Study on straightness measurement technology of slender rod based on time-domain three-point method

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Abstract. Straightness is the key geometric accuracy index of the slender rod of key parts of large machinery, which directly affects the manufacturing and installation accuracy, working efficiency and service life of mechanical products. In order to improve the manufacturing precision of the slender rod and overcome the limitations of the existing methods, a method for measuring the straightness of the slender rod based on the time-domain three-point method is proposed. According to the structural characteristics of the slender rod, the measurement principle and the overall scheme of the measurement system are given, and the mathematical model of the straightness measurement is established. Taking the core components of a construction machine as an example, the measurement and comparison of the designed measuring device and the laser tracker are used to prove that the measurement error of the designed measuring device is less than 0.005 mm. The measurement system analysis results show that the R&R of the designed measuring device has less than 10% of the research variation, indicating that its repeatability and reproducibility are good, which further proves that it can be applied to the actual production site.

1. Introduction

Straightness is the key geometric accuracy index of the slender rod of key parts of large machinery, which directly affects the manufacturing and installation accuracy, working efficiency and service life of mechanical products. Unfortunately, there is no effective method for detecting the straightness of the slender rod, which has become a technical problem in the mechanical industry [1-3].

In recent years, domestic and foreign scholars have carried out a lot of research work on geometric error measurement [4-5] of large mechanical parts, and accumulated rich technical achievements. Literatures [6-8] proposed a method for measuring the straightness of slender rods based on laser measurement. X C Chen [9] studied the straightness measurement of slender rod based on PSD and established a mathematical model. Gao W [10] introduced a scanning multi-probe system for measuring straightness profiles of cylinder workpieces, and the system consists of two probe-units, each having three displacement probes. Although it has been applied in actual production and has achieved relatively good measurement results, there are still some limitations in measurement accuracy and efficiency. In order to solve the technical difficulties of slender rod straightness measurement, the research team conducted a more in-depth study and found that the time-domain three-point method has a good potential for improving detection accuracy and efficiency of the slender rod detection. Yu X F [11] proposed a two-dimensional straightness measurement method based on...
the time-domain three-point method according to the characteristics of the large-size long axis and the mutual compensation mechanism of the two-dimensional probe. Wang P [12] studied the error amplification mechanism of data processing in the conventional time-domain three-point method, and proposed the processing method of error equivalent homogenization based on the comparison elimination method, and verified its effectiveness and practicability by simulation and experiment. The literatures [11-12] discussed the application feasibility of the time-domain three-point method in the straightness detection of shaft parts. However, it is not specifically proposed how to measure the straightness of the slender rod, which cannot effectively guide the actual production.

According to the structural characteristics of the slender rod, the principle and the overall scheme of the measurement system of the slender rod based on the time-domain three-point method are given, and the mathematical model of the straightness measurement is established. Then the structural design of the measuring device is carried out. Taking the core components of a construction machine as an example, the measurement device and the error analysis are carried out to verify the effectiveness and measurement accuracy of the measurement method.

2. Measurement principle and overall scheme of measurement system

The slender rod, such as the piston rod in hydraulic cylinder of truck crane telescopic arm, is structurally characterized by a diameter of less than 200 mm and a length of more than 3 000 mm. The straightness requirement is that the cylindrical actual busbar (referred to as the side busbar) must be located at a distance within two parallel planes. The finishing program is centerless grinding. The length of the slender rod is large and it is difficult to establish a cost-effective precision measurement benchmark. Therefore, this study considers the time-domain three-point method, which can separate the straightness error from the detection data and improve the accuracy of measurement.

Based on the principle of time-domain three-point error separation, the overall scheme of the slender rod straightness measurement system is shown in Figure 1. The measurement system of slender rod straightness includes workpiece, sensor, bracket, guide rail, support block, and platform. And three sensors are arranged in the horizontal and vertical directions of the bracket, respectively. The bracket moves along the rail during the measurement. The data acquisition interval of the measurement system is the same as the sensor spacing. After the test, the mathematical model of the slender rod straightness measurement based on the time-domain three-point method is used to calculate the relative radial run-out data of the workpiece side busbar through the industrial computer. And the side busbar straightness is obtained by the least squares method.

![Figure 1. The structure of the core parts of a construction machinery.](image)

3. Mathematical model of straightness measurement

According to the measurement principle and the overall scheme of the measurement system, a fixed spatial coordinate system XOY is established, as shown in Figure 2. The measuring device collects data along several sections in the axial direction of the workpiece during the measurement process, and the measurement interval is L. In the i-th cross-section, it is assumed that the workpiece side
busbar variation is $h_i$. The radial movement of the bracket relative to the workpiece is $\delta_i$, the axial rotation angle of the bracket relative to the workpiece is $\alpha_i$, and the detection data of the three sensors are $A_i$, $B_i$, and $C_i$, respectively. And $i=1, 2, 3...n-3$. Then the side busbar variation of workpiece is shown as Equation (1). The measuring device based on the mathematical model of the present study is shown in Figure 3.

$$
\begin{align}
    h_{i+3} &= C_{i+1} + A_{i+1} - 2B_{i+1} + 2h_{i+2} - h_{i+1} \\
    A_{i+1} &= h_{i+1} + \delta_{i+1} + L\tan\alpha_{i+1} \\
    B_{i+1} &= h_{i+2} + \delta_{i+1} \\
    C_{i+1} &= h_{i+3} + \delta_{i+1} - L\tan\alpha_{i+1}
\end{align}
$$ (1)

Figure 2. Coordinate System.

