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Adaptive learning control for thermal error compensation of 5-axis machine tools

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ABSTRACT

The research presented in this paper shows an adaptive approach for long-term thermal error compensation of 5-axis machine tools (MT). A system of differential equations is used to compute the model based compensation values. The model can predict thermal displacements of the tool center point (TCP) based on changes in the environmental temperature, load-dependent changes and boundary condition changes and states, like machining with or without cutting fluid. The model based compensation of the rotary axis of a 5-axis MT is then extended by on-machine measurements. The information gained by the process-intermittent probing is used to adaptively update the model parameters, so that the model learns how to predict thermal position and orientation errors and to maintain a small residual error of the thermally induced errors of the rotary axis over a long time. This approach not only increases the MT accuracy but also reduces the amount of time spent on preproduction model parameter identification. Additionally an algorithm has been developed to dynamically adjust the length of the on-machine measurement intervals to maintain a high productivity and a constant deviation of the machined parts.

Experimental results confirm that the adaptive learning control (ALC) for thermal errors shows a desirable long-term prediction accuracy.

1. Introduction and state of the art

Modern precision manufacturing processes are strongly connected to the accuracy of machine tools (MTs). Generally, 3-axis MTs are used to manufacture high precision parts with geometrically defined cutting edges, like milling. Nevertheless, there is an increasing demand for high precision 5-axis machined workpieces. Examples are found in the medical engineering and aerospace industries.

Thermal influences on MTs are one of the largest error sources on machined workpieces. According to Mayr et al. [1], up to 75% of the geometrical errors can be termed as thermally induced. Bryan [2] summarized the influences on the machined workpieces in his “thermal effects diagram”. Sources that can cause thermal errors are:

- Room environment
- Thermal memory from previous environment
- People
- Cutting process
- Machine
- Cutting fluids

In Fig. 1, a subdivision of the causes divided in external and internal influences is shown and the chain of effects that result in thermal errors at the tool center point (TCP) is illustrated as well as the possibilities for thermal error reduction on MTs. The Figure shows that power losses in the machine lead to a temperature field of the MT and an according deformation of the structure. These effects can be reduced by minimization of the causes when designing or revising a MT. The resulting TCP error, due to the deformation of the structure, can be compensated with the numerical control.

Gebhardt et al. [4] stated that the influence of process and people is neglected since a long time by researchers and the focus lies mainly on thermal TCP errors regarding influences of the environmental temperature change, running the main spindle and moving the linear axes. International standards developed regarding the

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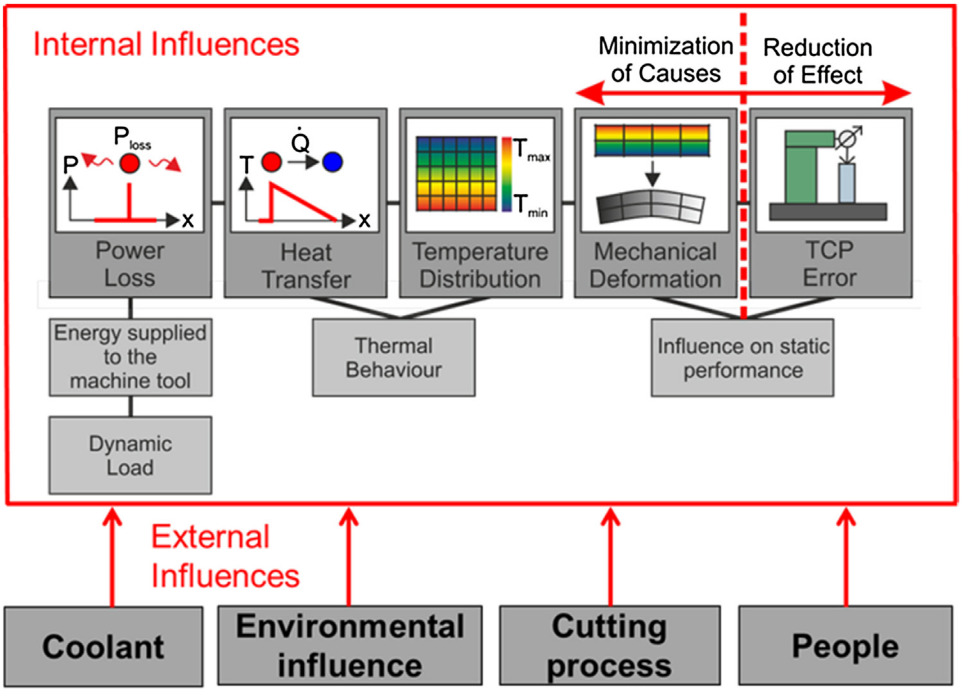

