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REALIZATION OF PROGRAMMABLE CONTROL USING A SET OF INDIVIDUALLY CONTROLLED ELECTROHYDRAULIC VALVES

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Abstract

This paper reports a study of electrohydraulic valve function programmability and characteristic interchangeability using a set of individually controlled cartridge type electrohydraulic (E/H) control valves. Such an integrated individually controllable E/H valve is defined as the programmable E/H control valve. A hybrid control algorithm was developed to realize different valve functions via programmable logic and to realize different interchangeable valve characteristics via a programmable valve modulation function. Evaluation test results verified that the programmable E/H control valve was capable of replacing different types of conventional proportional control valves and, more importantly, capable of realizing the flow regeneration function. The programmability of the programmable E/H control valve provides the flexibility of using the same firmware of an E/H control valve on various applications by simply downloading different control software.

Keywords: programmable E/H control valve, valve function programmability, valve characteristics interchangeability, flexible control software

1 Introduction

Proportional direction control valves are by far the most common means for motion control of hydraulic motors or cylinders in fluid power systems (McCloy and Martin, 1973). Normally, a proportional control valve uses a sliding spool to control the flow direction and to regulate the flow rate passing through the valve (Esposito, 2000). For different applications, the spool in a proportional control valve is often specially designed to provide the desired flow control characteristics. As a result, the valves cannot be interchangeable even if they have exactly the same size spools. In turn, it is inconvenient and costly to manufacture, distribute, and provide service to those specially designed proportional control valves.

A programmable E/H control valve ("programmable valve" hereafter) is an integration of a set of generic two-way proportional E/H valves and a programmable electronic controller. Such an integrated E/H valve set can be programmed to realize different valve functions and changeable flow control characteristics via different control software. These features make it possible to use a programmable valve to replace different types of conventional direction control valves and other auxiliary valves, such as line relief valves and flow make-up valves, for different applications. Therefore, the development of a programmable valve is very technically and economically attractive. Because a valve needs to control the amount of flow passing through different ports simultaneously to realize the different valve functions and changeable flow control characteristics, a fully functional programmable valve needs to have five individually controlled E/H valves to provide the required capabilities. A few successful efforts to develop programmable valves have been reported in the past a few years (Aardema and Koehler, 1999; Book and Goering, 1999; Ruan, Pei and Li, 2000).

This paper reports the development of a programmable valve which uses simple "on" or "off" logic to realize different valve functions and uses programmable modulation to realize interchangeable valve characteristics on a set of five individually controlled E/H valves. In the text below, the prototype of the programmable valve and the test bench used to evaluate valve characteristics and programmability will be introduced. The next section will present the design of control algorithms for realizing different valve functions and interchangeable flow control characteristics. The validation tests and result analyses are discussed in the following section. Finally, a positive conclusion on

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realizing the programmable valve functions and interchangeable control characteristics using the programmable valve is drawn from the obtained test results.

2 Development of a Prototype Valve and the Test Bench

The prototype programmable valve used in this research was constructed using five bi-direction spool-type proportional E/H valves and a computer-based valve controller. The individually controlled bi-directional valves ("base valves" hereafter) were non-production testing valves provided by Eaton Hydraulics (Eden Prairie, MN, USA). All five base valves were rated at 30 l/min at 6.9 MPa pressure drop across the valve. Three of the base valves were high gain valves and the other two were low gain valves (Fig. 1). The main difference between the high gain and low gain valves are that the high gain valves have 2.5 V deadband while the low gain valves have 1.4 V deadband. Such a design was used to validate the hypothesis that a programmable valve could be constructed using different base valves because of the programmability in the valve controller.

