

CALCULATING THERMAL LOCATION AND COMPONENT ERRORS ON MACHINE TOOLS

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ABSTRACT

The thermo-elastic deformations of machine tools caused by internal and external heat sources can contribute more than 50% to the overall geometrical inaccuracies of the workpiece [1]. Machine tool manufactures see in mastering thermal effects a key competence on the way to more accurate workpieces. Therefore measurement, numerical simulation and methods for compensation of thermal errors of machine tools moved increasingly into the foreground of latest research activities.

Demonstrative examples illustrate the advantages of observing the entire workspace of machine tools for thermal compensations during operating. Today machine tool controls are able to compute values for compensational movements based on thermally induced component and location errors.

With the effective simulation approach Finite Differences Element Method (FDEM) [2] and the advantages of linear systems of equations it is feasible to compute the spatial compensation values with the introduced method in real time.

INTRODUCTION

Mastering the influences resulting from temperature gradients and temperature changes on machine tools is of capital importance on the way to more exactness on workpieces and to improved process stability during manufacturing. Therefore a lot of work in measurements, numerical simulation and compensation of thermal effects on machine tools is done in latest research activities. Nevertheless all of these attempts are mostly based on just a few positions in the workspace.

Most of the numerical simulations are presented in the past are done with standard finite element software packages. The computation time of transient problems with the finite element method (FEM) is often huge. Kim et al. [3] developed separate models for the machine tool and for the linear scales which turned out to be the main thermal error source.

Wu et al. [4] just modeled the ball screw spindle to compute the thermal effect on a machine centers feed drive system.

In compensating thermal effects two different essential ways are applied. On one hand thermal deformations at the tool centre point (TCP) are reduced via design modifications. In this case commonly no controlled actuators are operating. On the other hand the TCP position is readjusted by controlled actuators [5]. Controlled actuators are commonly the machine tools feed drive system but also other actuators are used. E.g. plane heaters and cooling jackets [6].

The effective simulation approach FDEM allows computing the thermally induced TCP-displacements on machine tools with a three-dimensional physical model of the whole machine tool in real time [5]. Knowing the thermally induced TCP-displacements in the workspace modern machine tool controls are then able to readjust the position with the machine tools feed drive system.

MOTIVATION

It is often reported that compensation models for thermally induced TCP-displacements only consider measurements at one position in the workspace of machine tools. Nevertheless measurements and numerical simulation results of the thermally induced TCP-displacements at different positions in the work space have pointed out that the absolute value and the sign may vary substantially. In Figure 1 the measurement setup used for a five-axis-milling machine prototype to detect the TCP-displacements in several positions of the A-axis and the corresponding measured relative displacements in X-direction are diagramed.

The second example in Figure 2 shows the positioning error EYY of a three-axis-milling machine at different times during an operation loop. The computations are based on a FDEM simulation model of the machine tool.

Both examples illustrate clearly that it is necessary to consider more than one axis

position if a model is used to compensate thermal effects in the whole machine tool workspace with high accuracy.

