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Research on high-precision control of digital piezoelectric proportional valve based on PWM-PAM collaborative control☆

Linfei Li [a], Yuwen Wang [b], Yuchuan Zhu [a,*], Jie Ling [a]

[a] College of Mechanical & Electrical Engineering, Nanjing University of Aeronautics and Astronautics, No. 29 Yudao Street, Nanjing, 210016, China
[b] Nanjing Chenguang Group Co., Ltd, The intersection of Yuhua East Road and Yuhua Road in Qinhuai District is about 200 meters east., 210006, Nanjing, China

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ABSTRACT

Using high speed on/off valve (HSV) as the pilot stage to drive the main valve is a feasible technical path to realize large flow digital proportional valve, which is gradually receiving extensive attention from academia and engineering field. The traditional electromagnetic high speed on/off valve (EHSV) has the problems of insufficient dynamic characteristics and fixed flow resolution, which has become a key bottleneck restricting the high-precision displacement control of digital proportional valves. To address the above issues, a digital piezoelectric proportional valve (DPPV) with a piezoelectric high-speed on/off valve (PHSV) as the pilot stage is proposed. Furthermore, a PID control strategy based on Pulse Width Modulation and pulse amplitude modulation (PWM-PAM) coordinated regulation is designed, aiming to achieve adjustable resolution by online adjustment of the PWM duty cycle and amplitude. In this paper, the structure and working principle of the DPPV are systematically expounded, and its nonlinear mathematical model and simulation model are established. An experimental prototype is developed, and three displacement tracking experiments are carried out under different frequency and amplitude conditions. The experimental results show that, compared with the traditional PID control strategy based on differential PWM drive, the maximum error, average error and standard error of the valve spool displacement tracking driven by the proposed control strategy are significantly reduced, with the maximum reductions of 58.2 %, 59.5% and 95.5% respectively. In addition, compared with the existing control strategies of digital proportional valves at home and abroad, the control strategy proposed in this paper demonstrates more outstanding performance in terms of control accuracy.

1. Introduction

Electro-hydraulic servo valves are prone to faults such as nozzle blockage, spring tube fracture, howling and other faults during operation, making it difficult to meet the development needs of high reliability and long service life [1,2]. The use of high-speed on/off valve (HSV) as pilot-driven digital proportional valves, which can completely replace the nozzle-flapper structure in traditional electro-hydraulic servo valves, fundamentally mitigates the risk of failure in key components. This has become an important research hotspot in the field of hydraulic transmission and control [3,4]. However, due to the use of a HSV for periodic on/off control in the pilot stage, the discrete flow output characteristics can easily lead to high-frequency oscillations in the steady-state displacement of the main valve spool [5,6]. This reduces the control accuracy of the main valve spool and makes it challenging to meet the technical requirements of a high-precision digital drive system. Therefore, enhancing the steady-state accuracy of spool displacement in digital proportional valves, so that their control performance meets or even surpasses that of traditional high-performance electro-hydraulic proportional valves, has become a critical challenge in the field of hydraulic transmission and control.

Currently, research on digital proportional valve spool displacement control strategies is categorized by the number of spools into single-spool, double-spool, and four-spool configurations. For the single spool structure, Danfoss first realized the precise control of the main spool displacement through a full-bridge hydraulic damping circuit composed of four high-speed on/off valves [7]. On this basis, Qiang Gao et al. proposed a two-stage electro-hydraulic proportional valve with 'B - B' type hydraulic full-bridge pilot regulation and designed a differential pulse width modulation (PWM) controller, a model-free sliding

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* Corresponding author.
E-mail addresses: liyiming_3138@nuaa.edu.cn (L. Li), nuaawangyw@nuaa.edu.cn (Y. Wang), meeyczhu@nuaa.edu.cn (Y. Zhu), meejling@nuaa.edu.cn (J. Ling).

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mode controller and a model-based sliding mode controller [4,8,9]. Experimental results demonstrate that the model-based sliding mode controller offers the best tracking performance, with a steady-state error of 0.16 mm in the main spool displacement. In 2024, Qiming Liu et al. studied the impact of pilot stage control frequency on the control accuracy of the main valve by simulations. The results show that as the pilot drive frequency increases, the steady-state error of the main spool decreases from 0.017 mm to 0.014 mm [10]. Also in 2024, Li Nana et al. developed a fuzzy PID control strategy based on the Danfoss PVG configuration. Simulation results show that the steady-state error of the spool is reduced from 0.243 mm to 0.016 mm [11]. Furthermore, Hao Wang et al. proposed a high-pressure, large-flow water hydraulic proportional flow valve controlled by two high-speed on/off valves and applied a traditional PID control strategy to the spool displacement control in 2025. Experimental results demonstrate that the steady-state displacement error of the flow valve is only 0.18 mm [12,13].

Research on the dual-spool digital proportional valve dates back to the ZTS16 series multi-way valve proposed by Eaton [14–16]. On this basis, Zhao Ruilong et al. proposed to use two two-position three-way pilot valves to independently control two main spool configurations, and put forward an adaptive robust control strategy to address the influence of nonlinearity and unmodeled factors in the digital proportional valve [17–19]. The experimental results show that the steady-state error of the spool displacement is about 0.7 mm after applying this strategy. Zhongqi et al. used four two-position three-way HSVs as pilot valves to drive two three-position three-way main valve [20–23]. A PWM drive strategy based on fuzzy PID control of spool displacement feedback was proposed, which achieved a spool displacement control accuracy of 0.36 mm. For the four-spool digital proportional valve, Yinshui Liu and Liejiang Wei et al. used four groups of proportional valves with unilateral throttling function to form a water pressure digital proportional valve. The main spool displacement control error was controlled within 0.13 mm by PID control [24–26].

In summary, the experimental displacement accuracy of the digital proportional valve is only 0.1 mm, which is difficult to meet the high-precision control requirements. The issue arises from two aspects: structurally, the dynamic response of the pilot-stage HSV is insufficient, and the high-frequency PWM drive cannot effectively suppress flow fluctuations and pressure pulses; in terms of control, the existing method regulates the pilot pressure by adjusting the PWM duty cycle, which causes the HSV to operate only in fully open or fully closed states, resulting in fixed flow resolution and significant nonlinearity at low duty cycles. Thus, structural and control optimization is imperative to overcome these limitations and facilitate the application and development of digital proportional valves in high-precision control scenarios.