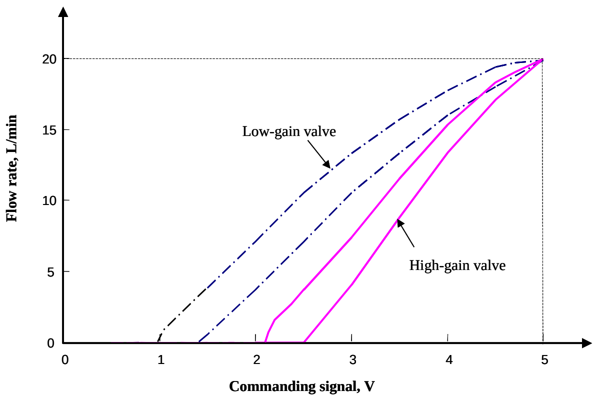

Fig. 1: *Flow control characteristics of low-gain and high-gain base valves*

To validate the programmable valve system, the integrated programmable E/H control valve was mounted on an E/H system test bench connected using hoses. This E/H system test bench consisted a fixed displacement pump with capacity of 20 l/min. A double acting differential cylinder with a bore diameter of 50.8 mm, rod diameter of 25.4 mm, and stroke of 203.2 mm was used as the testing actuator. Three Omega (Stamford, CT, USA) pressure sensors were used to monitor the pump discharge pressure and the cylinder head-end ("HE" hereafter) and rod-end ("RE" hereafter) chamber pressures. Figure 2 shows the system schematic of the PC valve constructed using five base valves. As shown in the schematic, those five base valves were designated to control the flow rate for pump-to-cylinder-head-chamber ("P-C_{HE}" hereafter), pump-to-cylinder-rod-chamber ("P-C_{RE}" hereafter), cylinder-head-chamber-to-tank ("C_{HE}-T" hereafter), cylinder-rod-chamber-to-tank ("C_{RE}-T" hereafter), and pump-to-tank ("P-T" hereafter) channels, respectively. With proper control strategy, all base valves can be operated cooperatively to provide equivalent functions of flow direction and flow rate control to a proportional direction control valve. With a proper modulation control, the P-T valve could also provide an additional function as a programmable line release valve for the system.

To implement proper control functions on the programmable valve, a computer-based control and measurement system was developed as the valve controller. Because the programmable E/H control valve was realized through controlling five individually controlled E/H valves coordinately, the design of valve controller is critical for achieving the desired performance of the programmable valve. The basic requirements for the valve controller are (1) capable of coordinating the operation of individual E/H control valves at precisely scheduled the time, (2) capable of modulating individual valves to achieve flow rate control, and (3) capable of compensating for valve dead bands.

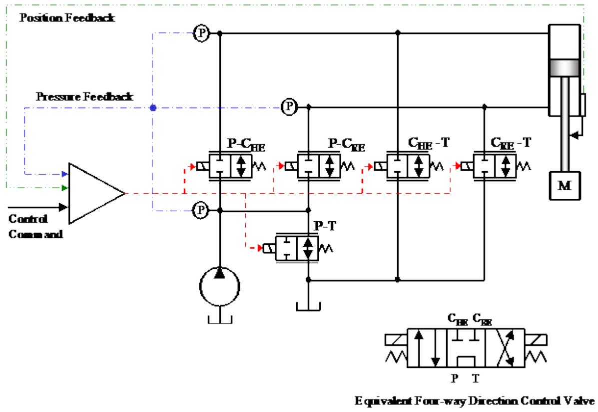

Fig. 2: *System schematic of the programmable E/H control valve constructed using five individually controlled bi-direction E/H valves (currently, the circuit is in a tandem-center arrangement)*

As shown in Fig. 3, this computer-based valve controller consisted of a *Matlab/Simulink*-based programming environment for supporting the programmable control algorithms, a *Wincon* (Quanser Consulting, Hamilton, Ontario, Canada) interface for applying the *Simulink*-based control programs in real-time valve control, a set of five valve control drivers for converting digital control signals into pulse width modulation (PWM) signals to drive the base valves, and several pressure sensor and a position sensor for providing feedback information to the controller.

