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

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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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Keywords: Modularity, Machine Tool Frames, Thermal Deformation, Sustainable Actuator

1. Introduction

The LEG^{2}O (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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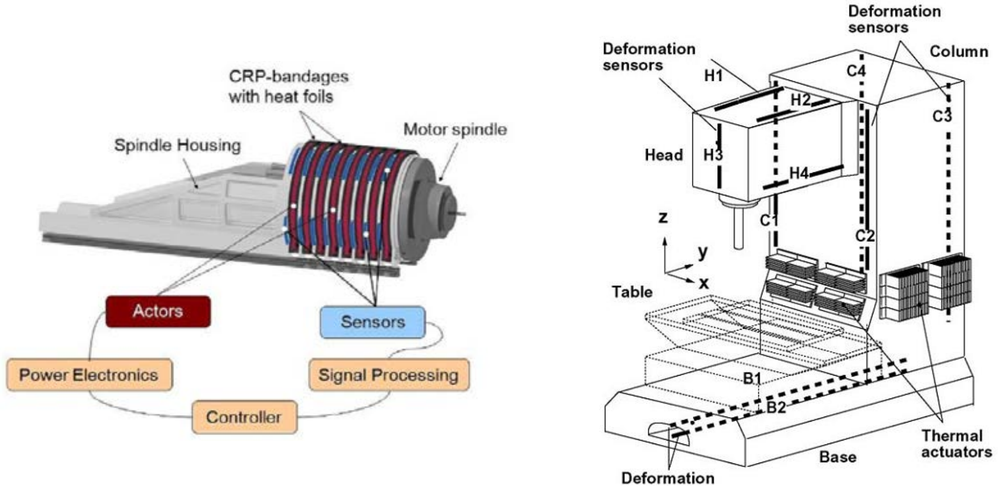

Fig. 1. Solutions to compensate errors due to thermal deformations; concept of integrated adaptronic spindle housing [10] (left); use of optimally located thermal actuators (heat pumps) to compensate the thermal deformations in a machine tool structure [11] (right).

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 reinforced fiber composites to compensate the tilting deformations seen in aluminum case spindle systems. Thermal energy is supplied to the carbon fiber bandages which strains the spindle casing and compensates for the tilting deviations. MITSUISHI ET AL. [11] have proposed the use of heat pumps as thermal actuators placed on the machine tool structure which control the form of the frame so as to compensate for the unwanted thermal deviations. Both systems have presented improvement in the thermal behavior of machine tools. The schematic representations of these solutions are shown in Fig. 1.

1.2. Motivation

The solution which is most commonly used in today's date to compensate thermal errors in machine tools is the utilization of manipulated control to the machine tool drive system. The inherent handicap of this solution is its inability to compensate for deformations in the degrees of freedom excluded in the drive system. These unsolved thermal deformations can not only provide inaccuracies in the motion of tool path, but they can also produce localized frictional heat generation on drive systems, increasing the thermal errors.

Adding to this, the LEG^{2}O modular building set provides further uncertainty regarding the structural configuration, number of degrees of freedom in the drive system, location of heat sources and even the geographical location of the machine tool. Considering these boundary conditions, the design for the compensation of quasi-static errors and more specifically the thermal errors becomes largely generic. The need for a compensation solution is evident which can inherently control the configuration of the machine tool structure, which is a majority mass contributing to the thermal deformations in the machine tool. The integrity of the geometrical properties of machine structures needs to be preserved. This will ultimately result in the correction of the tool center point as well as provide better working conditions for the linear drive and guide systems on the machine tool.

2. Design of modular thermal actuator

A number of solutions which provide conversion of thermal energy to mechanical displacement are seen in published research. The conversion of thermal energy to mechanical displacement can essentially be accomplished by utilizing two physical effects of materials, viz. thermal expansion and elasticity. The applications utilizing thermal expansion of materials are mostly used under no load as displacement actuators for positioning applications and various micro electro-mechanical systems (MEMS).