This study addresses the challenges of insufficient dynamic response, non-adjustable flow resolution, and poor control accuracy of the main valve when traditional electromagnetic high-speed on/off valve (EHSV) is employed as digital pilot stages [27,28]. A new type of digital piezoelectric proportional valve (DPPV) with B-B full bridge hydraulic circuit constructed by piezoelectric high speed on/off valve (PHSV) as the pilot stage is proposed. Furthermore, combined with the linear output characteristics of piezoelectric stack,a PID control strategy based on Pulse Width Modulation and pulse amplitude modulation (PWM-PAM) cooperative control is proposed. Based on the structural design, working principle analysis and mathematical modeling of the DPPV, the influence of key parameters is investigated by simulation, and the feasibility of the proposed control algorithm is validated. An experimental prototype is developed and a hydraulic test system is established. Three sets of sinusoidal displacement tracking experiments are conducted. Compared with existing digital proportional valve driven by EHSV in terms of spool displacement control performance, the results further validate the technical advantages and superiority of the DPPV and its control strategy proposed in this study.

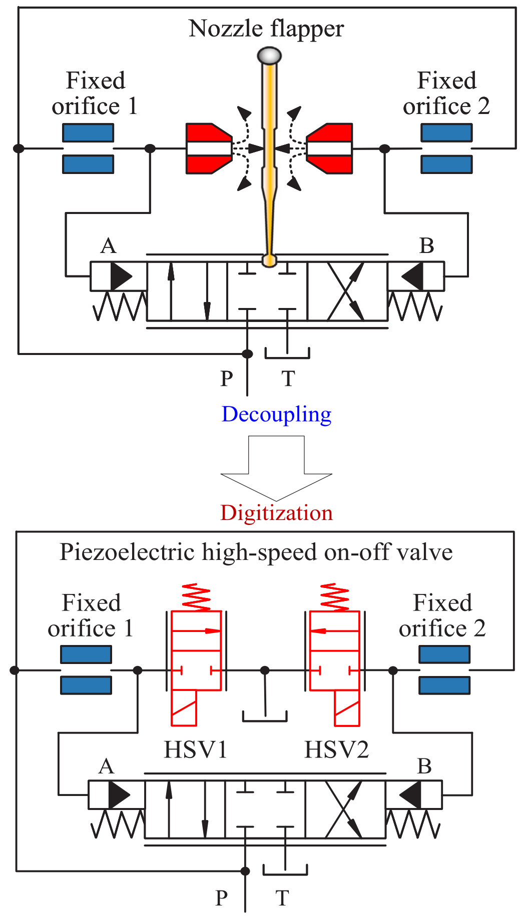


Fig. 1. The schematic diagram of digital piezoelectric proportional valve structure principle.

The remainder of this article is organized as follows. In Section 1, describes the working principles and structural design of the DPPV. In Section 2 and Section 3, the nonlinear mathematical model and characteristic analysis of the proposed DPPV are demonstrated respectively. The PID control strategy based on PWM-PAM coordinated control is designed and discussed in Section 4. The experimental investigations are presented in Section 5. Section 6 summarizes the key conclusions of this study.

2. The structure and working principle

In this paper, with reference to the double nozzle flapper valve, a B-B full bridge hydraulic resistance circuit is selected as the pilot stage configuration of the two stage electro-hydraulic servo valve. Two normally closed PHSVs are used to replace the variable nozzle flapper to form a DPPV. The structure principle is shown in Figs. 1 and 2.

As shown in Figs. 1 and 2, the working principle of the DPPV is as follows. When both sides of the PHSVs HSV1 and HSV2 are not energized, the pilot hydraulic oil is connected to the left and right control cavities of the three-position four-way main valve through two fixed orifices respectively. The pressure of the two control cavities is equal, and the main valve is guaranteed to be in the middle state. When the left PHSV HSV1 is energized alone, the pressure of the left control chamber of the main valve decreases, and the main valve moves to the left. Conversely, when the right PHSV HSV2 is energized alone, the pressure of the right control chamber of the main valve decreases, and the main valve moves to the right. By adjusting the duty cycle of the left and right PHSVs, the position servo control of the main valve can be realized.

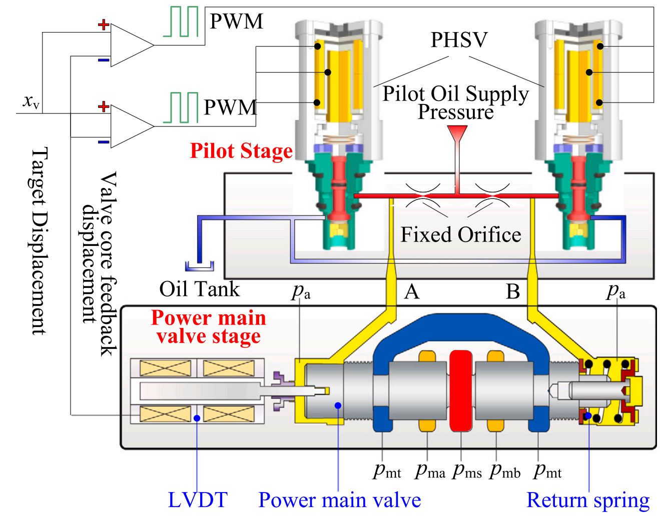


Fig. 2. Schematic diagram of the main valve spool structure of power.

3. Mathematical modeling

3.1. Pilot stage

The pilot stage of the DDPV mainly consists of two fixed orifices and twoPHSVs. The flow equations of the two fixed orifices are:

$$Q_{j1} = C_j A_j \sqrt{\frac{2(p_s - p_a)}{\rho}} = C_j \frac{\pi D_j^2}{4} \sqrt{\frac{2(p_s - p_a)}{\rho}} \tag{1}$$

$$Q_{j2} = C_j A_j \sqrt{\frac{2(p_s - p_b)}{\rho}} = C_j \frac{\pi D_j^2}{4} \sqrt{\frac{2(p_s - p_b)}{\rho}} \tag{2}$$

where D_j, A_j and C_j are the diameter, flow area and flow coefficient of the fixed orifice, respectively. p_s is the pilot stage oil supply pressure, p_a and p_b are the left and right control chamber pressures of the main valve stage.

The flow equations for the piezoelectric high-speed on/off valves HSV1 and HSV2 are:

$$Q_{h1} = C_d A_p \sqrt{\frac{2p_a}{\rho}} \tag{3}$$

$$Q_{h2} = C_d A_p \sqrt{\frac{2p_b}{\rho}} \tag{4}$$

where C_d and A_p are the flow coefficient and flow area of the PHSV, respectively, and the mathematical formula of the flow area A_p is referred to [29].

Neglecting the leakage of the main valve, taking the main valve $x_v > 0$ moving to the right as an example, the pressure in the left and right control chambers of the main valve can be expressed as:

$$\frac{dp_a}{dt} = \frac{\beta_e}{V_m + A_m x_m}\left((Q_{j1} - Q_{h1}) - A_m \frac{dx_m}{dt}\right) \tag{5}$$

$$\frac{dp_b}{dt} = \frac{\beta_e}{V_m - A_m x_m}\left(A_m \frac{dx_m}{dt} - (Q_{h2} - Q_{j2})\right) \tag{6}$$

where V_m is the initial volume of the control chamber when the main spool is in the middle position, A_m and x_m are the area and displacement of the left and right end faces of the main spool, respectively. β_e is the elastic modulus of the oil.

