Simulation and experimental research of digital valve control servo system based on CMAC-PID control method[①]

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Abstract

Digital valve control servo system is studied in this paper. In order to solve the system problems of poor control precision and slow response time, a CMAC-PID(cerebellar model articulation controller -PID) compound control method is proposed. This compound controller consists of two components: one is a traditional PID for the feedback control to guarantee stability of the system; the other is the CMAC control algorithm to form a feed-forward control for achieving high control precision and short response time of the controlled plant. Then the CMAC-PID compound control method is used in the digital valve control servo system to improve its control performance. Through simulation and experiment, the proposed CMAC-PID compound control method is superior to the traditional PID control for enhancing stability and robustness, and thus this compound control can be used as a new control strategy for the digital valve control servo system.

Key words: electro-servo system, digital hydraulic, digital valve, CMAC-PID compound control, rapid control prototyping technology

0   Introduction

With the progress of science and technology, green development and innovation-driven development have become a trend. Since the advantages of high transmission efficiency, high reliability, digital valves have attracted more and more attention[1]. It can also be used to control the hydraulic actuators and form the electro-hydraulic valve control servo system. Digital valves are defined as valves with digital control and digital output response characteristics. However, digital valves are controlled by digital signal and its flow is discrete rather than continuous, so the electro-hydraulic digital valve control servo system has the shortcome of poor control accuracy and slower response speed. How to improve the control accuracy and response speed has become a hot spot[2-4].

In order to get better control performance for digital valve control servo system, the control strategy must be improved. The traditional proportional-integral-deriva-tive (PID) control method is adopted in most electro-hydraulic valve control servo systems. However, practice has proved that the PID controller cannot satisfy the complex nonlinear systems because of its immutable parameters, low control accuracy and poor anti-inter-ference ability. With the progress of intelligent algo-rithm, fuzzy algorithm, BP neural network, genetic al-gorithm, some other algorithms are combined into PID controller[5-7]. Some scholars use the compound algo-rithm of fuzzy PID and feed-forward and feedback com-pound control method to achieve precise position con-trol[8-10]. All of these controllers are used on the electro-hydraulic digital valve control servo system with better control performance than the traditional PID con-troller.

Cerebellar model articulation controller (CMAC) can be used to simulate the learning structure of the cerebellum and can be effectively applied to the com-plex nonlinear system[11,12]. Some researchers propose the CMAC-PID compound control strategy and apply it in the pneumatic position servo system, electric servo

loading system, controlling of electro-hydraulic proportional valve and DC motor[13-17]. They all get better control performance than using traditional PID controller. However, few have applied the CMAC-PID in the electro-hydraulic digital valve control servo system. In this paper, the CMAC-PID compound controller in the electro-hydraulic digital valve control servo system is applied and compared with the traditional PID on the control performance through simulation and experiment.

1   Working principle of digital valve control servo system

In this paper, the working principle of digital valve control servo system is shown in Fig. 1.
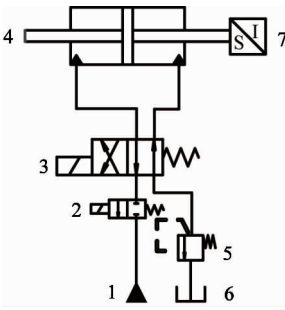
**Fig. 1**   Schematic diagram of digital valve control servo system

The system consists of the following seven parts: 1 constant-voltage source; 2 high speed switch type digital valve; 3 electromagnetic directional valve; 4 hydraulic cylinder; 5 relief valve; 6 oil tank; 7 displacement sensor. In this diagram, the combination of digital valve 2 and electromagnetic directional valve 3 can take the place of servo valve, which control the hydraulic cylinder. Digital valve controls the oil flow and the electromagnetic valve controls the direction of oil. Relief valve controls the back pressure of the load system. The displacement sensor can measure the displacement of hydraulic cylinder, which constitutes a closed-loop position control system. This system can achieve precise position control of the hydraulic cylinder.

2   Modeling of digital valve control servo system

## 2.1   Modeling of the high speed switch type digital valve

In the working process, the digital valve element will be affected by four types of forces, the F_h (hydraulic pressure force), the F_f (flow force), the F_m (electromagnetic force) and F_k (spring force). The force of

the digital valve element is shown in Fig. 2.
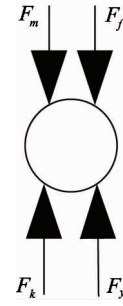
Fig. 2   Force diagram of the high speed switch type digital valve

The equivalent circuit diagram of the digital valve is shown in Fig. 3.
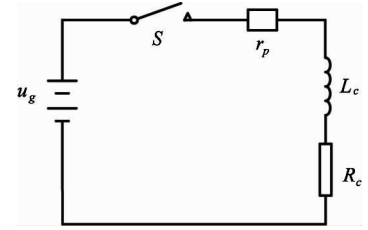
Fig. 3   The equivalent circuit diagram

By analyzing this diagram, the exciting coil voltage balance equation in digital valve is

$$K_u u_g = (R_c + r_p) i_c + L_c \frac{di_c}{dt} \qquad (1)$$

where, u_g is the signal voltage of amplifier (V), K_u is the gain of amplifier, R_c is the resistance of control coil (Ω), r_p is the internal resistance of amplifier (Ω), L_c is the inductance of control coil (H) and i_c is the electric current of control coil (A).

