

# Research on Thermal-Mechanical Coupling Modeling and Simulation of the Spindle Feed System of Machine Tool

Jianhua Xu, Wenhua Ye , Yang Feng and Chunyu Li

College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing, Jiangsu 210016, China

**Abstract.** Performance of spindle feed system affects the accuracy of machine tools directly. Aiming at the problem that most research works focused on mechanical characteristics or thermal characteristics of the feed system so far, the thermal-mechanical coupling characteristic is studied in this paper. The coupling mechanism and theoretical model are established for a machine tool feed system, its coupling modal and harmonic response are simulated and analyzed by the FEM software. By comparing with the mechanical characteristics, thermal-mechanical coupling characteristics has directly influence on the dynamic performance of spindle feed system, its displacement amplitude is significantly weakened.

## 1 Introduction

As a key component of machine tool, the dynamic performance of spindle feed system (SFS) has a non-negligible impact on machining accuracy. Many studies concerning the influence of mechanical properties on the SFS have been reported [1], [2]. And some others concerned the influence of thermal characteristics [3], [4]. However, the dynamic performance of the SFS is not only influenced by the mechanical properties or the thermal characteristics but also the interaction of them. It is necessary to study the thermal-mechanical coupling influence on the dynamic performance of the SFS. Research on the influence of thermal-mechanical coupling [5], [6] is quite few. Most of the researches have not made a comparison with the influence of the mechanical properties or the thermal characteristics.

Based on a five-axis linkage gantry machine tool SFS, the thermal-mechanical coupling model were established in this paper. Then the influence of the coupling effect on the dynamic performance of SFS was obtained by comparing the analysis results between thermal-mechanical coupling simulation and structure field simulation.

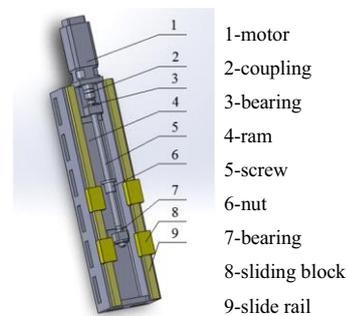
## 2 Thermal-mechanical coupling modeling

In this paper, the SFS of five-axis linkage gantry machine tool is taken as study object. Its mechanical structure is shown in Fig. 1.

In the SFS working process, displacement and velocity are time-varying. The internal force equilibrium equation turns into:

$$\sigma_{ij,i} + F_{Ni} + F_{Ti} - \rho u_{i,tt} - \mu u_{i,t} = 0 \quad (1)$$

where  $\sigma_{ij,i}$  is internal stress component,  $F_{Ni}$  and  $F_{Ti}$  are body forces caused by external force and temperature rise,  $u_{i,tt}$  is the second order derivative to time of the displacement component (i.e. acceleration),  $u_{i,t}$  is the first derivative of it (i.e. velocity),  $\rho$  is density,  $\mu$  is damping coefficient.



**Figure 1.** The 3D model of spindle feed system

By discretizing the Eq. (1). with finite element, the thermal-mechanical coupling dynamic model of SFS can be obtained. Which is shown as Eq. (2).

$$[M]\{\ddot{q}\} + [C]\{\dot{q}\} + [K]\{q\} = \{F_N\} + \{F_T\} \quad (2)$$

where  $\{\ddot{q}\}$ ,  $\{\dot{q}\}$  and  $\{q\}$  are respectively acceleration vector, velocity vector and displacement vector of SFS under the thermal-mechanical coupling effect,  $[M]$ ,  $[K]$  and  $[C]$  are the quality matrix, stiffness matrix and damping matrix of the SFS, respectively.  $\{F_N\}$  and  $\{F_T\}$  are node load vectors caused by external force and temperature rise.

For Eq. (2), its characteristic equation is Eq. (3), and it meets Eq. (4).

$$[K][A] = [M][A][\Lambda] \quad (3)$$

$$\begin{cases} [\phi]^T[M][A] = I \\ [\kappa]^T[K][A] = [\Lambda]. \end{cases} \quad (4)$$

where  $[A]=diag(\omega_1^2, \omega_2^2, \dots, \omega_n^2)$  is the natural frequencies matrix for SFS,  $I$  is unit matrix,  $[A]=[A_1, A_2, \dots, A_n]$  is matrix of modal shape of SFS. The natural frequency and vibration mode under the effect of thermal-mechanical coupling of the SFS can be obtained by the above equations.

According to Eq. (2), modal parameter of the SFS is related to the mass matrix, the stiffness matrix, the damping matrix of the system, the force it suffered and the thermal stress caused by temperature rise. The temperature has influence on the modal parameters of the SFS. The temperature field will affect the structure field. While the influence of structure field on temperature field is relatively small [7]. So the thermal-mechanical coupling of SFS is an one-way coupling.

