Coordinated Optimization Control of Shield Tunneling Machine Based on Predictive Function Control

Xuanyu Liu* and Ziming Zhao

***Abstract*—In order to avoid the ground uplift or collapse caused by shield tunneling, it is very important to keep the earth pressure balance in the shield chamber. Chamber pressure is the result of the combined action of multiple subsystems, therefore, a coordinated optimization control method based on predictive function control is proposed. Firstly, the mechanism model of the earth pressure in the shield chamber was established, and then the time domain function was converted into the frequency domain function, and the earth pressure prediction model with hysteresis was constructed. Then, based on the predictive function control, an earth pressure balance controller for the chamber was designed. According to the Smith's predictive control method, the optimal control law of the propulsion speed and the rotation speed of the screw conveyor was derived to realize the coordinated optimal control of multiple parameters of shield tunneling machine. Finally, the simulation results indicate that the method has high control accuracy and small overshoot. It can quickly track the earth pressure set value in shield chamber, and well realize the stable control of the excavation face.**

***Index Terms*—earth pressure balance (EPB) shield machine; chamber pressure; predictive function control; control law; coordinated optimal control**

I. INTRODUCTION

In recent years, with the acceleration of industrialization and urbanization, earth pressure balance shield machine has been widely used in the construction of underground tunnels in soft soil stratum. In the process of tunneling, the EPB shield machine mainly controls the earth pressure balance between that in shield chamber and the water and earth pressure in front of cutter head by adjusting the speed of screw conveyor or propulsion speed, so as to ensure the excavation face stable. In order to prevent catastrophic accidents caused by earth pressure imbalance during shield construction, it is necessary to maintain the earth pressure balance in the chamber [1], [2].

Many scholars have done a lot of research on the control of pressure balance in the chamber of EPB shield machine. Reference [3] analyzed the distribution of earth pressure in the chamber and the relationship between cutter head and soil. The mathematical model of earth pressure control in the chamber was established. Reference [4] established the earth pressure control model of the pressure chamber, based on the nonlinear constitutive relation of muck, and proposed the parameter identification method of the pressure control model of the chamber based on genetic algorithm. Reference [5] proposed a double-closed-loop control system used earth pressure feedback signal of the chamber and real-time residue discharge of screw conveyor as feedback signal to control earth pressure of the chamber. Reference [6] modeled the pressure regulating valve on the shield machine, and proposed an EPB control strategy based on adaptive robust control for the shield chamber. Reference [7] proposed an earth pressure control method based on the conservation of soil input and soil discharge, and verified the effectiveness of the model through simulation experiments. Reference [8] established the mathematical model of the EPB shield machine, and derived the mathematical expressions about the total thrust, rotation speed of screw conveyor, propulsion speed and the earth pressure in chamber. Reference [9] proposed a chamber earth pressure control method based on heuristic dynamic programming, and designed a chamber earth pressure HDP controller to achieve multi-parameter cooperative control. Reference [10] established a prediction model of the earth pressure in chamber considering cutter head torque based on particle swarm optimization (PSO) and BP neural network, and verified its effectiveness. Reference [11] established an earth pressure prediction model in soil chamber of shield machine based on data-driven method. Reference [12] proposed an EPB control system based on propulsion speed feedforward and pressure feedback of the chamber.

Most of the above studies on the EPB control of the chamber are single variable control and neglect the influence of time delay on the EPB control effect of the chamber. However, there is practical significance to the earth pressure balance control in chamber considering the coordinated control of propulsion speed and screw conveyor speed and the influence of time delay on the earth pressure. Therefore, a coordinated optimization control method based on predictive function control is proposed in this paper. The predictive function is designed based on the working principle of EPB shield machine, and the optimal control law of propulsion speed and screw conveyor speed is calculated. In the meantime, the Smith prediction method is used to overcome the time-delay problem in the actual construction process.