The DC solenoid electromagnetic force of the digital valve is generated in steady state:

$$F_m = \frac{\Phi^2}{2\mu_0 S} = \frac{(Ni)^2 \mu_0 S}{2K_f^2 b^2} \qquad (2)$$

where, μ_0 is the permeability of vacuum (N/A^2), S is the cross-sectional area of work air gap (m^2), K_f is the magnetic leakage factor, b is the length of work air gap (m), N is the number of coil and i is the electromagnet current (A).

This equation is simplified by the Taylor series and the second order infinitesimal quantity, is omitted

$$F_m = K_{mi} i - K_{mx} x \qquad (3)$$

where,

$$K_{mi} = \left. \left(\frac{N^2 i \mu_0 A}{(l_0 - x_0)^2} \right) \right|_{i=i_0} \qquad (4)$$

and K_{mi} is the electromagnetic force variation coefficient caused by the coil electric current change.

$$K_{mx} = -\left(\frac{N^2 i_0^2 \mu_0 A}{(l_0 - x)^3}\right)\Bigg|_{x=x_0} \quad (5)$$

and K_{mx} is the electromagnetic force variation coefficient caused by the valve element displacement change.

The flow force of the valve element is

$$F_f = 2C_v C_d W \Delta p \cos\theta \quad (6)$$

where, C_v is the velocity coefficient, usually $0.95 \sim 0.98$, C_d is the flux coefficient of valve port, W is the area-grads(m), Δp is the pressure drop of valve port (Pa) and θ is the angle of jet flow(°).

This equation is simplified by the Taylor series and the second order infinitesimal quantity is omitted:

$$F_f = -K_{fx}x + K_{fp}P \quad (7)$$

where,

$$K_{fx} = -\frac{\partial F_f}{\partial x}\Bigg|_{\substack{x=x_0 \\ P=P_0}} \quad (8)$$

here K_{fx} is the liquid force variation coefficient caused by the valve element displacement change.

Where,

$$K_{fp} = \frac{\partial F_f}{\partial P}\Bigg|_{\substack{x=x_0 \\ P=P_0}} \quad (9)$$

and K_{fp} is the liquid force variation coefficient caused by the pressure difference.

In the work schedule, the force balance equation of valve element is

$$F_m = m\frac{d^2 x}{dt^2} + B\frac{dx}{dt} + K(x_0 + x) + F_l \quad (10)$$

where, m is the mass of ball value and pushrod (kg), B is the viscous damping coefficient (N/(m/s)), K is the spring stiffness (N/m), x_0 is the precompressed spring length(m) and F_l is the fluid force of valve element(N).

The flow which passes the high speed switch type digital valve port is

$$q = C_d A \sqrt{\frac{2\Delta p}{\rho}} \quad (11)$$

where, C_d is the flow coefficient of ball valve port, A is the valve port area (m^2), Δp is the pressure drop of valve port(Pa), ρ is the oil density(kg/m³).

Eqs(1), (3), (7) and (10) take Laplace transform:

$$K_u U_g = (R_c + r_p)I_c + L_c I_c s \quad (12)$$
$$F_m = K_{mi}I - K_{mx}X \quad (13)$$
$$F_f = -K_{fx}X + K_{fp}P \quad (14)$$
$$F_m = mX_v s^2 + BX_v s^1 + K(X_0 + X) + F_l \quad (15)$$

Assuming:

$$\omega_c = \frac{R_c + r_p}{L_c} \quad (16)$$

$$\omega = \sqrt{\frac{k}{m}} \quad (17)$$

$$\zeta = \frac{B_p}{2\sqrt{km}} \quad (18)$$

where, ω_c is the coil angular frequency(rad/s), ω is the hydraulic inherent frequency(rad/s), ζ is the hydraulic damping ratio and $k = K + K_{fx} + K_{mx}$ (N/m) is the synthetic stiffness.

In conclusion, the high speed switch type digital valve block diagram is shown in Fig. 4.

