Finite element analysis and testing on the vibration mode of small grinding carriage in high-efficiency CNC grinding machine

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Abstract  The small grinding carriage is a key component of the high-efficiency computerized numerical control (CNC) grinding machine. The machining of the small grinding wheel is the last process of the workpiece on the grinding machine, and its vibration performance has an important influence on the grinding precision. A novel low vibration grinding carriage using finite element analysis method (FEM) was designed to validate its vibration performance before producing. In this study, the finite element model of the small grinding carriage was established. The finite element calculation was performed using the Block Lanczos algorithm, and the first natural frequency of the small grinding carriage was 283.2 Hz. Besides, the experimental modal analysis method of ambient excitation was used to test and analyze the small grinding carriage assembled to a grinding machine. The modal parameters of the system structure were identified based on the theoretical auto power spectrum. The first five natural frequencies and damping ratios of the small grinding carriage were obtained. The accuracy of the recognition results was verified using the modal judgment criteria. The two methods cross-validated the structure design of the small grinding wheel, which can avoid resonance during machining. The results provided in this paper can serve as a reference for the subsequent structural optimization design.

1. Introduction
The high-efficiency computerized numerical control (CNC) grinding machine is an important part of modern advanced manufacturing technology. It represents the fast development of heavy-duty grinding to improve machining efficiency as well as the development of numerical control technology to improve machining accuracy [1-2]. The grinding carriage is a key component of the high-efficiency CNC grinding machine, which realizes radial feed grinding under the control of the numerical control system.
The good dynamic performance of the grinding carriage is an important condition for ensuring efficient grinding of CNC grinding machines[3]. Finite element analysis and experimental testing of vibration modes can provide important analytical tools for structural optimization design and verification. Wang et al. used ABAQUS finite element analysis software to obtain the first nine mode shapes and modal frequencies of the large grinding carriage of the CNC grinding machine [4]. Cui et al. used MSC Patran and Nastran finite element analysis software to perform the modal analysis of the original grinding carriage [5]. Zheng and Liu et al. designed and optimized the structure of the grinding carriage [6-7]. These results provided guidance for the research in our current paper.

In this paper, we used a small grinding carriage from a high-efficiency CNC grinding machine that was independently designed by a company that is our collaborator, and the vibration mode was obtained by finite element analysis using HyperMesh software. The DH5922N dynamic signal analysis system produced by another company was used for the modal test. We then verified whether the vibration frequency of the designed small grinding carriage met the non-resonance requirements. The results provided in this paper provides a basis for structural optimization of the small grinding wheel and grinding machining.

2. Small Grinding Carriage Structure of the High-efficiency CNC Grinding Machine

The mechanical part of a particular high-efficiency CNC camshaft grinding machine that was independently developed by a company is mainly composed of a large grinding carriage, a small grinding carriage, a headstock, a tailstock, a work bench, and a bed. The large grinding wheel installed on the large grinding carriage can be used for rapid cutting. The small grinding wheel installed on the small grinding carriage is used for grinding the convex and concave composite surface of a cam. The follow grinding technology of the double grinding wheels can realize the machining of a cam with a concave surface in one clamping.

The small grinding carriage system adopts an upper and lower split structure, where the upper part is the small wheel headstock part, and the lower part is the grinding carriage pad feeding part, as shown in Figure 1. The small grinding wheel headstock part is composed of a motor, a motor mounting seat, a belt transmission, a small grinding wheel, and a mounting bottom plate. The small grinding wheel shaft uses the shaft motor belt transmission structure. The shaft motor uses the high-speed shaft unit with dynamic and static pressure bearing, which can ensure high rigidity and high stability at high speeds. Its power can reach 28 kW, and the maximum shaft speed can reach 20000 rpm. Belt transmission solves the problems regarding ultra-high speed durability and ultra-high speed vibration. The feeding part of the grinding carriage adopts the static pressure guide linear motor precision feeding system. The static pressure guiding rail is mainly composed of parallel rail main shafts, guide rail hydrostatic bearings, and pads. The main shaft of the guide rail has a diameter of 100 mm and a length of 1200 mm. The static pressure guide measured under normal conditions has a stiffness of 300 N/μT for a single hydrostatic bearing.