3.2. Power main valve stage

In this paper, the main valve of the Hengli Hydraulic 4WRKE10E100L type pilot-operated proportional valve is used as the main valve of the DPPV. The main valve adopts a three-position four-way slide valve, which is mainly composed of the power main valve, return spring and linear variable displacement transducer (LVDT) displacement sensor. The structure is shown in Fig. 2. The dynamic equation of the main valve is:

Table 1
The parameters of the digital piezoelectric proportional valve simulation model.

Name	Symbol	Value
The flow coefficient of fixed orifice	C_j	0.7
The diameter of the fixed orifice/mm	D_j	0.8
The initial volume of the control chamber/mm³	V_m	3750
Effective cross-sectional area of main valve/mm²	A_m	200
Equivalent mass of main valve/kg	m_m	0.2
Viscous damping coefficient/N/(m/s)	B_m	17.6
Spring stiffness/N/mm	k_m	50
Pre-tightening force of centering spring/N	F_{mp}	50
Friction/N	F_{mc}	8

$$m_m \ddot{x}_m = (p_a - p_b)A_m - k_m x_m - F_{mp} - B_m \dot{x}_m - F_{mc} - F_{ms} \tag{7}$$

where m_m and B_m represent the equivalent mass and viscous damping coefficient of the main valve, respectively, k_m and F_{mp} are the stiffness and initial preload of the centering spring respectively, F_{mc} and F_{ms} are the friction force and the steady-state hydrodynamic force of the main valve respectively.

The steady-state fluid force on the main valve can be expressed as:

$$F_{ms} = 2nC_{mv}C_{md}A_k \Delta p_k \cos\theta_m \tag{8}$$

where C_{mv} is the flow velocity coefficient of the U-shaped valve port, and θ_m is the jet angle of the valve port.

4. Analysis of influencing factors

4.1. Design of PID control strategy based on differential PWM

The stability error of DPPV is affected by the interaction of several parameters, including the PWM operating frequency, fixed orifice diameter, driving voltage of PHSV and pilot stage oil supply pressure. Revealing the action law of these key parameters can provide a theoretical basis for the design of subsequent control strategies.

This study uses a PID control strategy based on differential (PWM) to realize the control of the spool displacement of the DPPV. The actual duty cycles τ_1 and τ_2 of the piezoelectric high-speed on/off valves HSV1 and HSV2 are respectively:

$$\tau_1 = \tau_{10} - \tau \tag{9}$$

$$\tau_2 = \tau_{20} + \tau \tag{10}$$

where τ is the duty cycle control signal, τ_{10} and τ_{20} are the initial duty cycle signals of HSV1 and HSV2, respectively. Ideally, $\tau_{10} = \tau_{20} = 0$. The PID controller is introduced into the closed-loop control of the spool displacement, and the control duty cycle τ is expressed as:

$$\tau = k_p e(k) + k_i \sum_{i=0}^{k} e(i) + k_d[e(k) - e(k-1)] \tag{11}$$

where k_p, k_i and k_d are PID controller parameters, and e is the position error of the main valve.

4.2. Simulation modeling

Combined with the mathematical model of the DPPV and the PID control strategy, the simulation model of the DPPV is constructed by MATLAB. The simulation model of DPPV is shown in Fig. 3. The main parameters are shown in Table 1.

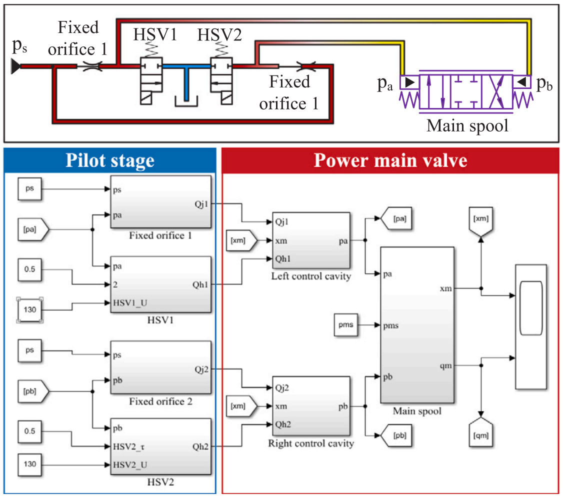


Fig. 3. The simulation model of digital piezoelectric proportional valve.

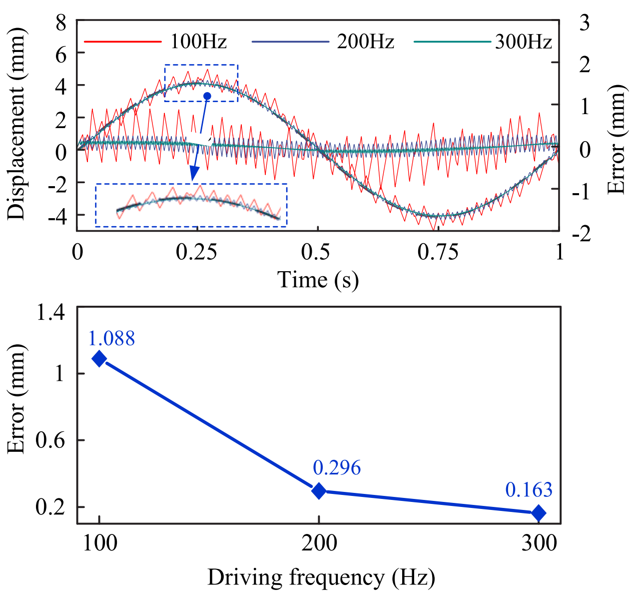


Fig. 4. The influence of different frequency PWM on the position control accuracy of the main valve.

4.3. Performance analysis

In the simulation model, the initial duty cycle τ_{10} and τ_{20} of the PHSVs are set to 0.5, the PWM operating frequency is 200 Hz, the driving voltage of the PHSV is 130 V, and the pilot stage oil supply pressure is 4 MPa. The parameters of the PID controller are identified by the MATLAB parameter estimation toolbox, where k_p = 2300, k_i = 3000, k_d = 0.

4.3.1. The operating frequency of PWM

In this study, according to the operating characteristics of the PHSV, the tracking characteristics of the main spool displacement under three PWM operating frequencies of 100 Hz, 200 Hz, and 300 Hz are compared and analyzed. The simulation results are shown in Fig. 4.

As can be seen from Fig. 4, the displacement control error is reduced from 1.088 mm at 100 Hz to 0.163 mm at 300 Hz. However, when the frequency continues to rise, the reduction of displacement control error gradually slows down, and the improvement effect of control accuracy tends to be saturated. Therefore, there are limitations in the method of further improving the accuracy of spool displacement control by simply increasing the driving frequency of PHSV.