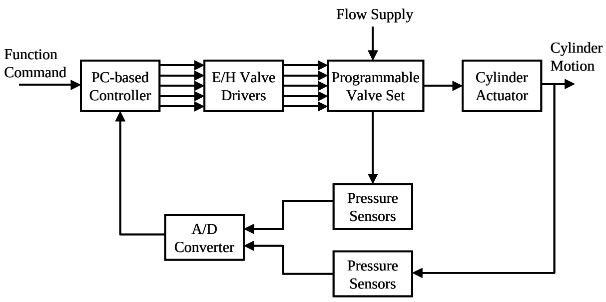

Fig. 3: *System block diagram of computer-based programmable E/H control valve control and measurement system*

Table 1: Control logic for realizing multiple functions using the programmable E/H control valve

Valve Function	P-C_{HE} Valve	P-C_{RE} Valve	C_{HE}–T Valve	C_{RE}–T Valve	P–T Valve
Open-center	Open	Open	Open	Open	Open
Closed-center	Closed	Closed	Closed	Closed	Modulated
Tandem-center	Closed	Closed	Closed	Closed	Open
Float-center	Closed	Closed	Open	Open	Modulated
Extension	Modulated	Closed	Closed	Open	Modulated
Retraction	Closed	Open	Modulated	Closed	Modulated
Flow regeneration	Open	Open	Closed	Modulated	Modulated

3 Hybrid Control Algorithm Design

To realize the flexible valve functions and characteristics, a hybrid control algorithm was developed for this programmable valve. This hybrid algorithm consists of two levels of control, namely function logic control and performance modulation control. The function logic control determines the valve operation status, including "open", "close" and "modulation", of each base valve for coordinating the integrated valve set to realize the desired function. The different combinations will lead to different functions of the integrated valve, such as directional control and flow regeneration control. Table 1 summarizes the control logic for realizing different functions on the programmable E/H control valve. The modulation control determines the degree of valve opening for those modulated base valves to realize desired cylinder motion control. In implementing modulation control, the P-T valve was controlled corresponding to the pump discharge pressure feedback signal, and the rest valves were controlled corresponding to the cylinder position feedback signal.

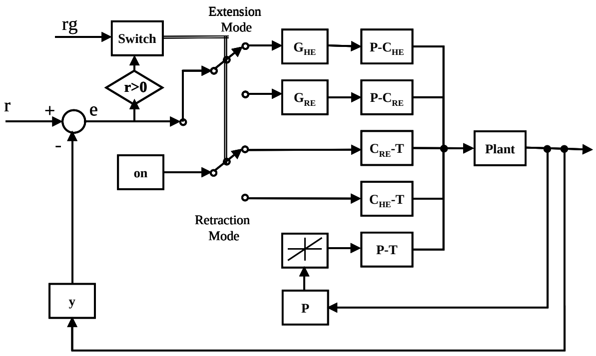

Fig. 4: *System block diagram of the hybrid control algorithm for the individually controlled E/H valves*

Figure 4 shows the control block diagram of the hybrid control algorithm for the programmable valve. To regulate the system pressure, a modulation controller was designed for the P-T valve based on the feedback system pressure signal. For performing position control, the hybrid controller uses the feedback position signal *y* and commanding signal *r* to determine both the amplitude and sign of the error *e* between the desired and the actual cylinder positions. The sign of the error is used to determine the desired direction of cylinder motion, and the amplitude of the error is used to regulate the opening of the corresponding base valves. A switch was used to select different valve combinations to realize different valve functions. Based on the designed cooperative base valve control logic, either the P-C_{HE} base valve or the P-C_{RE} base valve is modulated in implementing motion control. Because of the size difference in the cylinder HE and RE chambers and the possible difference in base valve characteristics of the corresponding base valve, the control plants for the P-C_{HE} and P-C_{RE} base valves are different. Therefore, two separate PID controllers are needed to control P-C_{HE} and P-C_{RE} base valves.