![Fig.1 Composition of the small grinding wheel station](image-url)

The high-speed small grinding wheel is used for fine grinding of the parts. It is the last process of the workpiece to be machined on the grinding machine, and it is the key step to ensure the surface quality of the parts. The modal parameters of the small carriage foundation directly determine the dynamic performance of the small grinding wheel. Therefore, it is necessary to carry out vibration...
modal finite element analysis and dynamic characteristic tests on the basic structure of the carriage to achieve structural design optimization.

3. Principle of Vibration Modal Analysis

Modal analysis is used to determine the vibration characteristics of the small grinding carriage components (i.e., natural frequency, damping ratio, and mode shape), which are important parameters in the design of dynamic load structures. Additionally, modal analysis is also a preliminary analysis process necessary for spectral analysis, modal superposition harmonic response analysis, and transient dynamic analysis [8-9].

3.1 Finite element modal analysis

The differential equation of motion for a free vibration system is

\[
[M][\ddot{x}] + [C][\dot{x}] + [K][x] = [Q],
\]

where \([M]\) is the total mass matrix of the structure, \([C]\) is the structural damping matrix, \([K]\) is the structural stiffness matrix, \([Q]\) is the applied load array, and \([x]\) is the node displacement array.

The basic equation for the typical undamped modal analysis is the classical eigenvalue problem:

\[
[K][\phi_i] = \omega_i^2 [M][\phi_i],
\]

where \([K]\) is the stiffness matrix, \([\phi_i]\) is the mode shape vector of the \(i\)th mode (feature vector), \(\omega_i\) is the natural frequency of the \(i\)th mode (\(\omega_i^2\) is the eigenvalue), and \([M]\) is the mass matrix.

The vibration response of the small grinding carriage was calculated by the Block Lanczos method, which is commonly used in the HyperMesh finite element analysis software. The Block Lanczos algorithm uses a set of vectors to implement Lanczos recursive calculations. This method is suitable for solving sparse matrices and has the advantages of high accuracy and fast calculation speed [10-12].

3.2 Experimental modal analysis

There are two types of experimental modal analyses: traditional experimental modal analysis and ambient excitation experimental modal analysis. The traditional experimental modal analysis uses the frequency response function (FRF) or the impulse response function (IRF). It must be excited by a vibration exciter or an external hammer, and the system response is measured. The transfer function matrix is calculated, and the modal parameters are obtained. Considering the large volume of the grinding machine used here, with a mass of 20 tons and a relatively dense layout, it is difficult to use the pulse shock generated by the exciter or the sine wave excitation to excite the mode of the small grinding carriage. Therefore, we used the ambient excitation method, which directly applies the ambient excitation. The modal parameters of the system are identified by the auto spectrum of the response output of the structure and the cross spectrum (including the amplitude, phase, coherence function, and transfer rate) between the reference output when the excitation is unknown [13].

The principle of modal analysis of ambient excitation is as follows: assuming that the small grinding carriage is a real modal system, the frequency response function can be written as

\[
h_{ak}(\omega) = \frac{x_a}{f_k} = \sum_{r=1}^{N_r} \frac{\{\phi\}_ar \{\phi\}_kr}{(j\omega - \lambda_r)(j\omega - \lambda_r^*)},
\]

where \(f_k\) is the excitation at point \(k\), \(x_a\) is the steady-state response at point \(a\), \(\{\phi\}_ar\) is the mode shape vector at point \(a\) of the mode shape of the \(r\)th mode, and \(\{\phi\}_kr\) is the mode shape vector at point \(k\) of the \(r\)th mode.

If the input signal in the ambient excitation is white noise, which is a process of stationary stochastic process, then its power spectral density function is approximately evenly distributed in all frequency units:

\[
f_k(\omega) = f(\omega) = \frac{c_1}{\omega^2},
\]

We define the response ratio between reference point \(p\) and other reference points as the transfer rate \(r_a(\omega)\). Then we have

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This equation is based on the assumption that the various modes of the structure are completely orthogonal, ignoring the contribution of other modes to the vibration component of a certain mode [14]. When \( p \) is the reference point, then a certain mode shape vector \( \{\phi\}_{pr} \) corresponds to the natural frequency \( \omega_r \). Namely, the denominator is constant, and the mode shape of the \( r \)th mode can be obtained from the transmission rate \( \alpha_a(\omega) \) of each point. Then, the mode shape of the structure can be obtained from the transmission rate curve.