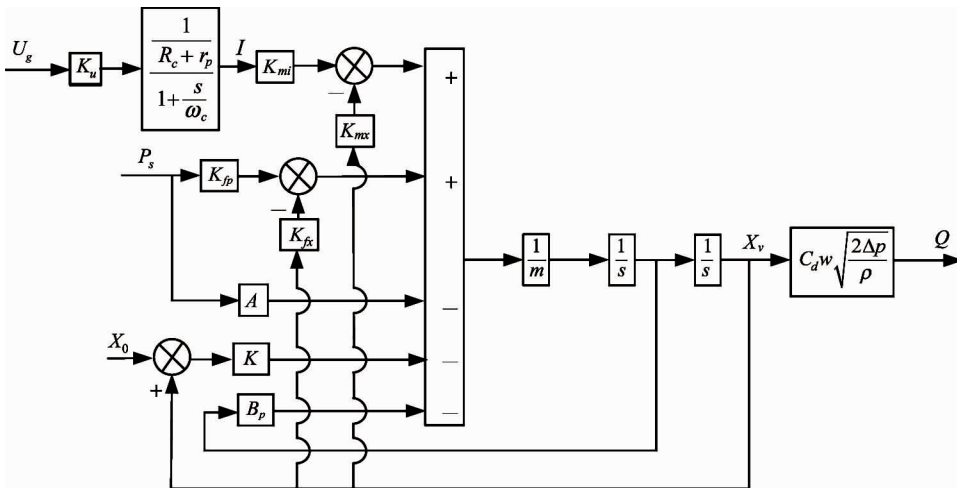**Fig. 4**   The high-speed switch type digital valve control diagram

2.2   Modeling of the electromagnetic valve and hydraulic cylinder

Since the inherent frequency of electromagnetic directional valve is close to the hydraulic inherent frequency, it is simplified into the second order oscilla-tion section.

$$\frac{U_g}{X_v} = \frac{K_v}{\dfrac{s^2}{\omega_{vh}^2} + 2\dfrac{\zeta_{vh}}{\omega_{vh}}s + 1} \quad (19)$$

where, U_g is the voltage of reversing valve (V), X_v is the displacement of reversing valve (m), K_v is the enlarged coefficients of reversing valve, ω_{vh} is the inherent frequency of reversing valve (rad/s) and ζ_{vh} is the damping ratio of reversing valve.

The electromagnetic valve for pressure and flow equation is

$$Q_L = K_q X_v - K_c P_L \qquad (20)$$

where, Q_L is the load flow of electromagnetic valve (m^3/s), K_q is the flow gain coefficient of electromagnetic value (m^2/s), K_c is the valve flow and pressure coefficient ((m^3/s)/Pa) and P_L is the load pressure (Pa).

The continuity equation of the hydraulic cylinder is

$$Q_L = A_p \frac{\mathrm{d}y_p}{\mathrm{d}t} + C_{tp} P_L + \frac{V_t}{4\beta_e} \frac{\mathrm{d}P_L}{\mathrm{d}t} \qquad (21)$$

where, A_P is the effective area of the hydraulic cylinder piston (m^2), C_{tp} is the total leakage coefficient of hydraulic cylinder ((m^3/s)/Pa), V_t is the total compressed volume of the hydraulic cylinder (m^3), β_e is the elastic modulus of effective volume (Pa) and y_p is the piston rod displacement (m).

The force balance equation of the hydraulic cylinder is

$$A_p P_L = m_t s^2 X_p + B_p s X_p + K X_p + F_L \qquad (22)$$

where, m_t is the mass of the piston and the load equivalent to the piston (kg), B_p is the viscous damping coefficient of piston and the load (N/(m/s)), K is the spring stiffness of load (N/m) and F_L is external load force (N).

From the above equations, omitting the elastic load and hydraulic cylinder leakage, the high-speed on-off digital valve control cylinder system block diagram is shown in Fig. 5.

Fig. 5   Digital valve control cylinder system control diagram

Finally, the position closed-loop control block diagram of the electro-hydraulic digital valve control servo cylinder system is shown in Fig. 6.

Fig. 6   Digital servo closed-loop position control diagram

3   Design of CMAC-PID adaptive controller

CMAC network is different from conventional neural networks. From the viewpoint of individual neuron, its input-output relationship is linear. However, the overall structure of CMAC network is nonlinear. The CMAC network has a strong nonlinear mapping and generalization ability for real-time control of complex nonlinear dynamic application.

3.1   CMAC network structure

A typical CMAC network consists of an input space, a storage space and an output space. The network realizes the mapping from input space to storage space and storage space to output space.

The dimensions of input space are determined by the dimensions of the controlled model. Each input vector from input space is mapped to the storage space (A) in accordance to certain rules.

The storage space (A) is divided into virtual storage space (AC) and practical storage space (AP). Each input vector has the corresponding memory spaces, the number of which is C (generalization parameter). The process of actual learning may not contain all the input state of the system, so the information

of AC should be mapped to AP according to a certain coding method, and right value is stored in the corresponding address of AP.

