

# Large array thermal machine monitor

Shuqing Zhang and Steven R. Patterson  
Department of Mechanical Engineering and Engineering Science  
University of North Carolina at Charlotte  
Charlotte, NC28223

## Abstract

A low cost temperature measurement system is described in this paper. A thermal model, which accommodates the failure of thermal sensors, is developed. The model can correct up to 80% of the thermal growth errors of the spindle in Z-axis.

*Keywords:* error correction, temperature measurement, thermal model.

## 1. Introduction

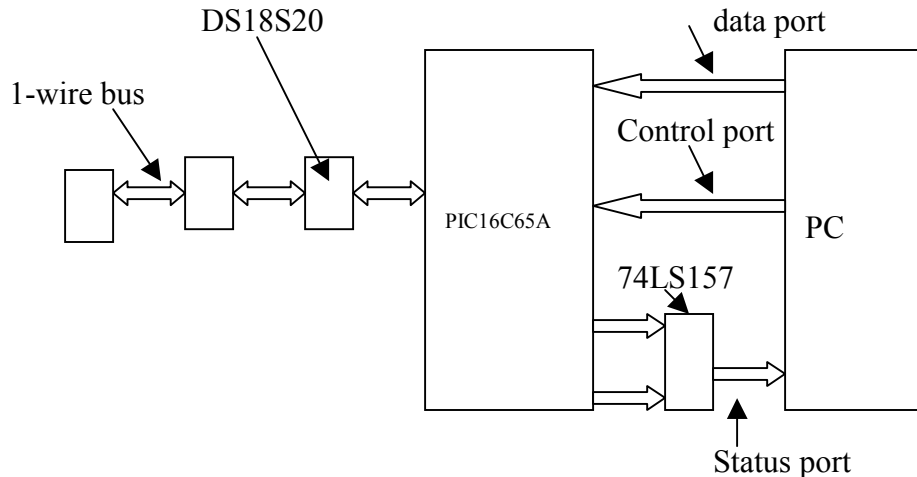
Thermal errors are generally considered one of the major machining errors in computer numerical control (CNC) Machining centers; in some cases thermal errors can contribute more than 50% of the total machining errors [1]. In particular, spindle thermal drifts are often the dominant source of errors among thermally induced errors. The solutions for reducing thermal errors are of two main types: improving the machine tool design and error compensation techniques [2]. In spite of the machine tools manufacturer's effort, there are always some residual thermal displacements, because it is very hard to optimize the design for different kind of operation conditions [3]. In recent years more research has been directed to the control of the CNC machining center; and several techniques have been reported for the correction and compensation of the thermal growth. To be effective in a production environment, a compensation system that corrects thermal errors must be both low-cost and robust.

There are two main techniques for compensating thermal growth of CNC machining center: the finite element calculation and empirical modeling [4]. It is often difficult to estimate boundary conditions and heat dissipation throughout the machine structure. As a result finite element techniques are used only for trend prediction rather than as a precise prediction method.

Thermal error prediction based on the empirical model approach is based on the measurement of the actual thermal state of the machining and requires an effective temperature measurement system to measure the temperature at key points on the machining center.

## 2. Temperature measurement system

In this paper a low-cost temperature measurement system is represented. It comprises an IC-based temperature measurement system, a micro-controller interface to a PC-based real-time data acquisition system. This temperature measurement system can drive a large array of thermal sensors. Figure 1 shows the block diagram of the temperature measurement system.



**Fig. 1. Block diagram of the sensor interface controller**

The high-precision 1-wire digital thermometer DS18S20 is used as the thermal sensor in the temperature measurement system. Each DS18S20 sensor communicates with a central microprocessor over a “1-wire” bus. Each DS18S20 sensor has a unique 64-bit serial code, and multiple sensors can coexist on the same “1-wire” bus. Thus it is straightforward to use one microprocessor to control many sensors distributed over a large area. A PIC16C65A is used as the central microprocessor, it communicates with the sensors over the “1-wire” bus and with the PC through the printer port. The PIC16C65A sends commands received from the PC to the DS18S20, and sends the temperature results from each sensor to the PC.

### 3. Modeling and evaluation

To test the systems on a machining center, 31 thermal sensors have been mounted on a Monarch VMC45 machining center. Because one of the major heat sources that influences the spindle growth is the spindle system and its bearings, the thermal sensors for the initial testing are mainly mounted around the spindle, gearbox and X-, Y-, W- and Z-slide scale.

Modeling and evaluation was conducted in three steps: (1) data collection on the Monarch VMC45, (2) data processing and modeling, (3) model evaluation on the same machining center. The data collection tests consist of: (1) a Warm-up run test (2) various spindle speed run test (3) a production cycle run test and (4) a cool-down run test of the spindle. A linear least squares regression thermal model has been developed based on the initial data. Because the VMC-45 is a “C” frame vertical machining center, the spindle thermal growth is mainly along the Z-axis. All data reported here refers to motion along the Z-axis.

Twenty-five thermal sensors have been used in the model. The correlation coefficients between the thermal sensors and the spindle-axis growths have been calculated in order to find the key locations of the heat sensors. Then the thermal sensors are ordered by the values of the correlation coefficients.