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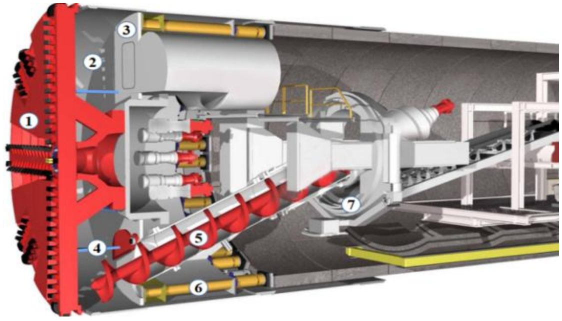
Finally, the effectiveness of the method is verified by simulation experiments.

II. The Tunneling Principle Of EPB Shield

The EPB shield machine is mainly composed of shield body, cutter head and its driving system, screw conveyor system, propulsion system, segment assembly system, synchronous grouting system and shield tail sealing device [13]. The structure diagram of EPB shield machine is shown in Fig. 1.



①Cutter head ②Chamber ③Chamber bulkhead ④Stirring rod

⑤Screw conveyor ⑥Propulsion hydraulic cylinder ⑦Segment assembler

Fig. 1 Structure diagram of EPB shield machine

The EPB shield machine has a pressure-bearing bulkhead installed in front of the shield body, which forms a closed soil chamber with the shield shell, cutter head and screw conveyor. The cutter head is in front of the chamber, and the screw conveyor is connected with the bulkhead at the bottom of the chamber. In the process of shield tunneling, the cutter head excavates the soil layer in front of it, and the cut soil fills all the space inside the chamber and screw conveyor. The shield body is pushed forward by the hydraulic cylinder. At the same time, the thrust is transmitted to the soil in the chamber through the pressure-bearing bulkhead, together with the lateral pressure produced by the self-weight of the soil body, which provides the protection pressure to balance the water and soil pressure of the excavation surface. Then, the soil in the chamber is discharged from the shield by the screw conveyor to maintain the balance between the soil amounts of entered and discharged. After that, the earth pressure inside and outside the chamber is controlled balance to maintain the excavation surface stable and prevent surface deformation [14]. The tunneling schematic diagram of the EPB shield machine is shown in Fig. 2.

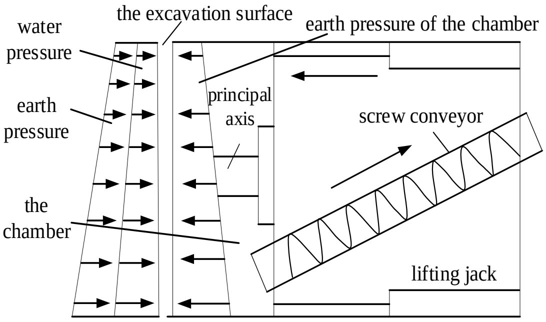


Fig. 2 Tunneling schematic diagram of the EPB shield machine

III. Design Of Predictive Function Controller For Earth Pressure Of The Chamber

Predictive functional control (PFC) is a new control algorithm developed on the basis of predictive control principle, which makes the control input more regular and has the advantages of simple algorithm, less computation, fast tracking and high control accuracy [15], [16]. Prediction function control mainly includes four parts: basis function, prediction model, feedback correction and rolling optimization which can be realized by many intelligent optimization methods [17], [18]. The structure diagram of PFC controller for earth pressure of the chamber is shown in Fig. 3.

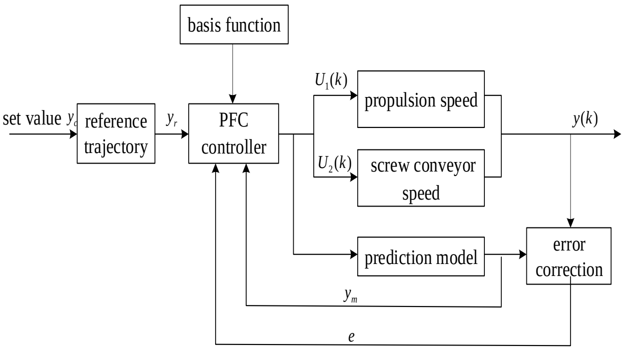


Fig. 3 Structure diagram of PFC controller for earth pressure of the chamber

A. Basis Function

The advantage of PFC is that the control input is structured and identified as a linear combination of pre-selected basis functions：

