Design of Control System for Independent Metering Valve

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An independent metering valve control system (IMVCS) controls the meter-in and meter-out orifices of a valve independently. This innovative structure achieves a better energy saving performance, but also requires a more complex control algorithm. A flow and pressure coupling control system is proposed to control both the flow rate of the load and the pressure in each chamber. A DSP controller with TI-RTOS real-time operating system and digital driving module is adopted for fast response and accurate control. A two level fuzzy PID control algorithm and a lookup table algorithm are applied to improve the performance of the IMVCS. Experimental results show that the created control system can effectively control an IMVCS, and realize the function of flow and pressure coupling control.

Keywords: Independent Metering, Control System, Two Level Fuzzy PID, Coupling Control
Target audience: Independent Metering Control, Control System

1 Introduction

Hydraulic systems are widely applied in many industrial applications because of their high power and force to weight ratio /1/. Usually, proportional directional valves are used in conventional hydraulic systems to realize the desired flow direction and flow rate control. With this kind of hydraulic system, the meter-in and meter-out orifices are mechanically connected, which makes the actuator easier to control. However, the conventional valve control system brings high energy consumption and throttling temperature increasing. In order to overcome these shortcomings, a new hydraulic technology named independent metering valve control system (IMVCS) is proposed, as shown in Figure 1. This innovation breaks the mechanical linkage of the meter-in and meter-out orifices, so that more additional degrees of freedom can be achieved. Therefore, the pressure and flow can be coupling controlled at desired values to realize a better energy saving and control performance of hydraulic systems.

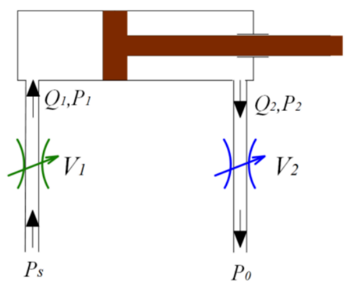


Figure 1: Independent metering valve control system.

Jan Ove Palmberg from Linköping University first proposed the concept of independent metering control /2/ according to the cartridge valve control theory presented by professor Backé /3/. Aardema used two conventional four way proportional valves to control the meter-in and meter-out orifices respectively /4/, which was an expensive method since it replaced one by two. Solutions for the function of IMVCS devices were also patented with four poppet valves by Caterpillar Inc /5/, Moog Inc /6/ and Husco International /7/. Yao, B focused on the energy saving performance of IMVCS with five programmable valves, four of which were used for the independent metering function and the last for flow regeneration, and realized a good performance in trajectory following precision /8/, /9/, /10/. Dresden University of Technology studied the structure of IMVCS, and parallel and series arrangements were discussed /11/, /12/. Linjama M used digital flow control units (DFCU) to replace the traditional spool valves, and the structure of DFCU had the function of independent metering control /13/, /14/. Zhejiang University investigated the multi-mode control method of IMVCS to improve the precision and efficiency of the system /15/. Industrial applications developed by Eaton /16/ and Danfoss /17/ were used in mobile machinery. Cearly, the IMVCS has existed for a long time, but it still hasn't been widely used in the practical hydraulic systems. The main reason is the increased degrees of freedom require more complex control algorithms and more expensive equipment /18/, which limits its real application.

This research focuses on the programmable control system of IMVCS. An embedded controller is designed, and a real-time multitasking control software is also developed. Built on the TI-RTOS embedded operating system and toolset, a lookup table algorithm is developed for flow control and a two-level fuzzy PID control algorithm is applied to modify pressure in real-time, so that the function of coupling control and fast response can be achieved.

2 Programmable Control System Design

2.1 Design of IMVCS controller

The controller of an IMVCS requires more powerful hardware performance and more optimized software algorithms than a conventional valve controller, since it needs to control two valves at the same time. A third generation of IMVCS controller is developed to give full play to the advantages of IMVCS, as shown in Figure 2. The controller includes five main parts: the DSP minimum system, power management module, signal processing module, CAN communication module and digital drive module of a voice coil motor (VCM).

Figure 2: IMVCS controller.

