

Pressure-Difference Control Method for the Pump Set of a Pile-Bottom Sediment Cleaning Robot Based on Flow-Balance Feedforward Compensation

Yongrui Wang

Shandong Agricultural University

Jinge Ma

Shandong Agricultural University

Shuguang Wang

Shandong Agricultural University

Qiang GAO

Shandong Agricultural University

Zhe Ren

Shandong Agricultural University

Duohua Wu

Shandong Agricultural University

Zhenbao LI

Shandong Agricultural University

Jian Zhang

Zhangj614@163.com

Shandong Agricultural University

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Abstract

Pressure difference fluctuations generated at the bottom of bored piles during mud pump suction can compromise the stability of the pile-bottom environment, while the high-pressure conditions at the pile bottom caused by unbalanced inflow and discharge flow rates may further intensify these fluctuations. This study proposes a fuzzy-PID pump set control method based on flow balance feedforward compensation to mitigate these fluctuations. The sealed sediment storage chamber serves as the controlled object. The inflow rate command is treated as the disturbance input, while the discharge pump speed functions as the control variable. The pressure difference between the interior and exterior of the sealed sediment storage chamber is selected as the system output. A dynamic pressure difference model of the pump set is established, and a feedforward fuzzy-PID composite controller is developed. Simulations are performed in MATLAB/Simulink under varying inflow disturbances, different values of the mud bulk modulus, and flow disturbances introduced after 50 s. The results demonstrate that, under different inflow disturbances, the feedforward fuzzy-PID controller reduces the peak deviation by approximately 85% compared to the fuzzy-PID and PID controllers, while shortening the settling time by approximately 36% to 47% and 46% to 53%, respectively. Under different values of the mud bulk modulus, the proposed controller reduces the peak deviation by approximately 85% and shortens the settling time by approximately 36% and 46%, respectively. Under flow disturbances introduced after 50 s, the controller decreases the peak deviation by approximately 85% to 89% and shortens the settling time by approximately 62% to 90% and 65% to 91%, respectively. These findings indicate that the proposed method effectively reduces the peak pressure difference, shortens the settling time, and mitigates steady-state fluctuations, providing effective support for the stable control of pump sets used in pile-bottom sediment cleaning robots.

Keywords Bored pile · Borehole cleaning · Flow balance · Feedforward + feedback control · Fuzzy-PID control

1 Introduction

Bored piles are widely used in foundation engineering under complex ground conditions. Pile-bottom sediment can create a "soft cushion" effect that reduces both end-bearing capacity and side resistance while increasing pile-head settlement. The resulting reduction in end-bearing capacity can exceed 80%, whereas the reduction in side resistance can exceed 70% [1, 2, 3]. Therefore, controlling pile-bottom sediment is a critical aspect of construction quality management for bored piles.

Previous studies have primarily focused on optimizing process combinations and operating parameters to improve borehole-cleaning efficiency under varying ground conditions. Liu et al. [4, 5, 6, 7] addressed collapse, necking, and excessive sediment thickness in bored piles constructed through

extra-thick sand layers and proposed staged borehole-cleaning procedures that combine positive-circulation drilling with reverse-circulation cleaning. Qi et al. [8] controlled pile-bottom sediment in super-long, large-diameter cast-in-place piles by combining primary cleaning after final drilling with secondary cleaning before concrete placement and evaluated the cleaning performance using mud density, sand content, and other indicators. Cheng et al. [9] investigated the limited sediment-discharge efficiency of air-lift reverse circulation from the perspective of liquid-solid-gas multiphase transport and reported that merely extending the cleaning duration cannot effectively resolve the sediment accumulation problem. Deng et al. [10] compared the cleaning performance of positive circulation, pump-suction reverse circulation, and air-lift reverse circulation and demonstrated that the effectiveness of air-lift reverse circulation depends on conduit position, air-supply parameters, mud purification, and the organization of secondary cleaning. Existing methods rely primarily on ground pumping, conduit circulation, and process combinations to remove sediment, while the cleaning action rarely acts directly on the sediment zone at the pile bottom. Therefore, under deep-hole, large-diameter, and complex-stratum conditions, cleaning efficiency remains limited by conduit position, borehole depth, mud properties, and pressure fluctuations, making localized sediment retention and secondary deposition difficult to prevent.

The cleaning actuator is relocated from the ground system to the pile-bottom operating end, forming a pile-bottom sediment cleaning robot capable of sediment disturbance, suction, discharge, and collection to enhance sediment-discharge capacity. However, the robot's suction-discharge operation disturbs the flow equilibrium within the sediment storage chamber, resulting in pressure fluctuations inside the chamber. If pressure regulation is delayed, the pressure difference between the chamber and the borehole mud deviates from the desired level, affecting suction-discharge stability and borehole-wall stability. Therefore, the pile-bottom sediment cleaning robot requires a pressure-balance control system to maintain stable chamber pressure during operation. Variable-frequency pump set control is widely applied in constant-pressure water supply, liquid-level control, and mud pressure regulation, providing a technical foundation for pressure regulation in the sediment storage chamber of a pile-bottom sediment cleaning robot. Wang et al. [11, 12, 13, 14, 15] developed variable-frequency constant-pressure water-supply system models and introduced fuzzy control and adaptive adjustment mechanisms for online PID parameter optimization. Ning et al. [16] proposed a gain-adjusted fuzzy-PID control method to mitigate system oscillation caused by the degraded performance of conventional PID control during pump switching. Sales et al. [17] proposed a fuzzy-logic-based pressure control method and compared its control performance under single-pump, two-pump series, and two-pump parallel operating modes. Page et al. [18] investigated remote real-time pressure management in water distribution systems using variable-speed pumps. Pawlowski et al. [19, 20] analyzed feedforward compensation methods under PID and MPC feedback structures for measurable disturbances in industrial processes with dead time. Wang et al. [21, 22] addressed nonlinearity, parameter uncertainty, and external disturbances in the air-chamber pressure regulation of slurry pressure balance shield tunneling machines by establishing a nonlinear state-space model and designing a nonlinear adaptive robust controller. Yang et al. [23, 24, 25] compared PID, fuzzy-PID, and neural-network PID controllers for liquid-level control in a single-capacity water tank. However, the sealed sediment storage chamber used in the sediment-cleaning process exhibits high fluid stiffness, strong disturbance, and coupled time-delay characteristics. MPC requires relatively intensive online receding-horizon computation, whereas the high-gain feedback used in robust control can

amplify high-frequency fluctuations caused by model mismatch in a high-stiffness fluid chamber. Therefore, a fast compensation control structure is suitable for inflow command.

Accordingly, this study proposes a pump set control system consisting of a sealed sediment storage chamber and two coordinated pumps for a pile-bottom sediment cleaning robot. A dynamic pressure-difference model of the sealed sediment storage chamber is established, and a fuzzy-PID control method based on flow-balance feedforward compensation is developed. Simulations are conducted in MATLAB/Simulink under different inflow disturbances, different values of the mud bulk modulus, and flow disturbances introduced after 50 s. The effects of the proposed method on peak pressure difference, settling time, and steady-state fluctuation are evaluated, providing support for the coordinated control of the pump set in pile-bottom sediment cleaning robots.

2 Pressure-difference control model of the pump set in the pile-bottom sediment cleaning robot

2.1 Pump set system composition

A dual-pump coordinated control system consisting of a sealed sediment storage chamber, an inflow pump, a discharge pump, pressure sensors, frequency-conversion drive units, and a controller is established, as shown in Fig. 1. The control objective is to maintain a stable pressure difference between the inside and outside of the sediment storage chamber. The inflow pump supplies mud into the chamber, whereas the discharge pump removes the filtered mud from the chamber. In the control model, the inflow rate serves as the primary disturbance input, the discharge-pump speed serves as the control input, and the pressure difference between the inside and outside of the sediment storage chamber serves as the process output. Based on this input-output relationship, a flow-balance feedforward compensation mechanism is introduced to pre-adjust the discharge-pump speed so that the inflow and discharge flow rates remain balanced throughout the dynamic process, suppressing pressure-difference fluctuations within the sediment storage chamber.