Materials with negative coefficient of thermal expansion in principle can be serially connected in the machine tool frame so as to contract on increase in temperature and maintain the structural integrity of the structure. But the problem with implementing this solution is the negative coefficients of thermal expansion of such materials are not large (approximately -2 µm/m°C). The manipulated expansion of common positive expansion coefficient materials can be manipulated to achieve the desired range of displacement to compensate for thermal deformations in the machine structures. The requirement now demands a material with high thermal coefficient of expansion and modulus of elasticity so as to provide thermal displacement with the stiffness of structure being maintained. And secondly a mechanism which is able to manipulate the displacement produced by the expansion of the material to compensate thermal deformations in machine tools.

The thermally actuated Z-tilt-tip module was designed with its functional actuator as a compliant mechanism. Different lever and displacement amplification mechanisms were modelled and compared for available displacement and stiffness. The drive of the mechanism was obtained from the thermal expansion of an aluminum bar.

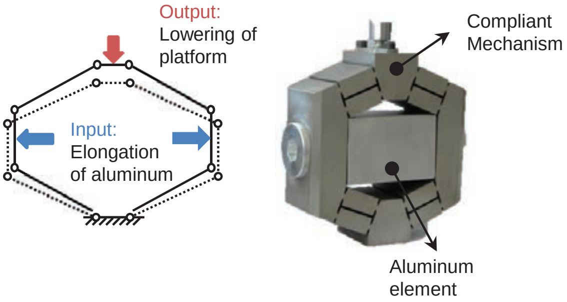

Fig. 2. Schematic of a bridge-type mechanism (left); double-bridge compliant mechanism with aluminum as actuating element (right).

The construction of the bridge type amplification mechanisms allows orthogonal transfer of motion from the input along with an amplification of the displacement. Depending on the angle of the bridge elements, the correlation between the input and output displacements can be optimized. Inwards motion of input interfaces generates upwards motion of output interface. The schematic of the mechanism is shown in Fig. 2. For improving the normal stiffness of the mechanism, a double bridge type compliant mechanism was selected. The construction of the mechanism lowers the output interface when the environmental temperature is increased.

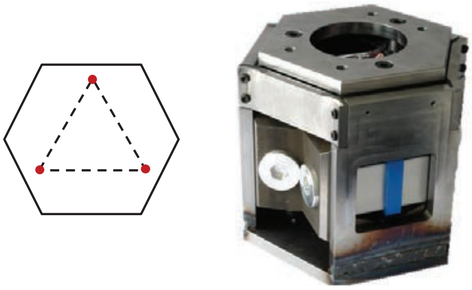

Fig. 3. Location of compliant mechanism in the actuator shown in top view (left); complete assembled thermal actuator (right).

The materials used for the actuator are compiled in Table 1 along with the amount of material used in each actuator. A combination of aluminum and Invar was used for the actuating element and the compliant mechanism respectively. Aluminum provides favorable properties for the actuating element, viz. high coefficient of thermal expansion (approximately 24 µm/m°C), high thermal conductivity and modulus of elasticity. On the other hand, Invar has a low thermal coefficient of expansion (approximately 1 µm/m°C) and high modulus of elasticity which provides good thermal invariance and high mechanical stiffness.

Three of these compliant mechanisms with the actuating element are arranged on the vertices of an equilateral triangle inside the supporting case. This configuration allows the actuator to control the movement of the output interface in normal and tilt-tip motions. Fig. 3 shows the locations of the compliant mechanism and a manufactured thermal actuator.

Table 1. Materials used in thermal actuator.

Component	Material	Weight
Actuating component	Aluminum Alloy	1.98 kg
Compliant Mechanism	Invar 36	10.84 kg
Casing and Support structure	Steel	10.13 kg

Thermo-electric modules (TEM) can convert electrical energy into a temperature gradient and work as a heat pump. Extensive research in developing new materials, applications and improving efficiencies is seen from the literature [12, 13, 14]. The low efficiency of thermoelectric coolers compared to conventional refrigeration systems is constantly reiterated in the review publications. Some of the advantages of thermoelectric devices are [13]:

- No moving parts, substantially less maintenance
- High life testing - exceed 10,000 hours of steady state operation
- No chloro-fluro-carbons or material replenishment required
- Easy and fully reversible direction of heat pumping by changing polarity
- Precise temperature control: ±0.1°C using appropriate controller design
- Function in severe environments

Due to these reasons, TEMs enable an enhanced thermal control of the actuating aluminum bar compared to natural convective and conductive heat flow.

