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Optimization of high speed machine tool spindle to minimize thermal distortion

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Abstract

Thermal errors contribute significantly to the dimensional error on machined components. Various machine design and operating factors are responsible for the thermal error. In the present work, experiments are performed to understand the effect of spindle rotational speed and the chiller unit setting on the temperature distribution in the spindle and consequently the thermal distortion of the Tool Center Point (TCP). A metrology fixture is fabricated and calibrated to measure TCP displacements as a precursor to experimentation. In addition, multiple temperature sensors are affixed at critical points within the spindle. It is seen that the temperature distribution across the outer race of front bearings is non-uniform (> 2.5°C) which in turn indicates that the heat extraction is not uniform across the spindle. Concurrently, significant tilt (yaw and pitch angles of the order of 50μ radian) is visible at speeds greater than 5000 rpm. In the second part of the paper, a thermal compensation model is developed in a linear regression framework. To improve robustness of the model and reduce redundancy, only five out of eighteen temperature sensors (two near front bearing, one each near rear bearing and motor coil and an ambient temperature) are chosen through Principal Component Analysis (PCA) and k-means clustering. The predictions of the model agrees well with the measurements taken from a different set of experiments.

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Keywords: Motorized spindle, thermal modeling and compensation, machining center, thermal distortion, optimization

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1. Introduction

Accuracy and precision of machined product along with speed of machining are among the important considerations for a machine tool manufacturer during the design of a general purpose machining center. Although various proving tests are undertaken in the form of leveling test, straightness calibration of axes using laser interferometer, full power tests, etc. during the assembly of a machining center, often significant variability is found in the geometrical accuracy and precision of machined end-products. The reason for such deviation from the ideal situation is the combination of following major error sources: geometric and kinematic error; cutting force induced error; tool-wear related error and thermal error. Among these errors, it is well known that about 40 to 70% is due to thermal issues [1]. For instance, geometrical accuracies of products machined in a typical 12-hour shift vary widely (whether the machine was warmed up or not, the change in the ambient temperature) due to the inherent transient behavior of the machine tool till stabilization is attained.

Thermo-elastic behavior of machine tool is dependent on a variety of internal and external factors. The major internal factors include the design and assembly of the machine tool and machining conditions while the variation in ambient temperature and existing temperature gradient in the machine shop are some of the external factors. Various approaches including analytical and/or numerical modeling (finite-element and finite-difference approaches) in conjunction with experimentation have been followed to describe the thermo-mechanical behavior of the machine tool [2]. However accurate thermo-mechanical modeling of a complete machining center under various operating conditions is quite difficult and complicated [3]. One of the vital machine tool component which is also a major heat source especially in the case of high speed machining is a motorized spindle. It is therefore important to first map the thermo-mechanical characteristics of motorized spindle.

Motorized spindle has two main heat sources: the motor and the spindle supporting bearings. Heat generation in the motor is because of the magnetic and electrical losses during the conversion of electrical power to mechanical work while it is due to friction for the case of bearings. Therefore in contrast to the belt-driven or gear-driven spindle, the mode of heat generation and dissipation should be taken into account during the design of motorized spindle. This internal heat generation causes spindle distortion in the form of TCP displacements which in turn results in the degradation of machine tool performance. In order to minimize this effect, machine tool manufacturers employ

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forced convection-type heat transfer with the coolant being either air, water or oil.

To further minimize TCP displacements in high precision machining centers, two approaches are commonly employed. The first one is to control the heat flow or optimize the mechanical design to reduce the sensitivity to heat flow either through the use of low Coefficient of Expansion (CoE) materials or the use of a novel cooling strategy which directly minimizes TCP displacement itself. The second approach is to allow for spindle distortion which is compensated electronically real-time. In the former case, recent research [4] has shown that differentiated recirculation systems for bearings and motor provide a better dissipation strategy than the traditional cooling system. In addition, further improvement is seen when heat dissipation rate is matched with the heat generation rate through the control of the coolant entry temperature [5].

Nomenclature

T_i	Temperature of i^{th} sensor in °C ($i = 1$ to 18).
ΔT_i	Temperature change of i^{th} sensor with respect to its initial temperature in °C.
u_i	Spindle displacement at i^{th} location in μm ($i = 0°$, 90°, 180°, 270° position).
δ	Thermal expansion of spindle in μm.
N	Spindle speed in rpm.
$\mathbf{A}$	Augmented temperature matrix with n temperature sensors in columns and m time steps in rows.
S_i	Singular value of $\mathbf{A}$ corresponding to i^{th} principal component.

Electronic thermal compensation through origin shifting or feedback interception method is the most popular way of reducing thermal errors. Extensive research is conducted to arrive at 'so-called' robust optimal model which relates the TCP displacements to various internal and external parameters such as temperatures, strains, spindle speed, etc. Various kinds of models using either least squares, regression analysis, transfer function, neural network, support vector machine or hybrid techniques have been developed and their detailed review is provided in [6]. In order to reduce the redundant data input during model fitting, approaches including correlation grouping, group searching have been employed and optimal sensor locations were chosen [7]. In addition to the models which use instantaneous values of internal and external parameters to estimate TCP displacements, some models employ thermo-mechanical history data as well in order to account for the thermal time constant of spindle unit and they show a better predictive capability [8].

The present work is aimed at understanding the thermo-mechanical behavior of stand-alone motorized spindle in an experimental-modeling framework. The first part of the paper is focused on experimentation wherein the effect of various operating parameters on the temperature distribution in the spindle and resulting TCP displacements are studied. Specifically, Section 2 describes the experimental setup, the design and validation of displacement measurement fixture, the effect of spindle rotational speed and spindle orientation on TCP displacements. The second part is focused on the thermal compensation methodology adopted wherein Section 3 introduces a novel way to group and select the temperature sensors for compensation model development using PCA and k-means clustering. The predictive capability of the developed model is then checked by performing an experiment very different from the ones used to build the model. Finally, a few concluding remarks are offered in Section 4.

2. Material and Methods

The experimental set-up includes a stand-alone motorized spindle which is mounted onto the milling head which in turn is rigidly fixed to the test bed. The bearings in the spindle are arranged in a double ∘-configuration and provision is made to cool the bearings and stator portion of the motor region (Fig. 1) through a recirculation-type chiller unit. Eighteen Pt100 Resistance Temperature Detector (RTD) sensors are affixed at several critical points in the spindle: four each in outer race of front bearings, five in outer race of rear bearings, one each for motor coil, ambient and housing temperature and finally one each at coolant entry and exit points. A custom-built software is used to synchronize the data from FANUC CNC controller (such as spindle speed and motor coil temperature) along with the temperatures from other RTD's, flow rate and chiller on/off information. Experiments are performed under no-load condition and the resulting thermal displacements are manually measured using high precision Millimess dial gages, which are rigidly clamped in a specially fabricated fixture, whose details are provided in subsection 2.1.

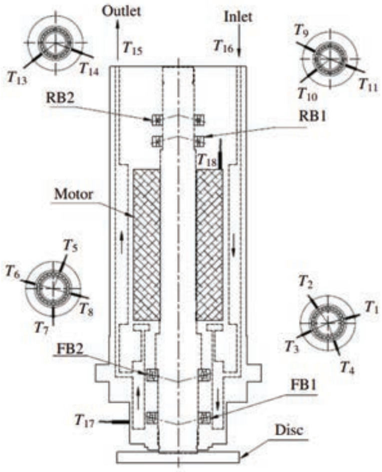

Fig. 1: A schematic of the motorized spindle with eighteen temperature sensors and a representative coolant channel.

2.1. Fixture development

A steel fixture (Fig. 2) is designed to measure spindle distortion at four designated points (Fig. 2; points u_i, $i = 0°, 90°, 180°, 270°$) on the rotating disk. This precision ground disk ($d = 210$ mm in diameter[1]) forms an extension of spin-

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[1] Larger disk diameter is chosen to magnify the measurements and reduce uncertainty.