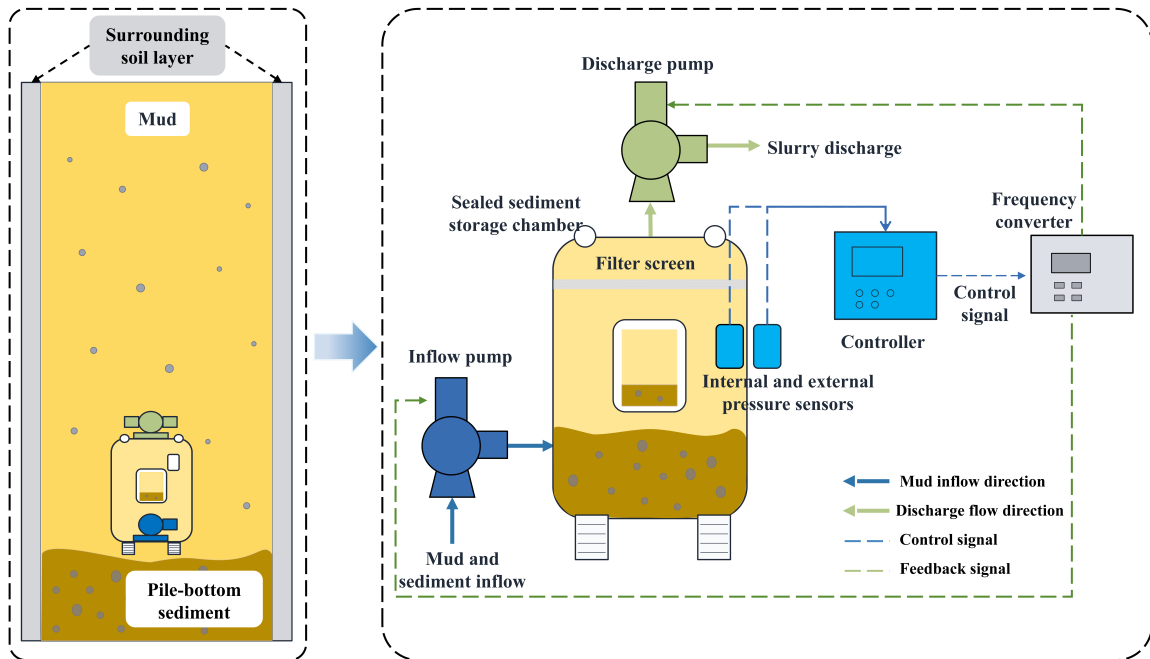


Fig. 1 Schematic diagram of the system

2.2 Mathematical model of the pump set pressure-difference control system

2.2.1 Derivation of the dynamic pressure-difference model of the sealed sediment storage chamber

The pump set of the sediment cleaning robot is simplified as a fluid-pressure system consisting of an inflow pump, a discharge pump, and a rigid, sealed sediment storage chamber to analyze the dynamic characteristics of the pump set control system. It is assumed that the chamber is continuously filled with mud, the pile-bottom mud pressure p_o remains constant, the transient internal pressure of the sediment storage chamber is denoted by p_i , and the initial condition satisfies the internal-external pressure equilibrium.

$$p = p_i - p_o \quad (1)$$

$$|p| \leq 0.1 \text{ MPa} \quad (2)$$

where p is the pressure difference between the inside and outside of the sealed sediment storage chamber (Pa), p_i is the internal pressure of the sealed sediment storage chamber (Pa), and p_o is the external pressure of the sealed sediment storage chamber (Pa).

The mud is approximated as a weakly compressible fluid under the assumptions of a rigid container, fixed volume, and small-disturbance linearization. The pressure difference p is proportional to the net volume change of mud:

$$p = \frac{K}{V} \cdot \int_0^t [q_{in}(\tau) - q_{out}(\tau)] d\tau \quad (3)$$

From Eq. (3):

$$\frac{dp(t)}{dt} = \frac{K}{V} \cdot \frac{d\Delta V(t)}{dt} \quad (4)$$

The dynamic pressure-difference equation of the sealed sediment storage chamber is obtained by expressing the volume-change rate as the difference between inflow and discharge flow rates as follows:

$$\frac{dp(t)}{dt} = \frac{K}{V} \cdot [q_{in}(t) - q_{out}(t)] \quad (5)$$

Taking the Laplace transform of Eq. (5) gives

$$P(s) = \frac{K}{Vs} \cdot [Q_{in}(s) - Q_{out}(s)] \quad (6)$$

where K is the bulk modulus of mud (Pa), V is the volume of the cylindrical sealed sediment storage chamber (m^3), $\Delta V(t)$ is the total volume difference (m^3), τ is the integration variable in the time domain (s), $q_{in}(\tau)$ is the transient volumetric flow rate of the inflow pump (m^3/s), $q_{out}(\tau)$ is the transient volumetric flow rate of the discharge pump (m^3/s), and s is the complex-frequency Laplace variable. $P(s)$ is the output pressure difference (Pa), $Q_{in}(s)$ and $Q_{out}(s)$ are the actual flow rates of the inflow and discharge pumps (m^3/s). The above dynamic pressure-difference model is utilized to describe the short-time small-disturbance pressure-difference response of the sealed sediment storage chamber near the selected operating point. When $q_{in} > q_{out}$, the chamber pressure increases. When $q_{in} < q_{out}$, the chamber pressure decreases.

2.2.2 Flow-rate-speed conversion model of the variable-frequency pump set

The small-disturbance model required for controller design is determined from the H - Q characteristic curve of the variable-frequency centrifugal pump and the pipeline-system characteristics. The variable-frequency centrifugal pump is locally linearized near the selected operating point. At the rated speed n_0 , the H - Q curve can be approximated as [28]

$$H_0(Q) = a_2 Q^2 + a_1 Q + a_0 \quad (7)$$

Based on the centrifugal-pump affinity laws, flow rate is proportional to rotational speed, and head is proportional to the square of rotational speed. Therefore, under variable-speed operation, the H - Q relationship is

$$H(Q, n) = a_0 \left(\frac{n}{n_0} \right)^2 + a_1 \left(\frac{n}{n_0} \right) Q + a_2 Q^2 \quad (8)$$

Linearization near the operating point (Q_0, n_0, H_0) gives

$$\Delta H = K_n \Delta n + K_H \Delta Q \quad (9)$$

The effects of local pipeline resistance, head disturbance, and pressure disturbance on the pump flow rate are incorporated into the equivalent gain near the operating point. Therefore, the local response of the pump flow rate to speed variation can be expressed as follows:

$$\Delta Q_{in} = k_{q,in} \cdot \Delta n_{in} \quad (10a)$$

$$\Delta Q_{out} = k_{q,out} \cdot \Delta n_{out} \quad (10b)$$

The speed-regulation processes of the inflow and discharge pumps are respectively equivalent to first-order inertial elements:

$$G_{m,in}(s) = \frac{N_{in}(s)}{N_{in}^*(s)} = \frac{1}{T_{m,in}s + 1} \quad (11a)$$

$$G_{m,out}(s) = \frac{N_{out}(s)}{N_{out}^*(s)} = \frac{1}{T_{m,out}s + 1} \quad (11b)$$

Under the initial conditions

$$T_{m,in} \frac{dn_{in}}{dt} + n_{in} = n_{in}^* \quad (12a)$$

$$T_{m,out} \frac{dn_{out}}{dt} + n_{out} = n_{out}^* \quad (12b)$$

where $H_0(Q)$ is the pump head at the rated speed (m), and Q is the pump flow rate (m^3/s). a_0 , a_1 , and a_2 are H - Q curve fitting parameters. K_n is the local gain of head with respect to speed, and K_H is the local gain of head with respect to flow rate. ΔQ_{in} and ΔQ_{out} are the flow-rate variations of the inflow and discharge pumps (m^3/s), respectively. Δn_{in} and Δn_{out} are the speed variations (r/min). $k_{q,in}$ and $k_{q,out}$ are the flow-rate gains with respect to pump speed. $T_{m,in}$ and $T_{m,out}$ are the motor inertia time constants (s). n_{in}^* and n_{out}^* are the target speed commands (r/min). $N_{in}(s)$ and $N_{out}(s)$ are the actual output speeds (r/min). $N_{in}^*(s)$ and $N_{out}^*(s)$ are the total speed control commands (r/min). $G_{m,in}(s)$ and $G_{m,out}(s)$ are the transfer functions of the speed dynamic elements. In the simulations of this study, the inflow and discharge pumps use the same performance parameters; therefore, $k_{q,in} = k_{q,out} = k_q$ and $T_{m,in} = T_{m,out} = T_m$. The parameters k_q and T_m were determined from the pump operating point and the pump-speed response, respectively. The flow-rate gain k_q represents the local slope of the flow-rate–speed relationship near the selected operating point, and T_m describes the first-order speed response of the variable-frequency pump.