The design of the PID controllers for those base valves was based on the plant dynamic model of the hydraulic system. Extension and retraction are the fundamental operations of a hydraulic cylinder, and are accomplished by controlling the directions of the fluid into different cylinder chambers. The programmable valve realizes the cylinder control functions by logically controlling all five base valves under different "on", "off", and "modulation" combinations. The base valve under "modulation" control mode is the critical valve to accomplish either position or velocity control. For instance, to realize the extension function, both P-C_{HE} and C_{RE}-T base valves should be on, and P-C_{RE} and C_{HE}-T should remain off to lead the pump flow to the cylinder head chamber and allow fluid in the rod chamber to return back to the tank. In this case, the P-C_{HE} valve is the critical valve controlled using a PID controller to accomplish the desired position or velocity control on the cylinder. By reversing the on-off status for the above four valves, it can realize the retraction function. In this case, the critical base valve for accomplishing desired position or velocity control is the P-C_{RE} valve.

Based on the compressible fluid continuity equation, Newton's second law, and hydraulic orifice equation, a linearized model of the valve controlled hydraulic system model (Zhang, 1999) can be used to describe the HE and RE plants of the programmable valve control system as follows.

$$\frac{V_{\mathrm{HE}} m}{A_{\mathrm{HE}} \beta} \delta \ddot{x} = K_{\mathrm{u}} \delta u_{\mathrm{HE}} - A_{\mathrm{HE}} \delta \dot{x} - K_{\mathrm{p}} \delta P_{\mathrm{HE}} \tag{1}$$

$$\frac{V_{\mathrm{RE}} m}{A_{\mathrm{RE}} \beta} \delta \ddot{x} = K_{\mathrm{u}} \delta u_{\mathrm{RE}} - A_{\mathrm{RE}} \delta \dot{x} - K_{\mathrm{p}} \delta P_{\mathrm{RE}} \tag{2}$$

The cylinder control transfer functions for HE and RE plants can be obtained from applying the Laplace Transform to Eq. 1 and 2.

$$G_{\mathrm{HE}}(s)=\frac{K_{\mathrm{u}}}{A_{\mathrm{HE}}s+K_{\mathrm{p}}\dfrac{m}{A_{\mathrm{HE}}}s^{2}+\dfrac{V_{\mathrm{HE}}m}{A_{\mathrm{HE}}\beta}s^{3}} \tag{3}$$

$$G_{\mathrm{RE}}(s)=\frac{K_{\mathrm{u}}}{A_{\mathrm{RE}}s+K_{\mathrm{p}}\dfrac{m}{A_{\mathrm{RE}}}s^{2}+\dfrac{V_{\mathrm{RE}}m}{A_{\mathrm{RE}}\beta}s^{3}} \tag{4}$$

Equations 3 and 4 indicate that both the HE and RE position control plants are third-order systems. Those two transfer functions also indicate that the natural frequencies and damping ratios are different between the HE and RE plants because of size difference between those plants.

$$\omega_{\mathrm{n,HE}}=A_{\mathrm{HE}}\sqrt{\frac{\beta}{V_{\mathrm{HE}}m}} \tag{5}$$

$$\omega_{\mathrm{n,RE}}=A_{\mathrm{RE}}\sqrt{\frac{\beta}{V_{\mathrm{RE}}m}} \tag{6}$$

$$\xi_{\mathrm{HE}}=\frac{K_{\mathrm{p}}}{2A_{\mathrm{HE}}}\sqrt{\frac{\beta m}{V_{\mathrm{HE}}}} \tag{7}$$

$$\xi_{\mathrm{RE}}=\frac{K_{\mathrm{p}}}{2A_{\mathrm{RE}}}\sqrt{\frac{\beta m}{V_{\mathrm{RE}}}} \tag{8}$$

One unique advantage of the integrated programmable valve is that it can achieve flow regeneration at light load extension operations. This flow regeneration is to utilize the piston area difference between the HE and RE of the cylinder, and recycle the returning fluid from the RE chamber to the HE chamber when the external load is light for achieving a higher extending speed without increasing the size of the hydraulic system at the cost of higher system pressure. To realize this function, the programmable valve needs to open P-C_{HE} and P-C_{RE} while keeping C_{RE}-T and C_{HE}-T closed to lead the returning flow from the RE chamber to the HE chamber. A special signal *rg* was used to turn the switch into the regeneration mode.

