Parameter identification and optimization of slide guide joint of CNC machine tools

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Abstract. The joint surface has an important influence on the performance of CNC machine tools. In order to identify the dynamic parameters of slide guide joint, the parametric finite element model of the joint is established and optimum design method is used based on the finite element simulation and modal test. Then the mode that has the most influence on the dynamics of slip joint is found through harmonic response analysis. Take the frequency of this mode as objective, the sensitivity analysis of the stiffness of each joint surface is carried out using Latin Hypercube Sampling and Monte Carlo Simulation. The result shows that the vertical stiffness of slip joint surface constituted by the bed and the slide plate has the most obvious influence on the structure. Therefore, this stiffness is taken as the optimization variable and the optimal value is obtained through studying the relationship between structural dynamic performance and stiffness. Take the stiffness values before and after optimization into the FEM of machine tool, and it is found that the dynamic performance of the machine tool is improved.

1. Introduction
The machine tool is a complicated structure combined by many parts with different functions and these connection is called joint surface or joint. Studies [1] have shown that joint surface of the machine tool account for 60%-80% of the stiffness, over 90% of the total damping, 40%-60% of the total flexibility and 85%-90% of the static deformation. Therefore, it is an effective way to improve the performance of the machine tool through improving the performance of the joint surface.

Scholars at home and abroad have done extensive research on the parameter identification of joint surface of machine tools. There are mainly three methods to identify parameters, including theoretical calculation method [2], test method [3] and a method combining theoretical calculation and test [4]. However, there are less research on parameter optimization of joint surface and the parameter optimization of joint surface is important to the property of machine tool.

To cure the above problems, this paper adopts optimum design method to identify the joint surface based on the finite element simulation and modal test data firstly. Then sensitivity analysis is used to get the most sensitive parameter of joint surface. At last, optimize this parameter to improve the property of the machine tool.

2. Parameter identification of slide guide joint

2.1. Establishment of parameterized FEM of slide guide joint
A CNC machine tool is taken as the research object in this paper and its 3-D model is shown in Figure 1. Slip joint surface is constituted by the bed and the slide plate. The optimum design module of ANSYS is used to identify the stiffness of slide guide joint surface, and the premise is to establish the parameterized model of slip joint. In practical work, the bed is bolted to the ground through anchor bolt and the quality of the bed is much greater than that of the slide plate. So the bed is simplified into
two fixed guide rails and the research object is the slide plate and the slip joint surface constituted by the slide plate and the bed, as shown in Figure 2.

Figure 1. 3D modal of CNC machine tool

The material of slide plate is HT250, the Young modulus is 1.2e5MPa, the density is 7.2e-9t/mm^3 and the Poisson’s ratio is 0.25. Solid185 unit is used to mesh the slide plate and the element size is 8. According to Yoshimura Yutakanori, although the contact area of the joint surfaces is different, as long as the average contact pressure is the same, the dynamic data of each unit area of the joint surface can be applied to the general joint surface with the same surface properties. Therefore, the four slip joint surfaces constituted by the bed and the slide plate are respectively equivalent to springs, the stiffness of which are denoted by $K_1$, $K_2$, $K_3$ and $K_4$, as shown in Figure 2. These springs are meshed with Combine14 and their initial stiffness are all set as $1 \times 10^6$N/mm.

2.2. Modal test of slip joint

In order to obtain the low-order natural frequencies and modes of vibration of the slide plate relative to the bed, the bed needs to be bolted to the ground through anchor bolt and the joint surface between the bed and the slide plate should be in accordance with the normal working condition. This experiment adopts the German M+P SO Analyzer data collection and analysis system, and single-input multi-output method is used. Choose the end point of the slide plate as exciting point and multiple response points are arranged evenly on the frame of slide plate. The frequency range of hammer excitation is 0–312.5Hz and the test site is shown in Figure 3. The imaginary frequency curves of driving point in the three directions X, Y and Z obtained in the test are shown in figure 4. The peaks of the imaginary frequency curves correspond to the natural frequencies, which are listed in Table 1.

2.3. Parameter identification of slip joint

Optimization design module of ANSYS has two kinds of optimization method, namely zero order method and first order method [5]. Zero method is a perfect method to deal with most engineering problems effectively. First order method is based on the sensitivity of the objective function to the design variables and is more suitable for accurate optimization analysis. In this paper, zero order method is used for rough optimization in the global design space firstly, and then first order method is used to optimize in the local design space until the most satisfactory solution is found.

