The Dynamic Characteristic Analysis of an A/B Biaxial Rotary Milling Head

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Abstract. The biaxial rotary CNC universal milling head is an important functional part of the five-axis CNC machine tool, and its dynamic performance directly affects the machining accuracy of the machine tool. In this paper, the modal analysis and thermal error analysis of an A/B biaxial rotary milling head were carried out. The first six natural frequencies and modal shapes were obtained by the finite element method, and the modal test was carried out by LMS Test.Lab. The transient temperature field of the milling head during machining was obtained by the finite element method, and the thermal deformation experiment was carried out. The experimental results verify the validity of the finite element model within an acceptable error range. This paper provides theoretical references for the structural optimization and thermal error compensation of the A/B biaxial rotary milling head.

1. Introduction
In the field of aerospace manufacturing, one of the most concerned functions of high-end CNC machine tools is five-axis machining. To achieve this function, biaxial rotary CNC universal milling heads are indispensable. In the process of the biaxial rotary milling head, in addition to the steady-state force, it is also affected by other factors such as alternating cutting force, cutting heat, thermal deformation, environmental temperature and so on. Sources of the processing error mainly include vibration and thermal deformation [1]. Vibration occurs when the milling head is subjected to alternating loads. When the load frequency is close to the natural frequency of the milling head, it is prone to resonance, resulting in deterioration of the performance of the machining system and control system. Various thermal loads during processing make the temperature rise of each part of the milling head asymmetric, result in varying degrees of thermal deformation of the structure and affect the processing accuracy. It is of great significance to improve the machining accuracy of the milling head by investigating its long-term working characteristics under the dynamic and thermal loads, that is, the dynamic characteristics of the milling head, so as to improve the performance of the five-axis machine tool and the level of the national manufacturing industry.

In recent years, many scholars have studied the dynamic characteristics of various milling heads by means of finite element simulation or field experiment, and obtained the corresponding parameters, which provides the basis for the structural optimization and thermal error compensation of milling heads. Bao (2012) introduced the model of the direct-drive A/C biaxial rotary milling head into ANSYS, and established the thermal error compensation system based on the thermal characteristics of the milling head. He also carried out the overall static analysis and modal analysis of the milling head, providing the basis for the improvement and optimization of the milling head structure [2].
Wang (2016) collected the natural frequencies, damping ratios and modal shapes of the first six modes of the woodworking biaxial rotary milling head by using the PULSE multi-analyser system, and verified the vibration resistance performance of the milling head [3].

The CNC machine tool with the A/B biaxial rotary milling head can complete the task of high-power and high torque cutting, and has the characteristics including unique tool path and simple equipment operation, which plays an important role in the manufacturing of large-scale integral aircraft structural parts with a long processing cycle. However, the research on the dynamic performance of the A/B biaxial rotary milling head is relatively less at present. This paper studies the dynamic characteristics of an A/B biaxial rotary milling head, including the modal analysis and thermal error analysis, in order to provide data support for the design and improvement of this type of milling head.

2. Modal analysis of the A/B biaxial rotary milling head

2.1. Modal finite element analysis

The schematic diagram and three-dimensional model of the milling head used in this research are shown in figure 1. The overall size is 1550mm × 830mm × 930mm. Its main structure includes axis A drive, axis B drive, main drive, spindle box, support frame and other parts. The axis A performs the swing of the spindle head around the axis X. And the axis B performs the swing of the spindle head around the axis Y. The servo motor drives the gear through the belt and worm gear, and finally drives the axis A and the axis B on the arc rack. The ratio of angular velocity of the axis A to the axis B is 1127.8

![Schematic diagram](a)
![3D model](b)

**Figure 1.** (a) Schematic diagram (b) 3D model.

In this study, the materials of the milling head are nodular cast iron and alloy structural steel, of which the spindle box is made of cast iron QT600-3, and the others are made of alloy structural steel. Among them, gears are made of alloy steel 12CrNi3A, the main shaft is made of alloy steel 42CrMo, bearings are made of bearing steel GCr5, and other parts are made of steel 45#.

