Practical application of thermal error correction
- 4 case studies
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Abstract

Thermal distortion of machine tool structures is widely recognised as a significant cause of component inaccuracy within modern CNC machining. It is difficult to develop a practical single compensation strategy which can deal with the different aspects of machine tool thermal behaviour. Systems which attempt to do this are usually complex and time consuming to implement. The approach adopted here is to devise a range of relatively simple error tracking techniques, and a formalised philosophy for determining which technique is appropriate in each case. The different techniques are illustrated by 4 case studies, and the application and effectiveness of each approach is discussed.

Introduction

Thermal errors in machine tools were formally recognised as a major source of workpiece error in the 1960’s [1,2]. Thermal errors are caused by temperature change of the machine structure which results in thermal deformation. There are three main mechanisms which produce structural temperature change:

- Heat generated internally by the machine - As energy from internal heat sources flows through the structure it produces significant temperature changes.
- Environmental temperature change - Change in the machine’s local air temperature will produce changes in the machine’s temperature.
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- Radiant external heat sources - Examples would be infra-red heaters or direct sunlight.

Most machine tools are subject to continuously changing operating conditions. They are rarely maintained at steady state and the heat generated internally will vary significantly as the machine is used. When this is combined with the effect of environmental temperature variation the result is that the machine tool structure is exposed to complex and changing temperature distributions. The complex structure of a machine tool and the varying temperature distributions produce thermal deformations that are difficult to quantify or predict.

A great deal of experimental work to quantify thermal errors has been carried out [3,4,5,6]. Researchers have produced distortions large enough to account for 75% of the total machining error [3,4,7].

The complexity of thermal errors has lead to the development of a wide range of approaches to attempt to reduce them. The designers of modern machine tools are aware of the affects of thermal distortion on machine performance and use modern technology and good design practice to minimise these effects. It would, however, be expensive and to a large extent impractical to attempt to eliminate all thermal errors through machine design. It is for this reason that thermal error compensation has become attractive as a cost effective solution to the thermal error problem.

Compensation is a process where the thermal error present at a particular time is corrected by adjusting the position of the tool and workpiece. Correction is normally achieved via the existing machine axes. The principal problem to be overcome when implementing a thermal error compensation system is to determine on-line the corrections required at a particular instant in time. A great many potential solutions to this problem have been investigated but it is possible to divide them into two broad categories of direct measurement and indirect measurement.

In direct measurement based systems the required compensation values are determined by making direct measurements of the error. Often normal machining is stopped and a probe is used to measure a datum on the machine [8] or a reference surface on the component or on a reference artefact [9,10,11]. Direct measurement can be very effective at correcting for slow changing thermal errors, but has the disadvantages of requiring potentially expensive additional measurement equipment and intruding on the production process reducing production efficiency.

In indirect measurement based systems the thermal error is calculated from measurements of some other parameter, most commonly temperature. This type of compensation system runs continuously as a background process and so does not interfere with the cutting process and production efficiency is maintained. In these systems temperature sensors are placed at a number of points on the machine structure, and a model is used to calculate distortion from these spot temperature measurements. Intuition and trial and error can
play a major part in deciding the number of sensors required and the optimum positions for the sensors. Also the models defining the relationship between temperature and distortion are developed entirely empirically \([12,13,14,15]\). These models may cope well with temperature distributions experienced during training, but their empirical nature means they may not be able to accurately predict distortion from temperature distributions that have never been experienced.

Most of the compensation systems developed have been applied to single machines as a means of proving concept. In most cases they could not easily and cost effectively be applied generally to machines of any type or structural configuration. For this reason the systems have not been adopted to any significant extent and thermal errors remain an important accuracy problem.

This research project has attempted to address these problems by developing a general methodology which would allow thermal error compensation to be applied to most types and configurations of machine tool quickly and cost effectively.

