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APPLYING INVERSE METHOD FOR HEAT TRANSFER OF HIGH SPEED SPINDLE

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Abstract:

This paper presents an inverse method for finding quantity of heat sources in high speed spindle. A commercial ANSYS software and Conjugate Gradient optimization method are used to construct the proposed inverse method. Simulations for different number of measurementpoints andlocations are performed. These results show that excellent estimation on heat generation can be obtained through using only two measurement points. The current methodology will provide a useful tool to investigate the complex heat transfer process in the high speed spindle.

Keywords: *Inverse method, High speed spindle,Conjugate Gradient Method, ANSYS Software.*

1. Introduction

When working under high speed, friction of bearings (and power loss of motorized) in the spindle will generate heat which leads to increase temperature and further cause thermal deformation in the spindle. Therefore,understanding temperature distribution in the spindle can give useful information for predicting and controlling thermal error. To estimatetemperature fieldin the spindle, the heat sources are indispensable. Palmgren[1] gave an empirical formula to estimate total bearing friction torque that was then used for calculating bearing heat generation. By adding the spinning friction moments to formula, Harris presented a new form for calculating heat generation of bearing in [2]. Palmgren's model has achieved popular acceptance as an accurate method. Bossmanns and Tu [3] proposed a model to determine quantitative heat source of the built-in motor and the bearings. Based on data from coast test, they established empirical equations which are function of preload and rotational speed for calculating bearing heat generated. Moorthy[4] introduced an improved analytical model for estimation of heat generation in angular contact ball bearings of high speed spindle. Through literature review, it can be seen that none of researches were investigated to obtain heat generated in bearings by using inverse heat transfer method. Recently, inverse method for estimating heat generation and interface temperature in ultrasonic welding [12, 13] and temperature-dependent thermophysical properties of material [14] was successfully studied.In this study, an inverse method is proposed to predict heat sources (heat generated by bearings)in the spindle. A combination of Mechanical Ansys Parametric Design Language (MAPDL) and Conjugate GradientMethod (CGM) is applied to find the unknown heat sources.

2. Thermal model of the high speed spindle

2.1 The high speed spindle structure

A direct driver spindle with 24000 rpm maximum speed, namely, TD30 is investigated in this study. To design the complex spindle, CATIA software is used to draw the spindle as shown in Fig. 1. To simplify the spindle model, small nuts, holes, and small structures are omitted. Material properties of each part in the spindle are listed in Table 1. A finite element (FE) model of the spindle is established in MAPDL. Because of the symmetric spindle, a small partition of the spindle (10) is considered instead of entire spindle. Meshed model of the spindle is displayed in Fig.2.

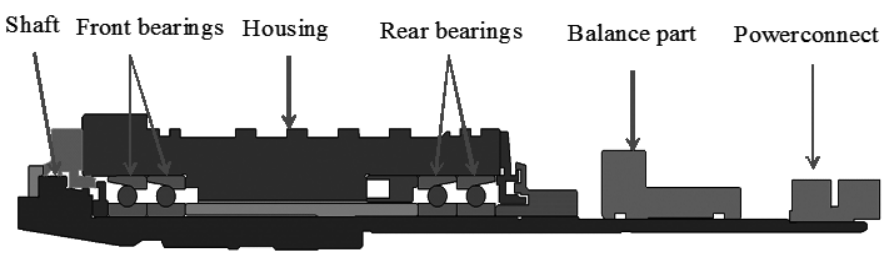

Fig. 1. *High speed spindle structure*

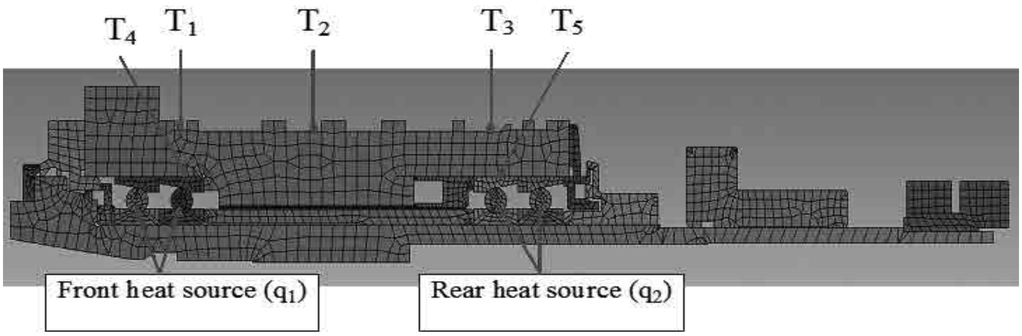

Fig. 2. *Meshed model of the spindle in ANSYS*

Table 1. *Material properties*

	Shaft	Housing	Inner/ Outer	Balls	Other parts
Material name	SCM 415	SCM440	SUJ2	Ce-ramic	S45C
Density (*kg/m*^{3})	7850	7800	7830	3200	7830
Thermal conduc-tivity *W/*(*m.K*)	46.6	43	46	30	47
Specific heat *kJ/*(*kg.K*)	460	450	470	850	480
Expansion coefficient (x$10^{-6}/^{o}C$)	12.5	11.8	12.5	3.0	12.8

2.2. Heat transfer coefficients

The spindle is assembled from many parts, this leads to create a lot of joint between these parts. Hence, the contact heat transfer at joint of spindle parts must be considered. Thermal contact resistance between the balls and outer/inner rings is given by [5]

$$R_{br} = \frac{1}{2\pi a k_{ball}} K\left(e, \frac{\pi}{2}\right) + \frac{1}{2\pi a k_{ring}} K\left(e, \frac{\pi}{2}\right) \qquad (1)$$

The contact between outer rings and housing through small air gap, so the thermal contact resistance coefficient is determined as [6, 7]:

$$R_{hr} = \frac{h_{ring}}{k_{ring} S} + \frac{h_{gap} - (T_{ring} - T_h)\cdot \alpha \cdot r_h}{k_{air} S} \qquad (2)$$

Thermal contact conductance of negative assembly of inner ring and shaft is computedas[8]:

$$\begin{cases} h = 1.13\left(\dfrac{k\tan\theta}{\sigma}\right)\left(\dfrac{p}{H}\right)^{0.94} \\ for\ plastic\ deformation\ (\psi \geq 1) \\ h = 1.55\left(\dfrac{k\tan\theta}{\sigma}\right)\left(\dfrac{p\sqrt{2}}{E\tan\theta}\right)^{0.94} \\ for\ plastic\ deformation\ (\psi < 1) \end{cases} \qquad (3)$$

The heat transfer convection in spindle includes force and free convection. The convection coefficient is defined by

$$h = \overline{N_u} k_{air} / d \qquad (4)$$

in which d is the equivalent diameter of the rotation bodies/cylinder or size of small gap; $\overline{Nu}$ is the average Nusselt number. $\overline{Nu}$ is calculated for different kind of convection as listed in Table2.

Table 2. *Nusselt number for convection boundary condition*

Convection boundary condition	Equations for calculating $\overline{Nu}$
Free convection of horizontal cylinder [9]	$\overline{Nu} = \left\{0.6 + \frac{0.387 Ra_D^{1/6}}{\left[1 + (0.559/\mathrm{Pr})^{9/16}\right]^{8/27}}\right\}^2$
Convection around rotation shaft [10]	$\overline{Nu} = 0.6366(\mathrm{Re.Pr})^{1/2}$
Forced convection in rotating annuli [11]	$\overline{Nu} = 0.409\left(\frac{Ta^2}{F_g}\right)^{0.241}$ $for\ 10^4 \leq Ta^2/F_g \leq 10^7$

3. Inverse method

Two unknown heat generations, which contain heat generation at front and rear bearings, are regards as:

$$\mathbf{w} = [q_1 \ \ q_2] \qquad (5)$$

Solution of an inverse problem is obtained when the object function is minimized with respect to each of unknown parameters. The object function has been defined to solve this inverse problem as:

$$J(\mathbf{w}) = \int_{t=0}^{t_f} \sum_{i=1}^{M} [T(t,x_i,z_i) - T_m(t,x_i,z_i)]^2 dt \qquad (6)$$

where $T(t,x_i,z_i)$ is the estimated temperature on the housing surface at the measured locations determined from the solution of the direct problem by using an updated estimation for the unknown quantity **w**. In order to minimize the objective function, the CGM is chosen in this study.The algorithm of proposed inverse method as follows:

Step 1: Set index of step k =1 and give initial $\mathbf{w}^{(1)} = \left[q_1^{(1)} \quad q_2^{(1)} \right]$

Step 2: Solve the direct problem by using MAPDL to obtain $T(t,x_i,z_i)$.

Step 3: Check the stop criterion $J(\mathbf{w}) < \varepsilon$. Continue if not satisfied.

Step 4: Calculate a gradient object function $\nabla J = \left[\frac{\partial J(\mathbf{w})}{\partial q_1} \quad \frac{\partial J(\mathbf{w})}{\partial q_2} \right]^T$ and conjugation coefficient $r = \sum_{j=1}^{M} [(\nabla J)^k]^2 \Big/ \sum_{j=1}^{M} [(\nabla J)^{k-1}]^2$.

Step 5: Compute the direction of descent $\mathbf{P}^{k+1} = \nabla J^k + r\mathbf{P}^k$.

Step 6: Compute the search step size:

$$\beta^k = \frac{\int_{t=0}^{t_f} \sum_{i=1}^{M} [T(t,x_i,z_i) - T_m(t,x_i,z_i)] \Delta T(t,x_i,z_i) dt}{\int_{t=0}^{t_f} \sum_{i=1}^{M} \Delta T^2(t,x_i,z_i) dt}$$

Step 7: Compute the new estimation $\mathbf{w}^{k+1} = \mathbf{w}^k - \beta^k \mathbf{P}^{k+1}$.

Step 8: Set $k = k + 1$ and go to **step 2**.

4. Simulation results and discussions

To illustrate for proposed inverse method, suppose that the running spindle with 15000 rpm speed for 7000 seconds under constant heat generation at front and rear bearings is used. The temperature at some locations is extracted and then employed as measured temperatures.

In order to consider possible effects of measurement pointnumber, inverse results of temperature and heat generation using given temperature from only one measurement point (T_1 or T_3) are shown in Figs. 3&4. It can be seen that estimated temperature, although, agrees excellently with exact temperature, unknown heat sources can't give correct solution. This phenomenon is occurred because one measurement temperature point doesn't provide enough information for estimating two unknowns. However, the accuracy of inverse solution was quickly improved when two points of measurement were applied. Figs. 5&6 display a comparison of estimation and exact solution of temperatures and heat generations using two measurement temperaturesat different locations. According to these figures, the predicted results are in very good agreement with exact values for both cases. However, estimated heat sources using two measurement points T4 and T5 are tiny better than that using two measured temperatures at T1 and T3. Clearly, the presented method can get reliable results as knowing temperatures at easy measuring positions (T_1 and T_3).

