diagram of the velocity controller.

EXPERIMENTAL RESULTS WITH PROPORTIONAL 4/3-WAY VALVE

Figure 4 shows step responses with open-loop velocity controller. Steady state velocity errors are between $-0,01$ m/s and $0,04$ m/s. The responses are also smooth and there are no big overshoots or oscillations. Open-loop control gives good results when the relation between the piston velocity and valve control signal is known accurately.

Figure 4. Open-loop step responses with directional valve, no load force.

Figure 5 shows step responses with open-loop controller with 500 N load force. Steady state velocity errors are between $-0,01$ m/s and $0,06$ m/s. Also quite large overshoot occurs in some responses in retracting direction because of the overrunning load force. This shows the fact that open-loop control is sensitive for variations and changes in load force.

Figure 5. Open-loop step responses with directional valve, 500 N load force.

Figure 6 shows open-loop velocity control results with 1 Hz and 3 Hz sinusoidal reference signal. Velocity tracking is quite good with 1 Hz frequency. With 3 Hz frequency the phase shift is about 30° . With 6 Hz frequency the phase shift is 60° and attenuation is -3 dB. Open-loop control works quite well with frequencies up to 5 Hz.

Figure 6. Sine responses with directional valve, open loop velocity controller.

Figures 7 and 8 show step responses with closed-loop velocity controller with and without load force. Steady state velocity error is between $-0,01\text{m/s}$ and $0,01\text{ m/s}$ in both cases. Integrating controller decreases steady state velocity error and the load force has no effect on the error. On the other hand closed-loop control leads to larger overshoots also without load force. It can be clearly seen that the closed-loop controller reduces the sensitivity for disturbances.

Figure 7. Closed-loop step responses with directional valve, no load force.

Figure 8. Closed-loop step responses with directional valve, 500 N load force.

Figure 9 shows closed-loop velocity control results with 1 Hz and 3 Hz sinusoidal reference signal. 1 Hz frequency works quite well. With 3 Hz frequency the phase shift is about 30° . With 6 Hz frequency the phase shift is 65° and attenuation is -3 dB . Tracking of the reference signal is better with closed-loop control.

Figure 9. Sine responses with directional valve, closed loop velocity controller.

EXPERIMENTAL RESULTS WITH PROPORTIONAL FLOW CONTROL VALVE

Figure 10 shows step responses with open-loop velocity controller with the flow control valve. Steady state velocity errors are between $-0,01\text{ m/s}$ and $0,01\text{ m/s}$. There are quite high overshoots and oscillations in responses. Some responses show quite high frequency oscillations which are probably caused by the pressure compensator of the valve. The valve is designed for

higher pressures and the pressure compensator does not work quite well with this low pressure.

Figure 10. Open-loop step responses with flow control valve, no load force.

Figure 11 shows open-loop velocity control results with 1 Hz and 3 Hz sinusoidal reference signal. With 1 Hz frequency the system is still working quite well. With 3 Hz frequency the phase shift is about 45° and the wave form is not very good. The on/off valve is changing its position at the zero velocity and this can be seen in the curves.

Figure 11. Sine responses with flow control valve, open loop velocity controller.

Figure 12 shows step responses with closed-loop velocity controller with flow control valve. Steady state velocity errors are between -0.02m/s and 0.02 m/s . Closed-loop controller seems to be increasing the steady state error with the flow control valve and overshoots are slightly bigger. The high frequency

oscillations are not as disturbing as with open-loop control.

Figure 12. Closed-loop step responses with flow control valve, no load force.

Figure 11 shows closed-loop velocity control results with 1 Hz and 3 Hz sinusoidal reference signal. The results are quite similar to those with open-loop control. 3 Hz frequency is working better with closed-loop control.

Figure 13. Sine responses with flow control valve, closed loop velocity controller.

CONCLUSIONS

Velocity control of low-pressure water hydraulic cylinder was studied. Velocity control was realized with proportional directional valve and proportional flow control valve.

The results show that the proportional directional valve works quite well in velocity control. Open-loop velocity control gives good results when the relation

between the piston velocity and valve control signal is known accurately. However, open-loop control is sensitive to disturbances. Load force reduces the accuracy and in many cases a closed-loop controller is needed to reduce sensitivity.

Integral controller with feedforward was used as a closed-loop controller. Closed-loop control reduces the sensitivity against load force and other disturbances. Also velocity accuracy was improved.

Results with the proportional flow control valve were not as good but showed that also flow control valve can be used in velocity control of cylinder drive. The difficulty in this kind of system is that the flow control valve cannot control the direction but it needs separate directional valve that changes the direction.

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