Simulation and Experimental Research on the Telescopic Cylinder Controlling of Socketed Rotary Reaming Device for Rotary Drilling Rig

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***Abstract* — Reaming pile is an energy-saving emission reduction cast-in-place pile and the rotary reaming device of rotary drilling rig is a kind of reaming facility for the reaming pile, on which the aperture is controlled by the telescopic cylinder. The problems existing on the former device on which the flow of hydraulic oil was used to control the aperture were studied and the design solution was improved. For the accurate aperture, the author carried out intelligent PID control on the expansion and contraction quantity of the telescopic cylinder, established a mathematic model, run simulation with MATLAB to verify the solution feasibility, guarantee the aperture effectively and then further verified it during the actual site construction.**

Keywords - Rotary reaming, telescopic cylinder, control, PID simulation, experiment

I. INTRODUCTION

Reaming pile is an energy-saving emission reduction cast-in-place pile. In the late 1980s, compacted multi-branch bearing disk concrete pile invented by Mr. Zhang Junsheng was another important invention in the history of pile foundation technology in China [1]. The stress characteristics of the compacted multi-branch bearing disk concrete pile is similar to those of the under-reamed pipe for manual hole digging and rammed bulb pile for mechanical compaction [2] [3]. However, the construction method of compaction is applicable for softer soil, not rocky soil. Ren Rongrong and Ma Kesheng used the FLAC 3D software to carry out analysis on the vertical bearing capacity of compacted bearing disk cast-in-place pile and obtained good effect [4]. Ren Jiajia and Qian Yongmei analyzed the failure mode of the soil mass around the compacted multi-branch bearing disk concrete pile combining the software simulation analysis and experimental phenomena and also reckoned the calculation mode of bearing capacity of king pile during punching shear failure and sliding failure of upper body. Feng Jianwei used the semi-compaction device of rotary drilling rig for reaming construction [6]. Tang Xiaoping and Ji Jing verified the feasibility of rock-embedded under-reamed pile of rotary drilling rig during actual construction [7]. Liu Sanyi and Xia Bairu studied the drilling technology and tools for rotary reaming, improved the design of transmitting torque and enhanced the strength of under-reamed drilling tools [8]. No studies on aperture control of reaming pile or on socketed reaming construction were seen in China.

Compared with the traditional bored cast-in-place pile, the reaming pile is featured the following: only an expanded end is formed at the bore bottom, without increasing the pile diameter. Under the condition of the same pile diameter and length, the bearing capacity of a single pile can be enhanced for over 30% and also the shock resistance and the uplift resistance of piles can be improved [9]. B. V. Bakholdin and V. I. Berman [10] think that the multi-section cast-in-place piles have higher bearing capacity compared with the traditional equivalent-diameter piles and the expanded end can exert the advantage of strong bearing capacity under very low pile top settlement.

For the sake of accurate reaming construction, control rotary reaming cylinders shall be available on the oil pipe to the shaft, in order to control the working device for reaming diameter, namely the rotary reaming device. The reaming diameter of existing reaming device of rotary drilling rig is calculated by measuring the flow of hydraulic oil entering into the rotary reaming cylinder. The following problems arise during the construction:

(1) In the process of boring deep holes, higher pressure will be formed in the pipeline because of slight leakiness on its top and connection with the air pressure, and drive the oil to enter into the large cavity of cylinder and increase the diameter. For example, a 6-bar pressure will be formed at the depth of 60m and drive the cylinder piston to increase the diameter.

evice is overloaded under the cutting force, the rotary reaming cylinder will extend or contract because of the protection mechanism of the balance valve, which will increase or decrease the diameter.

(2) The rotary reaming cylinder decreases the diameter because of internal leakage.

Therefore, an optimized solution shall be adopted to solve such problems. The former semi-closed-loop control of flow is changed to fully-closed-loop control to increase the control accuracy. In addition, electric proportional valve and PID are used for control and verification is carried out by means of simulation and field experiment.

II. OPTIMIZED SOLUTION

This optimized solution provides a kind of fully-closed-loop diameter control device for rotary reaming system of rotary drilling rig, mainly solves the problem of transverse extension diameter control of rotary reaming system at a certain depth underground, to form a fully-closed-loop control and improve the accuracy of size control.