2.2.3 Transfer functions of the inflow and discharge channels and system pressure response

During borehole cleaning, variations in the inflow rate change the mud volume within the sealed sediment storage chamber and cause fluctuations in the internal-external pressure difference. The discharge-pump speed command, and the process output, the transfer functions of the two channels are derived separately to establish the relationships among the inflow-rate command. Based on the locally linear proportional relationship between flow rate and rotational speed, the inflow-rate command is converted into the inflow-pump speed command:

$$N_{in}^*(s) = \frac{1}{k_{q,in}} Q_{in}^*(s) \quad (13)$$

The speed dynamic response of the inflow pump is

$$N_{in}(s) = \frac{1}{T_{m,in}s + 1} N_{in}^*(s) \quad (14)$$

The actual flow rate of the inflow pump is

$$Q_{in}(s) = k_{q,in} N_{in}(s) \quad (15)$$

The response relationship between the actual inflow-pump flow rate and the inflow-rate command is expressed as follows:

$$Q_{in}(s) = k_{q,in} \cdot \left[\frac{1}{k_{q,in}(T_{m,in}s + 1)} Q_{in}^*(s) \right] = \frac{1}{T_{m,in}s + 1} Q_{in}^*(s) \quad (16)$$

The transfer function of the inflow disturbance channel is determined as follows:

$$G_{in}(s) = \frac{P(s)}{Q_{in}^*(s)} = \frac{K}{V} \cdot \frac{1}{s(T_{m,in}s + 1)} \quad (17)$$

The discharge channel takes the target speed command of the discharge pump as the control input, and its motor speed response is

$$N_{out}(s) = \frac{1}{T_{m,out}s + 1} N_{out}^*(s) \quad (18)$$

The actual output flow rate of the discharge pump is

$$Q_{out}(s) = \frac{k_{q,out}}{T_{m,out}s + 1} N_{out}^*(s) \quad (19)$$

Substituting Eq. (19) into Eq. (6), the transfer function of the discharge control channel is described as follows:

$$G_{out}(s) = \frac{P(s)}{N_{out}^*(s)} = \frac{K}{V} \cdot \frac{k_{q,out}}{s(T_{m,out}s + 1)} \quad (20)$$

The system pressure response is obtained by linear superposition of the inflow disturbance channel and the discharge control channel:

$$P(s) = G_{in}(s)Q_{in}^*(s) - G_{out}(s)N_{out}^*(s) \quad (21)$$

$$P(s) = \frac{K}{V} \cdot \frac{1}{s(T_{m,in}s + 1)} Q_{in}^*(s) - \frac{K}{V} \cdot \frac{k_{q,out}}{s(T_{m,out}s + 1)} N_{out}^*(s) \quad (22)$$

where $Q_{in}^*(s)$ is the inflow-rate command (m³/s), $N_{in}^*(s)$ is the reference speed command of the inflow pump (r/min), $N_{in}(s)$ and $N_{out}(s)$ are the actual output speeds of the inflow and discharge pump motors (r/min), $G_{in}(s)$ is the disturbance-channel transfer function, and $G_{out}(s)$ is the transfer function of the discharge control channel.

2.3 Flow-balance feedforward compensation design

The inflow-pump flow-rate command serves as the primary disturbance variable that causes variations in the pressure difference. The feedforward channel calculates the discharge-pump compensation speed in advance based on the inflow-rate command [26, 27]. When the discharge flow rate remains balanced with the inflow rate, the net change in mud volume within the sealed sediment storage chamber approaches zero, reducing pressure-difference fluctuations. Therefore, the feedforward compensator can be approximated as a proportional conversion element that maps the

inflow-rate variation to the discharge-pump compensation speed. This compensation signal is superimposed on the fuzzy-PID feedback control signal to generate the total discharge-pump speed command.

The feedforward channel compensates for measurable disturbances before they affect the system output, whereas the feedback channel corrects the residual deviation resulting from model mismatch, parameter variations, and external disturbances. The two control components are linearly superimposed at the discharge-pump speed command input [28]:

$$N_{out}^*(s) = N_{fb}^*(s) + N_{ff}^*(s) \quad (23)$$

$$N_{ff}^*(s) = G_{ff}(s)Q_{in}^*(s) \quad (24)$$

Substituting the feedforward compensation term and the feedback correction term into the system pressure response gives

$$P(s) = [G_{in}(s) - G_{out}(s)G_{ff}(s)]Q_{in}^*(s) - G_{out}(s)N_{fb}^*(s) \quad (25)$$

The residual disturbance channel is

$$D_r(s) = G_{in}(s) - G_{out}(s)G_{ff}(s) \quad (26)$$

When the dynamic responses of the inflow and discharge pumps are approximately identical, and the local flow-rate gains with respect to pump speed are the same, setting $D_r(s)=0$ produces the ideal feedforward compensator.

$$G_{ff,0}(s) = \frac{G_{in}(s)}{G_{out}(s)} = \frac{1}{k_{q,out}} \frac{T_{m,out}s + 1}{T_{m,in}s + 1} \quad (27)$$

Feedforward compensation in an actual system for a measurable disturbance must be tuned together with model error, actuator saturation, and feedback-loop dynamics. Therefore, a feedforward compensation coefficient η is introduced, and the actual feedforward compensator is defined as follows:

$$G_{ff}(s) = \eta G_{ff,0}(s), 0 < \eta < 1 \quad (28)$$

The discharge-pump compensation speed can be obtained as follows:

$$N_{ff}^*(s) = \eta G_{ff,0}(s)Q_{in}^*(s) \quad (29)$$

The residual disturbance channel after introducing the feedforward compensation coefficient is

$$D_{r,\eta}(s) = G_{in}(s) - \eta G_{out}(s)G_{ff}(s) \quad (30)$$

The sensor measurement delay is denoted by τ , and the measured pressure difference considering the delay is calculated as follows:

$$P_m(s) = e^{-\tau s} P(s) \quad (31)$$

Near the operating point, the fuzzy-PID scheme can be equivalently regarded as a frozen-parameter PID controller:

$$G_p(s) = K_p + \frac{K_i}{s} + K_d s \quad (32)$$

The feedback correction speed command is given as follows:

$$N_{fb}^*(s) = G_p(s)[P_m(s) - P_{set}(s)] \quad (33)$$

A local stability analysis of the frozen-parameter closed-loop model is performed using the small-delay approximation. $P_m(s) \approx P(s)$ under this approximation, and the closed-loop transfer relationship can be described as follows:

$$P(s) = \frac{D_{r,\eta}(s)}{1 + G_{out}(s)G_p(s)} Q_{in}^* + \frac{G_{out}(s)G_p(s)}{1 + G_{out}(s)G_p(s)} P_{set}(s) \quad (34)$$

The gain magnitude of the discharge channel can be approximated as follows:

$$G_{out}(s) = \frac{Kk_{q,out}}{Vs(T_{m,out}s + 1)} \quad (35)$$

The closed-loop characteristic equation is

$$VT_{m,out}s^3 + (V + Kk_{q,out}K_d)s^2 + Kk_{q,out}K_p s + Kk_{q,out}K_i = 0 \quad (36)$$

Based on the Routh criterion, the local stability conditions of the frozen-parameter model under the small-delay approximation are

$$K_p > 0, K_i > 0, K_d > -\frac{V}{Kk_{q,out}} \quad (37)$$

$$V + Kk_{q,out}K_d)K_p > VT_{m,out}K_i \quad (38)$$

The pump-speed constraint is determined as follows:

$$N_{min} \leq N_{out}^* \leq N_{max} \quad (39)$$

The actual input speed is

$$N_{out,act}^*(s) = sat(N_{out}^*, N_{min}, N_{max}) \quad (40)$$

where $N_{ff}^*(s)$ is the feedforward compensation speed command of the discharge pump (r/min), $N_{fb}^*(s)$ is the feedback correction speed command of the discharge pump (r/min), $G_{ff}(s)$ is the actual feedforward compensator (r/min)/(m³/s), and $G_{ff,0}(s)$ is the ideal feedforward compensator (r/min)/(m³/s). η is the feedforward compensation coefficient. When $\eta=1$, the disturbance is fully compensated; when $0<\eta<1$, the residual disturbance is corrected by the feedback channel. In this study, $\eta=0.85$ is adopted as an under-compensation coefficient to retain a pump-speed margin and avoid overcompensation under model uncertainty. $D_r(s)$ is the residual disturbance channel after compensation (Pa/m³/s), and $D_{r,\eta}(s)$ is the residual disturbance channel after introducing the feedforward compensation coefficient (Pa/m³/s). e is the pressure-difference error, $P_m(s)$ is the measured pressure difference considering sensor delay (Pa), $G_p(s)$ is the equivalent PID controller, τ is the sensor measurement delay (s), $G_{out}(s)$ is the gain magnitude of the discharge control channel, N_{min} and N_{max} are the minimum and maximum allowable speeds of the discharge pump (r/min), respectively, and $N_{out,act}^*(s)$ is the actual input speed command (r/min).

3 Feedforward-Compensated fuzzy-PID Pump-Set Pressure-Difference Control Algorithm and Simulation

3.1 Controller structure

The feedforward-compensated fuzzy-PID control scheme consists of a fuzzy-PID feedback control module and a flow-balance feedforward compensation module. The fuzzy-PID feedback control module uses the pressure-difference error e and the rate of change of the error ec as inputs, adjusts the PID parameters online, and generates a speed feedback correction signal. The feedforward compensation module uses the inflow-rate variation as its input and calculates the required discharge-pump speed compensation in advance. These two components are superimposed to produce the total discharge-pump speed command, which is transmitted to the frequency-conversion drive unit to stabilize the internal-external pressure difference within the sealed sediment storage chamber. The Simulink simulation model is illustrated in Fig. 2.

