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Original Research Article

Thermal effect on the dynamic error of a high-precision worktable

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ABSTRACT

This paper investigates the thermal effect on the dynamic error of a high-precision machine worktable during operation. The thermo-mechanical model was established to obtain the motion errors of the worktable by considering the combined effects of varying internal heat sources and external thermal drifts. The temperature tests were performed to obtain the initial conditions of the model and provide a verification for the analytical convection coefficients and heat flux, which were obtained by inverse analysis. The predicted yawing errors of the worktable were confirmed by interferometer tests. Numerical and experimental results suggest that the environmental temperature fluctuation is the largest contributor to the motion errors of the worktable, and they increase with the increasing of environmental temperature. This study allows deeper insights into the underlying mechanisms that result in the motion accuracy variations of the worktable due to the thermal effects, which can provide a strategy for manufacture to further compensate the thermal error and realize ultra precision.

1. Introduction

With the rapid development of advanced manufacturing, the demand for accuracy of the worktable is increasingly high in precision machining field. Thermally induced errors are one of the principal factors among those that degrade dynamic performance of the worktable in machine tools [1]. Thermal error can never be completely avoided even on well-designed machines, but it can be controlled to a certain degree. Therefore, identifying and understanding how the thermal state of the worktable affects its kinematic accuracy is essential for further reducing or compensating the thermally induced motion errors which include translation error and rotation error.

In practical engineering, the internally generated heat and environmental thermal drifts exposes machine tool to complex temperature fields. As a result, the dynamic error of the worktable changes with time and axis positions. Many researches adopted finite element (FE) method to analyze the thermal behavior of the machine tool elements, which was proven to be efficient in identifying the thermal error

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components and their magnitudes [1–12]. However, the existing structure thermal performance numerical models mainly focus on the effect of internally generated heat with thermal dissipation boundary conditions [3–11], rarely considering the influences from external heat source fluctuations. Rakuff and Beaudet [12] stressed the importance and effect of the external thermal drifts in cutting process, and suggested the provision of temperature controlled enclosures for the machine to improve the machining accuracy. Mian et al. [13] quantified the significantly varying thermal error of a machine tool with environmental thermal fluctuations, which was induced by day and night changes or seasonal transitions, and the results were validated by long period tests. Hence, in order to accurately identify, predict and compensate the thermal error in a machine tool unit, the external heat source should be regarded as equally important as internal heat sources.

The study of thermo-mechanical effect on the dynamic behavior of modern high-precision worktable simultaneously considering the combined heat source of internally generated heat and environmental temperature variation appears to be rare. In view of all this, this paper presents a thermo-mechanical FE model to quantitatively reveal the underlying mechanism of how the dynamic behavior of the worktable is influenced by the combined effects of internal and external varying heat sources and nonlinear contacts between the machine elements, which has not been investigated in previous studies. The worktable-bed-linear guide assembly was included in the model to avoid the worktable isolated from the whole assembly system. The temperature tests were performed to obtain the initial conditions of the model and provide a verification for analytical convection coefficients and heat flux. As a validation of the model, the predicted yawing error of the worktable was confirmed by interferometer tests.

2. Thermo-mechanical modeling

2.1. Structural model

Fig. 1 shows the CAD model of worktable-bed-linear guide assembly. The worktable is fixed on a sliding board, which is driven by an attached linear motor in the feed direction, and the motor stator is bolted on a mineral casting bed. The linear rolling guide system is used to provide the slide support for the motion unit. The whole assembly is high-constrained structures, thermo-symmetric design is employed for all the components to minimize the effect of thermal deformation produced by other elements. Here, the bed is cast into a cavity structure, which results in the considerable mass reduction and economic benefit, but it also increases the complexity of the thermal deformation of the whole structure under non-homogeneous temperature fields.

2.2. Thermo-mechanical modeling

This paper presents a transient impact FE model to quantify thermo-mechanical effect on the motion errors of the worktable during operation, and the mesh of the assembly components is shown in Fig. 2. The model considers the combined effects of internal and external heat sources, nonlinear contact and surface convection of the structure, and they are described as follows.

2.3. Heat source

The main heat sources existed in a machine tool could be divided into two types: internal and external heat sources. The three important internal heat sources are: heat from drive motors and cooling units, frictional heat in bearings, and machining process heat. In this work, the cooling unit was placed outside the assembly, so the heat from it was ignored in the numerical simulation. In addition, the machining process was not included in this study, so there was no consideration of machining heat. The external heat source mainly comes from the variation in ambient temperature. Note that such variation always occurs even in the temperature controlled shop floor.

In practical engineering, the frictional heat generated in the modern linear rolling guides is limited due to the low friction contact. However, such heat generation will be significant and cannot be neglected when the operating condition is heavy. Here, the friction heat generated at the contact rolling interfaces between the balls and raceways is replaced by heat

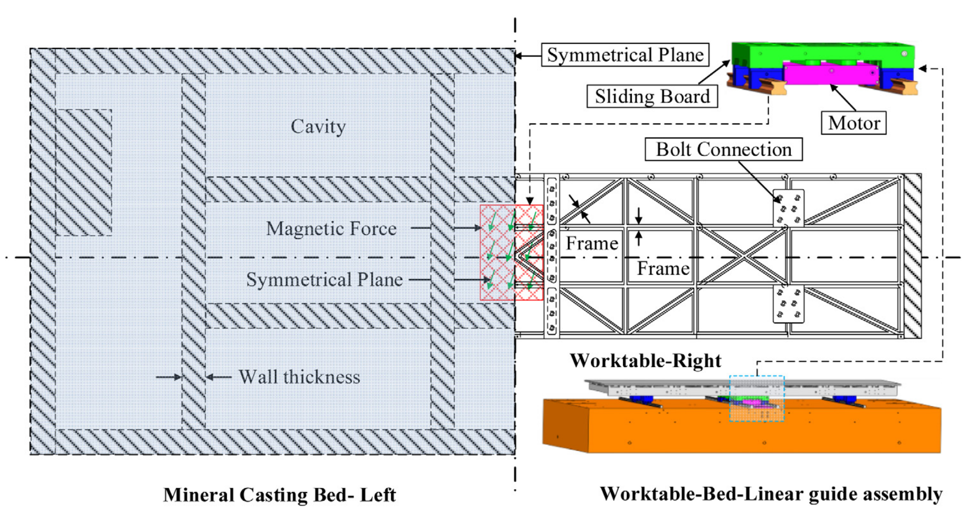

Fig. 1 – The components of worktable-bed-linear guide assembly.