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Structure Model Based Correction of Thermally Induced Motion Errors of Machine Tools

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Abstract

The article describes a correction approach for thermally induced motion errors of machine tools that utilizes physically based models of the thermal and thermo - elastic behavior of machine tools. After a classification and presentation of the functional principle of the model based approach functional core aspects, possible implementation variants and resulting requirements regarding the control are clarified. Examples are presented for which the functionality of the approach was proved and evaluated as well as compared to other model based thermal correction approaches.

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Keywords: thermal error; machine tool; correction; compensation; structure model; control; online

1. Introduction

The accuracy of machine tools significantly depends on thermo-elastic errors. Up to 75% of the error of the manufactured workpiece leads back to thermo-elastic errors [1]. The error changes slowly in accordance with the transient temperature field of the machine tool. On the one hand, thermal errors dominate the overall error of the machine tool [2]. On the other hand, there is a significant energy consumption of cooling and temperature control of the machine [3] as well as of air conditioning of the environment. Model based corrections of thermo-elastic errors are a solution to increase the machine accuracy without additional energy consumption. Mainly three possible model based approaches are known: characteristic diagram based correction (CDBC) [4], transfer function based correction (TFBC) [5], [6] and structure model based correction (SMBC) [7], [8].

Characteristic diagrams describe the correlation between measured temperatures, axis positions and the displacement at the tool center point (TCP). The characteristic diagrams are determined based on a database of

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measured or simulated temperatures at chosen positions and the according displacement of the TCP. The measured temperatures contain the transient thermal behavior of the machine tool. TFBC uses transfer functions, e.g. first order lag elements, to determine the displacements based on technological loads like velocity and motor current. These data usually can be gathered in the control. The transfer functions are fitted to input data and displacement captured in measurements or simulations. The transfer functions simulate the transient thermal behavior. CDBC and TFBC reach their best correction results for load cases which are used to determine the characteristic diagrams or to fit the transfer functions.

A structure model is a physically based model of the thermal and thermo-elastic behavior of the machine tool. Physically based models describe physical properties and behaviors like heat capacity, thermal conduction, heat flow, power loss caused by friction etc. In this way the transient thermal behavior is simulated. One kind of physically based model is finite element model. The model is used for correction of thermo-elastic errors at the tool center point (TCP) in the whole workspace. Therefore, the model has to be calculated in thermal real time. The necessary input data are gathered in the control (like in the TFBC). The structure model considers changes in the machine structure caused by relative motion of the machine tool's assemblies.

SMBC has several advantages in comparison to CDBC and TFBC. The structure model is physically based, therefore, the model accuracy is widely independent from a particular load case during operation. That's why this approach is suitable not only for series production, but also for applications with changing loads like in small series production up to "batch size one". The necessary measuring efforts for model and parameter adjustment are low in comparison to CDBC and TFBC. At least one temperature sensor is needed to describe the environmental condition in the structure model. To achieve these advantages higher modelling efforts and computing power compared to CDBC and TFBC are required as a consequence. This article focuses on the structure model based correction.

2. Structure model based correction

2.1. Principle

The structure model based correction approach can be divided into modules. This is reasonable because various functions needed to be executed with different time steps, different solvers for submodules, different model types and model environments are used. Additionally a modularization is helpful if the functions have to be implemented by different parties (e.g. manufacturer of machine tools and machine control). One example for the modular implementation of the structure model based correction is presented in Fig. 1. This module chain corresponds to functional chain introduced in [8] with the difference that the position dependent load profile is determined before the communication interface, the calculation of power loss and thermal conduction. This could be necessary to compress the data before they are transferred via the communication interface, due to the limitation of the interface.

In this section the following nomenclature is used, vectors are written in bold letters, scalars in normal letters and compressed values in square brackets. At first the technological loads (e.g. motor current $\mathbf{I}$, velocity $\mathbf{v}$, position $\mathbf{x}$, environmental temperature T_E, cooling *state*) are gathered in the control. The load data are prepared for the structure model. Therefore, the loads are processed, compressed and position dependent load profiles (e.g. $[\mathbf{I}_{(x)}]$, $[\mathbf{v}_{(x)}]$) are determined. The structure model consists of models for power loss $\dot{\mathbf{Q}}_V$ and thermal conduction $\mathbf{L}$, thermal model (temperature field $\mathbf{T}$), thermo-elastic model (deformation field $\mathbf{w}$) and correction model (correction values for axes $\mathbf{\Delta x}$). Afterwards the correction values are concentrated (e.g. determine polynomial coefficients $\mathbf{k}$) according to the approach utilized for the position dependent calculation of correction values $\mathbf{\Delta x}_{(x)}$ in the control.

Finally, the determined correction values are actuated via offsets to the axes set points. The requirements for the different modules are described in [9]. The specific implementation of the module chain depends on the boundary conditions of the control and the requirements of the structure model. Limiting factors of the control are computing power, bandwidth of the communication interfaces and available control functions for load data capturing and for error compensation.