Volumetric measurement of machine tool thermal deformation using an MT-Check probe

M. Moravek, J. Bures, O. Horejs
Czech Technical University in Prague, Faculty of Mechanical Engineering, Research Centre of Manufacturing Technology, Prague

Abstract

This paper is concerned with volumetric measurement of machine tool thermal deformation. For this purpose, a new method was developed including a measuring apparatus and software for processing the results. Using this method, it is possible to measure the deviation of the relative position of the tool to the workpiece. This deviation is caused by temperature change during machine tool operation. Deviations are measured alternately in several points of the working space in the form of a space vector. Using an interpolation method, a time variant field of deviation vectors is reconstructed. Temperatures of the load-bearing structure near the machine's internal thermal sources as well as some machine parameters are recorded during the measurement tests for further analysis. A series of tests performed have clearly shown that the value of thermal deformation of a machine tool depends on the position of the machine tool's axes in the working space and on the machine tool operating time. The results from the measurements tests clearly indicate that further research into this area is needed.

1 Introduction

The heat produced during the operation of a machine tool causes undesirable deformation of the machine tool structure. Thermally induced deformations cause deviation of the relative tool position to the workpiece and lead to the degradation of machine tool working accuracy. In practice, thermal effects on machine tools are measured and evaluated according to a standard, for example, ISO230-3 [1] or ASME B5.54 [2]. The measurement is performed using a precision mandrel clamped in the spindle. Position and orientation of the mandrel is sensed during the test using five linear displacement sensors mounted in a special fixture. This means that the measurement takes place at one position in the working space, usually in the middle, assuming that deformations are the same in the rest of the workspace. Since the heating of the machine tool structure is mostly asymmetrical, there are consequently asymmetrical deformations of the machine tool structure, which cause irregular changes of machine tool´s geometrical errors [3]. As a result we can expect significant changes of the final volumetric error throughout the whole machine tool´s working space.

The issue of the thermal behaviour of machine tools is solved by many different approaches [4], which focus on the following topics: measurement of temperatures and displacements (especially displacements at the tool centre point), computation of machine tool thermal errors and their reduction using thermomechanical transfer functions [5], machine tool temperature control using intelligent cooling system [6], and also a large number of FEM computations of machine tool thermal errors, including both temperature distribution and displacements [4].

The literature review shows that the relationship between the changes of volumetric error and machine tool´s thermal behaviour has not yet been comprehensively studied.

2 Development of the testing method

A measurement method was developed for testing and evaluating thermal effects on changes in machine tool volumetric error. The method allows volumetric measurements of thermally induced deformations at multiple points located throughout the workspace, with sufficient accuracy and speed to cover actual thermal state.

The measuring method consists of an MT-Check probe in combination with a ball-beam artefact, or separately placed balls. The reference ball centres represent points at which deformation will be measured.

2.1 Spindle and artefacts fixture

It was necessary to design special fixtures for mounting the measuring device on the machine tested. The main objective in the fixture design was to minimize thermal expansion and achieve sufficient rigidity.

Since it was planned to test the effects of the machine´s main internal heat sources (spindle and axes motors, ball screws and nuts, linear guideways) on the change in volumetric accuracy, it was necessary to design a spindle fixture which allows placing the MT-Check probe coaxially with the spindle axis as well as free rotation of the spindle. The spindle fixture consists of two steel plates connected by carbon composite tubes. The top plate is screwed to the headstock. The MT-Check is bolted to the bottom plate as well as an eddy current probe, which measures the axial deformation of the spindle rotor to the headstock body. See Figure 1. The same carbon composite tubes were used for artefact fixture design. Several lengths of artefact fixture tubes were made for variable placing of the artefact. The composition of the carbon fibres in composite tubes was chosen in order to minimize thermal expansion. Thermal deformation of the spindle fixture was experimentally tested with very good results. An axial elongation of approx. 2 μm was measured for a temperature increase of 20 °C. A layer of cork with a thickness of 1 mm was added between the layers of carbon fibres to improve damping properties of the tubes.

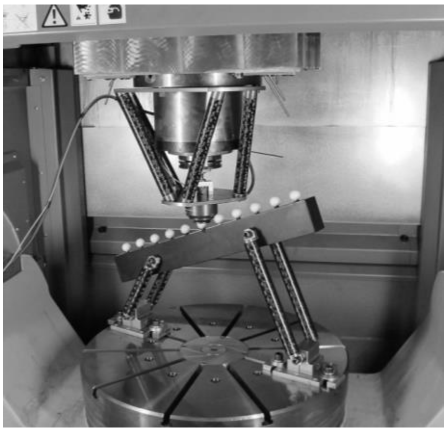

Figure 1: Spindle and artefact fixture mounted on tested machine.

