Analysis of control characteristics of intelligent digital pump combined with discrete variables

Jinyan Shi and Kechang Zhang*

Hunan Railway Professional Technology College,
ZhuZhou, 412001, China
Email: shijinyan2008@126.com
Email: zhangkechang2008@163.com
*Corresponding author

Abstract: In order to improve the control effect and operation effect of intelligent digital pump, this paper analyses the control characteristics of intelligent digital pump with discrete variable method, and obtains the transfer function of the control system of digital pump through the establishment and analysis of mathematical model. The variable mechanism of digital pump can be simplified as a mechanical-hydraulic servo system in which two-sided slide valves control differential cylinders. The digital pump system based on discrete variable technology is a parallel digital discrete system, which is composed of digital pump and control valve group. The control valve logic topology relation is adopted to realise the combined control of displacement through coded signals. Moreover, the proposed control configuration can significantly improve the displacement control accuracy under the same number of control units, and then reduce the variable impact amplitude. Based on the experimental bench and loader prototype, the digital pump steering system and control strategy are tested and analysed, which verifies the feasibility of this method proposed by this paper.

Keywords: discrete change; intelligent digital pump; intelligent control; control characteristics.

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Biographical notes: Jinyan Shi received her BSc degrees in Machine Design and Automation from Lanzhou Jiaotong University, China, MSc degree in Drive Technology and Intelligent System from Southwest Jiaotong University, China. Currently, she is a Professor at Hunan Railway Professional Technical College, and she is a key young teacher in Hunan Province, China. Her research field of centres on CFD.

Kechang Zhang received his BSc degrees in Mould Design and Manufacture from Xiangtan University, China. Currently, he is an Associate Professor at Hunan Railway Professional Technical College, and he is a National Technical Experts in China. His research field of centres on machine design.

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1 Introduction

Generally speaking, hydraulic control can be divided into throttle control and volume control. Variable displacement pump is an indispensable part of volume control, which is divided into displacement regulation, constant pressure, constant current, compound regulation and other forms. The latter three categories belong to the control of output parameters, while the displacement adjustment belongs to the control of geometric parameters, which is the basis of other adjustment forms. Therefore, the variable mechanism of hydraulic variable displacement pump is essentially a position control system. Digital pump is a complex system engineering from research and development to production, and the traditional research is far from meeting the actual production needs. From this point of view, if we want to improve the control level of comb pump, we must start with the key theory and key technology of the pump.

The electro-hydraulic servo valve has undergone significant structural changes while retaining high precision, mostly driven directly by various motors or motors, fully utilising computer technology for control, reducing sensitivity to pollution, reducing manufacturing requirements, and accelerating response time; proportional valves are not sensitive to oil, with built-in circuits and sensors. The structural size is miniaturised, and the reliability is high. Some response times are already less than 10 ms; the high-speed on-off valve has high response speed, good energy-saving performance, and does not require a D/A conversion interface. As a new type of digital electro-hydraulic conversion control component, high-speed on/off valve is irreplaceable by other hydraulic control valves in certain situations due to its unique performance. For example, with the increasingly strict emission regulations for automotive diesel engines in various countries, how to achieve high-pressure injection in diesel engine fuel injection systems has become a hot research topic. To achieve high-pressure injection, it is necessary to have high-performance switching valves, especially in terms of response speed, which should be equal to or less than 1ms, and the opening should be at least 0.7 mm. To meet this requirement, non high-speed switching valves are no exception. In addition, in some application areas of traditional servo valves (such as vibration test benches in laboratories), due to the high requirements for oil cleanliness and the increasing difficulty of maintenance, it is also necessary to replace them with hydraulic control valves that meet the requirements. Therefore, this project chooses a high-speed on/off valve as the control element for the digital control axial variable piston pump.

In order to improve the control effect of intelligent digital pump, this paper analyses the control characteristics of intelligent digital pump with discrete variable method, which provides reference for the stability control and technical progress of intelligent digital pump in the future.

2 Related work

The main impression that electro-hydraulic servo valves give people is that they can achieve high control accuracy, but have poor pollution resistance and are expensive. This is related to the high requirements for the machining of electro-hydraulic servo valves. With the advancement of technology, there have been some gratifying changes in electro-hydraulic servo valves, which can make up for the shortcomings in processing level in certain aspects. In terms of anti pollution ability, the new type of electro-hydraulic servo valve adopts a brushless DC servo motor as the driving structure, which directly drives the slide valve of the servo valve, thereby controlling the flow and direction of the system. Not only is the structure simple and reliable, but its dynamic characteristics and control accuracy are also significantly better than traditional nozzle baffle two-stage electro-hydraulic servo valves (Sharma and Kumar, 2021). In this type of valve, the controller and driving amplifier are externally installed and connected to the servo motor on the valve body through cables, thus forming the servo valve system. In terms of design and manufacturing, the traditional ‘pilot stage’ (consisting of a nozzle, a baffle, and a filtering device) and complex assembly process have been removed. A position feedback sensor with built-in valve core positioning and a DC brushless servo motor directly driving the valve core structure have been adopted (Xu et al., 2021). Although this electro-hydraulic servo valve adopts a single-stage structure, it is different from early servo valves that are directly driven by proportional electromagnetic components. Instead, it uses a miniature brushless DC servo motor connected to an eccentric mechanism and a ball joint to drive the valve core to move in an axial straight line. It is equipped with a built-in angular displacement feedback sensor and advanced DSP control device, which optimises the control performance of the system, the entire servo valve system has achieved excellent bandwidth current servo and almost proportional control characteristics (Agostinelli et al., 2021). In the new type of electro-hydraulic servo valve, there is also an electro-hydraulic servo valve that uses a permanent magnet force motor as the driving device. The valve uses integrated circuits to achieve closed-loop control of the valve core position. The centring spring keeps the valve core in the centre position, and the linear force motor overcomes the centring force of the spring to make the valve core deviate from the centre position in both directions and balance in a new position, solving the problem of proportional electromagnetic coils being able to generate force in only one direction. The closed-loop control electronic circuit of the valve core position is solidified and integrated into blocks, which are fixed inside the electro-hydraulic servo valve using special connection technology (Smith and Beretta, 2021).