The model was simplified in ANSYS Workbench, and the mesh was divided by automatic division method. After division, the number of generating units was 187330 and the number of nodes was 548754. Check the quality of the grid, and the average value was 0.78. It can be considered that the quality of the grid was satisfactory. Six degrees of freedom of the end face of the milling head were constrained, and the first six modes were extracted. The modal shapes are shown in figure 2, and the natural frequencies and characteristics of the modal shapes are shown in table 1.
Figure 2. Modal shapes of the milling head (a) first order (b) second order (c) third order (d) fourth order (e) fifth order (f) sixth order.

Generally, the low-order modes have great influence on the structure. As is shown in Table 1, the first two natural frequencies of the milling head are low. And both of them are within 60Hz, which causes the chatter of the milling head easily during processing. It can be seen from the modal shapes that the reason for the low natural frequency is the low structural rigidity of the whole milling head. Different from the integral rotary milling head, the main body of the A/B biaxial rotary milling head we studied is divided into two parts: the spindle box and the support frame. The spindle box is connected to the support frame through the rotation center, and the meshing contact of the rack and pinion is adopted at the axis B swing system. Consequently, the overall structural rigidity of the milling head is low. The rigidity of the milling head can be improved by adjusting the parameters of the rack and pinion meshing device, and strengthening the connection between the spindle box and the
support frame, so as to prevent the occurrence of resonance and the damage to the workpiece and the machine tool.

2.2. Modal test analysis
LMS Test.lab14A modal analysis system was used to carry out the modal test with original support. The method of single point excitation and multi-point measurement (SIMO) was used, and vibration pick-up points were selected according to the criteria in the study of Sun (2012) [4]. An example of point arrangement is shown in figure 3, and the selection of the excitation point is shown by the arrow in figure 4. The arrangement of vibration pick-up points on other surfaces of the milling head is similar. Simplify the whole assembly model in the Geometry, as shown in figure 5.

In the Modal Analysis, the Time MODF method was used to draw the steady-state diagram. Select the stable point at the peak of the frequency response function for modal extraction. The first six natural frequencies of the milling head are displayed in table 1.

2.3. Error analysis
The natural frequencies obtained by modal test analysis are compared with those obtained by finite element analysis, and the results are shown in table 1. The maximum relative error of the frequency is 14.3%. Except for the first two natural frequencies, the relative errors of the other frequencies are all within 10%. The software ANSYS Workbench has some shortcomings, such as inaccurate modelling and mesh division, which will lead to some error of the simulation. The finite element model is validated by modal test within an acceptable error range [5].
Table 1. Comparison of the results between modal test analysis and finite element analysis.

| Order | Frequency by modal test analysis/Hz | Frequency by finite element analysis/Hz | Relative error of the frequency/% | Modal shape |
|-------|------------------------------------|-----------------------------------------|----------------------------------|-------------|
| 1     | 42.062                             | 36.053                                  | 14.3                             | The support frame and the box rotate around axis Z. |
| 2     | 50.091                             | 56.145                                  | 12.1                             | The Box and the axis B system rotate around axis X. |
| 3     | 76.858                             | 79.693                                  | 3.7                              | The box does not move, and the support frame rotates around the axis X. |
| 4     | 86.613                             | 89.109                                  | 2.9                              | Take the plane YOZ as the symmetry plane, swing symmetrically left and right. |
| 5     | 95.190                             | 96.781                                  | 1.7                              | The milling head rotates along the axis Z as a whole. |
| 6     | 98.331                             | 104.140                                 | 5.9                              | The box extends up and down along the axis X. |

3. Thermal error analysis of the A/B biaxial rotary milling head

In the working process of the milling head, the heat sources from outside and inside make the temperature rise of each part of the milling head uneven, leading to the thermal deformation of each part, which will reduce the long-term working characteristics significantly. The purpose of thermal error analysis is to calculate the specific situation of the thermal deformation of the milling head when it works in various heat sources for a long time. And the effects of the thermal deformation on the system accuracy are also taken into consideration, so as to guide the structural optimization design and the thermal error compensation of control system. After calculating the transient temperature field of the milling head accurately, the thermal deformation can be reduced and the machining accuracy can be improved by modifying the relevant structural parameters of the milling head or taking cooling measures.