As shown in the Figure 1, in a semi-closed-loop control solution, the existing diameter is controlled by detecting the flow of hydraulic oil. However, in this solution, the displacement sensors are used to directly detect the expansion and contraction quantity of the cylinder.

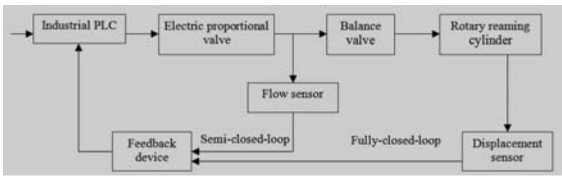

Fig. 1 Semi-closed-loop and Fully-closed-loop Control Scheme for Rotary Reaming System

As shown in the Figure 1, the fully-closed-loop control in this solution enjoys more advantages than the semi-closed-loop control on the former device.

The flow sensor is cancelled from the former diameter control device, the rotary reaming cylinders are redesigned, the displacement sensors are installed within the cylinder and a data line is used to feed back the information to the industrial PLC via a central gyrorotor, realizing the fully-closed-loop control. This solution can completely solve the three problems put forward in the Introduction part and eliminate the aperture out-of-tolerance phenomenon.

III. SOLUTION DESIGN

As shown in the Figures 2 and 3, the fully-closed-loop diameter control device for the rotary reaming system of rotary drilling rig is consisted of an industrial PLC, a central gyrorotor connected to the industrial PLC via a data line, rotary reaming cylinders connected to the data line via the central gyrorotor, an electric proportional valve connected to the industrial PLC via a control circuit, displacement sensors installed in the rotary reaming cylinders, an oil pump providing power for the rotary reaming cylinders, balanced valve installed in the large and small cavities of rotary reaming cylinders, as well as a hydraulic hose connecting the balanced valve and electric proportional valve via the central gyrorotor.

The fore and aft motion of the rotary reaming cylinders causes angular displacement between the rotary reaming door and the fixing body of reaming device, to enlarge the diameter of the outermost end of rotary reaming door, where a form-relieved tooth is installed, for the reaming operation.

The oil pump conveys the hydraulic oil to the electric proportional valve and the later opens according to the commands of industrial PLC and sends the oil to the balance valve. The balance valve opens and sends the hydraulic oil into the rotary reaming cylinders and the displacement sensors feed back the signals to the industrial PLC in real time. The PLC will compare the signals with the set parameters and go on working if no abnormality is found; it will give an alarm and stop working in case of any abnormality found. Operation will be stopped when the signals fed back by the displacement sensors are regarded to reach the specified location after being calculated by the industrial PLC.

During operation, the displacement sensors still feed back the signals in real time and the industrial PLC still calculates them in real time to monitor the tolerance range of the rotary reaming diameter. If it is out of range, a control signal will be sent out to adjust the electric proportional valve, to control the rotary reaming cylinders and finally realize the fully-closed-loop diameter control.

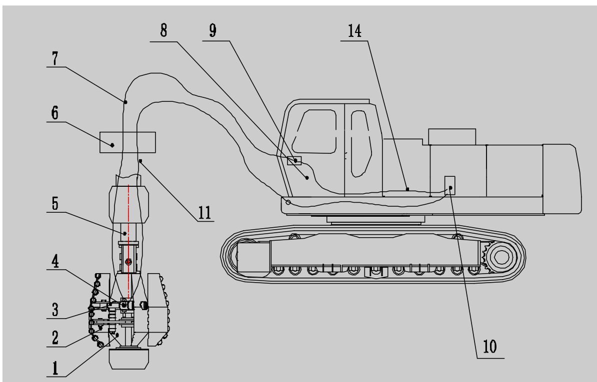

Fig. 2 Location Plan of Rotary Reaming Device Components Installed in the Rotary Drilling Rig

1 - Fixing body of rotary reaming device, 2 – Rotary reaming door, 3 – Rotary reaming cylinders I and II, 4 – Displacement sensors I and II, 5 – Drill rod, 6 – Central

gyrorotor, 7 – Data line, 8 – Rotary drilling rig chassis, 9 – Industrial PLC, 10 – Electric proportional valve, 11 – Hydraulic hose, 12 – Oil pump, 13 – Balance valve, 14 – Control circuit

