Modal Analysis of Three-point Contact Outside Diameter On-line Measuring Device Based on ANSYS Workbench*

Peilong Song*, Lai Hu, Fan Kan, Yaolong Chen

School of Mechanical Engineering, Xi’an Jiaotong University, 28 Xianning Road, Xi’an, Shaanxi 710049, P.R. China

*Corresponding author: spl.1225@stu.xjtu.edu.cn

Abstract. In the grinding process, because the grinding wheel will wear, it is difficult to control the grinding accuracy of the workpiece by the grinder itself. Using radial measuring instrument to measure workpiece size in real time, detect the change of workpiece size and guide the adjustment of grinding parameters can improve the production efficiency of grinder and reduce the machining cost, which is an important link in the machining process of grinder. Different from the traditional two-point contact on-line measurement technology of outer diameter, this paper designs and develops a set of three-point contact on-line measurement device of outer diameter based on the principle of bow height and chord length. In the measuring process, two fixed probes and one displacement sensing probe are in contact with the outer diameter of the workpiece at the same time, and the on-line measurement of the outer diameter of the workpiece is realized by solving the positional relationship among the three probes. In order to avoid resonance in the measuring process of the three-point contact external diameter online measuring device, In this paper, the modal analysis of the device is carried out in the environment of ANSYS Workbench 17.0, and the results show that the first-order and second-order natural frequencies of the free mode of the three-point contact on-line outer diameter measuring device are 648.57 Hz. When the measuring claw of the device is prestressed, the first-order and second-order natural frequencies of the device are 398.5 Hz and 403.94 Hz, respectively, which meet the requirements for on-line measurement of workpieces with rotational speeds in the range of 0-150rpm.

1. Introduction

In the grinding process, because the grinding wheel will wear, it is difficult to control the machining accuracy of the workpiece by the grinder itself [1, 2]. Using radial measuring instrument to measure workpiece size in real time, detect the change of workpiece size and guide the adjustment of grinding parameters can improve the production efficiency of grinder and reduce the machining cost, which is an important link in the machining process of grinder [3].

Most of the existing radial measuring instruments for on-line detection of the outer diameter of workpieces are of two-point contact type, such as the Italian Marbos measuring instrument [4]. The two-point contact measurement method is a direct measurement method. The diameter of the workpiece is solved by comparing the positions of the two ends of the diameter of the outer circle of the workpiece and finding the difference. The two-point contact measurement method requires that the two contacts
between the probe and the measured workpiece and the center of the measured section of the workpiece are collinear, and when the outer diameter of the workpiece to be measured changes, the position of the probe must be adjusted accordingly to ensure that the two probe can contact both ends of the diameter of the workpiece. Therefore, in the batch grinding process of the workpiece, this method has the problems that the measuring position is difficult to accurately locate and the position of the probe needs to be adjusted frequently [5]. The three-point contact measurement method of workpiece outer diameter proposed in this paper is an indirect measurement method based on bow height and chord length method. The outer diameter of workpiece is solved by calculating the relative position relationship between three points in contact with the outer circle of workpiece.

Based on the principle of bow height and chord length, a set of three-point contact on-line measuring device for outer diameter of workpiece is designed and developed in this paper, which can realize on-line measuring of outer diameter of workpiece with a single displacement sensor. When the device is used to measure the outer diameter of the workpiece, the three probe only need to contact the outer circle of the workpiece to be measured on one side, and the workpiece with the outer diameter within a certain range can be measured online without adjusting the position of the probe. Using this device in the grinding production process, the outer diameter of the workpiece can be measured in real time, so as to control the feeding and retreating of the grinder, and it is not necessary to stop the machine tool to measure the workpiece in the machining process, thus improving the production efficiency.

2. Finite element modeling analysis of three-point contact outside diameter on-line measuring device.

In order to understand the natural frequency and mode shape of the three-point contact outer diameter online measuring device, a three-dimensional model of the device is established in this paper as shown in figure 1.

