Study on measuring straightness of piston rod in large oil cylinders

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Abstract. The straightness detection methods of different geometric elements are described in detail in GB/T 11336-2004, but there are still many difficulties in how to implement the method in engineering, for example, how to detect straightness in the production process of piston rods in large oil cylinders. Based on time-domain three-point method and the various requirements of straightness measurement in the process of large piston rods’ production, a method for detecting the straightness of the large rod with large length-to-diameter ratio was proposed and the measuring device was successfully developed. In addition, the influences of the three error sources including axial rotation angle, probe spacing and sampling interval on the measurement results are discussed in detail. Considering the production cost and the accuracy of the device, the parameters of the straightness detection device are optimized. The effectiveness of the method was verified by field experiments. It’s very important that the study provides a technical basis for the straightness detection of large slender rods.

1. Introduction

Piston rod is one of the main parts of oil cylinder. When the straightness of piston rod, especially the piston rod of large oil cylinder, cannot meet the requirements, many unpredictable problems will occur, and even cause serious consequences. Therefore, how to guarantee the straightness of piston rod during processing is a key problem. For shorter piston rods, many factories use the dial gauge method, which is inefficient and error caused by manual reading. For longer piston rods, there are not many commercial instruments for straightness measurement, especially for long-distance rail straightness with high-precision measuring instruments [1]. So, the development of large piston rod detectors has important engineering significance.

The piston rod generally belongs to the large rod with large length-to-diameter ratio. For the straightness measurement of the slender rod, the multi-probe method in the indirect measurement method is often used [2-5], and the most typical one is the three-point method. The three-point method is divided into time-domain three-point method and frequency-domain three-point method [6-9]. What’s more, the time-domain three-point method is the most suitable method for straightness detection of piston rod [10-11]. However, there are many factors affecting the error in actual production, and there is almost no relevant error analysis research [12], which makes it impossible to apply to actual production.
In this study, the large oil cylinder piston rod is used as the research object, and the measurement method and device for detecting the straightness of the large rod with large length-to-diameter ratio based on the time-domain three-point method are given. On this basis, the error analysis of the detection system is carried out. The effectiveness of the research results is verified by the actual production test results.

2. Measuring principle and device
According to the structural features of slender rods and the error separation principle of time-domain three-point method, we establish a fixed coordinate system of XOY in space, as shown in Figure 1. During the detect process, the measuring device collects data along multiple cross sections of the workpiece in the axial direction. The data displayed by the three sensors A, B and C are $A_i$, $B_i$ and $C_i$, and the measuring distance between the two detection points is L. When $i$-section is detected, the change amount of the workpiece side generatrix is $h_i$, the axial rotation angle of the bracket relative to the workpiece is $\alpha_i$, and the radial displacement of the support relative to the workpiece is $\delta_i$. And $i=1, 2, 3...n-3$. The variation of workpiece’s side generatrix is calculated as shown in Equation (1). The measuring device designed according to the time-domain three-point method is shown in Figure 2. And the components inside the white frame represent the detection probe.

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

(1)

![Figure 1. Coordinate System.](image1)

![Figure 2. The measuring device based on the mathematical model.](image2)

The straightness of the side generatrix (cylindrical actual busbar) in the horizontal and vertical directions can be obtained according to the requirements of the slender rod’s dimensional and geometric tolerances. Taking the horizontal side generatrix as an example, the coordinates of the side generatrix data points are shown as Equation (2) in the straightness calculation coordinate system.

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

(2)

The straightness of the side generatrix 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)
Combining Equations (2) and (3), Equation (5) can be obtained. And 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 generatrix can be obtained in the same way.

\[ d_i = y_i - (kx_i + b) \]  

\[ f = \max(d_i) - \min(d_i) \]  

3. Error analysis

It is easy to find from Equation (1) that the measurement error of run-out of workpiece’s side generatrix is mainly influenced by axial rotation angle \( \alpha \), probe spacing and sampling interval. The impact of the above three key factors on the measurement result is now carried out.