In terms of high flow and high response electro-hydraulic servo valves, there are mainly two structural forms. One is to use a force motor as the electro-mechanical conversion element, drive the controllable element in the form of a slide valve as the first stage valve, and then control another slide valve type second stage valve by the first stage valve. The displacement of the first and second stage slide valves is detected by sensors, and a two-stage displacement feedback closed-loop control system is formed through an electric controller (Orrù et al., 2020). This form of servo valve has the advantages of frequency bandwidth, large output flow, and strong anti pollution ability, but its application range is limited by the complex system structure, large volume, and expensive price. Another method is to use an ordinary nozzle baffle and a slide valve type force feedback two-stage electro-hydraulic servo valve as the pilot stage to control the third stage slide valve. The displacement of the third stage slide valve is detected by sensors and forms a displacement feedback closed-loop control system through an electric controller. This form of servo valve also has a wide frequency band and large output flow. Although its anti pollution ability is significantly lower than the previous one, its price is cheaper, its structure is relatively simple, and its range of use is wider than the previous one (Qin et al., 2021).

In hydraulic transmission systems, hydraulic pumps, as core components, can achieve the conversion of mechanical and hydraulic pressure energy. They play an important role in hydraulic transmission systems and affect the control performance of the entire hydraulic system. Therefore, construction machinery has increasingly high requirements for the control performance of hydraulic pumps, such as controllability of flow and power, large flow control range, good dynamic response, and constant power control close to the theoretical quadratic curve (Zheng et al., 2022). Hydraulic digital control refers to the main signal that controls the action of hydraulic transmission mechanisms, expressed in digital quantities during collection, processing, and calculation. Compared to general hydraulic control, the advantage of hydraulic digital control lies in the introduction of advanced controllers, optimisation of control algorithms, innovation of variable mechanisms, and improvement of control methods. It has the advantages of energy conservation, flexible control, and high degree of automation. It can solve the defects of analogue circuit components such as large hysteresis errors, temperature drift problems, weak anti-interference performance, and can also save energy and reduce consumption, apply advanced control algorithms showing superiority in improving dynamic response and other aspects. With the rapid development of the semiconductor industry, more and more research is tending towards digital transformation of variable displacement pumps, and hydraulic components will gradually shift from analogue to digital (Subeesh and Mehta, 2021). In the near future, CNC hydraulic control may become the mainstream of hydraulic control.

Control based on variable speed often uses an electric motor as the prime mover. With the rapid development of modern control theory, power electronics, and motor drive technology, the performance of asynchronous motor variable frequency speed regulation is no less than that of DC motor speed regulation systems, and the dynamic response index is even better than that of DC motors that require frequent maintenance (Liu et al., 2023). Compared with traditional variable mechanisms that rely on position changes to adjust the output flow or pressure of hydraulic pumps, digital pump variable mechanisms based on a combination of variable frequency control and hydraulic control are easier to introduce advanced control algorithms. This type of digital pump combines variable frequency speed regulation technology with the pump, replacing the traditional method of adjusting the output flow or pressure of variable displacement pumps based on changes in stator eccentricity or inclined plate angle, to achieve variable control (Kang and Lee, 2022).

A variable frequency digital pump based on adaptive control proposed in Palanica et al. (2020). The study uses a variable frequency motor as the actuator, and generates sine pulse width modulation signals (SPWM) of different frequencies through computer software to control the frequency converter to output corresponding sinusoidal AC power. By controlling the motor speed, the pump flow is controlled. At the same time, the outlet oil pressure and motor speed are fed back to the processor and compared with the given values, so that the pump flow and pressure change according to the set curve until the desired control indicators are achieved

Zekri et al. (2022) uses a 52 microcontroller and a stepper motor to form a control system. The user provides parameters, and the processor drives the screw nut based on the feedback data from the sensor, which in turn drives the valve core, changes the inclination angle of the oil distribution plate, and ultimately changes the displacement. It selects small motors to verify the functions of forward and reverse rotation, acceleration and deceleration, stop, etc. but in reality, larger stepper motors and drive modules need to be selected than this specification.

Al Tobi et al. (2021) used a combination of mechanical design and MATLAB dynamic simulation to study the digital variable pump variable mechanism based on microcontroller control. It has the characteristics of simple structure, precise control, and low cost, making the system more convenient for design and manufacturing; simple and compact structure; the design adopts a relatively simple slide valve structure, which is easy to manufacture and install. However, the study did not explain the working principle of the variable pump control system, only qualitatively stating that flow control can be carried out.

Al Tobi et al. (2022) uses a stepper motor to drive the movement of the guide rail to convert the motor rotation angle into the displacement of the guide rail. When the rated flow value is set in the processor and the variable pump is started, the microcomputer controls the stepper motor to work. The gear on the motor spindle drives the rack to move in the guide rail seat. The movement of the rack is driven by the linkage rod to quickly move the servo rod until the variable pump flow reaches the given value. The research installed the prototype on the variable pump of the extruder, which improved the overall production efficiency by one-third. However, the control system adopts an open-loop form, directly controlling the stepper motor according to the output flow requirements. When the stepper motor experiences a loss of step, it cannot be compensated, which can easily lead to accumulated errors and seriously affect accuracy.

