Position Accuracy Measurement and Error Compensation of Servo Electric Cylinder Test Platform

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ABSTRACT

At present, the domestic electric platform mostly adopts semi-closed loop digital control, whose basic transmission form of the key components adopts rotary motor and trapezoidal screw (ball screw, roller screw), manufacturing precision and mechanical transmissions inevitably have assembly errors, pitch errors and gap errors. It is necessary to perform error analysis and compensation for high-precision electric cylinder platforms. In this paper, the above errors are further subdivided into linear error, nonlinear error, gap error, which is corresponded error measurement and compensation. The results show that the linear deviation of the measured position and deviation data of the forward and reverse strokes are linearly fitted by the least squares linear fitting method, and then the linear error compensation is performed by adjusting the command pulse amount. The average value of the linear proportional coefficient is taken as the average gap, and the gap error compensation is performed. After the cubic spline interpolation using as the nonlinear error compensation, which accords to GB/T17421.2-2000, the general rule of machine tool inspection Part 2: “the positioning accuracy of the numerical control axis and the determination of repeated positioning accuracy” calculated that the bidirectional positioning accuracy of the electric cylinder is increased from 0.1028 mm to 0.0245 mm, the bidirectional repeat positioning accuracy of the axis is increased from 0.0783 mm to 0.0249 mm, and the maximum backlash is reduced from 0.201 mm to 0.092 mm. These all meet the requirements of positioning accuracy and repeat positioning accuracy of 0.01 mm.

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INTRODUCTION

With the development of intelligent technology, intelligent molding equipment and corresponding control technologies also increase. [1] It is against this background that the electric platform has been widely used for its excellent positioning and thrust control performance. The electric cylinder is a key component of the electric platform, whose motion accuracy determines the accuracy. [2] The basic transmission form of the electric cylinder is a rotating electric machine and a trapezoidal screw (ball screw, roller screw), and the linear motion form can only be obtained indirectly through the mechanical structure. [3] Due to the manufacturing precision and assembly accuracy of these mechanical structures, assembly errors, pitch errors and gap errors are inevitable, which combined with a long-term. [5]

For the electric platform with high precision requirements, in order to reduce the error, as well as the mechanical aspect, by using a high-precision lead screw and a method of adding a preload force when mounting the screw, the assembly error and the influence of the gap error are reduced to some extent. [6] At the same time, it is necessary to correct the electric cylinder using the semi-closed loop digital control system to achieve the purpose of measuring the position accuracy of the electric cylinder and error compensation. (As shown: Figure 1).

The principle of electric cylinder correction uses semi-closed loop digital control system: First, the electric cylinder position servo system is modeled to measure various errors of error. Second, the algorithm of pitch error and gap error compensation is studied. Third, the algorithm of pitch error and gap error compensation is embedded into the servo control system. The signal changes of the encoder and displacement sensor (magnetic scale) are observed before and after compensation. The correctness of the algorithm is verified by experimental results. [7].

EXPERIMENTAL

The position accuracy of the electric cylinder includes two parts: measurement and error compensation. [8] In this paper, the pitch error and the gap error are subdivided into linear error, nonlinear error, gap error, and corresponding error measurement and compensation.

Figure 1. Schematic diagram of semi-closed loop control system of electric cylinder.
Electric Cylinder Error Measurement

In order to obtain the electric cylinder pitch error data, the effective stroke of the electric cylinder sleeve is first divided into several equidistant intervals, and the upper and lower limit positions are used as the measurement reference. After inputting the motion command, the electric cylinder sleeve moves by one interval, and the magnetic ruler is used to measure the actual movement amount of the electric cylinder sleeve. Finally, the difference between the actual movement amount and the theoretical movement amount is calculated. [4] Repeat this process to measure the error values for all equidistant interval points.

In order to obtain the electric cylinder clearance error data, firstly, the electric cylinder sleeve is moved to the measuring point in the forward direction, and the magnetic scale number is recorded; then the reverse point motion command is inputted, after the magnetic scale digital display indicates the value changes, the indication increment value is the backlash measurement error. [4] Repeat the above process until the error values of all equidistant interval points are measured.

