Study on straightening quality control for slender rod based on digital twin

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Abstract. For the technical problems of slender rod straightening quality control in the mechanical industry, a straightening quality control method for slender rod based on digital twin is proposed. According to the characteristics of the slender rod straightening process system, straightness detection device for slender rod suitable for production site is developed. Combined with the straightening process of the slender rod, straightening stroke model is given. Straightening quality control system for slender rod is established based on digital twin technology. Taking the piston rod of a large hydraulic cylinder as an example, straightening quality is controlled. The result shows that the theoretical calculation error rate of the straightening stroke is less than 0.5%. Straightness data of piston rod with quality control system is compared with straightness data of piston rod without quality control system. The result shows that the straightness consistency of the piston rod by quality control is good, and it is controlled within the range of 0-0.5mm. Straightening pass rate increased from 30% to 100%. This proves straightening quality control system for slender rod based on digital twin is effective. It can meet the needs of actual production. This study provides technical support for the optimization of slender rod straightening process parameters and high-precision machining.

1. Introduction
Slender rod is one of the most widely used shapes in the machinery industry, which directly affects the host performance. Straightness is the key technical index of the slender rod, which directly affects the manufacturing and installation accuracy, working efficiency and service life of mechanical products. Unfortunately, there is no effective method for the straightness detection of the slender rod and quality control, which has become a technical problem in the mechanical industry [1-4]. Therefore, overcoming the straightness detection and quality control technology for slender rod has great significance to improve the manufacturing accuracy of the slender rod, reduce the reject rate, reduce the production cost, and improve the reliability of the whole machine.

The literature review shows that digital twin technology has more effective in quality control. Digital twin refers to a simulation process that integrates multiple physical quantities, scales, and probabilities. It can digitally create a virtual model of a physical object and reflect the entire life cycle of a physical object process [5-7]. Some scholars have established the architecture of digital twin, and applied digital twin to the construction of machine tools and glass production lines [8-11]. Digital twin has significant application prospects in the quality control of the production process.
In this research, the straightening quality control technology of slender rod is taken as the research object. An online straightness detection device for slender rod is carried out. Through the digital twin technology, the real straightness control process and virtual simulation control process for slender rod are collected to achieve physical fusion, model fusion and data fusion. The real control process and virtual simulation can achieve the interaction and synergy. The straightness control level for slender rod can be improved.

2. Straightness on-line detection technology
In recent years, scholars have carried out a lot of research work on the geometric error measurement of large mechanical parts. However, the online straightness detection method for slender rod is still blank. As a result, the quality data cannot be effectively analyzed and controlled. An online inspection scheme suitable for the actual production site is proposed. Using this scheme, the straightness of the slender rod can be quickly and accurately detected and calculated at the production site.

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 3000 mm. In this study, it is planned to arrange a probe every 1m in the axial direction of the workpiece. The digital display meter is used as a sensor, and the wireless transmission system is used for data transmission. The tested part is rotated by the driving wheel. After each set angle, the host synchronously collects the data of the digital display meter, and sequentially detects the point coordinates uniformly distributed on the workpiece circumference. The circle center of each section is calculated according to the point coordinates using the least squares method, and then the straightness is calculated using the least squares. The measuring device is shown in Figure 1. It can complete the straightness detection, and provide the straightening position information for the straightening machine operator.

3. Straightening stroke model
Press straightening is that the slender rod is held from two fulcrum points, and the special straightening device is used to apply pressure with the indenter in the opposite direction of the slender rod largest bend. This can cause the slender rod to undergo a certain plastic deformation. When the straightening stroke setting position is reached, the indenter is raised to achieve the purpose of straightening slender rod.

Press straightening is actually an elastoplastic reverse bending process. The theoretical mathematical model of the straightening process represented by the load-deflection curve is shown in Figure 2. The straightening process is divided into 3 stages. The OA section is the elastic loading stage, $A$ is the maximum elastic deformation point of the material; The $AB$ section is the elastoplastic...
deformation stage, which is unloaded after loading to point $B$; The BC section is the elastic rebound stage, and elastically rebounds to point $C$ after unloading.

