Application Status of Computer-Based Finite Element Analysis Method in Mechanical Design

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Abstract. With the continuous development of economy and science, engineering and product design processes are getting higher and higher. However, traditional methods cannot completely solve the problems encountered in the design process. Aiming at this bottleneck, this paper relies on the finite element analysis method to analyze the mechanical design. Taking the square ram of a floor boring and milling machine as an example, a finite element model for modal analysis is established and the undamped free vibration of the square ram is studied. The experimental results verify the rationality of the finite element analysis method, and on this basis, the error reasons are discussed, which lays an important basis for subsequent research and optimization.

Keywords: Square Ram, Finite Element, Modal Analysis, Natural Frequency, Test

1. Introduction

With the development of science and technology, people have higher and higher requirements for the design and use of engineering and products. Traditional theoretical knowledge can no longer completely solve all the problems encountered in the design process. The theory and application of finite element have been rapidly developed. With the development, the function of finite element software is also increasing[1-2]. The unparalleled superiority of the finite element method in the design and development of products has become an important tool in mechanical design[3].

In the CNC machining process, the main factor that produces processing ripples is the relative vibration of the machine tool workpiece system. Relative vibration can be divided into two types of forced vibration caused by the outside world and self-excited vibration caused by the cutting itself according to its causes[4]. If the cutting force fluctuation is synchronized with a certain natural frequency of the machine tool, resonance may occur. Relative vibration will reduce the quality of the processed surface of the workpiece and affect the service life of the tool and even the machine tool. The square ram moves in the headstock, and the top shaft rotates in the square ram. The distance they extend from the headstock is generally relatively large. Excessive vibration can easily cause instability of the cutting movement, which is the most attention in the machine tool system. The parts[5-6]. Therefore, relying on the finite element analysis method, this article attempts to analyze the mechanical design. Taking the square ram of the floor boring and milling machine as an example, the finite element model of the modal analysis is established to study its undamped free vibration.
2. Finite element analysis

2.1. Basic principles
The basic principle of the finite element method: divide the continuous system into a finite number of partitions or units, propose an approximate solution for each unit, and then combine all the units according to the standard method to form a numerical approximation system of the original system, that is, form the corresponding numerical model.

At each node, we choose the linear piecewise function as the test function \( \phi_i(x) \), which is characterized by taking the value of 1 at node \( x_i \), taking 0 at \( x_j (j \neq i) \), and linear changes in other positions. The shape curve is shown in equation (1).

\[
\phi_i(x) = \begin{cases} 
(x-x_{i-1})/(x_i-x_{i-1}) & \text{if } x \in [x_{i-1}, x_i] \\
(x_{i+1}-x)/(x_{i+1}-x_i) & \text{if } x \in [x_i, x_{i+1}] \\
0 & \text{otherwise}
\end{cases}
\]  

2.2. Calculation steps
Mesh division. The basic method of finite element method is to replace the original continuum with a collection of finite element bodies. Therefore, the elastic body must be simplified first, and then the elastic body must be divided into discrete bodies composed of finite units. The units are connected by nodes. The collection of mountain elements, nodes, and node connections is called a grid.

Unit analysis. Taking the node displacement of the element as the basic variable, the element analysis must first determine an approximate expression for the displacement inside the element, then calculate the strain and stress of the element, and then establish the relationship between the nodal force and the nodal displacement in the element.

Overall analysis. Analyze the whole composed of each element, establish the relationship between the external load of the node and the displacement of the node to solve the displacement of the node. This process is called the overall analysis.

3. Finite element modal analysis of square ram

3.1. Establishment of finite element model
The TX6916 large-scale CNC floor mirror milling machine, designed and manufactured by the school-enterprise cooperation, adopts a square ram structure, end size (440.00 × 440.00) mm, Z-direction stroke 800.00 mm, and wall thickness 25.00 mm. During the production process, the motor drives the screw, and the screw is connected to the threaded hole to realize the feeding movement of the square ram. When finite element modeling, first define the material properties, real constants, and material element type properties. Related parameters: Young's modulus is 210 GPa, Poisson's ratio is 0.32, density is 7800 kg/m^3. The element type selected in the analysis is the SOLID element. This element is a widely used element in the analysis of elastic structure space problems. It is an 8-node element, which is conducive to complex shape functions. When building the model, considering the reduction of the scale of the problem, the model was appropriately simplified under the premise of little impact on accuracy, and detailed information such as threaded holes, fillets, and chamfers were removed. The finite element model of the square ram is constrained by the guide rail and the sliding block.