The total discharge-pump speed command can be described as follows:

$$N_{out}^* = N_{ff}^* + N_{fb}^* \quad (41)$$

The PID feedback control law is

$$N_{fb}^* = K_p e + K_i \int e dt + K_d ec \quad (42)$$

where N_{fb}^* is the discharge-pump speed correction command (r/min), and N^* is the total discharge-pump speed command (r/min).

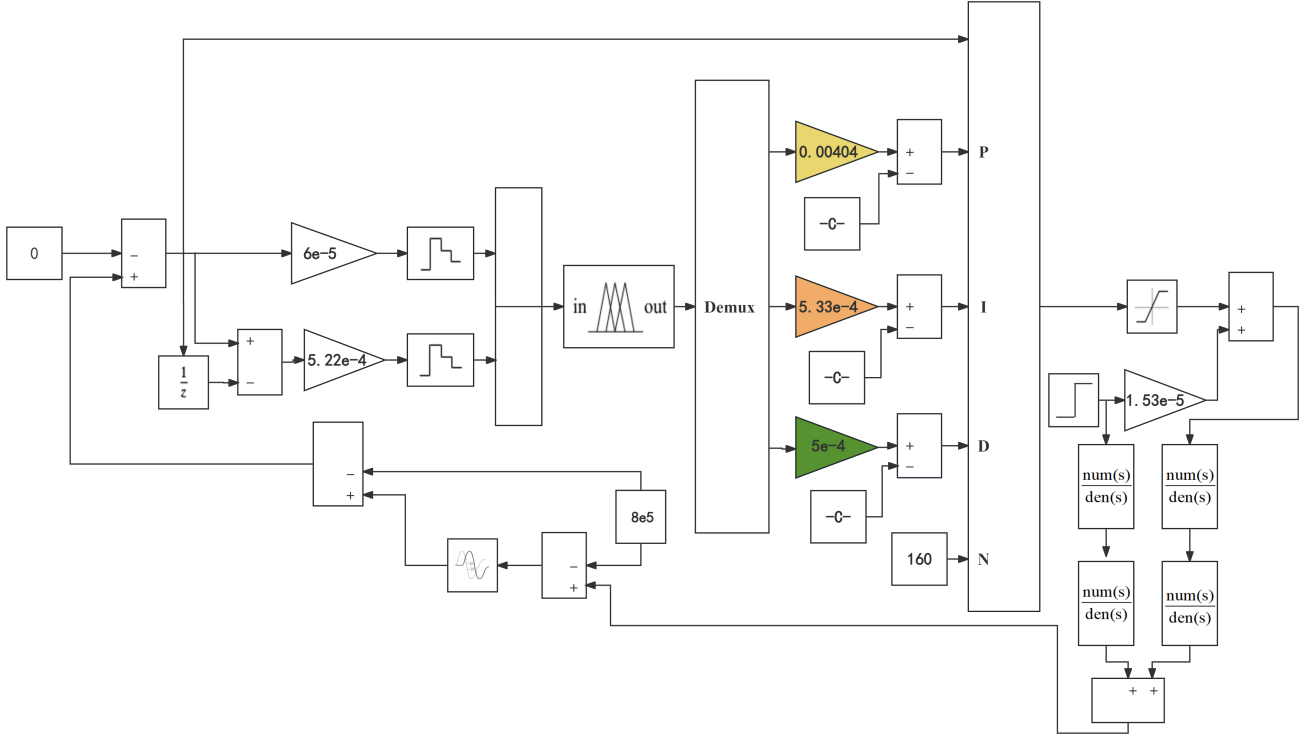


Fig. 2 Simulation model of the feedforward-compensated fuzzy adaptive PID controller

3.2 Fuzzification of input and output variables

A two-input, three-output fuzzy-PID control scheme is adopted in this study. The controller inputs are the pressure-difference error e and the rate of change of the error ec . The outputs are the PID parameter correction values ΔK_p , ΔK_i , and ΔK_d , which are utilized to update the proportional, integral, and derivative gains online.

The pressure-difference error e and the rate of change of the error ec are defined as follows:

$$e = p - p_{\text{set}}(t), \quad ec = \frac{de}{dt} \quad (43)$$

Through quantization factors, the pressure-difference error e and the rate of change of the error ec are mapped into the dimensionless fuzzy variables E and EC :

$$k_e = \frac{X_{\text{max}}}{e_{\text{max}}}, \quad k_{ec} = \frac{X_{\text{max}}}{ec_{\text{max}}} \quad (44)$$

$$E = \text{sat}(k_e e, -X_{\text{max}}, X_{\text{max}}), \quad EC = \text{sat}(k_{ec} ec, -X_{\text{max}}, X_{\text{max}}) \quad (45)$$

The PID parameter correction values are

$$\Delta K_p = K_{\Delta p} u_p, \quad \Delta K_i = K_{\Delta i} u_i, \quad \Delta K_d = K_{\Delta d} u_d \quad (46)$$

The online-tuned PID parameters are

$$K_p = K_{p0} + \Delta K_p \quad (47a)$$

$$K_i = K_{i0} + \Delta K_i \quad (47b)$$

$$K_d = K_{d0} + \Delta K_d \quad (47c)$$

where E and EC are the input variables of the fuzzy controller, k_e is the error quantization factor, k_{ec} is the quantization factor of the rate of change of the error, and X_{max} is the upper bound of the

normalized universe of discourse. sat is the saturation function. $K_{\Delta p}$, $K_{\Delta i}$, and $K_{\Delta d}$ are the scaling factors of the proportional, integral, and derivative parameter corrections. K_p , K_i , and K_d are the tuned proportional, integral, and derivative coefficients. K_{p0} , K_{i0} , and K_{d0} are the initial proportional, integral, and derivative coefficients. ΔK_p , ΔK_i , and ΔK_d are the correction values of the proportional, integral, and derivative coefficients.

3.3 Fuzzy control rules and defuzzification

The fuzzy controller input variables E and EC , together with the output variables u_p , u_i , and u_d , all use the normalized universe of discourse $[-6, 6]$ and are divided into seven linguistic values. The membership functions for all variables are triangular. Based on the fuzzy control rule table, 49 control rules are established to describe the mapping relationship among the pressure-difference error, the rate of change of the error, and the control outputs. The output of the fuzzy inference process remains a linguistic variable and therefore cannot be used directly for PID parameter correction. Instead, it must first be converted into a crisp numerical value through defuzzification using the centroid method. The variable assignments are presented in Table 1, the fuzzy control rules are provided in Table 2, and the membership-function distributions of the input variables E and EC are shown in Figs. 3 and 4.

Table 1 Assignment of fuzzy linguistic variables

Linguistic variable	Meaning	Query value
NB	Negative big	-6
NM	Negative medium	-4
NS	Negative small	-2
ZO	Zero	0
PS	Positive small	2
PM	Positive medium	4
PB	Positive big	6

Table 2 Fuzzy control rule table for ΔK_p , ΔK_i , and ΔK_d

E/EC	NB	NM	NS	ZO	PS	PM	PB
NB	NS/NS/NS	NS/ZO/ZO	NM/NS/ZO	NM/NS/PS	NB/NM/PM	NB/NM/PB	NB/NM/PB
NM	ZO/ZO/NS	ZO/PS/ZO	NS/ZO/ZO	NS/ZO/PS	NM/NS/PM	NM/NM/PM	NM/NM/PB
NS	PS/PS/NM	ZO/PS/NS	ZO/PS/ZO	ZO/PS/ZO	NS/ZO/PS	NS/NS/PM	NS/NS/PM
ZO	PM/PS/NS	PS/PS/ZO	ZO/PS/PS	ZO/ZO/ZO	ZO/PS/PS	ZO/ZO/PS	ZO/ZO/PS
PS	PM/ZO/NS	PM/ZO/ZO	PS/PS/PS	ZO/PS/PS	ZO/PS/PS	ZO/PS/PS	ZO/PS/PS
PM	PB/NS/NS	PM/NS/ZO	PS/ZO/PS	ZO/PS/PS	ZO/ZO/PS	ZO/ZO/PS	PS/ZO/PS
PB	PB/NM/NS	PM/NS/ZO	PS/ZO/PS	ZO/PS/PS	ZO/ZO/PS	PS/ZO/PS	PS/ZO/PS

