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An inverse method for estimating heat sources in a high speed spindle

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HIGHLIGHTS

- Time-varying heat sources in a spindle are estimated by using an inverse method.
- The inverse method is established by a combination of CGM and ANSYS software.
- The heat sources are accurately estimate based on only two measured temperatures.
- Inverse results agree well with given solutions even involved measurement noise.

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ABSTRACT

This article presents an inverse method for estimating time-varying heat sources in a high speed spindle under various working conditions. The method is established by developing a numerical code combining the mechanical ANSYS parametric design language and the conjugate gradient method. The proposed method features a high efficiency solution to direct and inverse problems. It requires a small number of iterations for the computational algorithm, while provides excellent accuracy in temperature and heat source estimations. Computational time is also taken into account through choosing the best form of conjugation coefficient as well as mesh size. Results show that based on only two measurement points, the proposed method can accurately obtain inverse results that agree well with exact solutions even if measurement noise is involved. These results also indicate that the proposed method has a strong potential for estimating the heat sources in a complex structure which is combined different materials.

1. Introduction

The high speed spindle (HSS) is an important component in machine tools popularly employed in engineering and various other industries. Numerous researches have directed considerable attention to improving the precision of the HSS as well as other machine tools. In these researches, thermal influence on the HSS has emerged as an important field and is interesting many researchers. Thermal induced errors account for more than 50% of the total error of a machine tool [1]. When the spindle starts to run, bearings inside the spindle generate friction at the interface of the balls and raceways; this friction induces heat and further increases the temperature of the spindle. The increased temperature causes nonlinear thermal effects on high speed spindle bearings [2] and further affects the accuracy, dynamic behavior and working life of the HSS. For a conventional spindle, the main heat source is the bearings. Palmgren [3] presented an empirical formula for estimating total bearing friction torque which is used in calculating bearing heat generation. His model is considered to be accurate. Harris [4] designed a quasi-static model of a high speed and then added the spinning friction moments to Palmgren's formula to further presented a new formulation for calculating heat generation of bearings [5]. The two models are popular formula for determining bearing friction torque and bearing heat generation.

Jin et al. [6] proposed an analytical approach to calculating the heat generation rate of the supporting bearing of the ball-screw system in machine tools. Moorthy and Raja [7] introduced an improved analytical model for estimating heat generation in an angular contact ball bearing. Based on heat generation in the bearing model [3–5], they considered the change in diameter clearance after assembly and during operation owing to thermal expansion of bearing parts. Some previous studies had tried to measure friction torque to compute the heat generation of a bearing. Bossmanns and Tu [8] established a test to find an empirical formula,

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Nomenclature

A	nominal contact area (m^2)
a, b	semi-axis of the ellipse contact area (m)
E	equivalent elastic modulus, $E = 2\left[1 - \upsilon_1^2/E_1 + 1 - \upsilon_2^2/E_2\right]^{-1}$
g	gravitational acceleration, 9.8 m/s^2
H	hardness of the softer material between two parts
h	convective heat transfer coefficient ($W/m^2\,°C$)
k_e	equivalent thermal conductivity of air (W/m °C)
k	equivalent thermal conductivity, $k = 2k_1k_2/(k_1 + k_2)$
$\overline{Nu}$	average Nusselt number
p	contact pressure (Pa)
Pr	Prandtl number, $Pr = v_{air}/\alpha_{air}$
$q(t)$	heat generation (W)
q_{out}	dissipated heat by convection (W)
Ra_D	Rayleigh number
Re	Reynolds number, $Re = \omega d^2/(2v_{air})$
r_m	mean radius, $r_m = (r_i + r_o)/2$
Δr	the annulus gap, $\Delta r = r_o - r_i$
S	surface area (m^2)
t	time (s)
t_f	final time (s)
$T(x, z, t)$	temperature (°C)
(x, z)	coordinate axis
$\vec{\mathbf{w}}$	unknown vector

Greek symbols

α	thermal diffusivity of air (m^2/s)
β	search step size
v	kinematic viscosity (mm^2/s)
ρ	density (kg/m^3)
σ	standard deviation of measurement error (°C)
σ_R	Gaussian surface roughness, $\sigma_R = 1.25(\sigma_{R1}^2 + \sigma_{R2}^2)^{0.5}$
υ	Poisson's ratio
ω	angular velocity (rad/s)
ϖ	random variable with normal distribution

Subscripts

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

which is function of speed and bearing preload for frictional torque and the resultant heat generation in bearing. In the thermo-mechanical model of a spindle, the friction in bearings was measured by monitoring the passive torque on an experimental test rig [9]. Friction was expressed as an empirical function of speed, preload, kinematic viscosity of the lubricant and bearing parameters. However, the formula only applies to the investigated spindle. For other spindles, the testing procedures must be repeated. Moreover, different numbers of bearings, bearing configurations and fluctuations of speed during spindle working were not considered. A review of pertinent literature shows that no researchers have investigated heat generation in the spindle-bearing using the inverse heat transfer method.

Interest has grown in the theory and application of inverse heat transfer problems as they are encountered in almost every branch of science and engineering [10]. The inverse method is applied to estimate temperature, heat generation, parameters, etc. which are far from easy to direct measure or calculate. Inverse algorithm and finite element methods were used to predict the heat flux boundary condition, heat generation, temperature boundary conditions and root temperatures on various shaped fins [11–13]. Also, Ngo et al. [14] proposed an inverse BFGS combined simple step method without solving sensitivity problems to estimate interface temperature, heat generation and convection heat transfer coefficients in the welding process. The CFX4.4 was combined Steepest Decent Method to solve three-dimensional inverse heat conduction for estimating the time-dependent heat flux generated in the high electric motor [15]. Brito et al. [16] presented a nonlinear inverse technique in connect with COMSOL to carry out the heat flux and the temperature on a turning cutting tool in transient regime. ANSYS software and an optimization algorithm were employed to solve the transient multidimensional inverse heat transfer problems [17]. Luchesi and Coelho [18] applied a transient two-dimensional inverse heat conduction to estimate the heat sources in a machining process. An excellent estimation of the time-varying heat generation during rotary welding process is presented in [19] for some test cases. All in all, various inverse methods have become useful tools for investigating the heat transfer process in the science and engineering fields.

This paper establishes an inverse method for estimating the time-varying heat sources in a high-speed spindle. A finite element model of the spindle with transient heat sources and boundary condition is constructed and solved using the mechanical ANSYS parametric design langue (MAPDL). Thereafter, the conjugate gradient method (CGM) for iterative minimization is applied to solve the inverse heat transfer problem for estimating parameters. This method is demonstrated using a high speed spindle with a given nonlinear heat generation.

2. Thermal model of a high speed spindle

2.1. High speed spindle structure

As schematically depicted in Fig. 1, a direct driver spindle with a 24,000 rpm maximum speed is studied in this work. Four angular contact ball bearings (NSK-40BNR), two placed at the front and

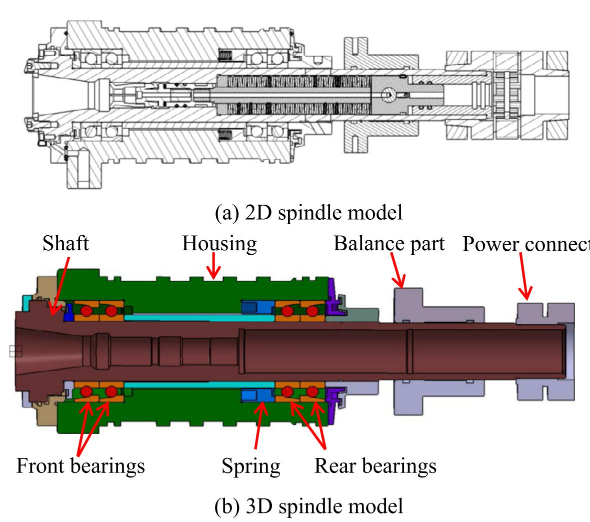

Fig. 1. High speed spindle structure.