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Measuring and modelling thermal distortion on CNC machine tools

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Abstract

Heat sources internal and external to a machine tool cause temperature gradients to arise due to resistance to heat flow in and around the machine tool and workpiece. This causes linear expansion and distortion of the structural elements from which the machine tool is constructed. The connectivity of the structural elements sets the effect of the expansion and distortion on the relative positions of the tool and workpiece, leading to thermal errors on the workpiece. Measurement on a wide range of machine tools confirms that temperature gradients are significant in their effect on machining accuracy and that they move and change shape during the machining process.

An analysis of machine tool structures and connectivity shows that both the position and magnitude of temperature gradients is important in its effect upon the relative movement of the tool and workpiece. A bending model that estimates the effects of thermal distortion using knowledge of the position of the temperature gradient is derived. The performance of the bending model is compared with a finite element analysis model and a model that has no knowledge of the position of temperature gradients. Results obtained from a vertical machining centre show that knowledge of the position and magnitude of temperature gradients is an essential part of predicting thermal distortion accurately.

1 Introduction

The estimation of thermal movement of a CNC machine tool structure that causes error in the workpiece is a complex task. Direct measurement of the movement is very difficult due to the aggressive environment of the machining area, except under certain circumstances where probing is practical. Probing can be used to measure thermal movement, but this involves the interruption of the machining process and position-dependent thermal errors cannot easily be measured in this way. Indirect measurement can be used to measure a quantity that is related to the thermal movement of the structural elements and a model used to transform this to an estimation of that movement. Temperature sensors can be easily fitted to a machine tool structural element and can measure the surface temperature well. However, temperature gradients throughout the bulk of an element cause both expansion and distortion of the structure. Unless the magnitude and form of these temperature gradients can be identified, thermal movements cannot be accurately estimated. Allen [1] measured temperature gradients using a thermal imaging system whilst exercising the machine tool and modelled these using the inputs of just three temperature sensors. The modelled temperature gradients were translated into one dimensional machine movements using a simple distortion model. This technique was shown to work well over a wide range of duty cycles. This paper describes the expansion of the distortion modelling into two dimensions.

2 Estimation of thermal distortion in two dimensions

Machine tool structural elements can be viewed as simple rectangular blocks of varying aspect ratios connected together in different configurations. Allen modelled these in a purely one-dimensional way to estimate longitudinal distortion, and the angle of thermally induced tilt of one end of the block with respect to the other. However, it is well known that the temperature gradients that cause this tilt also induce a transverse component due to bending of the structural element. It should be noted here that a three dimensional treatment is unlikely to be required as major heat sources on structural elements are often largely symmetrical in at least one plane.

Knowledge of the position of a heat source along the length of a structural element is required in order to identify the transverse displacement due to bending. It can be seen in Figure 1 that the position of a heat source relative to the anchor point has a significant effect upon the amount of transverse movement due to bending. A heat source near the anchor point induces a much greater transverse movement due to bending than a heat source far away from it. The ability to calculate the deflection of a structural element with a varying temperature gradient along its length caused by more than one heat source, a heat source that is diffused, or a heat source that is moving is essential for the practical estimation of thermal error.

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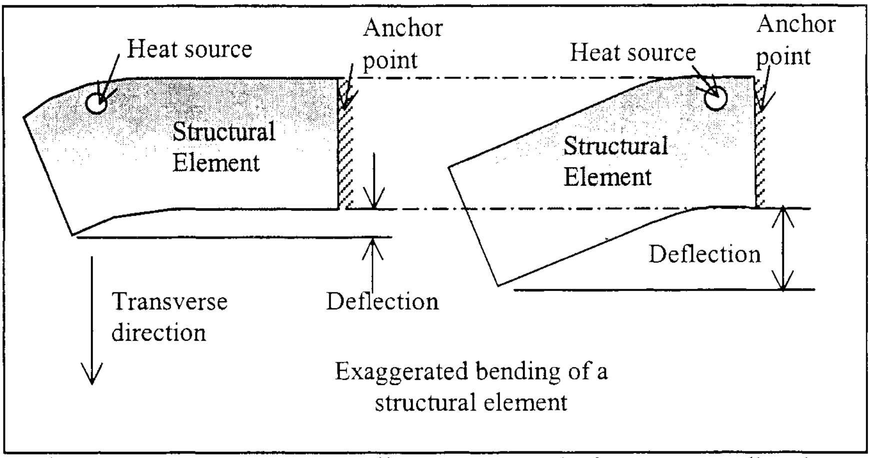