The slow dynamics due to the thermal system permits the use of an economically efficient power supply system for multiple TEMs with a single DC power supply. A single power supply is used to switch between the TEMs with the help of solid state (SS) relays connected in parallel. The relays are controlled by the control unit to cycle the ON time. A schematic of the architecture is shown in Fig. 4.

The approach enables for a high degree of modularity because it is possible to share one power supply with all TEMs. The system can be scaled by adding more solid state relays to supply power from the single DC power source instead of obtaining an individual power supply for every TEM. Table 2 compiles the cost of such a power supply solution for a single actuator along with the total cost of shared and unshared components.

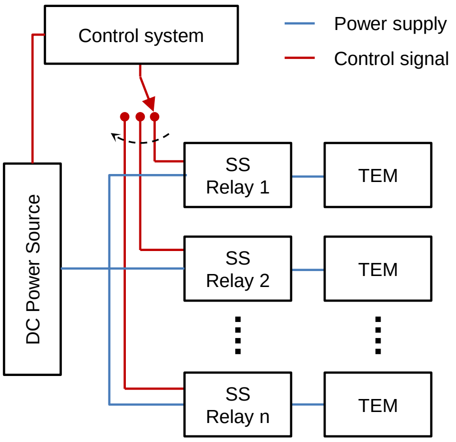

Fig. 4. Schematic of the power supply and control of the TE modules showing scalability.

Table 2. Cost of electrical components.

Component	Quantity for single actuator	Cost per piece (EUR)
Thermoelectric element	3	40
Solid state relay	3	250
DC supply for TE element	Shared	650
DC supply for relay	Shared	92
Cost of unshared components per actuator (EUR)		870
Cost for shared components (EUR)		742

3. Power consumption

3.1. Experimental setup and results

The assembly of a compliant mechanism with the actuating element was tested experimentally to find the equivalent power consumption for maintaining different displacements of the output interface. The setup of the experiment is shown in Fig. 5 implementing the previously explained power supply plan. A standard single stage thermoelectric element with 241 thermocouples in 50 mm × 50 mm (QC-241-30-15) is used to control the temperature of the actuating aluminum element. The temperature is measured with a surface Pt100 temperature sensor and the displacement of the output interface of the mechanism is measured using a laser triangulator (Micro-Epsilon optoNCDT2200). A current and voltage controllable 480W DC power supply (Camtec HSEUIreg480), with 15A maximum current, is used to power the thermoelectric element. The solid state relay is doublepole double-throw (Camtec UMS25), compatible with the working range of the power supply. A laboratory control and data acquisition system (ADwin-Pro II) is used to control and monitor the temperature, displacement, power supply and relay. A preliminary proportional current control on the thermoelectric element was implemented for an assembly of one compliant mechanism with the aluminum actuating element.

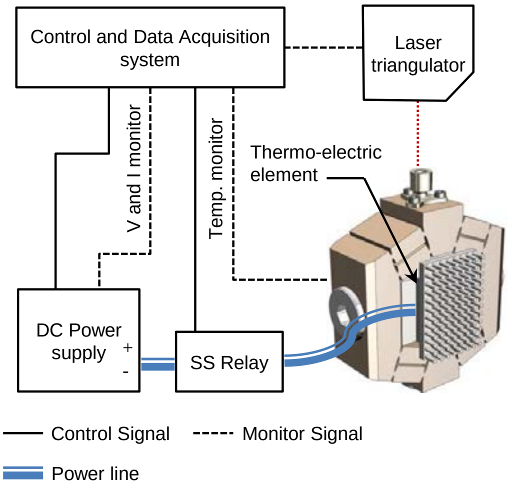

Fig. 5. Experimental setup to determine characteristic plot of the actuator.