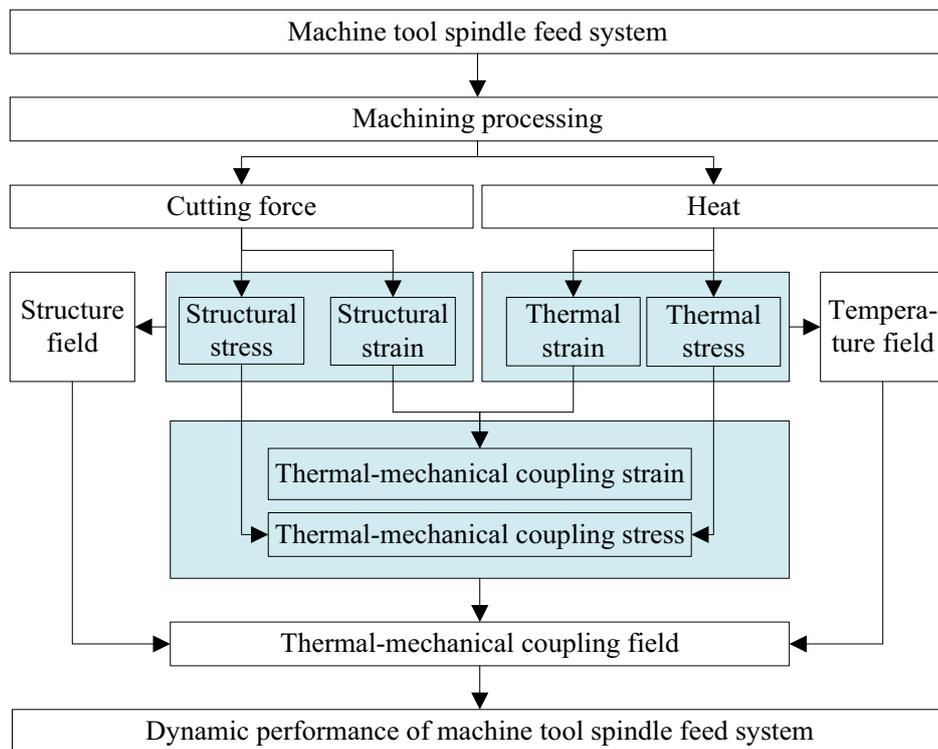


Figure 2. Thermal-mechanical coupling relationship

### 3 Simulation and analysis of thermal-mechanical coupling characteristics

#### 3.1 Simulation method

The thermal-mechanical coupling problem can be divided into three sub-problems: dynamic characteristics of structure, thermal effects and thermal-mechanical coupling effect. Their coupling relationship is illustrated in Fig. 2.

To compare and verify the influence on SFS dynamic performance by thermal-mechanical coupling effect, structure field simulation and thermal-mechanical coupling simulation are carried out. For the latter, modal analysis and harmonic response analysis are conducted respectively.

#### 3.2 Dynamic performance simulation

The modal analysis is carried out by simulation with a

finite element analysis software. The first six order natural frequencies are gained in coupling field and structure field respectively. The results are summarized in Table 1.

Table 1. Contrast of the first six natural frequencies

| Modal order | Structure field[Hz] | Coupling field[Hz] | Frequency deviation[%] |
|-------------|---------------------|--------------------|------------------------|
| 1           | 168.53              | 167.16             | 0.81%                  |
| 2           | 178.79              | 177.99             | 0.45%                  |
| 3           | 234.03              | 233.07             | 0.41%                  |
| 4           | 388.99              | 387.25             | 0.45%                  |
| 5           | 430.57              | 427.33             | 0.75%                  |
| 6           | 481.36              | 479.21             | 0.44%                  |

#### 3.3 Contrast and analysis of modal parameters

The contrast of modal parameters between the thermal-mechanical coupling field and the structure field is shown in Table 1. It shows that each order of natural frequencies makes no great difference. Among them, the first natural frequency is most significant (0.81%), the fifth natural frequency takes second place (0.75%), other are all within 0.5%. Deviation of each order natural

frequency are within 4 Hz. Therefore, the internal thermal stress of SFS has a relatively small influence on the modal parameters.