$$u(k+i)=\sum_{n=1}^{M}\mu_n f_n(i),\quad i=0,1,...,P \tag{1}$$

where $u(k+i)$ is the predictive control variable at time $k+i$, μ_n is the coefficient of the basis function, f_n is the basis function, M is the number of basis functions, P is the predictive time domain. The selection of basis functions depends on the setting of the reference trajectory and the properties of the controlled object. Generally, step functions, slope functions and exponential functions can be selected. In order to simplify the calculation, reduce the online calculation cost and do not affect the control efficiency of shield tunneling process, the step function is selected as the basis function in this paper.

B. Prediction Model

Through the analysis of the pressure control mechanism of the chamber, it can be concluded that the relation between the soil volume entered the chamber and the cross-sectional area and propulsion speed of the shield machine within Δt time is:

$$V_i = A\int v dt = Av\Delta t \tag{2}$$

where V_i is the volume of soil in the chamber, A is the cross-sectional area of the shield machine, v is the propulsion speed.

Within Δt time, the volume of muck discharged from the screw conveyor in the chamber is:

$$V_o = \int q dt = q\Delta t \tag{3}$$

$$q = \frac{A_s \omega h \eta}{2\pi} \tag{4}$$

where V_o is the volume of muck discharged, q is the discharging rate of screw conveyor, $A_s=\pi\ (r_s^2-r_f^2)$, A_s is the effective discharge area of screw conveyor, r_s is the radius of screw conveyor, r_f is the radius of screw conveyor shaft, ω is the screw conveyor speed, h is the pitch of screw conveyor, η is the efficiency of discharge.

Then within Δt time, the variation of soil volume in the chamber is:

$$\Delta V = V_i - V_o \tag{5}$$

According to the additional internal force of soil in unit area, the variation of soil volume and the variation of earth pressure in the chamber can be expressed as [19]:

$$\Delta p_b = E_t(k)\Delta\varepsilon \tag{6}$$

$$\Delta\varepsilon = \frac{\Delta L}{L} = \frac{A\Delta L}{AL} = \frac{\Delta V}{V_c} \tag{7}$$

where Δp_b is the variation of earth pressure in chamber, $E_t(k)$ is the modulus of soil deformation, V_c is the volume of the chamber.

By substituting Eq. (7) into Eq. (6), the relationship between the variation of earth pressure and the propulsion speed and the screw conveyor speed can be obtained:

$$\Delta p_b = \frac{E_t(k)}{V_c}\left[Av(k) - A_s\omega(k)h\eta\right]\Delta t \tag{8}$$

On the basis of Eq. (8), the time domain function is transformed into frequency domain function. Considering the inertia time of propulsion system and muck discharging system, as well as the influence of time delay on the earth pressure of the chamber, the prediction model can be obtained:

$$P_b(s) = \frac{k_1}{T_m s+1}e^{-\tau s}\cdot\frac{v}{s} - \frac{k_2}{T_n s+1}e^{-\tau s}\cdot\frac{\omega}{s} \tag{9}$$

where $k_1 = \dfrac{E_t(k)A}{V_c}$, $k_2 = \dfrac{E_t(k)A_s h}{V_c}$, $e^{-\tau s}$ is the delay part, τ is the delay time constant, T_m and T_n represent the inertia time of the propulsion system and the screw conveyor system respectively.

From Eq. (9), it can be seen that process channels of each system are in the form of transfer function, whose transfer function expression can be expressed as:

$$G_m(s) = \begin{bmatrix} \dfrac{k_{m1}}{T_m s+1} & -\dfrac{k_{m2}}{T_n s+1} \end{bmatrix} \tag{10}$$

Then the predictive output of the model can be expressed as:

$$y_m(s) = G_m(s)\begin{bmatrix} u_1(s) \\ u_2(s) \end{bmatrix} \tag{11}$$

where y_m is the earth pressure value in the chamber, u_1 is the propulsion speed, u_2 is the screw conveyor speed.