A TMS320F28335 DSP is selected as the core MCU, and its clock frequency reaches 150MHz with the ability of Floating Point Unit (FPU). Benefitting from the TI-RTOS embedded operating system, the controller can realize multi-thread real time operation with a closed-loop control of 0.5ms. The power management module provides different voltage values to make sure every part of controller operates effectively: 32V for VCMs, 24V for sensors, and both 3.3V and 1.9V for the DSP minimum system. The signal processing module amplifies the differential signal from the sensors, and transfers to DSP through sampling ports. The digital drive module is developed for VCM, which is a fast response proportional actuator of the pilot stage of the valve. In order to control the output force and moving direction of the VCM accurately, a bipolar "H" type PWM changing circuit is designed, as shown in Figure 3. A logic chip is used to reverse the PWM signal from DSP. The bipolar "H" type drive circuit receives two adverse PWM signals. When their duty ratio is 50%, the effects of two driving PWM signals are cancelled out, the output force of the VCM is zero, and the pilot spool stays at zero position. When the duty ratio is not equal to 50%, the two high frequency adverse PWM signal can be regarded as an effective analog power source, and the average voltage determines the direction and values of the VCM output force.

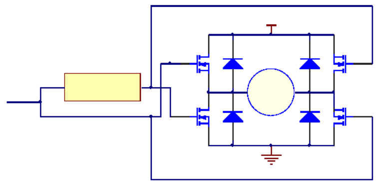


Figure 3: Voice coil motor driving circuit.

2.2 Design of host control system

A control program for the host computer is provided by LabVIEW, the interface for which is shown in Figure 4. Through CAN bus, the host computer is able to communicate with IMVCS controller. With the help of a Wifi module, this control program can achieve remote control and monitoring of the IMVCS. With the function of selectable operation mode, the user can easily change the operation mode between displacement control, pressure control and flow rate control, so that a most suitable operation mode will be applied under any working condition to achieve a better performance. In the interface, target value and control parameters can be set, a tracking signal can be produced, and dynamic data of the IMVCS can be saved for analysis.

Figure 4: Interface of host computer.

3 Control Algorithm Analysis

Based on TI-RTOS embedded operation system, a multi-threaded 1ms closed-loop control algorithm is programmed. Each valve has a dedicated spool displacement control thread, chamber pressure control thread, and flow rate control thread. In order to verify basic control performance of this control system, an optimized fuzzy PID strategy is applied in main spool displacement control, as illustrated in Figure 5. The output PWM is an adjustable duty ratio square wave of high frequency of 10KHZ. VCM is a fast pilot actuator with very low inductance, so a quick response will be ensured.

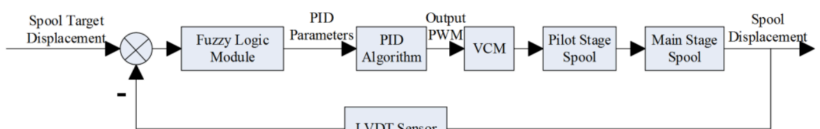


Figure 5: Main spool displacement control structure.

The equation of displacement fuzzy PID control algorithm can be written as

$$u(k) = \alpha_{dout}\{k_p e_d(k) + k_i \sum_{i=0}^{k}[\alpha_{di} e_d(i)] + \alpha_{dd} k_d [e_d(k) - e_d(k-1)]\} \quad (1)$$

where $u(k)$ is the output duty ratio, $e_d(k)$ is the error to the target displacement, k_p, k_i and k_d are parameters of PID algorithm, α_{dout}, α_{di} and α_{dd} are outputs of displacement fuzzy PID controller, and their rules are shown in Table 1.

e (μm)	α_{dout}	α_{di}	α_{dd}
0-100	1	1	5
100-200	0.75	(200-e)/100	(200-e)/20
>200	0.25	0	0

Table 1: Parameters of displacement fuzzy PID control.

Based on the operation principle of a bipolar "H" type drive circuit, the average voltage applied on the VCM can be written as

$$U = U_{\sup}[2u(k) - 1] \quad (2)$$

where U is effective average voltage value, and $U_{\sup}$ is supply voltage value of the bipolar "h" type drive circuit.