Fig. 1. Thermal chain of causes and TCP errors [3].

aforementioned thermal errors on MTs are ISO 230-3 [5], ISO 10791-10 [6], and ISO 13041-8 [7]. The procedures described in the standards are used for measuring the thermal error of MTs under no load or finishing conditions. Missing links in these standards, depicted by [8,9], are measurement procedures for thermal errors regarding rotary and swiveling axes of 5-axis MTs. Furthermore not considered in the standards are influences of cutting fluids on the accuracy of MTs. Mayr et al. [10] showed that these influences have a significant impact on the thermal behavior of the MT.

A popular and successful method to model thermal errors on MTs is the regression analysis which captures the relationship between the observed thermally induced errors and the thermal and losses related information, presented e.g. in [11–13]. Ideally the residual errors between the predicted model and the actual MT will approach zero. However, the predicted system behavior is always different from the real one. At the same time, the actual machining conditions may not be identical to the machining conditions used to derive an empirical model, which leads to model uncertainties. Mou and Liu [14] stated that this can cause problems especially for small batch productions, where the sequence of manufacturing processes changes frequently as do the direction and rate of change of thermal effects. Due to statistical uncertainties, assumptions in the model and the constantly changing boundary conditions, the error models derived from preprocess calibration are not necessarily accurate enough in the long term. They need to be verified and updated iteratively as the MT is continually used. The approach presented in this paper consists on a newly developed adaptive learning control (ALC) to predict time and load-varying thermal errors. By adopting current boundary and machining conditions obtained from various sensors, the parameters of the error model can be adapted to the present state.

Fig. 2 shows an illustration of the approach for adaptive thermal error compensation in this paper. A calibration phase at the beginning of the measurement, where thermal TCP-deviations and relevant thermal related information is captured, is used to obtain the first set of parameters for the thermal prediction model of the MT. This step is just required once, afterwards the already existing compensation model can be used, when starting the production run. After the calibration phase the model is capable of predicting the thermal deviations and compensate them on the MT in real-time. During production, on-machine measurements at specified positions in the workspace are used to capture the thermal TCP deviations at certain points in time. When the measured errors exceed a predefined threshold or the timespan since the last model parameter update surpasses a predefined value, the model parameters of the thermal model are updated. To update the model, the obtained data starting from a specific point in time is used.

2. Methodology for adaptive thermal compensation

2.1. Methodology

The goal of adaptive thermal compensation is to reduce the thermally induced TCP-deviations and to enhance the long-term accuracy of the MT in both material removal as well as on-machine inspections. The procedure is capable of adapting its model parameters to changes in the process and boundary conditions. This methodology is also able to adjust the on-machine measurement time intervals according to the predefined precision to ensure a high productivity at a constant uncertainty rate of the phenomenological model.

Fig. 3 shows a schematic diagram of the proposed methodology. First, a measurement procedure is derived which is capable of identifying the thermal position and orientation errors of a rotary axis with a touch probe and a precision artifact mounted on the machine table. The axis error model used in this paper is based on the rigid body assumption and the use of homogeneous transformation matrices (HTM) to obtain the thermal displacement of the TCP relatively to the workpiece position. The input of the HTM model are the predicted errors and the axis position of the MT and the output is an axes offset that shifts the axis origin in the opposite direction of the occurring thermal error. To predict the thermal errors, a phenomenological model is developed to predict the thermal behavior only by tracking multiple temperatures on and around the machine structure. The outputs of the phenomenological model, the predicted errors, are compared with the on-machine measurements

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