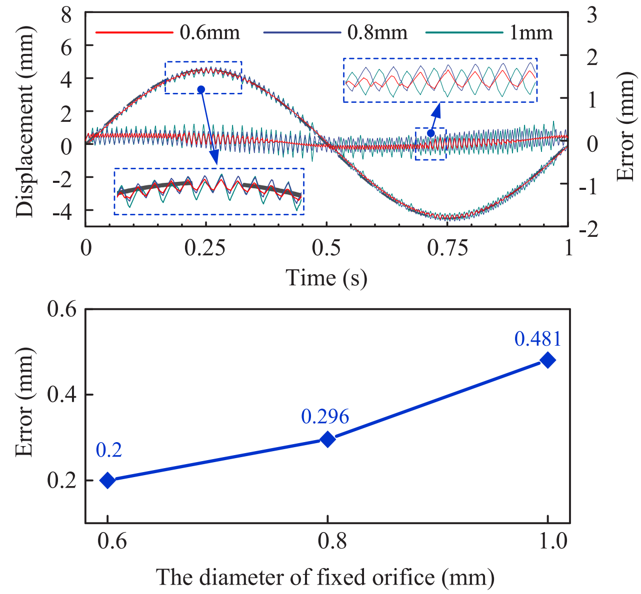


Fig. 5. The influence of fixed orifice diameter on the position control accuracy of the main valve.

4.3.2. The diameter of fixed orifice

The fixed orifice is an important part of the pilot stage of the DPPV, which directly affects the pressure gain of the pilot stage. In this study, on the basis of the existing fixed orifice dimension, the influence of three fixed orifice diameters of 0.6 mm, 0.8 mm and 1 mm on the control accuracy of the main valve position is explored. The simulation results are shown in Fig. 5.

From Fig. 5, as the diameter of the fixed orifice increases, the tracking error of the main valve gradually increases, rising from 0.200 mm at 0.6 mm to 0.481 mm at 1.0 mm. This is because the increase in the diameter of the fixed orifice causes an increase in the pilot stage pressure gain, but the damping characteristics of the main valve remain unchanged, making the system more sensitive to disturbances and parameter variations.

4.3.3. The driving voltage of DPPV

Considering the operating voltage range of the piezoelectric stack material, the influence laws of three driving voltages (70 V, 100 V, and 130 V) on the position control accuracy of the main valve are compared and analyzed. The simulation results of different driving voltages on the position control accuracy of the main valve are shown in Fig. 6.

As can be seen from Fig. 6, the control error of the main spool position is positively correlated with the driving voltage of the PHSV. The displacement error of the spool increases from 0.193 mm of the driving voltage of 70 V to 0.296 mm of 130 V, and the control accuracy is reduced by 53.3%. However, the pressure gain of the pilot stage decreases with the decrease of the driving voltage, which affects the dynamic response speed of the main valve.

4.3.4. The supply pressure of pilot stage

The oil supply pressure of the pilot stage is one of the key parameters of the DPPV, which directly affects the pressure gain of the pilot stage and the dynamic response speed of the main valve. In this study, considering the requirement of the main spool operation on the pilot supply pressure the pilot stage oil supply pressure is set to 2 MPa, 3 MPa, and 4 MPa, respectively.

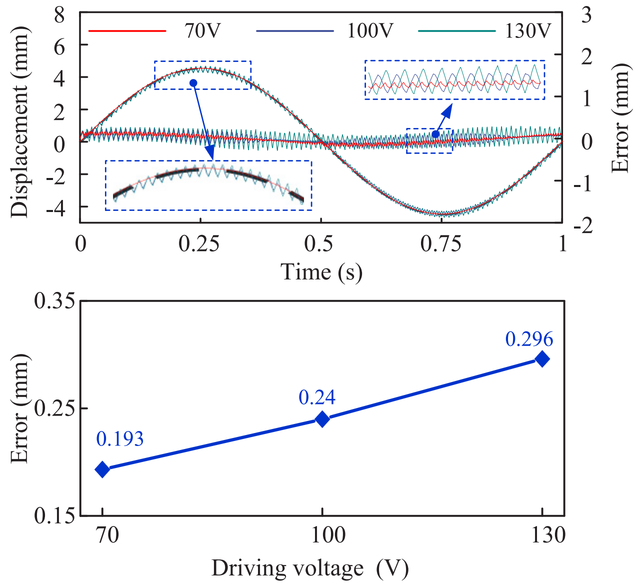


Fig. 6. The influence of different driving voltages on the position control accuracy of the main valve.

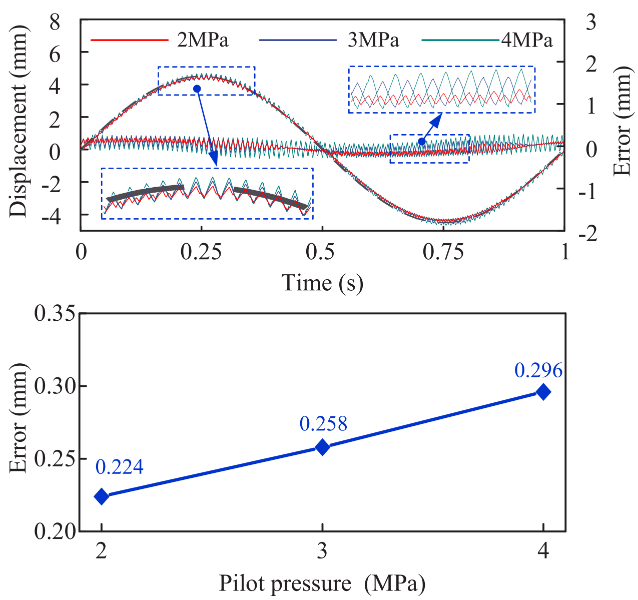


Fig. 7. The influence of different pilot stage oil supply pressure on the position control accuracy of the main valve.

The displacement tracking results of the main valve are shown in Fig. 7. It can be seen from the figure that with the increase of the pilot stage oil supply pressure, the position control error of the main valve increases approximately linearly, from 0.224 mm at 2 MPa to 0.296 mm at 4 MPa. The reason for this phenomenon is similar to that of the fixed orifice: the pilot pressure gain becomes larger, but the inherent damping of the system remains unchanged, which makes the main valve displacement control more sensitive to external interference.