In the pressure control thread, a two level closed-loop control algorithm is applied, as shown in Figure 6. A fuzzy PID control program developed especially for the pressure dynamics and stabilities is applied in the outer loop. The output results from the pressure PID algorithm module are the input target displacements of the inner displacement closed-loop control thread. Every cycle, the pressure sensor detects the chamber pressure and feeds back to the DSP system. Then, the pressure control module gives a new output for the inner displacement closed-loop control thread, and the spool moves to the target position. The above process repeats until the pressure reaches the desired value. At last, the chamber pressure can be controlled with the method of adjusting pressure difference through the valve by moving the spool.

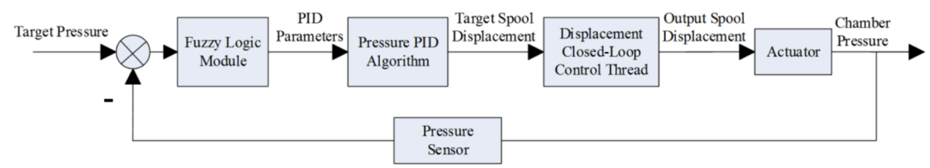


Figure 6: Pressure control structure.

The equation of pressure fuzzy PID control algorithm can be written as

$$Dis(k) = \alpha_{pout}\{k_p e_p(k) + k_i \sum_{i=0}^{k}[\alpha_{pi} e_p(i)] + \alpha_{pd} k_d [e_p(k) - e_p(k-1)]\} \quad (3)$$

where $Dis(k)$ is the output displacement value to the inner displacement closed-loop, $e_p(k)$ is the error to the target pressure value, α_{pout}, α_{pi} and α_{pd} are output of pressure fuzzy PID controller, and their rules are shown in Table 2.

e (bar)	α_{pout}	α_{pi}	α_{pd}
0-10	1	1	0
10-20	0.5	(20-e)/10	1
>20	0.25	0	0

Table 2: Parameters of pressure fuzzy PID control.

In the flow rate control thread, a lookup table algorithm is applied. A small database of flow rates with different differential pressures, different spool displacements and different temperatures is built. As Figure 7 shows, the sensors feedback current temperature and differential pressure to the DSP, which calculates the displacement position according to the target flow rate value and feedback values from sensors. Then, the displacement control thread moves the spool to the target. The above process will be repeated until output flow rate matches the target flow rate.

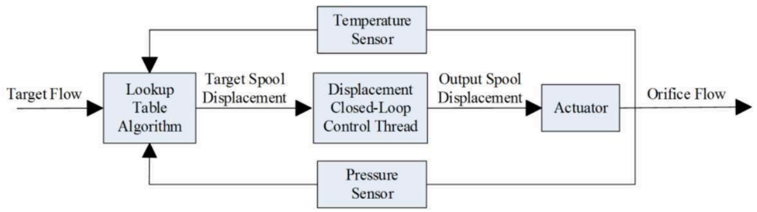


Figure 7: Flow rate control structure.

The principle of the flow rate database can be described as

$$Q=f(T,x,\Delta P) \tag{4}$$

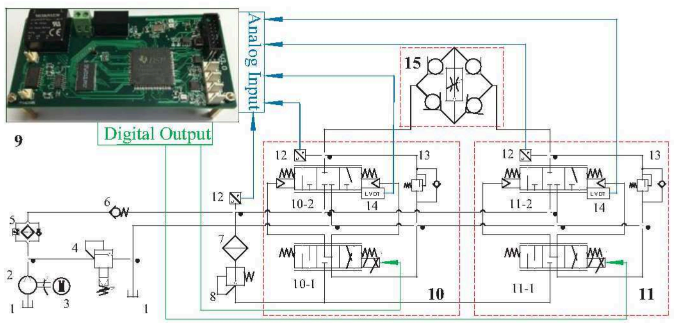
where Q is the flow rate, x is the spool displacement, T is the temperature, and ΔP differential pressure.

Therefore, the flow rate lookup table algorithm can be improved as

$$x=g(Q,T,\Delta P) \tag{5}$$

4 Experiments and Results

An experimental IMVCS is established, and its schematic is illustrated in Figure 8. The IMVCS mainly consists of a programmable controller, a pump, a hydraulic bridge circuit which is used as a load, and two two-stage proportional valves. Experiments about spool displacement control characteristics, chamber pressure control performance and flow rate control performance have been carried out in this section.



