Study on straightness prediction of centerless grinding of slender rod based on PCA and Markov

Xinchun Chen\textsuperscript{1,2,3}, Peng Ding\textsuperscript{1}, Can Wang\textsuperscript{1} and Naiqing Yan\textsuperscript{1}

\textsuperscript{1}Jiangsu XCMG Construction Machinery Research Institute Ltd, Xuzhou 221004, China
\textsuperscript{2}State Key Laboratory of Intelligent Manufacturing of Advanced Construction Machinery, Xuzhou Construction Machinery Group, Xuzhou 221004, China
\textsuperscript{3}E-mail: chenchunzhaoxin@163.com

Abstract. In order to optimize the processing parameters of slender rods and achieve high-precision machining, a method of straightness prediction of centerless grinding based on PCA and Markov is proposed. A straightness measuring device for slender rod is developed to collect data. The accumulated straightness data is divided into typical processing conditions. The parameters that affect the straightness of centerless grinding of slender rod are analyzed based on PCA. According to the correlation between the parameters and the degree of influence on the straightness, the construction of the processing conditions is further simplified. On this basis, the straightness prediction model based on PCA and Markov is established to predict the processing conditions of centerless grinding of slender rods. Taking the centerless grinding of the piston rod of a hydraulic cylinder as an example, the machining experimental research is conducted. The predictive value is compared with the actual measured value, and the result shows that the average error rate is 3.94\%, which indicates the effectiveness of the prediction method and meets the needs of actual production. This study provided technical support for parameters optimization of centerless grinding of slender rods parameter optimization and high-precision machining.

1. Introduction

With the continuous development of construction machinery, the processing quality requirements of mechanical parts are getting higher and higher. The slender rods of large mechanical parts are widely used as important parts in the construction machinery industry. How to effectively solve the processing quality problem of slender rods is particularly important [1]. The rigidity of the slender rod is poor, the processing is difficult, and the accuracy is high. Especially the straightness problem has become the bottleneck of factory processing. In order to better solve the production and processing problems of the slender rods, it analyzes from various factors affecting the processing. Reasonable processing parameters are developed to form an effective method for controlling the straightness of slender rods, which is of great significance for improving the quality of slender rods.

By consulting the literature, it is shown that the prediction methods of processing quality include particle swarm optimization and neural network algorithms. Combining the actual production needs and the processing of slender rods, the Markov method is more suitable for the study of the processing quality of slender rods in this paper. The Markov model is proposed by the Russian mathematician Markov, which is mainly used in speech recognition, stock prediction, text information, etc. [2-3]. Massive scholars have applied Markov prediction methods to the simulation of oil-gas reservoir...
lithofacies, railway passenger flow, vehicle driving conditions, and bearing fault detection and diagnosis [4-8], which have good results, fully reflecting the wide application of Markov prediction model and practicality.

This article takes the processing quality of slender rods as the research object, analyzes the raw material data, processing parameters, and equipment parameters that affect the processing of slender rods. Based on the range of straightness, the influencing factors of processing slender rods in different straightness ranges are set as typical processing conditions. The typical processing conditions are predicted by Markov theory to improve the processing quality of slender rods.

2. Centerless grinding conditions of slender rods
The structure of the slender rod is characterized by a diameter of less than 200mm and a length of more than 3000mm. This type of cylindrical surface is the key shape surface in the core parts of large machinery such as piston rod in hydraulic cylinder of truck crane telecrane arm.

For the processing of slender rods, the main process generally used is cold drawing-straightening-centerless grinding. Cold drawing is the previous process, the main role is to achieve a certain diameter and mechanical properties. The straightening process is mainly for the correction of circular run-out. The centerless grinding as a finishing process of the slender rod and the last process, it has a decisive influence on its accuracy. At present, there is no effective straightness detection method for the centerless grinding process, and quality measurement cannot be performed. Therefore, this article studies this situation. As shown in Figure 1, the straightness detection device is based on a centerless grinder to construct a straightness detection system. A 2D laser displacement sensor is arranged at 1m in the axial direction of the workpiece to measure the profile of each section, calculate the center of the circle, and finally use the least square method to perform straightness. The straightness during the centerless grinding process is measured, and a large amount of straightness data is collected. On the one hand, it controls the processing quality of the slender rod on the site, and on the other hand, it provides data accumulation for subsequent quality control research.

