IOP Conf. Series: Materials Science and Engineering **234** (2017) 012013 doi:10.1088/1757-899X/234/1/012013

Analysis of the Thermal Characteristics of Machine Tool Feed System Based on Finite Element Method

Xiaobo Mao[1], Kuanmin Mao[1], Yikang Du[1], Fengyun Wang[1] and Bo Yan[1]

[1]School of Mechanical Science and Engineering Huazhong University of science and Technology, Wuhan, 430074, China

kmmao4645@sina.com, maoxiaobo68@hust.edu.cn

Abstract. The loading of mobile heat source and boundary conditions setting are difficult problems in the analysis of thermal characteristics of machine tools. Taking the machine tool feed system as an example, a novel method for loading of mobile heat source was proposed by establishing a function which was constructed by the heat source and time. The convective heat transfer coefficient is the key parameter of boundary conditions, and it varies with the temperature. In this paper, a model of "variable convection heat transfer coefficient" was proposed, and the setting of boundary conditions of thermal analysis was closer to the real situation. Finally, comparing results of above method and experimental data, the accuracy and validity of this method was proved, meanwhile, the simulation calculation and simulation time was reducing greatly.

1. Introduction

In the total error of modern machine tool manufacturing, the thermal error caused by thermal deformation is as high as 40%~70% [1]. Thermal analysis is an effective method to reduce the thermal error, but the accuracy of this method depends on a high precision temperature field model [2, 3]. In addition, the boundary conditions are complicated problems for thermal analysis of machine tools, so the setting of boundary conditions are often inconsistent with the actual situation, especially the key parameter of convection heat transfer coefficients (CHTCs). The CHTCs varies with temperature. It is obviously not correct to use a fixed CHTCs value in the thermal analysis. However, it is very difficult to calculate CHTCs exactly [4]. Yang [5] designed a new algorithm of mobile heat source loading by APDL language, and programmed the calculation procedures. Using finite element method, a process of twin-wire submerged arc welding was performed and the rule of calculation and loading of mobile heat source was studied by Tang [6]. But both of the above methods had the large amount of calculation and complex programming. Zhao.[7] proposed a method for computing the CHTCs of spindle surface, which could make the CHTCs of spindle surface as the CHTCs of a flat plate when air flows along the spindle surface. A calculation method of CHCTs of spindle system based on RBF neural network was presented [8], and the accuracy of calculation was improved. However, they only gave the calculation method of the CHCTs, did not propose the setting method of CHCTs in the thermal analysis under different temperature.

As mentioned above, these methods of calculation and the setting of boundary conditions are not ideal. In this paper, a new method was proposed to simulate the mobile heat source, which could greatly reduce the amount of computation and simulation time. As for the setting of CHCTs in the thermal analysis, the authors presented a method which could set the variable CHCTs under different temperature in the thermal analysis. Furthermore, the setting of boundary conditions was closer to the actual situation, and it could improve the accuracy of the simulation analysis. An experiment was carried out in the feed system of a milling machine.

2. Thermal test of a feed system

The feed system of the milling machine consists of a table, a saddle, and a ball screw. To accurately establish the temperature field of the feed system, nine platinum resistance temperature sensors (T1-T9) were fixed in the feed system, as shown in figure 1. The ambient temperature of the machine tool is 11.2 ℃.

For thermal analysis of the feed system, the authors designed the following experiment: The feed speed of the table along the X axis was 4000 millimeter per minute, and the motor speed was 267 turns per minute. The total experiment time was four hours.

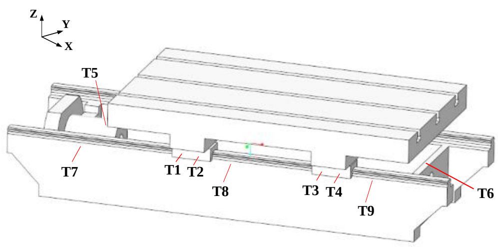

Figure 1. Solid model of the feed system.

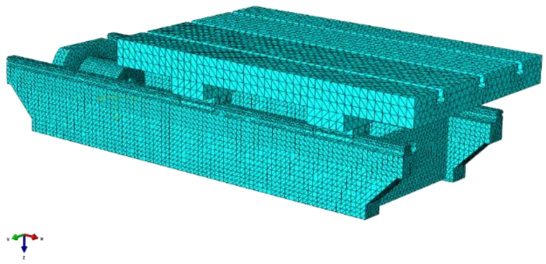

Figure 2. The FE model of the feed system.

