Pressure Balance Control System for Slurry Shield Based on Predictive Function Control

Xiuliang Li[1(✉)], Hepei Zhang[2], Yifan Xue[3], and Chengjun Shao[4]

[1] State Key Laboratory of Shield Machine and Boring Technology, State Key Laboratory of Industrial Control Technology, Zhejiang University, Zhejiang 310027, China
xiuliangli@csc.zju.edu.cn
[2] State Key Laboratory of Shield Machine and Boring Technology, Zhengzhou 450001, China
[3] Control Department, Zhejiang University, Zhejiang 310027, China
[4] Institute of Cyber-System and Control, Zhejiang University, Zhejiang 310027, China

Abstract. The most important part of the excavation for slurry shield machine is keeping the earth pressure and slurry circulation system pressure in balance. In this paper, an excavating face pressure balance principle for direct type slurry shield machine is analyzed and the pressure balance dynamic model is introduced. Then, a controller is designed based on predictive function control method. Finally, the controller initialization method is proposed to deal with the problem of controller switching from manual to automatic mode. Simulation results show the improved performance of proposed method.

Keywords: Slurry shield · Slurry circulation system · Predictive function control

1 Introduction

The slurry shield is an important branch of the modern shield method, which is widely applied around the world. Slurry shield method is the most commonly used method, especially underwater tunnel in soft soil in the river and sea [1-3]. The control of pressure for excavating face is an important part in the process of tunneling across the river. Once the control is improper, it will cause the working face collapse, the river flow backward and a series of safety problems.

According to the slurry circulation pressure control methods, the slurry shield can be divided into two basic types, indirect control type (German style with bubble chamber) and direct control type as Fig. 1 (Japanese style without bubble chamber) [1]. Unlike German style shield, direct control shield does not have bubble chamber part, the pressure of chamber is controlled by the flow of feed or discharge slurry pump. Slurry in chamber of direct control shield will be easier to be discharged than German style shield in the absence of bubble chamber. So the slurry in chamber will

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be less able to precipitate. However, the pressure in slurry will be under the big and fast disturbance by input/output feed pump flow and the driving speed. As the shield does not have bubble chamber part to buffer the impact of disturbance, the pressure balance control is more difficult compared to the German style shield. Yunpu Song has designed a dynamic model and controller for German style shield. But the design of pressure balance controller of direct control shield is rarely mentioned [4].

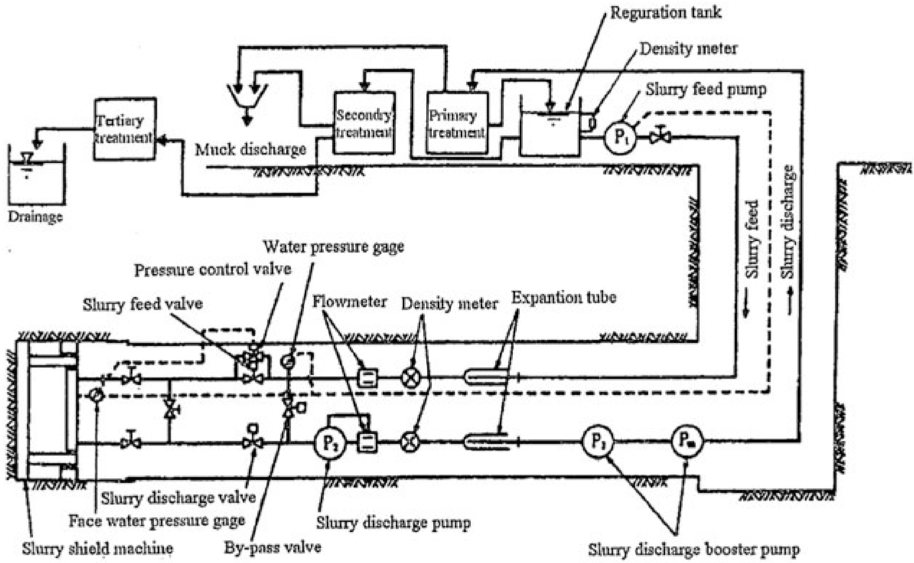

Fig. 1. Direct control type slurry shield: Slurry circulation system

This paper analyzes the composition and principle of circulation system, then establishes the pressure balance dynamic model for circulation system. A controller is designed based on predictive function control method which is easier to be implemented in program logic controller (PLC).