The auto-cross power spectrum method is a relatively simple method for identifying the natural frequency of the system in the frequency domain. The principle of this method is to calculate the auto spectrum \( P_a(\omega) \) of the measuring point \( a \) and the cross spectrum \( P_{ap}(\omega) \) with the reference point \( p \) according to the periodogram method. The auto spectrum \( P_a(\omega) \) has a square relation with the modulus \( |hi(\omega)| \) of the transfer function, and the cross spectrum \( P_{ap}(\omega) \) has the same relation with \( |hi(\omega)| \), which means that the three have the same pole. Therefore, the auto-cross power spectrum can be used to identify the natural frequency of the system, and the damping ratio of the system can be further determined by the half-power bandwidth method [15].

4. Vibration Mode Finite Element Analysis

4.1 Establishment of finite element model of small grinding carriage

In this paper, SolidWorks was used to build a three-dimensional model of a high-efficiency CNC camshaft grinder with a small grinding carriage, and the step format was saved. In order to improve the quality of meshing and to reduce the workload of finite element pre-processing, the small holes and round chamfers that are not considered in the finite element analysis were removed when the CAD model was built using SolidWorks. The geometric model is shown in Figure 2.

![Fig.2 Geometry model of the small grinding carriage](image)

The geometry model of the small grinding carriage in the step format was imported into the HyperMesh finite element analysis software. After the gap and coincidence problems were processed, the tetramesh module in the 3D option was selected for meshing. The quality of meshing has a substantial influence on the results of the finite element analysis. Because the small grinding carriage model was small, the Element size was set at 15, and some of the more complex transitional structures were mesh-encrypted using hexahedral elements for network division. The generated finite element mesh model is shown in Figure 3.
4.2 Finite element calculation and modal analysis

The profile Ansys module was selected in the HyperMesh finite element analysis software, and the material properties of the small grinding carriage were defined. The material of the high-efficiency CNC camshaft grinding machine small grinding carriage was gray cast iron HT200, and its specific performance parameters are shown in Table 1.

| Elastic modulus (MPa) | Poisson's ratio | Density (kg∙m⁻³) |
|-----------------------|----------------|-----------------|
| 140000                | 0.3            | 7800            |

After defining the material properties, we also created the cell properties and defined the frequency of modal analysis. HyperMesh set the modal analysis frequency to 1 kHz. In order to obtain an accurate mechanical response, it was necessary to apply reasonable boundary conditions to the four hydrostatic bearings, which were simplified to an elastic support boundary with only radial stiffness [16]. The Block Lanczos method was used to calculate the vibration response of the small grinding carriage. The first mode shape nephogram is shown in Figure 4.

The calculation results showed that the first natural frequency of the small grinding carriage was 283.2 Hz, while the maximum grinding speed of the small grinding wheel was 10000 r/min, and the maximum frequency was 167 Hz. The small grinding carriage system of our current design would not cause resonance during machining.

5. Small Grinding Carriage Vibration Test

5.1 Test system

Taking the small grinding carriage as the test object, the test system was mainly composed of a small grinding carriage, a vibration acquisition system, and modal analysis software. The vibration acquisition system included an IEPE type acceleration sensor, a sensor magnetic base, a DH5922N...
dynamic signal analyzer, and a portable computer with modal analysis software DHDAS. The main experimental instruments are shown in Table 2.

| Instruments | Quantity |
|-------------|----------|
| DH5922N Data acquisition and analysis system | 1 (16-channel) |
| DH131E Accelerometer | 12 |
| Laptop | 1 |

During the test, the software recorded the data of the accelerometers at each measuring point in real time. The experimental site is shown in Figure 5.

Fig.5 Experimental site

5.2 Arrangement of measuring points
The effective independent method is one of the most widely used methods in response point arrangement. It starts from all possible points and uses the information matrix formed by the modal matrix to rank the contribution of each measurement point to the independence of the target modal matrix. The candidate points with the smallest contributions are then deleted so that the modal vector of interest remains linear independent [17].

The test placed the sensor in two directions: the horizontal feed direction, X, and the vertical feed direction, Y. Since the longitudinal feed direction, Z, had a high stiffness, the vibration amplitude was small, and the contribution to the modal matrix was small, no layout was performed. The measuring points arranged in the horizontal feed direction were No. 3, No. 4, No. 5, No. 6, and No. 7 on the side wall of the small grinding wheel mounting base, and No. 8, No. 9, and No. 10 on the side wall of the upper pad, as shown in Figure 6. The measuring points arranged in the vertical feed direction were No. 11, No. 12, and No. 13 on the surface of the upper pad, No. 14 on the surface of the motor shaft mounting base, and No. 15 and No. 16 on the surface of the small grinding wheel mounting base plate (note: channel numbers 1 and 2 measured the rotation speed signal), as shown in Figure 7.