Figure 1: Heat source position affects movement in the transverse direction

The bending model considers a single structural element to be a simple beam with an anchor at the right hand side and bottom. The anchor represents the connection to another structural element or guide-way. The element is broken down into a number of thin segments, each of which has a linear temperature differential between its top and bottom surfaces as shown in Figure 2.

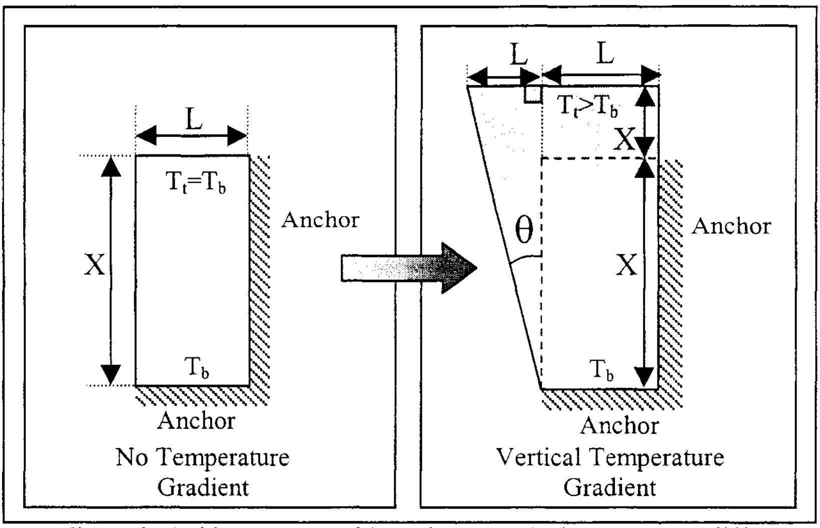

Figure 2: A thin segment subjected to a vertical temperature differential

This temperature differential causes expansion of the top of the element relative to the bottom, ΔL, and results in a loss of parallelism between one side of the segment and the other. The dimension X also grows by an amount ΔX. The anchor prevents movement of the right hand and bottom sides of the segment in

Figure 2, so the left-hand side exhibits an angular tilt θ. Simple geometry states that :

$$\tan\theta = \frac{\Delta L}{X + \Delta X} \tag{1}$$

However, if the expansion in the X direction (ΔX) is a small proportion of the total distance X :

$$\tan\theta \cong \frac{\Delta L}{X} \tag{2}$$

Also if ΔL is small in comparison with X, θ becomes small and this may be rewritten :

$$\theta \cong \frac{\Delta L}{X} \tag{3}$$

But ΔL is a result of the temperature differential between the top and bottom of the head, the length of the strip and the temperature coefficient of the material:

$$\Delta L = (T_t - T_b)\alpha L, \tag{4}$$

where: ΔL is the change in length due to the thermal expansion in µm,
T_t is the temperature of the top of the segment in °C,
T_b is the temperature of the bottom of the segment in °C,
α is the temperature coefficient in µm/m.°C,
L is the length of the strip in metres.

and so,

$$\theta = \frac{(T_t - T_b)\alpha L}{X} \tag{5}$$

If we then consider a new strip and move the anchor point to the left-hand side of the segment, but maintain the angle of tilt and perform the same calculation of tilt angle based upon the temperature gradient of this new segment, we get the arrangement shown in Figure 3. Note that the suffixes 1 and 2 have been included to distinguish the first and second segments.

