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Utilization of thermal energy to compensate quasi-static deformations in modular machine tool frames

Eckart Uhlmann[a], Mihir Saoji[a]*, Bernd Peukert[a]

[a]Institute for Machine Tools and Factory Management, Chair of Machine Tools and Manufacturing Technology, Technical University Berlin

* Corresponding author. Tel.: +49-30-244-52; fax: +49-30-244-56. *E-mail address:* saoji@iwf.tu-berlin.de

Abstract

One functional requirement of machine tool frames is to maintain relative geometric positioning of interfaces irrespective of any surrounding effects or conditions. Challenges for the absolute accuracy of axis positioning are quasi-static deformations in machine tool structures due to temperature variations caused by environment or the manufacturing process. On the advent of increased research in solid state materials for thermoelectric modules, the utilization of thermal energy as a beneficial source needs to be evaluated. This paper presents the conceptual design of a thermally actuated module which can compensate the previously mentioned quasi-static deformations in the framework of a building set for modular machine tool structures. The principle of different thermal expansion coefficients of materials is exploited in the design of the module to facilitate a compensating movement. The module works energy autarkic as well as controlled by external energy input.

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1. Introduction

The LEG^2O (German acronym for Leichbau sowie gewichts- und genauigkeitsoptimierte modulare Werkzeugmaschinengestelle within the CRC 1026: Sustainable Manufacturing) is a modular approach for building machine tool structures. It aims at developing lightweight and microsystem enhanced modular building blocks to provide a sustainable manufacturing paradigm for a future generation of machine tools. The development of the combined mechanical and microsystem enhanced components addresses the modular functionality with regards to mechanical, electronic and controlling aspects. It provides the possibility to change single components or the whole configuration constructed using these modules. PEUKERT ET AL. [1] present a geometric and functional analysis of machine tool structures. The hexagonal shape of the building blocks is derived from finding common forms of structural elements. The building blocks are classified according to their functionality as active and passive blocks. Active blocks are defined as controlled actuating elements in the structural configuration by conversion of input energy, while the passive blocks provide structural functionalities without consuming any energy during operation. Designs of machine tool frames incorporating lightweight construction, improved mobility and increased productivity and efficiency are targeted while maintaining a high level of accuracy.

1.1. Quasi-static errors in conventional machine tools

The modular approach for constructing machine tool frames implies comparable or better structural behavior to that of conventional monolithic machine tool frames in thermal and static domains. Conventional machine tools have been extensively studied and researched regarding the quasi-static behavior. Quasi-static errors are those between the tool and the workpiece that slowly vary with time. These errors comprise of geometric/kinematic errors, self-induced mechanical strains from dead weights and thermal strains developed during the operation of the machine tool and estimated to account for 70 % of the total error [2, 3]. An extensive amount of research is published and discussed regarding the identification and compensation techniques of these errors. It is seen that there has been regular review and compilation of the research work in this topic; [3, 4, 5, 6, 7] are some of the key compiled works to name a few. Thermal

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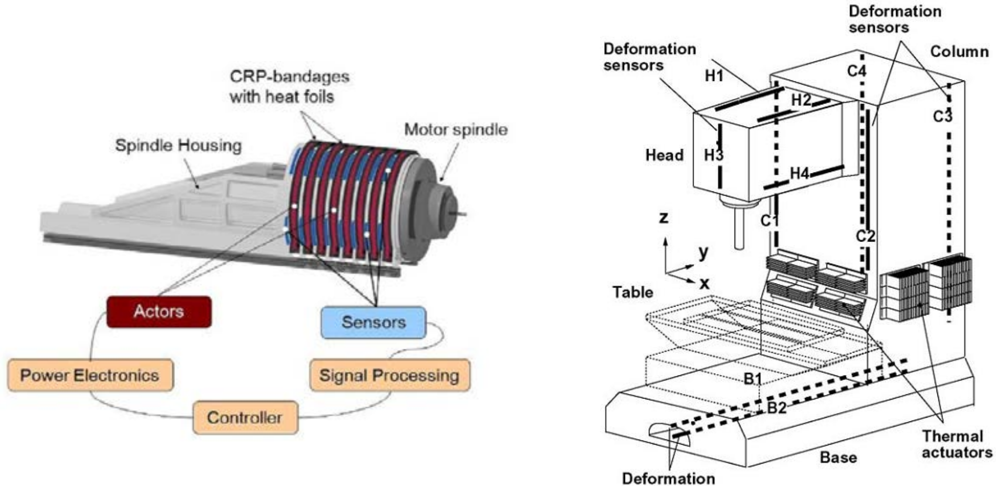