Figure 3. Detection device for straightness measurement.

The straightness of the side busbars in the horizontal and vertical directions are calculated according to the requirements of the slender rod’s tolerance of form and position. Taking the horizontal side busbar as an example, the coordinates of the side busbar data points are shown as Equation (2) in the straightness calculation coordinate system.

$$
\begin{align}
    x_i &= L(i - 1) \\
    y_i &= h_i
\end{align}
$$ (2)

The straightness of the side busbar is calculated according to the national standard [9]. First, the straight line is fitted through the least squares method. And the expressions of the line to be fitted in the coordinate system XOY are as shown in Equation (3) and Equation (4).

$$
y = kx + b
$$ (3)
Equation (5) can be obtained by combining the Equations (2) and (3). The straightness shown in Equation (6) is the difference between the maximum value and the minimum value, which calculated by Equation (5). The straightness of the vertical side busbar can be obtained in the same way.

\[
d_i = y_i - (kx_i + b) \\
f = \max(d_i) - \min(d_i)
\] (5) (6)

4. Measurement test and measurement system analysis

Taking the diameter of the outer cylindrical surface of the measured slender rod as Φ165 mm, the length is 7,480 mm, and the theoretical straightness is 0.35 mm as an example, as shown in Figure 4, The workpiece to be tested belongs to the core component of a construction machinery. Straightness is measured by laser tracker and measuring device, respectively. The purpose of comparing the two measurements is to verify the validity of the developed measurement method. And the measurement system analysis (MSA) method is used to analyze the repeatability and reproducibility of the measurement system.

**Figure 4.** The structure of the core parts of a construction machinery.

4.1. Measurement test

In the experimental verification of effectiveness of the study, the tested workpiece are masked with horizontal side busbars (Y+, Y-) and vertical side busbars (Z+, Z-), respectively. The straightness of the four side busbars were measured 10 times using the laser tracker and the detecting device, and the difference between the average values was calculated. The results of straightness measurement using the laser tracker and measuring device are shown in Table 1 and Table 2.
### Table 1. Results of straightness measurement by the laser tracker.

| Experiment times | Y+ /mm | Y- /mm | Z+ /mm | Z- /mm |
|------------------|--------|--------|--------|--------|
| 1                | 0.201  | 0.35   | 0.250  | 0.269  |
| 2                | 0.198  | 0.35   | 0.250  | 0.269  |
| 3                | 0.201  | 0.35   | 0.250  | 0.269  |
| 4                | 0.198  | 0.35   | 0.274  | 0.269  |
| 5                | 0.201  | 0.35   | 0.250  | 0.269  |
| 6                | 0.201  | 0.35   | 0.274  | 0.269  |
| 7                | 0.198  | 0.35   | 0.250  | 0.269  |
| 8                | 0.198  | 0.35   | 0.274  | 0.269  |
| 9                | 0.201  | 0.35   | 0.274  | 0.269  |
| 10               | 0.201  | 0.35   | 0.250  | 0.270  |
| average values   | 0.199  | 0.35   | 0.257  | 0.269  |

### Table 2. Results of straightness measurement by the measuring device.

| Experiment times | Y+ /mm | Y- /mm | Z+ /mm | Z- /mm |
|------------------|--------|--------|--------|--------|
| 1                | 0.212  | 0.349  | 0.265  | 0.270  |
| 2                | 0.197  | 0.350  | 0.261  | 0.269  |
| 3                | 0.209  | 0.349  | 0.261  | 0.262  |
| 4                | 0.199  | 0.348  | 0.262  | 0.263  |
| 5                | 0.200  | 0.347  | 0.264  | 0.267  |
| 6                | 0.210  | 0.349  | 0.261  | 0.270  |
| 7                | 0.198  | 0.347  | 0.261  | 0.266  |
| 8                | 0.206  | 0.348  | 0.263  | 0.262  |
| 9                | 0.198  | 0.348  | 0.261  | 0.263  |
| 10               | 0.203  | 0.349  | 0.262  | 0.267  |
| average values   | 0.203  | 0.348  | 0.262  | 0.266  |

The comparison results between the laser tracker and the detection device based on the measurement method of the present study are shown in Table 3. The measurement error of the detection device based on the measurement method of this study is 0.005 mm, which is less than one tenth of the straightness of the elongated rod of 0.35 mm, which satisfies the requirements of measurement and proves that the method is effective.