In Figure 2: $F_t$ is the load at the maximum elastic deformation of the material. $F_m$ is the load at the maximum straightening stroke. $\delta_A$ is the maximum elastic deformation of the material. $\delta_B$ is the deformation of the elastoplastic phase of the material. $X$ is the initial bending amount of the slender rod. $Y$ is the stroke required to straighten the slender rod. $k_1$ is the slope of the OA segment. $k_2$ is the slope of the AB segment. According to Hooke’s law, the slope of the elastic rebound phase is the same as the elastic loading phase, which is represented by $k_1$ in the figure. According to Figure 2, if the initial bending amount $X$ of the slender rod is equal to the length of the OC segment, the slender rod is straightened, and the corresponding straightening stroke is $Y$.

From the geometric relationship of Figure 2, the following equation can be deduced.

$$\delta_B = \frac{F_m - F}{k_2}$$

(1)

$$Y = \frac{k_1}{k_1 - k_2} X + \frac{F}{k_1}$$

(2)

From Equation (2), the calculation formulas of the elastic deformation stage $k_1$ and the elastoplastic deformation stage $k_2$ must be obtained to obtain the relationship between the press straightening stroke and the initial bending amount of the slender rod.

According to the calculation of the deflection of a simply supported beam in material mechanics, the relationship between load and deflection during the elastic deformation stage is shown by the following formula:

$$k_1 = \frac{6EI}{l^3}$$

(3)

In the formula: $l$ is the moment of inertia of the slender rod. $E$ is the elastic modulus of the material. $l$ is the fulcrum to pressure point distance.

The relationship between load and deflection is complicated in the elastoplastic deformation phase. Because the press straightening process is a small curvature bending process, the effect of stress neutral layer internal displacement can be ignored. The plane section assumption, one-way stress assumption, and ideal elastoplastic material assumption can be used.

Calculating the bending moment from the external load and internal stress integration, the following formula can be derived.

$$F_s = \frac{2M_\alpha}{l}$$

(4)

$$\delta = \frac{2l^3}{6EI} + \frac{M_s}{EI_\xi} \left( l^3 - \frac{l_0^3}{2} \right)$$

(5)

In the formula: $\xi$ is the elastic area ratio, which is used to reflect the elastoplastic deformation of the slender rod. When $\xi = 0$, the outermost fiber at the pressure point section begins to enter the elastoplastic deformation stage. When $\xi = 1$, plastic deformation occurs at the entire thickness of the pressure point section. $l_0$ is the length of the area where the elastic deformation occurs in the axial direction of the slender rod. $F_s$ is the load on the slender rod during the elastoplastic deformation phase. $M_s$ is the ultimate elasticity bending moment. $\alpha$ is the coefficient of load variation. The minimum value is 1 and the maximum value is 1.7.

According to (1), (4) and (5), the simultaneous formula for $k_2$ is as follows.

$$k_2 = \frac{4\xi_0 EI}{(1 + \alpha) l^3}$$

(6)

Substituting Formulas (3), (5), and (6) into Formula (2), the relationship between the pressure straightening stroke and the initial bending amount of the slender rod can be obtained.
From the mechanical properties of materials, we can get:

\[ Y = \frac{1 + a}{1 + a - \frac{2}{3} \xi a} X + \frac{M l^2}{3EI} \]  

From the formula: \( D \) is the outer diameter of the slender rod. \( \sigma_y \) is the yield strength of the material.

Let \[ a_0 = \frac{1 + a}{1 + a - \frac{2}{3} \xi a} \]

Equation (8) becomes:

\[ Y = a_0 X + \frac{\sigma_y l^2}{3ED} \]  

From the physical meaning of \( \xi \) and \( a \), we can get: \( 1 \leq \xi \leq 1.7, 0 \leq a \leq 1 \). When \( \xi = 0, a = 1.7 \). When \( \xi = 1, a = 1 \). Therefore, \( 1 \leq a_0 \leq 1.5 \). The function \( Y(X) \) is a monotonically increasing function.