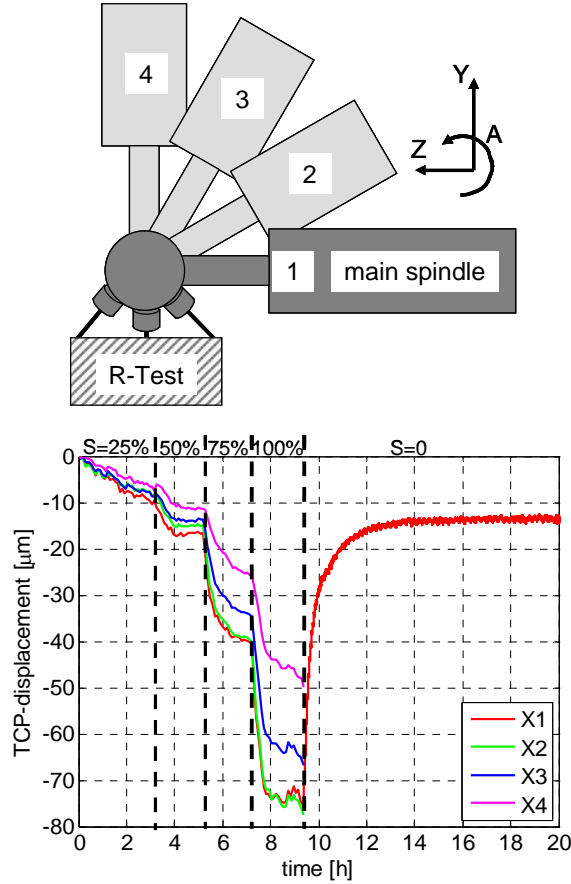


FIGURE 1. Top: measurement setup for a five-axis-milling machine. Bottom: thermally induced TCP-displacements in X-direction caused by rotating main spindle at different speeds (S).

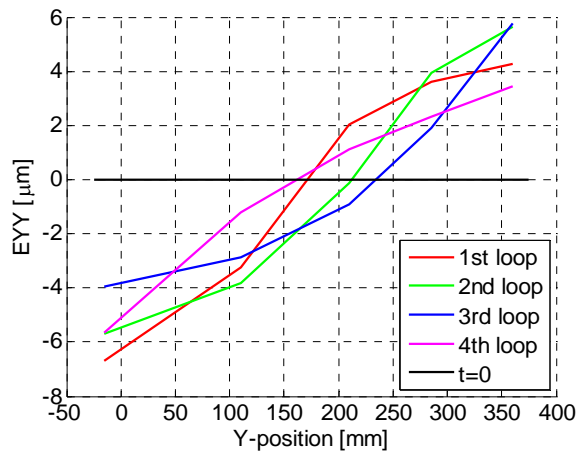


FIGURE 2. Numerical simulation result: Thermally induced positioning error EYY of a three-axis-milling machine without a linear scale during an operation loop.

REDUCING SYSTEMS OF EQUATIONS

For the computation of the thermally induced deformations with FDEM a linear system of equations (1) has to be solved [2,5].

$$\underline{M} \cdot \underline{u} = \underline{T} \quad (1)$$

Where \underline{M} is the system matrix, \underline{u} are the nodal displacements and \underline{T} is the temperature vector.

To compute the thermally induced deformations usually the whole mechanical structure, in this case the machine tool, is analyzed. In fact, for compensation just the displacements at the TCP are required.

Methods like substructure technique or elastic foundation, known from the Finite Element Method (FEM), allow reducing a large system of equations into smaller systems when just a reduced number of degrees of freedom have to be obtained. Nevertheless using these methods for equation (1) the right hand side vector \underline{T} has to be manipulated before the reduced system can be solved. An alternative way is to create a system like equation (2) where the right hand side vector \underline{T} does not require manipulation before the system can be solved.

$$\underline{u} = \underline{M}_{red}^{-1} \cdot \underline{T} \quad (2)$$

For large systems the inverse of the matrix \underline{M}^{-1} can not be handled with moderate effort. For small systems and if from a large system just a few degrees of freedom are required \underline{u} can be computed very effectively via a matrix-vector multiplication. Considering the second case just the required lines \underline{M}_{red}^{-1} of the inverse \underline{M}^{-1} have to be computed. \underline{M}_{red}^{-1} can efficiently be computed by solving equation (3).

$$\underline{M} \cdot \underline{M}_{red}^{-1T} = \underline{E}_{red} \quad (3)$$

\underline{E}_{red} are the required columns of the identity matrix.

COMPUTING TCP-DISPLACEMENTS

For a universal milling machine the manufactured workpieces and the used tools are wide ranged and mostly unknown to the compensation model builder. Instead of considering the geometry of the workpiece and the tool a global geometrical model can be used to compute the displacements at the TCP. In Figure 3 the calculation scheme for the tool-side TCP-displacements is illustrated. An equal model is used to compute the workpiece-side

TCP-displacements with known deformations of three nodes of the table.