Zhuge et al. (2023) adopts a high-speed on-off valve as the actuator, and its mechanical structure is to fix the proportional control mechanism of the high-speed on-off valve with the original servo rod that is adjusted by rotation, forming a variable pump controlled by pulse width modulation (PWM). D'Almeida et al. (2022) uses a high-speed on/off valve as a pilot control valve in a common variable servo mechanism, and controls the output of a constant pressure pump based on the pilot pressure. The high-speed switching valve can perform D/A conversion internally, and can directly receive digital signals to continuously control the output pressure of the variable pump, meeting the requirements of different loads on the working circuit oil pressure and output power under different working conditions.

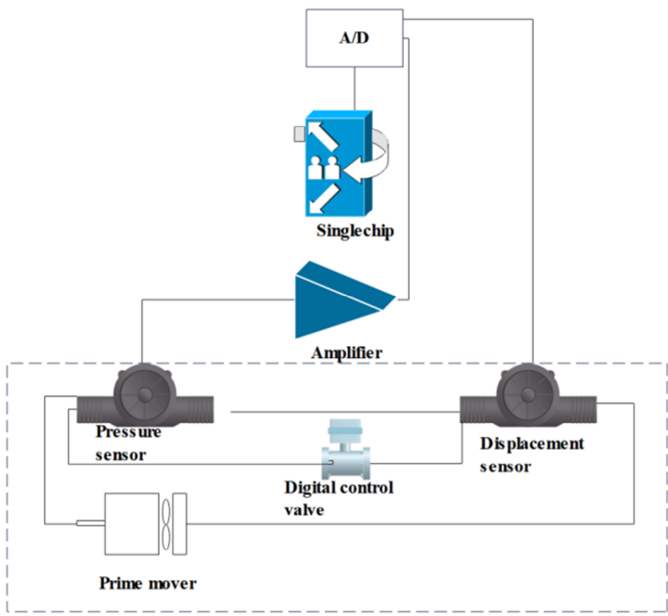
Nimri et al. (2020) established an accurate joint simulation model for the variable pump mechanism of a high-speed switching valve based on the upper computer software LabVIEW, finite element analysis software Maxwell, and hydraulic design simulation software AMESim. The static and dynamic performance was simulated and analysed, which can achieve pressure flow power composite control. The static performance of the digital pump was tested by building a digital pump test bench. This digital pump can achieve three control functions: pressure, flow, and power. These controls are more precise than the mechanical hydraulic type, and the static working curve obtained in the constant power stage is closer to the ideal hyperbolic curve. However, the study only conducted experimental research on static performance and did not conduct actual verification analysis on dynamic characteristics, including load step response dynamic characteristics and input signal step response dynamic characteristics

The key issue in the research of digital pump application technology is to quickly and accurately calculate the optimal combination of digital pump units based on load conditions and target states, improve pressure and flow stability, and achieve balanced control of energy consumption, pressure fluctuations, and the number of switching valves. The single point failure of traditional hydraulic systems often leads to the paralysis and failure of the entire system. The parallel digital hydraulic system achieves a parallel reliability structure by significantly increasing the number of components controlled in parallel. Studying fault-tolerant control methods for digital pump steering systems to ensure timely identification of faults and mode switching in the event of system failures is of great significance for protecting the personal and property safety of drivers and passengers.

3 Digital control

The schematic diagram of digital control axial piston pump is shown in Figure 1.

Figure 1 Schematic diagram of digital control axial piston pump (see online version for colours)



The output of hydraulic pump has two quantities, and one is pressure and the other is flow. The pressure is collected by the pressure sensor and sent to the single chip microcomputer after A/D conversion. The flow is collected by displacement sensor swashplate position signal of hydraulic pump after A/D conversion sent to single chip microcomputer, and then converted by single chip microcomputer. According to the preset variable curve of hydraulic pump, the single chip microcomputer processes and analyses the collected pressure and flow signals, and then outputs the control signal to the digital on-off valve, which controls the hydraulic oil entering the large end of the variable piston of hydraulic pump, so that the variable piston moves in the expected direction and changes the displacement of hydraulic pump and realises the required control. For the axial variable displacement piston pump circuit control system, there are mainly three parts: amplifier, pressure sensor and angular displacement sensor. Among them, amplifier is the most important part of the whole circuit system.

The amplifier mainly includes control signal generation, signal processing, preamplifier stage, power amplifier stage, measurement amplifier stage, feedback correction circuit, chatter signal generator and other basic units. The first is the signal generation, that is, the filtered signal is input into the amplifier through the signal generator. In order to meet the requirements of load and working conditions, it is necessary to process the input command signal after initial adjustment. Signal processing mainly includes adjusting the pressure gain, the lowest pressure, the pressure phase compensation, the pressure pulsation adjustment, the flow amplitude adjustment, the flow gain adjustment and the minimum flow adjustment. In the process of signal processing, we also need to measure, amplify and correct the feedback command signals of pressure sensor and angular displacement sensor. The processing of feedback signals mainly includes flow zero adjustment and gain adjustment of angular displacement sensor feedback signals and zero adjustment and gain adjustment of pressure sensor feedback signals. In the whole process of signal processing, it is necessary to use the regulator to adjust the signal. The regulator is a component unit of the electric feedback amplifier. Its function is to improve the steady-state and dynamic quality of the electric feedback dead-loop system, make the system stable and reach a certain control accuracy, suppress the interference and improve the dynamic characteristics. When the system has low pressure and small flow rate, the amplifier will compensate the feedback command signal, including the compensation of low pressure and small flow rate and the compensation of volumetric efficiency. In order to reduce the friction hysteresis of the proportional electromagnet and obtain the control current whose chatter component and amplitude can be independently adjusted, the command signal needs to be vibrated by the chatter signal generator, and the current signal after vibration processing can be directly input into the high-speed on-off valve (Syed et al., 2022).