In the output layer, the total output of the network is the plus of the C memory cells' weight (w) in the actual storage space AP:

$$F(s_i) = \sum_{j=1}^{c} w_j \qquad (23)$$
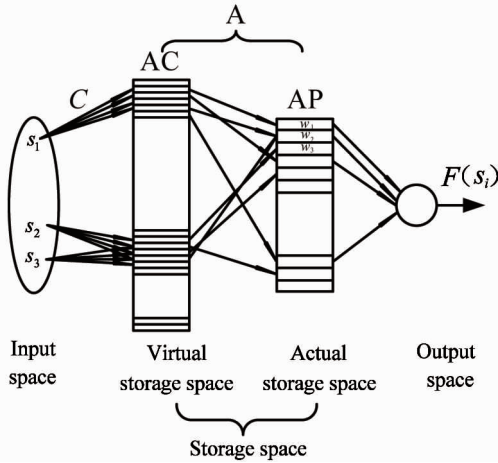
The CMAC network structure is shown in Fig. 7.

Fig. 7   Structure of CMAC neural network

Fig. 7 shows that the network output is a linear combination of weights, while the network is addressed by linear change and random compression. So the CMAC network has the ability to map nonlinear functions.

3.2   CMAC network working principle

On the basis of the CMAC network structure, the working principle of the whole network is divided into the following steps:

Step 1 Quantification of input vector

Since the input space is one-dimensional, the quantification method can be described as:

Input $s \in [a,b]$, M is the quantification stages, and u is the quantification value.

$$\Delta u = (b - a)/(M - 1) \qquad (24)$$
$$u(i) = a + \Delta u * (i - 1) \quad (i = 1,2,\cdots,M) \qquad (25)$$

Step 2 The input space to the virtual storage space

After the quantification, the input value requires to be mapped to the virtual memory space. According to the CMAC network principles, an input value could and should be used to activate C memory cells in the virtual storage space simultaneously.

Step 3 Virtual mapping to the actual mapping

The mapping from the virtual storage space (AC) to the actual storage space (AP) commonly uses hash coding method. Since the input space of this article is one-dimensional and small, one to one mapping is used instead of hash mapping in coding.

Step 4 Learning algorithm

CMAC network uses a supervised learning method, which requires the presence of a tutor outside the network. The tutor provides desired output for the neural network according to their experience and knowledge. The error between the CMAC output value and the desired output value is used to adjust the weights in the C memory cells. Adjusting the weights is used to reduce errors and to approximate to the desired output.

CMAC network commonly uses δ learning rule to adjust the weights, and δ learning rule can be called least mean square (LMS) rule. Its objective of adjusting weights is to get the least mean square, which can be described as

$$E = \frac{1}{2c}e(t)^2 \qquad (26)$$
$$e(t) = r(t) - y(t) \qquad (27)$$

where, $r(t)$ is the given signal, and $y(t)$ is the feedback signal. According to the gradient descent method, the CMAC network weights adjusting formula is

$$\Delta w_j(t) = -\eta \frac{\partial E}{\partial w} = \eta \frac{(r(t) - y(t))}{c} \cdot \frac{\partial y}{\partial w}$$
$$= \eta \frac{e(t)}{c} \qquad (28)$$
$$w_j(t) = w_j(t-1) + \Delta w_j(t) + \alpha(w_j(t-1) - w_j(t-2)) \qquad (29)$$
$$w_p = [w_1 \quad w_2 \quad \cdots \quad w_c] \qquad (30)$$

where, η is the learning rate, $\eta \in (0,1)$, α is the momentum factor, $\alpha \in (0,1)$. Simultaneously, the selection of quantification stages M and generalization parameter C is also very important. M determines the CMAC network's approximation accuracy, which increases with the increasing of the quantification levels. But the required memory space will be greater with the increasing of M. Generally, for the generalization parameter C, quantification stages M are 10 times more than parameter C. Only in this way, can the CMAC network achieve a better approximation accuracy of nonlinear function.

3.3   Design of CMAC-PID compound controller

In this paper, traditional PID is used as feedback control, in order to ensure the stability of the system, CMAC network is used as feed-forward control, in order to improve the control accuracy of the system. The plus of PID output and the CMAC network output is the total output. And the total output controls the controlled object. The compound control structure is shown in Fig. 8.
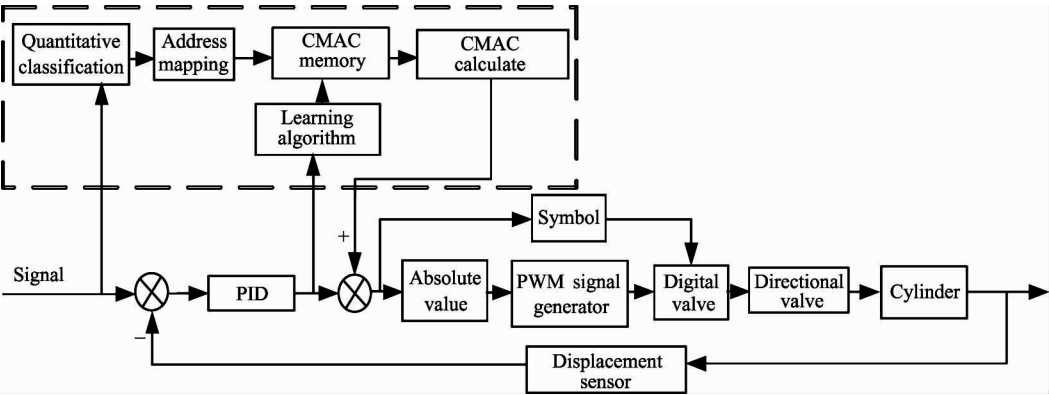
Fig. 8   Structure of CMAC-PID compound control for digital valve control system