4 Validation Tests and Results Discussion

To demonstrate the hybrid control algorithm as applied to five individually controlled E/H valves, a series of position controls of a gravity loaded actuator were conducted for different valve center functions (including tandem-center and closed-center) and various control modes (including normal or flow regeneration modes). Validation results from those tests indicated that a programmable valve was capable of achieving all tested control functions. The frequency response tests on the system using a programmable valve showed that the bandwidth of the hybrid control system was 3.2 Hz. In this conceptual study, the valves for controlling returning flow paths were fully open because the gravity load was in the same magnitude. However, modulation controls on the returning valves are recommended for actual applications. To report the validation results without loss generality and without an overwhelming detailed test data presentation, this paper only represents the case of tandem-center and flow regeneration operations.

Tandem-center direction control valves are widely used on off-road vehicles as the main control valves for systems equipped with a fixed displacement pumps. In a conventional tandem-center direction control valve, the spool blocks both cylinder ports and connects the pump port to the tank port (P-T port open) when the spool is at the neutral position. As the spool is being pushed away from its neutral position, it gradually closes the P-T port and opens the P-C_{HE} and C_{RE}-T ports to direct the pump flow to enter cylinder HE and allow cylinder RE flow to bleed back to the tank in an extension operation (or retracting opens P-C_{RE} and C_{HE}-T ports to direct the pump flow to enter cylinder RE and allow cylinder HE flow to bleed back to the tank). After the spool is pushed away from its neutral position for a certain distance, the spool will fully close the P-T port and fully open the P-C_{HE} and C_{RE}-T ports (or P-C_{RE} and C_{HE}-T ports).

To accomplish the same control using the programmable valve, all individual base valves should be operated according to the control logic defined in Table 1. The first test was to evaluate the capability of the programmable valve realizing the conventional tandem-center function. While at the neutral position, the P-C_{HE}, P-C_{RE}, C_{HE}-T, and C_{RE}-T valves were all closed to block the cylinder ports and the P-T valve was fully open to allow pump flow bleed to the tank. During the extension operation (or retraction operation), the P-C_{HE} and the C_{RE}-T (or P-C_{RE} and C_{HE}-T) valves were fully open to send the pump flow into cylinder HE chamber (or RE chamber) and to bleed the fluid in cylinder RE chamber (or HE chamber) back to the tank. The P-T valve was modulated to control the system pressure, and the P-C_{RE} and the C_{HE}-T (or P-C_{HE} and C_{RE}-T) were closed to block the corresponding ports. The desired cylinder position of this validation test was to extend the cylinder slowly from completely retracted (zero extension) to 100 mm and hold it for 1.7 s before retracting again. Figure 5(a) through (e) show the control signals to each of the five individually controlled base valves. Figure 5(f) shows the position control performance from the programmable valve. The time delay of the cylinder response to the extension control was about 0.3 s and to retraction control was about 0.4 s. The long time delay from the tandem-center operation was because the cylinder could not start to move until the opening of P-T valve was small enough to build up the system pressure to push the gravity load. Because the extension is in the direction of gravity, it resulted in a shorter time delay in extension than in retraction. The validation test result indicated that the programmable valve was capable of realizing satisfactory position control under a tandem-center operating condition. Similar results were obtained from validation tests under open-center, closed-center and float-center conditions.