2.2 Data acquisition and processing.

A comprehensive solution of the influence of thermal deformation on volumetric error changes requires combining a large amount of data from several different sources. A scheme of data acquisition and processing is shown in Figure 2.

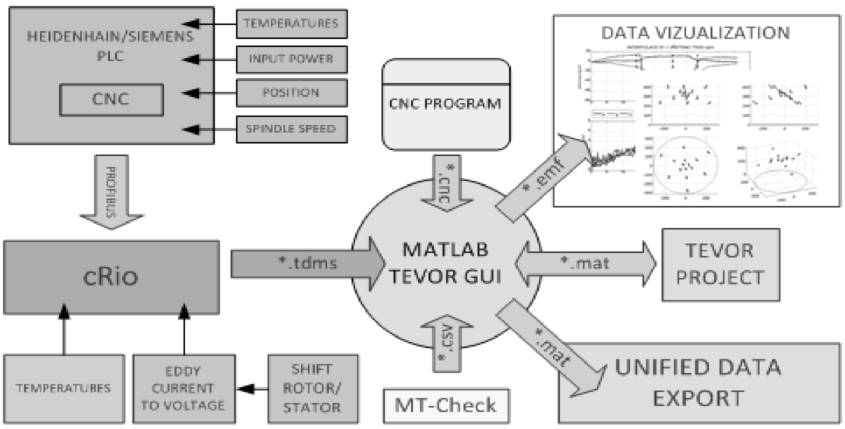

Figure 2: Scheme of data acquisition and processing.

It contains information about deformation measured by the MT-Check probe, coordinates of reference balls and time courses of variables that could correlate with the deformation vector. The variables are temperatures of main sources of heat, ambient and working space temperature, input performance of each motor, feed rate, and spindle speed. Processing of all input data is realised in the TEVOR software programmed in Matlab. TEVOR allows importing data from the MT-Check, identifying measuring moment on the ball and using the CNC code to find a specific reference ball. This data is then interpolated to the time course, which shows the change of deformation vector in each measuring point. Time courses of deformation vector changes are also synchronised with time courses of measured temperatures and other important data. Such processed data can be used for visualisation creation or exported to Matlab interface for further analysis and calculations.

3 Testing

Tests were carried out on a five-axis vertical milling centre with a tilting and rotating table. The machine tool axis configuration was CAFYXZ. See Figure 3. Important machine parameters are listed in Table 1.

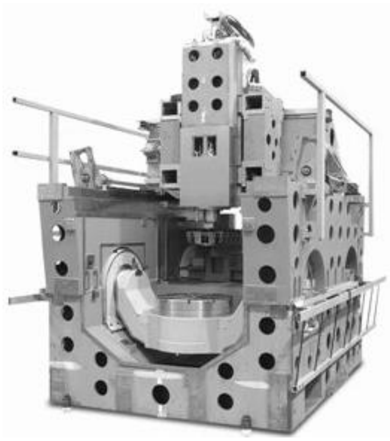

Figure 3: Structure of tested machine

Table 1: Parameters of tested machine tool.

Control system	iTNC 530
Taper	ISO 50
Spindle speed/rpm	20 ~ 10 000
Spindle power/kW	20/26
X axis travel/mm	700
Y axis travel/mm	820
Z axis travel/mm	550
A axis travel/°	-30 ~ 120
C axis travel/°	unlimited

3.1 Tests layout

A ball beam artefact with 11 balls was used for measurement. In order to cover a bigger part of machine tool working space, the artefact was oriented by the C axis to three positions, divided by 120°. In every position, only 5 chosen balls were measured to decrease measuring time. In total, 15 points were measured, regularly spaced in the machine tool´s working space. Feed rate of the measuring movement was 2 000 mm·min^{-1}. This feed rate has not a significant influence on temperature increase of a machine tool structure. In this configuration with a feed rate of 2 000 mm·min^{-1}, one measuring cycle took 4 minutes and 20 seconds, which is sufficient to capture one instantaneous thermal condition.

3.2 Tests condition

A series of measurements was carried out on the tested machine. The measurements tested the impact of long-term operation of internal heat sources separately. The influence of spindle rotation at low and high speed was tested, as well as movement of machine tool linear and rotary axes. All parameters such as feed rate, spindle speed, time duration and period of deformation measurement during measurement are listed in Table 2. The whole test was separated into two parts. The loading part where the machine was heated up until steady state, and cooling down part where the machine cooled down close to ambient temperature.