Compensation for Electric Cylinder Error

LINEAR ERROR COMPENSATION

As shown in Figure 2, in order to obtain the linear error of the electric cylinder, the positional deviation data of the measured forward and reverse strokes can be linearly fitted by the least squares linear fitting method. After linear fitting, the corresponding two straight lines are obtained. Take the average of the slopes of the two lines as the linear scale factor of the deviation data. [4]

![Figure 2. Schematic diagram of linear fit of positional deviation of forward and reverse strokes graph.](image-url)
Here, the theoretical position of the i measuring point is $s_i$, position deviation is $e_i$, $1 \leq i \leq n$, so the equation for linear fitting is:

$$
\begin{bmatrix}
    n \\
    \sum_{i=1}^{n} s_i \\
    \sum_{i=1}^{n} s_i^2
\end{bmatrix} \begin{bmatrix} b_k \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^{n} e_i \\
\sum_{i=0}^{n} e_i s_i \end{bmatrix}
$$

(1)

The linear fitting equation for obtaining the positional deviation of the forward and reverse strokes is:

$$
e_+ = k_+ s + b_+
$$

$$
e_- = k_- s + b_-
$$

(2)

Further, the average value of the slopes of the two straight lines is obtained as the linear proportional coefficient of the deviation data:

$$
K = (k_+ + k_-)/2.
$$

(3)

The above calculations provide linear error compensation for the electric cylinder. Linear error compensation is performed by correcting the pulse equivalent of the system. Let the pulse equivalent be $E_p$, pulse is not corrected before the instruction $N_*$. Pulse command after correction is $N_*$. Let the number of command pulses corresponding to the displacement be $N_*$. Then there is

$$
\begin{cases}
    s = NE_p \\
    s = N_*E_p + ks
\end{cases}
$$

(4)

$$
N_* = (1 - k) N
$$

(5)

BACKLASH ERROR COMPENSATION.

The gap is caused by wear between the components of the transmission system. This article uses a trapezoidal screw to drive the trapezoidal nut as an example. When the lead screw and the nut are worn due to long-term use, the two cannot be in close contact. If the forward and reverse commutation occurs at this time, the screw is only idling at this time. There is no movement of the drive nut and the electric cylinder sleeve, that is, the servo motor is idling and the electric cylinder sleeve is stationary, which cause an error between the position of the servo motor encoder feedback and the actual movement position of the electric cylinder sleeve.
If the backlash of the electric cylinder does not change obviously, the gap compensation can be performed with the average gap. Let the target position of the i measuring point be $s_i$, the forward and reverse stroke position deviation are $e_{i+}$ and $e_{i-}$, $1 \leq i \leq n$. [9]

Average return clearance:

$$\overline{B} = \frac{1}{n} \sum_{i=1}^{n} (e_{i-} - e_{i+})$$  \hspace{1cm} (6)

The Advantech PCI-1220U motion control card selected in this paper with a reverse fixed clearance compensation function, which can easily perform average gap compensation.

NONLINEAR ERROR COMPENSATION

The nonlinear error compensation can be performed if the system still cannot meet the accuracy requirements after linear error compensation. In order to achieve nonlinear error compensation for all points through limited point data, interpolation is needed for calculation. [10-11]

In this paper, by comparing the piecewise linear interpolation and cubic spline interpolation method, the cubic spline interpolation method with higher precision is selected as the nonlinear error compensation scheme, and it has been applied in the test, and a good interpolation effect has been obtained.

RESULTS AND DISCUSSION

Electric Cylinder Error Measurement Result

According to the above measurement method, this paper tests the position accuracy of an electric cylinder of a trapezoidal screw mechanism of a company. The total effective stroke of this type of electric cylinder is 200 mm, and one measuring point is set every 10 mm. After each measuring point 10 times, taking the average position deviation, the forward and reverse strokes are measured, and the data is as shown. The black deviation point shown in Figure3 is the positive stroke measurement point, while the red is the negative stroke measurement point.