1.Tank 2.Pump 3.Motor 4. Electro-hydraulic proportional relief valve 5.High pressure filter 6.Check valve 7.Filter 8.Pressure reducing valve 9.Programmable controller 10,11.Two- stage valve 12.Pressure sensor 13.Safety valve 14.LVDT 15. Hydraulic bridge circuit

Figure 8: Schematic of the experimental system.

IMVCS performance, especially where pressure control and flow rate control are concerned, is heavily dependent on spool displacement performance. Therefore, experiments are performed to determine the displacement dynamics of the developed control system. Step response of the two valves switching their operation conditions at the same time are illustrated in Figure 9. Positive displacement means the operation port is connected with the tank, while, negative displacement means the operation port is connected with the supply pressure. Response times of steps from -3000μm to 1500μm and 3000μm to -1500μm are 58.5ms and 59.3ms respectively with an allowable error and an overshoot of 1%. From the curves, it is easily observable that the two valves transition from one displacement level to the other at nearly equivalent rates, which will ensure a better moving performance of the actuator.

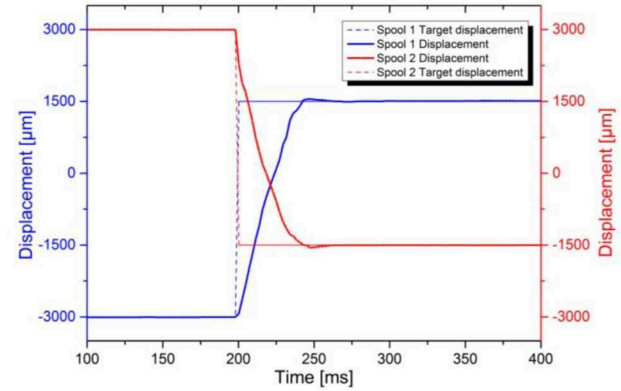


Figure 9: Displacement sept response performance.

Experiments of using the control system to follow a displacement sine signal are also carried out to verify the advantages of the programmable control system. Figure 10 shows the results when tracking a sine signal of 10HZ with an amplitude of 0.2mm. It can be seen that the spool closely tracks the target and there is almost no reduction of amplitude, though there is an average delay time of about 6ms. The successful results of the basic displacement control experiments validate that the developed control system has excellent displacement control, which will enhance the pressure and flow control performance.

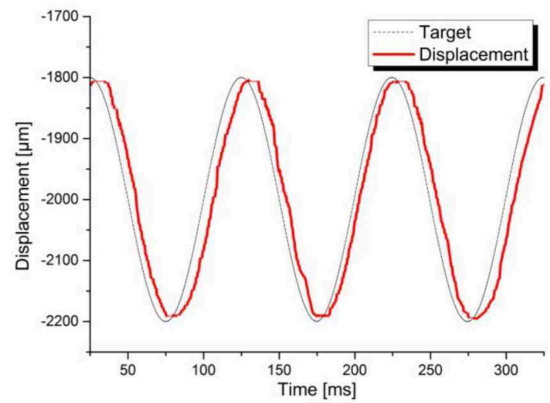
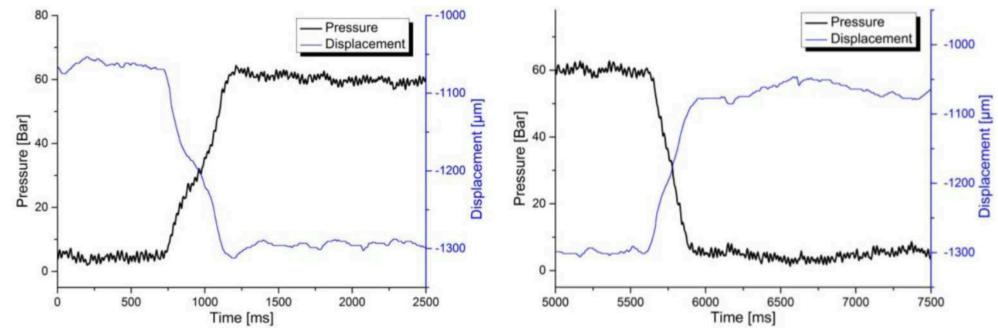