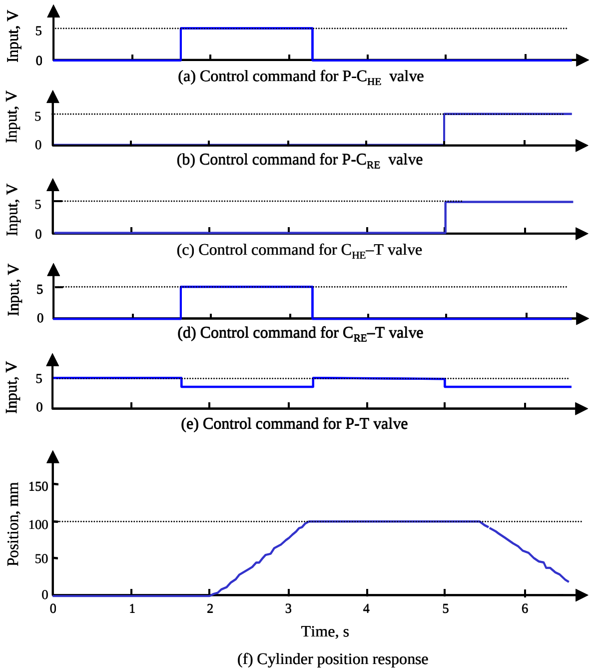

Fig. 5: *Cylinder position responses to a simple on-off logic control for realizing the direction control function of a tandem-center valve*

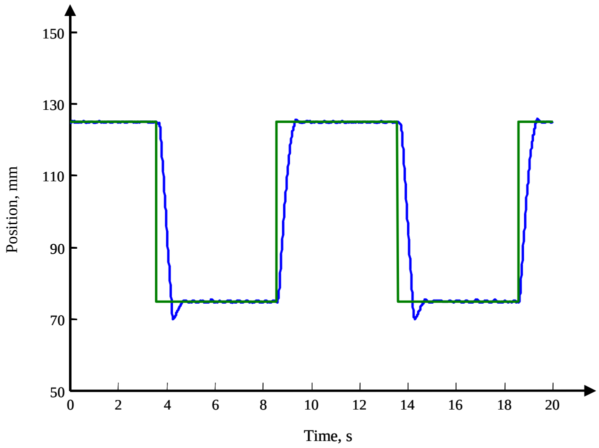

Fig. 6: *Cylinder position control performance under a step-input control signal for the hydraulic system controlled using the programmable E/H control*

The validation tests also included step and ramp response tests to evaluate the position control performance using the programmable valve. Figure 6 shows the position control results obtained from a step response test. Two proportional (P) controllers were used as the modulation controllers for both the P-C_{HE} and P-C_{RE} valves. The corresponding proportional gains for both controllers were K_{HE} = 0.50 and K_{HE} = 0.35. With a step position control command to retract the cylinder from an extension position of 125 mm to 75 mm, all the individually controlled based valves could respond to the control command promptly and in coordination. It took about 1.1 s to reach the new stabilized position accurately (position error less than 1 mm). A noticeable position overshoot (about 5 mm) was observed before the cylinder stabilized at the new desired position. It indicated that hybrid controller had an automatic error correction capability which could select the active base valves according to the error sign to correct the position error. For comparison, when a step extension command was used to extend the cylinder from 75 mm to 125 mm, it took about 0.7 s to reach the new stabilized position accurately. The main reason for the faster stabilization in the extending position control was that it did not result in an overshoot because the cylinder motion direction was against the gravity. The ramp test results (Fig. 7) indicated the programmable valve was capable of tracking the ramp position precisely with a consistent error. Such consistent tracking error in response to a ramp-input was a typical result for a type 1 system for feedback control (Franklin, Power and Emami-Naeini, 1994).

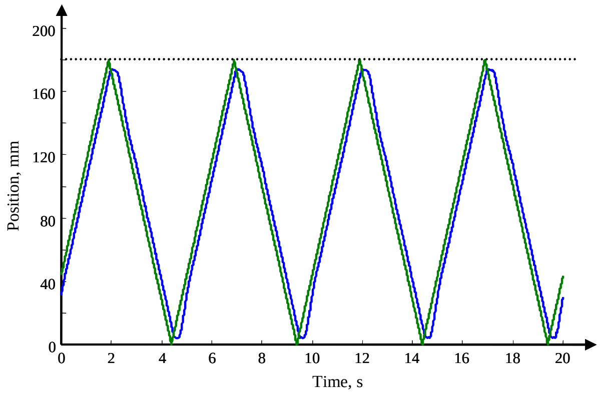

Fig. 7: *Cylinder position control performance under a ramp-input control signal for the hydraulic system controlled using the programmable E/H control valve*

