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A thermal error model for large machine tools that considers environmental thermal hysteresis effects

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ABSTRACT

Environmental temperature has an enormous influence on large machine tools with regards to thermal deformation, which is different from the effect on ordinary-sized machine tools. The thermal deformation has hysteresis effects due to environmental temperature, and the hysteresis time fluctuates with seasonal weather. This paper focused on the hysteresis nonlinear characteristic, analyzing the thermal effect caused by external heat sources. Fourier synthesis, time series analysis and the Newton cooling law were combined to build a time-varying analytical model between environmental temperature and the corresponding thermal error for a large machine tool. A multiple linear regression model based on the least squares principle was used to model the internal heat source effects simultaneously. The two models were united to make up a synthetic thermal error prediction model called the environmental temperature consideration prediction model (ETCP model). A series of experiments were performed using a large gantry type machine tool to verify the accuracy and efficiency of the predicted model under random environments, random times and random machining conditions throughout an entire year. The proposed model showed high robustness and universality, with over 85% thermal error, with up to 0.2 mm was predicted. The mathematical model was easily integrated into the NC system and could greatly reduce the thermal error of large machine tools under ordinary workshop conditions, especially for long-period cycle machining.

1. Introduction

Machine tools are susceptible to exogenous influences, which are primarily derived from varying environmental conditions, such as day and night or seasonal transitions, when the temperature is not controlled and large temperature swings can occur [1]. Large machine tools are particularly susceptible because it is impractical to keep them at constant room temperature, and even maintaining a constant temperature of their structure is difficult [2]. Varying environmental temperatures cause heat to flow through the machine structure, which results in non-linear deformation whether the machine is in operation or in a static mode. This environmentally stimulated heating combines with internally generated heat, resulting in a significant increase in thermal error, especially when a large machine tool is operated for long-term regimes [1].

Changing environmental temperatures cause thermal drift even if the spindle is running [4]. Until now, the thermal error of the main spindle and feed shaft has been the focus of research, without considering the hysteresis influence of environmental temperature changes [5]. Numerous thermal error models have revealed the relationship between the thermal error and the temperature from a few different perspectives [6,8,9,11,12], but seldom has an exact mathematical model been built with high accuracy and robustness including environmental temperature, which is more important for large machine tools and seriously prevents the widespread application of the thermal error compensation.

Past experiences prove that environmental influences cannot be neglected [14]. The importance of environmental temperature

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variation was recently acknowledged. Thermal errors in a machine tool are determined by not only the current thermal environment but also the previous thermal status of the machine tool. The previous environmental memorizing characteristics are called hysteresis effects, the hysteresis phenomenon is the major factor causing the low robustness of the static modeling approach [17]. Brecher C. described a compensation approach with one environmental temperature sensor and internal operational information. The parameters of the time delay elements were determined by a systematic calibration procedure. Practical experiments showed that with this elementary method, a reduction in the thermo-elastic displacements of more than 80% of the initial value was possible [8]. Jedrzejewski et al. noted that the temperature of a machine tool changed with a certain delay relative to variation in the ambient temperature. The application of ambient temperature hysteresis allows for a more accurate prediction of thermal error [18].

Thermal effects on large machine tools are usually long-term effects, with environmental influences generally leading to slow changes in machine tool temperatures that affect the entire volumetric performance [15]. Mian NS et al. [3] developed an offline technique using FEA to simulate the effects of the major internal heat sources of a small vertical milling machine and the effects of ambient temperature pockets that build up during the machine operation. The simulation results closely matched the experimental results because of the consideration of environmental temperature fluctuation. E. Creighton [16] presented a high-speed micro-milling spindle displacement compensation scheme based on the exponential growth model. Ambient conditions were not accounted for in the model, but the intermittent tool length checks along with the use of the development scheme helped to reduce the errors due to ambient conditions. The result proved the importance of the environmental temperature effect.

However, experiments and investigations have also indicated that the environmental hysteresis effect varies with seasonal weather temperature. Existing hysteresis effect analyses are insufficient for long-term application under random conditions, especially for large machine tools with bigger volumes, longer strokes and heavier cutting loads.