3. Development of the FE simulation model

The temperature of the ball screw nut cannot be measured directly for the research of the feed system. However, two temperature sensors (T5 and T6) were fixed on near both ends of the ball screw, so the ball screw was not established in the solid model of the feed system. The finite element model was obtained with software of the ABAQUS, as shown in figure 2.

3.1. Determination of the material properties

There are two major materials in the feed system. Uniloy alloy was applied to guide ways, and carbon steel was applied to saddle and table. The two material properties were assigned them respective structures in the ABAQUS, and values of the properties are shown in table 1.

Table 1. Properties of the material.

Material	Uniloy Alloy	Carbon Steel
Density (Kgm^{-3})	7820	7840
Modulus of elasticity (*Gpa*)	206	200
Poisson's ratio	0.3	0.3
Linear expansion coefficient ($10^{-5}K^{-1}$)	1.1	0.85
Thermal conductivity ($Wm^{-1}K^{-1}$)	16.3	49.8
Specific heat capacity ($Jm^{-1}K^{-1}$)	460	465

3.2. Thermal sources analysis

The thermal sources of the feed system was from the motor, guide ways and the bearing. The heat generation of the guide ways, motor and bearing could be calculated by the following equation [9, 10].

$$Q = \mu F v \tag{1}$$

$$H = \frac{M_T n_1}{9550}(1-\eta) \tag{2}$$

$$H_f = 1.047\times 10^{-4} n_2 M \tag{3}$$

Where M_T is the output torque of the motor, n_1 is the rotating speed of the motor, H_f is the heat generated power (w), n_2 is the rotating speed of the bearing (*rpm*), M is the frictional torque of the bearing (*Nmm*).

4. Heat source loading and bounding condition setting

4.1. Mobile heat source block loading

Thermal load could be calculated by equation (1)-(3), and it was loaded into the structural analysis in the form of heat flux. In this paper, the friction between the guide ways and the slider was mobile heat source. The amount and time of the simulation were greatly increasing if the thermal source was loaded by the current method of mobile heat source. Consequently, a new method for the loading of mobile heat source was proposed by establishing a function which was constructed by the heat source and time. The "table" commend of "Amplitude" in the ABAQUS was used to establish the function. To achieve the purpose of mobile heat source loading, the segmentation of heat flux and thermal loading schedule were designed. The heat flux density and the section loading time were shown in figure 3 and table 2.

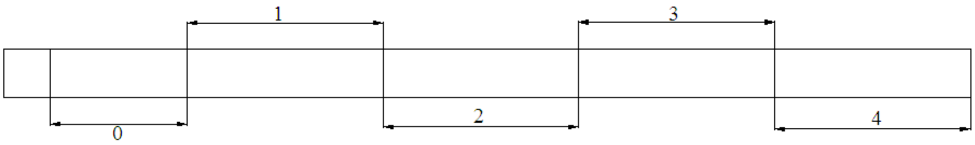

Figure 3. The segmentation of heat flux.

Table 2. The segmentation of thermal loading schedule.

Parts \ Time(s)	1.5	3	4.5	6	7.5	9	10.5	12
1	■							■
2		■					■	
3			■			■		
4				■	■			

4.2. Variable heat transfer coefficient setting

The CHCTs was varying with temperature, but in the process of the thermal analysis, the temperature was changing with time. It was obvious that the analysis error had increased if the fixed CHCTs was used in thermal analysis. Therefore, the temperature was divided several intervals in the thermal analysis, and different CHCTs set up in each section of the temperature range in this paper. Then, a modal of variable CHCTs was established, and the method was closer to the reality and could improve the precision of thermal analysis. As for the variable CHTCs, the setting of them could be realised by ABAQUS, which was shown in figure 9.

Taking the cylindrical surface of the motor end connector as an example, the temperature interval was set to 2 °C. The CHTCs was calculated respectively when the temperature T_m was taking different values, such as 12 °C, 13 °C, 14 °C, 15 °C and 16 °C.

MATLAB was used to calculate the values of five CHCTs (Δ = 2 °C, 4 °C, 6 °C, 8 °C, and 10 °C), which were corresponding five temperature intervals in the temperature range of 13 °C ~ 21°C. The values of the five CHTCs could be seen in table 3. Hence, with the help of the "interaction" module in the Abaqus, the setting of variable CHCTs was realizing, as shown in figure 9.