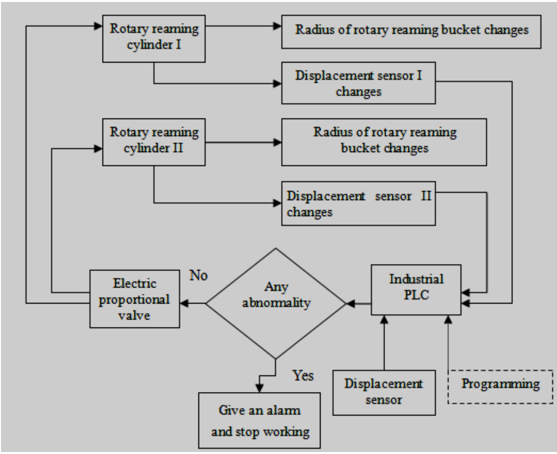

Fig. 3 Schematic Diagram for Control of Rotary Reaming Device

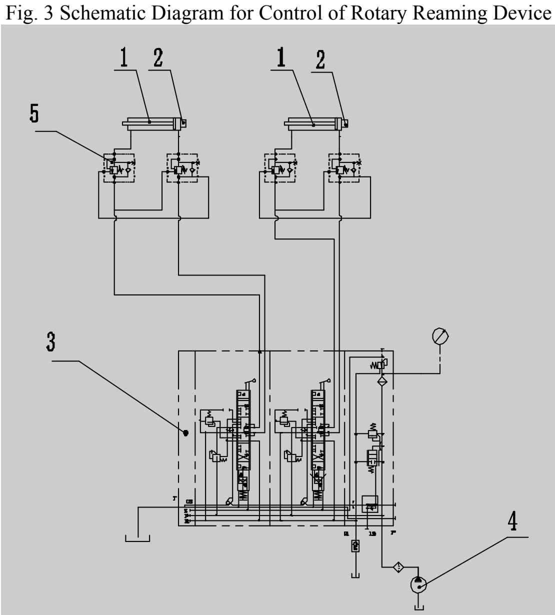

Fig. 4 Hydraulic Schematic Diagram for the Optimized Rotary Reaming Device
1 –Rotary reaming cylinders I and II, 2 – Displacement sensors I and II, 3 – Electric proportional valve, 4 – Oil pump, 5 – Balance valve

IV. PID CONTROL

(1) Control principle

The electro-hydraulic proportional control system is a closed-loop control system which accepts and processes the continuously changing signals so that the controlled object in the system can complete the program regularly or track the command signals. At present, mainly servo valve, proportional valve and digital valve are used as the electro-hydraulic valves for closed-loop control. Among them, the serve valve enjoys mature technologies and reliable performance, but requires higher cleanliness of media and higher cost. The digital valve is a new type of control valve under development and can be connected to computers directly. However, the electro-hydraulic proportional valves can not only control the working parameters (pressure and flow) of the hydraulic system continuously and proportionally, but also enjoy low price and strong pollution resistance. It responds slower and has lower accuracy than the servo valve, but for this system, it can fully meet the requirements.

In the rotary reaming diameter automatic deviation correction system, a load sensing pump drives two telescopic cylinders for the realization of reaming of the reaming device. The cylinders are controlled separately by two pieces of electro-hydraulic proportional valves. As shown in the Figure 5, the displacement sensor installed on the telescopic boom detects the flex displacement of the telescopic boom Δl_i , compares it with the set signals after A/D conversion and generates the displacement deviation. The PID controller will generate the control signals after deviation correction algorithm operation based on the displacement deviation and respectively transfer them to the electro-hydraulic proportional valves connected to the telescopic cylinders after D/A converter, to form the closed-loop electro-hydraulic proportional control system and realize the automatic deviation correction control of the expansion and contraction quantity of telescopic boom. The principle of automatic control system with single telescopic cylinder is shown in the Figure 5.

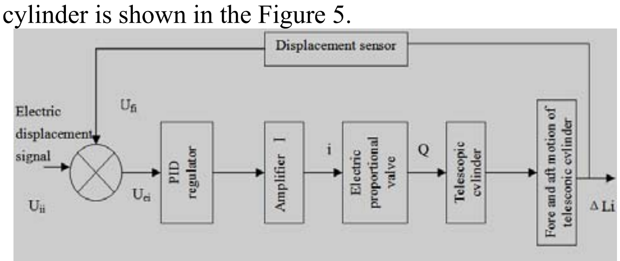

Fig. 5 Schematic Diagram for the Automatic Control System of the Telescopic Cylinder

(2) Mathematical modeling for system

To control automatically the deviation correction of telescopic cylinder and design a controller reaching the control precision, response speed and reliability, simulation analysis and research on the controlled object shall be carried out. Therefore, a mathematical model shall be established for the system.

