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ABSTRACT

Continuous usage of machine tools during manufacturing processes causes heat generation in the moving elements, resulting in distortion of the machine tool structure. Simulation of this thermal behaviour can be a powerful tool for supporting the design process and predicting errors. Determining accurate heat transfer parameters is needed to improve the prediction accuracy of the physical thermal models. First, the energy balance technique was used to calculate the parameters empirically. Due to uncertainties in the boundary conditions for this technique, an additional novel 2D optimisation technique based on thermal imaging data was used to calibrate the calculated parameters. The effectiveness of the technique was proved using FEA models of the machine. Good correlation of up to 80 % was achieved between simulated thermal characteristics and the experimental data.

1. Introduction

Machine tools accuracy is adversely affected by internal and external heat sources within and around the machine tool structure. Internal heat generation is primarily caused by the friction in moving elements such as bearings, belt drives and motors. External heat sources include workshop radiators, lighting and machine tools in the local vicinity. These influences cannot be eliminated completely by reduction of generated heat, nevertheless they can be reduced. Machine tool spindle systems (the spindle assembly and the headslide) is one of the primary components, and a significant contributor to the total thermal error as a result of the significant heat generated from high spindle speeds [1-3].

Thermal error models are often established by calculating the relationships between displacement of the tool relative to the workpiece and measured temperature changes. A significant amount of research has been done on modelling thermal error to understand and reduce its effect in machine tools.

Among these models are Multivariable Linear Regression (MLR), Artificial Neural Network (ANN) and Recurrent Neural Network (RNN) [4-6].

These empirical thermal error modelling techniques greatly rely on the collection of large amount of data, which requires large amounts of machine downtime, under different working conditions. Moreover, these techniques cannot give great details of the internal states of the heat flow inside the machine elements, which define machine tool behaviour. This is one of the most important drawbacks of these empirical models.

Another widespread approach for thermal error modelling is using the Finite Element Analysis (FEA) method due to its capability to manage complex geometry of machine structures [5; 7]. Furthermore, the calculation techniques for solving the FEA system equations are computationally less expensive due to modern powerful computer processors. Haitao *et al.* [1] modelled the thermal characteristic of a machine tool spindle using FEA. Simulation results showed a good agreement of 85 % with the experimental data. Zhang *et al.* [8] proposed a full machine tool temperature field and thermal displacement modelling using FEA method. There was close correlation between simulated and experimental results; the residual error was about 20 %. However, the accuracy of the simulation results depend heavily on whether the boundary conditions such as heat transfer coefficients and heat power of heat sources are well defined [1].

A great number of methods have been proposed to calculate the heat transfer coefficients of machine tools based on machine elements type such as bearings and belt drive [7-9]. Correlations between experiment and predicted data can further be improved by considering uncertainties related to the thermal parameters as efficiency of the machine tool elements deteriorate with usage in comparison to a new machine tool. A few researchers have used methods such as energy balance technique in order to calculate heat transfer coefficients [10; 11]. They reported that thermal error can be reduced to less than $10\,\mu m$ by applying the energy balance method.

Thermal simulation accuracy of machine tools mainly depends on the definition of initial conditions and the appropriate boundary conditions; therefore it is essential to develop an accurate technique to obtain more realistic thermal parameters. This paper presents a novel 2D optimisation technique utilising thermal imaging data in order to tune the previously calculated boundary condition parameters. Firstly, the heat transfer coefficient (HTC) is calculated for the spindle system of a vertical machining centre (VMC) based on experimental data using an energy balance technique. Secondly, a 3D FEA model is created by using Dassault Systemes Simulation (Part of the SolidWorks suite of software). Thirdly, simulation of the spindle system is conducted and compared with the experimental data. Typically good results are obtained from this process. However, the preliminary coefficients are then used in the 2D optimisation technique which provides updates to the parameters to attempt to improve the simulation accuracy. Finally, simulation results are verified by a comparison between the experiment and simulation results.

2. Thermal characteristic test of a spindle system

A spindle system entails a headslide, spindle motor and spindle assembly. In order to measure the deformations of the spindle system, a test bar was assembled, as shown in Figure 2. Two eddy current Non-Contact Displacement Transducers (NCDTs) were also utilised to measure deformations: one sensor placed in the Y direction and the other one placed in the Z direction. Due to symmetry of the spindle system, displacement in the X-axis was not considered. To obtain temperature distribution of the spindle system, a thermal imaging camera, which has a stated accuracy of ±2 ^{o}C, was used to monitor the heat flow through the spindle system while the spindle rotated at a constant speed of 8 000 rpm (close to its maximum speed of 9 000 rpm) with the cooling system turned off. The experiment took 3h (two hours heating and stopped for one hour cool down). The location of thermal imaging camera was chosen so that the heat flow into the spindle assembly, headslide and motor could be monitored. Thermal image accuracy was improved by applying masking tape (identified emissivity of 0.95) on the shiny surfaces and averaging the images to decrease noise [12]. Although not precisely controlled, the ambient temperature of the workshop remained fairly constant between 21 ^{o}C and 22 ^{o}C throughout the experiment. The test platform is shown in Figure 1.