An aluminum pin fin heat exchanger was attached on the other side of the TEM for convective heat transfer from the surrounding air. The aluminum bar temperature was controlled till steady state and increased in steps of 5°C until the temperature was 70°C with a constant room temperature of 25°C. The corresponding deflection of the output interface of the mechanism and the voltage and current provided by the DC power supply were monitored. Fig. 6 gives the characteristic plot showing the equivalent power consumption and change in temperature with respect to compensation displacement for three compliant mechanisms controlled with TEMs. The temperature of the aluminum bar was controlled to each step for 500 seconds. The convective heat exchanger (Alutronic PO75-50-15-AL) 15 mm × 50 mm × 75 mm with 96 pin fins transfers the heat to the environment by natural convection.

The temperature controlled side of a TEM is conventionally called a source and the other side as a sink. The actuating aluminum element in the thermal actuator is therefore the source side for the TEM. Sink side thermal resistance should be lower than that of the source side to control the source temperature below room temperature. The convective heat exchanger used as a sink in the experiment allows a stable control of the source temperature above room temperature. In future work, the sink side will be designed to form a better thermal connection between the actuating aluminum element (source) and the machine tool structure (sink) constructed using the passive blocks. In this way, the machine tool structure will behave as larger heat sink with higher heat capacity than the actuating aluminum element. This will allow a larger controllable range below room temperature of the source side. An additional side effect is that heating up the actuator for compensation of thermal expansion actively removes heat from the machine tool structure.

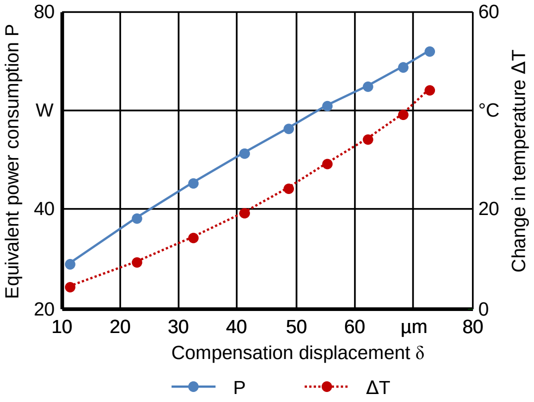

Fig. 6. Characteristic plot of thermal actuator.

3.2. Thermal actuator in a modular framework

The use of such thermal actuators can be understood in a modular framework based on the power consumption and displacement achieved by the actuator. A vertical column constructed using the passive blocks is assumed to have a rise in temperature of 5°C. The corresponding thermal deflection of the column is more along the length of the column due to the direct proportionality. The amount of thermal deflection can be calculated using the length of the column, the coefficient of thermal expansion and the rise in temperature. The power consumption, in order to compensate for this deformation, is found from the characteristics of the actuator and compiled for the different combinations of number of passive blocks and active thermal actuators used together.

Table 3. Steady state power requirements in Watts (W) for number of thermal actuators used to compensate passive blocks to a change in temperature of 5°C.

		Number of thermal actuators used				
		1	2	3	4	5
Number of passive blocks	1	0	-	-	-	-
	2	30	2	-	-	-
	3	40	30	3	-	-
	4	50	40	35	5	-
	5	58	50	40	38	6

A single actuator is seen as enough to compensate for the expansion of a single passive block. The use cases where the amount of actuator blocks used are more than the passive blocks are not considered since that condition will provide over compensation for the column. As seen from Table 3, the power requirement is least when the number of thermal actuators and passive blocks are equal.

4. Conclusion

The paper describes the conceptual design of a thermally activated Z-tilt-tip actuator developed to compensate quasi-static thermal deformations of machine tool structures. The amount of different materials used in the construction of an actuator is mentioned. A cost effective solution for powering the TEMs in the actuator is presented which enables easy scaling of number of actuators used in a machine tool configuration. The concept of a thermally powered displacement actuator is presented with techno-economical characteristics of such a system. The merits of such an actuator in a modular framework are capable of enhancing the integrity of machine tool frame without a huge impact on the costs and energy demands. The current design will be updated for minimizing the cost of manufacturing and an extensive life-cycle analysis of the actuator will be pursued to evaluate the sustainability impact of the actuator. A detailed analysis providing an approach to find the optimum placement in the defined topology of the machine tool structure for such a thermal actuator will be developed.

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