Through the above simulation analysis, it can be seen that the four parameters of PWM operating frequency, fixed orifice diameter, driving voltage and pilot stage oil supply pressure constitute a multi-dimensional coupling system, which has a significant impact on the static displacement control accuracy of DPPV. Therefore, the high-precision adjustment of the main valve displacement can be achieved

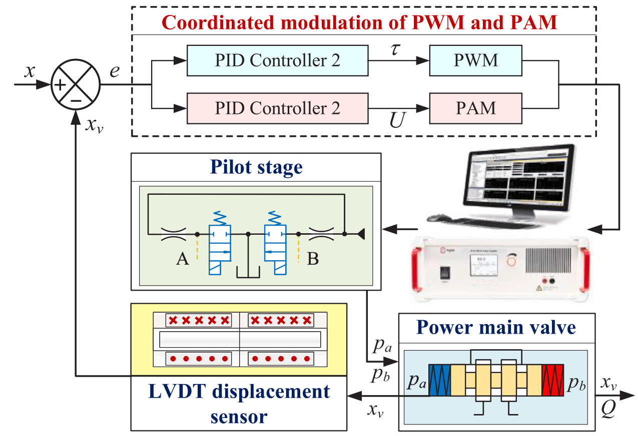


Fig. 8. The principal diagram of PID compound control strategy based on PWM - PAM cooperative modulation.

by reasonably optimizing and coordinating the above key parameters (such as the driving voltage of the PHSV).

5. The intelligent drive control of main valve

5.1. PID control strategy based on PWM – PAM coordinated regulation

In this study, considering the characteristics of PWM discrete control of PHSV and continuous flow regulation control of PAM, a ‘digital’ + ‘analog’ PID composite control strategy based on PWM-PAM cooperative modulation (abbreviated as: PWM-PAM control) is proposed. The purpose is to control the pressure gain and flow resolution of the pilot stage by adjusting the amplitude and duty cycle of the driving voltage of the DPPV [30,31]. The specific working principle is as follows: When the position error of the main valve is small, the flow resolution is improved by reducing the duty cycle and output amplitude of the control signal. On the contrary, when the position error of the main valve is large, the high flow gain is achieved by increasing the duty cycle and output amplitude of the control signal. The principle of PID compound control strategy based on PWM-PAM coordinated modulation is shown in Fig. 8.

As can be seen from Fig. 8, the PID compound control strategy based on PWM-PAM cooperative modulation includes two PID controllers. Among them, PID controller 1 adjusts the PWM signal duty cycle τ according to the displacement error e; PID controller 2 adjusts the driving voltage U of the piezoelectric high-speed on/off valve according to the displacement error e, that is, changes the PWM signal amplitude.

The control signals of the PHSVs HSV1 and HSV2 are in differential form, which can be expressed as:

$$\tau_1 = \tau_{10} - \tau \tag{12}$$

$$U_1 = U_{10} - U \tag{13}$$

$$\tau_2 = \tau_{20} + \tau \tag{14}$$

$$U_2 = U_{20} + U \tag{15}$$

where τ_{10} and τ_{20} are the initial duty cycle of the PWM signal of the PHSV, and their values are both 0.5; U_{10} and U_{20} are the initial driving voltage of the PHSV, both of which are 65 V.

5.2. Analysis of simulation results

The simulation model of PID composite control strategy based on PWM-PAM cooperative modulation is built by Matlab / Simulink, as shown in Fig. 9. Within the preset range of PID parameters, the PID parameters of the PWM and PAM controllers are tuned using the

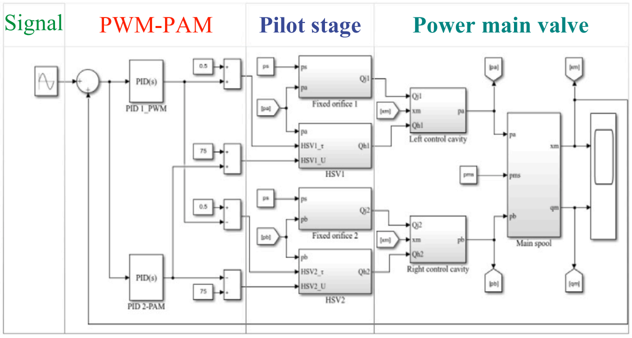


Fig. 9. The simulation model of PID composite control strategy based on PWM - PAM cooperative modulation.

Table 2
Performance indicators of sinusoidal displacement tracking under Condition one.

Controller type	M_e (mm)	μ (mm)	σ (mm)
PID	0.306	0.117	0.071
PWM-PAM	0.119	0.025	0.017

Control System Tuner in MATLAB, with the optimization objective of minimizing the steady-state error of the spool displacement. Finally, the parameters of PID controller 1 are $k_p = 3800$, $k_i = 10000$, $k_d = 0$. For PID controller 2, the parameters of PID controller 2 are $k_p = 200000$, $k_i = 1100000$, and $k_d = 0$. Additionally, to accurately evaluate the control performance of the controller, the maximum error M_e, the average error μ and the standard deviation of the error σ are used as the evaluation indexes to measure the performance of the controller.

In order to verify the feasibility of the control strategy proposed in this paper, this study explores the displacement tracking effect of the DPPV under $x_d = 4.5\sin(\pi t)$ and $x_d = 4.5\sin(3\pi t)$ conditions.

Condition 1: The main valve tracks a sinusoidal displacement trajectory with an amplitude of 4.5 mm and a frequency of 0.5 Hz, whose mathematical expression is $x = 4.5\sin(\pi t)$. Fig. 10 and Table 2 show the simulation results under different control strategies.

From Fig. 10 and Table 2, it can be clearly seen that the displacement tracking error shows a periodic fluctuation. Compared with the traditional PID control strategy, the displacement tracking error of the main spool driven by the proposed control strategy is significantly reduced. the maximum error M_e, average error μ and standard error σ of the main spool are reduced by 61.1%, 78.6% and 76.1%, respectively. The reason for this phenomenon is that the control strategy proposed in this paper can adjust the output displacement of the PHSV according to the displacement error signal of the valve spool, so as to achieve large error and large flow gain, small error and high flow resolution.

Condition 2: The main valve tracks a sinusoidal displacement trajectory with an amplitude of 4.5 mm and a frequency of 1.5 Hz, whose mathematical expression is $x = 4.5\sin(3\pi t)$. The simulation results of the two controllers for this sinusoidal displacement trajectory are compared as shown in Fig. 11.

From Fig. 11 and Table 3,compared with the PID controller, the PWM-PAM controller shows obvious advantages in the control accuracy of the main spool. Specifically, the maximum error, average error and standard error of the main spool under the control of PWM-PAM controller are 0.142 mm, 0.048 mm and 0.028 mm, respectively. The results of this simulation strongly further validate the feasibility and effectiveness of the proposed control strategy.

6. Experimental studies and results

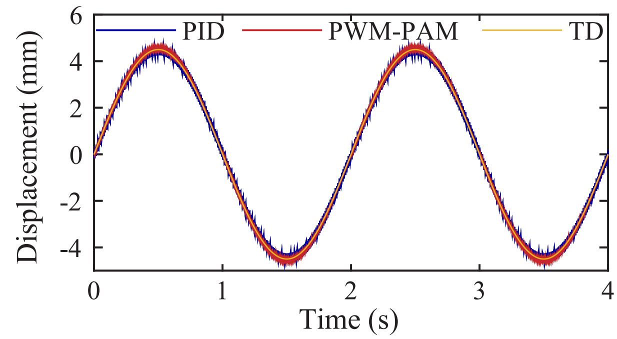
To verify the effectiveness of the PID composite control strategy based on PWM-PAM comodulation proposed in this paper, The DDPV experimental test system with pilot control of PHSV is built, as shown in Fig. 12. The experimental system is mainly composed of three parts: hardware-in-the-loop simulation system, the hydraulic power pack and the DPPV.