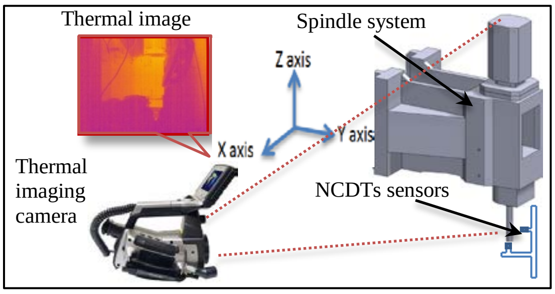

Figure 1. Thermal characteristics test platform

3. Development of the FEA simulation model

The finite element analysis (FEA) model of the machine tool spindle system was developed using SolidWorks to study and predict the thermal characteristics. Figure 2 shows the 3D model. Heat loss from the back of the headslide through the vertical axis guideways is negligible therefore the remaining structure is not modelled for this specific work.

Due to the complexities of the spindle system structure, some unimportant details such as small holes, curvature, chamfers, and bolt holes were simplified during 3D model creation. This helps to reduce mesh elements that would otherwise affect the computational time for FEA simulation [8; 13]. The spindle system FEA model was partitioned to 10127 elements. Three internal heat sources of the spindle were considered; spindle motor, upper and lower spindle bearings. The bearings are located close to the spindle nose and the top of the spindle system respectively.

The spindle system is made of three major materials, and these material properties were assigned to their corresponding structures in the FEA analysis software. The spindle and associated rotational parts are made of steel, the test bar from Aluminium and the headslide casting structure from grey cast iron. The material properties are presented in Table 1. For the various joints which are bolted together, a clamping force of 100 KN is used (based on average bolt/nut tightening torque) to help determine the effect of thermal contact resistance based on experimental work by Mian [14]. The estimated value is 0.0004 ((m^2.^{o}C)/W)).

Table 1. Spindle system material properties

Material	Grey cast iron	Steel	Aluminium
Density (kg/m^3)	7200	7800	2700
Modulus of elasticity (Pa)	$6.61*10^{10}$	$2*10^{11}$	$7.2*10^{10}$
Poisson's ratio	0.27	0.32	0.33
Specific heat (j/kg.^{o}C)	510	500	960
Thermal conductivity (W/m.K)	45	30	120
Thermal expansion coefficient(m/m/°C)	$1.2*10^{-5}$	$1.2*10^{-5}$	$2.5*10^{-5}$

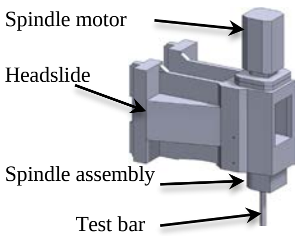

Figure 2. CAD model of the spindle system

4. Definition of the initial and boundary conditions

The simulation accuracy depends on accurate determination of the initial conditions and boundary conditions based on the characteristics of the machine structure and the thermal properties [7; 8]. These conditions are: (1) initial conditions analysis such as the initial temperature, the ambient temperature, and the thermal parameters for the various materials from which the spindle system components are made. (2) heat power calculation of heat sources such as spindle motor and bearings in this case (3) convective heat transfer coefficient calculations such as the natural convection between the static surfaces of the headslide and the air and the forced heat transfer coefficients between the rotating surfaces of the test bar and the air. (4) Thermal contact conductance at the structural joints. Conditions, which have not been mentioned yet will be explained in detail as follows:

4.1 Heat power calculation of heat sources

Heat power of the heat sources was calculated using the energy balance method (see equation (1)), as explained by Mian [11] based on thermal image data, structural materials and environmental temperature data.

$$Q=(mC_p(T_2-T_1))/t+hA(T_{surface}-T_{air}) \quad (1)$$

Where Q is the heat power (W), m is the mass (kg), C_p is the specific heat capacity (j/kg/^{o}C), (T_2-T_1) is the temperature change (^{o}C), t is the time (s), h is the coefficient of convection W/(m^2.^{o}C) , $T_{surface}$ is the surface temperature (^{o}C) and T_{air} is the ambient temperature (^{o}C).

By using the data and formulae mentioned, the motor heat power and the friction heat power of the spindle bearings for the machine can be calculated (See Table 2).