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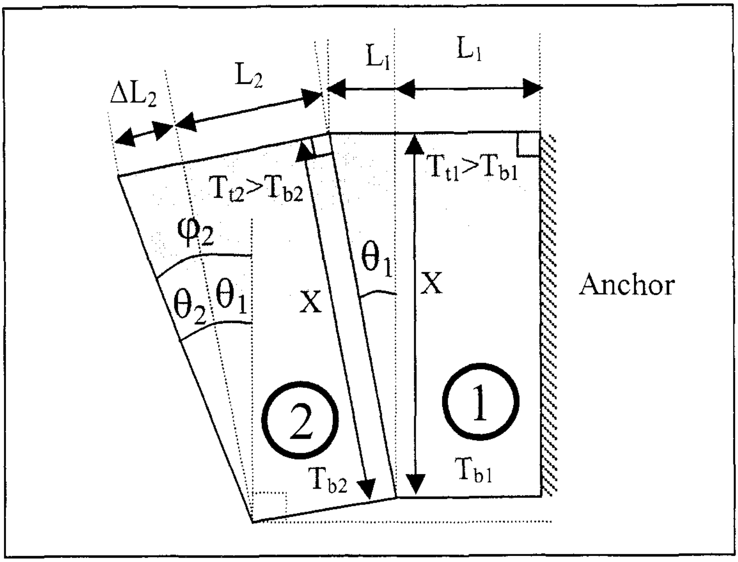

Figure 3: Two segments connected together

It can be seen that segment 2 creates a new angle, θ_2. However, the total angle of the left-hand side of segment 2, φ_2 is now $\theta_1 + \theta_2$. Thus the left-hand side of each segment of length L has an angular tilt which is determined by the sum of all the preceding tilt angles or:

$$\varphi_n = \sum_{m=1}^{n} \theta_m , \qquad (6)$$

where n is the number of segments.

It may be readily seen that as the tilt angle increases, so does the orientation angle of each segment. This results in a gradual translation of the structural element as the segments move further from the anchor. However, the angle added by the final segment does not cause a translation. This is shown in Figure 5.

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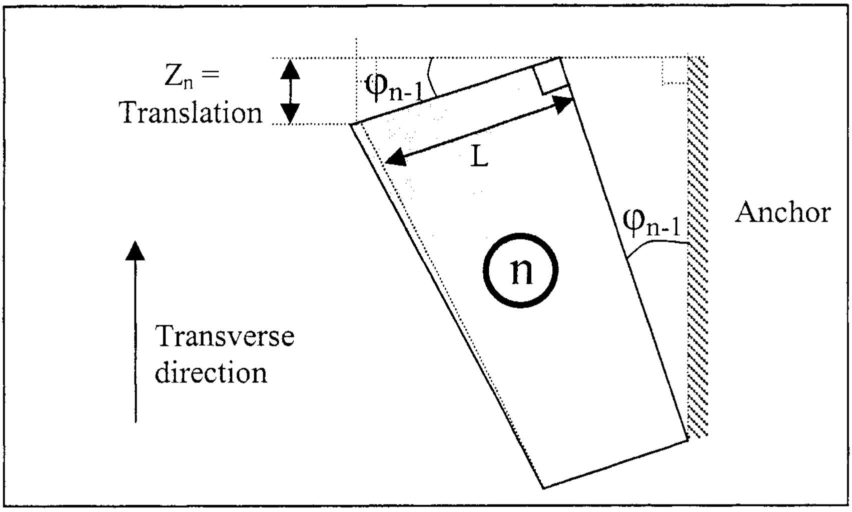

Figure 5: Translation of the structural element

The translation may be calculated for each segment using simple geometry because the right hand side of the strip is undeformed and so retains it's 90° angle, and the linear expansion of the small distance L is small. The translation angle of each segment is caused by the sum of the preceding angles, thus:

$$Z_n = L \sin \varphi_{n-1}, \tag{7}$$

where Z_n is the translation of segment n,
L is the length of the segment,
φ_{n-1} is the orientation angle of all the segments so far.

It is anticipated that the angle φ is always small on heated machine tool structural elements due to the rate of heat conduction from the top to bottom of the elements, and the large cross sectional area of the elements. Thus:

$$Z_n = L\varphi_{n-1} \tag{8}$$

and substituting for φ:

$$Z_n = L \sum_{m=1}^{n-1} \frac{(T_{tm} - T_{bm})\alpha L}{X} \tag{9}$$

Whilst the effect of the translation of each segment relative to the original anchor is small due to the small size of each segment and the small angle, the sum of the translations will produce a significant effect where temperature gradients are large. This is shown in Figure 7. It should be noted that the temperature gradients and all the angles shown are positive. It is entirely possible that the temperature gradient may be reversed at some point along the structural element, producing negative angles. The model presented will clearly deal with this situation and so may be regarded as general.

