FLEXIBLE MODELLING AND COMPENSATION OF MACHINE TOOL THERMAL ERRORS

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1 Introduction

Geometric errors on CNC machine tools have reduced significantly over the past few decades and compensation either through the controller or with retrofit systems have helped improve accuracy even further. This move is driven by a trend of ever tightening tolerances on components manufactured on these machines, especially where simplified assembly is required such as the Aerospace industries. Thermal errors have affected the accuracy of production machines for a long time but now for many industries with large machines and small error budgets, they are the dominant source of inaccuracy and are often the most difficult to reduce. Many solutions exist for the machine tool builder to reduce the errors that can be applied at the design stage including symmetric structures, low coefficient materials, liquid cooling systems etc. Design effort and cooling systems can add significant cost and usually cannot eliminate the errors but only help reduce them. Active and pre-calibrated compensation can be an important and effective alternative with some machine tool builders incorporating temperature sensors on the machine at the build stage. These systems are invariably controller-based using a simple model to estimate error at the tool and they are usually specific to a machine or range of machines within the company. These systems can produce good results for linear repeatable thermal errors and they work best in conjunction with good design [1].

Generally most thermal errors measured between the tool and workpiece are caused by a complex interaction of structural distortions having different heat sources, thermal time constants and expansion coefficients. Because of these causes the errors are time-varying and non-linear and are therefore difficult to model accurately. Significant research in the field of thermal error compensation has produced a number of sophisticated retrofit techniques for modelling thermal errors that employ techniques such as Neural Networks and multiple linear regression analyses [2, 3, 4, 5]. These systems can produce excellent results but often require complicated hardware and software systems and testing regimes to train the models or optimise temperature sensor positions for the particular machine or application.

This paper discusses new compensation capabilities and model development techniques that build on work by White [6, 7] to enhance the efficiency of application and machine accuracy. The philosophy relies on comprehensive measurement of temperature and a flexible compensation system that uses a novel programming language dedicated to modelling non-rigid behaviour of machine structural elements. The system practicality has been proven through industrial application.

Machine downtime, although undesirable, is required for completion of most phases of a thermal compensation system particularly the measurement of machine thermal behaviour, hardware implementation of temperatures sensors and compensation system and finally validation testing. It has already been mentioned that many successful modelling techniques require long testing regimes to provide sufficient information for robust model creation. The techniques described in this paper are designed to minimise this requirement in all areas.

2 Machine measurement

Acquiring as much temperature information from the machine during the initial testing phase is critical for making efficient use of the machine availability. Most machine heat sources are easily identified but thermal imaging can be used to enhance this process or determine the magnitude of heat generation during normal production. Once the main heat sources are identified a detailed study of the temperature distribution is required during a strategic test while measuring error. A thermal imaging system is set-up to capture images on a time basis while the heat sources are excited. This information is ideal for efficient determination of the correct compensation methodology, particularly temperature sensor density and placement. It is important to measure all other structural elements and environment that may contribute to the measured error. Low cost, accurate and compact digital temperature sensors are used extensively for this purpose.

Error between the tool and workpiece is measured using a spindle analyser or laser similar to that described by the ISO Standard 230 part 3. Most methods are based on this standard, however, measurement for compensation has
different requirements often resulting in variations to the tests to maximise the information that can be obtained. A variety of results are reported by Longstaff [8].

3 Model development

Detail about the modelling methodology is described by White [6]. Generally, the machine elements are analysed in their simplest form as far as possible. This enables reliable calculations of distortion such as bending and expansion using knowledge of the relevant structural dimensions and detailed temperature data. Small models of structures affected by running the spindle, the axes and changes in the environment or workpiece are combined to produce a comprehensive model with final compensation values for each axis direction.

3.1 Temperature

Figure 1 shows a saddle structure from a gantry machine that has a ballnut mounted at the rear. The image is part of a sequence that can be analysed using the MatLab software shown. Virtual sensors and sensor strips are placed on the image from which detailed temperature gradient information can then be extracted and used in the development model as shown by the graph in figure 1. This simulation of the individual temperature sensors and sensor strips that will finally be applied to the machine enables accurate determination of the hardware requirements.