In order to identify the stiffness of slip joint, the mathematical model of optimal design is established as follows:

**Design variable:**

$$X = \{K_1, K_2, K_3, K_4\}^T$$  \hspace{1cm} (1)

$K_1$ and $K_2$ stand for the vertical stiffness of slide guide joint surface, and $K_3$ and $K_4$ stand for the lateral stiffness of slide guide joint surface.

**State variable:**

$$f_{\text{test}} - \alpha \leq f_{\text{calc}} \leq f_{\text{test}} + \alpha$$  \hspace{1cm} (2)
Figure 3. Modal test of slide guide joint

Figure 4. Virtual frequency curves of driving point (a) X direction (b) Y direction (c) Z direction

a is a constant, $f_{\text{test}}$ is the natural frequencies of joint obtained by modal test, $f_{\text{cal}}$ is the natural frequencies of joint obtained by FEA.

Objective function: $\min \{X\} = \sum a_i (f_{\text{cal}} - f_{\text{test}})^2$ \hspace{1cm} (3)

$a_i$ is the weight of the natural frequency of each order and it is chosen according to the contribution of the natural frequency of each order to the objective function.

The first four natural frequencies obtained by the modal test are substituted into the objective function. After a few calculations of iteration in ANSYS, the stiffness values of each slip joint surface is acquired, respectively as:

$K_1 = 8.2 \times 10^6 \text{N/mm}$, $K_2 = 2.0 \times 10^6 \text{N/mm}$, $K_3 = 8.3 \times 10^6 \text{N/mm}$, $K_4 = 4.2 \times 10^6 \text{N/mm}$.

The stiffness values are substituted into the FEM of slide guide joint, and the first four natural frequencies and modes of vibration are gotten. From Table 1, it can be seen that the error of the natural frequency of various orders obtained by FEA and modal test is within 10%, which can be acceptable. From Figure 5, it can be seen that the first order mode of vibration of the slide plate relative to the bed is turning, the second order mode of vibration is yawing, the third order mode of vibration is the coupling of the up and down translation and the left and right translation, and the fourth order mode of vibration is turning. The first four modes of vibration obtained by FEA and modal test are almost
consistent, so it can be concluded that the stiffness values of joint surface identified by the method used in this paper is accurate.

**Table 1.** The comparison between the first four natural frequencies of finite element analysis and modal test of slide guide joint

| steps                  | FEA (Hz) | 1     | 2     | 3     | 4     |
|------------------------|----------|-------|-------|-------|-------|
| FEA (Hz)               | 109.53   | 186.92| 215.63| 255.20|
| modal test (Hz)        | 121.88   | 193.75| 210.94| 240.63|
| errors                 | 10.13%   | 3.53% | 2.22% | 6.05% |

**Figure 5.** The comparison between the first four mode shapes of finite element analysis and modal test of slide guide joint (a) the first order (b) the second order (c) the third order (d) the fourth order

3. **Sensitivity analysis and optimization of stiffness of slip joint surface**

3.1. **Harmonic analysis of slip joint**

In order to find the mode that has the greatest influence on the dynamic performance of the structure, the harmonic analysis of slip joint is carried out. A point on the connecting part of the slide plate and the work table is selected as the observation point, and its displacement response amplitude curve is shown in Figure 6. In the direction X and Z, the maximum peaks appear at the first order natural frequency. In the Y direction, the maximum peak appears in the third order natural frequency. Therefore, the first and the third order modes are the most important modes affecting the dynamic performance of the slip joint.
3.2. Sensitivity analysis of stiffness of slip joint surface

Since the first and the third order modes have great influence on the dynamic performance of the slip joint, the natural frequency of these two modes are taken as the index to analyse the dynamic sensitivity of stiffness of each joint surface. The design variables are $K_1$, $K_2$, $K_3$, and $K_4$, the values of which have many uncertainties and randomness for the reason that the stiffness of slip joint is influenced by physical factors such as surface roughness and lubricant medium. Therefore, the design variables follow the Gaussian distribution. Use Latin Hypercube Sampling and Monte Carlo Simulation to simulate, and after sampling 200 times, the natural frequency has been convergent. The sensitivity of dynamic performance of the slide guide joint is shown in Figure 7. It can be seen that the stiffness $K_2$ has the most impact on the first order natural frequency, followed by stiffness $K_1$. Likewise, the stiffness $K_2$ has the most impact on the third order natural frequency, followed by stiffness $K_1$. In addition, the values of stiffness are all positively correlated with the natural frequencies.