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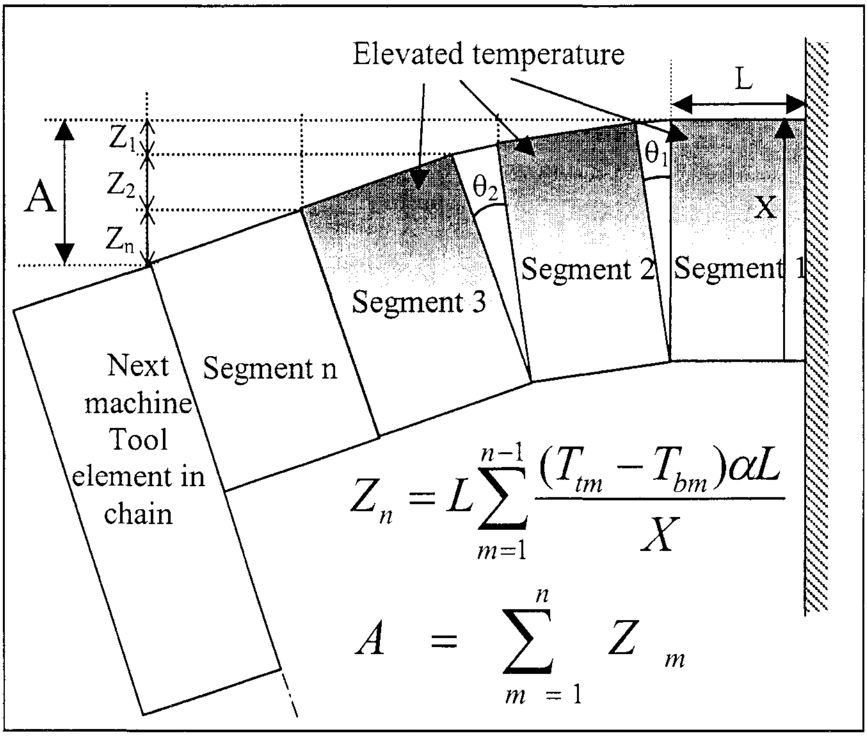

Figure 7: Completed bending model

3 Validation of the bending model

The bending model was compared with an analytical expression presented by Gim [2] which describes the transverse bending of a cantilever beam subjected to an average temperature gradient between its top and bottom surfaces:

$$v = -\frac{\alpha \Delta T}{2h} Z^2 \tag{10}$$

where : v is the transverse displacement,
α is the coefficient of expansion,
T is the temperature gradient between the top and the bottom of the beam,
h is the distance between the top and bottom of the beam,
Z is length of the beam.

It is important to understand the effect of a varying number of segments on the accuracy of the bending model. Thus a range of average temperatures were entered into the bending model developed here, which calculated the displacement of the end of a typical machine tool head, 420mm long and 215mm deep. This displacement for a varying number of segments along the beam was compared with those computed by the analytical expression, given in Table 1 and shows that the bending model consistently underestimates the bending by various amounts, according to the number of segments along the beam. Doubling the number of segments halves the error. This confirms that the percentage error of the bending model is reasonably low for a small number of segments along the beam over the temperature ranges likely to be seen on a machine tool.

Table 1: Comparison between the analytical bending expression and the bending model

Average Vertical Temperature Difference (°C)	Transverse deflection from Bending Model (µm)				Transverse deflection from Bending Expression (µm)	Underestimation of bending model (%)			
	Number of segments along beam					Number of segments along beam			
	7	14	20	1000		7	14	20	1000
2	-8.2	-8.9	-9.1	-9.6	-9.6	15	8	5	0
5	-20.6	-22.3	-22.8	-24.0	-24.0	15	8	5	0
7	-28.8	-31.2	-31.9	-33.6	-33.6	15	8	5	0
10	-41.1	-44.6	-45.6	-47.9	-48.0	15	8	5	0
13	-53.5	-57.9	-59.3	-62.3	-62.4	15	8	5	0