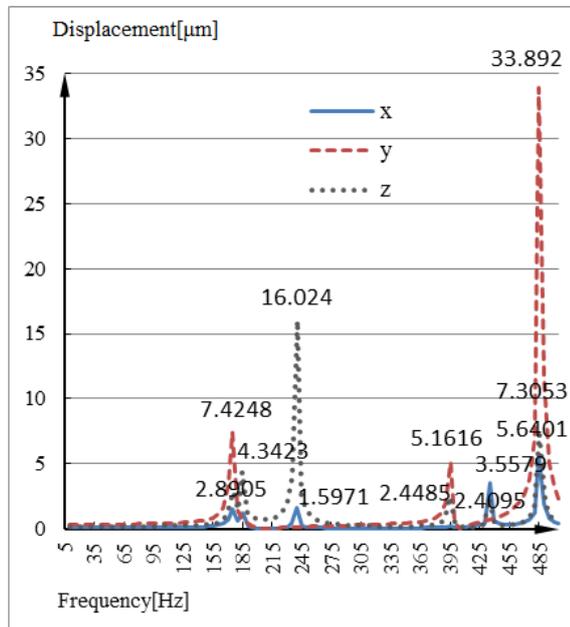


Figure 3. Displacement-frequency curves in the structure field

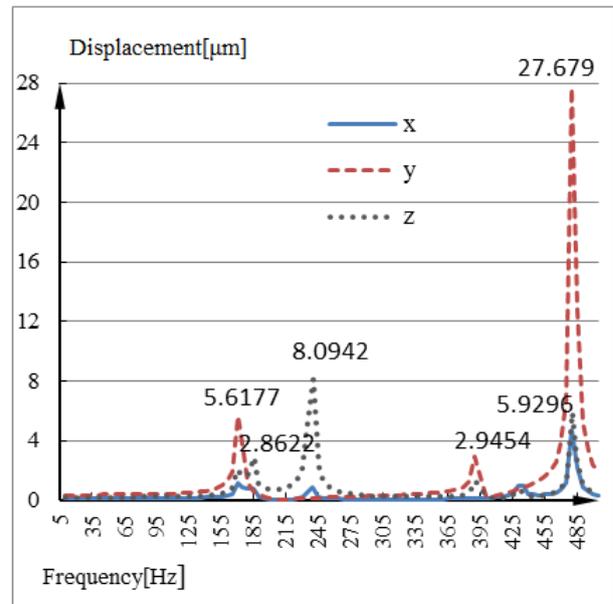


Figure 4. Displacement- frequency curves in the thermal-mechanical coupling field

Table 2. Summary and contrast of displacement amplitudes

| Amplitude in different directions |                     | Frequency |         |         |         |         |         |
|-----------------------------------|---------------------|-----------|---------|---------|---------|---------|---------|
|                                   |                     | 170 Hz    | 180 Hz  | 240 Hz  | 390 Hz  | 430 Hz  | 480 Hz  |
| X                                 | Structure field[μm] | 1.5226    | 1.267   | 1.5971  |         | 3.5579  | 5.6401  |
|                                   | Coupling field[μm]  | 1.1336    | 0.797   | 0.83468 |         | 1.0037  | 4.7087  |
|                                   | Deviation[%]        | -25.55%   | -37.10% | -47.63% |         | -71.79% | -16.51% |
| Y                                 | Structure field[μm] |           | 7.4248  |         | 5.1616  |         | 33.892  |
|                                   | Coupling field[μm]  |           | 5.6177  |         | 2.9454  |         | 27.679  |
|                                   | Deviation[%]        |           | -24.34% |         | -42.94% |         | -18.33% |
| Z                                 | Structure field[μm] | 2.8905    | 4.3423  | 16.024  | 2.4485  | 2.4095  | 7.3053  |
|                                   | Coupling field[μm]  | 2.0539    | 2.8622  | 8.0942  | 1.2624  | 0.71359 | 5.9296  |
|                                   | Deviation[%]        | -28.94%   | -34.09% | -49.49% | -48.44% | -70.38% | -18.83% |

### 3.4 Harmonic response analysis and contrast

By contrasting the displacement-frequency curves in Fig. 3 and Fig. 4, it can be found that their changing trend are similar, but the amplitudes in coupling field are less than that of the structure field.

A comparison of displacement amplitudes in three directions are listed in Table 2. For X, the maximum reduction in displacement is 71.79% at frequency 430Hz. For Y, the maximum reduction is 42.94% at 390 Hz. For Z, the maximum reduction is 70.38% at 430Hz.

According to the analysis above, the displacement of the SFS is reduced under the coupling field. That is, the thermal-mechanical coupling effect plays a weakening role in the displacement.

## 4 Conclusions

In this paper, the thermal-mechanical coupling mechanism and its theoretical coupling model are established for the SFS of machine tools. The coupling modal and harmonic response are simulated and analyzed by FEM. The simulation results show that the thermal stress caused by the temperature rise has little influence on the modal parameters, but the displacement amplitude has been significantly weakened under thermal-mechanical coupling effect.

## Acknowledgment

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