Design of Cantilever Deflection Compensation Mechanism for Three-Stage Cylinder

Jinwei Fan, Haohao Tao*
Beijing University of Technology, Beijing 100124, China

*Corresponding author e-mail: Taohao_hao@163.com

Abstract. In order to solve the problem of large deflection caused by insufficient rigidity of the existing three-stage cylinder cantilever mechanism, a new design scheme is proposed. By installing lifting hydraulic cylinder at the front end of the first stage cylinder of the multi-stage cylinder and installing hinged structure at the back end of the first stage cylinder, the pitch angle of the whole cantilever is changed to compensate the deflection of the cantilever. The simulation and data fitting are carried out by using ANSYS and MATLAB software, and the measurement mode of the existing laser rangefinder is improved, and the electrical control system of the device is optimized. Finally, the deflection of the device is further reduced by optimizing the structure and control system.

1. Introduction
The internal depth of a solid rocket motor grain is up to 7 meters. In order to complete the inspection of the grain, a nondestructive testing device for the inner wall surface of the grain is designed [1, 2]. The device is mainly composed of lifting car, three-stage telescopic cylinder, servo motor, industrial camera, etc. Due to the large torque generated by the servo motor and industrial camera at the front end of the three-stage cylinder, in order to ensure the detection accuracy, two-way detection is adopted during the detection, so the expansion distance of the three-stage cylinder is controlled at 3.5m [3]. The testing device has been designed and manufactured, and has been put into trial operation. As shown in Figure 1.

When the expansion distance is large, due to the gravity influence of servo motor and industrial camera, there is still a large deflection, which affects the shooting accuracy. Therefore, a three-stage cylinder cantilever deflection compensation mechanism and deflection error detection device are designed to ensure that the deflection at any working position of the cantilever is controlled within 3mm.

2. Hardware structure

2.1. Overall structure
The nondestructive testing device for the inner wall surface of the whole grain is composed of lifting car, three-stage cylinder, servo motor, industrial camera, electrical cabinet, air pump, etc. the overall structure is similar to the cantilever beam, and the three-stage cylinder is horizontally installed on the lifting car, when the three-stage cylinder extends out, it will produce large deflection. The simulation effect diagram is shown in Figure 2.
In order to meet the accuracy requirements during shooting and reduce the deflection, the existing structure has been improved. By using the principle of reverse compensation, the structure of the three-stage cylinder placed horizontally has been changed, so that the front of the three-stage cylinder is cocked up to a certain height, and an elevation angle is generated between the three-stage cylinder and the horizontal plane of the base plate. By controlling the elevation angle of the three-stage cylinder, the industrial camera at the front end of the three-stage cylinder can meet the shooting position requirements at any extended position.

A hydraulic cylinder is installed at the connection between the front end of the lifting car and the third stage cylinder. The hydraulic cylinder is installed on the lifting car, and the cylinder body is hinged with the third stage cylinder. The rear end of the third stage cylinder is hinged with the lifting car. When the third stage cylinder stretches out for a long time and the industrial camera has a deflection, the hydraulic cylinder works, which makes the third stage cylinder and the trolley have an elevation angle to compensate for the deflection. The design drawing of deflection compensation device is shown in Figure 3.

2.2. Laser rangefinder
Compared with the structural diagram in Fig. 2 and Fig. 3, the laser rangefinder is also installed independently due to the change of the pitch angle of the third stage cylinder. In order to monitor the deflection of the front end of the third stage cylinder, the laser reflecting plate is changed. The comparison between the new and old reflectors is shown in Fig. 4 and Fig. 5.

The height of the new reflection plate is only 10 mm, and the laser rangefinder points to the middle. When the deflection exceeds the rated range by 3 mm, the laser rangefinder cannot get the reflection
data, so the control system cannot measure the distance, the system reports an error, and the deflection compensation is carried out again. However, due to the large area of the reflection plate in Figure 5, when a large deflection occurs, it can only feedback the extension distance of the third stage cylinder, and cannot monitor the deflection in real time. This device can ensure the deflection of the system and improve the working accuracy of the industrial camera.

3. Finite element simulation analysis

3.1. Simulation analysis of three-stage cylinder

In the process of equipment debugging, the existing equipment has been analyzed, and the finite element analysis of cantilever beam has been carried out by using ANSYS software. Suppose $E$ is the elastic modulus of multistage cylinder, $J$ is the moment of inertia of multistage cylinder to neutral axis, $W$ is the applied load, $l$ is the length value of multistage cylinder, $\Delta$ is the deflection, and $k_\Delta$ is the rigidity of multistage cylinder \([4-6]\). Deflection of multistage cylinder: 

$$\Delta = \frac{Wl^3}{3EJ}.$$ 

Stiffness of multistage cylinder: 

$$k_\Delta = \frac{W}{\Delta} = \frac{3EJ}{l^3}.$$ 

Because there is a lot of smoke and dust in the working environment, and the fuel rods inside the solid rocket motor need to strictly prohibit fireworks, so the existing servo motor is equipped with an explosion-proof enclosure. After the enclosure is installed, the total mass of the image acquisition equipment at the front end of the three-stage cylinder reaches 5kg. In the simulated working environment, a pressure of 50N is applied at the motor bracket, and the bottom of the lifting plate is used as the fixed end for ANSYS simulation analysis, when the cylinder extends 3.5m from the farthest limit position, the result is as shown in Figure 6.

As shown in Figure 6, the maximum deflection of the cantilever of the third stage cylinder is generated on the motor bracket at the front end, and the maximum deflection is 16.391mm. The existing equipment must be modified. After the design, a hydraulic cylinder is installed at the front end. When the hydraulic cylinder extends and raises the elevation angle of the third stage cylinder, a 50N load is still applied, and the same fixed end is used for ANSYS simulation analysis, as shown in Figure 7.

As shown in Figure 7, when the third stage cylinder extends to 3.5m, the deflection is only 1.53mm, and it meets the 3mm error identification range of the laser rangefinder. The deflection of the farthest end of the device can be reduced by 90.66% when the hydraulic cylinder works normally. This set of equipment is of great significance in actual production.

3.2. Linkage of hydraulic cylinder and three-stage cylinder

Due to the production and assembly of the three-stage cylinder, the rigidity of the cylinder block and other reasons, the deflection at the front end of the three-stage cylinder is not linear with the extension
distance of the three-stage cylinder. In this paper, 11 points are selected for simulation analysis, and the corresponding deflection value of each point is obtained, as shown in Table 1.

| Distance | 300 | 600 | 900 | 1200 | 1500 | 1800 | 2100 | 2400 | 2700 | 3000 |
|---------|-----|-----|-----|------|------|------|------|------|------|------|
| Deflection | 0.083 | 0.099 | 0.182 | 0.495 | 0.980 | 1.664 | 3.342 | 5.034 | 8.492 | 10.681 |

4. Conclusion
In this paper, the existing cantilever inner wall detection device of three-stage cylinder can improve the accuracy by adding hydraulic cylinder and changing the elevation angle of three-stage cylinder. The deflection can be reduced by 14.861mm and 90.66% at the far end of the third stage cylinder. Secondly, the deflection data of the three-stage cylinder are obtained by simulating the different extending positions of the three-stage cylinder. The MATLAB is used to trace the points, and the least square method is used to fit the data to get the function curve of the deflection and extending distance of the three-stage cylinder. Finally, based on the PMAC motion controller, the motion relationship between the hydraulic cylinder and the third stage cylinder is determined by using the deflection and extension distance function, and the control system is further integrated to reduce the deflection of the device.

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