Table 2: Parameters of tests performed.

Loaded component	Feed rate /mm·min^{-1}	Speed /rpm	Travel /mm /°	Loading		Cooling down	
				Time /hour	Mes. period /minute	Time /hour	Mes. period /minute
Spindle		500	-	10	10	12	10
Spindle		7 500	-	10	10	12	10
X axis	10 000	-	600	10	15	12	10
Y axis	10 000	-	600	10	15	12	10
Z axis	10 000	-	570	10	15	12	10
A axis	3 000	-	150	15	15	15	10
C axis	5 000	-	360	15	15	15	10

4 Results

A series of measurement was performed to test the influence of individual heat sources on volumetric error changes during long-term operation.

4.1 Influence of spindle rotation

The influence of spindle rotation on volumetric error changes was tested at low (500 rpm) and high (7 500 rpm) speed. The maximum deformations caused by the spindle rotation at high speed exceeded the value of 100 µm. Figure 4 shows vectors of volumetric errors at measured points in steady state, which occurred after about 8 hours of spindle rotation. The differences in volumetric error in measured points are small. The maximum difference reached a maximum of 10 µm.

Small differences in volumetric errors in the individual measuring points are probably due to a limited spread of heat in the headstock structure. Heat spreads gradually from the spindle motor and bearings into the headstock body. Temperature rise can also be seen on the temperature sensor located on the ball nut of the Z axis. The temperature increase is only in the order of few units of degrees. The temperature sensor placed on a machine tool crossbeam did not sense any changes in temperature. Thus it can be assumed that the deformation will be caused mainly by thermal deformation of the headstock. The headstock moves as a whole body and hence deformation should be the same throughout the workspace.

A second test of spindle rotation influence was performed at a speed of 500 rpm. Nevertheless, the measured temperature at low and high speeds does not differ much; the deformations at low speeds are lower. This may be caused by a difference in the displacement of the rotor relative to the stator. The mutual displacement of the stator towards the rotor after being heated reached the values of 40 μm at high speed, while at low speed it was only approx. 15 μm.

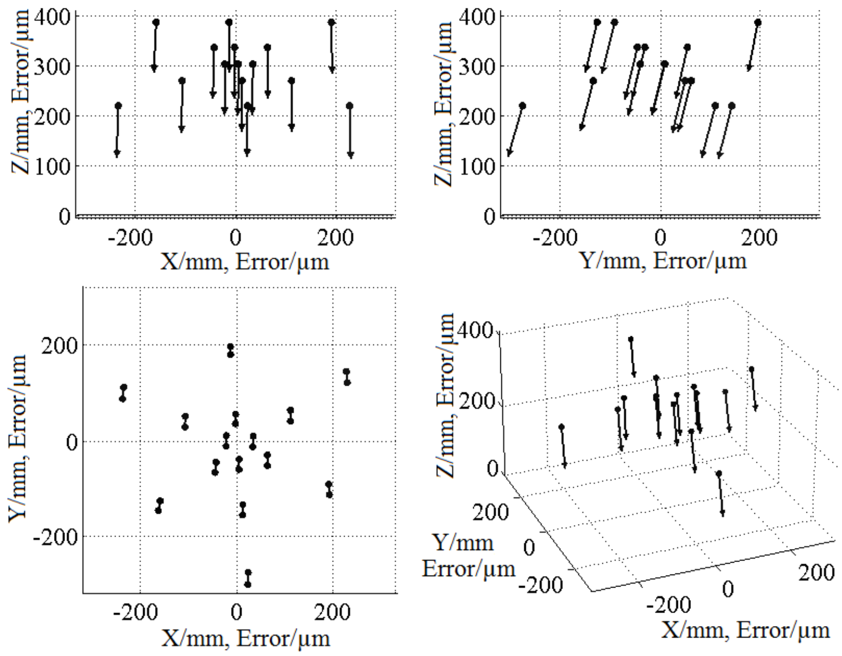

Figure 4: Spatial representation of the deformation vectors - steady state, rotation of the spindle 7 500 rpm.