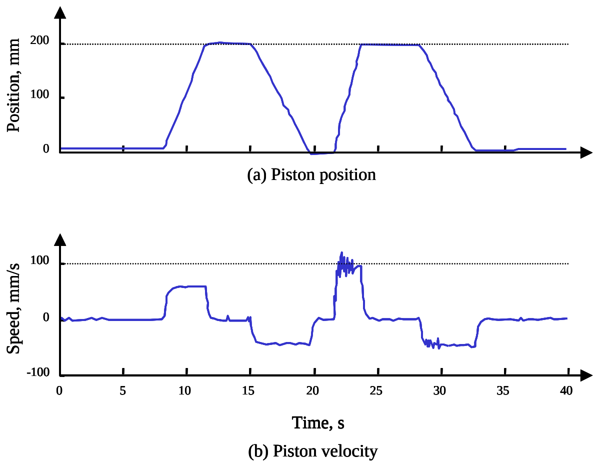

Fig. 8: *Comparison of system responses in cylinder position obtained from normal and flow-regeneration operating modes*

The flow regeneration capability of the programmable valve was also investigated. In this investigation, the cylinder was first extended from completely retracted to 200 mm under normal extension mode, then extended between the same positions under flow regeneration mode. Figure 8 shows the position control results and speed responses obtained from this test. The results indicated that the cylinder extension speed was increased from 60 mm/s in the normal mode to 95 mm/s in the flow regeneration mode, which represented a 58 % increase in cylinder velocity. To pay the price for the higher cylinder extension velocity, the system pressure was increased 133 % from the normal extension mode. The test showed that the programmable valve was capable of realizing the flow regeneration function and providing a higher extension velocity at light loads.

5 Conclusions

The programmability of valve functions and control characteristics of a programmable E/H control valve was investigated in this research. This programmable valve consisted of five individually controlled E/H valves. A hybrid controller was used to coordinate the operation of all base valves via a logic control and to regulate the flow rate via a proportional control. Validation tests on position control of a gravity loaded hydraulic cylinder indicated that the programmable valve was capable of realizing various valve functions (including tandem-center, open-center, float-center and closed-center) and different control modes (including normal and flow regeneration) by simply changing the control software. This research has validated the concept of a programmable valve in laboratory conditions. Before adopting the programmable valve in actual applications, it is recommended to investigate the practicability of using this programmable valve to replace conventional direction control valves in those systems.

Acknowledgements

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Nomenclature

A_{HE}	cylinder head-end (HE) piston area	[m^2]
A_{RE}	cylinder rod-end (RE) piston area	[m^2]
G_{HE}	transfer function of cylinder HE plant	[-]
G_{RE}	transfer function of cylinder RE plant	[-]
K_u	system control input gain	[m^{3}s^{-1}V^{-1}]
K_p	system pressure gain	[kg^{-1}m^{4}s]
m	total mass of moving parts attached on the cylinder	[kg]
δP_{HE}	pressure increment in cylinder HE chambers	[kgm^{-1}s^{-2}]
δP_{RE}	pressure increment in cylinder HE chambers	[kgm^{-1}s^{-2}]
u_{HE}	control signal to P-C$_{HE}$ valve	[V]
u_{RE}	control signal to P-C$_{RE}$ valve	[V]
V_{HE}	cylinder HE chamber volume	[m^3]
V_{RE}	cylinder RE chamber volume	[m^3]
$\delta\dot{x}$	velocity increment of the cylinder piston	[ms^{-1}]
β	effective bulk modulus of the fluid	[kgm^{-1}s^{-2}]
$\omega_{n,HE}$	natural frequency of cylinder HE plant	[s^{-1}]
$\omega_{n,RE}$	natural frequency of cylinder RE plant	[s^{-1}]
ξ_{HE}	damping ratio of cylinder HE plant	[-]
ξ_{RE}	damping ratio of cylinder RE plant	**[-]**

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