According to the digital valve control servo cylinder system block diagram and CMAC-PID compound control block diagram, a CMAC-PID compound control simulation model is built in Matlab / Simulink, the simulation parameters of this system are set as Table 1.

Table 1   Simulation parameters of digital valve control servo system

Parameters	Value	Unit
Cylinder piston area	3.368×10^{-4}	m^2
Pipeline volume	56.55×10^{-6}	m^2
Cylinder stroke	0.05	m
Liquid volume modulus	8×10^{-8}	Pa
Damping coefficient	1000	N/(m/s)
Equivalent load mass	1.5	kg

3.4   Simulation study

The given position step signal is 0.02m, oil pressure is 7MPa, the operating frequency is 10Hz, according to the system parameters to determine the PID parameters: $K_p = 150$, $K_i = 0$, $K_d = 0.02$. To prevent over-learning phenomenon, learning rate is set as 0.001. The traditional PID control simulation curve and the CMAC-PID compound control simulation curve are shown in Fig. 9 ~ Fig. 13.

Fig. 9 ~ Fig. 13 show that after using CMAC-PID compound control method, the transient and steady state performance are improved, which proves that this proposed control algorithm is effective.
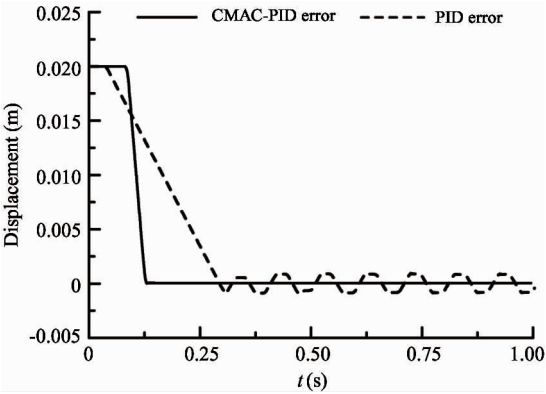
Fig. 10   Contrast of the error curve
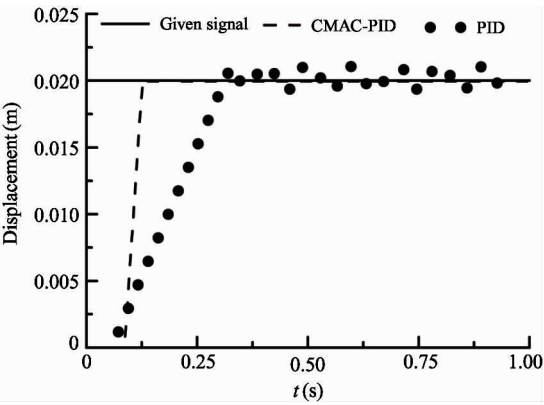
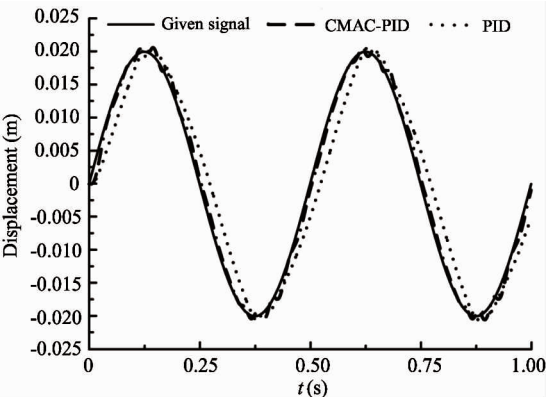
Fig. 9   Contrast of the step response curve