![Figure 1. Model of three-point contact on-line measuring device for outer diameter, 1. Basal body 2. Adjusting screw 3. Compression spring 4. Spring cap 5. Precision guide rod 6. Linear bearing 7. Connecting plate 8. Measure-hand 9. Ruby probe 10. Flange screw 11. Contact displacement sensor 12. Flange nut](image-url)

When the measuring device measures the outer diameter of the workpiece during grinding, at first, that device is place on one side of the workpiece, so that the three measuring heads are completely in
contact with the outer diameter of the workpiece. Then a certain initial measuring allowance is given, and the effective measuring range have evaluated the displacement sensor. Meanwhile, the spring inside the matrix is in a compressed state, and the elastic force of the spring on the precision guide rod uniformly acts on the measuring claw through the connecting plate to ensure that the upper and lower fixed measuring needles of the measuring claw are always in contact with the outer diameter of the workpiece.

The displacement sensor is fixed on the connecting plate through a group of flange screws and nuts, and the relative position of the displacement sensor and the measuring claw can be appropriately adjusted according to the size of the outer diameter of the workpiece to be measured, so as to ensure that the probe of the displacement sensor is always in contact with the outer diameter of the workpiece. The design of the connecting plate can facilitate the disassembly and installation of the measuring claw. When the outer diameter of the workpiece to be measured changes, different types of measuring claw can be easily replaced to measure the workpiece. The two adjusting screws at the end of the base body are used to adjust the deformation of the compression spring to ensure that the upper and lower guide rods are subjected to uniform and equal thrust.

3. Modal theory analysis
The differential equation of general vibration of mechanical structure can be expressed as;

\[ M \ddot{x} + C \dot{x} + Kx = F \]  \hspace{1cm} (1)

Where: M is the mass matrix, X is the node displacement vector, K is the stiffness matrix, C is the damping matrix, and F is the external excitation.

The natural frequency of the three-point contact external diameter on-line measuring device can be obtained by analyzing the dynamic response of the device without load, that is, the external excitation \( F=0 \) and the damping \( C=0 \), then its differential equation (1) becomes;

\[ M \ddot{x} + Kx = 0 \]  \hspace{1cm} (2)

Assuming that the coordinates of the system do synchronous harmonic vibration, the solution of equation (2) can be expressed as;

\[ x = A \sin(\omega_n t + \varphi) \]  \hspace{1cm} (3)

Where: \( A \) is node amplitude; \( \omega_n \) is natural frequency; \( \varphi \) is that phase angle.

Substituting equation (3) into equation (2) and eliminating \( \sin(\omega_n t + \varphi) \) gives \( (K - \omega_n^2 M) A = 0 \) \hspace{1cm} (4)

So;

\[ B = K - \omega_n^2 M \]  \hspace{1cm} (5)

Then B is called the characteristic matrix, so that the characteristic equation of the system can be obtained as;

\[ \left| K - \omega_n^2 M \right| = 0 \]  \hspace{1cm} (6)

Equation (6) is a polynomial of degree n, from which n eigenvalues and eigenvectors can be obtained, i.e. n degrees of freedom. The vibration system has n natural frequencies and structural modes [6].
4. Modal finite element simulation

4.1. Free modal simulation

In the measurement process of the three-point contact on-line measuring device for outer diameter, the low-order vibration has a great influence on the dynamic characteristics of the device. Combined with the actual measurement situation of the device, and fully considering the influence of the installation position on the measuring device, the accuracy of the calculation results is guaranteed.

In the Workbench environment of AN system file system, finite element modal analysis is carried out on the measuring device to obtain the first six free modes of the device. The first six modes of the device are shown in the figure 2.