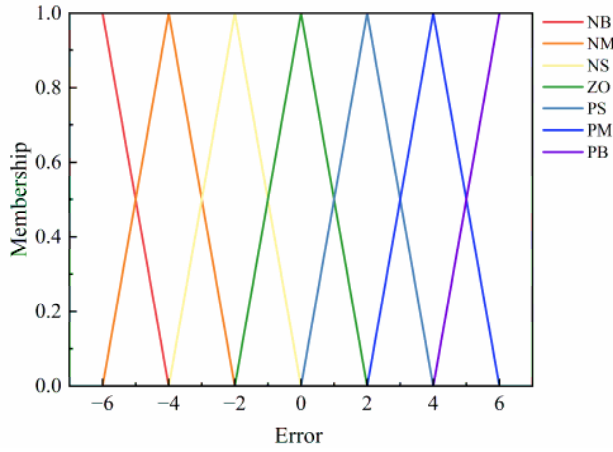


Fig. 3 Membership functions of E

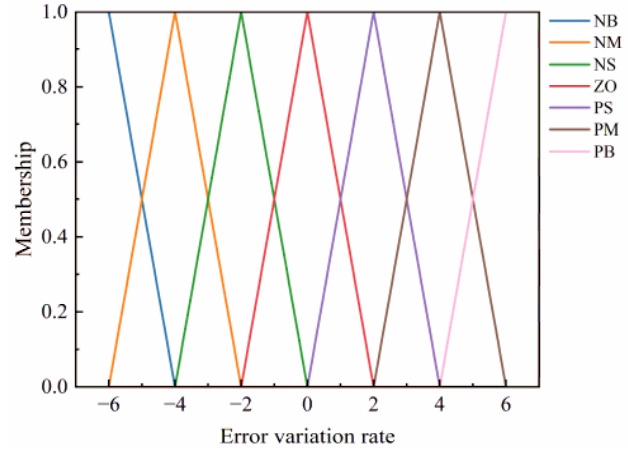


Fig. 4 Membership functions of EC

4 Simulation and Result Analysis

4.1 Operating conditions

A series of combined simulation tests is designed to evaluate the control performance of the feedforward fuzzy-PID algorithm under different operating conditions by varying three factors: the inflow-pump disturbance amplitude, the bulk modulus of the mud, and the flow disturbance introduced after 50 s. The model parameters and simulation conditions are listed in Table 3.

Table 3 Model parameters and simulation conditions

Parameter name	Simulation parameter	Unit	Parameter symbol
Volume of the sealed sediment storage chamber	0.1667	m^3	V
External mud pressure	0.5	MPa	p_o
Internal pressure of sealed sediment storage chamber	0.5	MPa	p_i
Sensor time delay	0.01	s	τ
Flow-rate gain with respect to pump speed	5.56×10^{-6}	$\text{m}^3 \text{s}^{-1} / (\text{r} \cdot \text{min}^{-1})$	k_q
Equivalent motor inertia time constant	3.338	s	T_m
Quantization factors of error and rate of change of the error	6×10^{-5} , 5.22×10^{-4}	Pa^{-1} , $\text{s} \cdot \text{Pa}^{-1}$	k_e , k_{ec}
Scaling factors of PID parameter corrections	4.04×10^{-3} , 5.33×10^{-4} , 5×10^{-4}	/	ΔK_p , ΔK_i , ΔK_d
Initial PID parameters	0.02425, 0.0032, 0.003	/	K_{p0} , K_{i0} , K_{d0}
Speed limits of inflow and discharge pumps	0–3000	r/min	/
Flow limits of inflow and discharge pumps	0–60	m^3/h	/
Flow disturbance after 50 s	0.001, 0.0015, 0.002, 0.0025	m^3/s	Q_{in}^*
Bulk modulus of mud	1.9, 2.0, 2.1, 2.2	GPa	K
Inflow disturbance	20, 30, 40, 50	m^3/h	ΔQ_{in}^*

4.2 Control performance under different operating conditions

Four performance indices were selected to compare the different control methods to evaluate the dynamic response and steady-state performance of the pressure-difference control system: peak deviation, settling time, steady-state error, and post-settling oscillation amplitude. These indices are defined as follows. Peak deviation is the maximum absolute value of the pressure-difference deviation after the disturbance is applied. Settling time is the time required for the pressure-difference deviation to enter and remain within the ± 1000 Pa error band. Steady-state error is the average absolute value

of the pressure-difference deviation over the interval from 50 s to 60 s. Post-settling oscillation amplitude is the absolute value of the peak pressure-difference deviation within the same interval.

4.2.1 Control performance under different inflow step disturbances

Four operating conditions are selected to analyze the influence of the initial inflow step disturbance on pressure-difference control performance for simulation: $Q_{in}=20, 30, 40$, and $50 \text{ m}^3/\text{h}$. The three control methods are compared, as shown in Figs. 5 and 6.

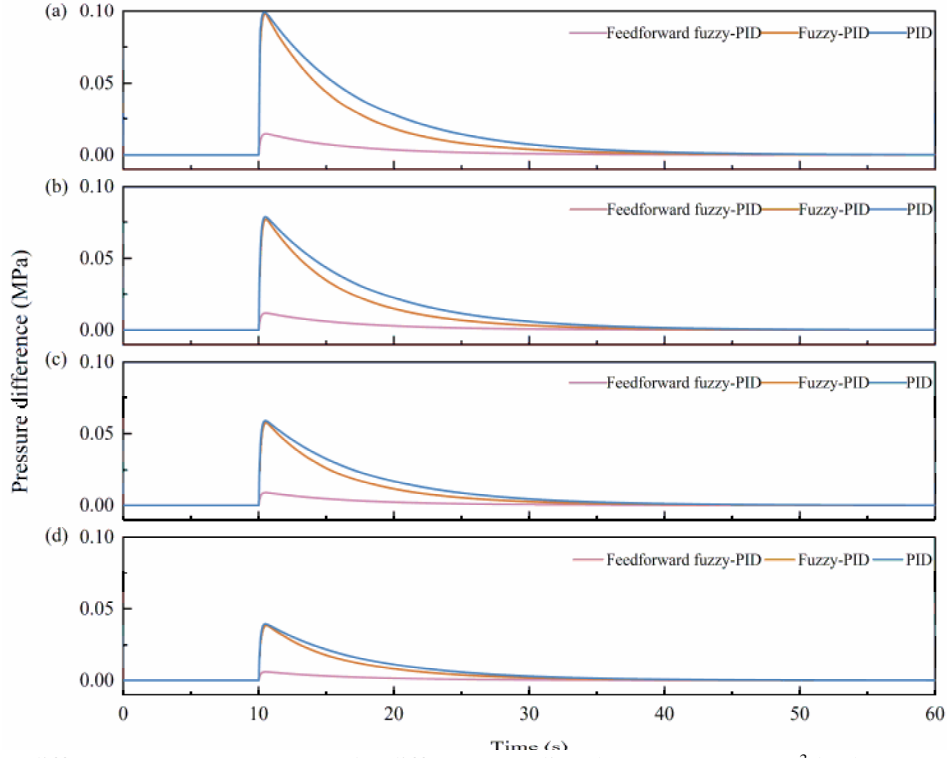


Fig. 5 Pressure-difference response curves under different step disturbances: (a) 0–20 m^3/h ; (b) 0–30 m^3/h ; (c) 0–40 m^3/h ; (d) 0–50 m^3/h

The inflow step disturbance disrupts the balance between the inflow and discharge flow rates, and the resulting residual flow-rate difference causes the pressure difference in the sealed sediment storage chamber to increase rapidly. The peak deviations achieved using feedforward fuzzy-PID range from 5.89 to 14.51 kPa, whereas those obtained using fuzzy-PID and PID range from 38.53 to 97.78 kPa and from 39.55 to 99.04 kPa, respectively, representing an approximate reduction of 85%. The settling time ranges from 13.07 to 18.85 s, which is 10.69 to 11.42 s shorter than that of fuzzy-PID and 14.96 to 15.95 s shorter than that of PID. The steady-state error ranges from 14.43 to 31.37 Pa, whereas the post-settling oscillation amplitude ranges from 19.44 to 42.21 Pa, both of which are lower than the corresponding values obtained using the two feedback control methods. Therefore, feedforward compensation reduces the residual flow-rate difference during the initial stage of the disturbance, while fuzzy-PID feedback corrects model error during the later stage. These two mechanisms jointly enhance peak suppression, response speed, and steady-state control performance.