Fig. 11   Contrast of the sine response curve
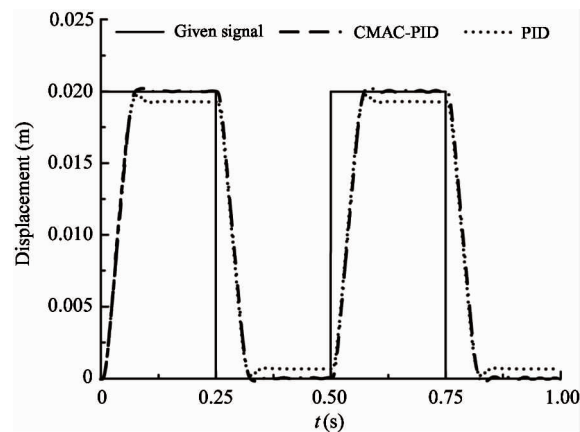
Fig. 12   Contrast of the square-wave response curve

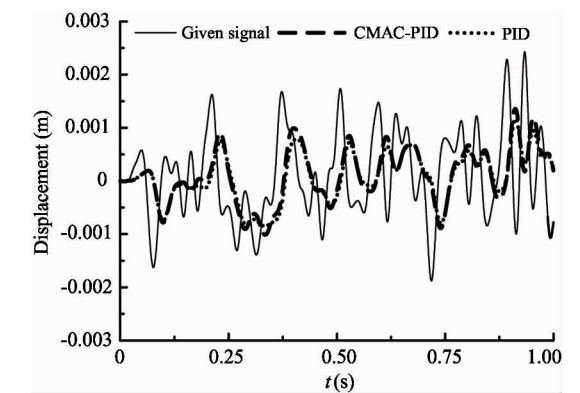**Fig. 13**   Contrast of the random signal response curve

4   Experiment study

4.1   Experiment scheme

An experiment is conducted in the electro-hydraulic digital valve control servo system test bench as shown in Fig. 14.
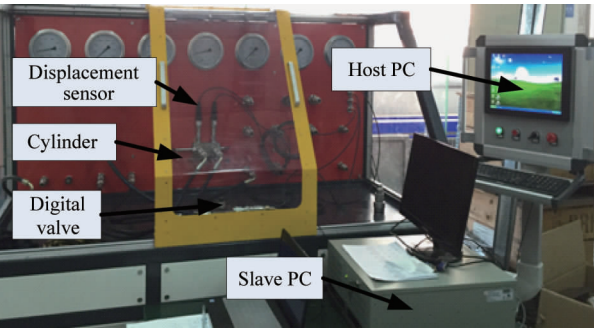

Fig. 14   Electro-hydraulic digital valve control servo system experiment bench

The experiment scheme is shown in Fig. 15. The Host PC controls the system through the Matlab / Simulink software, then the control program runs in the

Slave PC by the xPCTarget. The Slave PC outputs the signal by controlling cards. The card ACL-6126 and PCL-731 control the high-speed switch type digital valve, and the card PCL-731 controls the solenoid directional valve. Hydraulic components output the signal to the DAQ Card PCL-1716 through the sensors, and the PCL-1716 transmits the signal to the Slave PC. This experiment scheme achieves precise control of the hydraulic cylinder position.
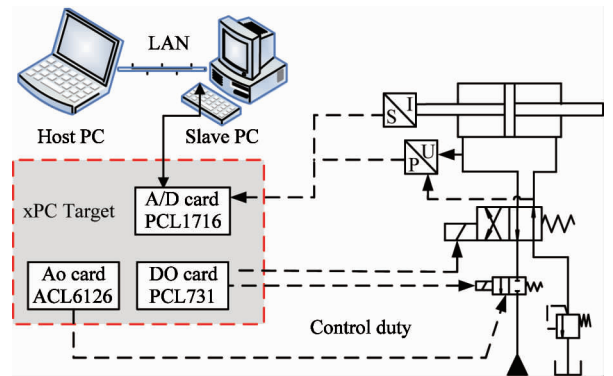

Fig. 15   Experiment scheme

Card PCI-1716 is a multi-channel high resolution DAQ Card of 16-bit. Card ACL-6126 is an analog control card with 6 channels and 12-bit resolution. The card can output voltage signals. Card PCL-731 provides 48 digital output channels. The parameters of main control components and sensors in this system are shown in the following tables.

Table 2   Parameters of the high-speed switch type digital valve

Parameters	Value	Unit
Supply voltage	12 ~ 24	VDC
Range	0.2 ~ 30	L/min
Nonlinear	±0.5%	–
Output	4 ~ 20	mA
Error	±0.5%	–
Viscosity range	10 ~ 500	$mm^2/S(cSt)$
Max pressure	63	MPa

Table 3   Parameters of displacement sensor

Parameters	Value	Unit
Rated pressure	7	MPa
No-load flow	8	L/min
Internal leakage	0	L/min
Supply voltage	24	V
Effective duty cycle	0.14 ~ 0.86	–
Repeat accuracy	±0.05	ms

Table 4   Parameters of flow sensor

Parameters	Value	Unit
Range	± 25	mm
Nonlinear	± 0.5% FRO	–
Input voltage(Sine wave)	3	V
Frequency	2.5	kHz