(1) The hardware-in-the-loop simulation system is composed of a real-time control system (Box-03 device developed by Beijing Lingsi Chuangqi Technology Co., Ltd) and a power amplifier (Aigtek ATA-P2010), which is used for signal acquisition, output and power amplification with a magnification factor of 16.

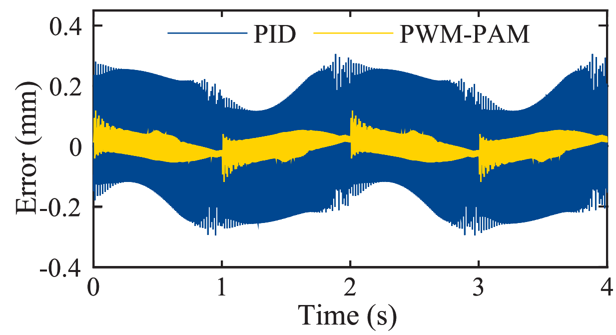
(2) The hydraulic power pack is composed of hydraulic pump, filter, relief valve, accumulator and throttle valve. Its rated flow are 8L/min@10MPa.

(3) The DDPV is mainly composed of PHSV, fixed orifice, pilot stage oil circuit block, three-position four-way slide valve (Hengli Hydraulic 4WRKE10E100L proportional directional valve main valve stage) with LVDT. Among them, the three piezoelectric stacks of the PHSV are driven in parallel by a power amplifier. The main parameters of the experimental setup are listed in Table 4.

In order to fully and scientifically compare the effectiveness of each control strategy, the PID parameters adopted in this section are consistent with those obtained from the simulation in the previous section. This section conducts experiments on three working conditions, involving the sinusoidal position tracking of the main valve with variable amplitude and variable frequency.



(a) Displacement under different control strategies

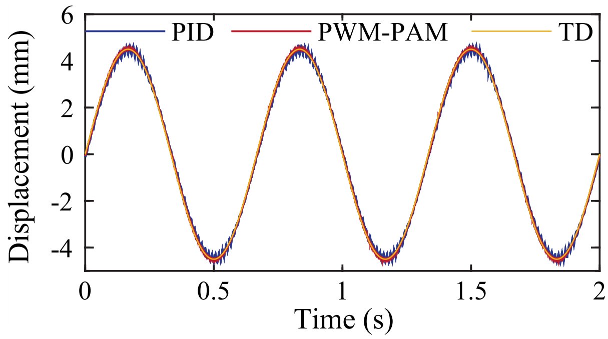


(b) Displacement error under different control strategies

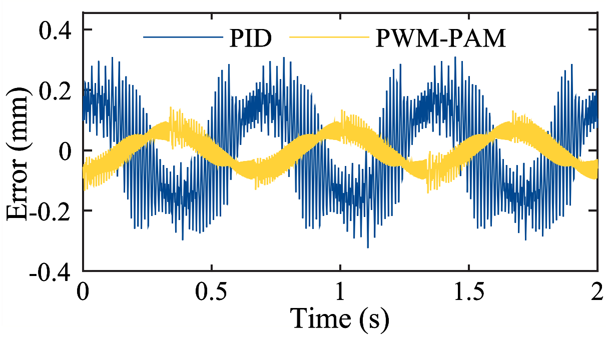
Fig. 10. Simulation results of displacement control of DPPV under different control strategies. (Condition 1: $x = 4.5\sin(\pi t)$, PID: PID control strategy based on differential PWM, PWM-PAM: PID composite control strategy based on PWM-PAM cooperative modulation).

Table 3
Performance indicators of sinusoidal displacement tracking under Condition two.

Controller type	M_e (mm)	μ (mm)	σ (mm)
PID	0.325	0.129	0.085
PWM-PAM	0.142	0.048	0.028



(a) Displacement under different control strategies



(b) Displacement error under different control strategies

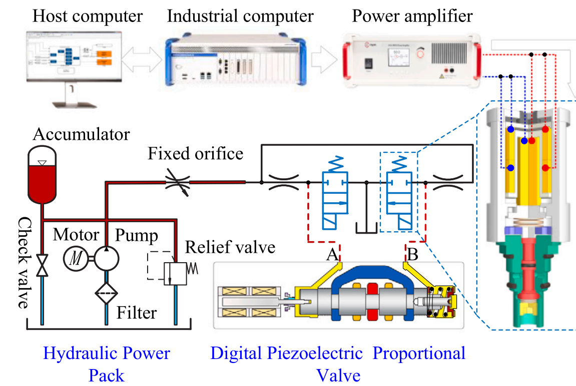
Fig. 11. Simulation results of displacement control of DPPV under different control strategies. (Condition 2: $x = 4.5\sin(3\pi t)$, PID: PID control strategy based on differential PWM, PWM-PAM: PID composite control strategy based on PWM-PAM cooperative modulation, TD: target displacement).

Table 4
Main parameters of experimental.

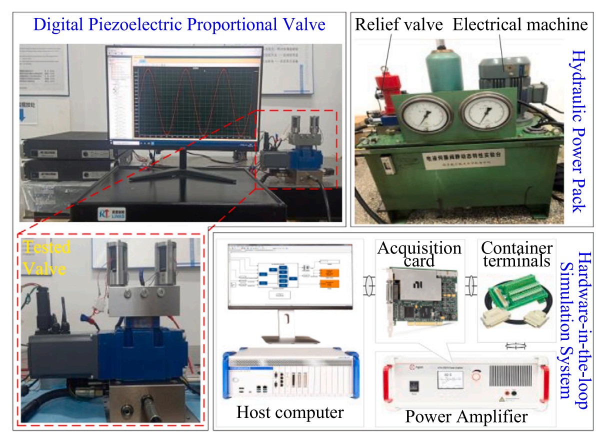
Name	Parameter	Valve
Pump station	Pressure (Max)	10MPa
	Flow (Max)	8L/min
Pressure sensor	Test specification	0 ~ 10MPa
	Test accuracy	± 0.5%
	Sampling frequency	100000 Hz
LVDT	Test specification	± 7.5 mm
	Test accuracy	± 0.5%
	Sampling frequency	500 Hz
Power amplifier	Amplification gain	16
Hardware-in-the-loop simulation system	Sampling frequency	20000 Hz

Condition 1: The main valve tracks a sinusoidal position signal with an amplitude of 4.5 mm and a frequency of 0.5 Hz. The experimental comparison results of the two controllers are shown in Fig. 13. It can be seen from Figs. 13(a) and 16 that similar to the simulation results, the maximum tracking errors for both control strategies occur near the peak and valley points of the main valve target position signal. Furthermore, under the PWM-PAM controller, the maximum error (M_e), average error (μ), and standard error (σ) of the main valve tracking are 0.135 mm, 0.047 mm, and 0.031 mm, respectively. Compared to the PID control strategy, these errors are reduced by 58.2%, 59.5%, and 55.1%, respectively.