![Figure 1. Straightness detection device for piston rod blank of centerless grinding.](image)

The straightness data is obtained based on the straightness detection system, and the straightness data is divided into corresponding raw material data, processing parameters, and equipment parameters, it is a typical processing condition of centerless grinding of slender rods, the raw material data includes the material type (1. cold drawing; 2. Hot rolling), diameter of outer circle, wall thickness, length, straightness; processing parameters include motor flow of grinding wheel, speed of rough grinding, speed of fine grinding, speed of external guide wheel, speed of internal guide wheel, rough grinding times, rough grinding depth, fine grinding times, fine grinding depth; equipment parameters include type (1. domestic production; 2. import), service life, cumulative number of processed workpieces, grain number of grinding wheels, grinding wheel width, operator.

According to the actual production needs, combined with production data and experience accumulation, straightness tolerance solutions under different processing conditions are shown in Table 1. According to the scheme given in Table 1, it provides a solution to the problem of straightness out of
tolerance, improves the machining quality of centerless grinding of slender rods, effectively controls the straightness problem, and guarantees the processing quality.

Table 1. Straightness tolerance solutions.

| Serial number | Processing conditions | Solution                |
|---------------|-----------------------|-------------------------|
| 1             | 0.2-0.4               | meet processing requirements |
| 2             | 0.4-0.6               | grind again              |
| 3             | 0.6-0.8               | grind twice              |
| 4             | 0.8-1.0               | grind again three times  |
| 5             | 1.0-1.2               | grind again four times   |
| 6             | 1.2-1.4               | grind again five times   |
| 7             | 1.4-1.6               | return to the straightening process to re-align |
| 8             | 1.6-1.8               | return to the straightening process to re-align |

3. PCA of straightness conditions

There are many parameters such as material, processing, and equipment in the division of centerless grinding processing conditions for slender rods. The correlation between the parameters is relatively large, and it is not easy to predict and optimize the straightness. In order to better perform straightness prediction and quality control, this study is based on the classification of processing conditions. Some of the influencing factors based on the correlation between various parameters and the effect on straightness are discarded by PCA. The construction of processing conditions is further simplified, analysis indicators are reduced, and the workload is greatly reduced in the future.

According to the large data of quality, the original parameter matrix (straightness is the number of rows, and the influence parameter is the number of columns) is established, it consists of three parts of data: raw materials, processing parameters, and equipment parameters.

\[
R = \begin{bmatrix}
X_{11} & X_{12} & \cdots & X_{1n} \\
X_{21} & X_{22} & \cdots & X_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
X_{m1} & X_{m2} & \cdots & X_{mn}
\end{bmatrix}
\]

(1)

According to the PCA mathematics, matrix \(R=[x_{ij}]_{m\times n}\) standardization, correlation matrix establishment, eigenvalue solution, main elements of the matrix from left to right, cumulative contribution rate calculation, and determine the main elements are ordered.

The original parameter matrix \(R=[x_{ij}]_{m\times n}\) is standardized to obtain a matrix \(X=[x^*_{ij}]_{m\times n}\), where:

\[
x^*_j = \frac{x_j - \bar{x}}{s_j}, i=1,2,...,m; j=1,2,...,n, \bar{x}_j = \frac{\sum_{i=1}^m x^*_j}{m}, s_j = \sqrt{\frac{\sum_{i=1}^m (x_{ij} - \bar{x}_j)^2}{m-1}}
\]

(2)

The correlation matrix \(C\) of the standardized matrix \(X\) is solved:

\[
C = (r_{ik})_{n\times n}, r_{jk} = \frac{1}{m-1} \sum_{i=1}^m (z_{ij}, z_{ik}), j, k = 1,2,...,n
\]

(3)

The eigenvalues of matrix \(C\) are solved and arrange them from large to small as:

\[
\lambda_1 \geq \lambda_2 \geq \cdots \geq \lambda_n
\]

(4)

The contribution rate of \(i\)-th principal component is calculated:
4. Straightness prediction based on Markov

According to the straightness large data, the straightness dynamic response characteristics are analyzed, and the prediction methods such as neural network and response surface methodology are compared. Finally, Markov prediction theory is determined to establish a straightness prediction model, which improves the prediction accuracy of quality parameters and saves calculation time.