4.2   Traditional PID as compared with CMAC-PID in control performance

In this experiment, the supply oil pressure is 7Mpa, rated flow is 15L/min, the back pressure of the overflow valve is 3Mpa and the given signal is 0.02m step signal. The parameters of PID: $K_p = 170$, $K_i = 0$, $K_d = 0.1$. This experiment is performed in different carrier frequencies of 1Hz, 10Hz and 50Hz respectively. The three groups of response curve under two different control strategies are shown in Fig. 16.
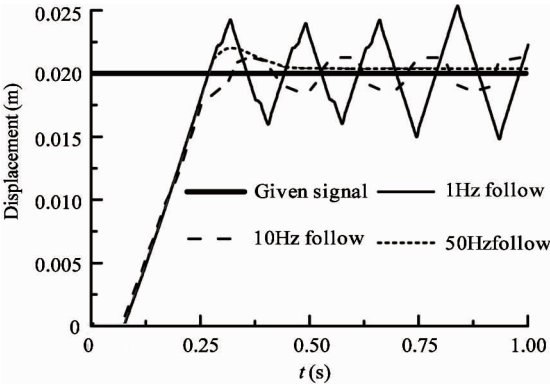
(a) Traditional PID
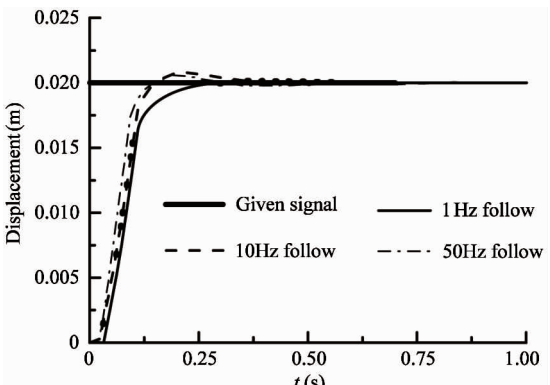
(b) CMAC -PID

Fig. 16   The step response curve comparison figure through experiment

The given signals are sine, square-wave and random. The amplitude of these signals is 0.02m. The frequency of sine and square-wave signals is 2Hz. The parameters of PID: $K_p = 170$, $K_i = 0$, $K_d = 0.1$. This experiment is done with carrier frequency of 10Hz. The response curves under two different control strategies are shown in Fig. 17 ~ Fig. 19.
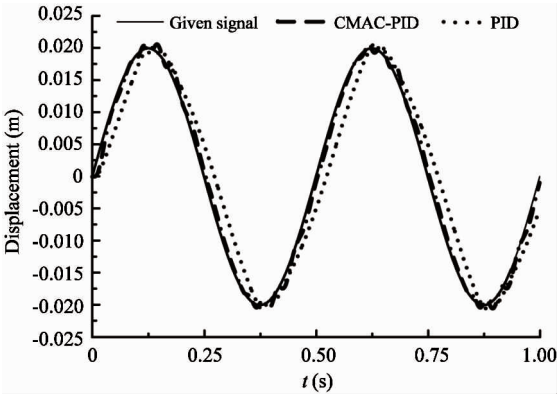

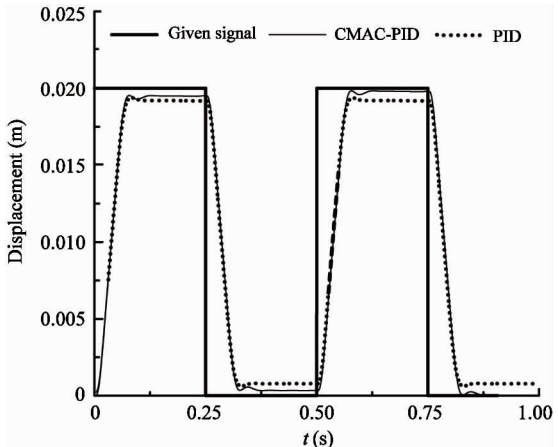**Fig. 17**   Response curve comparison for input signals of sine-wave

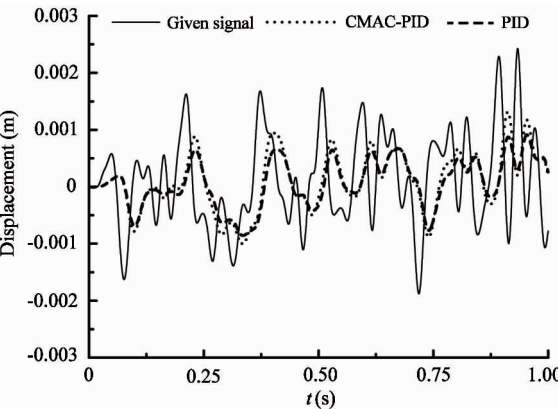**Fig. 18**   Response curve comparison for input signals of square-wave

Fig. 19   Response curve comparison for input signals of random signals

Comparison in Fig. 16 ~ Fig. 19 proves that the simulation model of this system is effective which can reflect the basic characteristic of the system. It can be seen from Fig. 16(a) and Fig. 16(b) that the control precision under steady state and the transient response

are improved with the increase of carrier frequency. Through the experiment and Fig. 16 ~ Fig. 19, it is known that the transient response characteristics improve significantly, delaying time, rising time and adjusting time of the responses for the step signal, sine signal, square-wave signal and random signal decrease remarkably under the control of CMAC-PID. The simulation and the experiment prove the effectiveness of the CMAC-PID compound control method.