3.1. Effect of axial rotation angle \( \alpha \)

Based on the time-domain three-point method, the mathematical model of error separation is established on the basis of no deflection of the measuring datum, and the sensor measuring point is the same as the theoretical measuring point. It can be seen from Equation (1), \( \alpha \) terms are offset each other when calculating \( h_{i+3} \), and the measurement error is not introduced to the Equation (1). However, due to the existence of axial rotation angle \( \alpha \), the sensor measuring point has moved, that is, the sensor measuring point is not at the measuring point position at the previous moment, as shown in Figure 3. Taking the sensor C as an example, the measuring point is offset, the detection error introduced by the deviation of measurement points can be obtained in Equation (7), and \( h'(x_c) \) is the theoretical straightness of the workpiece.

\[ \Delta h_i = h'(x_c)(h_i + l_0 - L \tan \frac{\alpha_i}{2})\tan \alpha_i \]  

Figure 3. Influence of axial rotation angle \( \alpha \).  

Figure 4. Schematic diagram of the influence of the probe spacing.
3.2. Effect of probe spacing
As shown in Figure 4, the detection error caused by the probe spacing is usually accompanied by the axial rotation angle $\alpha$. Taking sensor C as an example, the installation error is $\Delta l$, the detection error can be obtained through Equation (8).

$$\Delta h = h'(x) \left[ (h_i + l_0 - L\tan\frac{\alpha}{2})\tan\alpha_i - \frac{\Delta l}{\cos\alpha_i} \right] + \Delta l\tan\alpha_i$$  \hspace{1cm} (8)

3.3. Effect of sampling interval
Sampling interval is also an important factor leading to the detection error, and this error also includes the factors of axial rotation angle $\alpha$ and the probe spacing, as shown in Figure 5. Similarly, set the error of sampling interval as $Y_0$, and take sensor C as an example, the detection error is shown in Equation (9).

$$\Delta h = h'(x) \left[ (h_i + l_0 - L\tan\frac{\alpha}{2})\tan\alpha_i - \frac{\Delta l}{\cos\alpha_i} + Y_0 \right] + \Delta l\tan\alpha_i$$  \hspace{1cm} (9)

4. Test verification
In order to verify the study, the workpiece’s outer surface is Φ165mm and the length is 7480mm. The straightness requirement is that the side generatrix must be located at a distance within two parallel planes. Straightness is measured by laser tracker and measuring device, respectively. In the detection process, firstly, the value of the influence factor of the preset measurement error is adjusted in the straightness detecting device shown in Figure 2, such as $L=100$mm, $h_i=0.3$mm, $l_0=50$mm, and the straightness of the workpiece was 0.05mm/100mm. Then, straightness test is carried out, and the detection result is compared with the result of laser tracker to obtain the actual measurement error. By comparing the actual measurement error with the theoretical calculation error, the measuring error deviation can be obtained. In addition, the validity of the detection device is verified by comparing with the result of the laser tracker.

4.1. Test verification of axial rotation angle $\alpha$
According to the analysis of $\alpha$, experiments of different angle were designed. The results are shown in Table 1. It can be seen that the measurement error increases with the increasing of $\alpha$. And the measurement error deviation remains unchanged, which proved that the influence rule of deviation error is correct. And the actual measurement error is greater than 0.001 mm when the angle larger than 1°. Therefore, straightness detecting device should be ensured that the angle is less than 1°.
Table 1. Experimental results of axial rotation angle $\alpha$.

| Number | Number | Axial rotation angle $\alpha$ (°) | Result of detecting device (mm) | Result of the laser tracker (mm) | Actual measurement error (mm) | Theoretical calculation error (mm) | Measurement error deviation (mm) |
|--------|--------|----------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| 1      | 0      | 0                                | 0.372                           | 0.372                           | 7.45*10^-4                     | 0                               | 7.45*10^-4                     |
| 2      | 0.25   | 0.371                            | 0.371                           | 8.11*10^-4                     | 6.56*10^-5                     | 7.45*10^-4                     |
| 3      | 0.5    | 0.371                            | 0.371                           | 8.76*10^-4                     | 1.31*10^-4                     | 7.44*10^-4                     |
| 4      | 0.75   | 0.371                            | 0.370                           | 9.40*10^-4                     | 1.95*10^-4                     | 7.45*10^-4                     |
| 5      | 1      | 0.370                            | 0.369                           | 1.00*10^-3                     | 2.59*10^-4                     | 7.45*10^-4                     |
| 6      | 1.25   | 0.372                            | 0.371                           | 1.07*10^-3                     | 3.22*10^-4                     | 7.45*10^-4                     |
| 7      | 1.5    | 0.372                            | 0.371                           | 1.13*10^-3                     | 3.85*10^-4                     | 7.45*10^-4                     |
| 8      | 1.75   | 0.373                            | 0.372                           | 1.19*10^-3                     | 4.47*10^-4                     | 7.44*10^-4                     |
| 9      | 2      | 0.372                            | 0.371                           | 1.25*10^-3                     | 5.09*10^-4                     | 7.45*10^-4                     |