2 The Dynamic Model of Slurry Circulation System in Continuous Excavation Process

In order to simplify the problem, this paper only take the pressure balance problem in continuous excavation mode into account, ignoring the shutdown mode and by-pass mode. In continuous excavation mode, the pressure of chamber is controlled by the flowrate of slurry feed pump P1, and the slurry is discharged by the flowrate of slurry discharge pump P2. The schematic diagram of slurry circulation system is Fig. 2.

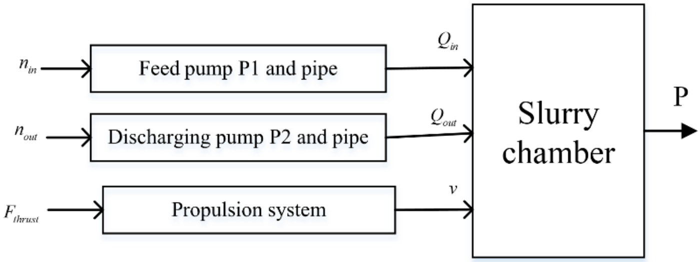

Fig. 2. Schematic diagram of slurry circulation system

2.1 Pressure Model of Slurry Chamber

This paper assumes the chamber is in a sealed environment and the pressure gradient distribution in chamber is ignored. In continuous excavation mode, the amount of slurry in chamber will be changed by the excavation soil, the slurry flowrate of feed pump and discharge pump, the elastic modulus of slurry in chamber can be expressed as [5]

$$K = -\frac{dP}{dV/V_0} \tag{1}$$

which K is modulus of elasticity. P is pressure of slurry, V_0 is the volume of chamber.

The volume variation of slurry in chamber is

$$dV = Q_{out} - Q_{in} - v \times A \tag{2}$$

where v is shield advanced rate, A is excavation area of shield, Q_{out} is flowrate of feed pump P1, Q_{in} is discharge flowrate of pump P2.

Combine equation 1 and equation 2

$$dP = -\frac{Q_{out} - Q_{in} - v\pi r^2}{\pi r^2 d} \tag{3}$$

where r is radius of excavation face, d is the length of chamber.

At normal state, the chamber is not full of slurry and there is some air in the top of chamber), which will affect transient process of pressure. Density of slurry will change by excavating. The transfer function model of pressure in chamber can be described as below

$$P(s) = \frac{K_{in}}{s(T_{in} \times s + 1)} Q_{in}(s) + \frac{K_v}{s(T_v \times s + 1)} v(s) - \frac{K_{out}}{s(T_{out} \times s + 1)} Q_{out}(s) \tag{4}$$

2.2 Model of Pump and Pipe

Slurry pipeline contains two main part: feed pump pipeline and discharge pump pipelines. According to the principle of hydrodynamics, the fluid mechanical energy of slurry is affected by pipe friction and the gravity of slurry in pipe. As the mechanical energy of the fluid in pipe is driving by slurry pump, then the model of slurry pipe is

$$h_e = \Delta Z + \frac{\Delta p}{\rho g} + h_f \tag{5}$$

which h_e is the pressure head of pipe, ΔZ is the height difference between pipe inlet and outlet, Δp is the static pressure difference between pipe inlet and outlet. ρ is the density of slurry, g is acceleration of gravity. h_f is the pressure head caused by friction loss.

h_f is include two part, first part is the friction loss h_{f1} which caused by the friction between liquid flow and pipe

$$h_{f1} = \lambda \frac{l}{d} \frac{u^2}{2g} \tag{6}$$

where u is fluid flowrate, l is the length of pipe, d is the diameter of pipe, λ is friction coefficient, $\lambda = 64\frac{1}{\mathrm{Re}} = 64\frac{du\rho}{\mu}$ as the slurry flow in pipe is laminar flow. The other part is the pressure loss h_{f2} caused by turn valves and sudden changes in fluid which can be calculated by local resistance coefficient method.

$$f_{f2} = \xi \frac{u^2}{2g} \tag{7}$$

where ξ is constant for a certain type of pipes or valves.

Since slurry is transported by the centrifugal pump, the centrifugal pump characteristic curve equation can be used to describe the relationship between pump work point and fluid velocity in pipe.

$$K_{motor} n^3 = \frac{HQ\rho g}{\eta} \tag{8}$$

where K_{motor} is the power conversion coefficient from motor to bearing, n is rotational speed of motor, H is the lift head of pump, Q is flowrate of pump, ρ is liquid density, η is the efficiency of pump.

2.3 Model of Propulsion System

Since the pressure of excavation face and thrust pressure must keep in balance, according to Newton's law of motion, the speed of shield is

$$m\dot{v} = F_{thrust} - PA + cv + f \tag{9}$$

where c is damping coefficient, f is sliding friction.