The establishment of system mathematical model is the premise and foundation of analysing system performance. Through the establishment and analysis of mathematical model, the transfer function of digital pump control system is obtained. The variable mechanism of digital pump can be simplified as a mechanical-hydraulic servo system with bilateral slide valves controlling differential cylinders. Because the variable part of digital pump is a typical double-sided slide valve control hydraulic cylinder system, the valve control hydraulic cylinder part is mainly analysed. Flow control by the input signal of single chip microcomputer is the pulse signal sent by single chip microcomputer, which controls the high-speed on-off valve through amplification link, thus controlling the variable piston, and then controlling the swashplate swing angle, and controlling the liquid flow through the rotation of the swashplate swing angle. This part can be regarded as a proportional link. Angular displacement of swashplate swing angle is (Shan et al., 2020):

$$\theta = \theta_S N \tag{1}$$

In equation, θ – angular displacement of swashplate swing angle rotation, degree; θ_S – step angle of swashplate swing angle, degree; N – the number of pulses at the swashplate wobble angle.

The swashplate swinging angle can control the opening area of the valve, both of which are controlled by the swinging angle of the swashplate. In this way, the rotary motion of the swashplate swing angle can be changed into the open area of the valve core:

$$x_v = \frac{P}{360°}\theta \tag{2}$$

In equation, x_v – spool opening area, m^2; d – diameter of spool, m; θ – angular displacement of swashplate swing angle rotation. The linearised flow equation of degree valve is (Zhu et al., 2023a):

$$\Delta Q_L = K_q \Delta X_v - K_c \Delta P_c \tag{3}$$

The flow continuity equation applied to the control chamber C is:

$$Q_L = A_h \frac{dx_p}{dt} + C_{ip} P_c + \frac{V_c}{\beta_e}\frac{dP_c}{dt} \tag{4}$$

In equation, C_{ip} – internal leakage coefficient of hydraulic cylinder; A_h – piston area of hydraulic cylinder control chamber, m^2; V_c – volume of hydraulic cylinder control chamber, m^3. The forces acting on the variable piston include hydraulic pressure, variable adjustment force, viscous friction force, inertia force of swashplate, hydraulic force, gravity, etc. Compared with other forces, gravity and hydraulic force are too small to be ignored, and the force balance equation between piston and load can be obtained as (Loukatos et al., 2023):

$$p_C A_h - p_S A_r = m_t \frac{d^2 x_p}{dt^2} + B_p \frac{dx_p}{dt} + Kx_p + F_L \tag{5}$$

In equation, A_r – piston effective area on the piston rod side, m^2; K_q – flow gain; K_c – flow-pressure coefficient; ρ – oil density; Kg/m^3; m_t – total mass of piston and load, Kg; B_p – total viscous damping coefficient of piston and load converted to piston; K – load spring stiffness, N/m; F_L – any unexpected load force, N.

The Laplace transformation of its increment is (Saddiqi et al., 2023):

$$\Delta p_C A_h = m_l s^2 \Delta X_p + B_p s \Delta X_p + K \Delta x_p + \Delta F_L \tag{6}$$

The pump output flow equation is:

$$q_{v,p} = K_f n X_p \tag{7}$$

In equation, K_f – equivalent displacement of pump (constant); n– nominal speed of motor, r/min.

Considering that the resistance when the piston moves is small and negligible, the total input displacement of the piston when X_v and F_L acting at the same time can be obtained from equations (4), (6) and (7) as follows (Yue et al., 2023):

$$X_p = \frac{\frac{K_q}{A_h} X_v - \frac{K_{ce}}{A_h^2}\left(1 + \frac{V_0}{\beta_e K_{ce}} s\right) F_L}{\frac{V_0 m_t}{\beta_e A_h^2} s^3 + \left(\frac{m_t K_{ce}}{A_h^2} + \frac{B_p V_0}{\beta_e A_h^2}\right) s^2 + \left(1 + \frac{B_p K_{ce}}{A_h^2} + \frac{K V_0}{\beta_e A_h^2}\right) s + \frac{K_{ce} K}{A_h^2}} \tag{8}$$

In equation, K_{ce} – total flow-pressure coefficient, $K_{ce} = K_c + C_{ip}$. Generally, $\frac{B_p K_{ce}}{A_h^2} \leq 1$.

When the load spring stiffness is 0, that is, $K = 0$, equation (8) can be simplified as (Zhu et al., 2023b):

$$X_p = \frac{\frac{K_q}{A_h} X_v - \frac{K_{ce}}{A_h^2}\left(1 + \frac{V_0}{\beta_e K_{ce}} s\right) F_L}{s\left(\frac{s^2}{\omega_h^2} + \frac{2\varsigma_h}{\omega_h} s + 1\right)} \tag{9}$$

ω_h – hydraulic natural frequency, $\omega_h = \sqrt{\frac{\beta_e A_h^2}{V_0 m_t}}$, ς_h – quasi piezoresistiveir by, $\varsigma_h = \frac{K_{ce}}{2A_h}\sqrt{\frac{\beta_e m_t}{V_0}} + \frac{B_p}{2A_h}\sqrt{\frac{V_0}{\beta_e m_t}}$.

The transfer function of piston displacement to spool displacement is (Tian et al., 2023):

$$\frac{X_p}{X_v} = \frac{\frac{K_q}{A_h}}{s\left(\frac{s^2}{\omega_h^2} + \frac{2\varsigma_h}{\omega_h} s + 1\right)} \tag{10}$$

Combining equations (1), (2), (8) and (10), the open-loop transfer function for a given input can be obtained as follows:

$$G_K(s) = \frac{K_Q K_V K_p}{\frac{s^3}{\omega_h^2} + \frac{2\varsigma_h}{\omega_h} s^2 + s} \tag{11}$$