4.2 Influence of machine tool axis movement

Thermal loading of the machine tool using long-term movement of individual linear and rotary axes caused significantly smaller deformations than spindle rotation. The values of deformations were similar for all machine tool axes. In contrast, the directions of the volumetric errors vectors varied considerably. Figure 5 shows the spatial representation of the volumetric error vectors in individual measuring points captured at steady state, which occurs 14 hours of loading by Y axis movement. The maximum value of the deformations exceeded 30 µm. The maximum difference in the magnitude of volumetric errors in individual measuring points is about 30 %. In particular, the different direction of the individual vectors, mainly observable in the XY and XZ planes, is of interest.

The results are similar for the remaining machine tool axes. They differ primarily in the spatial orientation of the volumetric error vectors and partially in their size.

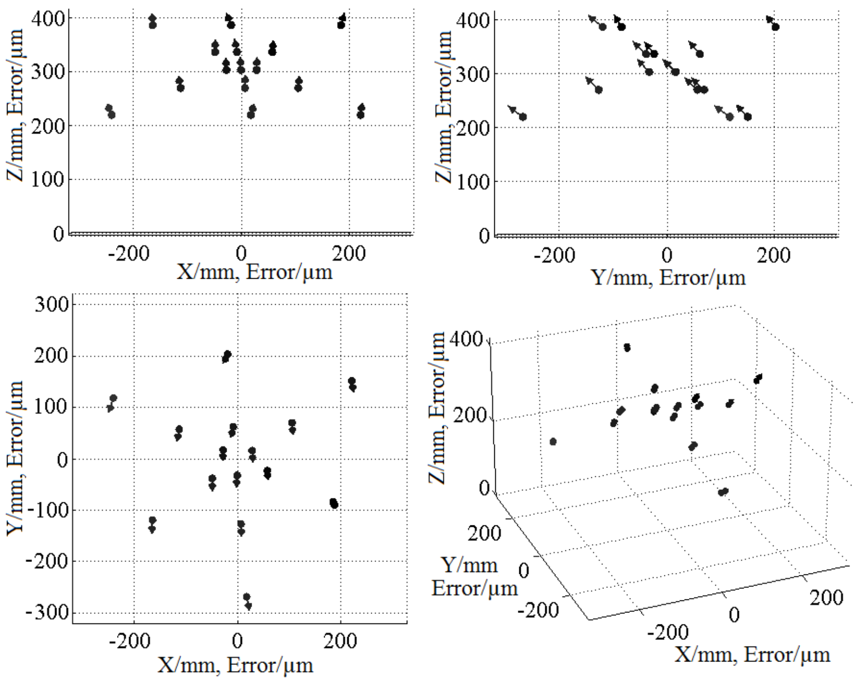

Figure 5: Spatial representation of the deformation vectors - steady state, Y axis movement.

5 Conclusion

Based on the measured results, it can be argued that thermally induced changes of volumetric error are not constant in the whole volume of machine tool working space. They depend on the position of the machine tool axes and also on loading time. Magnitude of the volumetric error change also depends on the source of heating. Very small differences between volumetric error changes in

all measured points were detected when loading was realised by rotating spindle. In contrast, if the linear axis were used for loading, considerable differences between volumetric errors changes measured in individual points were detected.
Also, functionality of the developed method was verified for volumetric measurement of thermally induced deformations of machine tools.
The next step is to perform similar tests on different types of milling machines and also to identify an appropriate method for the creation of software compensation based on measured data.

6 References

[1] ISO 230-3, Test code for machine tools - Part 3: Determination of thermal effects.
[2] ASME B5-2005, Methods for Performance Evaluation of Computer Numerically Controlled Machining Centers.
[3] G. H. Florussen, F. L. Delbressine, M. J. van de Molengraft a P. H. Schellekens, Assessing geometrical errors of multi-axis machines by three-dimensional length measurements, Measurement, 2001.
[4] J. Jedrzejewski, E. Uhlman, A. M. Donmez, W. Knapp, F. Hartig, K. Wendt, T. Moriwaki, P. Shore, R. Schmitt, C. Brecher, T. Wurz a T. Wegener, Thermal issues in machine tools, Manufacturing Technology 61, pp. 771-791, 2012.
[5] O. Horejs, M. Mares, P. Kohut, P. Barta a J. Hornych, Compensation of machine tool thermal errors based on transfer functions, Modern Machinery (MM) Science Journal, pp. 162-165, 2010.
[6] J. Hornych, P. Barta a M. Mares, Thermomechanical transfer functions and control of a machine tool cooling system, Modern Machinery (MM) Science Journal, pp. 96-97, 2009.

7 Acknowledgements

The results have been obtained as part of the TE01020075 Competence Center – Manufacturing Technology project supported by the Technology Agency of the Czech Republic.