Firstly, the prediction model when τ=0 is obtained:

$$G'_m(s) = \begin{bmatrix} \dfrac{k_{m1}}{T_m s+1} & -\dfrac{k_{m2}}{T_n s+1} \end{bmatrix} \tag{12}$$

Then the predictive output is:

$$y'_m(s) = G'_m(s)\begin{bmatrix} u_1(s) \\ u_2(s) \end{bmatrix} \tag{13}$$

Then, a zero-order hold is added to discretize the predictive output, and the difference equation can be obtained as follows:

$$\begin{aligned} y'_m(k+1) &= (\alpha_1+\alpha_2)y'_m(k) - \alpha_1\alpha_2 y'_m(k-1) \\ &+k_{m1}(1-\alpha_2)\left[u_1(k) - \alpha_2 u_2(k-1)\right] \\ &-k_{m2}(1-\alpha_2)\left[u_2(k) - \alpha_1 u_2(k-1)\right] \end{aligned} \tag{14}$$

where $\alpha_1=e^{-Ts/Tm}$, $\alpha_2=e^{-Ts/Tn}$, T_s is the sampling time.

When the step function is used as the basis function, the properties of the step function can be obtained:

$$u(k+i) = u(k) \qquad i = 1,2,... \tag{15}$$

Through Eq. (14), (15) and mathematical induction, the predictive output values of the future P-step model can be derived:

$$\begin{aligned} y'_m(k+P) = {} & \frac{\alpha_1^{P+1}-\alpha_2^{P+1}}{\alpha_1-\alpha_2}y'_m(k) - \alpha_1\alpha_2\frac{\alpha_1^{P}-\alpha_2^{P}}{\alpha_1-\alpha_2} \\ & \times y'_m(k-1) + k_{m1}(1-\alpha_1^{P})u_1(k) - k_{m1}(1-\alpha_1) \\ & \times\alpha_2\frac{\alpha_1^{P}-\alpha_2^{P}}{\alpha_1-\alpha_2}u_1(k-1) - k_{m2}(1-\alpha_2^{P})u_2(k) \\ & -k_{m2}(1-\alpha_2)\alpha_1\frac{\alpha_1^{P}-\alpha_2^{P}}{\alpha_1-\alpha_2}u_2(k-1) \end{aligned} \tag{16}$$

C. Feedback Correction And Reference Trajectory

Considering that there will be errors between the prediction model and the actual output, the difference between the actual output and the predictive output at the current moment is introduced to represent the prediction error:

$$e(k+i) = y_p(k) - y_m(k) \tag{17}$$

where $y_p(k)$ is the actual output value at the current time, $y_m(k)$ is the predictive output value at the current time.

Then the future predictive output value is revised to:

$$\hat{y}_m(k+i) = y_m(k+i) + e(k+i) \tag{18}$$

Choose the first order exponential form as the reference trajectory:

$$y_r(k+i) = y_c(k+i) - \lambda^i\left[y_c(k) - y_p(k)\right] \tag{19}$$

where y_r is the reference trajectory, y_c is the set value,

$\lambda=e^{-Ts/Tr}$, λ is the softening factor, T_r is the reference trajectory time constant.