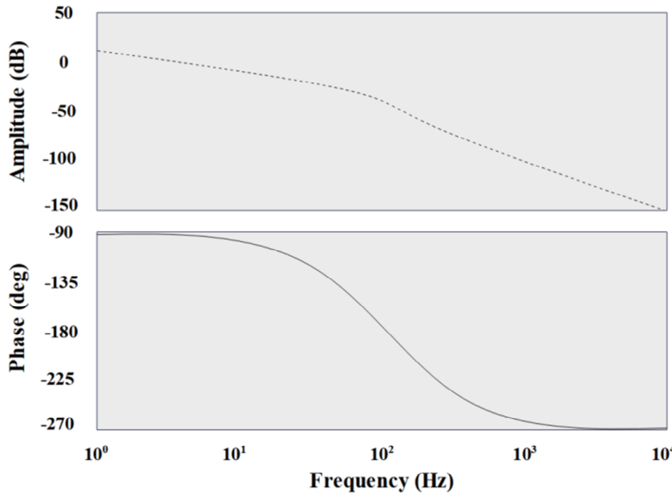
Similarly, its closed-loop transfer function is:

$$G_B(s) = \frac{K_Q K_V}{\frac{s^3}{\omega_h^2} + \frac{2\varsigma_h}{\omega_h} s^2 + s + K_V K_P} \tag{12}$$

The first condition that the system can be applied in practice is that the system should be stable, and the dynamic analysis and design of hydraulic system are carried out on the premise of stability requirements. The frequency characteristic method can be used to analyse the stability of the system, which is mainly carried out by Byrd diagram. It is effective to use it to analyse the stability of the system. When the parameters of the studied system change, Byrd diagram can be drawn quickly, so the stability can be studied in a large range of parameter changes (Almazrouei et al., 2023).

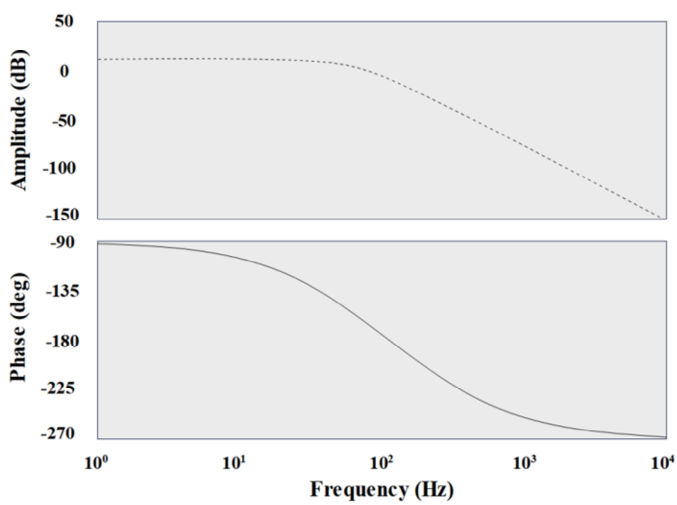
From equation (11), the open-loop transfer function of the system in this subject is obtained, and the open-loop Byrd diagram of the system is drawn, as shown in Figure 2

Figure 2 Open-loop Byrd diagram of the system



The relative stability of the system is usually measured by phase angle margin γ and gain margin k_g. Phase angle margin γ is the sum of the phase φ_c at the gain crossing frequency ω_c and 180°. The gain margin is the reciprocal of the gain at the phase crossing frequency ω_c, that is, $k_g = \dfrac{1}{G(j\omega)}$ (Jiao et al., 2023).

Figure 3 Closed-loop Byrd diagram of the system



As shown in Figure 2, the stability requirement of the system has been met. The closed-loop transfer function of the system is obtained from equation (12), and the closed-loop frequency characteristic curve of the system can be drawn as shown in Figure 3.

As shown in Figure 3, it can be judged that the system has good response speed and relative stability. Since the type I servo system is being discussed, when the logarithmic amplitude of the closed-loop amplitude-frequency characteristic drops to three decibels below the zero frequency value, the frequency range $0 \le \omega \le \omega_d$ corresponding to the cut-off frequency of the system can be obtained as the bandwidth of the system. Bandwidth is a characterisation of system response speed, reflecting the ability of system to reproduce input signals, and the system with large bandwidth has fast response speed. The stability of the system is a necessary condition for the normal operation of the system, but only stability can not ensure the normal operation of the system. Error is another important index of control system. The Laplace transformation formula of the steady-state error of the system is (Tong et al., 2023):

$$\Delta X(S) = \Phi_{\varepsilon}(S) X_v(S) + \Phi_{\varepsilon f}(S) F(S) \tag{13}$$

In equation,

$$\Phi_{\varepsilon}(S) = \left[1 - \frac{G_k(S)}{1 + G_k(S)}\right] = \frac{1}{1 + G_k(S)} = \frac{S\left(\dfrac{S^2}{\omega_h^2} + \dfrac{2\varsigma_h}{\omega_h} S + 1\right)}{S\left(\dfrac{S^2}{\omega_h^2} + \dfrac{2\varsigma_h}{\omega_h} S + 1\right) + K_v}$$

and

$$\Phi_{\varepsilon f}(S) = -\frac{X_p(S)}{F(S)} = \frac{\dfrac{K_{ce}}{A_h^2}\left(1 + \dfrac{V_0}{\beta_e K_{ce}} S\right)}{s\left(\dfrac{S^2}{\omega_h^2} + \dfrac{2\varsigma_h}{\omega_h} S + 1\right) + K_v}.$$

$\Phi_{\varepsilon}(S)$ and $\Phi_{\varepsilon f}(S)$ are the error transfer function of the system to the input signal and the error transfer function of the interference signal respectively.