3.1. Thermal transient simulation analysis of the milling head

In ANSYS Workbench, the heat flux coefficient and the heat transfer coefficient calculated were taken as thermal load conditions, and the thermal transient analysis was carried out to obtain the temperature and deformation values of the milling head at different times. In order to observe the change of the temperature field of spindle parts conveniently, the other parts except spindle and its corresponding parts were set transparent, and the change of the temperature field of the milling head and spindle was extracted. Take the temperature values of all measuring points (the locations of the measuring points are shown in figure 6) every 1800 seconds for recording, as is shown in table 2.

Figure 6. location of external test points.
Use the transient therm-structure coupling analysis module to solve the tip displacement at different times, and extract the tip displacement values in X, Y and Z directions and summarize them into table 3.

3.2. Thermal experiment analysis of the milling head
In order to verify the correctness of the theoretical analysis, the temperature rise under the actual working condition of the milling head was measured. By setting the acquisition software, temperature data were collected every 600 seconds, and displacement data were collected every second. 21 points for temperature measuring were arranged in total [6], among which 10 bearings and 2 gears were defined as measuring points 1-12. The specific positions of the other measuring points were shown in figure 6. The points 13-17 were on the outer surface of the spindle box. One point was arranged every 120mm. The points 15, 18 and 19 corresponded to bearings. The point 20 corresponded to the cutter head and the point 21 corresponded to the surface of the support frame.

3.3. Comparative analysis between experimental results and simulation results

3.3.1. Comparative analysis of temperature results. Collect the temperature values of measuring points at bearing 7, gear 1, cutter head and box surface 1 (i.e. measuring point 15, whose position is opposite to the heat source bearing). Compare the simulation results with the experimental results, analyse the error of the simulation results, and arrange the data as shown in table 2 below.

| Table 2. Comparison between the temperature measured by simulation and measured by experiment. |
|----------------------------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Location of measuring point     | Time/s         | 1800           | 3600           | 5400           | 7200           | 9000           | 10800          |
| Bearing 7                       | Simulation value / °C | 38.4           | 44             | 46.2           | 47.8           | 48             | 48.2           |
|                                 | Experimental value / °C | 35.6           | 42             | 44.5           | 45.4           | 46             | 46.4           |
|                                 | Error / °C       | 2.8            | 2              | 1.7            | 2.4            | 2              | 1.8            |
| Gear 1                          | Simulation value / °C | 29.3           | 34.2           | 34.5           | 34.8           | 35.5           | 36             |
|                                 | Experimental value / °C | 25.5           | 31.7           | 32.5           | 33.2           | 33             | 32.5           |
|                                 | Error / °C       | 3.8            | 2.5            | 2              | 1.6            | 2.5            | 3.5            |
| Box surface 1                   | Simulation value / °C | 28.4           | 32.7           | 36.4           | 37.3           | 38.4           | 39.6           |
|                                 | Experimental value / °C | 24.1           | 34.5           | 34.9           | 35.2           | 35.8           | 36.3           |
|                                 | Error / °C       | 4.3            | -1.8           | 1.5            | 2.1            | 2.6            | 3.3            |
| Cutter head                     | Simulation value / °C | 36.3           | 42.6           | 44.8           | 45.6           | 45.8           | 45.6           |
|                                 | Experimental value / °C | 32.5           | 40.7           | 41.9           | 42.8           | 43.1           | 43.7           |
|                                 | Error / °C       | 3.8            | 1.9            | 2.9            | 2.8            | 2.7            | 1.9            |
It can be seen from table 2 that the simulation value is generally higher than the experimental value as to temperature. And the error is different at different times, among which the error at 1800s is the largest. Nonetheless all the error is within 5°C. Observing the temperature comparison of all the measuring points, these rules are still valid, and the error values are generally concentrated at 2°C-4°C. It can be found that the rising trend of the experiment results is similar to that of the simulation results through scatter. The results above show that the temperature simulation results are effective and the error is acceptable in the engineering practice.

