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Procedia CIRP 28 (2015) 28 – 33

www.elsevier.com/locate/procedia

3rd CIRP Global Web Conference

Model based prediction approach for internal machine tool heat sources on the level of subsystems

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Abstract

Modern machine tools are highly sophisticated mechatronic systems. Each subsystem's energy efficiency is important regarding thermal effects of the machine: Losses in the subsystems are mainly heat sources, causing temperature gradients and thermal elongation. Knowledge about the internal heat sources is therefore mandatory for high precision machining, as well as for the design of compensation strategies. This paper presents a modeling approach to estimate the heat release of machine tool subsystems and predict boundary conditions for thermal models. The simulation results are verified by measurements on an internal cooling system of a lathe.

Selection and peer-review under responsibility of the International Scientific Committee of the "3rd CIRP Global Web Conference" in the person of the Conference Chair Dr. Alessandra Caggiano.

Keywords: Machine tool; Energetic models; Spindle cooling; Heat source prediction; Temperature measurement

1. Introduction

1.1. Motivation

Precision and process stability are key success factors in manufacturing industry. The challenge thereby is not only to achieve a certain machining quality, but also to maintain these properties under various disturbances. A major source for disturbances are thermal effects, causing up to 80% of all geometric errors on workpieces [1] . The formation of these errors can be summed up as follows: Driven by different heat sources, temperature gradients are formed, leading to thermal elongations and therefore to displacements at the tool center point (TCP) [2, 3] . For the sake of simplicity, for heat sources as for heat sinks the term heat source is used, since heat sinks are negative signed heat sources. Heat sources can have different underlying effects and causations. A general categorization is given with internal and external heat sources. While external heat sources represent the interaction with the environment, internal heat sources have their origin within the machine tool housing. Examples are ohmic losses, friction or decompression of process gas. Since a machine tool is an assembly of different components with certain inefficiencies, each of its components is a potential internal heat source. The machine tool components used depend on the type of the machine. Examples are main spindle drives, bearings, servo motors, lubricant pumps, compressed air consumers, control devices and many others. This list is neither mandatory nor complete for the big diversity of different types and sizes of machine tools existing. More important is that each machine has components to provide the process energy and axis movements, but also auxiliary components like temperature control and chip

c_p	specific heat capacity	[J/(kg·K)]
m	mass	[kg]
Q	thermal energy	[J]
P	electric power	[W]
p	pressure	[Pa]
T	torque	[Nm]
α	heat transfer coefficient (HTC)	[W/(K·m^2)]
β	coefficient of performance (COP)	[-]
η	efficiency	[-]
ρ	density	[kg/m^3]
ϑ	temperature	[K]
ω	rotational speed	[rad/s]

2212-8271

Selection and peer-review under responsibility of the International Scientific Committee of the "3rd CIRP Global Web Conference" in the person of the Conference Chair Dr. Alessandra Caggiano.
doi:10.1016/j.procir.2015.04.006

removal in order to guarantee the required process and machine conditions. Investigations show that the auxiliary components have a substantial contribution to the total power demands of modern machine tools [4-6] .

Thus, heat loss of each machine tool component influences its precision, the process ability and process stability. If the influences can be predicted, two actions become accessible:

- First, the design of better machine concepts with respect to thermal effects, and
- Second, active compensation of thermal effects by prediction of heat losses.

In this paper an approach is described predicting heat sources as sum of the energy consumed as well as its interaction with the environment. Using basic conservation laws and the laws of physics, heat sources could be quantified in dependency of the consumed electricity and resources, as well as its interaction with the environment. The computational results using this approach are compared to measurements on the level of machine tool components. The approach therefore develops general energetic models of machine tool components.

1.2. State of Research

The demand of an energy efficient production is the driver for the development of energetic machine tool models. Since machine tools are known to consume significantly more energy during their use-phase than containing gray energy [7] , the operational phase has to be optimized. In order to face this challenge, different approaches are available. An overview of the state of art in energy flow modelling of manufacturing systems is given by Thiede et.al. [8] . The authors present further a holistic system definition, including single machines in a factory building. Li et.al. [9] present an empirical approach to predict the power consumption of a single machine in dependency of the process parameters. Using measurements on a lathe, the authors identify the necessary empirical parameters. A different approach is chosen by Braun et.al. [10] and Gontarz et.al [11] . They subdivide the machine tool into its components. The energetic behavior of each component is computed using component models based on physical laws. Gontarz et.al. further developed a simulation platform, including a component library, which allows computing the energetic behavior of machine tool concepts and the involved components in early development stages. Using physical laws the approach of Gontarz et.al. is able to compute, besides the power consumption on component level, heat losses.

For computing thermally induced TCP-displacements several models are developed. An overview is given in [1] . Ess [3] developed a computation routine based on Finite Element Method (FEM) for efficient modelling and computation of machine tool typical load cases. In [12] a computation approach Finite Differences Element Method (FDEM) is described for computing thermally induced TCP-errors efficient. In [3, 12] further methods for model order reduction are described reducing the output to the relevant TCP-displacements. Gebhardt et al. [13] developed thermal error reduction models based on differential equations and phenomenological system modelling approaches for five-axis machine tools. The models are able to compute axis correction movements for reducing thermal errors in real time.

Most equipment for energy measurements in manufacturing is measuring effective electrical power $P_{eff}(t)$. There are various commercially available measurement systems for power measurements as indicated by Kordonowy [14] . In research Behrendt et al. [15] and Avram et al. [16] use conventional single channel 3-phase metering systems in their measurement activities. For the analysis of all relevant subsystems a multichannel approach with synchronized multimeters are needed as used by [3] and [17] .

1.3. Research Gap

As shown in the literature review, the simulation and prediction of thermal deformations and TCP errors are known processes. Up to know the model approaches focus on the spindle and main drives. Auxiliary units, such as pumps or electronics are not included. In energetic modelling physical and modular approaches to compute the energy demand of single machine tool components have successfully been shown. The gap in modelling between energetic models and thermal models computing the TCP errors have not been investigated until now. In this work an approach is shown that uses the outputs of an energetic model for machine tool components as input parameters to compute the interaction of the components with its environment. The results can easily be implemented in existing thermal machine tool models and be used as boundary conditions for computing TCP errors.

2. Model Developing Procedure

To quantify the capability of energetic models in thermal simulations, as well as the identification of research gaps for a complete union of the two model domains, a model developing procedure is suggested in the following section. The procedure must assure the following outcomes: