USING INVERSE METHOD FOR EVALUATING THERMAL CHARACTERISTICS OF A MICRO HIGH SPEED MOTORIZED SPINDLE

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ABSTRACT

A combination of finite element and conjugate gradient methods to establish an inverse method for estimating heat sources as well as temperatures of a micro high speed motorized spindle is presented in this article. The proposed method is simple in constructing the direct problem by using COMSOL software. Experiment setup and measurement process are introduced. Results show that inverse solutions agree with experimental data based on temperatures at only one measurement point. Influence of speed on heat sources and temperatures is indicated. Temperature distribution in the spindle is also given and discussed. From these findings, it can be said that the proposed method is appropriate for inversely determining the heat source in micro high speed motorized spindle. The obtained results provide useful information to estimate thermal deformation.

Keywords: inverse method, thermal characteristics, heat source, motorized spindle, COMSOL software.

1. INTRODUCTION

Thermal problems always exist in any spindle and further cause inaccuracy in machine tools. Understanding thermal characteristics in high speed spindle can help us to avoid or compensate thermal errors for improving precision of machine tools. A lot of researchers have built the thermal model of the spindle to explore heat transfer process and carry out the thermal results. Bossmanns and Tu [1] applied finite different method to construct a thermal model for high speed motorized spindle. Based on the heat source models in [2], they developed the heat transfer model to predict temperature distribution in the spindle. The results were then validated by experiments. Based on calculated heat generation in [3, 4], Zivkovic et al. [5] used finite element ANSYS software to simulate temperature field determining thermal deformation and preload in traditional spindle. Applying ANSYS software for establishment of finite element
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thermal model of the high speed spindle to analyze temperature and thermal deformation was introduced [6, 7]. Through above literature reviews, the thermal models were analyzed and simulated based on given heat source.

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 [8]. Ngo et al. [9] 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. Some inverse methods which combined finite element thermal model and optimization algorithm were also issued [10 - 12]. Therefore, various inverse methods have become useful tools for investigating the heat transfer processes. Presented paper adopts the inverse method proposed in [13] to evaluate thermal characteristic of a micro high speed motorized spindle. However, COMSOL software is chosen to construct FE model instead of ANSYS software because it easily incorporates with main Matlab code.

2. FINITE ELEMENT MODEL FOR THE SPINDLE

COMSOL multiphysics software is used to create the FE model for the spindle. Because of symmetric spindle, a 2D model with its simplicity as well as greatly reducing computation time is applied. Figures 1 and 2 show the structure and meshed model of the spindle, respectively. In Figure 1, a rotor is attached on shaft while stator is embedded inside housing. The motor will make a torque to induce rotation of the shaft under a support of front and rear bearings. The maximum speed of the spindle can reach 60,000 rpm.

When running, the input power is transformed into heat at motor and bearings. These heats are then transferred to other parts and further resulting increased temperature in whole spindle. Besides, dissipation heat is instantaneously happened through radiation and convection processes. Because temperature in the spindle is not too high, radiation is neglected in this study. Therefore, convection mainly contributes to dissipate heat from the spindle. The convective coefficients for different kinds are presented as following:

\[ h = \frac{\overline{Nu} k_{air}}{d} \]  \hspace{1cm} (1)

where \( d \) is the equivalent diameter; \( k_{air} \) is the thermal conductivity of air; and \( \overline{Nu} \) is the average Nusselt number which is expressed as:

\[ \overline{Nu} = \left\{ \begin{array}{c} 0.6 + \frac{0.387(Ra_d)^{1/6}}{1 + (0.559 / Pr)^{9/16}} \\text{, [14], for stationary surfaces} \\
2(\Delta r / r) / \ln(1 + \Delta r / r) \\text{, [15], for rotational surfaces} \\
2 \\text{, for } Ta^2 / F_g < 1700 \\
0.128(Ta^2 / F_g)^{0.367} \\text{, for } 1700 \leq Ta^2 / F_g < 10^4 \\
0.409(Ta^2 / F_g)^{0.241} \\text{, for } 10^3 \leq Ta^2 / F_g \leq 10^7 \end{array} \right. \]  \hspace{1cm} (2)

\[ \overline{Nu} = 0.6366(Re Pr)^{1/2} \]  \hspace{1cm} (3)

\[ \overline{Nu} = \left\{ \begin{array}{c} 2(\Delta r / r) / \ln(1 + \Delta r / r) \\text{, for } Ta^2 / F_g < 1700 \\
0.128(Ta^2 / F_g)^{0.367} \\text{, for } 1700 \leq Ta^2 / F_g < 10^4 \\
0.409(Ta^2 / F_g)^{0.241} \\text{, for } 10^3 \leq Ta^2 / F_g \leq 10^7 \end{array} \right. \]  \hspace{1cm} (4)
Because of time-varying air temperature at annulus, an equivalent thermal conductivity of air is employed in calculation. This value is evaluated by [13]:

\[ k_e = h\Delta r = \frac{N_u}{k_{air}} \frac{\Delta r}{d} \]  

(5)

Although, heat generation in the spindle comes from motor and bearings, but magnitude of bearing heat generation is much small compare to that of motor. Hence, we only consider heat generated by motor. Setting heat source, convective coefficients and initial condition, the FE model in COMSOL can be completely established.

3. INVERSE ALGORITHM

The inverse method is implemented based on knowledge of the measurement temperatures on housing surface which are gained by experiments. The unknown heat generation by motor, \( q \), is discretized into period time, \( \Delta t \), for applying the inverse process. The unknown heat source vector of the nth period is give as:

\[ \mathbf{w}_n = q_n \text{ for } t_n \leq t \leq t_{n+1}, \quad t_n = n\Delta t, \quad n = 1, 2, 3, \ldots \]  

(6)

To find the solution of the inverse problem, Conjugate Gradient Method is used to minimize the object function that is written as:

\[ J(\mathbf{w}) = \int_{t_0}^{t_{n+1}} \left[ \sum_{i=1}^{M} [T(x_i, z_i, t) - T_m(x_i, z_i, t)]^2 \right] dt \]  

(7)

where \( T(x_i, z_i, t) \) is the estimated temperature, which is determined from solving direct problem, at the measured locations. \( T_m(x_i, z_i, t) \) is the measured temperature obtained at measured points. \( M \) is the number of measurement points. The flowchart of the inverse
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algorithm is figured out as Figure 3. Completing the inverse algorithm, the heat sources as well as temperature distribution in the spindle are found out.

\[
\begin{align*}
J(w) &= \int \sum_{m=1}^{M} \int \left[ T(x_r, r_t) - T_n(x_r, r_t) \right]^2 dt \\
\beta' &= \frac{\int \sum_{m=1}^{M} \int \left[ T(x_r, r_t) - T_n(x_r, r_t) \right] \Delta T(x_r, r_t) dt}{\int \sum_{m=1}^{M} \Delta T^2(x_r, r_t) dt}
\end{align*}
\]

Figure 3. Flowchart of the inverse algorithm.

4. EXPERIMENT PROCESS

Experiments are performed to measure temperatures of the spindle and environment. Figure 4 shows the schematics of the experiment. The micro high speed motorized spindle is put on insulation supports. The spindle is provided power by source supply which can control current to achieve the desired speeds. Multi-thermocouples have been placed on housing surface and table to measure temperatures. The signal from thermocouples is collected by Lion Data Acquisition.
and next transfer to computer for processing as well as monitoring. The experiment is conducted for several speeds for 20000 sec. The spindle is run until reaching steady state of temperatures. All measured temperature data will become input data in the inverse procedure.

![Schematics of experiment](image4.png)

Figure 4. Schematics of experiment.