Let each processing condition divided by the degree of straightness be regarded as a state as $E_1, E_2, ..., E_n$, a total of $n$ possible states, and the processing condition at time $t$ is denoted as $x_t$. Let $x_t \in (E_1, E_2, ..., E_n)$. The observed value of m straightness is $v_1, v_2, ..., v_m$, and the straightness observed at time $t$ is $o_t$, $o_t \in (v_1, v_2, ..., v_m)$. Let $P_{ij}$ be the state transition probability from state $E_i$ to state $E_j$.

\[
P = \begin{bmatrix}
P_{11} & P_{12} & \cdots & P_{1n} \\
P_{21} & P_{22} & \cdots & P_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
P_{n1} & P_{n2} & \cdots & P_{nn}
\end{bmatrix}
\]  

(6)

$P$ is called the state transition probability matrix.

If the predicted straightness is currently in state $E_i$, then at the next moment, it may change from state $E_i$ to any one of $E_1, E_2, ..., E_i, ..., E_n$. In order to find calculate the state transition probability matrix $P$, the transition probability $P_{ij}$ of each state transitioning to any other state is found. In order to find each $P_{ij}$, it is calculated the idea of frequency approximation probability.

\[
P_{ij} = \frac{a_{ij}}{\sum_j a_{ij}}
\]  

(7)

$a_{ij}$ is the number of observations from state $E_i$ to state $E_j$.

The state probability $\pi(k)$ represents the probability that an event is in $E_j$ at the $k$-th moment after $k$ state transitions under the condition that the initial state ($k = 0$) is known.

\[
\sum_j \pi_j (k) = 1
\]  

(8)

Markov model is shown below:

\[
\pi(n) = \pi(0)P^n
\]  

(9)

In the formula, $\pi(n)$ is the state probability vector at time $n$, and $\pi(0)$ is the initial state probability vector. According to the Markov model, the state of future straightness can be predicted.

5. Experimental verification

The straightness data obtained by processing the piston rod of a hydraulic cylinder on a centerless grinder is taken as an example, a machining experiment is conducted to conduct a PCA of the factors that may affect the straightness of the piston rod to simplify data processing. For the accumulated straightness data, the processing conditions of centerless grinding of slender rods are predicted based on Markov prediction method.

5.1. PCA

The correlation between the factors is large and difficult to process, the dimension reduction was carried out based on the PCA. The centerless grinding of slender rods is tracked. Since the material type used is hot-rolled steel pipe, centerless grinder is imported equipment, and the data is based on the same year,
the other 17 parameters in addition to these three factors in part 2 are taken as the research target. The original matrix composed of the straightness related parameters is represented by \( R \). \( R \) is shown in Formula (10). The characteristic root of the correlation matrix \( C \) can be obtained: \( \lambda_1=11.2002, \lambda_2=1.9197, \lambda_3=1.2331, \lambda_4=1.0702, \lambda_5=0.7050, \lambda_6=0.4237, \lambda_7=0.1997, \lambda_8=0.1694, \lambda_9=0.0790, \lambda_{10}=\lambda_{11}=\lambda_{12}=\lambda_{13}=\lambda_{14}=\lambda_{15}=\lambda_{16}=\lambda_{17}=0. \)

The contribution of each principal component that affects the straightness of centerless grinding of the slender rod is shown in Table 2.

![Table 2. Contribution ratio of main components.](image)

The first four factors are selected, and the cumulative contribution rate reaches 90.72%, which can meet the actual processing requirements. The parameters that affect the straightness of the centerless grinding of slender rod are analyzed based on PCA. The number will be reduced from 17 to 4, which
greatly reduces the workload of regulating and analyzing the straightness. It is significant for actual production and processing.