D. Rolling Optimization

The purpose of rolling optimization in predictive function control is to find the coefficients of each basis function $\mu_1,\mu_2,\cdots,\mu_M$, and makes the predictive output $y_m(k+i)$ as close as possible to the reference trajectory $y_r(k+i)$. In this paper, quadratic performance index is selected as the objective function, which is represented by the minimum error sum of the squares between the predictive output and the reference trajectory:

$$\begin{aligned} &\min J=\min\left[y_r(k+i)-y_m(k+i)\right]^2 \\ &\quad s.t\quad u_{1\min}\le u_1(k)\le u_{1\max} \\ &\qquad\quad\ u_{2\min}\le u_2(k)\le u_{2\max} \end{aligned} \tag{20}$$

Separate order:

$$\begin{aligned} \frac{\partial J}{\partial u_1(k)}=0 \\ \frac{\partial J}{\partial u_2(k)}=0 \end{aligned} \tag{21}$$

The optimal control law of the propulsion speed and the screw conveyor speed at $\tau=0$ can be obtained as follows:

$$\begin{aligned} u_1(k)=&\frac{1}{k_{m1}(1-\alpha_1^P)}\cdot[y_r(k+P)-e(k+P) \\ &-\frac{\alpha_1^{P+1}-\alpha_2^{P+1}}{\alpha_1-\alpha_2}y_m'(k)+\alpha_1\alpha_2\frac{\alpha_1^P-\alpha_2^P}{\alpha_1-\alpha_2}y_m'(k-1) \\ &+k_{m1}(1-\alpha_1)\alpha_2\frac{\alpha_1^P-\alpha_2^P}{\alpha_1-\alpha_2}u_1(k-1) \\ &+k_{m2}(1-\alpha_2)\alpha_1\frac{\alpha_1^P-\alpha_2^P}{\alpha_1-\alpha_2}u_2(k-1)] \end{aligned} \tag{22}$$

$$\begin{aligned} u_2(k)=&\frac{1}{k_{m2}(1-\alpha_2^P)}\cdot[y_r(k+P)-e(k+P) \\ &-\frac{\alpha_1^{P+1}-\alpha_2^{P+1}}{\alpha_1-\alpha_2}y_m'(k)+\alpha_1\alpha_2\frac{\alpha_1^P-\alpha_2^P}{\alpha_1-\alpha_2}y_m'(k-1) \\ &+k_{m1}(1-\alpha_1)\alpha_2\frac{\alpha_1^P-\alpha_2^P}{\alpha_1-\alpha_2}u_1(k-1) \\ &+k_{m2}(1-\alpha_2)\alpha_1\frac{\alpha_1^P-\alpha_2^P}{\alpha_1-\alpha_2}u_2(k-1)] \end{aligned} \tag{23}$$

Generally, during the shield tunneling process $\tau\neq0$. When $\tau\neq0$, according to Smith prediction control method, the predictive function control still uses the models of Eq. (22) and (23) to correct the actual measured values. The correction method is as follows:

$$y_{pav}(k)=y_p(k)+y_m(k)-y_m(k-D) \tag{24}$$

where $y_{pav}(k)$ is the corrected process output value, $D=\tau/T_s$.

If $y_p(k)$ is replaced by the correction value $y_{pav}(k)$, considering the time delay of the propulsion speed and the screw conveyor speed, the optimal control law is:

$$\begin{aligned} u_1(k)=&\frac{1}{k_{m1}(1-\alpha_1^P)}\cdot[y_c(k+P)-\lambda^P y_c(k) \\ &-y_{pav}(k)(1-\lambda^P)+y_m'(k)-\frac{\alpha_1^{P+1}-\alpha_2^{P+1}}{\alpha_1-\alpha_2}y_m'(k) \\ &+\alpha_1\alpha_2\frac{\alpha_1^P-\alpha_2^P}{\alpha_1-\alpha_2}y_m'(k-1)+k_{m1}(1-\alpha_1)\alpha_2 \\ &\times\frac{\alpha_1^P-\alpha_2^P}{\alpha_1-\alpha_2}u_1(k-1)+k_{m2}(1-\alpha_2)\alpha_1\frac{\alpha_1^P-\alpha_2^P}{\alpha_1-\alpha_2}u_2(k-1)] \end{aligned} \tag{25}$$