Practical tests have identified that temperature gradients exist not only in the transverse direction, but also in the longitudinal direction on machine tool structural elements. Thus a finite element model was developed using ABAQUS to compare the effect of complex temperature gradients on the bending model and the bending expression that has no knowledge of the position of the temperature gradients. Theoretical linear temperature gradients were applied to a beam 0.308m long and 0.122m high in both transverse and longitudinal directions, with the results shown in Table 2. It can be seen that the expression that calculates average bending works well where there is no temperature gradient between the front and rear of the head. However, this expression over or underestimates the bending where a significant longitudinal temperature gradient does exist. The bending model performs well over all the circumstances tested, even though a limited number of segments have been used in the calculation.

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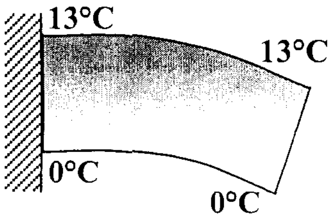
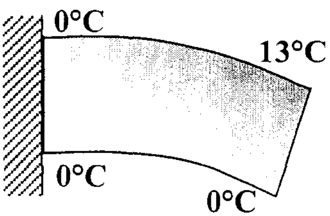
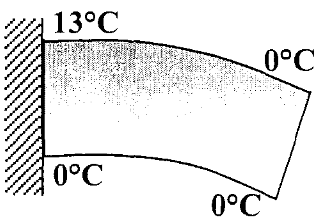
Table 2: Bending with a range of temperature gradients

	Average Bending 59.1μm FEA Bending 58.7μm (27x20 elements) Bending Model 58.5μm (27 elements)
	Average Bending 29.6μm FEA Bending 19.8μm (27x20 elements) Bending Model 18.3μm (27 elements)
	Average Bending 29.6μm FEA Bending 38.9μm (27x20 elements) Bending Model 38.7μm (27 elements)

Data from thermal images was used to compare the thermal movements of various parts of a machine tool head during a heating and cooling test. These expansion and distortion components are shown in Figure 8. It can be seen that the rate of change of the bending component is faster than all the other components, including the spindle growth, and that the magnitude of the bending component is almost equal to the spindle growth. The clear implication here is that the bending is significant when assessing the movement of the tool in the Z axis direction, particularly in situations where the spindle is impacted by significant amounts of coolant, causing its expansion to be limited.

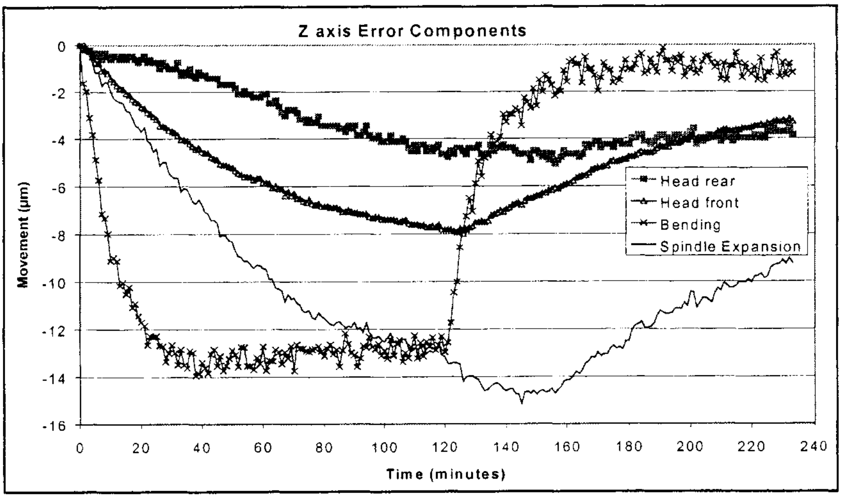


Figure 8: The Z axis error components

4 Practical application of the bending model

The bending model was applied to the Z axis of a vertical machining centre. A total of 58 temperature sensors in two lines of 29 were applied to the head. A 180 minute heating and cooling test was performed to identify an optimisation factor for the top and bottom temperature sensors lines. After optimisation, the machine tool was run through a wide variety of duty cycles with and without coolant present. The results are shown in Figure 9.