3 Controller Design for Slurry Circulation System

In the design of the controller for slurry shield excavating face balance system, PID control method is typically used in project. However, equation 9 shows that the excavating face pressure is affected not only by the advance rate, but also by the feed pump flowrate and the discharge pump flowrate, even by slurry density. To prevent the mud sedimentation, the flowrate of discharge pump should not be below critical velocity. In order to provide adequate pressure head, the feed pump should work in a small work point region. Conventional PID control method cannot take these measured disturbance and constraints into account, overshoot and fluctuations will appear in the excavation pressure control. Based on predictive function control (PFC) method which can deal with above factors, the controller can be designed as Fig. 3.

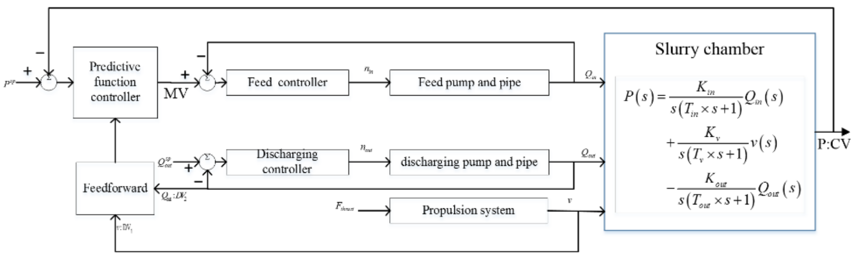

Fig. 3. Controller design for slurry circulation system

The flowrate of feed pump and discharge pump are controlled by traditional controller, such as PID. The pressure balance system is controlled by PFC with discharge flowrate and advanced velocity as feedforward [6].

3.1 Predictive Function Control

The desired increment Δp in Fig. 4 at $n+h$ will be given by

$$\Delta p=\varepsilon(n+h)=\varepsilon(n),\ \ where\ \Delta p=\varepsilon(n)\left(1-\lambda^h\right),\lambda=e^{\frac{T_s}{T}}$$
$$and\ \Delta p=\left(\text{Setpoint}-\text{Process output(n)}\right)\left(1-\lambda^h\right) \tag{10}$$

where T is the time constant of system, T_s is sample period of controller.

The model output increment Δm may be easily calculated because it is evaluated in the mathematical domain where all relevant information is known. The increment will be composed of the free output $S_L(n+h)$ in conjunction with the forced output $S_F(n+h)$ that contains the projection of the required MV:

$$\left(\text{Setpoint}-\text{Process output(n)}\right)\left(1-\lambda^h\right)=\text{forced output}\left(n+h\right)+\text{free output}\left(n+h\right)-\text{model output}\left(n\right) \tag{11}$$

$$MV(n)=\frac{\text{Desired increment-Free output increment}}{\text{Unit forced output}} \tag{12}$$

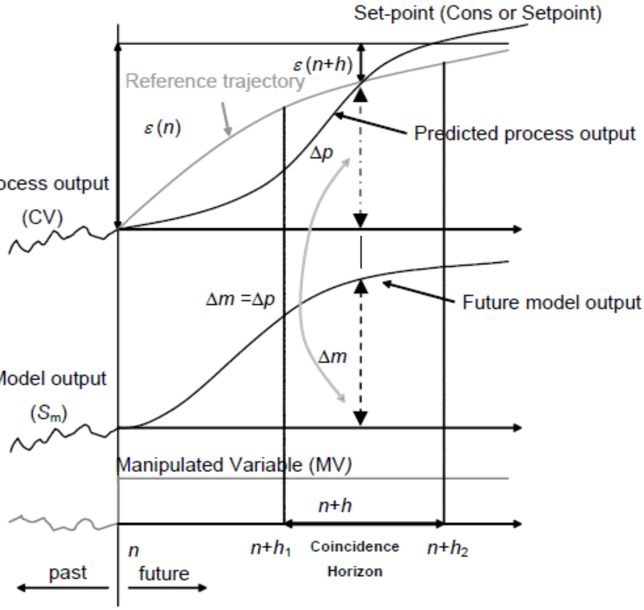

Fig. 4. Reference trajectory of PFC

3.2 PFC of an Integrator Process

From equation 12, the process between CV and MV can be considered as an integrator process system with a first order transfer function.

$$CV(s) = MV(s)\frac{K_p}{s(1+sT)} = MV(s)M_0(s) \tag{13}$$

As the process contains integral action, the model should be decomposed the unstable model into two stable processes as Fig. 5.