Our Research Philosophy

In order to overcome the weaknesses of previous techniques this research project has rationalised the process of applying thermal error compensation by splitting it into two phases. In phase one the thermal behavior of the machine tool is fully assessed. This provides an understanding of the magnitude and type of thermal errors present in the machine. It also allows the machine structural elements responsible for significant thermal errors to be identified. With this knowledge, phase 2, the choice and application of an appropriate error compensation technique is greatly simplified. A range of different error compensation techniques have been developed that are suited to correcting particular types of thermal error. In doing this it has been recognised that it is impractical to expect a single error compensation technique to perform adequately for all machines, all types of thermal error and all production processes.

Methods for Assessing Machine Tool Thermal Behaviour

A number of techniques have been developed to assess a machine’s thermal behavior, both for measuring machine temperature change and for measuring machine distortion. These techniques are briefly described below.

Machine Temperature Assessment Using Thermal Imaging

During this test a sequence of thermal images is recorded whilst the machine runs through a simple duty cycle. A machine tool can be considered as being made up of a number of discrete structural elements. Under normal operation
some structural elements will undergo greater temperature changes and so are likely to produce greater thermal errors. The recorded thermal images give a complete, high resolution picture of temperature distribution across the machine. They allow the machine structural elements that are likely to produce significant thermal errors to be quickly and easily identified. The thermal images can also be processed by computer to further aid the integration of thermal compensation to the machine.

**Machine Distortion Assessment**

In addition to the thermal imaging tests equipment is set-up to directly measure thermal distortion between the tool and workpiece. The equipment comprises of non-contact sensors that measure against a spindle mounted mandrel for measuring drift and a laser interferometer for measuring positioning change. The measurements are logged intermittently using a computer. The error measurements allow the relative magnitude and rate of change of different thermal errors to be determined. The measurements are also used in conjunction with the thermal image sequence to attribute thermal errors to particular structural elements.

As well as knowing the magnitude of the machine distortion it is also important to understand the ways in which thermal deformation of the structure affects workpiece accuracy. In general the thermal errors can be divided into two categories. The first category are those errors that change as a function of temperature but not axis position. These errors effectively change the machine offsets and are known as *position independent thermal errors* (PITE). The second category of errors are those that change as a function of axis position as well as temperature. They effectively alter the linear positioning of the machine and are known as *position dependent thermal errors* (PDTE). Defining these categories of thermal error has proved useful for further simplifying the problem and for helping to select the most suitable compensation technique.

The effect of a PITE on component accuracy is strongly dependent on the rate of change of the PITE relative to the time taken to produce a component. Even large changes in a PITE may result in little error if there is no significant change during the time taken to machine a component. A PITE can be particularly significant if the component is rotated as part of the manufacturing process and the distance between cuts made before and after rotation is critical, as any offset that exists between the tool and workpiece will produce double the error on the component when it is reversed.

A PDTE will produce component errors if the change in linear positioning of the machine does not match the change in linear positioning required by the thermal expansion of the component.
Thermal Error Compensation Techniques

This section outlines some of the compensation techniques that have been developed through the research. Each technique is illustrated by a case study.

Novel In-Direct Measurement Based Compensation

A distortion assessment of a 3-axis CNC machining centre identified a rapidly changing PITE in the Y direction. An initial investigation of the thermal images revealed that the error was produced mainly by thermal distortion of the headslide, which is heated internally by the main spindle bearings. The error was changing too rapidly to be tracked efficiently by direct measurement so a novel technique for determining compensation values from spot temperature measurements [16] was implemented.

A more analytical approach has been taken to in-direct measurement based compensation than that taken by previous researchers. Rather than use a single statistical model to relate temperature measurements directly to error two distinct models, the temperature model and the distortion model, are used to calculate compensation values.

The temperature model calculates temperature distribution from spot temperature measurements. Software has been developed which analyses a sequence of thermal images and automatically determines optimum sensor locations and optimum coefficient values for the temperature model. Normally separate models would be built for each significant structural element. A simple heating-cooling test with the thermal imaging camera focused on the structural element and recording images at intervals normally provides enough data to build an accurate temperature model. For this machine six spot temperature measurements were made along two lines on the side of the headslide at the level of the two spindle bearings. Measuring in-line with the spindle bearings is important as it is the movement of these bearings that determines the movement of the spindle. The temperature model was used to calculate the temperature distribution along the length of the two lines.

