Compensation of Thermal Effects on Machine Tools using a FDEM Simulation Approach

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Abstract

The operating accuracy of metal cutting machine tools is finally based on the accuracy of the relative movement between the work-piece and tool. If this relative movement is, because of any disturbance, inaccurate, an error is directly reproduced on the work-pieces [1]. A lot of experimental work was done to quantify thermal induced errors based on work-pieces. The results are reported in literature and it can be seen that thermal effect in machining can contribute to up to 70% of the overall geometrical inaccuracies of work-pieces [2].

The Finite Difference Element Method (FDEM) is a very effective simulation approach which was especially developed to calculate the transient thermal behaviour of mechanical systems such as machine tools. The FDEM combines the advantages of Finite Difference Method (FDM) and Finite Element Method (FEM). The transient temperature distribution is calculated very efficiently using the FDM. The FDEM uses FEM to obtain thermally induced deformations [3] from a given temperature field.

With the advantage, that for a compensation model of a machine tool only the displacements at the TCP (tool centre point) relative to the work-piece coordinate system are important, the linear system of equations of the FEM can be reduced to remaining six nodes to calculate the relative TCP-displacement in the relevant five degrees of freedom. Such a small system of linear equations allows the FDEM to be used for calculation of thermal compensation values in real time.

A compensation model of a small three-axis milling machine is given as example, which shows the use of the FDEM for compensating thermally induced TCP-displacements caused by a moving linear axis. It is able to compute the temperature distribution and TCP-displacements in real time. The

example compares the calculated TCP-displacements with measurements, thus verifying the quality of the compensation method before the model is installed on the machine tools numerical control.

1 Introduction

To reduce thermal errors on machine tools and also on coordinate measurement machines nowadays two essential approaches are discussed [2], namely via design modifications and without any controlled actuators or by compensational movements of some controlled actuators.

To improve the thermal behaviour of machine tools via design modifications without any controlled actuators it is important to realise where thermally induced TCP-displacements arise by reason of temperature distribution on defined load cases such as spindle running or moving linear axes. With the international standard ISO 230-3:2001 a systematic way to analyse the thermal behaviour of machine tools is given [4].

To forecast in future thermal effects of machine tools during early stages of development, before a prototype is finished, thermal simulation of machine tools moves into the foreground of newer research activities. A lot of work was recently done to develop simulation models to compute the thermal behaviour of machine tools spindles and feed drive systems based on FEM [5-10].

A hybrid model of a high-speed precision machining centres headstock based on the two computational methods FEM and FDM was developed to determine its optimal operating characteristics in detail. The simulation allows to evaluate thermal and structural properties of a machine model [11]. Other authors developed a modified lumped capacitance method (MLCM) to model the heat flux in CNC (computer numerical control) machine tools feed drive systems, solving with FEM [9,12].

The thermal compensation methods with controlled actuators are mostly based on behaviour models. Some of these developed methods are able to handle simultaneously detected temperatures. The used algorithms are wide ranged:

- linear behaviour models
- neural networks
- fuzzy logic
- Bayesian networks [13]
- ...

Some models are considering the thermal behaviour of the entire machine tool, others are just considering parts of the machine tool. An overview to the developed methods is given in [14]. To compensate a 3-axis machine tool with a mathematic model consisting of PT-1 and PT-2 elements a model with 495 parameters, which have to be determined by measurements and a fitting procedure, was presented by Brecher [18].

The feed drive systems of machine tools are often used as controlled actuators to compensate thermal deformations. A concept called “intelligent machine” was presented where the controlled actuators are heat and cooling jackets on the machine tools structure. The advantage of this method is that deformations in five degrees of freedom can be compensated on three-axis machining centres [14,15].

2 FDEM, a staggered algorithm

The FDEM is a staggered algorithm which is especially developed to calculate the transient thermo-mechanical behaviour of mechanical systems such as machine tools. The basic idea is to combine the advantages of FDM and FEM. The solving problem is thereby separated into two steps.

In the first step the FDM is used to solve the multidimensional temperature distribution of the system to be analysed. If transient simulations are necessary the results of these calculations are the temperature distribution of the system at discrete time points in the simulation time. These time points can either be predetermined by the operator or chosen based on mathematical rules by the software package (solver e.g.) if it can handle variable time steps. The temperature distribution in steady state can also be calculated easily with the same system used for the transient simulations by solving the system with setting all heat flows to zero.