The system is controlled based on the electro-hydraulic proportion. The transfer function of cylinder is obtained after Laplace transform is applied to the three fundamental equations of the proportional valve control cylinder, i.e. the linearized load flow equation for the proportional valve, the load equation for the hydraulic cylinder and the balance equation for piston stress of the hydraulic cylinder [11] (excluding the elastic load):

$$X_p = \frac{\frac{K_q}{A} X_v - \frac{K_c}{A^2}\left(\frac{V_t}{4\beta_e K_c}s+1\right)F}{\left(\frac{s^2}{\omega_h^2}+\frac{2\xi_h}{\omega_h}+1\right)s} \qquad (4\text{-}1)$$

Where:

K_q — Flow gain of valve, $(m^3/s)/m$;

X_v — Opening of valve, m;

K_c — Flow and pressure coefficients of valve, $(m^3/s)/pa$;

A — Effective cross-area of piston, m^3;

X_p — Piston displacement, m;

V_t — Equivalent volume of hydraulic cylinder, m^3;

F — Driving force generated by the hydraulic cylinder, N;

β_e — Effective modulus of volume elasticity, $N/m^2(Pa)$;

ω_h — Natural frequency of cylinder, $\omega_h = \sqrt{\frac{4\beta_e A^2}{V_t m}}$, rad/s;

ξ_h — Damping coefficient of cylinder, $\xi_h = \frac{K_c+C_t}{A}\sqrt{\frac{\beta_e m}{V_t}} + \frac{B_c}{4A}\sqrt{\frac{V_t}{\beta_e m}}$;

m — Mass of piston and load, Kg;

B_c — Coefficient of viscosity of piston and load, $N/(m/s)$;

C_t — Overall leakage coefficient of hydraulic cylinder, $(m^3/s)/Pa$

Whereas the proportional valve is controlled with current, the valve opening of unit current is set as K_x in m/A. The valve opening $X_v = K_x i$ and valve flow $Q = K_q X_v$, therefore, $Q = K_q K_x i$, i.e., the transfer function of the proportional valve is $K = Q/i = K_q K_x$.

System requirements: internal diameter of telescopic cylinder $D = 80mm$, piston rod diameter $d = 56mm$ and required kinematic velocity 0.5~3m/min. Select the proportional valve based on the system requirements. The transfer function of the proportional valve can be reckoned as $K = 0.000695 m^3/s\cdot A$ based on the product parameters: rated current $600mA$ and rated flow $25L/\min$.

After proportional selection, determine the parameters in the formula (4-1) based on the given parameters and existing engineering experience and obtain the natural frequency of telescopic cylinder as $\omega_h = 64 rad/s$ and damping coefficient as $\xi_h = 0.03$. The transfer function between the input current of proportional valve and the displacement of telescopic cylinder is obtained as [12]:

$$\frac{X_p}{i} = \frac{\frac{K}{A}}{\left(\frac{s^2}{\omega_h^2}+\frac{2\xi_h}{\omega_h}+1\right)s} \qquad (4\text{-}2)$$

Transfer function between the external carrying capacity and the telescopic cylinder is as:

$$\frac{X_p}{F} = \frac{-\frac{K_c}{A^2}\left(\frac{V_t}{4\beta_e K_c}s+1\right)}{\left(\frac{s^2}{\omega_h^2}+\frac{2\xi_h}{\omega_h}+1\right)s} \qquad (4\text{-}3)$$

(3) Proportional amplifier

The deviation signal, by use of the proportional amplifier, converts the input voltage to the current signal transferred to the proportional valve. Select the proportional amplifier based on the description of proportional valve and obtain the amplification factor K1=0.08A/V.

Block diagram of the whole control system based on Simulink is obtained as shown in the Figure 6 below after connection and building of the above links.