The distortion model is used to calculate thermal error from temperature distribution. It is usually analytically based but may feature some statistical tuning. Thermal image data and direct distortion measurements are used to determine the form of the distortion model, and to optimise and test the distortion model off-line using a computer. In this case the distortion model was simply based on the calculation of free expansion along the two temperature measurement lines on the headslide. This calculation is simply a function of the temperature distribution along the lines, the coefficient of thermal expansion of the headslide material and the geometry of the headslide. Statistical tuning was used to optimise the distortion model. This was required as parameters such as the coefficient of thermal expansion were not known exactly.
This technique was successful at determining headslide distortion even when the machine was excited by temperature distributions not experienced during the machine assessment phase. Its main advantage over previous systems is its ability to calculate thermal errors accurately using models built on data acquired during relatively short tests.

The graph below shows the results of this compensation technique applied to the machine headslide. These results were obtained from a heating and cooling test that lasted approximately 3 hours. The system works well with the compensation holding errors within a 10µm band. The rate of change of error has also been greatly reduced which should have a significant effect on workpiece accuracy. The models used are able to deal equally well with the temperature distributions produced by both heating and cooling.

Figure 1: Results of Temperature Measurement Based Thermal Compensation Applied to a Machining Centre Headslide

Implementation of Intermittent Re-datuming on a CNC Planing Machine

A CNC planing machine was being used to produce symmetrical parts. During planing the parts were supported in vees on two ground diameters, produced in a previous operation. The parts were planed on one side, rotated through 180° and planed on the other side. The machine user was having difficulty achieving the tolerance for the spacing between the faces produced before and after rotation, with errors as great as 100µm being experienced.

A temperature and distortion assessment of the machine found that the main thermal effect was a slowly changing PITE in the Z direction (i.e. the tool moving normal to the planed surface). Although the total change in PITE over an 8 hour period could be around 80µm the change over the time required to produce a single component was only around 10-15µm, much less than the 100µm being experienced.

A detailed study of the manufacturing process pin-pointed the problem. The error was produced as a result of the way the machine was referenced to
the workpiece. Although the machine was under CNC control the referencing process was carried out manually. Referencing was achieved by bringing the tool to a point 25µm away from a ground diameter. Whilst this worked well the referencing was only being carried out for the first workpiece in a batch, with the user relying on the stability of the machine for producing subsequent components. It may take several days to produce all the components in a batch during which time the machine could move significantly. As the workpiece was supported on a ground diameter any shift in the reference position produced a corresponding error in the workpiece. Reversing the component effectively doubled any error.

The PITE changed slowly and there was a single dominant direction of movement. Consequently it could be measured directly by probing at quite large time intervals, without causing any significant machining delays. In this particular case probing was not available on the machine but it was recommended that referencing be carried out for each new component and repeated immediately after the component was rotated. This has effectively solved the problem and the user has reported that components are now being consistently produced to specification with a corresponding increase in product quality and reduction in production costs.

Although this is a fairly simple case it illustrates the strength of gaining a thorough understanding of the machine’s behaviour and using this to decide on the best solution. In this case the solution was implemented at virtually no cost and resulted in reduced rework and scrap.

**Compensation for Linear Scale Expansion Using a Thermally Stable Bar**

In a 3-axis CNC machining centre a significant PDTE was experienced in one of the axes that produced a changing linear positioning error. The axis was fitted with a rotary encoder mounted on the servo motor, and the ballscrew was axially clamped at one end only with the other end being free to slide. As a consequence the ballscrew expanded freely when heated and was a major source of the PDTE.

The first stage in reducing this error was to fit a linear scale to the axis in order to remove the effect of ballscrew expansion from the positioning loop. This reduced the PDTE from a maximum of approximately 50µm to a maximum of 20µm for similar duty cycles. The scale had the additional effect of virtually eliminating the axis reversal error. As a general rule if thermal stability is required in an axis fitted with a free ended ballscrew then linear scales should be fitted to the axis.