As can be seen from the figure 2, the first-order and second-order natural frequencies of the device are 648.57 Hz. It is known that the rotation speed range of the workpiece measured by the on-line measuring device is 0-150 rpm, that is, the rotation frequency of the workpiece is 0-2.5 Hz, which is far less than the natural frequency of the on-line measuring device.
4.2. Prestress modal simulation

When the three-point contact on-line outer diameter measuring device measures the outer diameter of the workpiece on-line, the measuring claw will be pushed by the spring, and the three probe heads installed on the measuring claw will be subjected to the supporting force and friction force of the workpiece surface at the same time. When the workpiece with radius R rotates counterclockwise, it undergoes force analysis and calculation, and the pre-imposed constraint and load state on the device is shown in figure 3.

![Figure 3. Pre-applied constraint load state](image)

The description of each load is shown in table 1.

| Support force of fixed probe on workpiece pair | Friction force of fixed probe on workpiece pair | Support force of workpiece to lower fixed probe | Friction between workpiece and lower fixed probe | Support force of workpiece to sensor probe | Friction between workpiece and sensor probe |
|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-------------------------------------------|-------------------------------------------|
| Force 1                                      | Force 2                                       | Force 3                                       | Force 4                                       | Force 5                                   | Force 6                                   |
| 2.359                                        | 0.5662                                       | 1.1556                                        | 0.2773                                        | 0.315                                     | 0.0473                                    |

![Table 1. Pre-applied load (N)](image)

The prestressed modal finite element analysis of the three-point contact outer diameter online measuring device is carried out to obtain the first six free modes of the device. The first six mode shapes of the device are shown in the figure 4.

(a)First-order mode(398.5Hz)  
(b)Second-order mode(403.9Hz)
As can be seen from figure 4, after the three probes of the device are prestressed, the first-order and second-order natural frequencies of the device are 398.5 Hz and 403.9 Hz, which are 38.6% and 37.7% lower than the free mode, respectively. However, the natural frequency of the device is still much larger than the rotation frequency of the workpiece, meeting the use requirements.

5. Conclusion
Through the modal simulation analysis of the three-point contact on-line outside diameter measuring device in the ANSYS Workbench 17.0 environment, it is concluded that the first and second free mode vibration frequencies of the device are 648.57 Hz. When the measuring claw is loaded with prestress, the vibration frequencies of the first and second modes of the device are 398.5 Hz and 403.94 Hz, which are 38.6% and 37.7% lower than the free mode, respectively. However, the natural frequency of the device is still far greater than the maximum rotation frequency of the workpiece by 2.5 Hz, which meets the measurement requirements.

Acknowledgment
This research was funded by the National Key R&D Pro-gram of "Manufacturing Basic Technology and Key Compo-nents" (No. 2018YFB2000502 and No. 2020YFB2009604).

Reference
[1] Y Fukuhara, S Suzuki, H Sasahara. Real-time grinding state discrimination strategy by use of monitor-embedded grinding wheels [J]. Precision Engineering, 2018: 128-136.
[2] Wegener K, Hoffmeister H W, Karpschewski B, et al. Conditioning and monitoring of grinding wheels [J]. CIRP Annals - Manufacturing Technology, 2011, 60(2): 757-777.
[3] Zhu Dehua. Integration of contact measurement technology and non-contact measurement technology [J]. Technology and Market, 2012 (05): 171.
[4] Wang Yueqin. Replacing foreign MARPOSS with domestic excircle active measuring instrument [J]. Machine Tool Electrical Appliance, 1997 (05): 41-42.
[5] Pan Feng. Dynamic accuracy of automatic measuring instrument [M]. Beijing: Mechanical Industry Press, 1983: 96-124.
[6] LIU Xi-jun, JIA Qi-fen, ZHANG Wen-de. Engineering vibration and measurement techniques [M]. Tianjin University Press, 1999.

[7] First, confirm that you have the correct template for your paper size. This template has been tailored for output on the A4 paper size. If you are using US letter-sized paper, please close this file and download the file “MSW_USltr_format”.