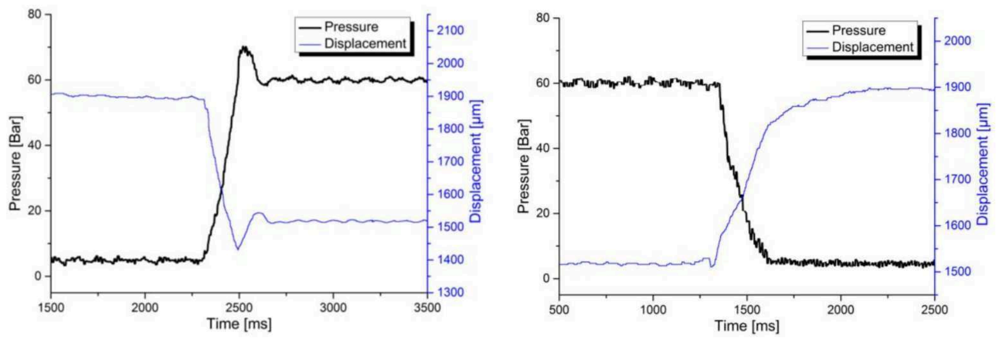
Figure 10: Displacement sine signal tracking performance.

In IMVCS, the pressure in the chamber can be independently controlled at a desired value to improve the controllability and stability of the actuator, while combining the energy saving performance. Therefore, pressure control experiments are carried out to confirm this. During all pressure control experiments, the flow rate of the pump is set as 60L/min. The throttle valve in the hydraulic bridge circuit is open with a fixed opening area to simulate a constant load. Based on the two-level fuzzy PID control algorithm mentioned above, inlet chamber pressure control experiments are carried out, and outlet spool is controlled with an opening orifice of 3mm, so that the pressure loss through the orifice can be neglected, and the results are shown in Figure 11. The response time of rising step from 5bar to 60bar is about 500ms, and response time of drop step from 60bar to 5bar is decreased to 250ms. Both of the two pictures show no overshoot during the whole pressure control process. As to the pressure control of outlet chamber, it is usually used to improve the controllability of the actuator. During the outlet chamber pressure control experiments, the inlet spool is also controlled with an opening orifice of 3mm, and the results are illustrated in Figure 12. When tracking a step signal from 5bar to 60bar, pressure can be established within 130ms, and remains stable within 250ms. Unfortunately, the closer to the critical closing position of the main spool, the more sensitive the back pressure of the chamber will be. Therefore, an overshoot of about 16% is caused by only a very small excess movement of the spool. When it comes to tracking a drop step signal, the system gives a better performance with an adjusting time of about 150ms, and no overshoot. Both the inlet and outlet chamber pressure control experiments show that the developed control system is effective in pressure control.



(a) Rising step response *(b) Drop step response*

Figure 11: Inlet chamber pressure control performance.



(a) Rising step response *(b) Drop step response*

Figure 12: Outlet chamber pressure control performance.

Flow and pressure coupling control is one of the most important functions of IMVCS, so experiments to test the system's coupling control performance are carried out. The main purpose of this experiment is to keep the inlet pressure constant while controlling the flow rate of the outlet. The results are shown in Figure 13 and Figure 14. Because conventional flow meters cannot adequately detect transient flow, the flow data in the figures are calculated by Equation (4). Inlet port of load is controlled at 60bar, and the flow control algorithm is applied to the outlet port. Figure 13 shows the performance when tracking a flow rising step from 20L/min to 40L/min. The flow response time is about 150ms and pressure adjusting time is about 100ms. Figure 14 shows the performance when tracking a flow drop step from 40L/min to 20L/min. The flow response time is about 150ms and pressure adjusting time extends to about 300ms, which is caused by the decreasing of the opening area of the outlet valve, and makes both outlet and inlet chamber pressure increase greatly, and cause a longer time to adjust the pressure. However, in general this programmable control system has excellent performance in flow and pressure coupling control, which has huge potential for energy saving in hydraulic systems.