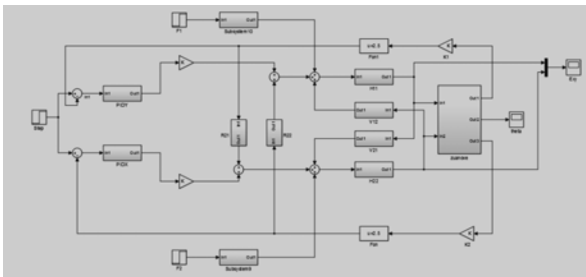

Fig. 6 System Simulation Structure Chart

(4) PID control algorithm

The optimized control theory has proven that: PID control can satisfy the control requirements of most industrial objects and PID algorithm contains the main past, current and future information in the dynamic control process, with almost the best configuration. The proportion (P) represents the current information and plays a role of deviation correction to make the process respond rapidly; the differential coefficient (D) represents the future information, plays a role of anticipatory control in case of signal change and it is beneficial to overcoming the oscillation, improving the system stability and expediting the system transient process; and the integral (I) represents the information accumulated in the past and it can eliminate the static error and improve the static error performance of the system. These three actions cooperate with each other perfectly and can make the dynamic process rapid, stable and accurate and obtain a good control result. In addition, the inherent decoupling function of PID controller can eliminate the mutual interference among the variables. Therefore, PID control algorithm is adopted for the telescopic cylinder control system. The algorithm block diagram in the Simulink is shown in the Figure 7.

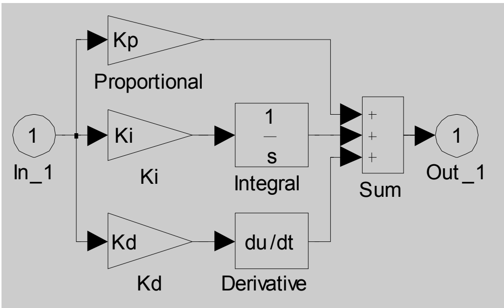

Fig.7 Structure Chart for PID Regulator

(5) Simulation analysis

Kp can expedite the system response. As shown in the Figure 8, the simulation time set is 20s. Increasing Kp can expedite the response and decrease the steady state error of system. The Kp value is adjusted continuously. When Kp = 1, the system becomes stable at 7.11s, with the steady state value 0.8159, not meeting the system precision requirements. Therefore, an integration element is required.

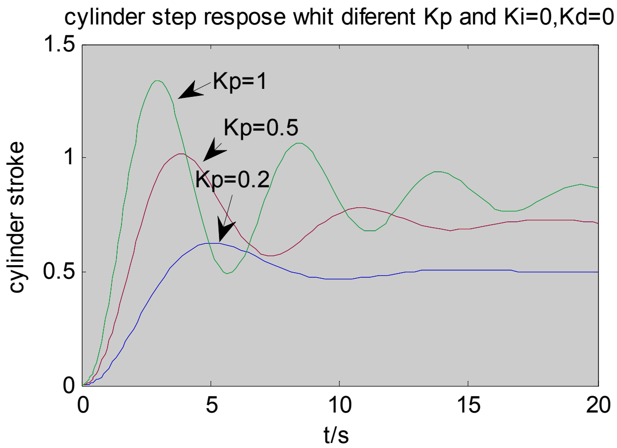

Fig.8 PID with Kp=0.2,0.5,1

Addition of integration element can reduce or even eliminate the steady state error, but its increment will enhance the system overshoot and make the system unstable. Therefore, a differentiation element is required. At last, a better result is obtained when Kp=0.5, Ki=0.2, Kd=0.3 as shown in the Figure 9.

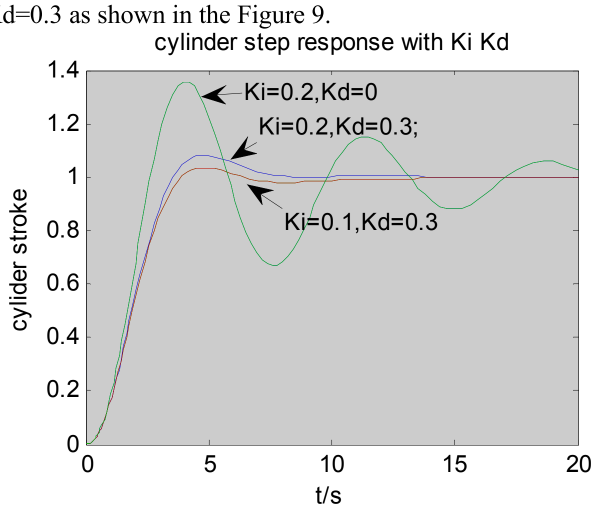

Fig.9 PID with Kp=0.5, Ki=0.1, 0.3, Kd=0,0.3

The cut-and-trial method is used in the PID parameter setting in this system and the setting results may be not unique. During actual engineering, the flow functions as the controlled object, with small time constant and noise. Therefore, the Kp value is low. Further more, considering the influence of external causes like temperature and dead zone of proportional valve, the integral factor Ki may be set as a lower value to make the control effect better.