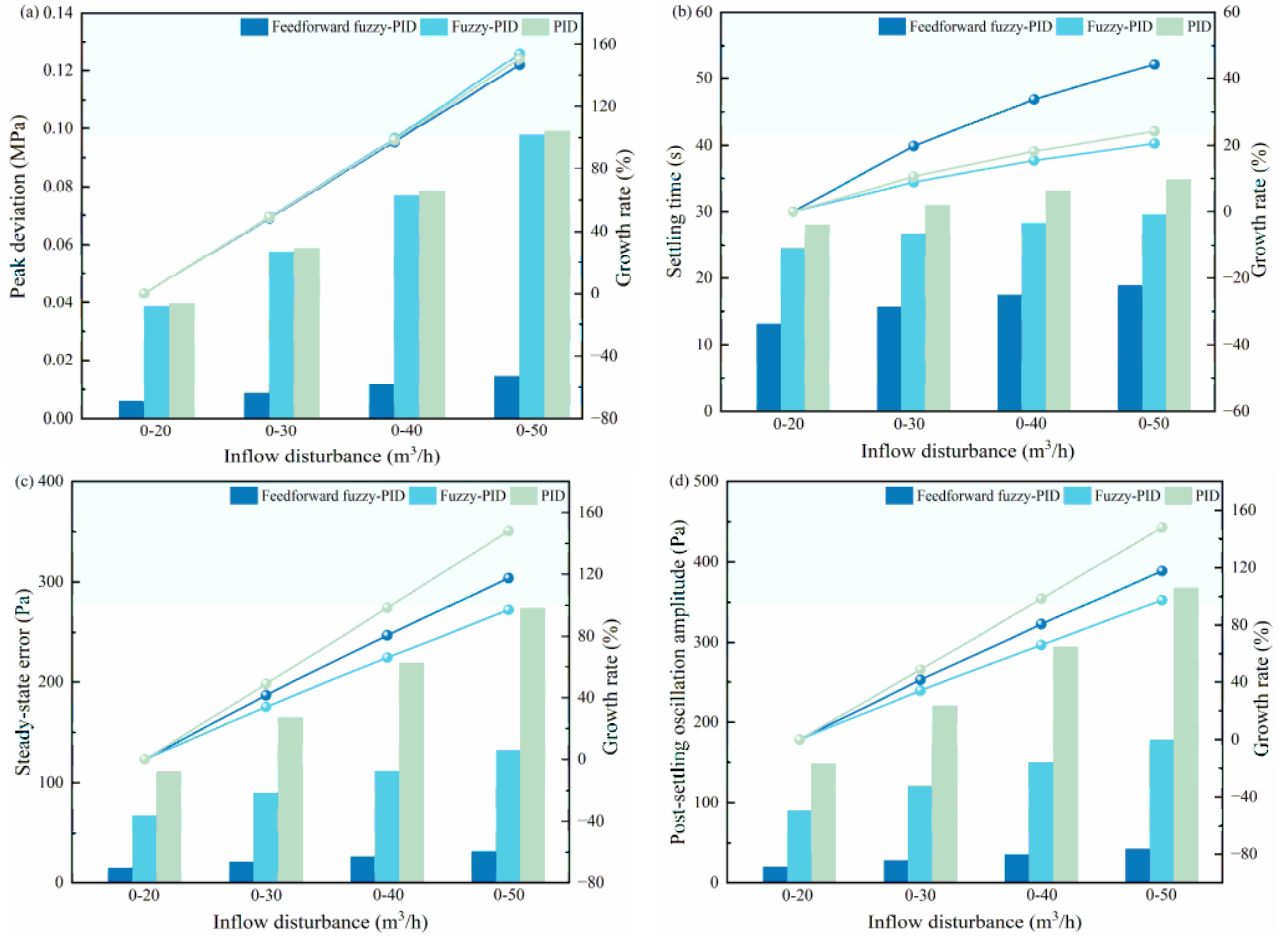


Fig. 6 Comparison under four operating conditions: (a) Peak deviation; (b) settling time; (c) steady-state error; (d) post-settling oscillation amplitude

As the inflow disturbance increases from 20 to 50 m³/h, the peak deviations obtained with feedforward fuzzy-PID increase from 5.9 to 14.5 kPa, whereas those obtained with fuzzy-PID and PID increase from 38.5 to 97.8 kPa and from 39.6 to 99.0 kPa, respectively. The settling time increases from 13.1 to 18.9 s, remaining shorter than the corresponding settling times obtained with fuzzy-PID (24.5-29.5 s) and PID (28.0-34.8 s). The increase in the settling time of feedforward fuzzy-PID is the most pronounced, whereas the response-speed growth rate of fuzzy-PID is more gradual. This behavior occurs because feedforward compensation reduces the disturbance-input amplitude but does not alter the dynamic constraints associated with the pump-set inertia and the feedback closed loop. As the disturbance amplitude increases, the discharge pump requires a greater speed correction, and the equivalent motor inertia time constant introduces a delayed response during flow compensation. The fuzzy-PID controller adjusts the control parameters online based on the error and its rate of change, improving the controller's adaptability to variations in disturbance intensity and resulting in a smoother performance trend. The growth rates of the steady-state error and post-settling oscillation amplitude are the smallest for fuzzy-PID, whereas the corresponding values are the largest for PID. This behavior is attributed to the adaptive tuning of PID parameters based on fuzzy rules, enabling fuzzy-PID to suppress residual deviations and reduce sustained oscillations more effectively during the later stage of the disturbance. In contrast, PID employs fixed parameters and is therefore less capable of simultaneously achieving rapid response and high steady-state accuracy, making it more susceptible to insufficient compensation and larger residual steady-state errors under disturbances of varying amplitudes.

4.2.2 Control performance under different values of the bulk modulus of mud

Four operating conditions with K values of 1.9, 2.0, 2.1, and 2.2 GPa are selected for simulation, and the three control methods are compared to analyze the influence of changes in the bulk modulus of mud on the dynamic response and steady-state performance of the pressure-difference control system, as shown in Figs. 7 and 8.

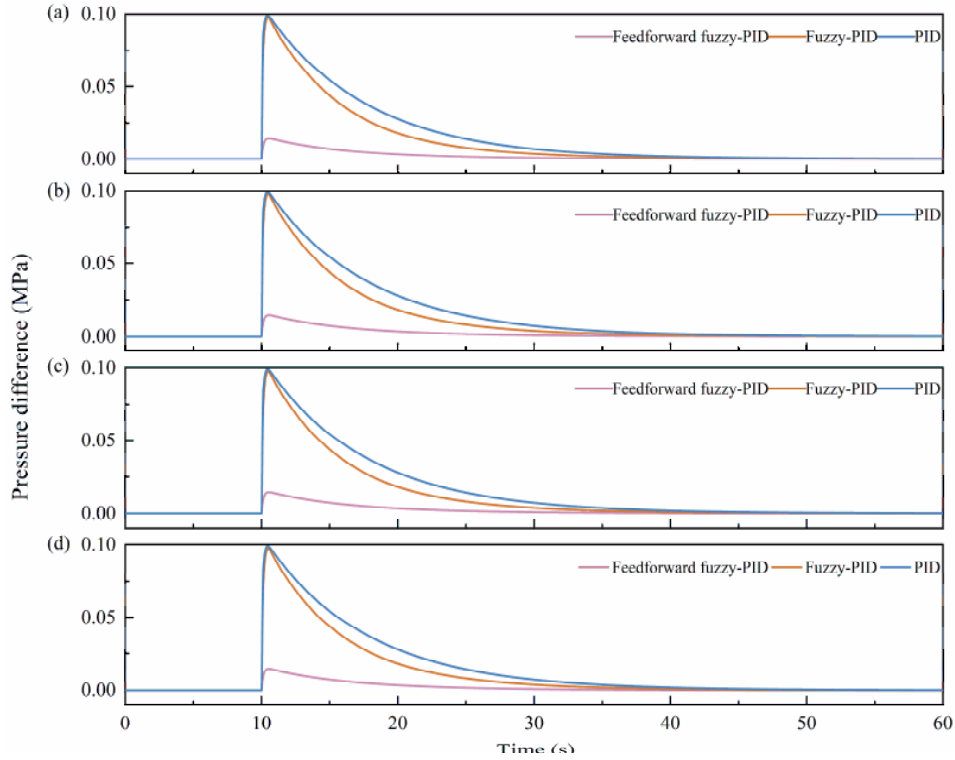
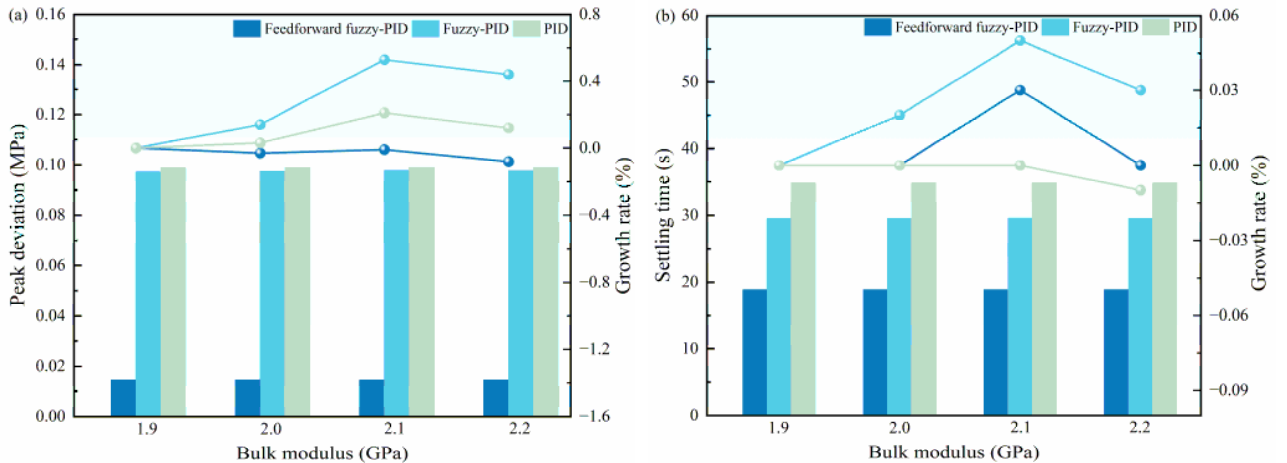


