AUTOMATIC COMPENSATION OF THERMAL DISTURBANCES IN MACHINE TOOLS

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This study deals with a practical method of reducing the effects of thermal disturbances upon the accuracy of machine tools by controlled feed adjustment of the tool. The spatial displacement between the cutting tool and the workpiece closely correlates with the temperature increase in the machine tool. The equation which describes the relation between the displacement and the temperature for a certain operating condition can be written as a linear combination of temperature values. One of the major conditions for the application of these equations is a good reproducibility of the thermal behaviour. The implementation of this method in a computerized numerical system is very simple. Experiments with lathes have shown that this way leads to reasonable results.

1. Introduction

The relative displacement between the cutting tool and the workpiece yields a machining error. The type and size of error depends on the progress of the displacement vector. A reduction of machining inaccuracy can be achieved if in process readjustment of the magnitude of the displacement vector but opposite direction is made.

The compensation method described below is based upon the fact that the characteristics of the thermal behaviour of any particular machine tool are more or less constant physical properties. Therefore the correlation between rising temperatures in a machine tool and the relative displacement between the cutting tool and the workpiece must also be stable for respective running conditions. De Haas [1] first suggested that this correlation can be determined experimentally. As the thermal behaviour is assumed to be reproducible within narrow limits its characteristics can be derived from measurements of temperatures and displacements. Once the relation between the temperatures and the displacements is known the tool position can be readjusted according to in-process gauging of temperatures thus compensating the thermal error [2].

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2. Theoretical Contemplations

The unknown function which actually describes the relation could be approximated in different ways. Fig. 1 is a plot of the axial displacement (z-coordinate) over the temperature increase in a spindle bearing. Data were taken

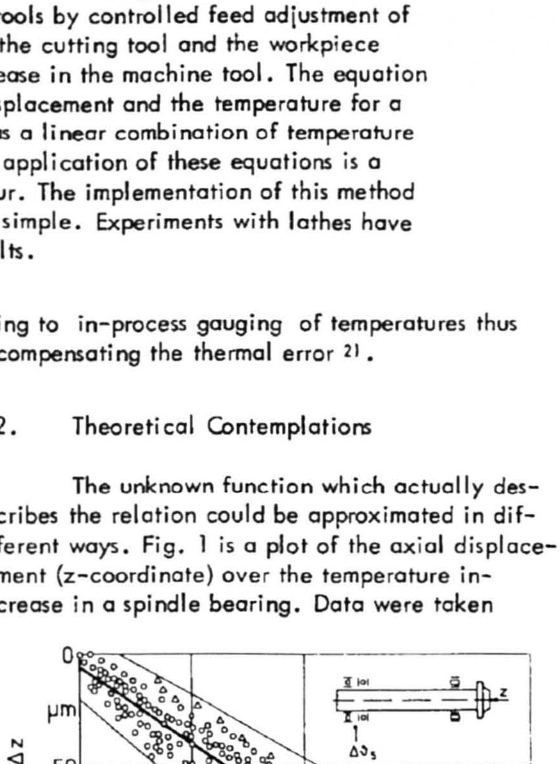

Fig. 1 Relation between the axial displacement and a temperature increase of a lathe for certain operating conditions

from experiments with a lathe at certain running times for different running conditions. Obviously all points scatter evenly around a regression line. Hence the axial displacement of this lathe could be approximated for all running conditions through the simple regression equation

$$\Delta z = -5.9 - 3.4\,\Delta\vartheta_5 .$$

In other instances the residual error for such a simple type of regression may be too large. When the displacement curves are like those shown in Fig. 2 for example where positive as well as negative displacements occur. As machine temperatures always increase steadily the displacement/temperature relation must involve effects of opposite direction with different time constants. A

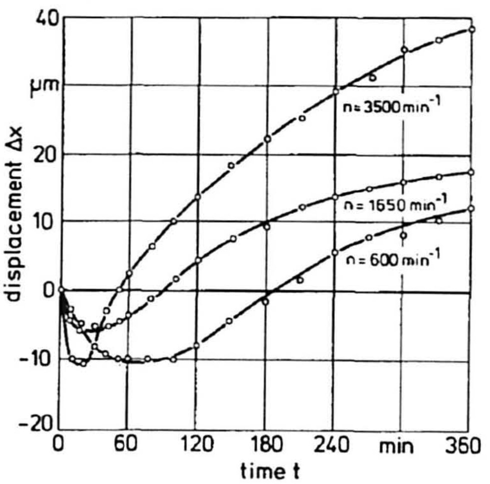

Fig. 2 Radial displacement of a high speed spindle

linear equation introducing only one temperature as one independent variable will be not sufficient in such a case. The function $\Delta x = f\,(\Delta\vartheta_j)$ can still be approximated by using either a linear combination of several machine temperatures or a non-linear equation for one temperature (for example a polynomial of degree k, k > 1). Especially in the latter approach the decision in which part of the machine tool this temperature is to be measured is crucial. As the thermal behaviour is dependent on inner and outer heat sources as well, the temperature difference in one measuring point will generally not suffice for computing a close enough regression.