4.2 Determination of convective heat transfer coefficient

Natural and forced heat transfer convective coefficients were applied for spindle system components throughout FEA simulations. Natural convective coefficient of 6 W/(m^2.^{o}C) were applied around stationary surfaces exposed to air, such as headslide and forced convective coefficient of 92 W/(m^2.^{o}C) was applied around the rotating parts that are exposed to the air, such as test bar when the spindle is active and a value of 6 W/(m^2.^{o}C) applied while the spindle is not rotating, these figures were determined empirically by Mian [11].

5 Thermal simulation of the spindle system

Simulation of the spindle system was performed using transient thermal analyses available within the SolidWorks software. The initial temperature for the whole structure was set to 21°C and the duration of the transient analysis was set to 3 hours, which matches the experiment time. Boundary conditions obtained previously were applied to the FEA model to obtain the temperature field of the spindle system. The back of the headslide was fixed as constrained and then based on the temperature gradient field, thermal deformations of the spindle system in Y and Z axes were obtained. Results for the X axis were neglected as error in this direction is negligible due to the machine symmetry.

Figure 3 shows the simulated temperature (a) and displacement field (b) of the FEA model. The simulated displacement data were obtained from the nodes located at the same displacement sensor positions used to monitor Y and Z axes. The residual errors from the simulation results (see Figure 4) can be observed as 5 µm in the Y axis and 10 µm in the Z axes. The simulated and the experimental profiles, however, are not in good agreement as it was expected. This implies that the existing method for calculating some of the thermal parameters requires improvement.

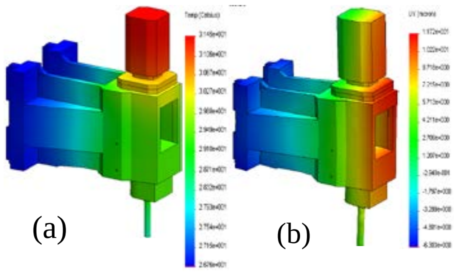

Figure 3. Thermal simulation results for the spindle system

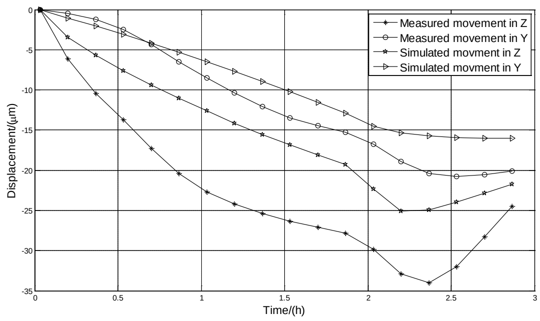

Figure 4. Displacement in Y and Z axes using energy balance method

6 2D optimisation model establishment

Abuaniza *et al.* [10] conducted heat flow comparison of headslide side between experimental and simulated data. Although high correlation was achieved between experimental and simulated data, some difference still remained. Therefore, optimisation technique can improve simulation results. In order to simulate the headslide surface temperature throughout the heating cycle and optimise the parameters, a reduced 2D heat transfer model of the rectangular surface of the side of the headslide was created in MATLAB. This enabled a relatively large number of points from the thermal images to be compared against the simulated temperature profile as described in section 7. The model is comprised of the same three heat sources (motor and upper and lower bearings) and thermal properties. In order to compute the heat power for the different elements of the 2D model, the following equations were used.

$$Q=-KA(\Delta T/\Delta x)+ hA(T_{surface}-T_{air}) \quad (2)$$

$$Q=mC_p\Delta T/t \quad (3)$$

Where K is the thermal conductivity (W/(m.K)), A is the Area (m^2), ΔT is the surface temperature difference (^oC), Δx is the distance (m), h is the convective coefficient ($W/(m^2.^oC)$), m is the mass (kg), C_p is the specific heat (j/kg.^oC), $T_{surface}$ is the surface temperature, T_{air} is the air temperature, t is the time (s), Figure 5 shows 2D model of headslide.

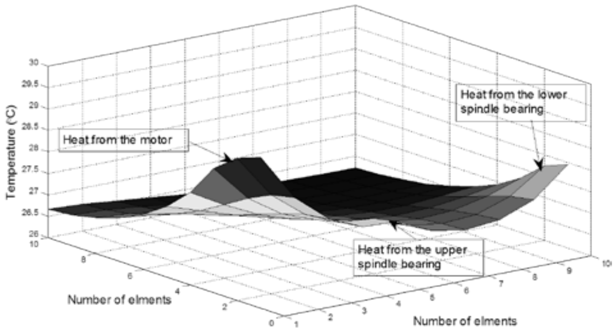

Figure 5. 2D temperature rise model of headslide

7 Thermal parameters optimization

In order to determine optimal thermal parameters over the previously defined case of spindle system simulation problem, a MATLAB optimisation function utilising the Nelder–Mead method [15] was used to minimise the sum-of-the-squares error between the experimental data (thermal images data) and simulated data.