### Table 3. Comparison of measurement results of the two methods.

|         | laser tracker | detection device | measurement error |
|---------|---------------|-----------------|-------------------|
| Y+/mm   | 0.199         | 0.203           | 0.004             |
| Y-/mm   | 0.351         | 0.348           | 0.003             |
| Z+/mm   | 0.257         | 0.262           | 0.005             |
| Z-/mm   | 0.269         | 0.266           | 0.003             |

### 4.2. Measurement system analysis

On the basis of the effective measurement method, the measurement system based on the measuring device is analyzed, and the effectiveness of the method can be further analyzed.

The measurement system analysis test requires 3 surveyors and 5 workpieces. And each person repeats the measurement twice, and the straightness test results are shown in Table 4.

It is not difficult to find that the actual straightness values of the workpieces 3, 4 and 5 are larger than the tolerance value is 0.35 mm, indicating that they are out of tolerance. At the same time, the test results also show that the detection device can identify the unqualified workpiece.
### Table 4. Test results of measurement system analysis.

| Standard sequence | Operating sequence | Workpiece | Surveyor | Straightness /mm |
|-------------------|--------------------|-----------|----------|------------------|
| 1                 | 1                  | 1         | 1        | 0.305            |
| 2                 | 2                  | 1         | 2        | 0.308            |
| 3                 | 3                  | 1         | 3        | 0.303            |
| 4                 | 4                  | 2         | 1        | 0.339            |
| 5                 | 5                  | 2         | 2        | 0.339            |
| 6                 | 6                  | 2         | 3        | 0.340            |
| 7                 | 7                  | 3         | 1        | 0.788            |
| 8                 | 8                  | 3         | 2        | 0.791            |
| 9                 | 9                  | 3         | 3        | 0.795            |
| 10                | 10                 | 4         | 1        | 0.642            |
| 11                | 11                 | 4         | 2        | 0.635            |
| 12                | 12                 | 4         | 3        | 0.634            |
| 13                | 13                 | 5         | 1        | 0.594            |
| 14                | 14                 | 5         | 2        | 0.591            |
| 15                | 15                 | 5         | 3        | 0.593            |
| 16                | 16                 | 1         | 1        | 0.303            |
| 17                | 17                 | 1         | 2        | 0.301            |
| 18                | 18                 | 1         | 3        | 0.304            |
| 19                | 19                 | 2         | 1        | 0.339            |
| 20                | 20                 | 2         | 2        | 0.338            |
| 21                | 21                 | 2         | 3        | 0.341            |
| 22                | 22                 | 3         | 1        | 0.794            |
| 23                | 23                 | 3         | 2        | 0.795            |
| 24                | 24                 | 3         | 3        | 0.794            |
| 25                | 25                 | 4         | 1        | 0.632            |
| 26                | 26                 | 4         | 2        | 0.630            |
| 27                | 27                 | 4         | 3        | 0.628            |
| 28                | 28                 | 5         | 1        | 0.587            |
| 29                | 29                 | 5         | 2        | 0.588            |
| 30                | 30                 | 5         | 3        | 0.582            |

### Table 5. Results of measurement system analysis.

| Source            | Standard deviation (SD) | Study variation (6*SD) | %Study variation |
|-------------------|-------------------------|------------------------|------------------|
| Gauge R&R         | 0.003527                | 0.02116                | 1.71             |
| Repeatability     | 0.003527                | 0.02116                | 1.71             |
| Reproducibility   | 0.000000                | 0.000000               | 0.00             |
| Surveyor          | 0.000000                | 0.000000               | 0.00             |
| Workpiece         | 0.206609                | 1.23948                | 99.99            |
| Total variation   | 0.206609                | 1.23966                | 100.00           |
The results in Table 4 were further calculated by using the Minitab Gage R&R research tool, and the measurement system analysis results were obtained as shown in Table 5. We can conclude that the total percentage of R&R in the measurement variant is 1.71% and less than 10%, which proves that the repeatability and reproducibility of the detection device can meet the actual production requirements.

5. Conclusions
This study focuses on the principle of straightness measurement, mathematical model, test verification, measurement system analysis of slender rods, and draws the following conclusions.

(1) According to the structural characteristics of the slender rod of the core part of engineering machinery, the straightness measurement method of the slender rod is proposed, and the mathematical model is established, which provides a theoretical basis for the design of the measuring device.

(2) Compared with the measurement results of the laser tracker, the measurement error of the detection device based on the time-domain three-point method is less than 0.005 mm, and the total percentage of R&R in the measurement variant is 1.71%, less than 10%, which proves that the repeatability and reproducibility of the detection device can meet the actual production requirements.

(3) This study provides technical support for critical geometric error measurement such as slender straightness of large mechanical parts.

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