With ballscrew expansion eliminated from the position loop the remaining PDTE was produced by expansion of the linear scale itself. To measure this expansion directly a thermally stable invar bar was mounted alongside the scale. The bar was clamped at one end and supported along its length on mounts that allowed axial movement. A non-contact displacement transducer measured relative movement between the free end of the bar and the scale. If
the PDTE is assumed to change linearly then the thermally stable bar gives a direct measure of the expansion of the scale.

Figure 2 shows the results of using the thermally stable bar to correct for scale expansion. The data shows the change in positioning error at the extreme of axis travel measured at intervals during the test. The changes were produced by a combination of environmental temperature change and heat produced by cycling the axis at 2 m/min.

Figure 2: Results of Direct Measurement Based Compensation for Axis Scale Expansion

![Graph showing movement in microns over time](image)

In this case the thermally stable bar gives a good measure of the error. Using a combination of a linear scale and the thermally stable bar allowed the change in linear positioning to be reduced to less than 10% of its original value.

In compensating for scale expansion the axis has been made thermally stable. In order for the machine to produce accurate components the workpiece must also be made thermally stable. The obvious way of doing this is to measure the temperature of the workpiece and, knowing the material properties, calculate the required correction. The ability of this machine to produce accurate components using workpiece thermal compensation was tested. A single aluminum block was used as the workpiece, and a series of three identical machining operations were carried out. The workpiece was initially placed in a refrigerator overnight to reduce its temperature to approximately 10°C. It was then mounted on the machine and its temperature was measured. This single temperature measurement was used in the compensation system to correct for workpiece thermal errors. Faces 300mm apart were produced with and without workpiece thermal compensation. The workpiece was then placed in a temperature controlled CMM room overnight to allow it to stabilise. The machining operation was repeated with the workpiece at the CMM room temperature, this operation acted as the control. The distance between the faces was then measured using the CMM. The results of this measurement are shown in table 1.
Table 1: Results of Workpiece Temperature Compensation

<table>
<thead>
<tr>
<th>Control</th>
<th>299.996 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without Workpiece Temperature Compensation</td>
<td>300.059 mm</td>
</tr>
<tr>
<td>With Workpiece Temperature Compensation</td>
<td>299.998 mm</td>
</tr>
</tbody>
</table>

For this idealised situation the compensation is very effective. Obviously it relies on the assumption of a uniform and invariant temperature distribution and how realistic this is in practice would require further investigation.

**Direct Measurement Based Compensation Applied to a CNC Lathe**

In this case a rapidly changing PITE was being experienced in the Z axis (axis parallel to the spindle) of a large CNC lathe. The temperature and distortion assessment of the machine identified thermal expansion of the spindle shaft as being the cause of this error. The spindle had a low thermal mass and was heated directly by the main spindle bearings. As a consequence it heated and cooled very rapidly. The spindle was supported in two sets of bearings. The rear bearing was fixed to provide axial location, while the front bearing was free to prevent the bearings being overloaded by spindle shaft expansion. This bearing arrangement caused the spindle to expand forwards out of the headslide, resulting in large machining errors.

Figure 3: Results of Direct Measurement Based Thermal Compensation Applied to a Large CNC Lathe

Normally when faced with a rapidly changing PITE temperature sensor based compensation would be used, as described in the first case study. In this case the most significant structural element was the spindle shaft and the rotation of the spindle made accurate temperature measurements difficult to obtain. An alternative technique was therefore developed based on continuous
direct measurement of the thermal error. An analogue non-contact displacement sensor was mounted on the machine headstock to measure on the back of the chuck, and provide a direct measure of relative movement between headstock and chuck. The signal from the sensor was used to provide a compensation signal for the Z axis drive. The results of applying the compensation for a heating and cooling duty cycle are shown in figure 3.

The system works well with the compensation holding errors within a 20μm band. As the technique is based on direct measurement it will cope with errors produced by any relative movement between spindle and headstock.

Conclusions

- Techniques have been developed which use thermal imaging and error measurement to rapidly assess machine tool thermal error behaviour.
- A general philosophy of machine tool thermal error behaviour has been formulated. This can be used to help in the analysis and categorisation of individual machines.
- A range of practical techniques have been developed to address the specific thermal problems of individual machine tools. These techniques have been applied to various types and configuration of machine tool and have been shown to work well.

References