3.2. Modal simulation analysis
Modal analysis is the basis of dynamic problem analysis. Among the modal extraction methods, the Subspac method and Lanczos method have the characteristics of high accuracy and fast calculation
speed. See the Block Lanczos method to solve the problem. The results are shown in Table 1. Show.

The improvement of the dynamic performance of the square ram depends on the increase of the natural vibration frequency and the change of the vibration form. After finite element modeling and analysis, it is known that the stiffness of the square ram and the constraint position of the slider directly affect its natural frequency and vibration shape, which in turn affects the overall mode of the machine tool.

| Fruit order | Natural frequency (Hz) | Mode description |
|-------------|------------------------|-----------------|
| Level one   | 45.98                  | Whole X swing   |
| Second order| 102.60                 | Overall Y swing |
| Third order | 260.70                 | Bending vibration around Y axis |
| Fourth order| 314.50                 | Overall torsional vibration around Z axis |
| Fifth order | 388.20                 | Overall Z vibration |

Note: The involved direction is based on the machine coordinate system. The machine coordinate system takes the carriage feed direction as X direction, the spindle box feed direction as Y direction, and the square ram feed direction as Z direction.

4. Modal characteristic test

4.1. Test purpose

The purpose of the test is to find out the natural frequency and the first few modes of the square ram, verify the effectiveness of the finite element analysis, and observe whether there is a resonance frequency in actual production. The square ram of the TX6916 CNC milling machine was tested by the hammer impulse excitation method and the milling test.

4.2. Test plan and conditions

4.2.1. Hammer method test.

Hammering excitation pulse corresponds to a certain frequency range component, which is a wide-band fast excitation method. Signal acquisition is carried out by the hammering method of single-point excitation and multi-point pickup, that is, one input force signal corresponds to three output acceleration sensor induction signals.

The acceleration sensor is pasted on the output end of the square ram according to the coordinate system of the machine tool to cut the double, Y, and Z directions (as a reference point to detect the natural frequency of the square ram) and three points in the Y direction to detect the Y direction swing of the square ram. In the same way, paste three points in the X direction, pick up the vibration acceleration signal, and detect the X direction swing of the square ram. In order to eliminate the influence of random errors, a method of multiple sampling with the same excitation at the same measuring point is adopted, so that there are more than 5 valid measured data in each measuring direction at each measuring point. The output endpoint measures the vibration acceleration signals in the X, Y, and Z directions of a certain time under hammer excitation.

4.2.2. Milling test

In order to observe whether there is a resonance frequency in the actual production of the square ram and to supplement the modal characteristic test of the hammering method, a milling test was carried out. The test device and experimental program are the same as the hammer pulse excitation method test, and the parameter settings are changed. Using disc milling cutter, outer diameter 200.00mm, 12 teeth, blade material is cemented carbide, plane milling large end face 45 steel, square ram elongation 550.00mm, spindle speed 400.00r/min, feed halo is 80.00mm/ min, cutting depth is 1.00mm, single channel sampling frequency is 5k, single sample sampling time is 22s, data sampling is random sampling. Cutting conditions: continuous cutting, especially cooling and lubrication.
Since the size of the end face of the square ram is much smaller than the total length, the milling force is mainly concentrated on the XOY plane during milling, and the vibrations in the X and Y directions are obvious. Therefore, the deformation of the end face is ignored in the test. Piece test.

In the test, due to various interference reasons, the test data often contains various interference factors. In order to obtain more accurate results, it is necessary to take some necessary measures in data processing: (1) Multiple sampling, hammering method test, each measuring point has more than 5 valid measured data in each measuring direction; milling test at different positions The number of samples is 3, which enables the signal to be averaged in the frequency domain; (2) The calibration value of the input and output signal (i.e., the signal amplification factor) also needs to be continuously adjusted during the test to make the signal output waveform better, but not overloaded. (3) From displacement to acceleration, the amplitude must be multiplied by $w^2$ ($w$ is the signal frequency). The high-frequency response is obvious in the hammering test. The high-frequency part of the collected acceleration signal is actually amplified, and the frequency part of interest becomes smaller. To this end, time-domain method integration is used to convert the acceleration signal into a speed signal. The integration method adopts Simpson algorithm. The Simpson algorithm is derived from the Newton-Cotes formula, which is an interpolation type integration algorithm, which has higher integration accuracy than the rectangular formula. (4) Use DEWESoft software and MATLAB to analyze the vibration signals collected in the experiment in time domain and frequency domain. According to the measured vibration time domain signal of each measuring point, the power spectral density curve of the measuring point is analyzed and obtained, and the natural frequency of each order is determined by the peak value of the power spectral density curve. (5) Analyze the amplitude of each frequency peak and the corresponding phase value, take the reference point as the mode unit value for normalization, and identify the modal characteristics of each order in combination with the phase relationship.