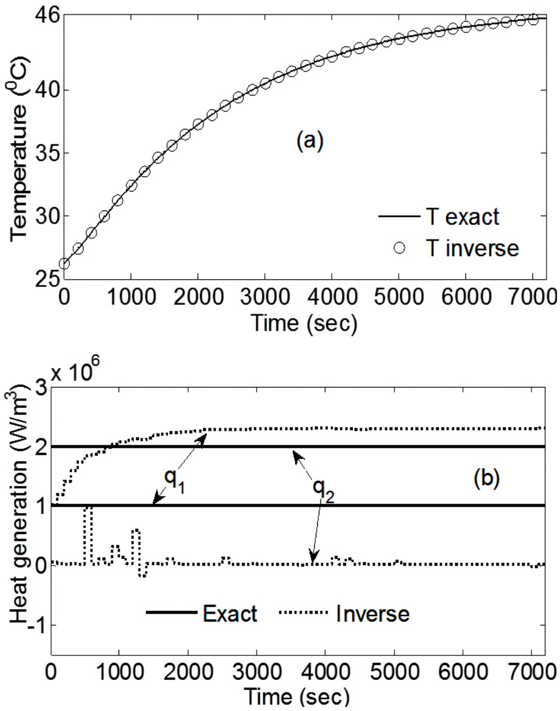

Fig. 3. *Inverse results using T_1;*
(a) Temperature; (b) Heat generation

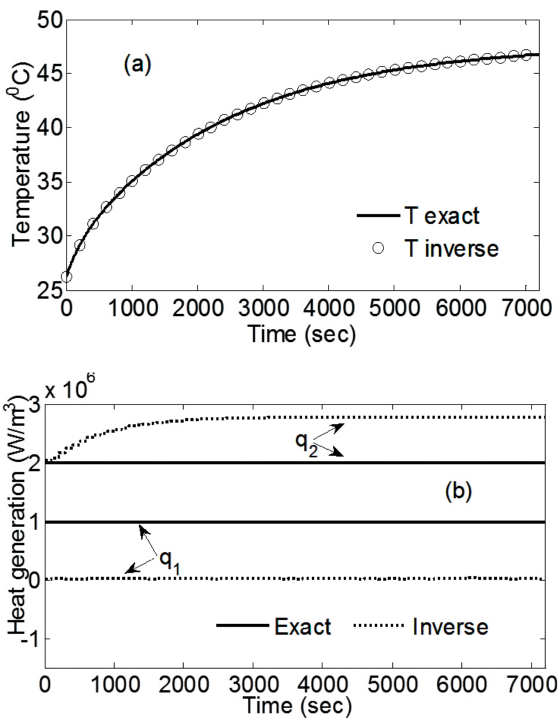

Fig. 4. *Inverse results using T_3;*
(a) Temperature; (b) Heat generation

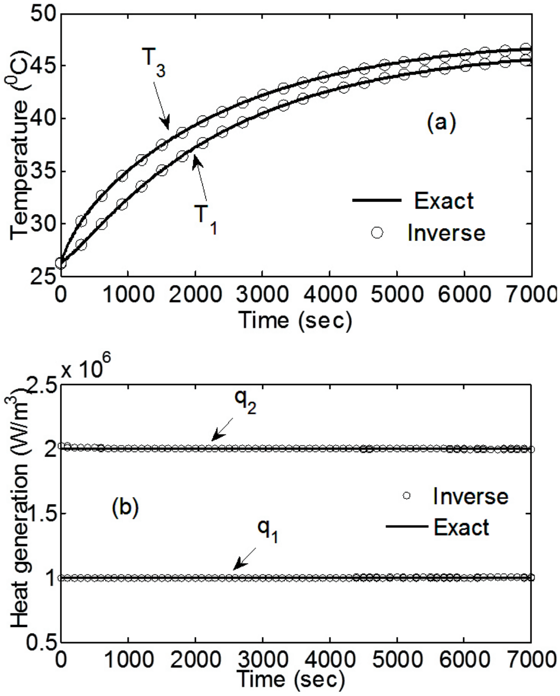

Fig. 5. *Inverse results using T_1 and T_3; (a) Temperatures; (b) Heat generation*