From Equation (9), the press straightening stroke is positively related to the distance between the two fulcrum points and the yield strength of the material. It is negatively related to the outer diameter and elastic modulus of the slender rod. During the quality control of straightness of slender rod, straightening process parameters such as straightening stroke and fulcrum distance are optimized according to the press straightening stroke established by Equation (9). The best straightening process can be received to direct the straightening process of slender rod.

### 4. Quality control system

#### 4.1. Data composition of straightening quality control system based on digital twin

The straightening quality control system data of slender rod includes the straightening results and machining process parameter data which mainly include raw material data, processing process data, and test data.

The raw material data includes the name of the raw material supplier, the raw material belongs to domestic or imported products, the raw material specification model number, and the raw material processing method. The processing data includes the slender rod model number, slender rod size parameters, equipment manufacturer, equipment model number, processing parameters such as pressure, holding time, number of depressions, indenter form, operator. Detection data includes detection equipment information, detection equipment movement information, detection process data and detection results.

#### 4.2. Framework of straightening quality control system based on digital twin

The straightening quality control frame based on digital twin is shown in Figure 3, which is mainly composed of a physical straightening station, a virtual straightening station, and a straightening quality control system for slender rod.

The physical straightening station is a collection of existing physical entities in the straightening process of slender rod, including straightening machine, operator, slender rod, straightness testing equipment based on straightening machine, etc. It is mainly responsible for straightening processing and straightness detection of slender rod. Compared with traditional straightening processing, digital twin straightening processing needs to have multiple elements of interconnection and data fusion capabilities.

Virtual straightening station is that through modeling technology, the physical and straightening of the physical straightening station is processed from the aspects of factors, behaviors and rules to
perform virtual reconstruction and digital mirroring. By constructing virtual straightening processing and straightness detection, the processing progress and working status of the slender rod, straightening machine and straightness detection equipment in the physical straightening station are dynamically, real-time and accurately mapped in the virtual space. Therefore, the operating status of the physical straightening station can be monitored and tracked at any time.

**Figure 3.** Framework of straightening quality control system based on digital twin.

The straightening quality control system for slender rod mainly implements the straightness detection of slender rod and the monitoring, prediction and optimization of the straightening process. The system is a platform connecting the physical straightening station and the virtual straightening station and its functional modules are shown in Figures 4.

**Figure 4.** Functional module of straightening quality control system for slender rod.

5. **Experimental verification**

In order to verify the validity of this study, the piston rod of a large hydraulic cylinder was used as the research object for straightening quality control. The piston rod parameters are as follows. The material is 45 steel and it is normalized. The diameter of the outer circle is 180mm, the diameter of the inner circle is 150mm, the length is 7600mm, and the straightness requirement is less than 0.5mm. The characteristic parameters of the material measured by the tensile test are the elastic modulus of 200 GPa and the yield limit is 380 MPa. For this sample, the distance between the straightening support points is set to 4000mm. On this basis, the five straightening strokes of each of the piston rods with an initial bending deformation of 1mm, 2mm, 3mm, 4mm, and 5mm at the actual production site are tracked. The results are shown in Table 1. The plane section assumption, one-way stress assumption, and ideal elastoplastic material assumption are adopted in the derivation of Formula (9). In order to compensate for the theoretical calculation error of the straightening stroke caused by the simplified assumption, the data in Table 1 is averaged to calculate the coefficient \( a_0 \). The actual straightening
average value is calculated for the actual straightening stroke. The coefficient $a_0$ and the average value are calculated according to Formula (9). The average value of coefficient $a_0$ is used as the final value $a_0$ of Formula (9) to calculate the theoretical straightening stroke. By comparing the actual straightening stroke with the theoretical straightening stroke, the theoretical calculation error rate relative to the actual straightening stroke is less than 0.5%. It meets the actual production requirement. It proves that the straightening stroke model proposed in this study is effective.