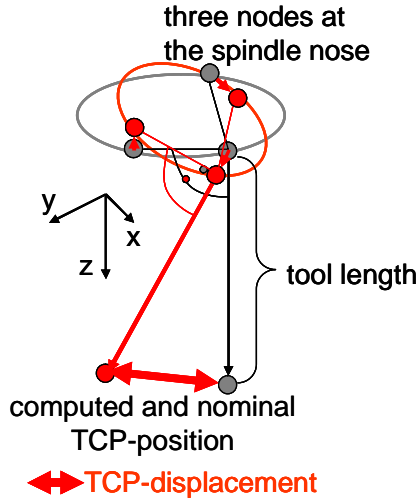


FIGURE 3. Computation scheme of the tool-side TCP displacement based on tool length and the displacements of three nodes at the spindle nose

EXAMPLE 1: THERMAL LOCATION AND COMPONENT ERRORS OF A THREE-AXIS-MILLING MACHINE

Bringmann [7] developed a method to compute the location and component errors of a three-axis-milling machine by measuring the deviations with a 3D-ball plate. His measuring results are the deviations at a 3-D space lattice. Using this method to compute the thermal component and location errors of a machine tool it is necessary to get the thermally induced TCP-displacements in the workspace from different FEM models at a 3D space lattice also. With the FDEM the machine tool is meshed in a way that different positions along the traverse path of the axes can be modeled and the interaction between the elements of the feed drive system parts do not lose there validity. This enables to compute the TCP-displacements at defined axes positions in the workspace with different FEM-models of the machine tool and a given temperature field. The FEM-models are arranged in a way that the computed results give the TCP-displacements in a 3-D space lattice of the machine tool workspace. From the displacements in the space lattice the component and location errors of all three axes are derived.

As illustrative example for the method the positioning error EYY along the Y-axis is explained. The 3-D space lattice is shown on the right hand side in FIGURE 5; caused by the

different axis length five positions are used in X- and Y-, three positions are used in Z-direction. In a first step the Y-deviations along the Y-axis at the corresponding 15 lines in the X-Z-plane are computed. Thermal deformations can change the zero position YOY what is representing a Y-movement of the 3-D space lattice according to the machine tool coordinate system. Therefore first the computed EYY of all 15 lines have to be reduced by the average value of the corresponding line.

$$EYY_{new}(X, Y, Z) = EYY(X, Y, Z) - \frac{1}{5} \sum_{i=1}^5 EYY(X, Y_i, Z) \quad (4)$$

The positioning correction value EYY_{cor} of a Y-position is the average of the 15 errors in the X-Z-plane computed with (4).

$$EYY_{cor}(Y) = \frac{1}{15} \cdot \sum_{i=1}^5 \sum_{j=1}^3 EYY_{new}(X_i, Y, Z_j) \quad (5)$$

EXAMPLE 2: THERMAL LOCATION AND COMPONENT ERRORS OF A ROTARY AXIS OF A MACHINE TOOL

A similar procedure described for linear axes is used to compute thermal location and component error for rotary axes. Several FEM-models with different axis positions of the rotary axis are used to compute TCP-displacements in defined positions. The example in Figure 5 illustrates the procedure with the pictured model of a B-axis of a machine tool in Figure 4.

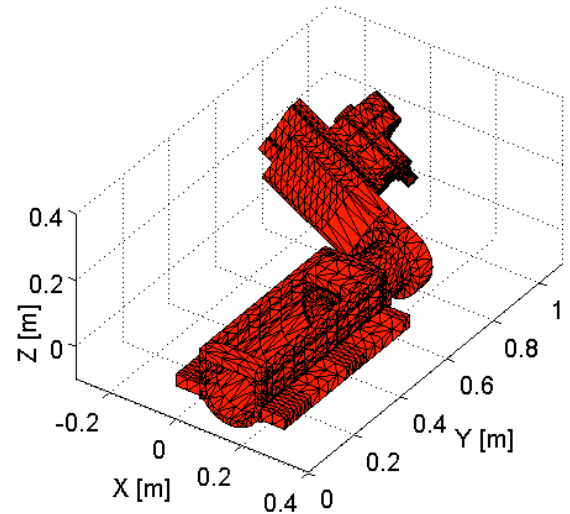


FIGURE 4. Model of the B-axis.

