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Investigation into effect of thermal expansion on thermally induced error of ball screw feed drive system of precision machine tools

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ABSTRACT

In order to investigate the effect of thermal expansion on the ball screw feed drive system of a precision boring machine tool, theoretical modeling of and experimental study on thermally induced error along with heat generation characteristics are focused in this paper. A series of thermal experiments are conducted on the machine tool to measure and collect the thermodynamic data with the feed drive system operating at different speeds. Based on the heat generation and transfer analysis of ball screw system, thermal expansion of screw shaft in the axial direction is modeled mathematically. Relationships between the thermal error and axial elongation are established to characterize the thermal error distribution considering the thermal expansion coefficient as a temperature-variant parameter. It turns out that the thermal error varies with different working positions through the ball screw length and working time nonlinearly, and there definitely exists certain transform from the thermal expansion to the thermal error obtained by measurement. In addition, regression analysis is employed to carry out the theoretical modeling of thermal error with the temperature data of the critical heat generation points. The relations between temperature rise and thermal error are formulated directly while taking the thermal expansion as an implicit variable. Experiments under a different condition are preformed and the proposed methods for thermal error modeling prove to be effective and accurate enough to be used in the machining process as well.

1. Introduction

Machine tools and their components are sensitive to temperature change that could exert an influence on mechanical structure deformation thereby inducing thermal error of motion drive systems. As a result, it reduces the geometrical and machining accuracy. It is proved previously that thermal errors account for up to 75% of the overall geometrical errors of machined work pieces in precision machining [1]. Therefore, this topic is specially focused in recent research activities.

Of all factors that contribute to the thermal error of a machine tool, thermal error of ball screw system plays a very important role. In the past decades, research has been conducted to minimize the thermal effects on the machining accuracy especially for precision CNC machine tools, including error measurement, modeling, prediction and heat generation reduction. In order to investigate the thermal effect, theoretical modeling and analysis based on numerical simulation are frequently performed. Kim estimated the two dimensional temperature distributions of a ball screw system at various moving speeds by finite element method [2]. However, it is on assumptions that temperature distribution on the ball screw shaft is uniform and frictional heat generation from the nut and bearings is a constant value, turning out to be an inexact method. X Ming developed an integrated thermal model by the aid of the finite-element method to analyze the temperature distribution of a ball screw feed drive system, considering the thermal contact resistance between the bearing and its housing [3]. Ahn formulated the heat transfer problems of the ball screw system and designed an observer to estimate the whole temperature field [4]. Otakar carried out a closed loop finite element analysis of ball screw drive system and developed numerical models to confirm the influence of bearing preload on thermal stability of the ball screw drive system [5]. As a well-known behavior of metallic materials, temperature change of the ball screw system usually leads to deformation of the metallic components while thermal expansion caused by heat generation adversely affects the machining precision. Wu analyzed the relationship between temperature increase and thermal deformation of a ball screw feed drive system, and estimated the strength of the heat source with the measured temperature profile by inverse analysis [6]. Huang selected front bearing, nut and back bearing as

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independent variables and used multiple regression method to analyze the thermal deformation of a ball screw feed drive system [7], but the ambient temperature definitely has a close relation with heat convection of such a long slender screw shaft.

Error compensation is the final objective of thermal research work, and various compensation methods are proposed by researchers. Wu developed a new technique to reduce the error by detecting the thermal expansion and sending a feedback to the microprocessor after calculation based on the mathematical models built in advance [8]. Hsieh presented a control scheme for a mechanically coupled dual ball screw system to decrease the positioning error resulted under the actual working conditions [9]. Although thermal expansion is concerned in such research, the thermal expansion coefficient of the screw shaft is often taken as a constant, which rarely proved to be the case.

On the other hand, researchers have been taking great efforts on balancing the heat generation of the feed drive systems. Xu designed an air cooling ball screw system to avoid thermal errors and evaluated the thermal error. In this way, the feed drive system can achieve thermal equilibrium faster and reduce the peak temperature rise effectively [10]. Yang applied the computational approach to estimate the influence of cooling conditions on thermal deformation and indicated that the positioning accuracy can be improved through some effective cooling countermeasures [11]. Yongping developed a cooling device and incorporated into the ball screw drive system to cool the high speed units down [12]. These studies mainly pay attention to practicing the effective cooling methods instead of investigation into the thermal deformation mechanism of the screw shaft.