4.2. Test verification of probe spacing

Different probe spacing tests were designed according to the analysis results, and the results are shown in Table 2. With the increasing of the spacing, the measurement error gradually increases, and the measurement error deviation changes slightly. It proves that rule of error influence is correct.

Table 2. Experimental results of probe spacing.

| Number | Number | Probe spacing (mm) | Result of detecting device (mm) | Result of the laser tracker (mm) | Actual measurement error (mm) | Theoretical calculation error (mm) | Measurement error deviation (mm) |
|--------|--------|-------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| 1      | 0      | 0                 | 0.369                           | 0.369                           | 2.09*10^-4                     | 1.31*10^-4                     | 7.81*10^-5                     |
| 2      | 0.05   | 0.371             | 0.371                           | 6.29*10^-4                     | 5.52*10^-4                     | 7.65*10^-5                     |
| 3      | 0.1    | 0.371             | 0.370                           | 1.05*10^-3                     | 9.73*10^-4                     | 7.70*10^-5                     |
| 4      | 0.15   | 0.369             | 0.370                           | 1.47*10^-3                     | 1.4*10^-3                      | 7.45*10^-5                     |
| 5      | 0.2    | 0.373             | 0.371                           | 1.90*10^-3                     | 1.81*10^-3                     | 7.67*10^-5                     |
| 6      | 0.25   | 0.373             | 0.371                           | 2.31*10^-3                     | 2.24*10^-3                     | 7.72*10^-5                     |
| 7      | 0.3    | 0.373             | 0.370                           | 2.74*10^-3                     | 2.66*10^-3                     | 7.83*10^-5                     |
| 8      | 0.35   | 0.372             | 0.369                           | 3.16*10^-3                     | 3.08*10^-3                     | 7.59*10^-5                     |
| 9      | 0.4    | 0.375             | 0.371                           | 3.58*10^-3                     | 3.50*10^-3                     | 7.72*10^-5                     |

4.3. Test verification of sampling interval

The test results of different sampling interval on the error are shown in Table 3. With the increasing of sampling interval, the measurement error increases gradually, and the measurement error deviation changes less. And when the sampling interval is larger than 1.2 mm, the actual measurement error is greater than 0.001 mm, so it should be ensured that the sampling interval is less than 1.2 mm.

4.4. Optimization of straightness detection device

According to the experimental verification results in Tables 1-3, the smaller the axial rotation angle $\alpha$, probe spacing and sampling interval are, the higher device accuracy will be. However, the reduction of the axial rotation angle $\alpha$ and the sampling interval will increase the production cost, and it is difficult to meet the requirement of the smaller probe spacing. Therefore, the straightness detection device will be optimized as the following parameters, the axial rotation angle is 0.5°, probe spacing is 0.05mm, and sampling interval is 0.6mm. After the optimization, the piston rod of the large oil cylinder was tested, and the effectiveness of the detection device is verified by comparison with the detect results of laser tracker.
Before the test, the straightness of four side generatrices on the circumference of the workpiece were marked as horizontal side generatrices (Y+, Y-) and vertical side generatrices (Z+, Z-), respectively.

Laser tracker and detection device were used to measure the straightness of four side generatrices for 10 times and calculate the average value. As shown in Table 4, the measure error of the detection device is 0.002mm, which is less than one-tenth of the slender rod’s straightness. It meets the measurement requirements and proves that the method is effective.