Table 3. Convective heat transfer coefficients (CHTCs).

Wall Temperature (T)	CHTCs (h)
$13°C$	3.42
$15°C$	4.08
$17°C$	4.5
$19°C$	4.8
$21°C$	5.1

5. Thermal simulation of the feed system

Sequentially coupled thermal stress analysis was performed by ABAQUS. The temperature distribution of the feed system was obtained by using "heat transfer" module, which was shown in figure 4. The simulated values of temperature measuring of the feed system were shown in figure 6. After that, the temperature field was loaded into the solid model as a predefined load, meanwhile, the "variable boundary conditions" was set using the "static general" module. The thermal deformation of the feed system was shown in figure 5.

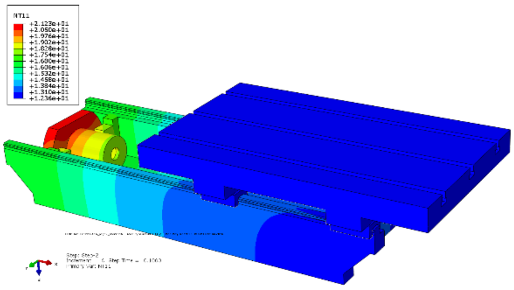

Figure 4. Temperature distribution of the feed system.

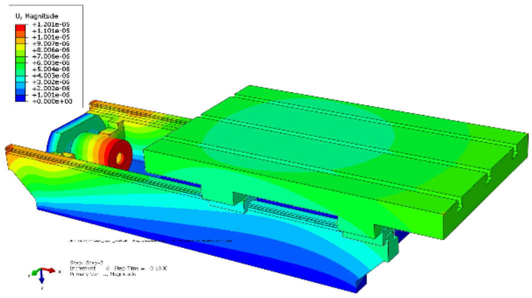

Figure 5. Thermal deformation of the feed system.

It could be seen that motor heat generation occupies the main position in heat source of the machine tool feed system from the figure 4 and figure 5. And the same time, the sliding friction heat between saddle and slider was the second heat source in the total heat source of the feed system. As a result, thermal deformation of the machine feed system was bigger than that the bearing end of the motor. This phenomenon was not only related to the characteristic of the machine tool itself, but also related to the design of the experimental methods.

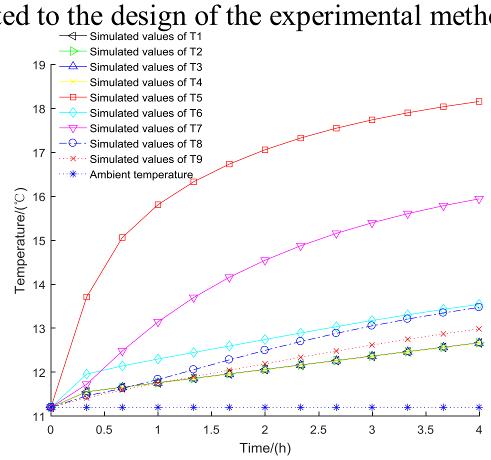

Figure 6. The simulated values of the feed system.

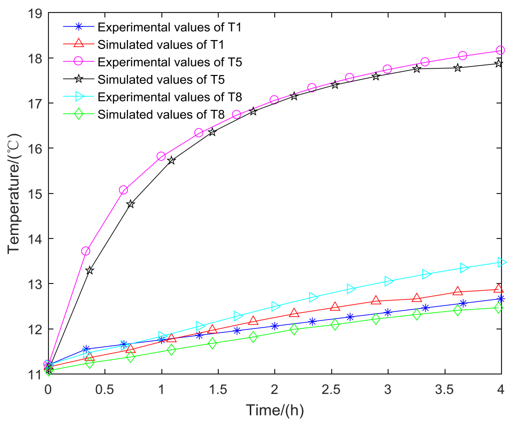

Figure 7 The comparison of the temperature values.

6. Experimental verification

To verify accuracy of the setting of “variable boundary conditions” and the method for loading of mobile heat source, the confirmatory experiment was carried out on the milling machine. The experimental site and test platform were shown in figure 8.