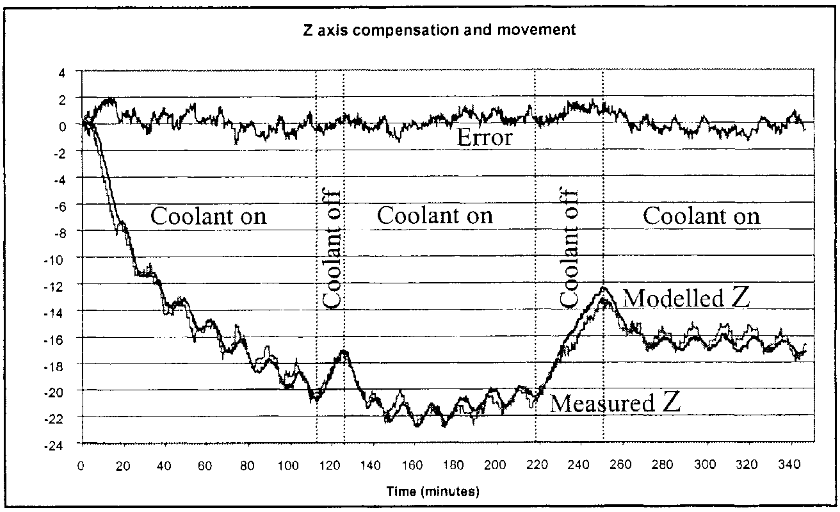


Figure 9: The bending model applied to a machine tool

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It can be seen that the bending model performs very well, with the residual unestimated thermal movement error range of approximately 3.5μm over a 6 hour test. Data recovered from the test was re-analysed to test the effect of using a bending model that has no knowledge of the position of temperature gradients to estimate Z axis movement. The results are shown in Figure 10. It can be seen that the model predicts the Z axis movement well except when the coolant is turned off. At these points there is a significant deviation of the estimated output of the model that is a large proportion of the total thermal movement.

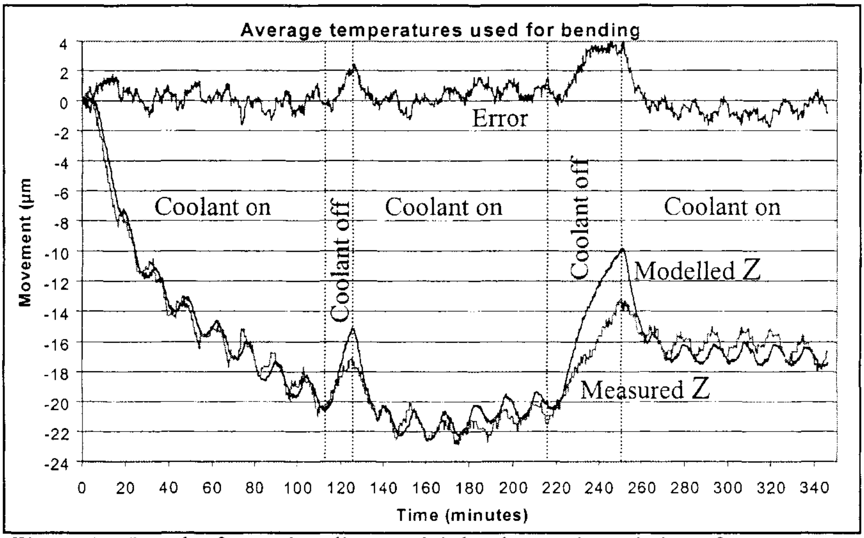

Figure 10: Results from a bending model that has no knowledge of temperature gradient.

5 Conclusions

The transverse effect of bending is important in its effect on machine tool thermal errors in terms of magnitude and rate of change. A simple bending model is able to predict the transverse effect of bending well in comparison with a finite element model. It is essential that a model that attempts to estimate the transverse effect of bending has a knowledge of the position and magnitude of the temperature gradient in machine tools. A model that did not have this knowledge exhibited significantly larger residual errors under certain conditions.

References

[1] Allen J P, A general approach to CNC machine tool thermal error reduction, PhD thesis, University of Huddersfield, 1997.

[2] Gim T, Modelling and evaluation of time-varying thermal errors in machine tools, PhD thesis, University of Cranfield, 1998.