It can be seen from the previous research that thermal issues in ball screw system are somewhat complicated and difficult to obtain an exact solution. Numerical computation based simulation accompanied by measurement is a very effective way to address the thermal issues of feed drive systems. However, many related studies have failed in exploring deeper into the relationships between heat generation, thermal expansion and the resultant thermal errors although it is rarely easy to build an accurate mathematical model incorporating the uncertainties existing in heat transfer. Therefore, modeling of thermal behavior of ball screw system plays a very important role in improving the positing accuracy of feed drive systems.

In this paper, based on a precision boring machine tool we measured and modeled the thermal characteristics of its ball screw feed drive system. Heat generation and transfer of the ball screw system are investigated based on mathematical analysis. Thermal elongation of screw shaft is estimated with thermal expansion definition based calculation and regression analysis requiring the collection of the critical temperature variables. In addition, the established models and the modeling method are verified by experiments under a different working condition.

2. Heat generation and thermal equilibrium

As is well known heat generation is the root of temperature rise and thermal deformation of the ball screw system, which consequently leads to thermal error. So the heat transfer process of the feed drive system as a whole should be analyzed before we explore deep into the thermal expansion effect. Certain assumptions are made as follows to simplify the problems: (1) temperature distribution in the radial direction of the screw shaft is uniform; (2) grooves on the screw shaft surface are negligible to take the ball screw as a solid round rod; (3) thermal resistances induced by interfaces between the mechanical parts are not exerting influences on the results; (4) heat diffusion through lubrication is negligible.

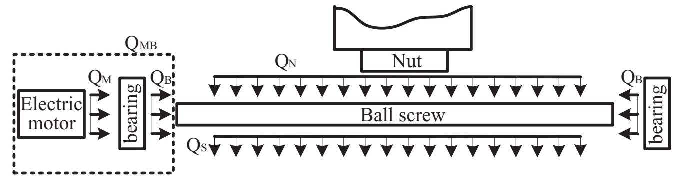

Fig. 1. Schematic of heat generation of a ball screw system.

2.1. Heat generation

Heat is generated by driving and driven parts in an electromechanical system acting as energy loss. The typical heat sources of the ball screw drive system mainly consist of electric motor, bearings and nut, as shown in Fig. 1. The heat generation of electric motor depends on its energy efficiency while those of bearing and nut arise from the frictions between moving parts.

The amount of heat generated by an electric motor is approximately expressed in terms of its input and output power as

$$Q_M = P_{in} - P_{out} \tag{1}$$

where Q_M is the heat generation rate of electric motor, P_{in} is the electric power input into the electric motor and can be obtained by the product of voltage and current, P_{out} is the mechanical power output by the electric motor in the form of torque and rotation. All input and output parameters are easy to know for estimating the heat generation.

The major heat generation of the bearings is caused by the friction between the balls and the races [13]. This heat can be defined as

$$Q_B = 1.047 \times 10^{-4}\ \mathrm{nM} \tag{2}$$

where Q_B is the heat generation rate, M is the total frictional torque of the bearing and n is the rotational speed.

Heat generation by the ball screw nut arises mainly from the friction between the balls and the grooves of screw and nut, which can be defined [14,15] as

$$Q_N = 0.12\pi f_0 \nu_0 n M \tag{3}$$

where Q_N is the heat generation rate of the nut, f_0 is the coefficient related to nut type and lubrication method, and ν_0 is the kinematic viscosity of the lubricant.

Although the nut length in the axial direction is much shorter than ball screw shaft, the generated heat is taken as almost applied uniformly along the shaft surface due to its continuous reciprocating motion.

2.2. Heat transfer

2.2.1. Energy change of system

Considering the ball screw drive system as a whole, according to energy conservation law we have

$$Q_H = Q_C + Q_R + cm\Delta T/\Delta t \tag{4}$$

where Q_H is the overall heat generated, $Q_H = Q_M + Q_B + Q_N$, Q_C is the heat loss by convection, Q_R is the heat loss by radiation, and $cm\Delta T/\Delta t$ is the rate of increase in internal energy.

The convective heat transfer can be written as

$$Q_C = h_C A_C (T - T_0) \tag{5}$$

where h_C is the convective heat transfer coefficient, A_C is the surface of the body, T is the temperature of the body, is the temperature of air adjacent to the surface.

The radiative heat transfer can be written as