3.3.2. Comparative analysis of displacement results. The simulation displacement is compared with the experimental displacement at the corresponding time, and the error is calculated, as shown in table 3.

| Direction | Time/s   | 1800 | 3600 | 5400 | 7200 | 9000 | 10800 |
|-----------|----------|------|------|------|------|------|-------|
| X         | Simulation value /mm | 0.0038 | 0.0066 | 0.0082 | 0.0082 | 0.0085 | 0.0087 |
|           | Experimental value /mm | 0.0028 | 0.0048 | 0.0067 | 0.0077 | 0.0082 | 0.0081 |
|           | Relative error       | 36%   | 37.5% | 22.3% | 6.5%  | 3.7%  | 7.4%  |
| Y         | Simulation value /mm | 0.0039 | 0.0075 | 0.0103 | 0.0119 | 0.0122 | 0.0129 |
|           | Experimental value /mm | 0.0037 | 0.0066 | 0.0091 | 0.0107 | 0.0115 | 0.0118 |
|           | Relative error       | 5.4%  | 13.6% | 13.2% | 11.2% | 6.1%  | 9.3%  |
| Z         | Simulation value /mm | 0.0217 | 0.0438 | 0.0630 | 0.0736 | 0.0776 | 0.0778 |
|           | Experimental value /mm | 0.0237 | 0.0406 | 0.0565 | 0.0672 | 0.0705 | 0.0703 |
|           | Relative error       | -9.2% | 7.9%  | 11.5% | 9.5%  | 10.1% | 10.7% |

It can be seen from table 3 that the relative error between the simulation value and the experimental value of the thermal deformation displacement in each direction of the tool tip is quite large, and it even reaches more than 30% in direction X when the time reaches 1800s and 3600s. It tends to be stable after 7200s and is within 10% in direction X. The symmetrical structure of the milling head results in small deformation in direction X in the experiment, while the simulation results of displacement are larger due to the simplification of the model and other reasons. In directions Y and Z, all the relative error of the displacement at different times is within 15%. It can be seen through scatter that the trends of simulation and experimental results are basically the same, and the simulation values of the displacement at the tool tip are generally higher than the experimental ones, which is consistent with the analysis of temperature.

4. Conclusion
From the simulation and experiment results we can conclude several important points:

1. In this paper, a kind of A/B biaxial rotary milling head is taken as the research object. Through the modal analysis of ANSYS Workbench, the first six natural frequencies and modal shapes of the milling head are obtained. The first six frequencies of the milling head are also measured by LMS Test.Lab. The relative error between simulation and experiment is almost acceptable. The first two frequencies of the milling head is relatively low, so the rigidity of the milling head can be improved to
prevent the resonance of the milling head working under the alternating load, resulting in deformation and damage.

2. The transient thermal model and the transient therm-structure coupling model of the milling head system are established by using the finite element method. In order to verify the accuracy of the model, temperature and displacement measurements are carried out on the key points of the milling head under the actual processing conditions. The error of temperature and displacement is acceptable. The data of tool tip displacement obtained from the experiment can be of great help to the research of thermal error compensation of this kind of milling head.

3. The finite element model of modal analysis and thermal error analysis can truly reflect the working condition of the milling head system. Analyse and optimize the dynamic characteristics of milling head through the finite element method, then reduce the machining error caused by chatter and thermal deformation, so as to improve the machining accuracy and the level of CNC machine tools.

Acknowledgement
The authors would like to thank the National Science and Technology Major Special Project (China) High grade CNC machine tools and basic manufacturing equipment (2016ZX04003001), January 2016 to December 2019.

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