The error transfer function of the above formula is expanded into Taylor series near the origin, and the expansion is substituted into equation (13). After that, the steady-state error of the system can be obtained by inverse Laplace transformation:

$$\Delta X_p(t) = \sum_{i=0}^{\infty} \frac{C_i}{i!} X_v^{(i)}(t) + \sum_{i=0}^{\infty} \frac{C_{ji}}{i!} F^{(i)}(t) \tag{14}$$

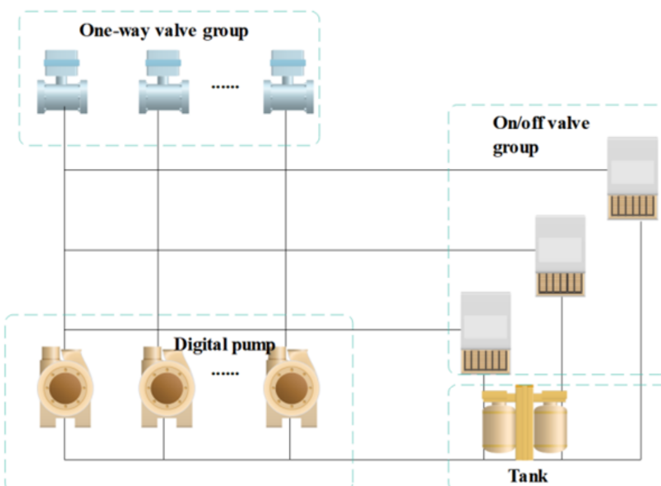
Therefore, it can be seen that in order to improve the steady-state accuracy, the system must have a high enough open-loop gain (Zheng et al., 2023).

4 Model analysis

The digital controlled variable pump studied in this project involves adding a variable controller consisting of a microcontroller, pressure and displacement sensors, and a digital on/off valve outside the variable pump. The microcontroller serves as the control host, and the pressure and displacement sensor signals are fed back to the microcontroller after A/D conversion. The control output of the microcontroller is driven by an amplifier to drive a digital switching valve for variable control. The digital on-off valve, asymmetric hydraulic cylinder, amplifier, pressure sensor, analogue-to-digital converter (A/D), and microcontroller form an electro-hydraulic servo control system. The core of the control system is the microcontroller. The pressure signal detected by the pressure sensor is converted into digital information through A/D conversion, which is input to the CPU. After comparison and processing, a control command (PWM control signal) is generated, which drives the digital on-off valve through the amplifier. PWM is used to control the on-off of the digital on-off valve, forming a pulse liquid flow in the system circuit and completing the loading control of the working object.

The digital pump system based on discrete variable technology is a parallel digital discrete system, which is composed of digital pump and control valve group. The control valve logic topology relationship is adopted to realise the combined control of displacement through coded signals, and the digital variable output is realised. It has certain advantages in anti-interference, energy saving, fault tolerance and universality, and can replace traditional variables in many application fields. The configuration of n-bit digital pump system is shown in Figure 4.

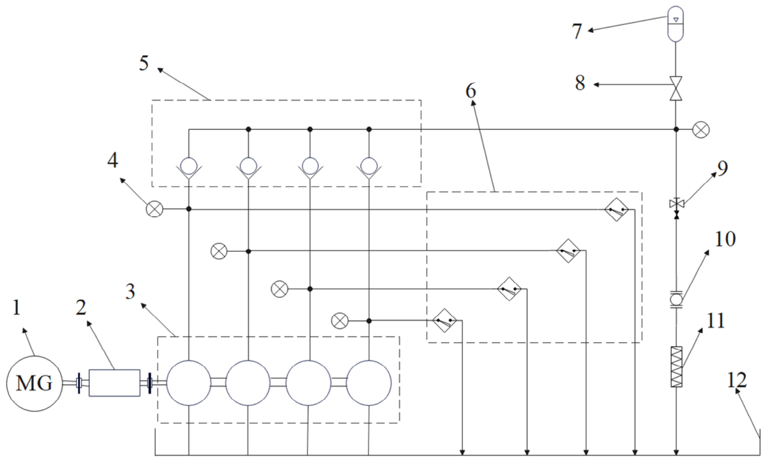
Figure 4 The configuration of digital pump system (see online version for colours)



Considering the installation space, control difficulty, linearity of displacement and large output flow range, four-bit binary code is selected in this study, and the displacement is 5, 10, 20 and 40 mL/r respectively. The overflow valve is used to simulate loading. Moreover, an accumulator is arranged at the outlet of the system, which can absorb the flow pulsation and impact of the system. A stop valve is set in front of the accumulator, and whether the accumulator is connected to the system can be selected. The principle is shown in Figure 5.

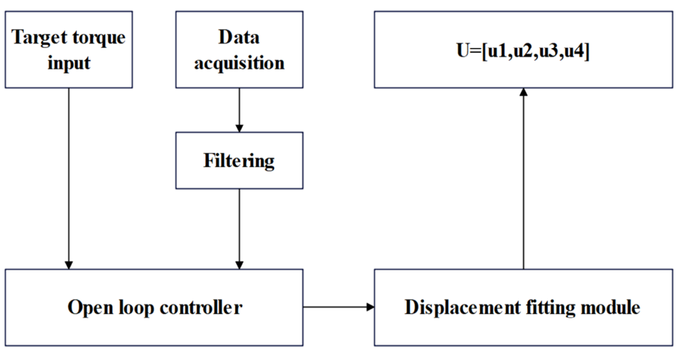
According to different control objectives, digital pump system can usually be divided into position control, speed control and force (torque) control. Force and torque control is more dynamic, and can more significantly characterise the instantaneous system parameters of variable switching. This section studies the displacement control characteristics from the perspective of torque control.