5. RESULTS AND DISCUSSION

The inverse solutions are obtained based on knowing measured temperatures at housing. Figure 5 depicts a comparison of estimated and measured temperature and heat source when using three temperatures under 20000 rpm. It indicates that the inverse temperatures agree fairly well with measurement data; and heat source rapidly increases to reach a peak value of 7.268E5 W/m3 after about 400 sec. After that, the heat source gradually downward and becomes stationary state. Trend of the heat generated by motor (heat source) accords with result reported in [2]. The discrepancy between estimated and exact temperatures as in Figure 5 might be caused by neglect of bearing heat generations. However, the difference in temperature is smaller than 1.5°C and the results are still good enough.

![Inverse solution based on measured temperatures at T1, T2 and T3.](image5.png)

Figure 5. Inverse solution based on measured temperatures at T1, T2 and T3.
A case of using one measured temperature is continuously performed and inverse results are displayed in Figures 6 and 7. Results show that the estimated temperatures are in agreement with exact solution for both cases of utilized temperatures at T₂ and T₄. However, the inverse heat sources of these two cases are very different. While the heat estimated by using T₂ closes to that by using three temperatures, it is very different when employing T₄ (refer to Figure 8). Clearly, location of T₄ is farther motor than T₂. This is reason caused inaccuracy of inverse heat solution. Hence, it can conclude that the distance of measurement location and heat source significantly affects inverse results. In addition, observed in Figure 8, there is a small difference (<4.6 %) between estimated heats when utilizing T₂ and three temperatures. Therefore, the inverse algorithm can use only known temperatures at one point T₂ to carry out value of the heat source. Thus, using one measurement location, computation time is greatly saved while obtained heat source is still accurate enough.

Figure 6. Inverse solution based on measured temperature at T₂.

Figure 7. Inverse solution based on measured temperature at T₄.
A comparison of temperatures and heat sources of two speeds 10000 rpm and 20000 rpm is shown in Figure 9. It reveals that temperature and heat source increase with increasing spindle speed. Like above cases, the inverse temperatures are in fairly conformity with the measurement temperatures for both speeds. The steady state temperatures for 10000 rpm and 20000 rpm are sequentially 47.09°C and 52.37°C. The maximum estimated heat sources are 5.298E5 W/m³ and 7.605E5 W/m³ for 10000 rpm and 20000 rpm, respectively. Evidently, spindle speed greatly influences the magnitude of heat source and further resulting in temperatures.

![Figure 8. Comparison of estimated heat sources.](image)

![Figure 9. Results of different speeds.](image)

Besides, temperature field in the spindle are pointed out. Figure 10 shows the temperature distribution in the spindle at various times under speed of 10000 rpm. It indicates that during
running the highest temperature occurs at motor and lowest temperature appears at end of the spindle. The temperature field at 15000 sec and 20000 sec describe cooling process in the spindle. Due to effects of convective, temperature at outside surface will be decreased faster than that at core spindle (shaft). In addition, a uniform temperature along axial direction in motor range is exhibited. This may advantage to not only simplify thermal model for the spindle but also calculate thermal error.

Figure 10. Temperature field in the spindle.

6. CONCLUSIONS

Thermal characteristics of a micro high speed spindle are successfully investigated through inverse method based on a combination of FE thermal model and conjugate gradient method. Experiments for getting temperatures at some locals on housing surface are performed. Results indicate that the proposed method can acquire inverse solution by using only one measurement point at T₂. The trend of heat source in this paper is consistent with earlier research. Influence of speed on quantity of heat sources and temperatures is considered. Additionally, temperature distribution in the spindle are figured out and discussed. It believes that current method may utilize to inversely determine thermal characteristics of complex structures.

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TÔM TẮT

SỬ DỤNG PHƯƠNG PHÁP NGƯỜI ĐỂ ĐÁNH GIÁ ĐẶC TÍNH Nhiệt CỦA MỘT TRỤC TỐC ĐỘ CAO NHỎ CÓ GÁN MOTOR

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Từ khóa: phương pháp ngược, đặc điểm nhiệt, nguồn nhiệt, trụ tốc độ gắn motor, phần mềm COMSOL.