It can be seen from Figure 3 that as the forward and reverse strokes increasing, the positional deviation strokes gradually, indicating that the electric cylinder has a large linear position deviation; and the deviation contains a fluctuation component, indicating it contains a certain nonlinear position deviation; there is a certain difference between the positive and negative stroking positioning positions, indicating that there is a back gap in the system.
According to GB/T17421.2-2000 “General Rules for Machine Tool Inspection Part 2: Determination of Positioning Accuracy and Repeated Positioning Accuracy of CNC Axis” is used to calculate the initial position accuracy and backlash of the electric cylinder. The data is shown in TABLE I.

| Axis                  | Positive positioning accuracy | Negative positioning accuracy | Bidirectional positioning accuracy | Positive repeat positioning accuracy | Negative repeat positioning accuracy | Bidirectional repeat positioning accuracy | Maximum backlash |
|-----------------------|-------------------------------|-------------------------------|-----------------------------------|-------------------------------------|-------------------------------------|------------------------------------------|--------------------|
| Axis                  | mm                            | mm                            | mm                                | mm                                  | mm                                  | mm                                       | mm                 |
| Axis                  | 0.0454                        | 0.01018                       | 0.1028                            | 0.0400                              | 0.0783                              | 0.0783                                   | 0.2010             |

![Figure 3. Measured electric cylinder positioning error graph.](image)

![Figure 4. Positive stroke linear fitting result graph.](image)

![Figure 5. Negative stroke linear fitting result graph.](image)
Linearity Error and Average Gap Compensation

The error data of 20 points in the previous section is used as the fitting point, and the linear fitting results are shown in Figure 4 and Figure 5. The equation for fitting a line is:

Positive trip: \( e_+ = 0.00135s - 0.01715 \)
Negative trip: \( e_- = 0.00229s + 0.00143 \)

Average scale factor of systematic linear error: \( k = 0.00182 \)
Average backlash: \( \bar{B} = 0.1073 \)

Linear error compensation in the positive strokes of the electric cylinder, linear error compensation and average clearance compensation in the negative stroke, re-measure the position accuracy of the system after compensation, measure one point every 10 mm, a total of 18 measuring points, each measuring point 5 times, the positive and negative strokes are measured once. The test result is shown in Figure 6.

![Figure 6. Linear error compensation, backlash compensation and position accuracy of electric cylinder after nonlinear compensation graph.](image)

| Axis                  | Positive positioning accuracy | Negative positioning accuracy | Bidirectional positioning accuracy | Positive repeat positioning accuracy | Negative repeat positioning accuracy | Bidirectional repeat positioning accuracy | Maximum backlash |
|-----------------------|-------------------------------|-------------------------------|-----------------------------------|-------------------------------------|--------------------------------------|------------------------------------------|------------------|
| Axis                  | mm                            | mm                            | mm                                | mm                                  | mm                                   | mm                                       | mm               |
| Axis                  | 0.0230                        | 0.0262                        | 0.0271                            | 0.0251                              | 0.0278                               | 0.0278                                   | 0.1340           |

The positional accuracy of the electric cylinder after linear error compensation and backlash compensation is obtained. And the backlash data is shown in TABLE II. The position accuracy of the electric cylinder has been greatly improved.
Nonlinear Error Compensation

A point is measured every 10 mm in the previous section, and a total of 18 points are used as measurement points for nonlinear error compensation. After the linear measurement and the average gap compensation, the 18 measuring points are subjected to piecewise linear interpolation, cubic spline interpolation and other nonlinear error compensation for the positive and negative strokes, as shown in Figure 7 and Figure 8.

According to Figure 7 and Figure 8, the piecewise linear interpolation is simple to calculate and applied to the interpolation problem with less smoothness. But its shortcoming can only guarantee continuity and lose the smoothness of the original function. The cubic spline interpolation can guarantee the smoothness of the original function, obtain a smooth curve, and the precision loss rate is small. Therefore, cubic spline interpolation is used as the final nonlinear error compensation method.

For these 18 measuring points, each measuring point is measured 5 times, and each of the positive and negative strokes are measured once. The test results are shown in Figure 9. The black deviation point is the positive stroke measurement point, while the red is the negative stroke measurement point.

Linear error compensation, backlash error compensation and nonlinear error compensation are obtained. The position accuracy and backlash data of the electric cylinder are shown in TABLE III.

![Figure 7. Positive stroke nonlinear error compensation result graph.](image7)

![Figure 8. Negative stroke nonlinear error compensation result graph.](image8)
DISCUSSION AND CONCLUSIONS

After linear error compensation, nonlinear error compensation and average gap error compensation, the bidirectional positioning accuracy of the electric cylinder shaft is reduced from 0.1028 mm to 0.0245 mm, the bidirectional repeat positioning accuracy of the shaft is reduced from 0.0783 mm to 0.0249 mm, and the maximum clearance is reduced to 0.092 mm. The compensated results all meet the requirements of positioning accuracy and repeatability of 0.01 mm.

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