Figure 5 Schematic diagram of test bench of digital pump system



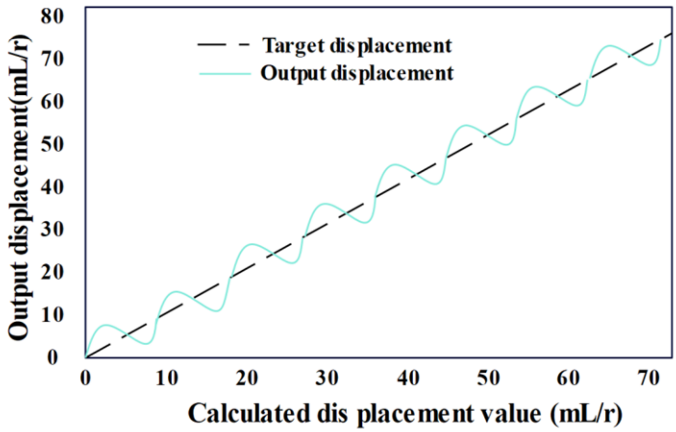
1. Motor; 2. Speed and torque sensor; 3. Digital pump/motor; 4. Pressure sensor; 5. One-way valve group; 6. On-off valve group; 7. Accumulator; 8. Globe valve; 9. Proportional relief valve; 10. Flowmeter; 11. Filter; 12. Fuel tank;

Figure 6 Control flowchart



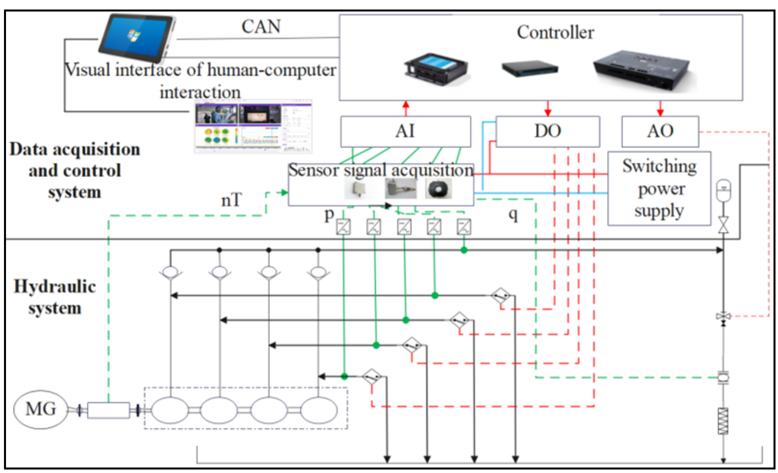
The control flow of the control method based on the best fitting resolution is shown in Figure 6. The target torque is taken as the input, and the target displacement of the digital pump is calculated by the controller in combination with the change of system pressure. According to the control algorithm, the displacement fitting module discretises the target displacement and converts it into the discrete control signal of solenoid valve matrix. The fitting resolution of digital pump displacement, that is, displacement fitting correction coefficient, determines the mean error of displacement fitting. In order to achieve the best fitting effect and make the actual output displacement of the digital pump change evenly up and down the target displacement, the fitting resolution is generally selected as V/min^2, and the fitting effect is shown in Figure 7. Considering the influence of shafting loss, pressure loss and oil temperature, it will lead to additional torque, which needs calibration compensation.

Figure 7 Displacement fitting effect (see online version for colours)



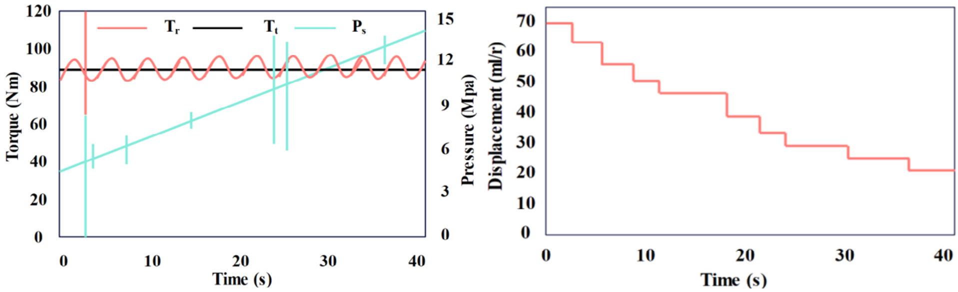
Notes: T_t is the target torque; V_O and V_r are the target displacement and the actual output displacement respectively; p_s is the system pressure; U is the control matrix of solenoid valve group.

Figure 8 Test principle of digital pump system (see online version for colours)



The man-machine interface of data acquisition and control system is realised by LabVIEW programming, which is mainly divided into operation area, acquisition area and data storage and monitoring area. The operation is divided into switching control and proportional control. Switching control is used to control and display the working state of solenoid valve, and proportional control is used to control the analogue change or fixed loading of relief valve. The loading pressure of the system is changed by setting different output voltages. The fixed loading mode can also be realised by using the pilot relief valve adjusting knob. Figure 8 shows the test principle of digital pump system.

Figure 9 Constant torque control characteristics, (a) torque and pressure change curve (b) digital pump displacement (see online version for colours)



(a) (b)

The experimental bench consists of a pilot control module, a steering execution module, a controller, and an industrial computer. The pilot control module mainly includes an oil source valve, a stepper motor, a bus type stepper driver, and a steering gear. The steering execution module mainly includes digital pump and its control valve group, flow amplification valve, steering cylinder, etc. The industrial computer inputs control instructions through a visual interface, and the signal of the steering system is fed back to the controller for control logic processing. The controller outputs control signals to control the speed, displacement, and simulated loading of the steering system, and real-time monitoring and storage of the status information of the steering system

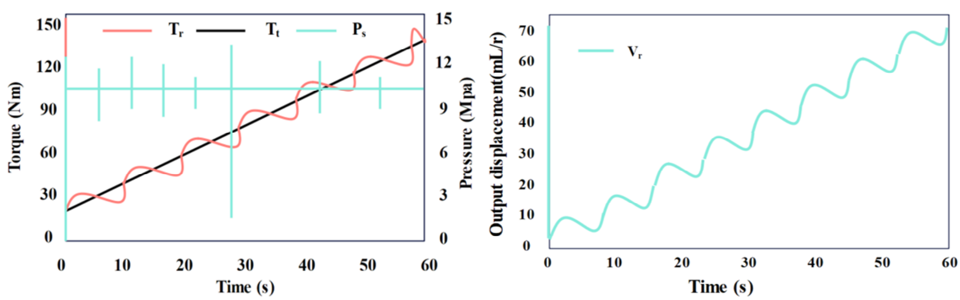
Based on the description of the pilot control module, steering execution module, controller, and industrial computer. Install pressure sensors at the control chambers at both ends of the flow amplification valve and at the inlet and outlet of the oil cylinder to test the pilot pressure and load pressure; install a displacement sensor at one end of the oil cylinder to test its displacement; install flow meters at the outlet of the digital pump and the inlet of the oil cylinder to test the system's oil supply flow rate and load flow rate, respectively; The steering gear speed is obtained through closed-loop feedback from a bus type driver.