$$\begin{aligned} u_2(k)=&\frac{1}{k_{m2}(1-\alpha_2^P)}\cdot[y_c(k+P)-\lambda^P y_c(k) \\ &-y_{pav}(k)(1-\lambda^P)+y_m'(k)-\frac{\alpha_1^{P+1}-\alpha_2^{P+1}}{\alpha_1-\alpha_2}y_m'(k) \\ &+\alpha_1\alpha_2\frac{\alpha_1^P-\alpha_2^P}{\alpha_1-\alpha_2}y_m'(k-1)+k_{m1}(1-\alpha_1)\alpha_2 \\ &\times\frac{\alpha_1^P-\alpha_2^P}{\alpha_1-\alpha_2}u_1(k-1)+k_{m2}(1-\alpha_2)\alpha_1\frac{\alpha_1^P-\alpha_2^P}{\alpha_1-\alpha_2}u_2(k-1)] \end{aligned} \tag{26}$$

IV. SIMULATION EXPERIMENT

In order to verify the effectiveness of the designed controller, the pressure control system of the chamber of EPB shield machine is taken as the research object in this paper, and the performance of the earth pressure controller of the chamber is tested. The pressure in the chamber is mainly affected by the subsystems such as cutter head, propulsion and slag discharge. It is related to the rotation speed of cutter head, propulsion force, propulsion speed and screw conveyor speed. In the actual excavation process, the screw conveyor speed or propulsion speed is usually adjusted only under the same geological conditions and working conditions. In this paper, the earth pressure balance of the chamber is controlled by coordinated adjustment of propulsion speed and screw conveyor speed. The simulation experiments are carried out by using MATLAB. The data involved in the simulation process are all derived from the actual EPB shield machine construction site in Beijing metro tunnel. The parameters of shield machine are shown in Table 1.

Table 1 Shield machine parameters

Parameter	Value
Shield diameter/mm	6250
Cross-sectional area of the shield machine/m^2	30.96
Chamber volume/m³	27.86
Effective earth discharge area of screw conveyor/m^2	0.396
Screw conveyor pitch/m	0.8
Maximum propulsion speed/mm/min	80
Screw conveyor maximum speed/r/min	15

A. Project Overview For Data Collection

The data for simulation are collected from a section of a metro construction tunnel. According to the age of stratum formation, the geological characteristics of the tunnel engineering are divided into two primary layers, artificially accumulating layer and quaternary sedimentary layer, which mainly include miscellaneous fill, sandy clay, silty clay, fine sand, and pebbles. The schematic illustration of the tunnel is shown in Fig. 4. The burial depth of this tunnel ranges from 8.2 m to 26.8 m. The depth of the water table ranges from 16.02 m to 25.46 m and the tunnel across the Liangshui River.

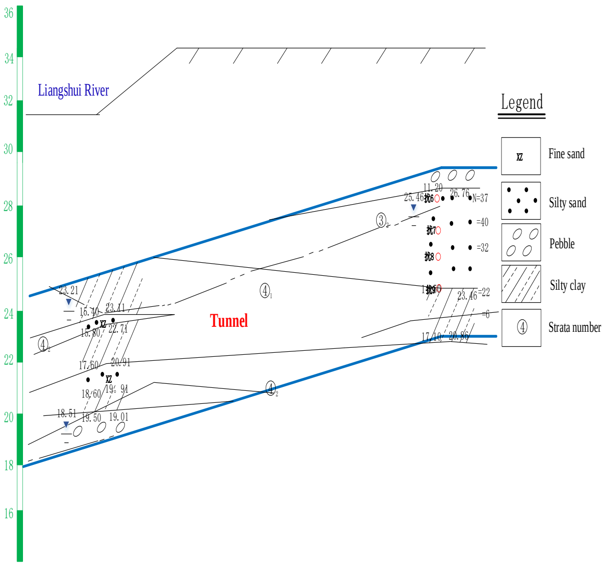


Fig. 4 Geology vertical section profile of the tunnel

The diameter of the shield machine is 6.25 m and the excavation diameter is 6.28 m. Four pressure sensors S_1, S_2, S_3, S_4 are employed to monitor the earth pressure in soil chamber. They are placed on the horizontal and vertical lines perpendicular of the center of the bulkhead, and the distance from the circumference is 0.9 m, as shown in Fig. 5. In actual tunneling construction process, the earth pressure of point S_1 is usually taken as the control target, and the other earth pressure of the sensors S_2, S_3, S_4 are taken as reference. When the earth pressure of S_1 deviates from the set value, the shield machine operator will adjust the control parameters to keep the earth pressure balance. Therefore, in this paper the pressure data are collected from the sensor S_1 to carry out the simulation.