Fig. 7 Pressure-difference response curves under different values of the bulk modulus: (a) 1.9 GPa; (b) 2.0 GPa; (c) 2.1 GPa; (d) 2.2 GPa

When the bulk modulus of mud varies from 1.9 to 2.2 GPa, the peak deviations obtained with feedforward fuzzy-PID remain stable at approximately 14.41 kPa, whereas those obtained with fuzzy-PID and PID range from 96.61 to 96.89 kPa and from 98.92 to 99.04 kPa, respectively, representing an approximate reduction of 85%. The settling time remains constant at 18.84 s, which is approximately 10.65 s shorter than that of fuzzy-PID and approximately 15.96 s shorter than that of PID. The steady-state error ranges from 31.30 to 31.31 Pa, representing reductions of approximately 76% and 89% compared to fuzzy-PID and PID, respectively. The post-settling oscillation amplitude ranges from 42.05 to 42.06 Pa and is also lower than the corresponding values obtained with the two feedback control methods. These results indicate that the feedforward fuzzy-PID scheme exhibits low sensitivity to variations in the bulk modulus of mud within the tested range.



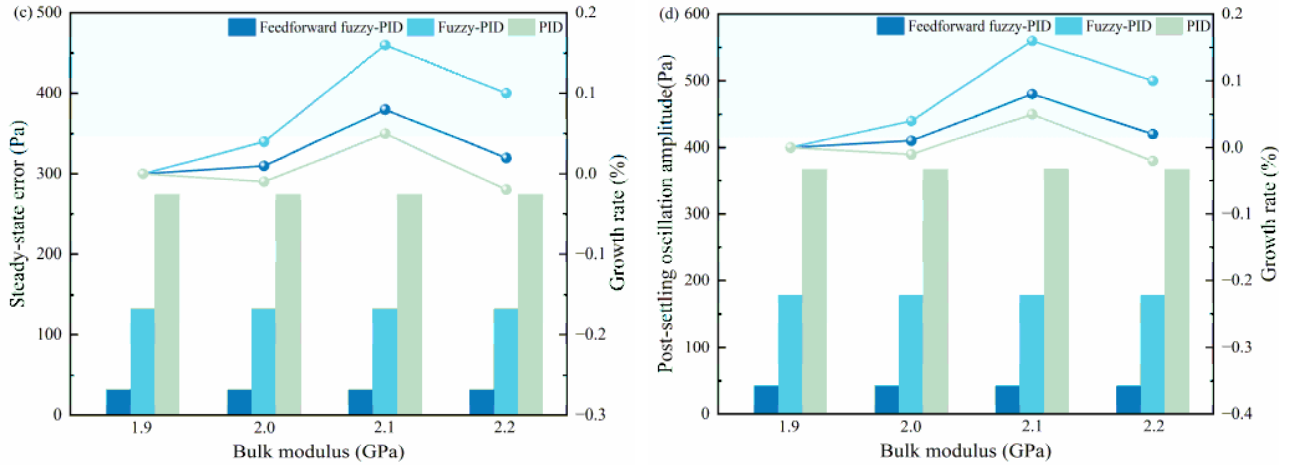


Fig. 8 Comparison under four operating conditions: (a) Peak deviation; (b) settling time; (c) steady-state error; (d) post-settling oscillation amplitude

As K increases from 1.9 to 2.2 GPa, the peak deviation of feedforward fuzzy-PID decreases by only 0.92 Pa, the settling time remains unchanged, and both the steady-state error and post-settling oscillation amplitude increase by only 0.01 Pa. In contrast, the peak deviation, steady-state error, post-settling oscillation amplitude, and average pressure deviation of fuzzy-PID increase by 281.58, 0.10, 0.13, and 28.04 Pa, respectively. Similarly, the peak deviation and average pressure deviation of PID increase by 124.42 and 11.72 Pa, respectively. Although the overall variations among the three control methods are relatively small, their growth characteristics differ. The peak deviation, settling time, and other performance indices of fuzzy-PID and PID initially increase and then decrease, whereas feedforward fuzzy-PID and PID exhibit negative growth in steady-state error and post-settling oscillation amplitude. This behavior occurs because changes in the bulk modulus of mud modify the conversion gain from the residual flow-rate difference to the pressure difference through K/V , while the inflow-disturbance amplitude remains unchanged under these operating conditions. Therefore, the system response is governed primarily by the closed-loop control adjustment process. As K/V increases, the same residual flow-rate difference produces a greater pressure-difference change rate, causing the performance indices to increase. Simultaneously, the faster pressure-difference variation enables the feedback controller to correct the discharge-pump speed earlier, accelerating the attenuation of the residual flow-rate difference. Feedforward fuzzy-PID compensates for the inflow disturbance in advance, reducing the residual flow-rate difference entering the feedback loop. Therefore, its peak deviation, steady-state error, and post-settling oscillation amplitude vary only slightly, indicating that the method has low sensitivity to changes in the bulk modulus of mud.

4.2.3 Control performance under flow disturbances after 50 s

Four disturbance-flow operating conditions of 0.001, 0.0015, 0.002, and 0.0025 m³/s are selected for simulation, and the three control methods are compared to analyze the influence of flow disturbances superimposed during the stable stage on pressure-difference control performance, as shown in Figs. 9 and 10.

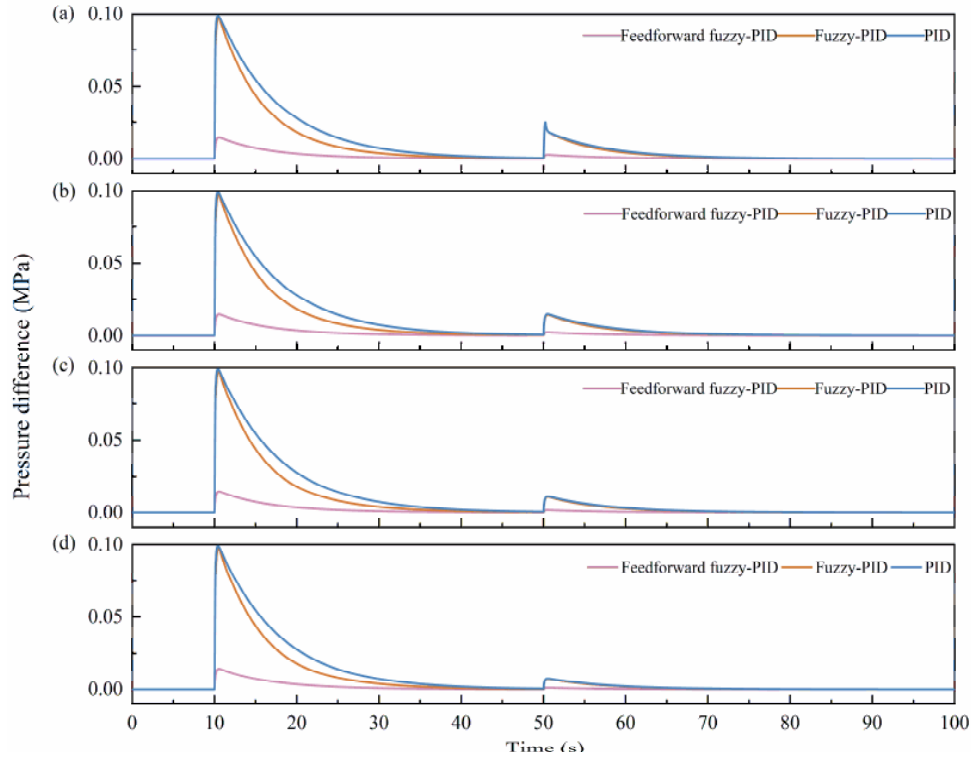
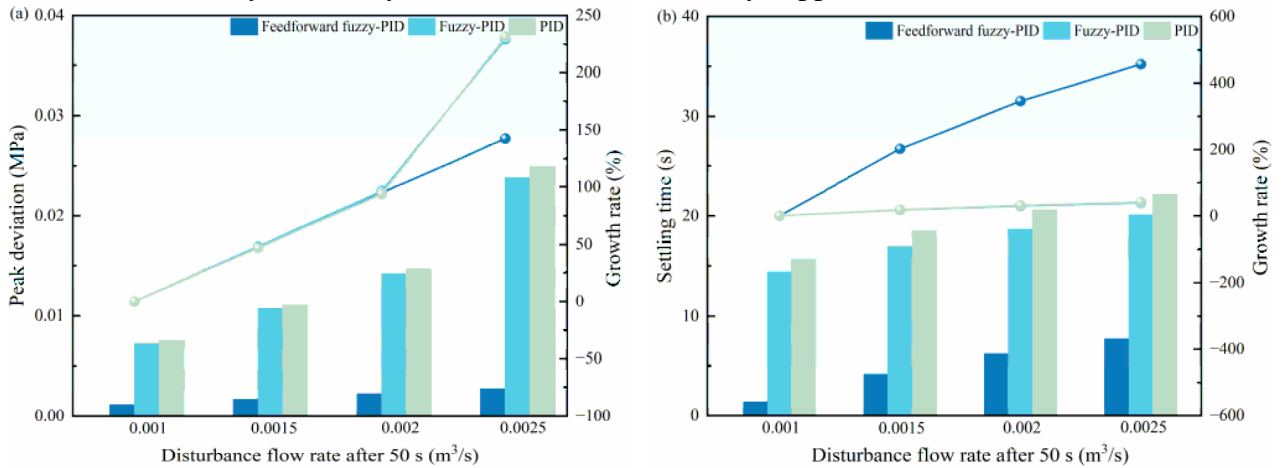