The data acquisition and conversion module consists of two parts: the CAN communication module and the I/O module. The CAN communication module analyses and processes the messages transmitted by the CAN bus. The I/O module processes the analogue and digital signals of each input and output through A/D conversion and range conversion, including the reception and processing of signals such as pressure, flow, speed, and displacement. The fault monitoring and processing module is used to implement redundant control strategies based on parameter measurement methods. This module receives the main component status parameters collected by the data acquisition and conversion module to achieve real-time monitoring and judgment of the system status. If the system state information conforms to the fault state characteristics and the fault characteristics are maintained during the fault buffering period, the fault response mechanism is activated to complete the mode switching.

The simulation model is built based on AMESim-MATLAB/Simulink platform. In order to fit the actual system more, this paper uses AMESimHCD (hydraulic component design) library to build the key components of solenoid valve and proportional relief valve, and compared with the experimental data to modify the model. Typical working conditions (constant target torque, linear increase of system pressure and constant system pressure, linear increase of target torque) are simulated to study the variable effect of the system. The simulation results are shown in Figures 9 and 10. In the figure, T_r is the actual torque.

Figure 9 shows the simulation results of constant torque control characteristics. Torque output value changes up and down around the target torque in a certain threshold as expected. Because digital variables are different from continuous variables and have certain variable steps, certain step effects and variable errors will be produced in the variable process. The variation error is far less than the target value except for several obvious impact points, which preliminarily verifies the feasibility of digital pump variable. However, due to signal interference, pressure fluctuation and other factors, the displacement of digital pump is repeatedly switched at several displacement switching points, which has a very adverse impact on the service life of components and the stability of the system.

Figure 10 Ramp torque control characteristics, (a) torque and pressure change curve (b) digital pump displacement (see online version for colours)



(a) (b)

Figure 10 shows the simulation results of ramp torque control characteristics. Similar to the simulation results of constant torque, the output torque changes up and down around the target torque within a certain threshold as expected, and certain step effect and variable error will be produced in the variable process, but the overall trend has certain linearity and symmetry, which verifies the feasibility of digital pump variables.

This article conducts research on the variable control characteristics and energy-saving application technology of digital pumps, proposes variable control and variable pressure shock suppression methods for digital pumps, and improves the control performance of digital pumps. On this basis, its application value in the field of energy-saving technology was explored, and a digital pump steering hydraulic system and its control strategy were constructed, and the fault tolerance performance of the system was studied. Based on the experimental bench and loader prototype, experimental testing and analysis were conducted on the proposed digital pump steering system and control strategy, which is of great significance for promoting the development of digital pumps. The variable mode of hydraulic pumps is controlled by computer software, which can make the control of variable pumps flexible and achieve various control methods according to the requirements of the supporting host. This greatly enriches the variable control methods of hydraulic pumps and can be applied to variable motors, which are difficult or impossible to achieve with mechanical control devices. Due to the application of fuzzy adaptive control to variable pump variables, it avoids the dispersion error and modelling error of precise mathematical models for different mechanisms or systems, and can play the role of simulating human thinking patterns, constructing control systems with a certain degree of intelligence.

5 Conclusions

Digital pumps are composed of several quantitative pumps which work in parallel and whose displacement is combined according to certain coding rules. It realises different combinations of displacement and digital variable output through the logic topology relationship of control valve, which takes into account the advantages of gauge pump and variable pump and makes up for their shortcomings. However, there are still some control problems in parallel digital pump. Because of the machining error, nonlinear dead zone and the performance difference of electrical components in the control valve, the state switching and variable step size of the digital pump are uncertain, and its dynamic and static characteristics are difficult to keep consistent. At the same time, the uncertain relationship between the switching frequency and the control performance of the digital pump increases the difficulty of controlling the digital variable. Aiming at the problem of variable pressure shock in the process of digital variable, the formation mechanism of variable pressure shock is deeply analysed, and the proposed control configuration can significantly improve the displacement control accuracy under the same number of control units, and then reduce the amplitude of variable pressure shock. Based on the experimental bench and loader prototype, the digital pump steering system and control strategy are tested and analysed, which verifies the feasibility of this method.

The digital controlled variable pump studied in this project involves adding a variable controller consisting of a microcontroller, pressure and displacement sensors, and a digital on/off valve outside the variable pump. The microcontroller serves as the control host, and the pressure and displacement sensor signals are fed into the microcontroller after A/D conversion. The control output of the microcontroller is driven by an amplifier to drive a digital switching valve for variable control. After theoretical analysis and simulation research on the digital control axial piston pump control system and the overall digital pump system, the digital pump has good stability and dynamic characteristics, which can meet the requirements of general industrial applications, especially small and medium-sized enterprises.

The simulation research on digital controlled axial variable pump in this article still needs further investigation. Due to the focus of the project being on high-speed on-off valves, further research on the swash plate variable displacement piston pump has not been conducted. For the overall system of digital controlled axial variable pump, each link affects the performance of the entire pump system. Optimising parameters and conducting simulation research on the entire digital controlled axial variable pump system is of great significance for future improvement design and process improvement.

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