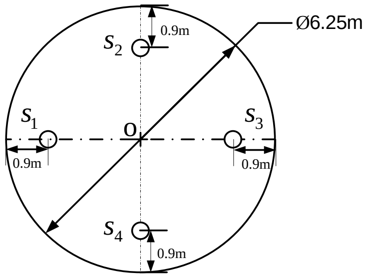


Fig. 5 Pressure sensors distribution on bulkhead in chamber

B. Simulation Results

In the simulation experiment, the predictive time domain P=20, the control time domain m=2, the sampling time T_s=1, the propulsion speed $u_1(k)$ and the screw conveyor speed $u_2(k)$ are 0-80mm/min and 0-15r/min respectively. The simulation results are shown as Fig. 6-Fig. 8.

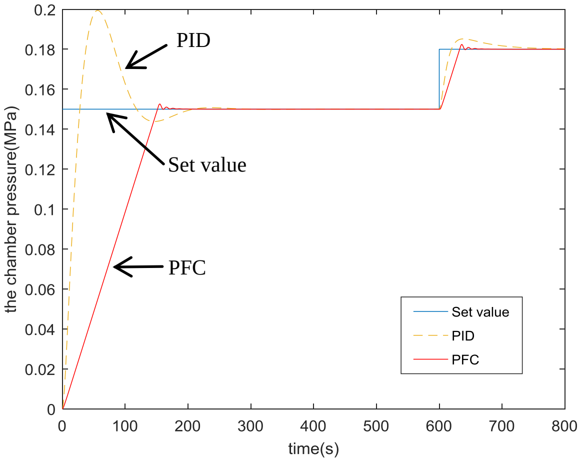


Fig. 6 The effect comparison of PFC and PID control for chamber pressure

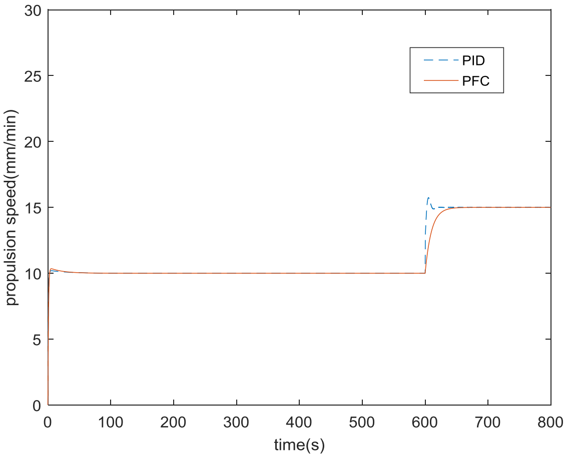


Fig. 7 The propulsion speed change comparison of PFC and PID control

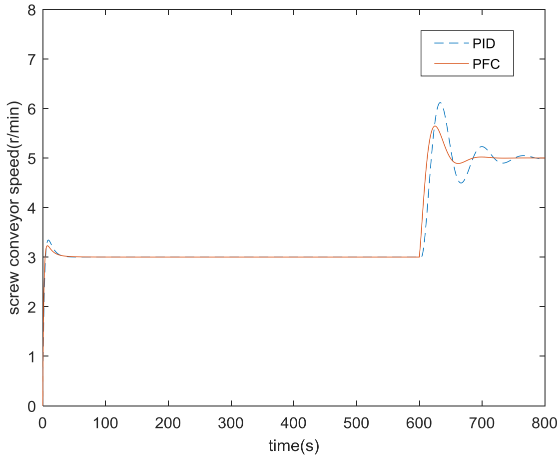


Fig. 8 The screw conveyor speed change comparison of PFC and PID control

The control effect of earth pressure in chamber is shown in Fig. 6. The earth pressure balance is controlled by adjusting the propulsion speed and screw conveyor speed. The first 600s EPB shield machine tunnels forward at a speed of 10mm/min, and the screw conveyor speed is 3r/min. At this time, the chamber pressure of the shield machine keeps stable at 0.15 MPa. We can see that the predictive function controller can quickly track the earth pressure setting value 0.15 MPa, but the PID controller tracks the pressure setting value after a large overshoot. At 600 s, due to the change of geological conditions, the pressure of the chamber rises from 0.15 MPa to 0.18 MPa. We can see that the PID controller still needs a longer period and a lager range adjustment than the PFC controller. It is indicated that the PFC controller has small overshoot, high control accuracy. It can track the pressure setting value in the chamber effectively and quickly, thereby reducing the occurrence of ground uplift or collapse.

In the meantime, the optimal propulsion speed and screw conveyor speed are shown in Fig. 7 and Fig. 8. From Fig. 7, we can see that the optimal propulsion speed is smoothly increased to 15mm/min. From Fig. 8 we can see that the the screw conveyor speed varies a long time with the change of geological conditions, but the variation range and time are less than those of the PID controller.

Table 2 Quantitative analysis of simulation results

Method	Rise time (s)	Overshoot (%)	Settling time (s)	Steady-state error (%)
PID	26.35	15.78	93.67	1.276
PFC	41.62	2.53	61.25	0