V. EXPERIMENTAL VERIFICATION

An experiment verification of the rotary reaming device of rotary drilling rig was carried out on a construction site in Ningbo High-tech Zone. As shown in the Figure 10, the screen of visualized intelligent detection system for rotary drilling rig reaming displays the real-time working data and graphs detected by the displacement sensor. Pile diameter is 900mm and the maximum reaming diameter is 1460mm. To ensure the dimensions and strength, the real-time reaming diameter is set as 1480mm.

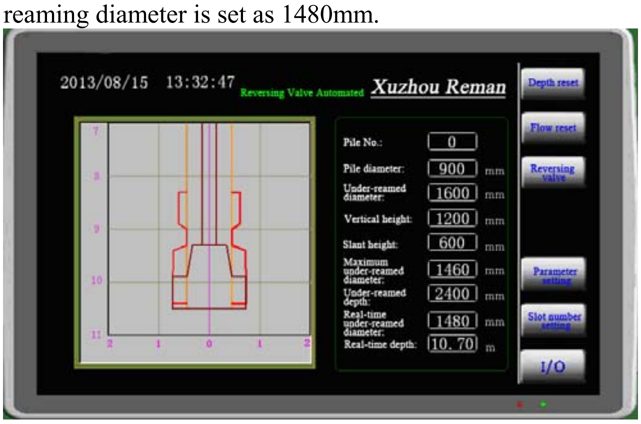

Fig.10 Working Screen and Actual Work of the Intelligent Rotary Reaming Detection System

Fig.11 Detection of Rotary Reaming Aperture

As shown in the Figure 11, use the aperture detector for actual detection after the rotary reaming device of rotary drilling rig finishes the work. Refer to the following table and Figure 12 for the actual detection results.

Depth (m)	8	10	12	14	16	18	20
Aperture (mm)	905	906	1482	900	907	903	895

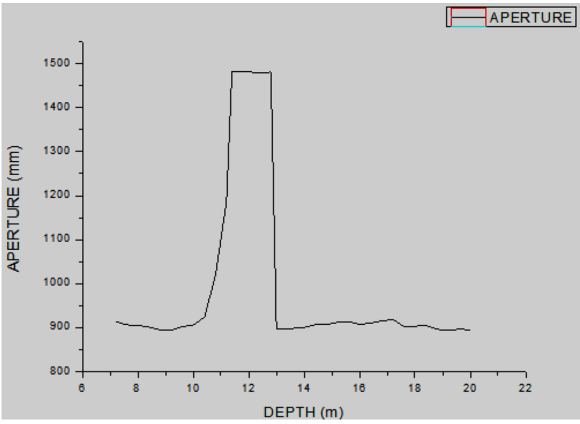

Fig 12 Experimental Apertures

VI. CONCLUSION

During new production pilot, not high reaming accuracy was found on the rotary reaming device of rotary drilling rig. The detection mode was improved from the flow detection to direct displacement detection instead. Compared with the semi-closed-loop control, the fully-closed-loop control had higher accuracy of diameter size and was more reliable. To ensure the smoothness of the diameter size control, PID control was used, which improved the technical parameters and performance of the product. The actual detection on the construction site showed the pile nominal diameter 900mm and actual maximum error +18mm, with a deviation of +2% and the reaming nominal diameter 1,480mm and actual maximum error +13mm, with a deviation of +0.8%. It was seen from the data that reaming had higher accuracy than boring, which explained that the boring accuracy was controlled by the drilling tools and rod. In addition, the aperture enjoyed an upper deviation consciously. That was why the upper deviation is higher. However, the extruding size of cylinder was directly detected during reaming. As a fully-closed-loop control, the reaming accuracy was higher. The experiment got a quite ideal result. Higher cost is a defect of this design solution and is mainly caused by the displacement sensor, electric proportional and PID. However, it is necessary to increase the cost input to gain higher benefit. In this way, the reaming device can ensure the compliance of aperture with the construction requirements.

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