Fig. 9 Pressure-difference response curves under different disturbance flow rates: (a) 0.001 m³/s; (b) 0.0015 m³/s; (c) 0.002 m³/s; (d) 0.0025 m³/s

When a flow disturbance is introduced after the system has stabilized, the original inflow-discharge balance is disrupted, and the resulting short-term residual flow-rate difference induces a secondary pressure-difference fluctuation. The peak deviations obtained with feedforward fuzzy-PID range from 1.11 to 2.69 kPa, whereas those obtained with fuzzy-PID and PID range from 7.22 to 23.79 and from 7.53 to 24.94 kPa, respectively, corresponding to reductions of approximately 85%–89%. The settling time ranges from 1.385 to 7.705 s, which is 12.40–13.03 s shorter than that of fuzzy-PID and 14.28–14.48 s shorter than that of PID. The steady-state error and post-settling oscillation amplitude are both lower than the corresponding values obtained with the two feedback control methods. These results demonstrate that feedforward compensation adjusts the discharge-pump speed before the secondary disturbance generates a pressure-difference response, while fuzzy-PID feedback further eliminates the residual deviation. Therefore, both the transient peak and the steady-state fluctuation caused by secondary disturbances are effectively suppressed.



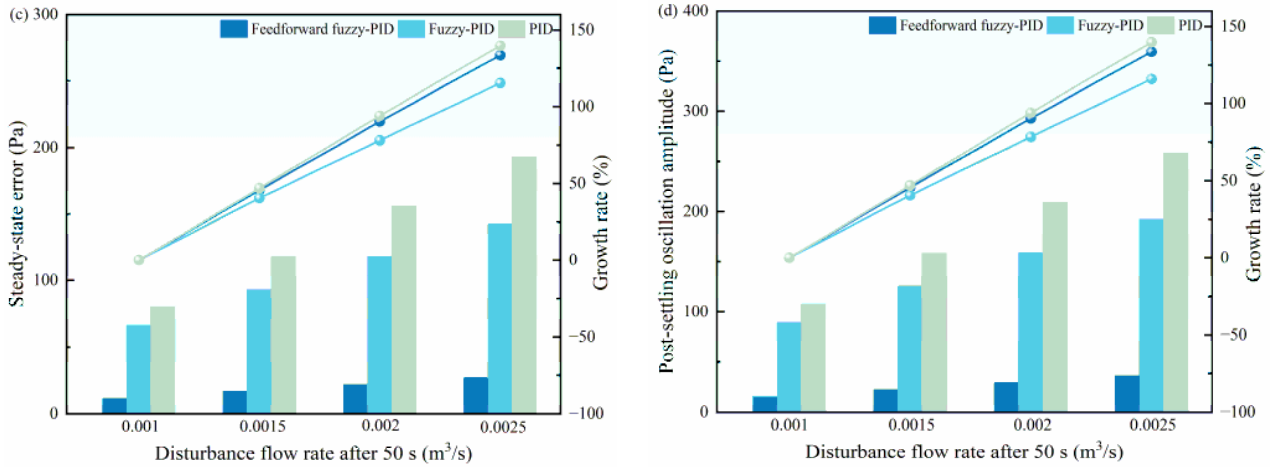


Fig. 10 Comparative results under flow disturbances after 50 s: (a) Peak deviation; (b) settling time; (c) steady-state error; (d) post-settling oscillation amplitude

As the disturbance flow rate increases from 0.001 to 0.0025 m³/s, the peak deviation of feedforward fuzzy-PID increases by 1.58 kPa, which is substantially lower than the corresponding increases observed for fuzzy-PID (16.57 kPa) and PID (17.41 kPa). Although the relative growth rate of the settling time for feedforward fuzzy-PID is relatively high, its absolute settling time remains within 1.39-7.7 s, which is still shorter than those of fuzzy-PID and PID. The peak pressure-difference growth rates of all three control methods generally increase; however, the peak-deviation growth curves of fuzzy-PID and PID exhibit pronounced inflection points, whereas feedforward fuzzy-PID maintains a faster response than both fuzzy-PID and PID. The peak growth rate of feedforward fuzzy-PID increases from 95% to 142%, indicating that feedforward compensation continues to suppress the rapid amplification of the pressure-difference peak effectively under increasing disturbance conditions. In contrast, the greater degree of flow-rate mismatch causes the pressure rise rate to exceed the effective compensation capability of the feedback controller, resulting in a sharp increase in the peak pressure-difference growth rates of fuzzy-PID and PID. The settling-time growth rate of feedforward fuzzy-PID increases from 202.17% to 456.32%. This behavior occurs because the baseline settling time of feedforward fuzzy-PID under the reference disturbance is relatively short, limiting the absolute increase, while the feedforward element does not rely on the pressure-difference error as its driving signal. Therefore, its response speed remains higher than that of fuzzy-PID and PID. Both fuzzy-PID and PID depend on error feedback and are therefore influenced by sensing, computation, and pump-set inertia delays. Overall, feedforward fuzzy-PID provides superior peak suppression while maintaining the fastest absolute response speed.

5 Conclusions

This study integrates mechanism-based modeling, flow-balance feedforward compensation, fuzzy-PID feedback control, and comparative Simulink simulations to address pressure instability, borehole-wall disturbance, and limited cleaning efficiency during sediment suction and discharge in conventional borehole-cleaning processes. A dynamic pressure-difference model of the mud pump system is established, a flow-balance-based feedforward compensation relationship is derived, and the effectiveness of the proposed pressure-regulation strategy is verified. The main conclusions are as follows.

(1) A dynamic pressure-difference model of the sealed sediment storage chamber is established. In this model, the inflow-rate command serves as the known disturbance input, the discharge-pump speed serves as the control input, and the pressure difference between the interior and exterior of the sediment storage chamber serves as the process output. The model characterizes the dynamic

relationship through which the mismatch between the inflow and discharge flow rates causes pressure-difference variations within the chamber.

(2) A flow-balance-based feedforward compensation relationship is derived. Based on the transfer functions of the inflow disturbance channel and the discharge control channel, a mapping relationship between inflow-rate variations and the discharge-pump compensation speed is established, enabling the discharge pump to compensate proactively for inflow-command disturbances before a pressure-difference error is generated.

(3) Under different inflow disturbances, the peak deviations achieved by the feedforward fuzzy-PID controller range from 5.89 to 14.51 kPa, corresponding to an approximately 85% reduction compared to fuzzy-PID and PID. The steady-state error and post-settling oscillation amplitude are also lower than the corresponding values achieved by the other two control methods. Under different values of the mud bulk modulus, the peak deviation of the feedforward fuzzy-PID controller remains approximately 14.41 kPa, the settling time remains 18.84 s, and both the steady-state error and post-settling oscillation amplitude exhibit only minor variations. Under different flow disturbances applied after 50 s, the peak deviation of the feedforward fuzzy-PID controller ranges from 1.11 to 2.69 kPa, corresponding to an 85% to 89% reduction compared to fuzzy-PID and PID. Its steady-state error is reduced by 81% to 83% and 86% relative to fuzzy-PID and PID, respectively.

The present study is limited to a short-duration, small-disturbance pressure-difference model in which the sealed sediment storage chamber is assumed to be rigid and completely filled with mud. In addition, the inflow and discharge pumps are assumed to exhibit similar local flow-rate gains and speed-response dynamics near the selected operating point. Future work focuses on parameter-perturbation simulations and prototype testing under actual sediment-cleaning conditions.

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