The developed thermal model can be run in another MatLab environment to acquire compensation results for comparison with the measured data captured during the initial testing phase. Manual or automatic adjustment of the model including trying different positions and resolutions for the temperature sensors can be tested offline easily. Through offline model optimization, a high level of confidence can be realized for the location of the temperature sensors for permanent installation. This minimizes the machine downtime and labor involved with sensor application, many of which may be embedded in the machine structure to enhance material temperature measurement accuracy.

Figure 1. Virtual temperature sensor placement for model and hardware optimisation

4 Software implementation

The latest version of the University of Huddersfield compensation software VCS runs in the popular Siemens open architecture 840D controller. Many advantages are obtained by integrating into the controller both for geometric [9] and thermal compensation. Significant advantages include low cost and efficient implementation of compensation for geometric and thermal errors and having access to information about the current machining process such as workpiece offsets, materials, tool offsets and much more. This information enables compensation for differential expansion caused by inevitable variations in temperature of the feedback system and the workpiece.
5 Results sample

This section contains a sample of the results obtained from compensation on a small vertical milling machine.

5.1 Spindle movement

Model validation usually involves a random duty cycle. In this example a random duty spindle running cycle was used. Figure 2 shows the uncompensated and compensated error in the Y and Z directions. Position independent thermal error in Y-axis direction reduced from 71µm to 7.5µm (≈90%) and Z axis error reduced from 14 to 3.5 (≈75%). This improvement would be seen in short-term machining operations or where the machine was in a temperature controlled environment.

![Figure 2. Compensation results for random spindle duty cycle](image)

Monitoring the spindle movement over days rather than hours enables daily cyclic environmental temperature fluctuations and associated errors to be measured. Compensation results show a reduction in the magnitude of the environmental errors by more than 50% to just ±7µm over a 65 hour test. This is obviously time consuming and would therefore be carried out only if significant errors were being experienced, for example if machining times are long combined with environmental fluctuations [8].

5.2 Position dependent thermal error (PDTE)

PDTE can become dominant where cycle times for finishing cuts are small compared to the often slow changing Position Independent Thermal Errors (PITE), especially on large workpieces or where the workpiece coefficient of thermal expansion does not match that of the machine feedback system. For scale and workpiece errors we need the respective expansion coefficients, temperatures and a thermal datum. Most of these parameters change depending on workpiece so the flexible thermal modelling system can obtain this information from the NC as an offset such as G54 or as a parameter in the part program. With this information the workpiece error can be calculated using:

\[ x_{\text{WorkError}} = \text{workTempAboveRef} \times (\text{PosnX}/1000 - X_{\text{WorkDatum}}) \times \text{workCoeffExp} \]

Combined with similar calculations for scale error and using a reference temperature such as 20°C, the error in the scale and workpiece can be compensated. Figure 3 (a) shows position error before and after compensation using a laser interferometer measuring with reference to 20°C. Both the PITE (scale offset) and PDTE (scale expansion) constituents are significantly reduced.

![Figure 3. PDTE compensation and temperature of workpiece and scale during finishing operations](image)
Further PITE validation was achieved during cutting trials using NAS979 test pieces machined in a non-temperature controlled environment. Temperature of the scale and workpiece as shown in Figure 3 (b) were used. Pre thermal compensation, the mean error from 5 representative dimensions of approximately 200mm was 27µm. With thermal compensation active, the mean error is 2µm which is a reduction of 91%. These significant improvements in accuracy can be expected when machining occurs with the workpiece at a different temperature to that of the position feedback system.

6 Conclusions

A flexible thermal compensation system has been devised that can compensate for all significant thermal errors on machine tools including many non-thermally related non-rigid errors. The system has been implemented on a PC and in two standard controllers [9, 10] for improved efficiency of application and reduced cost.

An error measurement and modelling methodology is briefly described which includes techniques implemented to facilitate model development and improve model accuracy offline and thermal imaging is an important part of this process. Hardware modification for permanent application of temperature sensors can then be implemented with confidence, requiring fewer validation tests and saving downtime. This is important for industrial applications.

A sample of results is presented for tests similar to those found in the ISO 230-3 standard and cutting trials. Typical accuracy improvements of greater than 70% are achieved for position independent and position dependent thermal errors including compensation for errors caused by environmental fluctuations.

Acknowledgements

The work contained in this paper has been supported by the EPSRC under the REDUCE (GR/R35186/01) and CAPM (GR/R13401/01) grants.

References