To demonstrate the performance of the controller proposed in this paper, the quantitative comparison analysis of the simulation results between PID controller and PFC controller is shown in Table 2. For comparison, the quantitative performance indexes of the two controllers are given. From Table 2 we can see that the overshoot has been reduced from 15.78% to 2.53%, and the settling time has been reduced from 93.67 s to 61.25 s. The steady-state error has been reduced to 0, which indicates the PFC has higher control precision. Only the rise time increases from 26.35 s to 41.62 s, for the PFC controller needs to establish the prediction model and rolling optimize computation. But it does not affect the control results of the earth pressure in chamber, because the tunneling is a slow time variable, great inertia and large time lag process. Above all, we can see that the overall performance of PFC is better than that of PID. It is a good way to control the earth pressure balance in chamber in actual tunneling engineering.

From the simulation results, we can see that the coordinated optimization control of shield tunneling machine is come true. During the tunneling process, the propulsion speed and screw conveyor speed can be adjusted simultaneously, and the control effect of earth pressure balance is better than that adjust one control parameter. So this method provides a very effective way of ensuring the construction safety in the tunnel engineering. It lays theory foundation for realizing the shield machine intelligent.

V. CONCLUSION

In this paper, an earth pressure prediction model in the chamber is established based on the excavation mechanism of EPB shield machine. On this basis, the optimal control law of the propulsion speed and the screw conveyor speed is derived considering the time delay. The multi-parameter coordinated optimization control of the EPB shield machine is realized. The conclusions are obtained as follows by simulations.

(1) Compared with the PID controller, the results show that the earth pressure PFC controller can track the earth pressure setting value in the chamber more quickly and effectively under the coordinated control of the propulsion speed and the screw conveyor speed.

(2) Under different geology conditions, the PFC controller not only has higher steady-state precision but can effectively restrain the overshoot. This method has good stability and adaptability.

(3) The proposed method can realize the purpose of safe and efficient tunneling construction of shield machine. It provides a new idea for the earth pressure balance control of the excavation face in actual tunnel project. It will lay the foundation for realizing intelligent optimization control of shield machine.

(4) In order to control the excavation face of shield machine stable better, the best way is that the earth pressure of all points S_1, S_2, S_3, S_4 can be considered as control targets. So the earth pressure dynamic change of the entire excavation face can be controlled. It is our research focus in future.

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