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Simulation of thermal behavior of a CNC machine tool spindle

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Abstract

The thermal deformations of a CNC machine tool spindle are the major contributor of thermal error. It is very significant both theoretically and practically to study how to accurately simulate the thermal error of the spindle. Firstly, this paper proposes a method for computing the coefficient of convection heat transfer of the spindle surface by referencing the theory on computing the coefficient of convection heat transfer of a flat plate when air flows along it. Secondly, the temperature field and thermal errors of the spindle are dynamically simulated under the actions of thermal loads using the finite element method. Thirdly, the characteristics of heat flow and thermal deformation within the spindle are analyzed according to the simulation results. Fourthly, the selection principle of thermal key points, which are indispensable for building a robust thermal error model, is provided based on the thermal error sensitivity technology. At last, a verification experiment is implemented on a CNC turning center, and the results show the simulation results are satisfying to replace the experiment results for further studies.

Keywords: CNC machine tool; Thermal error; Simulation; Finite element method; Thermal key points

0. Introduction

Improvement of the CNC machine tool accuracy is all the time the most important pursuit for researchers in precision manufacturing field. Errors that affect the machine tool accuracy can be classified as (1) geometric errors, (2) thermal errors and (3) cutting force-induced errors. Among these errors, thermal errors account for 70 percent of the total errors [1]. Spindle is the core component of a CNC machine tool, and also the important contributor to the total thermal errors due to the large amounts of heat from its high-speed revolution. So the studies on thermal deformations of the spindle are indispensable parts for reducing the total thermal errors.

Building a robust thermal error model is the first step for correcting the thermal errors. The mechanism causing the machine tool deformations is so complex that it is impractical to theoretically derive an analytical expression as the thermal error model by use of all initial conditions and operating conditions for a machine tool. As far as most modeling methods are concerned, the thermal error models are all got by finding the best mapping relations between the thermal errors and some thermal key points' temperatures changes. For example, the neural networks technologies map the temperature data to the thermal error to predict the thermal errors [2–4] and successive regression analysis [5] is used to solve the coefficients of a polynomial thermal errors model. Ref. [6] revises the multivariable regression analysis by replacing the traditional optimization objective function with a new one to build a robust thermal error model. In all the modeling methods above, without single exception, the temperatures and thermal errors data used come from a lot of experiments, which are inevitably involved in the studies of all kinds of advanced measurement technologies in order to make these collected data as accurate as possible. As a consequence, the laser ball bar [7], noncontact laser technique [8] and hemispherical ball bar [9] have been developed to meet these increasing demands. Numerical computation is another important branch on studying machine tools' thermal deformations. The structural design of headstocks of precision lathes was optimized based on the computation

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results with finite element method in reference [10]. Chen et al [11] investigated thermal-bending behavior of the spindle simplified as a simple beam.

As mentioned above, it is such a hard work and high costs to collect data from experiments that the studies on replacing an experiment with a simulation have become more and more significant in this field. However, it has almost not been seen to simulate the spindle's thermal deformation without structural simplifications that can make simulation results unreliable. This paper takes a turning center spindle as an example and explains how to simulate its thermal behaviors as accurate as possible and also provides a method for selecting the thermal key points. Simulation results are verified by a measuring experiment on the same turning center.

1. Numerical simulation of spindle temperature field and thermal errors

It is very difficult to get the analytical solution of the spindle temperature field because the heat flows towards all directions in which the temperature is lower inside the spindle when it flows into the spindle in the radial direction only at the interface of the spindle and the bearing. So the finite element method is used to get the numerical solutions for temperatures and thermal errors. The numerical solutions can approximate the analytical solutions very well as long as the spindle structure is correctly and finely meshed. The reliability of the simulation results also depends on whether the boundary conditions such as the power of heat sources and heat transfer coefficients are well defined.

1.1. Computation of the power of spindle heat sources

In the current CNC machine tools the spindle speed is directly controlled by the spindle motor not by the traditional gearbox and therefore the heat generated by spindle bearings is the dominant heat causing thermal deformations. The heat can be computed by the following equation [12]:

$$H_f = 1.047 \times 10^{-4}\,\mathrm{nM}, \tag{1}$$

where n is the rotating speed of the spindle (rpm), $M$is the total frictional torque of the bearing (Nmm), H_f is the heat generated (w). The frictional torque M consists of two components: one is caused by the applied load and the other one by the viscosity of lubricant. The former can be approximated by the following equation:

$$M_l = f_1 p_1 d_{\mathrm{m}}, \tag{2}$$

where f_1 is a factor related to the bearing type and load; p_1 is the bearing load (N) and d_{m} is the mean diameter of the bearing (mm). The latter can be computed by

$$M_v = 10^{-7} f_0 (v_0 n)^{2/3} d_{\mathrm{m}}^3 \quad \text{if} \quad v_0 \quad n \geqslant 2000, \tag{3}$$

$$M_v = 160 \times 10^{-7} f_0 d_{\mathrm{m}}^3 \quad \text{if} \quad v_0 n < 2000, \tag{4}$$

where f_0 is a factor related to bearing type and lubrication method and v_0 is the kinematic viscosityof the lubricant ($\mathrm{mm^2/s}$).

1.2. Computation of the coefficient of convection heat transfer

When the spindle rotates, air flows along the spindle surface at the constant speed, which is very similar to the situation in which the air flows along a flat plate. This kind of convection form is called forced convection. According to the theory on computing the coefficient of convection heat transfer of a flat plate when air flows along it, the coefficient of convection heat transfer of spindle surface can be computed by the following equation:

$$h = 0.664 \frac{\lambda}{l} \mathrm{Re}^{1/2} Pr^{1/3}, \tag{5}$$

$$\mathrm{Re} = \frac{ul}{v}, \tag{6}$$

where h is the coefficient of convection heat transfer (W/($\mathrm{m^2\,K}$)), and λ, Re and Pr are the thermal conductivity, Reynolds number and Prandtl number of the air. u, v, l are the velocity of flow (m/s), kinematic viscosity ($\mathrm{m^2/s}$) of the air and the cross-section perimeter of the spindle (m), respectively, which can be computed as follow:

$$u = \frac{\pi d n}{60}, \tag{7}$$

$$l = \pi d, \tag{8}$$

where d and n are the spindle diameter (m) and spindle speed (rpm) respectively. Substituting Eqs. (6)–(8) into Eq. (5) gives the following equation:

$$h = 0.664 \lambda \left(\frac{n}{60v}\right)^{1/2} Pr^{1/3}. \tag{9}$$

Under normal temperature, the kinematic viscosity of the air v equals to $16 \times 10\,\mathrm{m^2/s}$, Prandtl number of the air Pr equals to 0.701. When the spindle stops rotating, the convection form becomes the natural convection and the coefficients of convection heat transfer is assumed to be $10\,\mathrm{W/(m^2\,K)}$ according to the practical experiences.

1.3. Simulation of the spindle temperature field and thermal error

The machine tool spindle is usually a multi-diameter and hollow part. However, it is often simplified as a one-dimensional bar to investigate its thermal behavior, which makes the bigger deflections away from its real thermal behaviors. A turning center spindle is studied here. The spindle thermal errors are mainly caused by its radial and axial thermal expansion. The geometry and thermal loads of the spindle are all symmetric about the spindle axis and therefore only a half of the spindle is simulated in order to