Because of different boundary conditions acting on the FDM-nodes the values of the elements of the FDM-matrix system is varying with a huge spread. Therefore normally solving the transient temperature distribution with a FDM-system is a stiff system of differential equations in time. It is advisable to use in such cases special developed implicit numerical integration methods with variable time step to solve the system effectively. The savings of computation time in comparison to explicit methods with constant time steps can be enormous.

After calculating the transient temperature distribution of the mechanical system the FDEM uses finite elements to solve the thermally induced deformations. The FEM is well investigated and often used for solving problems with deforming bodies. But there is another important reason why choosing FEM in this case: As mentioned above the results of the FDM step are the temperature distribution at discrete time points in the simulation time. Every temperature distribution results in the FEM system of equations in a load vector on the right hand. All the vectors on the right hand side can be collected into a right hand side matrix and solved collectively.

Solving such an equation system needs just very little additional computing time. Therefore the saving of computation time can be enormous. As example the computing time (Z) for the Gauss elimination is given by equation (1) [16].

$$Z = \frac{1}{3}(n^3 + n) + m \cdot n^2 \qquad (1)$$

Where n is the size of the matrix and m is the number of vectors on the right hand side. It can be seen that the computing time is given by the size of the matrix with the term n^3 and the numbers of vectors on the right hand side have just an influence of the weighted n^2.

Figure 1 points out the procedure of the FDEM simulation approach.

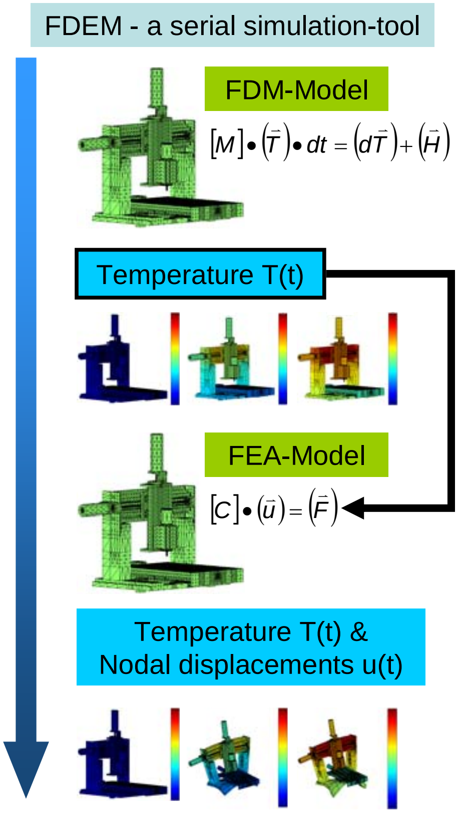

Figure 1: schematic of the FDEM; here: M = FDM model matrix, $d\vec{T}$ = temp. change, $\vec{H}$ = constant vector, C = FEA model matrix, $\vec{F}$ = thermal forces

3 FDEM for compensation

3.1 Calculating deformations in workspace

Bringmann [17] developed a method to identify all component and location errors of machine tools using a 3D ball plate artefact. His artefact originally is a 2-D ball plate which is supported with several spacer elements with different highs in the workspace.

With every spacer element the positions of the spheres are measured using a CMM. Based on this measurement the deviation of each ball with every spacer element from the required position is calculated. On this way the deviations in three directions at discrete points in a "3-D space lattice" are obtained.

3.2 "Thermal location and component error"

The method can therefore be used to calculate the "thermal component location errors" of a machine tool if the deviations of the TCP are known in a 3D space lattice. Originally the 3D ball plate was used for geometrical calibration of machine tools. For this, rigid body motions had not to be considered. Thermally induced deformations on machine tools can induce rigid body motions between the work-piece and tool. Therefore the method has to be modified that it can also handle rigid body motions.

3.3 Deformation on a 3D space lattice

3.3.1 Calculating TCP-displacements in work-space

The FDEM simulation approach presented in section 2 is used to calculate the temperature distribution and thermally induced deformation of machine tools.