From Fig. 13(b), it can be further observed that, compared with traditional PID control, the PWM-PAM controller adjusts the duty cycle and driving amplitude of control valves 1 and 2 in real time according to the control error. During a complete displacement tracking period, the maximum output amplitudes of control valves 1 and 2 reach 6.2 V (the resultant driving voltage is 99 V) and 7.0 V (the resultant driving voltage is 112 V), respectively. The synergistic regulation of duty cycle and amplitude effectively improves the flow resolution of the pilot stage, serving as a key enabler of high-precision position control for the valve spool.



(a) the experimental principle of the test bench



(b) the physical diagram of the test bench

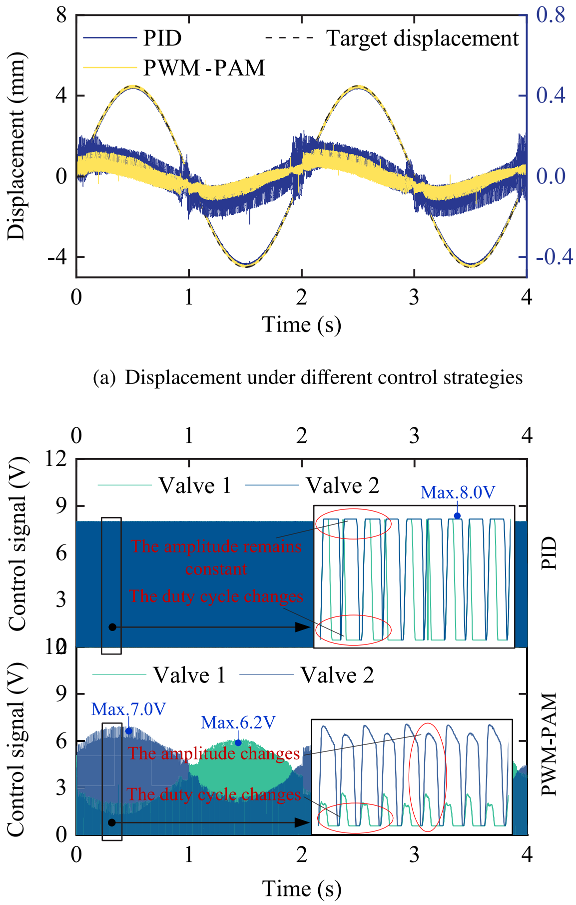
Fig. 12. The experimental test system of digital piezoelectric proportional valve.

Condition 2: The sinusoidal position signal with the main valve tracking amplitude of 4.5 mm and the frequency of 1.5 Hz, $x = 4.5\sin(3\pi t)$. The experimental comparison results of the two controllers are shown in Fig. 14.

As shown in Figs. 14(a) and 16, compared with condition 1, the fluctuation of spool displacement tracking error increases. This is primarily due to the insufficient dynamic response capability of the pilot-stage HSV, which struggles to provide the necessary pressure gain for high-frequency spool motion. Nevertheless, the PWM-PAM control strategy still exhibits effective control performance, with the maximum error (M_e), average error (μ), and standard error (σ) of the main valve tracking being 0.243 mm, 0.068 mm, and 0.046 mm, respectively. Compared with the PID control strategy, these errors are reduced by 30%, 40.9%, and 40.3%, respectively.

As shown in Fig. 14(b), under the PWM-PAM control strategy, the maximum control signal amplitudes for pilot-stage control valves 1 and 2 occur at the trough and peak of the displacement signal, reaching 6.7 V (the resultant driving voltage is 107 V) and 8.0 V (the resultant driving voltage is 128 V), respectively. These values are higher than those of Valve 1 and Valve 2 in Working Condition 1. The reason for this phenomenon is to improve the output capacity of the PHSV by increasing the amplitude of the control signal, so as to meet the demand of the main valve for dynamic response performance.

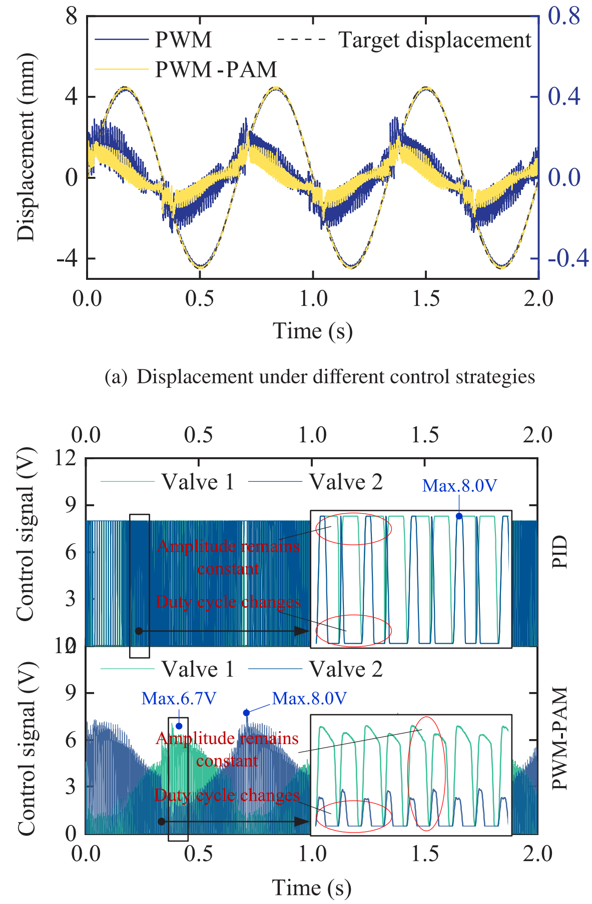
Condition 3: The sinusoidal position signal with the main valve tracking amplitude of 3 mm and the frequency of 1.5 Hz, $x = 3_{\sin}(3\pi t)$.



(a) Displacement under different control strategies

(b) Control signal of pilot stage control valve

Fig. 13. Experiment results of displacement control of DPPV under different control strategies (Condition 1: $x = 4.5\sin(\pi t)$, PID: PID control strategy based on differential PWM, PWM-PAM: PID composite control strategy based on PWM-PAM cooperative modulation, TD: target displacement).



(a) Displacement under different control strategies

(b) Control signal of pilot stage control valve

Fig. 14. Experiment results of displacement control of DPPV under different control strategies (Condition 2: $x = 4.5\sin(3\pi t)$, PID: PID control strategy based on differential PWM, PWM-PAM: PID composite control strategy based on PWM-PAM cooperative modulation, TD: target displacement).