5   Conclusion

In this paper, the electro-hydraulic digital valve control servo system is conducted using one digital valve and one directional valve. Also the simulation model of the system and the CMAC-PID compound control method are established. The following can be concluded from the simulation and experiment:

The accuracy of this system and the transient response characteristics increase as the digital valve working frequency increases. When the carrier frequency is 50Hz, this servo system can realize the stability control and the stable precision error is controlled within 0.7mm.

Compared with traditional PID, the transient response characteristics increase significantly, the response time decreases by almost 25% under different carrier frequency using the CMAC-PID controller.

Compared with the traditional PID, the stable precision improves significantly and the stable precision error is controlled within 0.1mm using the CMAC-PID controller.

References

[1] Linjama M, Laamanen A, Vilenius M. Is it time for digital hydraulics. In: Proceedings of the 8th Scandinavian International Conference on Fluid Power, Tampere, Finland, 2003. 347-356

[2] Xu Y Z, Chen W N. Hydraulic high-speed on-off valve and Its application on industries. *Hydraulics Pneumatics & Seals*, 2012, 32(1): 72-77

[3] Ding F, Yao J D, Da J, et al. Advances on high-speed on-off valves. *Chinese Journal of Construction Machinery*, 2011, 9(3): 351-358(In Chinese)

[4] Wang W W, Song J, Li L, et al. High speed on-off solenoid valve with proportional control based on high frequency PWM control. *Journal of Tsinghua University(Science and Technology)*, 2011, 51(5): 715-719(In Chinese)

[5] Paloniitty M, Linjama M, Huhtala K. Equal coded digital hydraulic valve system-improving tracking control with

pulse frequency modulation. *Procedia Engineering*, 2015, 106: 83-91

[6] He J, Yuan S Y. High-speed on/off valve hydraulic position control system based on DSP. *China Mechanical Engineering*, 2010, 21(24): 2929-2931(In Chinese)

[7] Gao Q H, Liu Z H, Niu H L, et al. Position control of hydraulic cylinder controlled by high-speed on-off valve. *China Mechanical Engineering*, 2015, 25(20): 2775-2781(In Chinese)

[8] He J, Yuan S Y. H_∞ Control for hydraulic cylinder position control system based on high-speed on/off value. *Control Engineering of China*, 2008, 15(S1): 79-84

[9] Lin Y. Research and Digital Simulation of High speed on/off Valve: [M. S Dissertation]. Wuhan: School of Mechanical and Electronic Engineering, Wuhan University of Technology, 2005. 9-18(In Chinese)

[10] Meng D Y, Tao G L, Li A M, et al. Adaptive robust control of pneumatic cylinders using fast switching on/off solenoid valves. *Journal of Mechanical Engineering*, 2015, 50(10): 180-188

[11] Liu J K. Advanced PID Control MATLAB Simulation. Beijing: Electronic Industry Press, 2004. 183-193

[12] Zhang Z X. Neural Network Control and MATLAB Simulation. Harbin: Harbin Industrial University Press, 2011. 165-186(In Chinese)

[13] Liu D, Jiang J, Zhang D W. Simulation study of controlling DC motor of based on CMAC neural network PID control algorithm. *Instrumentation Technology*, 2014, 1: 45-49

[14] Qian X S, Li J, Lei P F. The application of CMAC-PID parallel control algorithm in electro-hydraulic servo system. *Computer Measurement & Control*, 2015, 23(11): 3674-3681

[15] Jia C Y, Shan X Y, Cui Y C. Modeling and simulation of hydraulic roll bending system based on CMAC neural network and PID coupling control strategy. *Journal of Iron and Steel Research, International*, 2013, 20(10):17-22

[16] Rong Y R. Study of Controlling ZTS16 Electro-hydraulic Proportional Valve Based On CMAC-PID Compound control strategy: [M. S dissertation]. Changsha: College of Mechanical and Electrical Engineering, Central South University, 2010. 23-33(In Chinese)

[17] Li Q, Yuan R B, Yang H F. Study on hybrid control of pneumatic position servo system based on CMAC and PID. *Fluid Power Transmission & Control*, 2009, 5: 19-21

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