When choosing temperature measuring points for a multiple linear regression one could attempt to sense all heat sources which possibly contribute to the overall displacement. But even if the location of all heat sources was known the necessary number of measuring points would be too large for practical purposes. System cost increase with every additional measuring points. Therefore the number should be minimized. For estimation of an appropriate number of measuring points the multiple correlation coefficient is a decisive figure. It can be computed after the regression coefficients for the least square fit have been determined. The square of the multiple correlation coefficient is that proportion of the total variation of the displacement which is explained through the regression. If, for example, a value of 90 per cent is desired, as many temperatures must be taken into the regression as required for this closeness of approximation. For a fixed number of measuring points the optimal combination of temperatures is that which yields the highest multiple correlation coefficient. A reasonable lower limit for the closeness of regression function and true function must correspond to the accuracy of tool positioning in the machine tool (smallest step, reversing tolerance, reproducibility).

The following example will illustrate the total procedure.

3. Experimental Results

On an NC-lathe the displacements were measured between a test mandrel and a set of non-contacting inductiv transducers fixed to the carriage. The set-up covered all five coordinates of the spindle dislocation and allowed direct estimation of machining errors. The temperature measuring system consisted of a copper bar with

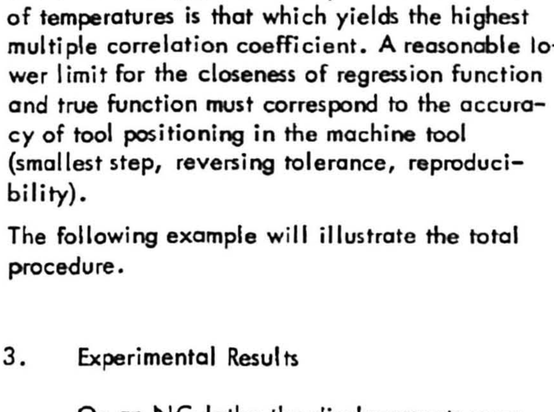

Fig. 3 Schematic view of the temperature measuring system

holes for copper-constantan thermocouples. The set-up is shown in Fig. 3 . The bar was bolted with its front end onto the gear box close to the rear spindle bearing where the highest increase of temperature was to be expected. An additional thermocouple was used to sense the ambient temperature. The runs for each ground idling condition were repeated several times. Fig. 4 is a plot of some displacement curves. For this particular machine tool the spindle displacement in the x-direction is small as compared to the y- and z-coordinates. Without limiting the method in general, it can be said that for this lathe a compensation of the x-coordinate would not be worthwhile. The displacement in y-direction may also be neglected because it does not affect the

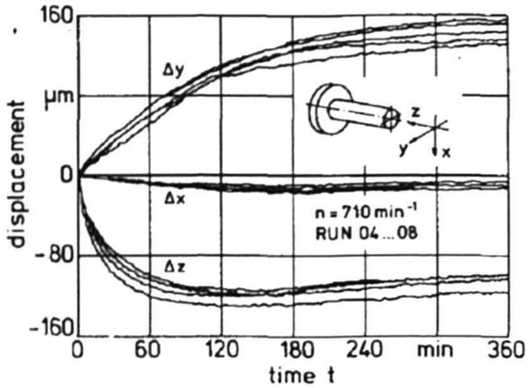

Fig. 4 Measured displacements of the spindle of an NC-lathe

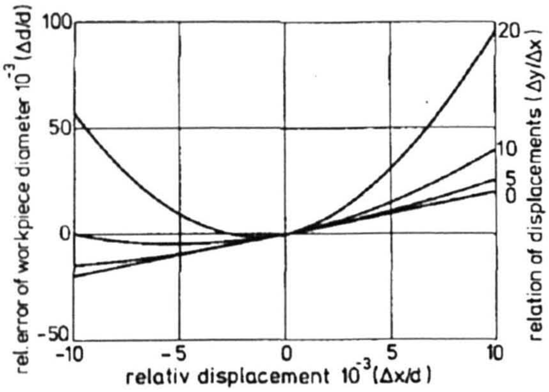

Fig. 5 Effects of the displacements in x- and y-direction to the error of the workpiece diameter

turning diameter significantly. The geometrical explanation for this is given in Fig. 5. The displacement in axial direction however is rather large and ought to be compensated. Otherwise the machine would have a low facing accuracy in automatic operation.

The diagram in Fig. 6 was obtained by plotting the z-displacement over two arbitrarily selected temperatures. The parallelism among the regression lines is an indication for the reproducibility of the measurements. It can be concluded from this example that the measuring points with high temperature increases are favourable in so far as the total deviation from regression lines is less than for lower temperatures.

