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Modelling of cutting process impact on machine tool thermal behaviour based on experimental data

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Abstract

Achieving high workpiece accuracy is a long-term goal of machine tool designers. There are many causes of workpiece inaccuracy, with thermal errors being the most dominant. An indirect compensation (using predictive models) is a promising strategy to reduce thermal errors without increasing machine tool cost. The most significant drawback is that the majority of applied models presume machines operate under load-free conditions without any reference to cutting processes. This article aims to extend the model validity by accounting for cutting process influence and verify the model during experiments involving different tools and cutting parameters. Moreover, several compensation model structures are considered.

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Keywords: Machine tool; Cutting process; Thermal error; Real-time compensation

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1. Introduction

Thermally induced displacements at the tool center point (TCP) of a machine tool (MT) structure cannot be sufficiently reduced by design concept and/or by temperature control without high additional costs. On the contrary, indirect (software) compensation of thermally induced displacements at the TCP is one of the most widely employed techniques to reduce MT thermal errors due to its cost-effectiveness and ease of implementation.

Ordinarily, approximation models are based on measured auxiliary variables [1] (temperatures, spindle speed, etc.) used for calculation of the resulting thermally induced displacements at the TCP. Many strategies were investigated to establish the models, e.g. multiple linear regressions [2], artificial neural networks [3], transfer functions (TF) [4, 5], etc. (for more details see [6, 7]).

Although real-time software compensations of thermal errors exist, these compensations have a number of serious drawbacks. The majority of these models only presume MTs under load-free rotation of the main spindle (air cutting) without any reference to the cutting process despite its essential impact on workpiece accuracy [1].

Thermal distortion under the spindle load condition was investigated using a stressing unit in [8]. A robust compensation of MT thermal errors in consideration of rough machining was developed but verification on real cutting processes is missing. The result of [9] showed that the prediction accuracy of solely air cutting models are unacceptable in real cutting applications. Methods to compensate for MT thermal errors should include cutting process effects to ensure their robustness.

In [5] a general approach was introduced to dynamic thermal errors modelling (based on TF) of MT under load-free conditions. This approach was successfully applied to 3 different MT structures. The work was extended to the real cutting process description based on measured spindle power carried out on a 3-axis vertical milling centre under rough machining [10]. In this article the approach is applied to a 5-axis milling machine and the effectiveness of three compensation model structures during various cutting processes are tested.

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2. Experimental setup

MT thermal deformations measured between the workpiece surface and TCP (δ_{TCP}) generally consist of three elements (according to eq.(1)): MT **frame** deformation (δ_{frame}; influence of feed drive activity, spindle bearings, removed material, ambient temperature etc.), **tool** elongation (δ_{tool}; impact of cutting process) and **workpiece** deformation ($\delta_{workpiece}$).

$$\delta_{TCP} = \delta_{frame} + \delta_{tool} + \delta_{workpiece} \tag{1}$$

A model of the MT frame thermal deformation is provided by previous work [5] and analysis of workpiece deformation is out of scope of this article. This paper mainly focuses on issues concerning tool thermal elongation.

All experiments were performed on a 5-axis milling centre with a 630 mm rotary table diameter. The MT was equipped with a number of temperature probes (Pt100, Class A, 3850 ppm/K) placed close to thermal sinks and sources. These probes were primarily used for safety purposes and were installed directly into the MT control system. Two from the discussed probes along with a spindle power record $P_{spindle}$ were utilised in the thermal deformation modelling process. These probes were namely $T_{spindle}$ (temperature of spindle bearings) and $T_{ambient}$ (temperature of the MT surrounding). Additionally, the MT was equipped with an industrial infrared (IR) temperature sensor (Optris CT-SF15-C1) T_{tool} for non-contact monitoring of tool temperature development during the cutting process and following phases. The body of the sensor and its cabling was safely covered in a flexi hose, which is commonly used for cooling liquid circuits.