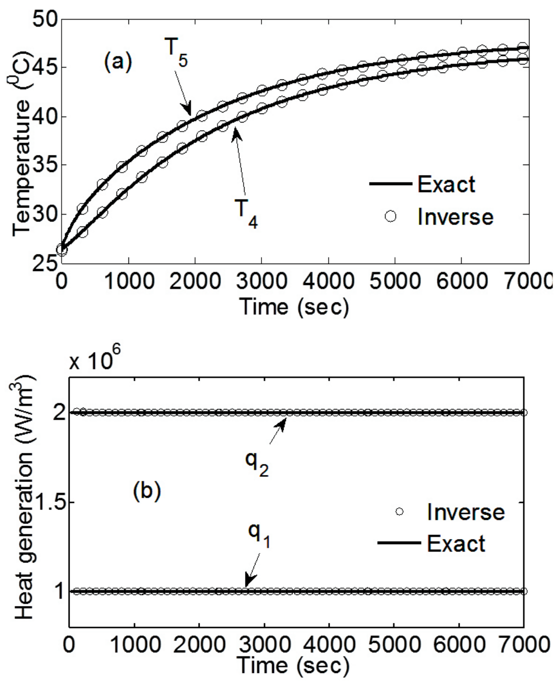

Fig. 6. *Inverse results using T_4 and T_5; (a) Temperatures; (b) Heat generation*

Fig. 7 indicates an excellent performance results between inverse and exact solutions when employing three measurement points. However, the accuracy of case using three points is slightly higher than that of using two points. From analysis of these findings, one is said that the proposed method can accurately estimate heat generations in high speed spindle through using only two measurement positions.

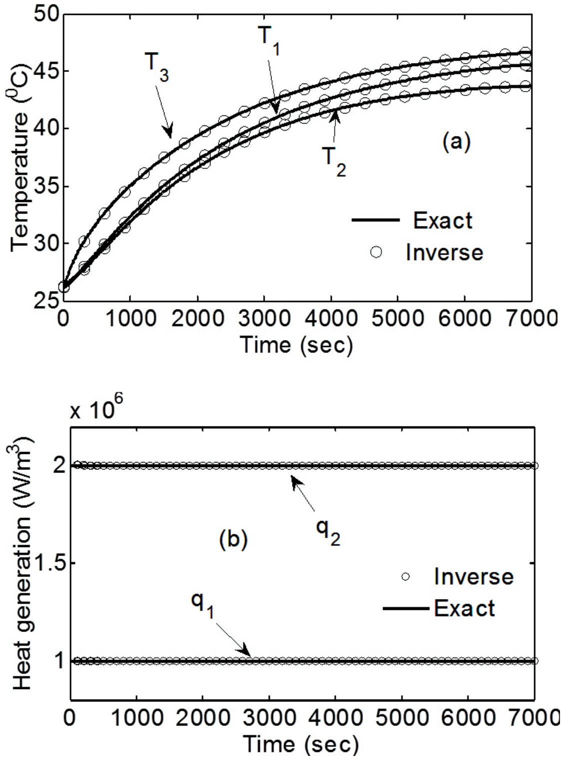

Fig. 7. Inverse results using T_1, T_2, and T_3; (a) Temperatures; (b) Heat generation

5. Conclusion

An inverse method for determining unknown heat generations in high speed spindle are successfully applied in this study. Results show that measurement point number affects accuracy of numerical solution. These results lead to a conclusion that two unknown heat generations in the spindle can precisely be evaluated with minimum two measurement points. This method may apply to give a simple method to predict quantity of heat generation for different kind of spindle.

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ỨNG DỤNG PHƯƠNG PHÁP NGHỊCH TRONG TRUYỀN NHIỆT CỦA TRỤC CHÍNH TỐC ĐỘ CAO

Tóm tắt:

Bài báo này trình bày một phương pháp nghịch để tìm nguồn nhiệt sinh ra trong trục chính làm việc với tốc độ cao. Phương pháp nghịch đề xuất được xây dựng bằng cách sử dụng phần mềm thương mại ANSYS và phương pháp tối ưu liên hợp Gradient. Các mô phỏng với số điểm đo và vị trí đo khác nhau được thực hiện. Kết quả cho thấy nguồn nhiệt có thể được dự đoán với độ chính xác cao khi chỉ cần sử dụng nhiệt độ đo tại 2 điểm. Phương pháp hiện tại sẽ cung cấp một công cụ hữu ích cho việc nghiên cứu quá trình truyền nhiệt phức tạp trong các trục chính làm việc với tốc độ cao.

Từ khóa: *Phương pháp nghịch, Trục chính tốc độ cao, Phương pháp liên hợp Gradient, Phần mềm ANSYS.*