Fig.6 Arrangement of measurement points in feed direction
After determining the position of the measurement point, the sensor was screwed onto the magnet and attached to the surface of each measured point. Then the sensor of each measurement point was connected with the DH5922N dynamic signal analysis system, and the signal was fed back to the test software through network transmission. The sampling frequency was set at 1 kHz, and the vibration acceleration response of each measurement point was measured in the process of gradually increasing the rotational speed of the small grinding wheel motor to 10000 r/min.

5.3 Data analysis

1) Time domain curve analysis
The real-time response curves of the vibration acceleration of each measuring point were analyzed. The vibration acceleration amplitude of each measurement point was between 1.2 and 5.2 m/s². The vibration of the small grinding wheel was the most severe, largely because of its weak structure, and the vibration of the upper pad was stable. The vibration intensity was larger in the horizontal feed direction than in the vertical feed direction. According to the ISO 2372 standard of the International Organization for Standardization, the German Society of Engineers Standard VDI 2056, and the British Standard BS4675, the mechanical vibration intensity criterion [18] can be used to obtain the vibration level of the carriage as level A, and the vibration condition was excellent.

2) Auto-cross power spectrum analysis
The Hanning window was used to filter the time domain curve to eliminate noise in the signal and improve the frequency resolution. The 11th measurement point with a larger vibration amplitude was selected as the auto-cross power spectrum analysis in response to the reference point, and the results are shown in Figure 8.

Selecting the obvious peak point, we obtained the first five modal frequencies and damping as shown in Table 3.
Table 3 Modal frequency and damping ratio of various modes

| Modal order | Modal frequency (Hz) | Damping ratio (%) |
|-------------|---------------------|-------------------|
| 1           | 41.99               | 0.9               |
| 2           | 83.01               | 0.7               |
| 3           | 174.06              | 0.4               |
| 4           | 218.75              | 0.1               |
| 5           | 349.61              | 0.2               |

The working speed of the small grinding wheel was between 6000 and 10000 r/min, that is, the frequency ranged from 100 Hz to 167 Hz. Therefore, resonance can be avoided during the working process of the small grinding wheel. However, the first two modes of the modal frequency were low, so the self-excited vibration phenomenon may occur during the acceleration of the small grinding wheel.

3) Modal correlation analysis of each mode

The modal assurance criterion (i.e., MAC matrix) is a common method for evaluating the intersection angle of experimental modal vectors. The advantage is that the consistency of the mode shapes can be compared without considering the stiffness and mass of the structure [19]. The matrix calculation formula of MAC is

$$MAC_{ij} = \left(\frac{\langle \phi_i^T \phi_j \rangle^2}{\langle \phi_i^2 \rangle \langle \phi_j^2 \rangle} \right),$$

where $\{ \phi_i \}$ and $\{ \phi_j \}$ are the ith and jth modal vectors, respectively.

As shown in the above equation, when the ith and the jth mode shapes were exactly the same, the MAC value was equal to one, indicating complete correlation. When the ith and jth mode shapes were completely orthogonal, the MAC value was equal to zero.

The various modal MAC diagrams obtained from the results of the above tests are shown in Figure 9. The correlation between the modes was small, which satisfied the assumptions in the principle of modal analysis. Therefore, the test results were reliable.

6. Conclusions

1) The three-dimensional model of the high-efficiency CNC camshaft grinder small carriage was established by SolidWorks. The finite element mesh was divided by HyperMesh finite element software. The vibration response of the small carriage was calculated by the Block Lanczos method. The first mode shape nephogram and modal frequency were obtained. The simulation verified that the small carriage system of this design does not cause resonance during processing.

2) The DH5922N dynamic signal analysis system was used to build a small carriage vibration test system. The ambient excitation modal analysis method was used for the analysis. The first five modal
frequencies and damping ratios were obtained, which further verified that the small carriage can avoid resonance during the working process.

3) Both simulation and experimental methods were used to show that the design of the small grinding wheel system was reasonable. However, it is still necessary to strengthen the structural stiffness in order to avoid the possibility of self-excited vibration. This paper provides a reference for the subsequent structural optimization design.

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