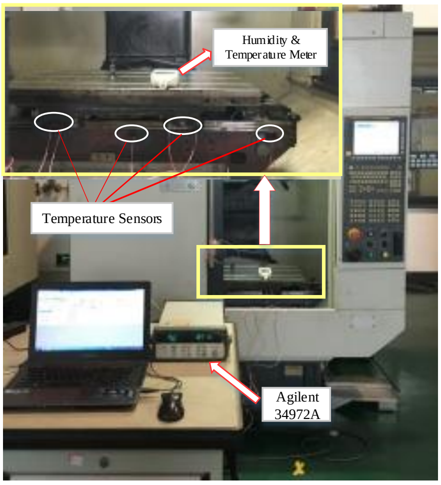

Figure 8 The test platform.

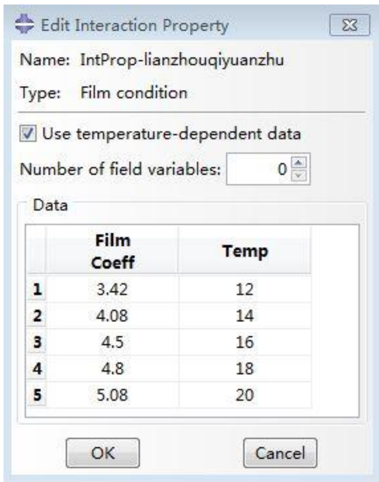

Figure 9. Variable CHCTs setting

The simulated results showed that the temperature of T5 was the highest, and the temperature difference between the four measuring points on the slider was very small. T7, T8 and T9 were fixed on a same part, so the temperature values of these were also very close. Finally, the simulated results of three measuring points which were fixed on the different components T1, T5 and T8 were selected to compare with the experimental values, as shown in figure 7. In addition, simulated and measured temperature values were also compared, which was shown in table 4. It could be seen that the simulation results were relatively close to the experimental results. Therefore, the loading of mobile heat source and boundary conditions of the FE model were correct.

Table 4. Comparison of the temperature values and simulation errors.

No. of the points	Simulated values($^\circ C$)	Experimental values ($^\circ C$)	Simulation errors (%)
T1	12.57	12.90	-0.026
T2	12.66	12.94	-0.022
T3	12.67	12.99	-0.025
T4	12.66	12.80	-0.011
T5	18.16	17.90	0.014
T6	13.54	13.06	0.035
T7	15.95	13.70	0.141
T8	13.48	12.51	0.072
T9	12.99	12.26	0.056

7. Conclusions

In this paper, a novel method of variable boundary conditions was proposed. According to the method, thermal stress, temperature field and thermal deformation of the feed system were simulated. In addition, the amount and time of the simulation were decreasing, and the validity and precision of the simulation results were confirmed by the experiment. It could provide a new idea for the setting of

IOP Conf. Series: Materials Science and Engineering **234** (2017) 012013 doi:10.1088/1757-899X/234/1/012013

boundary conditions in the thermal analysis of NC machine tools, and it also has reference value and practical significance in the thermal analysis of the machine tools.

Acknowledgements
This work was supported by the High-End CNC Machine Tools and Basic Manufacturing Equipment Technology Major Projects (Grant no. 2013ZX04005-011).

References
[1] Won Soo Y, Kim Soo K and Dong Woo C 1999, International Journal of Machine Tools and Manufacture,39: 1087-1101.
[2] Shyh-Chour H. 1995, International Journal of Machine Tools and Manufacture, 35(8): 1099 - 1104.
[3] Jianfu Z, Pingfa F, Chen C, Dingwen Y, and Zhijun W. 2013, The International Journal of Advanced Manufacturing Technology, 68 (5-8): 1517-1527.
[4] Jungdo S and Daigil L. 2004, Composite Structures, 66 (1-4): 429-438.
[5] Xiuzhi Y, Shengfu Y, Rungang Y and Zimou T. 2010, J . Huazhong Univ . of Sci .& Tech . (Natural Science Edition), 38: 101-104.
[6] Zimou T, Baosheng Y and Xiuzhi Y. 2010, Hot Working Technology, 39:.130-137.
[7] Haitao Z, Jianguo Y and Jinhua S. 2007, International Journal of Machine Tools and Manufacture, 47 (6): 1003-1010.
[8] Dianxin L, Pingfa F, Jianfu Z, Zhijun W and Dingwen Y. 2014, The International Journal of Advanced Manufacturing Technology, 70: 1445-1454.
[9] Dai S. Application Manual of Machine Tool Rolling Bearings. China Machine Press, 1993.
[10] Min X, Shuyun J and Ying C. 2007, International Journal of Machine Tools and Manufacture, 47 (1): 53-62.