THERMAL ISSUES IN MACHINE TOOLS AND COORDINATE MEASURING MACHINE SIMILARITIES AND DIFFERENCES.

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Abstract:
Thermal issues are relatively well developed and described in machine tools and their development is quite rapid in recent decades. This is related to increased awareness of the impact of thermal conditions on the accuracy and efficiency of their work and the increased requirements of users (up to 75% of the overall geometrical errors of machined workpieces can be induced by the effects of temperatures). There is a large stock of published research and case studies aimed at compensation and reduction of thermal error of machine tools.

Branch of coordinate measuring machine (CMM) is strongly associated with the machine tool industry. There are a lot of convergence in approach to this theme in both subject groups. Both in the construction of machine tools and measuring machines as the key point of interest is the influence of various physical phenomena on the behavior of the executive point, in the case of measuring machines is the end of the measuring head, in the case of machine tools is a tool centre point (TCP). Considerable amount of research on the effects of thermal phenomena in the case of machine tools is carried out without taking into account the cutting forces, which also conforms research approach in both concerned areas. An important difference, however, is the fact that the compensation of thermal deformation in machine tools must be made immediately during work, if we want to improve the geometric parameters of the workpiece, which involves the introduction of some actuators, or correction of the trajectory in real time. While the result of work of the measurement machine are stored data that can be corrected or processed after the process of measuring and correction does not make any material actuator. Order of magnitude of precision in the case of machine tools and CMM is also different.

Thermal phenomena associated with measuring machines are relatively well developed in the case of steady thermal state, and the uniform temperature gradient. Mathematical models are described, compensation systems have been developed. There are publications concerned with selected aspects of the measuring machine work, or selected components that generate heat inside or outside of the machine structure. However problem of modeling of the whole machine and studies of thermal effects, and time-varying or locally occurring phenomenon ,based on numerical methods is relatively poorly studied. This probably results from the fact that both numerical methods and hardware have developed enough to address this issue only in recent decades. Important here is the economic aspect (the cost of computing hardware and software), and the performance parameters, which allow the calculation of the real-time close to the real-time or made in acceptable period of time post factum.

Keywords: CMM, Thermal issues, machine tool

1. INTRODUCTION

Research of thermal error in machine tools has long been highly developed in the industry. It is estimated that up to 75% of the overall geometrical errors of machined workpieces can be induced by the effects of temperatures. Because of the size of this industrial segment and huge financial resources dedicated to the development, these research can be a solid base for the work on of similar phenomena in a much smaller area which is the construction and exploitation of measuring machines (CMM).

Issues connected with thermal phenomena in the machine tool industry has been extensively described in the collective work [1], which is a reference point for the comparative analysis of research on this issue in relation to the production and maintenance of measuring machines.

2. Measurement of thermal errors and temperatures.

The correct solution of the problems resulting from the influence of thermal effects on the accuracy and other operational machines parameters, requires a proper diagnosis and measure of occurring phenomena. Therefore, we will start with a review of methods and devices for measuring the thermal deformation, measurement of positioning errors in space, and temperature measurements in both sectors we are interested: measuring machines and machine tools.

2.1 Measurement of thermal deformations

Methods of measurements of thermal deformations in the two compared fields in many cases overlap. The tests are difficult to implement due to the fact that it is necessary to measure all relevant geometrical elements with low measurement uncertainty and in short period of time. The measurement method depends from sources of error, and a set of parameters of global and local character. For machine tools have been developed standard methods for the analysis of temperature effects. For example, measuring the thermal distortion caused by moving linear axis of machining center is made by a contact probe using a touch-trigger probe. Is used the special temperature chamber of strictly controlled thermal parameters. They are used Telescopic double ball bar measurement setup for thermal distortions in machine space. One ball is mounted in the spindle and the second affiliated with workbench. Touch trigger probes are often used between machining operations to measure the gauges made of material with low thermal expansion (traditionally invar, ceramic glass, or carbon fibre-reinforced plastic (CFRP)). On machine tool frame are placed deformation sensors with strain gauges for measuring the thermal deformations to determine the TCP displacements.

The above-described standard measurement procedures are used for the machines without cutting forces. Described procedures are common to the two compared fields. The main difference are researches related to measurements of thermal deformation of machining spindles (electro - spindle), that in the machine tool industry are priorities research, while in measuring machines rotating axle does not occur. For such studies are usually used equipment called R-tests, in the spindle will be mounted rod with a set of five contact sensors to determine thermal movement in three axes and two rotary axes. In the case of the rotating spindles are used contactless sensors, for example, optical or capacitive. Significant differences, there is also an acceptable error and measurement uncertainty, which in the case of measuring machines must be on a much lower level compared to mid-range machine tools. Next important difference follows from the fact that on the CMM there are no forces and the thermal sources coming from the cutting forces, which in the case machine tools can have a significant impact on the value of thermal errors.

