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Estimating time-varying heat sources in a high speed spindle based on two measurement temperatures

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ABSTRACT

Combined the finite element model and the conjugate gradient method, this article presents an inverse method to estimate time-varying heat sources in a high speed spindle based on experimental temperatures of housing surface. An experimental setup and process to measure temperatures for inversely predicting heat generation sources in high speed spindle and validating inverse results are developed. Two measured temperatures are used to estimate two unknown heat generation sources for constant and time-varying spindle speeds. Two other measured temperatures are utilized to validate the inverse results. Results show that the estimated temperatures correlate well with the measured data, and also that the heat generation prediction is satisfactory. In addition, temperatures from the proposed inverse method are consistent with measured temperatures at the verification points. It can be concluded that the proposed inverse method is a promising method for determining heat sources in the heat transfer of complicated structures with different materials.

1. Introduction

During the working process, precision and productivity of machine tools decline due to overheating. Thermal error may account for 40–70% of total machine tool errors [1–3]. Thermal errors usually result from the effects of internal heat sources (heat generated from bearings, an inside motor, cutting process, the cooling system, etc.) and external heat sources (environmental temperature variations, solar and personal radiation) [4–6]. The high speed spindle is one of the most significant internal heat sources and is a key component of machine tools [7]. In a conventional spindle, the heat source is generated by bearings, which account for 30–50% of total spindle deformations [8]. In addition, preload and stiffness of the high speed spindle bearing are nonlinearly changed under thermal effects and they further affect the accuracy, dynamic behavior and working life of the spindle [9]. Therefore, estimating heat sources and temperature distribution in the high speed spindle is very important; it is necessary to control and compensate for thermal error in the high speed spindle as well as the entire machine tool.

In recent years, numerical analysis methods such as the finite element (FE) method, finite different method, finite different element method and the thermal resistance network have been used to analyze the distribution of the temperature fields and variation of thermal deformation of machine tools. To construct a thermal model of the spindle, heat sources, heat sinks and convective coefficients must be determined. A formula for calculating heat source value was established by Palmgren [10] and improved by Harris [11]. The formula has achieved popular acceptance as an accurate method. FE method was employed to construct the thermal model of a high speed spindle [7,12–15]. In these researches, the magnitude of the heat sources and convection coefficients were calculated and put to FE model for thermal loading and boundary condition, respectively. A steady or transient state temperature of the spindle was obtained and validated by experimental temperatures. Based on the computation of heat generation and heat transfer coefficients, a finite difference thermal model of a motorized milling spindle was developed to predict spindle steady and transient state temperatures [16]. The results were verified by tests under different spindle speeds. Liu et al. [17] have established a thermal resistance network model of a spindle bearing-bearing pedestal to characterize temperature distribution in motorized spindle system parts. Their model reveals a small

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Nomenclature

A	nominal contact area (m^2)
a,b	semi-axis of the ellipse contact area (m)
C	thermal contact conductance ($W/m^2\ ^\circ C$)
$C_p(T)$	specific heat ($J/kg\ ^\circ C$)
E	elastic modulus (Pa)
g	gravitational acceleration, $9.8m/s^2$
H	hardness of the softer material (HB)
h	convection heat transfer coefficient ($W/m^2\ ^\circ C$)
J	object function
$\nabla \mathbf{J}$	gradient of object function
k_e	equivalent thermal conductivity of air ($W/m\ ^\circ C$)
$k(T)$	thermal conductivity ($W/m\ ^\circ C$)
M	number of measurement points
$\overline{Nu}$	average Nusselt number
$\overrightarrow{\mathbf{P}}$	search direction
p	contact pressure (Pa)
Pr	Prandtl number, $Pr = \nu_{air}/\alpha_{air}$
$q(t)$	heat generation (W)
q_c	total heat flow (W)
q_{out}	dissipated heat by convection (W)
R	thermal contact resistance ($m^2\ ^\circ C/W$)
$\mathrm{Ra_D}$	Rayleigh number
Re	Reynolds number, $Re = \omega d^2/(2\nu_{air})$
r^k	conjugation coefficient
S	surface area (m^2)
t	time (s)
t_f	final time (s)
$T(x,z,t)$	temperature (°C)
(x,z)	coordinate axis
$\overrightarrow{\mathbf{w}}$	unknown vector