![Figure 6](image)

**Figure 6.** Displacement response amplitude curve in each direction of connection point on slide carriage (a) X direction (b) Y direction (c) Z direction

3.3. Optimization of stiffness of the slip joint surface

From the sensitivity analysis above, it can be seen that the stiffness $K_2$ has the most influence on the dynamic performance of slip joint, followed by $K_1$. Therefore, in order to improve the dynamic performance of slip joint, the values of $K_1$ and $K_2$ should be improved. Change separately $K_2$ and $K_1$, and observe the changes of the first four steps natural frequency, as shown in Figure 8 and Figure 9. With the increase of $K_2$, the natural frequency of each order is improved, and the amplitude of improvement decreases gradually. When $K_2$ equals to $9.5 \times 10^6$, the natural frequency of each order tends to be stable. Due to the increase of the stiffness of slip joint will increase the manufacturing cost, $9.5 \times 10^6$ can be selected as the optimal value of $K_2$. Likewise, with the increase of $K_1$, the natural frequency of each order is improved, and the amplitude of improvement decreases gradually. When $K_1$...
equals to $4 \times 10^6$, the natural frequency of each order tends to be stable, so $4 \times 10^6$ can be selected as the optimal value of $K_1$.

Figure 8. Variation of each natural frequency with stiffness $K_2$

Figure 9. Variation of each natural frequency with stiffness $K_1$

4. Dynamic analysis of machine tool

A finite element model of machine tool considering joint surface is established. The axial stiffness of ball screw obtained by using the calculation formula in the book named *Basis of ball screw*. Take the stiffness of the slip joint surface before and after optimization into the machine tool, and modal analysis and harmonic analysis are carried out. Table 2 lists the variation of the natural frequencies of the machine tool before and after optimization. Table 3 lists the change of the maximum displacement amplitude of harmonic analysis, and Figure 10 shows the displacement amplitude curves of the machine tool before and after optimization.

It can be seen from Table 2 that the natural frequency of each order is improved in varying degrees after optimization. From Table 3 and Figure 10, it can be seen that the amplitude of displacement response in each direction is decreased to different extent, which shows that the vibration of the machine tool has been restrained.

Table 2. Natural frequencies of machine tool before and after optimization

| Steps | 1   | 2   | 3   | 4   | 5   | 6   |
|-------|-----|-----|-----|-----|-----|-----|
| Before (Hz) | 86.81 | 89.91 | 99.22 | 147.41 | 149.84 | 164.87 |
| After (Hz)   | 87.92 | 95.58 | 99.63 | 149.15 | 151.72 | 168.94 |
| Ratio       | 1.3\% | 6.3\% | 0.4\% | 1.2\% | 1.3\% | 2.5\% |

Table 3. The maximum displacement amplitude of each direction before and after optimization

| Direction | X    | Y    | Z    |
|-----------|------|------|------|
| Before /mm| 0.01248 | 0.00322 | 0.00854 |
| After /mm | 0.01217 | 0.00263 | 0.00835 |
| Ratio     | 2.5\% | 18.3\% | 2.2\% |

5. Conclusions

In this paper, the finite element analysis, modal test and optimization method are used to identify and optimize the parameters of slide guide joint surface of CNC machine tool, and the dynamic performance of the machine tool has been improved. The main content and conclusions are as follows.

1) The parametric finite element model of slide guide joint is established firstly, and then optimum design method is adopted to identify the vertical stiffness and lateral stiffness of the slide guide joint surface based on the finite element simulation and modal test data. The accuracy of this method is verified by comparing the results of FEA with that of modal test.
Figure 10. Displacement response amplitude curves before and after optimization

2) From the result of harmonic analysis, the natural frequencies of the first and third order modes have the most influence on the dynamic performance of slip joint. Take these frequencies as objective, the sensitivity analysis of stiffness of each joint surface is carried out using Latin Hypercube Sampling and Monte Carlo Simulation. It is found that the vertical stiffness of slip joint surface constituted by the bed and the slide plate has the most obvious influence on structural dynamic performance.

3) With the increase of $K_2$ and $K_1$ respectively, the natural frequency of each order increases and tends to be stable. Find the optimal value of $K_2$ and $K_1$ and take the stiffness of the slip joint surface before and after optimization into the machine tool. The results of modal analysis and harmonic analysis show that the dynamic performance of the machine tool has been improved.

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