Fig. 1. Solutions to compensate errors due to thermal deformations; concept of integrated adaptronic spindle housing [10] (left); use of optimally located thermal actuators (heat pumps) to compensate the thermal deformations in a machine tool structure [11] (right).

errors originating due to thermal deformation of machine elements cause inaccuracies in the positioning of tool. The errors generated due to thermal deformations account for 40 to 70 % of the total dimensional and shape errors of the workpiece. BRYAN compiles testimonials from leading researchers in various institutes around the world regarding the status of thermal error research and points out the need for increased research work in the field [4].

WECK AND BRECHER [8] provide a concise account of various temperature variations related to machine tool environments and processes. A layering of temperature along the height and length of a machine hall shows variations of 3° to 4°C. Meteorological data for average solar radiations over a period of 12 months is presented along with temperature trends over day and night. An overall variation of 24°C is seen seasonally and a difference of 4°C to 5°C in day and night temperatures is observed throughout the year. Temperature variation and corresponding deflections are presented for various machine tools. Cyclic temperature changes of 3°C/hour are seen in the supporting column of a machining center occurring from spindle rotation. The corresponding translator deflections were about 10 μm/hour. More examples of machining centers, lathes and milling machine tools show a similar frequency and magnitude of temperature change and corresponding translational or rotational deflections.

Thermal errors in machine tools are dealt with broadly by two techniques which are largely seen in various published works, i.e. by minimizing the causes of thermal errors and by compensating the effects of thermal deformations. Minimizing the causes of thermal errors can be achieved by reducing temperature variations or reducing thermal sensitivity of machines. Reducing temperature variations includes the variations in the environment and/or in the structure of the machine tools. Reduction of thermal sensitivity of machines can be achieved by design principles (thermally symmetric designs) or by using materials with low coefficient of thermal expansion.

WECK ET AL. [5] compile the state of the art in techniques for increasing machine tool accuracy. The research points out that the first step for reducing thermal drift errors in machine tools is to minimize the power loss of internal heat sources, if that is inevitable then the heat source should be insulated, shifted to a location where it has no influence on the structural deformation or it should be cooled. Hybrid ceramic bearings for reduced friction, optimization of lubrication systems, insulation and use of low thermal coefficient of thermal expansion are some of the techniques reviewed in the paper. RAMESH ET AL. [6] point out that although these methods reduce the thermal deformation, the techniques tend to be very expensive. Nevertheless, the design should be optimized before designing compensation solutions.

Compensation techniques using controlled actuators require an error model to correct the thermal deviations. Mostly the controlled actuators used for compensating thermal deviations in machine tools are the drive axes of the machine. The error model generated from direct or indirect measurement of the deviation is fed to the main controller of the drives. Apart from the drive axes, it is also commonly seen that piezoelectric driven actuators are used for compensation either at the structure or as a workpiece holder [9]. Other approaches involve the strategic use of thermo-elastic behavior of frame components as actuators to compensate for thermal deformations [10, 11]. The strategic generation of thermally determined deformations by means of thermal actuators (heating/cooling) equalizes undesirable thermally determined deformations. These initiatives are distinguished from the commonly implemented electromechanical and piezo-electrical actuators, in that thermal expansion is exploited instead of mechanical or piezoelectric deformations [9]. UHLMANN AND MARCKS [10] utilize the negative coefficient of thermal expansion of carbon