The thermal growth of the spindle has been modeled as

$$Z = a_0 + a_1(T_1 - 20) + a_2(T_2 - 20) + \dots + a_{25}(T_{25} - 20) \quad (1)$$

where

$Z$  -- thermal growth errors predicted along Z-axis

$T_i$  -- the value of thermal sensors,  $i=1,2,\dots, 25$

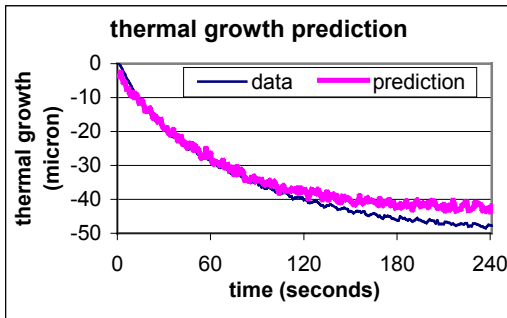
$a_i$  -- the parameters of the model,  $i=1,2,\dots,25$

The covariance matrix of the parameters shows the parameters  $a_i$  are not statistically independent and their errors are correlated. In this paper the model is modified. If Vector A is the original parameters, vector B is the modified parameters and matrix C is the eigenvector matrix of the covariance matrix, then

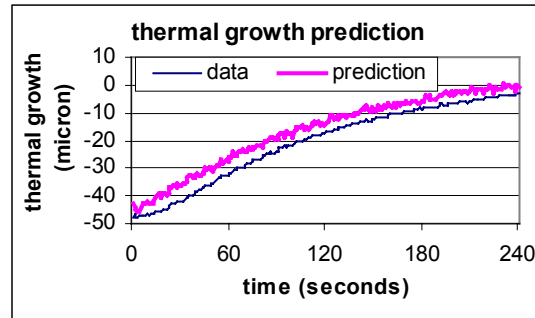
$$B = C^{-1} * A \quad (2)$$

After the modification the parameters in vector B are statistically independent and their errors are not correlated. So if one sensor fails, it will not affect other parameters in the model.

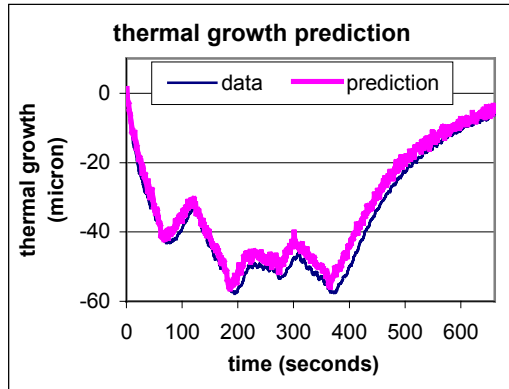
Thermal models developed by data from different operational conditions have been evaluated. Figure 2-4 shows the evaluations of the thermal model under three different operational conditions: warm-up run, cool down run, and production cycle run.



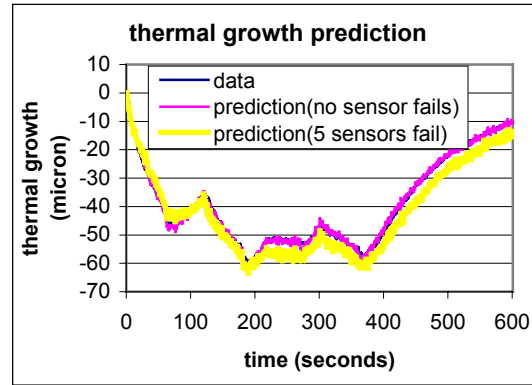
**Fig. 2 Thermal growth prediction during Warm up run test with speed of 1500rpm**



**Fig. 3 Thermal growth prediction during cool down run test**



**Fig. 4 Thermal growth prediction during production cycle run test**



**Fig. 5 Thermal growth prediction by model when 5 thermal sensors fail**

A thermal model that gracefully accommodates the failure of thermal sensors has been developed. Because the thermal model is based on the temperature and spindle thermal growth measurement, it will be affected by the failure of thermal sensors. The experiment results show that if one thermal sensor fails, the uncorrected thermal growth prediction error of the model is up to 2 mm; if five thermal sensors fail, the uncorrected thermal growth prediction error is more than 5mm. The correlation coefficient between the thermal sensors is calculated, and then a failed sensor can be replaced by a linear combination of other sensors that have high correlation coefficient with it. The resulting corrected thermal growth prediction is minimally affected by the failure of a small number of thermal sensors. Figure 5 shows the comparison of thermal growth prediction by the model with and without thermal sensor's failure.

## References

- [1] M.Weck, P. Mckeown, 1995, Reduction and Compensation of thermal Errors in Machine tools. Annals of the CIRP, Vol. 44.
- [2] J.S.Chen, J.X.Yuan, etc, 1993, Real-time Compensation for time-variant Volumetric Errors on a Machining Center. Transactions of the ASME, November, Vol. 115.
- [3] S.Fraser, M. H. Attia, M. O. M. Osman, 1998, Modeling, Identification and Control of Thermal Deformation of Machine Tool Structures, Part 1: Concept of Generalized Modeling, Journal of Manufacturing Science and Engineering, Aug., vol. 120.
- [4] K. C. Lau, 1993, Development of A Spindle Thermal Error Characterization and Compensation Sensor System for Machining Center Accuracy Enhancement.