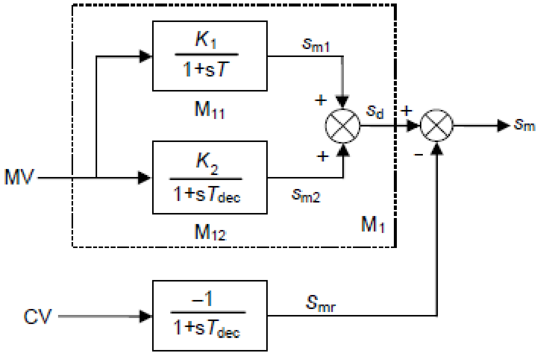

Fig. 5. Decomposition of a first-order process with integrator

The control equation is given by:

$$\mathrm{MV}(n)=\frac{(\text{Setpoint-CV}(n))l_h+s_{m1}(n)b_{mh}+s_{m2}b_{sh}-SS}{K_1b_{mh}+K_2b_{sh}}$$

$$\text{where } l_h=1-e^{\frac{3hT_s}{\text{TRBF}}},\ b_{mh}=1-a_m^h,b_{sh}=1-a_s^h,SS=s_{mr}(n)b_{sh}-\mathrm{CV}(n)b_{sh}$$

$$s_{m1}(n)=s_{m1}(n-1)a_m+b_mK_1e(n-1)$$

$$s_{m2}(n)=s_{m2}(n-1)a_s+b_sK_2e(n-1) \tag{14}$$

$$s_{mr}(n)=s_{mr}(n-1)a_s+\mathrm{CV}(n-1)$$

$$s_m(n)=s_{m1}(n)+s_{m2}(n)+s_{mr}(n)$$

$$K_2=\frac{K_pT_{dec}^2}{T_{dec}-T},K_1=K_pT_{dec}-K_2,a_s=e^{-\frac{T_s}{T_{dec}}},b_s=1-a_s$$

3.3 Feedforward Compensation

Measured disturbance compensation is a procedure of great practical benefit, which should be incorporated as often as possible into the regulator design process. The concept is simple: to counteract the effects of a disturbance before it appears. The disturbance at instant $n+h$ creates a control increment Δ_{pert} that depends on the free and forced outputs of the process. The past measured disturbance produces an output $s_{m_{pert}}(n)$ in response to the known disturbance transfer function. Under these conditions, the free output $S_{L_{pert}}(n+h)$ which depends only on the past measured disturbance is known. On the other hand, the forced output $S_{F_{pert}}(n+i)$ is unknown and therefore a prediction of the disturbance must be made as $\mathrm{Pert}(n+i)=\mathrm{Pert}(n), 0<i<h-1$. This results in a step characteristic response of the process multiplied by the local value of the measured disturbance

$$S_{F_{pert}}(n+h)=G_0(h)\mathrm{Pert}(n),\ \text{where } G_0(h) \text{ is a gain function of } h \tag{15}$$

The term $\Delta\mathrm{pert}(n+h)$ is added to the control equation as feedforward, given.

$$\mathrm{MV}(n)=\frac{(\text{Setpoint-CV}(n))l_h+s_m(n)-\left(s_m(n)a_m^k+s_{L_{pert}}(n+h)+s_{F_{pert}}(n+h)-s_{m_{pert}}(n)\right)}{K_1b_{mh}+K_2b_{sh}} \tag{16}$$

3.4 Controller Initialization When Switch from Manual to Automatic

It is a relatively simple exercise to transfer from an automatic to manual mode of regulation. But, switching from a manual to automatic mode is always a little agonizing for operators, particularly when the system contains an integrator. We need to provide a smooth transition between the MV's at the point of switching. The PFC controller has been installed for a long period of time and the operator wishes to transfer from manual to automatic mode for some reason. Any installed PFC, working offline, is permanently computing its MV, which is not applied. This particular PFC mode is defined by two characteristics: 1).Tracking mode: The set-point is set equal to the CV; 2).Internal model: The applied MV, generated by another controller or from manual mode, is the input to the internal model.

4 Simulation Results

Model parameters are divided into two categories, one is the mechanism parameters such as friction coefficient in pipe, fluid density, sliding friction coefficient and so on which is remained unchanged during the construction process, the other type is construction data such as advanced speed, pressure, flowrate and so on. These parameters must be determined before simulation conclusion

The elastic modulus of slurry mixed with soil is approximately equal to water $K = 10^9\,\mathrm{Pa}$.

