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Thermal error characteristic analysis and modeling for machine tools due to time-varying environmental temperature

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ABSTRACT

The accuracy of machine tools is affected by both internal heat sources and time-varying environmental temperature. Therefore, the thermal deformation caused by environmental temperature variation is an important factor, which requires attention during thermal error modeling. In order to analyze the influence of time-varying environmental temperature on the thermal error of the machine tool, this paper proposed a thermal error modeling approach by using the thermal error transfer function of the machine tool. The approach was implemented in the following three steps. First, the thermal time constant of major components was calculated, according to structural parameters. Then, the thermal error transfer function of the components was derived. Finally, the thermal error transfer function of the whole machine was built based on the construction relationship. The analytical approaches of time domain and frequency domain were applied to obtain the thermal characteristics of machine tools based on the thermal error transfer function. Numerical simulations and the Z-axis operating experiment of three-axis milling machine were performed to verify the accuracy and effectiveness of the thermal error predicted model. The result shows that the proposed model is versatile and general with a clear modeling mechanism, which would provide a useful tool for the analysis and optimization design of machine tools with good thermal robustness.

1. Introduction

Environmental temperature fluctuations in the shop floor change the temperature of the machine tool. This causes thermal deformation of the structure and affects the machining accuracy [1,2]. The environmental temperature fluctuations in the workshop are mainly a result of day-and-night temperature differences and seasonal transitions. Several differences exist between the influence of environmental temperature and the influence of the internal heat source on machine tools. First, the environmental temperature acts on the whole machine tool through convective heat transfer, while the internal heat source generally results in a partial rise in the temperature of the object; Second, the environmental temperature changes slowly with periodic fluctuations in days or seasons, while on account of the internal heat source, the temperature of the machine tool varies so fast that it takes a few hours to reach thermal equilibrium. Hence, several research methods are employed because the effect mechanism of environmental temperature on the machine tool differs from that of the internal heat source. In order to avoid the influence of time-varying environmental temperature on the machine tool accuracy, researchers have proposed numerous approaches.

Beyan [3] proposed an approach in which the whole machine was sprayed with the cooling oil to reduce the influence of internal and external heat source on machine precision. Zhao [4] applied the temperature control system and a relevant control algorithm to enable the maintenance of a constant temperature in the confined space that surrounds the machine tool. This allowed the machine tools to maintain a higher processing accuracy. Both the forementioned approaches were easy to implement on the small-sized machine tool but inapplicable to the large-sized machine tool. The effect of the ambient temperature on the thermal error of the large-sized machine tool was greater when compared with the small and medium-sized machine tools [5]. Thus, it is important to investigate the influence of the environmental temperature on the precision of machine tools. The previously discussed approaches also require relatively high costs to control the thermal error through the machine tool derived ambient temperature.

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Software compensation is another effective approach to reduce the thermal error of the machine tools. The next paragraph discusses relevant research that investigated the application of software compensation in controlling the influence on the thermal error of the environmental temperature.

Researchers have recognized that the environmental temperature has a significant impact on the thermal error of the machine tool. The environmental temperature was chosen as a system input variable [6–8] in the modeling of thermal error. Mian et al. conducted a series of works [9,10] on the numerical simulation of thermal error. They explained both the influence of internal heat source and the environmental temperature. The effect of environmental temperature on the thermal error model of the machine tool was explored based on FEA in literature [11]. The effects of the diurnal temperature and the seasonal temperature change on the thermal error were specified, thereby reducing the measuring time for thermal error modeling. Gomez-Acedo [12] considered the environment temperature, the spindle speed and the spindle box temperature as input variables in building the multivariate state space thermal error model. The model revealed that the workshop temperature change was a major influential factor. In this paper, a model was implemented abased on the heat conduction mechanism, which overcame the disadvantage of the long measurement period for the traditional machine tool under the environmental temperature.