**Table 1.** Straightening stroke calculation results and experimental data.

| Initial bending/mm | Actual straightening stroke/mm | Actual straightening stroke average/mm | Coefficient $a_0$ | Coefficient $a_0$ average | Theoretical calculation result straightening stroke/mm | Error/mm | Error rate/% |
|-------------------|---------------------------------|----------------------------------------|-------------------|---------------------------|---------------------------------------------|---------|-------------|
| 14.170            | 14.138                          |                                        |                   |                           | 0.007                                       | 0.05    |              |
|                   | 14.206                          | 14.176                                 | 1.474             |                           | 14.177                                      | -0.029  | 0.2         |
|                   | 14.180                          |                                        |                   |                           | -0.003                                      | 0.02    |              |
|                   | 14.188                          |                                        |                   |                           | -0.011                                      | 0.08    |              |
|                   | 15.593                          |                                        |                   |                           | 0.059                                       | 0.38    |              |
|                   | 15.713                          |                                        |                   |                           | -0.061                                      | 0.39    |              |
| 1 14.703           | 15.659                          | 14.697                                 | 1.479             |                           | 15.652                                      | -0.051  | 0.32         |
|                   | 15.603                          |                                        |                   |                           | 0.049                                       | 0.31    |              |
|                   | 15.683                          |                                        |                   |                           | -0.031                                      | 0.2     |              |
|                   | 17.134                          |                                        |                   |                           | -0.007                                      | 0.04    |              |
|                   | 17.124                          |                                        |                   |                           | 0.003                                       | 0.02    |              |
| 2 17.144           | 17.118                          | 14.697                                 | 1.472             | 1.475                     | 17.127                                      | -0.017  | 0.1          |
|                   | 17.084                          |                                        |                   |                           | 0.043                                       | 0.25    |              |
|                   | 17.104                          |                                        |                   |                           | 0.023                                       | 0.13    |              |
|                   | 18.605                          |                                        |                   |                           | -0.003                                      | 0.02    |              |
|                   | 18.568                          |                                        |                   |                           | 0.034                                       | 0.18    |              |
| 3 18.595           | 18.596                          | 14.697                                 | 1.474             |                           | 18.602                                      | 0.007   | 0.04         |
|                   | 18.604                          |                                        |                   |                           | -0.002                                      | 0.01    |              |
|                   | 18.610                          |                                        |                   |                           | -0.008                                      | 0.04    |              |
|                   | 20.105                          |                                        |                   |                           | -0.028                                      | 0.14    |              |
|                   | 20.098                          |                                        |                   |                           | -0.021                                      | 0.1     |              |
| 4 20.034           | 20.080                          | 14.697                                 | 1.476             |                           | 20.077                                      | 0.043   | 0.21         |
|                   | 20.065                          |                                        |                   |                           | 0.012                                       | 0.06    |              |
|                   | 20.097                          |                                        |                   |                           | -0.020                                      | 0.1     |              |

**Figure 5.** Straightness quality curve before and after quality control application.
In order to verify the effectiveness of the quality control system built in this study, for the above piston rods, 30 piston rods with quality control and 30 piston rods without quality control are tracked. The straightness comparison between the piston rods with quality control and the piston rods without quality control is shown in Figure 5. The comparison results show that the straightness of the piston rod is in good consistency and it is controlled within the range of 0-0.5mm with the quality control. The pass rate of straightness straightened products is increased from 30% to 100%. It proves that the straightening quality system for slender rod based on digital twin is effective and it meets the needs of actual production.

6. Conclusions
This study focuses on the straightening quality control technology for slender rod based on digital twin. It has carried out research on the straightness detection technology of slender rod, straightening stroke model research, and construction of straightness control system, and draws the following conclusions.

(1) The straightening stroke model was established and was positively related to the distance between the two fulcrum points, the yield strength of the material, and negatively related to the outer diameter and elastic modulus of the slender rod. The experimental results show that the theoretical calculation error rate of the straightening stroke is less than 0.5%, which meets the actual production.

(2) The straightening quality control system for slender rod based on the digital twin technology was established. The experiments show that the straightness of the piston rod is in good consistency and it is controlled within the range of 0-0.5mm with the quality control. The qualified rate of slender rod is increased from 30% to 100%. It proves that straightening quality system based on digital twin is effective and it meets the needs of actual production.

(3) This study provides technical support for critical geometric error measurement and optimization of processing technology such as the straightness for slender rods of large mechanical parts.

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