Table 3. Experimental results of sampling interval.

| Number | Sampling interval (mm) | Result of detecting device(mm) | Result of the laser tracker (mm) | Actual measurement error(mm) | Theoretical calculation error(mm) | Measurement error deviation (mm) |
|--------|------------------------|--------------------------------|---------------------------------|------------------------------|----------------------------------|---------------------------------|
| 1      | 0                      | 0.368                          | 0.368                           | 6.38*10^{-4}                 | 5.52*10^{-4}                     | 8.64*10^{-5}                   |
| 2      | 0.25                   | 0.368                          | 0.368                           | 7.14*10^{-4}                 | 6.27*10^{-4}                     | 8.72*10^{-5}                   |
| 3      | 0.50                   | 0.369                          | 0.369                           | 7.89*10^{-4}                 | 7.02*10^{-4}                     | 8.70*10^{-5}                   |
| 4      | 0.75                   | 0.370                          | 0.371                           | 7.86*10^{-4}                 | 7.77*10^{-4}                     | 8.77*10^{-5}                   |
| 5      | 1.00                   | 0.371                          | 0.370                           | 8.61*10^{-4}                 | 8.52*10^{-4}                     | 8.81*10^{-5}                   |
| 6      | 1.25                   | 0.372                          | 0.371                           | 9.36*10^{-4}                 | 9.27*10^{-4}                     | 8.72*10^{-5}                   |
| 7      | 1.50                   | 0.372                          | 0.371                           | 1.09*10^{-3}                 | 10^{-3}                          | 8.63*10^{-5}                   |
| 8      | 1.75                   | 0.370                          | 0.369                           | 1.17*10^{-3}                 | 1.08*10^{-3}                     | 8.69*10^{-5}                   |
| 9      | 2.00                   | 0.372                          | 0.371                           | 1.24*10^{-3}                 | 1.15*10^{-3}                     | 8.72*10^{-5}                   |

Table 4. Comparison of measurement results.

| Side generatrix | Result of the laser tracker (mm) | Result of detecting device(mm) | Measurement error(mm) |
|-----------------|----------------------------------|--------------------------------|-----------------------|
| Y+/mm           | 0.221                            | 0.220                          | 0.001                 |
| Y-/mm           | 0.345                            | 0.347                          | 0.002                 |
| Z+/mm           | 0.324                            | 0.322                          | 0.002                 |
| Z-/mm           | 0.378                            | 0.376                          | 0.002                 |

5. Conclusions
This study focuses on the straightness measurement principle, measurement system error and test verification of the piston rod of the large oil cylinder, and draws the following conclusions:
(1) The straightness measurement method and device of slender rod based on the time-domain three-point method are presented according to the structural characteristics of slender rod of core components of construction machinery.
(2) In this paper, the influences of three error sources, such as axial rotation angle α, probe spacing and sampling interval, on the measurement results are discussed in detail. Considering the production cost and the accuracy of the device, the parameters of the straightness detection device are optimized as follows: the axial rotation angle is 0.5°, the probe spacing is 0.05 mm, and the sampling interval is 0.6 mm.
(3) Compared with the measurement results of the laser tracker, the measurement error of the slender rod straightness detection device optimized by this study is less than 0.003 mm, which meets the actual production demand.
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References
[1] Ning Y P and Liu Z F 2005 Modern Manufacturing Engineering 82-84
[2] Ding G Q 2012 Research on Ultraprecision Measurement and Calibration Method Based on the Error Separation Technique (Shanghai Jiaotong University)
[3] Cheng W M, Zhang W N, Song W, et al. 2011 Third International Conference on Measuring Technology and Mechatronics Automation IEEE Xplore 354-357
[4] Qian L H, Lv L and Xia H 2017 Modular Machine Tool & Automatic Manufacturing Technique 77-80
[5] Kume T, Satoh M, Suwada T, et al. 2015 Precision Engineering 39 173-178
[6] Tu X F, Wang F, et al. 2013 China Mechanical Engineering 24 1901-1905
[7] Su H, Hong M S, et al. 2003 Chinese Journal of Scientific Instrument 24 275-280
[8] Li S M, Yu D G, et al. 2015 Coal Mine Machinery 36 164-167
[9] Zhang L, Jin J Q and Zhang Y 1998 Chinese Journal of Scientific Instrument 19 659-662
[10] Yu X F, Wang P, Pei L M, et al. 2013 China Mechanical Engineering 24 1901-1905
[11] Wang P, Yu X F, Meng F L, et al. 2013 China Mechanical Engineering 24 1733-1737
[12] Liu W, Tao T and Zeng H 2016 Optical Measurement Technology & Instrumentation