Initial and final temperatures at the end of heating cycle were extracted as an array of 10×10 from the thermal images of headslide, see Figure 6. This data was used to fit the 2D model simulated data in order to optimise the spindle system heat power; see Figure 7 for the comparison between the experimental and simulated temperature array. Some differences still exist which are estimated to come from the noise in the thermal imaging data and 2D filtering at each selected time frames along with filtering of selected nodes in the time domain are being implemented to further improve the fitting accuracy. Table 2 shows the heat power of the spindle system heat sources before and after the preliminary optimisation process.

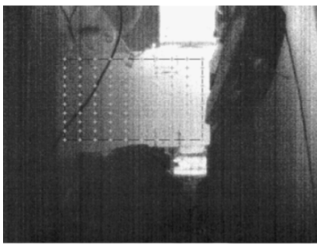

Figure 6. Experiment temperature data extraction from IR image

Table 2. Heat power magnitude

Heat sources	**Heat power (W) Energy Balance technique**	**Heat power (W) Optimisation technique**
Motor	50	46
Lower spindle bearing	12	15
Upper spindle bearing	8	10

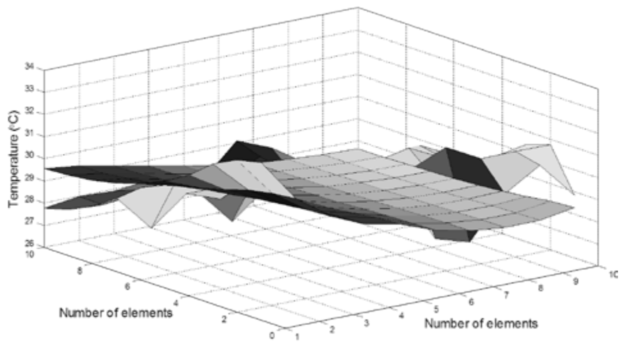

Figure 7. Experimental and model temperature data fit

8 Results and discussion of optimised heat power figures

The optimised heat power values were used to simulate the FEA model in order to obtain the optimised thermal behaviour of the spindle system. Figure 8 shows a comparison of experimental and simulated data for the displacement.

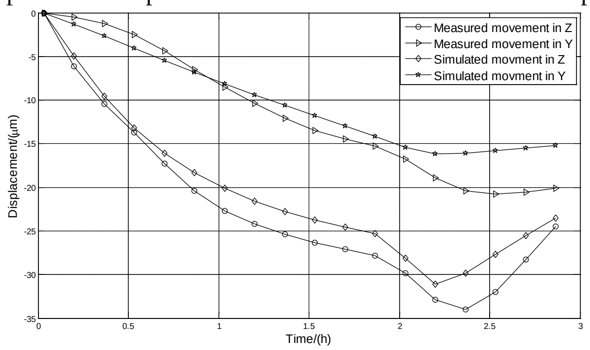

Figure 8. Displacement in Y and Z axes using optimisation method

The results show that there is an improvement in the spindle system accuracy using the proposed optimisation technique. It can be observed that the amount of the residual thermal errors in both the Y and Z axes have been reduced after using the optimisation technique to 20 % during heating cycle and 50 % during the cooling cycle when compared to the energy balance technique. This preliminary validation shows that the proposed optimisation technique can enhance the model's prediction capability by approximately 20 %. Further improvements are anticipated if the simplified optimisation model of the structure can incorporate the 3D effects (mainly hysteresis) of varying material thickness in more detail.

9 Conclusions

This paper proposed a method for optimising the identification of thermal parameters of a spindle and headslide on a vertical milling machine to improve the simulation accuracy of the thermal characteristics. Actual temperature rise and spindle displacement in Y and Z axes were obtained from an experiment. An FEA model was established and simulated using the energy balance method and optimisation technique method, utilising thermal parameters obtained from analysis of experiment data and optimisation method respectively. A new methodology for machine-tool thermal parameters optimisation was presented in this work. Accuracy and effectiveness of the thermal error model and optimisation technique was also evaluated in this paper.

From the comparison between the energy balance results and optimisation technique results, it can be observed that the optimised heat power parameters can improve the FEA model prediction results and obtain improved accuracy compared to simulation using parameters obtained by energy balance techniques. Results from simulating the resulting displacement show correlation with the actual movement of the tool in the spindle up to 80 %. Considering the small amount of machine downtime required to obtain the model parameters, this result is very encouraging.

10 References

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