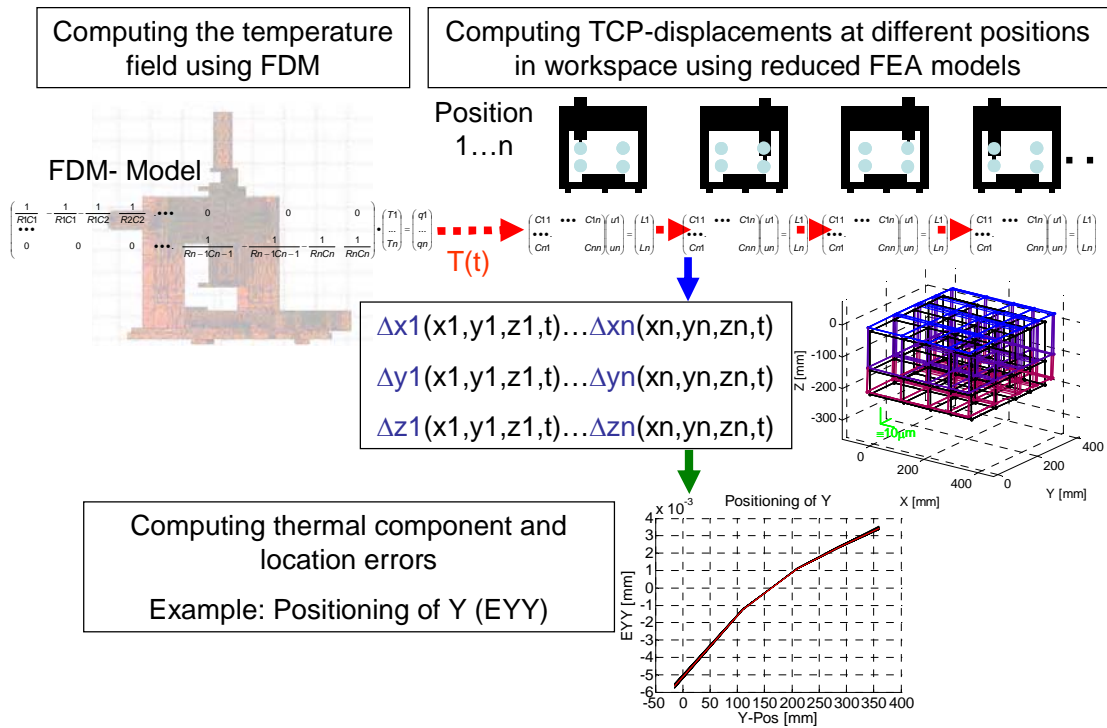


FIGURE 5. Schematic of the procedure: Illustrated by computing thermal component and location errors of a three-axis-milling machine

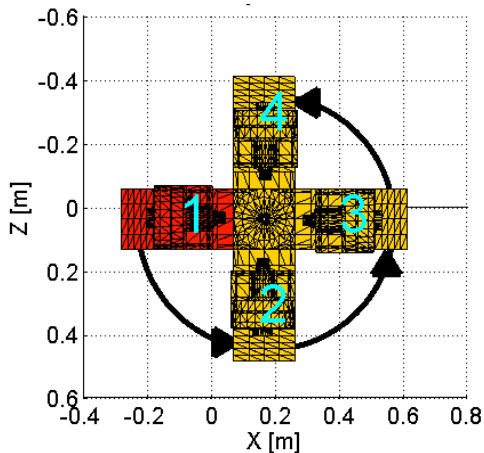


FIGURE 5. Test cycle of rotary axis

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