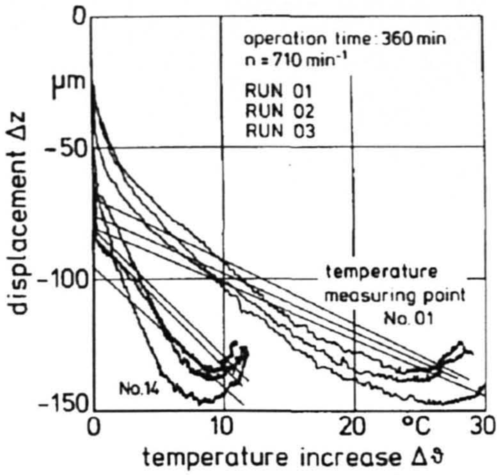

Fig. 6 Relation between the measured displacement Δz and several temperature increases

For the calculations a computer program for stepwise multiple linear regression (31) was used which performs an automatic preselection of temperature measuring points. The following table

regression step	temperature measuring points No					mean RUN 04 to RUN 08
	RUN 04	RUN 05	RUN 06	RUN 07	RUN 08	
1.	02	01	01	01	03	02
2.	10	10	10	10	10	11
3.	14	14	04	08	06	00
4.	04	04	00	04	00	10
5.	05	00	06	13	05	05
6.	12	09	11	05	14	14
7.	01	11	12	02	08	04
8.	11	07	03	07	12	07
9.	06	05	09	14	11	06
10.	03	02	07	00	04	03
11.	00	08	13	09	13	01
12.	09	12	14	06	02	09
13.	07	13	02	03	09	13
14.	13	03	05	12	07	12
15.	08	06	08	11	01	08

Table: Sequence of the number of temperature measuring points entered into the multiple linear regression

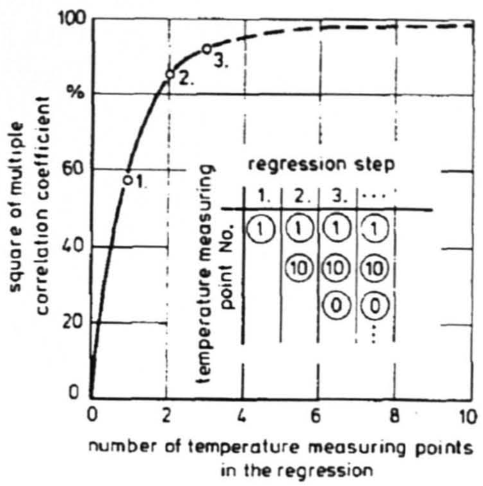

Fig. 7 Increase of the approximation degree in dependence of the number of the temperature measuring points

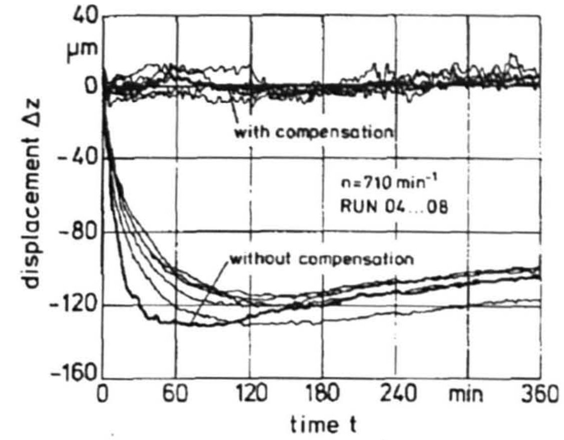

Fig. 8 Axial displacement of the spindle of an NC-lathe without and with compensation by using computer numerical control (CNC)

gives the sequence of temperatures entered into the regression for each of five repeated runs and for their mean values. In all cases regression with the first three temperatures explained already more than 90 per cent of the relation between the temperatures and z-displacement. The initial combinations always included a temperature measuring point close to the machine, one in the middle of the bar (involving transportation lag) and one sensing the ambient temperature influence. The increase of the multiple correlation coefficient for the temperature measuring points number 1, 10 and 0 is shown in Fig. 7. The equation of the mean multiple regression for this running condition is

$$\Delta z = -12.9 - 5.6\Delta\vartheta_0 - 16.8\Delta\vartheta_1 + 26.2\Delta\vartheta_{10}.$$

Fig. 8 shows the measured z-displacement curves of residuals taken after regression. The standard deviation of the approximation for each run is between 3.8 µm and 6.7 µm. The stronger line of this figure was measured during probative run for this operation condition. A software program based on the above regression equation implemented the computer numerical control (CNC) for the thermal compensation. Throughout the running time of six hours all remaining axial displacements were beyond ±10 µm. When using just three temperature measuring points the cost for metering equipment as well as the amount of occupied computer memory is extremly small.

4. Summary

Experiments with an NC-lathe have shown that the relation between the spindle displacement of the cutting tool relative to the workpiece and temperature increases in the machine tool can be expressed in form of linear equations. The constant coefficients are determined by multiple linear regression. The implementation of these equations in a computerized numerical control system leads to reasonable results. When using this compensation method for the above mentioned respective condition, the remaining axial displacement was beyond ±10 µm. Due to the geometrical explanations the radial displacements in x- and y-direction may be neglected.

References

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2) R. Ichimiya, K. Yokoyama and Y. Watanabe: Experimental Study on Thermal Deformations of Machine Tool, Research Report of the Faculty of Engineering, No. 25, Niigata Univ., (Jan. 1976)
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