The thermal error model built by researchers based on the above modeling approaches, only accounted for the environmental temperature as a variable. It failed to analyze the role of the environmental temperature on the thermal error in detail. This problem requires an in-depth investigation. Rakuff [13] object calculated the temperature of the machine tool by using a heat transfer differential equation with lumped heat capacity. In order to solve the differential equation, the environmental temperature was imitated by the sine function. This may result in a considerable calculation error. The thermal time constant of the machine tool system was recognized by the temperature step signal response. The approach was verified by an experiment that was carried on a diamond turning machine. Tan [14] proposed a thermal error model by considering the environmental temperature. In this model, the temperature of the machine tool was calculated by a lumped heat transfer equation. Then, the measured environmental temperature series was fitted with the Fourier series. This was followed by solving the coefficient of Fourier series through the least square method. Finally, the environmental temperature described in the Fourier series served as an input for calculating the temperature of the machine tool through a differential equation. As the Fourier series described the environment temperature, the approach had a higher precision than that of the Rakuff approach. However, the real-time application may be less effective as the solutions of the Fourier coefficient and the differential equation with Fourier series are more complicated.

Pseudo-hysteresis between temperature and thermal deformation may affect the accuracy of the thermal error model. A dynamic model was mainly employed to reduce the effect of pseudo-hysteresis [15]. Hence, the typical dynamic model, i.e., the transform function model, was widely used by several researchers [16,17]. The thermal error transform function model was created based on the temperature and thermal deformation data. It was experimentally verified on a real machine tool. The results indicated that the transform function model was more robust and portable than the polynomial model. It is necessary to estimate the structure or the order of the transform function and then determine the parameters. This is a time consuming process and thus constitutes a major drawback of the above-mentioned methods.

The above researches provided several useful references for the thermal error modeling of the machine tool under the environmental temperature. However, each approach has its own characteristics, making it difficult for researchers to understand and utilize these approaches. This paper proposes a more versatile and general approach to obtain the thermal error transfer function of each object of the machine tool based on the heat transfer mechanism. Based on the assembly dimension chain principle, all the objects of the machine tool influenced by the thermal error were chosen as constitution loops. The unknown thermal error of motion axis was selected as a closed loop. Thus, the thermal error dimension chain is completed. The thermal error transfer function of the whole machine is obtained on the basis of the dimension chain relationships. The thermal error transfer function is used to analyze the deformation rules of the machine tool under the time-varying environmental temperature. Because of the established heat transfer function, the thermal error characteristics of the machine tool can be studied with time domain and frequency domain methods. This study enables researchers to acquire a thorough understanding of the change law of the thermal error of the machine tool under the time-varying environmental temperature.

2. The establishment of the thermal error transfer function

In the study of the object transient heat transfer function issue, the change law [18] of the object temperature was obtained by the lumped heat capacity method. The internal temperature gradient of objects was not considered. The lumped capacity heat transfer differential equation is given by:

$$-hA_s(T_b - T_e) = \rho Vc\frac{dT_b}{dt} \tag{1}$$

where T_b is the object temperature; T_e is the outside environmental temperature; h is the convective heat transfer coefficient of the object surface; A_s is the effective convective heat transfer area of the object; ρ is the material density; V is the object volume; and c is the material specific heat capacity.

The solution of Eq. (1) is given by:

$$T_b = T_e - (T_e - T_0)\exp\left[\left(\frac{-hA_s}{\rho VC}\right)t\right] \tag{2}$$

where: T_0 is the initial temperature of the object.

By using Eq. (2), the object temperature can be obtained based on the environmental temperature. However, the equation cannot reflect certain characteristics of the object under the thermal environment, and T_e is generally a constant quantity. In order to further investigate the thermal characteristics of the object under the time-varying condition, T_e is assumed to be a variable. Also, $\tau = \frac{\rho Vc}{hA_s}$ (τ has time dimension), is called the thermal time constant. It reflects the change in the speed of the object with respect to the outside environmental temperature. Hence, Eq. (1) can be rewritten as follows:

$$\tau\frac{dT_b}{dt} + T_b = T_e \tag{3}$$

Setting a certain temperature as the reference state acted as the system zero reference point. For example, 20 °C could be taken as a zero reference point. The output and input transfer function can be deduced using Laplace transform of Eq. (3) as follows:

$$G_{T_b - T_e}(s) = \frac{T_b(s)}{T_e(s)} = \frac{1}{\tau s + 1} \tag{4}$$

Eq. (4) is called the temperature transfer function. The differential equation is converted to algebraic equation of complex field based on the above Laplace transform. This saved a considerable amount of time spent in calculating the solution. It also had the obvious physical significance of the frequency characteristic derived by the transfer function. Therefore, use of the transfer function and frequency characteristics makes it convenient to analyze,