Greek symbols

α	thermal diffusivity of air (m^2/s)
β	search step size
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
σ	standard deviation of measurement error (°C)
σ_R	Gaussian surface roughness
υ	Poisson's ratio
ω	angular velocity (rad/s)
ϖ	random variable with normal distribution

Superscripts

k	value of last iteration

Subscripts

air	properties for air
ball	properties for ball
m	measurement point
ring	properties for ring
∞	properties for ambient temperature

difference compared to the ANSYS Workbench simulation and experimental temperatures. The mentioned reviews show that determining heat generation value is one of the most important tasks in predicting the spindle temperature field using a numerical analysis method. These values are usually calculated based on empirical formulae.

Currently, the inverse method is a useful tool in general engineering as well as in particular heat transfer problems. Fraser et al. [18] developed a real-time method for estimating transient heat input to machine tool structures. The solution of the inverse thermal problem is carried out in the form of a convolution integral of the thermal transfer function and the measured temperatures at two points near the heat source. The authors illustrate some cases with and without random temperature measurement errors based on an FE model of a three-dimensional structure. In addition, experimental verification of their method was performed [19]. A three-dimensional inverse heat conduction problem for determining the time-dependent heat flux generated in the high speed electric motor was developed by Huang and Lo [20]. In their work, the steepest descent method and a general purpose commercial code CFX4.4 were applied to establish an inverse algorithm. Two different functional forms for heat fluxes with different temperature measurement errors were used in the numerical analysis to validate the inverse algorithm. This inverse algorithm was further applied to estimate the applied heat flux of titanium drilling [21]. Both simulated and experimental temperatures were used to estimate the heat flux of the drilling process. Samadi et al. [22] estimated the transient heat flux imposed on the rake face of a cutting tool by combining a sequential function specification method and mechanical ANSYS parametric design langue (MAPDL). Duda [23] also employed ANSYS for solving transient multidimensional inverse heat transfer problems. His method can be applied to complex-shape-bodies with temperature-dependent thermophysical properties. Numerical examples of transient heat conduction and radiation were presented to demonstrate his method. Wang and his coworkers [24,25] combined the inverse algorithm and finite element method to predict heat flux boundary conditions, heat generation, temperature boundary conditions and root temperatures on the various shaped fins. In addition, an inverse BFGS method combined with a simple step method without solving the sensitivity problem was presented by Ngo et al. [26] for estimating interface temperature, heat generation and convection heat transfer coefficients in the welding process. The parameter controlling the alloy solidification was estimated through inverse method that used the gradient method to minimize the least squares criterion [27]. The method was implemented for the recurrent fragment of steel casting. Huang et al. [28] applied the inverse method for determining heat generation and range of heat distribution in 2-D ultrasonic seam-welding problems. Their method accurately predicts unknown heat generation and temperatures at the welding interface where they cannot directly measured. Wang et al. [29] presented an inverse method to reconstruct the heat flux produced by bone grinding tools. They used experimental data incorporated with an inverse heat transfer method to mathematically estimate time-varying the heat flux distribution. On the whole, the inverse method has been successfully applied to estimating heat sources as well as heat transfer coefficients in many heat transfer problems. The inverse algorithm, which combines an optimization method and commercial software, is also widely used in the inverse field.

In this article, the time-varying heat sources in a high speed spindle under various working condition are estimated by using the inverse method based on two measured temperature. An experimental setup and process to measure temperatures on the spindle at several points are presented. The method to determine the heat transfer coefficients used in the FE model and the inverse procedure are given in detail. Two measured temperatures on spindle housing surface closed the bearings are employed to predict the