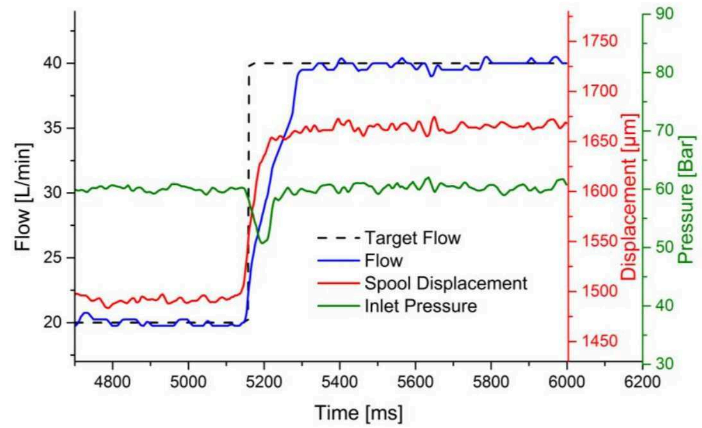


Figure 13: Flow and pressure coupling control performance-1.

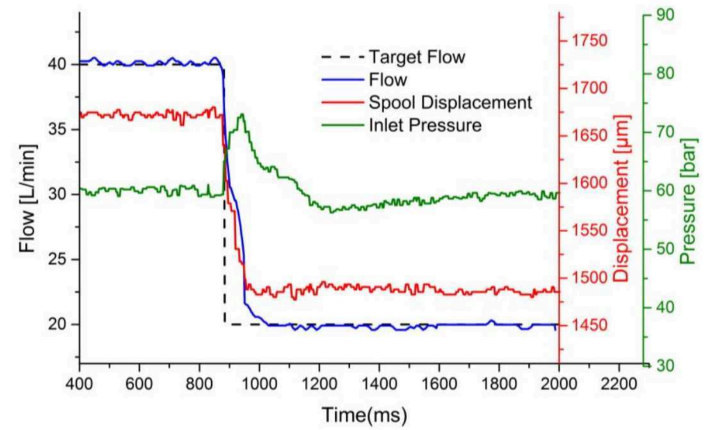


Figure 14: Flow and pressure coupling control performance-2.

5 Summary and Conclusion

Although a large amount of experimental research has been done about independent metering control based on the developed control system, the theoretical analysis and real application of such systems still needs effort. From hardware to software, a programmable control system including embedded lower controller and host control system are developed for IMVCS, and a multitasking software is programed based on TI-RTOS real time operation system. A series of experiments of IMVCS are carried out, and the results show the superiority of the fuzzy PID control algorithm and lookup table algorithm. With the help of the programmable control system, IMVCS can easily achieve good performance in displacement, pressure and flow control, which can expand its application area, and provide a huge potential for energy-efficient control. Further study will concentrate on energy saving performance and controllability of the actuator.

6 Acknowledgements

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Nomenclature

Variable	*Description*	*Unit*
$u(k)$	Output Duty Ratio of PWM	[-]
$e_d(k)$	Error to the Target Displacement	[μm]
k_p	Proportional Gain of PID Algorithm	[-]
k_i	Integral Gain of PID Algorithm	[-]
k_d	Differential Gain of PID Algorithm	[-]
α_{dout}	Output of Displacement Fuzzy PID controller	[-]
α_{di}	Output of Displacement Fuzzy PID controller	[-]
α_{dd}	Output of Displacement Fuzzy PID controller	[-]
U	Effective Average Voltage Value	V
U_{sup}	Supply Voltage Value of the Bipolar "H" Type Drive Circuit	V
$Dis(k)$	Output Displacement Value to the Inner Displacement Closed-loop	[μm]
$e_p(k)$	Error to the Target Pressure Value	[bar]
α_{pout}	Output of Pressure Fuzzy PID Controller	[-]
α_{pi}	Output of Pressure Fuzzy PID Controller	[-]
α_{pd}	Output of Pressure Fuzzy PID Controller	[-]
Q	Flow Rate	[L/min]
x	Spool Displacement	[μm]
T	Temperature	[K]
ΔP	Differential Pressure	[bar]

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