5.2. Straightness prediction analysis

Based on the actual centerless grinding of slender rods as an example, a 2D laser displacement sensor is used to perform straightness detection, and the actual processing data on the site in Table 3 is accumulated for analysis and preparation for subsequent straightness detection.

| Times | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   | 12   |
|-------|------|------|------|------|------|------|------|------|------|------|------|------|
| Straightness /mm | 0.856 | 0.884 | 0.353 | 0.818 | 1.112 | 1.32 | 0.796 | 1.026 | 1.015 | 1.062 | 0.854 | 1.644 |

Each processing condition divided in part 2 is taken as corresponding to each state, the state transition matrix $P$ can be obtained according to Formula (11):

$$P = \begin{bmatrix}
0 & 0 & 0.5 & 0.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0.33 & 0.33 & 0 & 0 & 0 & 0.33 & 0 & 0 & 0 & 0 & 0 \\
0.25 & 0 & 0 & 0.5 & 0.25 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0.167 & 0.167 & 0 & 0.33 & 0.167 & 0 & 0 & 0 & 0.167 & 0 & 0 & 0 \\
0 & 0 & 0 & 0.25 & 0.5 & 0.25 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}$$

The measured straightness data is used as the initial state in the fourth operating condition, so the initial state probability vector is $\pi(0)=[0 \ 0 \ 0 \ 1 \ 0 \ 0 \ 0 \ 0]$. According to the straightness prediction model based on PCA and Markov, the probability of occurrence of various processing conditions in the next 30 times is predicted, and the first processing condition is taken as an example, as shown in Figure 2.

![Figure 2](image)

Figure 2. Predicting the probability of occurrence of the first operating condition.

The straightness prediction model based on PCA and Markov has nothing to do with the initial state. From Figure 2, it can be found that at the 17th time, the probability of occurrence of each processing condition is completely stable at a certain value. The probability of the 17th prediction is $\pi(17)=[0.0870 \ 0.1304 \ 0.1739 \ 0.2609 \ 0.1739 \ 0.0869 \ 0.0435 \ 0.0435]$.

The accuracy of the straightness prediction model based on PCA and Markov is verified by tracking the actual production and processing for 3 months. It can be known that the prediction error rate of Markov processing condition prediction model is 3.94%, and the difference is small, which is within the acceptable range. Figure 3 is a comparison chart of the predicted operating conditions.
The Markov prediction method can obtain the probability that each processing condition may occur in the future processing. Due to the problem of straightness out of tolerance, we improved the factors affecting the straightness of centerless grinding of slender rods and adjusted related parameters. According to the conclusions obtained by the PCA, the four parameters determined can be adjusted to achieve the purpose of regulating straightness. Then, through the solution of the straightness difference given in Table 1, centerless grinding is performed.

6. Conclusions
In this study, straightness prediction of centerless grinding of slender rods was carried out, including work condition construction, PCA, prediction model establishment, and experimental verification. The following conclusions were reached:

(1) The correlation between the influence parameters of the straightness of the centerless grinding of the slender rods are eliminated by PCA. The number of analysis and quality control is reduced, and the construction of the processing conditions is further simplified.

(2) The probability of occurrence of various processing conditions is predicted by the straightness prediction model based on PCA and Markov. The predictive value is compared with the measured value, the error rate is only 3.94%, which is within the acceptable range and meets the actual production and processing requirements.

(3) This study provides technical support for the parameters optimization of centerless grinding of slender rods and high-precision machining.

Acknowledgements
The authors gratefully acknowledge the financial supports from Natural Science Foundation of Jiangsu Province of China (BK20180175), The Key R & D Program of Xuzhou of Jiangsu Province (KC18096) and The Six Talent Peaks Program of Jiangsu Province (2016-GDZB-111).

References
[1] Chen X C, Wang C and Xue C Y 2018 Construction Machinery 49 27-32
[2] Wu Y Z 2016 Computer System Applications 25 204-208
[3] Y L D, Gu Y and Zhang M 2016 Computer Simulation 33 409-412
[4] Wang Z Z, Huang X and Liang Y R 2018 Journal of Central South University 25 1399-1408
[5] Pan S S, Zhu W Q, Hu R C and Huan R H 2017 Journal of Zhejiang University-Science A (Applied Physics & Engineering) 18 83-91
[6] Ma C W and Wang X M 2019 Journal of Dalian Jiaotong University 40 18-21
[7] Cao Y, Li J, Liu Y and Qu D W 2019 Journal of Northeastern University 40 77-81
[8] Zhang X N, Lei W and Li B 2017 Journal of Xi’an Jiaotong University 51 1-7