The experimental comparison results of the two controllers are shown in Fig. 15.

From Figs. 15 and 16, it can be observed that when the PWM-PAM control strategy is applied, the maximum error (M_e), average error (μ), and standard error (σ) of the spool main valve tracking are 0.154 mm, 0.048 mm and 0.032 mm, respectively. Compared with the PID control strategy, the maximum error, the average error and the standard error under the PWM-PAM control strategy are reduced by 54.3%, 60.6% and 58.9% respectively, which further verifies the superiority of the PWM-PAM control strategy. Additionally, the maximum control signal amplitudes for pilot-stage control valves 1 and 2 are 5.8 V (the resultant driving voltage is 93 V) and 6.7 V (the resultant driving voltage is 107 V), respectively. These values are lower than the control signal amplitudes for valves 1 and 2 in the Condition 2, but are close to the corresponding amplitudes in the Condition 1.

As shown in Fig. 17, the comparative analysis results between the PID composite control strategy based on PWM-PAM coordinated modulation and the digital proportional valve spool displacement control strategy proposed by Dr. Gao Qiang are illustrated [8]. The PID compound control strategy based on PWM-PAM coordinated modulation is adopted, which maximizes the advantages of high frequency response and high flow resolution of PHSV, and further improves the control accuracy of DPPV. The maximum error M_e, average error μ and standard error σ of the spool displacement tracking are increased by 71%, 40% and 71% respectively.

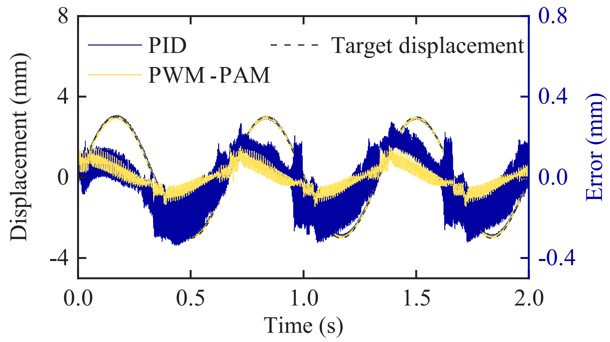
7. Conclusions

In this paper, a new type of digital piezoelectric proportional valve (DPPV) is proposed, which adopts a piezoelectric high speed on/off valve (PHSV) as the pilot stage to drive the main spool. A PID control strategy based on coordinated PWM and PAM regulation is proposed, effectively addressing the limitations of traditional digital electromagnetic proportional valves, such as the inability to adjust flow resolution at the pilot stage and the relatively low control accuracy of the main valve. It achieves the high precision control of the valve spool across the entire operating range.

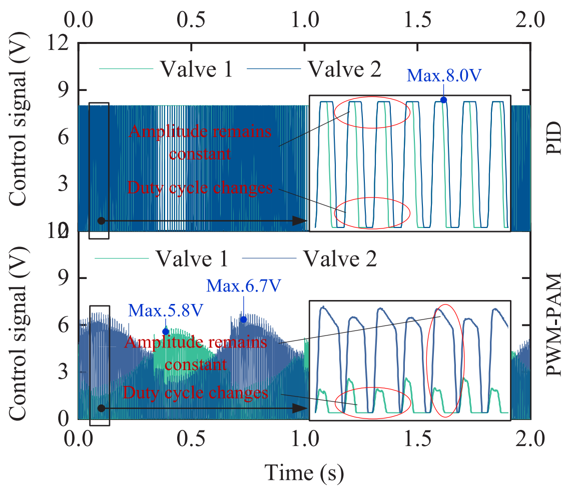
(1) Increasing the frequency of the PWM drive signal will significantly improve the displacement control accuracy of the DPPV. However, increasing the drive amplitude, supply pressure or the diameter of the fixed throttle hole will reduce the control performance of the main valve spool displacement.

(2) Compared with the traditional PID control strategy, the control strategy proposed in this paper can significantly improve the displacement control accuracy of the DPPV. The maximum error, average error and standard error of spool displacement tracking are reduced by 58.2%, 59.5% and 95.5%, respectively.

(3) Compared with the research from Nanjing University of Aeronautics and Astronautics, the control strategy proposed in this paper achieves a control accuracy of valve spool displacement at the 0.01 mm level, with the maximum error, average error, and standard error reduced by 71%, 40%, and 71%, respectively.



(a) Displacement under different control strategies



(b) Control signal of pilot stage control valve

Fig. 15. Experiment results of displacement control of DPPV under different control strategies (Condition 3: $x = 3\sin(3\pi t)$, PID: PID control strategy based on differential PWM, PWM-PAM: PID composite control strategy based on PWM-PAM cooperative modulation, TD: target displacement).

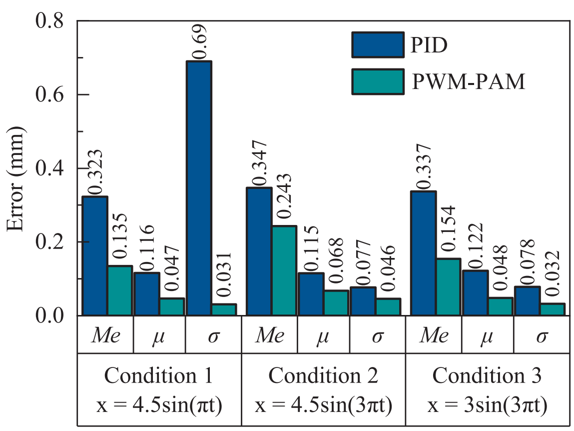


Fig. 16. Comparison results of spool displacement under different working conditions for two control strategies. (M_e: maximum error, τ: average error, σ: standard error).

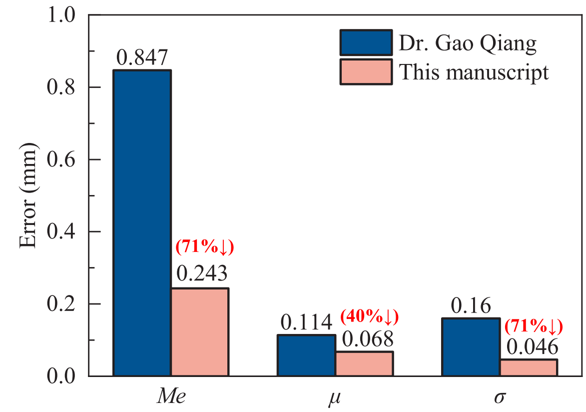


Fig. 17. Comparison results of control accuracy of valve spool displacement of digital proportional valves at home and abroad.

CRediT authorship contribution statement

Linfei Li: Writing – original draft, Software, Investigation. **Yuwen Wang:** Software, Methodology. **Yuchuan Zhu:** Writing – review & editing, Methodology, Funding acquisition. **Jie Ling:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The authors are unable or have chosen not to specify which data has been used.

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