Positions of thermal probes, a workpiece (solid cylindrical shape) placement and measuring positions of the spindle and a tool in the MT workspace are depicted in Fig.1(a).

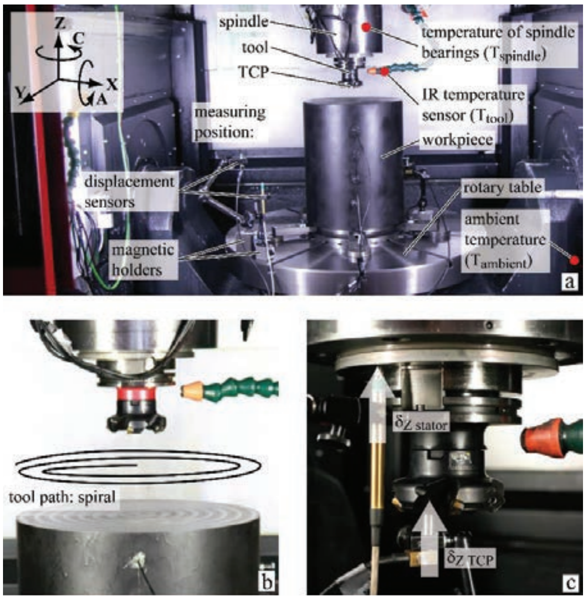

Fig. 1. Experimental setup on 5-axis milling machine; overview (a), cutting process (b), measuring position (c).

The MT should be in a steady state with its surrounding as a precondition to initiate the testing. All experiments include a load phase (cutting process) followed by a cool-down phase. The load phase of the testing consists of cycle repetition of two parts: cutting (Fig.1(b)) and measuring (Fig.1(c)). The **cutting part** means removal of one layer of workpiece material by following a specific tool path. The tool path was set up as a spiral for an even spindle load during cutting. The **measuring part** (deformations were recorded only in the most affected *Z* direction) following the cutting was executed with the help of two inductive contact sensors recording displacement of the MT frame (measured at the stator part of the spindle, further denoted as $\delta_{Z\ stator}$) and TCP ($\delta_{Z\ TCP}$). The sensors were mounted in magnetic holders attached to the MT table. The cutting and measuring parts were repeated in the load phase until supposed achievement of MT steady state with all active thermal sinks and sources (up to 6 hours). The cooling phase followed with the permanent spindle placement in the measuring position (Fig.1(c)). The MT was in a feed-drive-on mode during the cool-down phase.

The demanded value of the tool thermal elongation ($\delta_{Z\ tool}$) was obtained by the difference between the two measured deformational elements:

$$\delta_{Z\,tool} = \delta_{Z\,TCP} - \delta_{Z\,stator} \tag{2}$$

Three different tools were used for individual tests:

- Ø25 mm - finishing process,
- Ø63 mm - semi-finishing process and
- Ø100 mm - rough machining.

All results and conclusions are closely associated with conditions of experiments:

- cutting process is only face milling,
- dry machining,
- workpiece material is medium-carbon steel 1.0503.

3. Compensation models of thermal errors

A discrete TF was used to describe the link between the excitation (temperature, spindle power) and its response (thermal displacement). The differential form of the TF in the time domain is introduced in eq.(3):

$$y(k) = \frac{u(k-n)\cdot a_n + \cdots + u(k-1)\cdot a_1}{b_0} + \\ + \frac{u(k)\cdot a_0 - y(k-m)\cdot b_m - \cdots - y(k-1)\cdot b_1}{b_0}, \tag{3}$$

where *u(k)* is a TF input vector in time domain, *y(k)* is an output vector in time domain, a_n are parameters-to-be-identified of the TF input and b_m of the TF output, *k-n* (*k-m*) means the n-multiple (m-multiple) delay in sampling frequency. Linear parametric models of ARX (autoregressive with external input) or OE (output error) were used for the parameter estimations. The stability of each TF was examined