This paper focuses on the mapping relation between the environmental temperature and the corresponding thermal error. The frequency characteristic, the periodicity of the environmental temperature and the non-linear hysteresis response of the machine tool is discussed, and the proposed methodology is put forward in Section 2. A mathematical mapping function between the environmental temperature and the thermal error is modeled in Section 3. The environmental temperature consideration prediction model (ETCP model) is identified and its robustness and accuracy are experimentally proven in Section 4 in comparison with the multiple regression analysis (MRA) method. The modeling characteristics and the conclusion are discussed in Section 5.

2. Thermal effect analysis and modeling method proposal

2.1. Periodicity characteristics of the environmental temperature

The machine shop temperature fluctuates similarly to the outdoor atmospheric temperatures, but it varies more slowly, with hysteresis in the time-domain and proportionality in the response amplitude relative to those of the outdoors, which is of daily periodicity, annual periodicity and aperiodicity character simultaneously [4]. Fig. 1a displays a set of continuous environmental temperature data for 20 days in April in a workshop where an XK2650 large gantry type machine tool is located. The measured temperature (Fig. 1b) shows obvious daily periodicity. The amplitude spectrum in Fig. 1c with a Fourier transform revealed that the peak energy focuses on the equivalence base frequency of daily periodicity (shown at 'A') and doubling frequency (shown at 'B') but is faint at the tripling frequency (shown at 'C') and higher frequencies. Fig. 1c also shows the apparent slow varying trend term at the lower frequency (shown at 'D'), which was irregular and resulted from varying atmosphere aperiodicity.

2.2. Thermal hysteresis effects

The hysteresis time between the environmental temperature and the corresponding thermal deformation changes with climate and seasonal weather. Fig. 2 shows a typical hysteresis effect in summer and in winter at a downtime measurement for the large gantry machine tool. The ambient temperature changed over a range of 3–5 °C, and the thermal deformation in the X direction reached 0.1–0.2 mm under varying weather conditions. In the summer, under higher temperatures, the hysteresis time was approximately 120 min. The machine shop experienced its lowest environmental temperature at approximately 6:20 in the morning. In the winter, when temperatures are low, the hysteresis time was approximately 90 min,and the lowest temperature appeared at approximately 7:20 in the morning. These results make sense because hysteresis time is related to the surface convective heat transfer coefficient, which is a function of the air heat conductivity coefficient, whereas the conductivity coefficient varies with the air temperature.

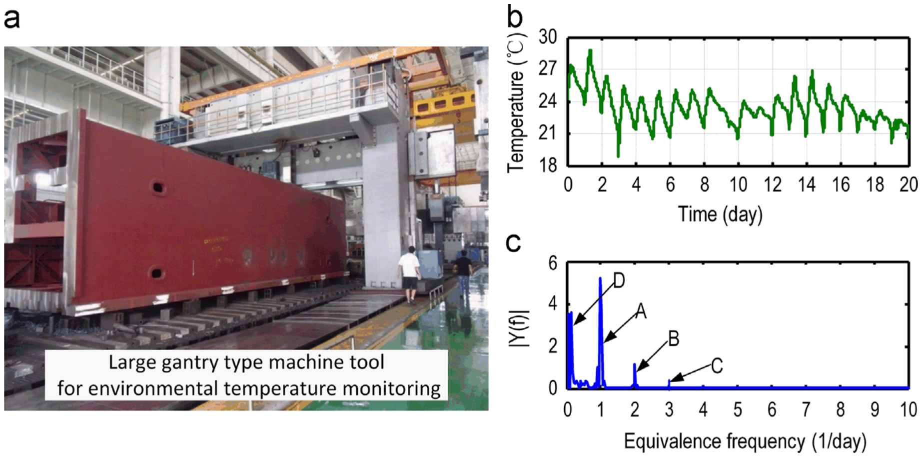

Fig. 1. Periodicity characteristics of environmental temperature.