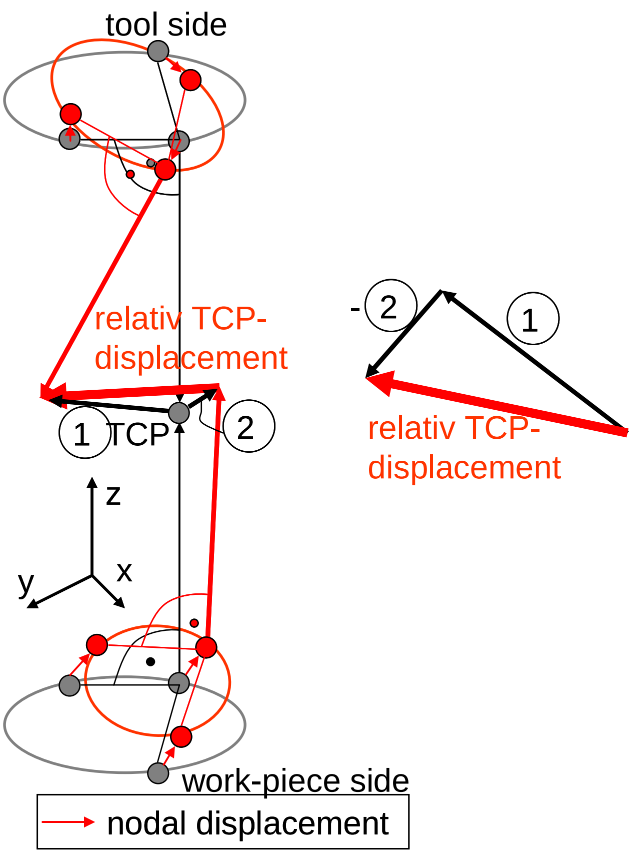

Figure 2: calculating relative TCP-displacement

If the approach is used to calculate values which enable actuators such as machine tools feed drive systems to compensate for thermally induced deformations just the information of the TCP-displacement is required.

With methods like “substructure technique” and “elastic foundation” known for the FEM one can eliminate degrees of freedom in a linear system of equations. In the second step the FDEM uses a linear system of equations to solve the thermally induced deformations. This system can be reduced to 18 degrees of freedom, three translatoric components of motion for three nodes on the tool side and three nodes on the work-piece side. The relative motion around the spindle axis is normally omitted. Figure 2 illustrates the calculation of the TCP-displacements.

3.3.2 More than one FEM model required

To calculate the TCP-displacements at the points of the 3D space lattice a FEM-model is built up for every point. In Figure 3 the building of the 3D space lattice is illustrated. All systems of equations of the FEM models are reduced to 18 degrees of freedom ($M_1 \dots M_n$).

Using a staggered algorithm it is possible to use the results of the first step, the temperature distribution, as input for more than one following model. In the first step the temperature distribution $\overline{T}$ in the machine tool is computed, using FDM. The TCP-displacements ($u_1 \dots u_n$) on every lattice point with this temperature distribution is calculated in the following step.

$$\begin{pmatrix} u_1 \\ \dots \\ u_n \end{pmatrix} = \begin{bmatrix} M_1 \\ \dots \\ M_n \end{bmatrix} \cdot \overline{T} \quad (2)$$

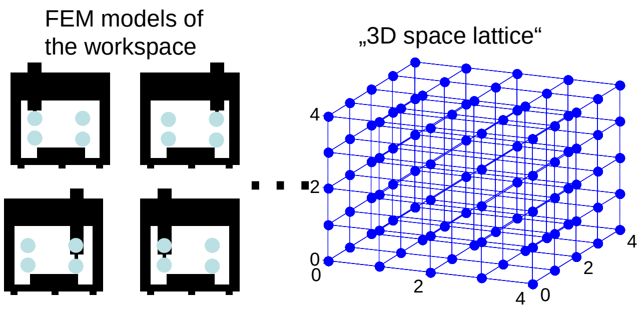

Figure 3: Building the 3D space lattice

3.4 Consideration of measurement results

As in the look ahead of a NC control the relative thermal displacements of the TCP in the future can be computed based on the information of the NC program with its set points for the spindle speed, the feed rates. From these the set points for the positions of the actuators can be modified such that the relative TCP displacement will be zero, when the nominal position is reached.

But there are other important conditions that impact the thermally induced TCP-displacement: These values, the environmental temperature profile for example, can not be estimated in advance and have to be measured. Therefore the compensation model of the machine tool must be able to handle temperature measurements. Such measurements are then set as boundary conditions in the FDM model of the machine tool. Figure 4 illustrates the procedure.