In the process of modal parameter identification, make full use of the data of multiple measurements at each measuring point, and reduce the influence of random errors and abnormal data on the accuracy of modal parameter identification by using methods such as multiple averaging and point elimination. The frequency spectrum diagram of the direction vibration velocity of a certain measurement point at the same direction at 60mm away from the output end face of the square ram under hammer excitation is shown in Figure 1. The frequency spectrum of the vibration velocity in a certain measured direction of the measuring point at the same distance under the excitation of milling is shown in Figure 2.

Figure 1. The frequency spectrum of a measured vibration velocity under hammer excitation.
4.3. Hammer method test analysis

After the modal characteristics test of the square ram of the TX6916 CNC floor boring and milling machine, the test data of the hammer pulse excitation method is analyzed to obtain the first two natural frequencies and vibration modes of the square ram, as shown in Table 2. Among them, the natural frequency of 50Hz vibration mode is the overall X-direction swing; the natural frequency of 105Hz, the vibration mode is the overall Y-direction swing. The test obtained that the square ram has a natural frequency of 320 Hz, and the output end face measuring point X, Y direction vibration velocity phase is reversed, in line with the overall torsional vibration characteristics around the Z axis.

| Measuring point | 1          | 2          | 3          |
|-----------------|------------|------------|------------|
| X direction     |            |            |            |
| 50Hz            | 5.758      | 4.307      | 3.295      |
| Phase (°)       | -29.34     | -19.5      | -28.69     |
| Y direction     |            |            |            |
| 105Hz           | 4.923      | 3.972      | 3.266      |
| Measuring point | 1          | 2          | 3          |
| Amplitude (e-8m/s) | 156.1    | 165.8      | 149.7      |

The test results are similar to the first five natural frequencies of the square ram finite element modal analysis. Comparing the calculated value with the experimental value, the relative error is within 10% except for the third-order mode.

The reasons for the data error are: (1) The test measurement point tube, excitation direction, hammer material, etc. lead to the hammer pulse not being able to excite all natural frequencies; (2) The hammer excitation response time history 0.2s, in the frequency domain analysis The frequency resolution is 5Hz; (3) The accuracy of the material's elastic modulus, mass density, and boundary conditions setting during modeling will affect the results of modal analysis; (4) The finite element modeling process For rigid connection, the calculation result is obtained under the condition of infinite free vibration damping.

4.4. Milling test analysis

A set of experimental chatter frequencies were obtained through milling experiments. The peak frequency of square ram is 50Hz, 161.8Hz, 323.7Hz, 440.2Hz and so on. The first three orders are the common-mode parameter identification process of the square ram. The data of multiple star measurements at each measuring point are fully utilized, and the vibration frequency, of which the 50Hz mode is the overall X-directional swing. By improving the structural parameters of the other side ram, the dynamic performance of the side ram can be effectively improved, and the resonance of the side ram due to other co-frequency interference or excitation can be avoided. In the same period of the experiment, a static hammering test was performed on the boring shaft. The preliminary frequency
domain analysis revealed that the boring shaft has a natural frequency of 440.2 Hz. The square ram in the milling test has a large value at this frequency, which is most likely due to forced vibration caused by the unbalance of the sharp shaft.

5. Conclusion
With the continuous development and application of the finite element analysis method in various fields, it will continue to mature and improve, improve the design efficiency of the enterprise, optimize the design plan, and shorten the product development cycle. This paper tries to analyze the natural vibration characteristics of the square ram based on the finite element method, builds a model and conducts experiments. When optimizing the design, the square ram can be adjusted by adding stiffeners, fixing the pre-tightening force of the bolts, and changing the constraint position. The stiffness of the ram plays the purpose of increasing the natural frequency. The test results have guiding significance for the structural optimization design of the boring and milling machine.

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