Assume the length of chamber is 4*m* and diameter of chamber is 8*m*. Then, $V_0 = 201.0619 m^3$.

Assume the mass of head shield is $m = 100000\,kg$, sliding friction in practice can be set to $f = 0.03 F_{thrust}$, advanced speed is $v = 6.67\times10^{-4}\,m/s\,(2.4\,\mathrm{m/h})$, the pressure of excavation face is $P = 6\times10^5\,\mathrm{Pa}$. $Q_{out} = 0.0556\,m^3/s\,(200\,\mathrm{m}^3/h)$.

The parameters above are original data needed to determine the model. Under the condition of steady state operating point of the system, the other parameter can be calculated $F_{thrust} = 3.11\times10^7\,N, Q_{in} = 0.0221\,m^3/s$.

According to pump and pipe model, the steady state rotational speed of feed and discharge pump motor is $n_{in} = 7.3579\,r/s, n_{out} = 2.7289\,r/s$.

With these parameter, the model simulation result can be seen in Fig. 6

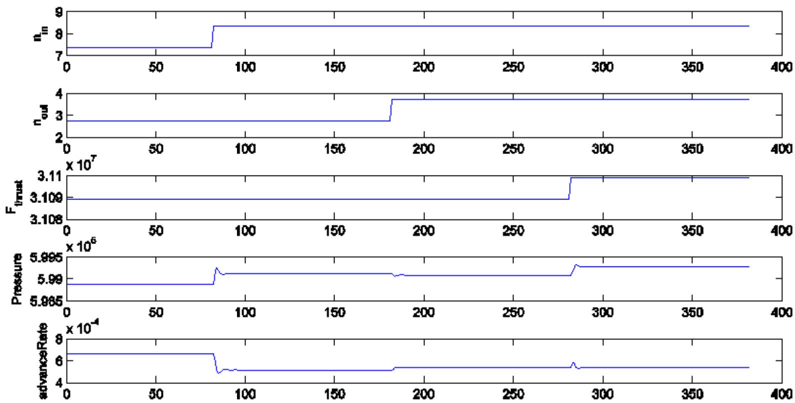

Fig. 6. Simulation result for slurry circulation system model

In order to simplify the system analysis and simulation, the equation 16 is dimensionless. The simulation result can be seen in Fig. 7. Here, the controlled variable is drifting at the beginning of the simulation. The INIT period of the controller lasts 50seconds. During that time span, the controller is estimating the slope of the controlled variable, in order to properly initialize the model. A manual phase is considered from 270 to 300s. From simulation result, we can see that the controller could track pressure setpoint changes even under the disturbance, and the controller could smoothly switch from manual to automatic mode.

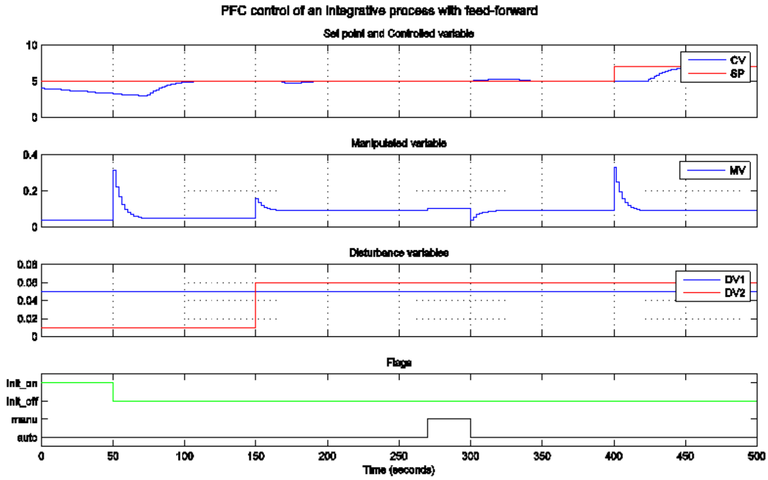

Fig. 7. PFC controller simulation result

5 Conclusion

The most important part of the excavation for slurry shield machine is keeping balance between the earth pressure and slurry circulation system pressure, especially for direct control type shield without air chamber. In this paper, an excavating face pressure balance principle for of direct type slurry shield machine is analyzed and its pressure balance dynamic model is introduced. Then, a controller is designed based on predictive function control method. Finally, the controller initialization method is proposed to deal with the problem of controller switching from manual to automatic mode. Simulation result shows the model and controller have achieved the desired design goals.

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