4 Example: compensation of a three-axis milling machine

The method was tested on a three-axis milling machine shown in Figure 5. To compute the "thermal location and component errors" a 3D space lattice with 125 lattice points was chosen. Considering the kinematics of the machine tool the TCP-displacements at the 125 lattice points can be calculated with 29 reduced FEM models of the machine tool. 25 models are needed for the points in the y-z-plane to compute the tool side displacements and five models are needed to compute the table side displacements along the x-axis. One of the models can be used to calculate tool side and table side displacements (25+5-1=29). For every position in the y-z-plane only three degrees of freedom are important (25x3=75). To compute the table side displacements for every position along the x-axis the displacements of three nodes in three directions are important (5x3x3=45). Finally only 120 (75+45) degrees of freedom are required to get the spatial TCP-displacements at the 125 lattice points.

To test the procedure the TCP-displacements and boundary conditions for a thermal load case during the operating time is measured. For a finishing operation we reproduced the compensation procedure on standard PC which has nearly the same power as available on a standard machine tool control. As time step, to update the compensation values, ten minutes was chosen, based on measurements previously carried out. In Figure 6 the calculated thermally induced TCP-displacements after six hours machining time with an augmentation factor of 6'000 are shown. These calculated values are compared with measurements at five locations in the work space and have shown a good correlation. After numerically applying the compensation scheme based on location and component errors the remaining maximum TCP-displacements have been reduced by a ratio of 50.

5 Conclusion

Based on the approach presented above, the spatial thermal TCP-displacements can be estimated on line and transferred to the NC in location and component error formulation.

As next steps towards a broader industrial application of the method presented here which by principle is capable to represent the spatial thermal behaviour of machine tools, the simulation models have to be improved. The improvements required primarily concern the introduction of detailed models covering the internal heat sources, boundary conditions, temperature dependent component properties and influence of cooling lubricant.

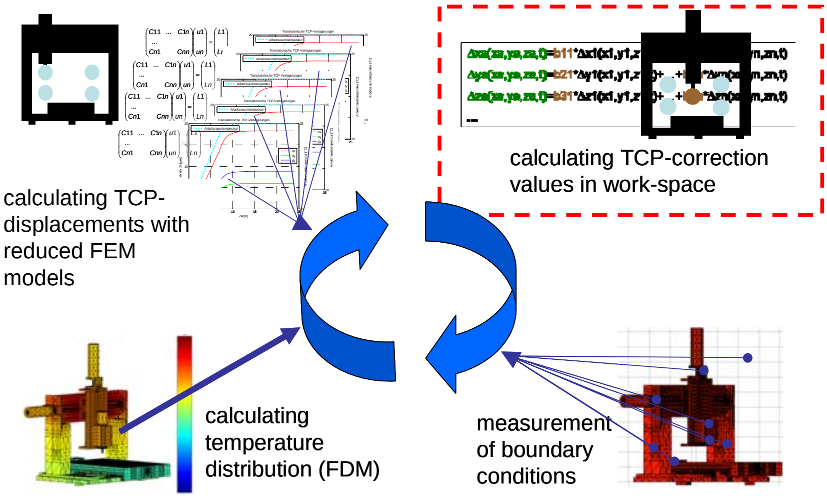

Figure 4: compensation procedure

Figure 5: Three-axis milling machine

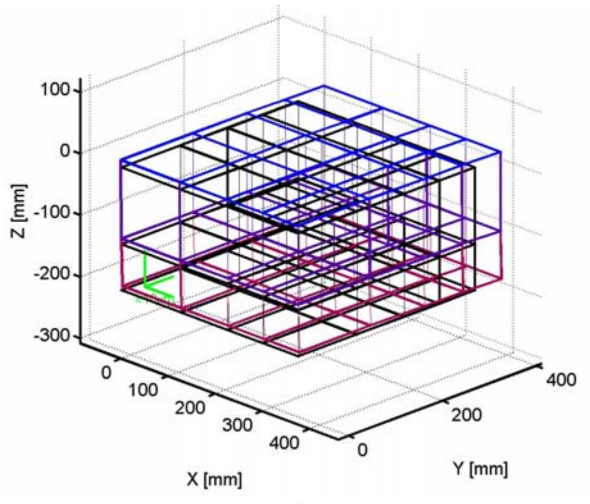

Figure 6: Calculated TCP-displacements in workspace, before compensation distortion is shown with an augmentation factor of 6’000

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