2.2 Measuring volumetric positioning errors.

In the case of machine tools and CMM measurement of volumetric positioning errors and local displacement vectors carried out under the same conditions and using similar means. There are several measurement systems that can be used for the volumetric calibration of machine tools, like geometrical gauge (e.g. reference plate with holes, calibration spheres), laser interferometers. If thermal influence on the volumetric positioning accuracy shall be measured, the calibration procedure has to be repeated at different temperature levels. During the measurement procedure, the machine tool's temperature should be sufficiently stable. Therefore, measurement time becomes very important. In the last few years an innovative solution for the fast volumetric calibration of machine tools, which has been successfully used in the manufacturing industry. This is the calibration of machine tools by multilateration using high quality tracking interferometers (TI) called Laser Tracer. This equipment allow determining geometrical errors (volumetric map errors) throughout the working space automatically. This allows to carry out the compensation cycle time drastically shorter (The measurement time for a working volume of 1 m^3 can thereby be reduced to less than 1 h).

2.3 Temperature measurement

The methods used to measure the temperature in both of the interesting areas show no significant differences. In the past were based on platinum resistance thermometers (Pt100, Pt1000),today also are used other types of thermometers like thermocouples, negative temperature coefficient thermistors (NTC thermistor), and positive temperature coefficient thermistors (PTC thermistor), or Recently developed semiconductor thermo elements like the ''Smart Probes''. Fluorescent paint was used to measure the temperature distribution. A special type of chemical compound absorbs light when it is irradiated with another frequency than the light source. The absorption of light is temperature dependent.

Currently, due to the drop in prices has become widely used pyrometric tools such as infrared camera. Their application, however, is related to the need to establish an appropriate emission factors of examined objects, which factors are dependent of the type of material, surface treatment, the camera angle and roughness. It is necessary to develop reliable procedures for determining the actual emission factors.

3.Computing thermal errors

Both in the case of machine tools and measuring machines we can use a similar methodology in the approach to the calculation of thermal errors. The simplest model is a model showing the deviation from the reference temperature 20 ° C (uniform temperature for the entire model) under the assumption isotropic CTE, it shows the linear dimensional change.

A more complicated model is often described in the literature [1,2] is a model of the space variable temperature with constant gradient. Uniformly changing temperature causes bending of the machine parts, which can be described by mathematical formulas and eventually corrected. Such a model created by the author is shown in Figure 1, 2 below.

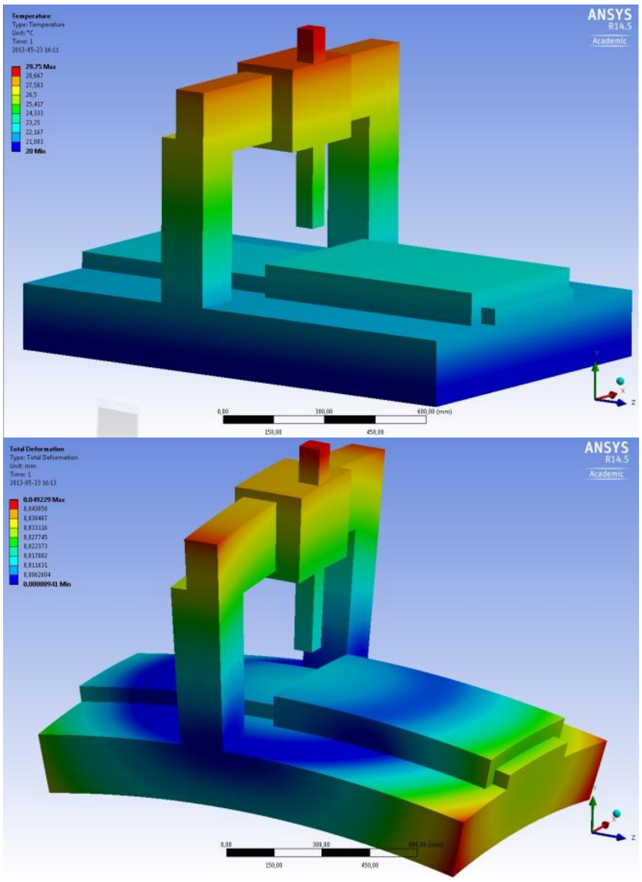

Fig.1, 2 Temperature gradient distribution on model of measuring machine along the vertical axis and his deformation .

The next level of complexity of the thermal model, this non-linear changes in temperature caused by local internal or external heat sources and interactions between the individual components. Model takes into account the phenomenon of convection, radiation and cooling by different media. In the simplest form, the model is calculated in thermal steady state, more complicated model includes thermal parameters which change over time (transient state).

Another method is the modeling one part of machine in order to verify the assumptions, or to prepare for further modeling whole machine .

Apart from the purely analytical approach to thermal models in CAD, is often used mixed models, in which the selected items are described in separate procedures, based for example of experimental studies describing confirmed relations, based on separate specialized programs, or on data obtained from the manufacturers of the hardware. Often experimental data are analyzed using a neural network to optimize and eliminate irrelevant parameters. The above mentioned rules can be applied both to the machine tools and measuring machines. The main difference is the special attention placed in the thermal analysis of machine tools for modeling some of the hardware. The main attention is paid to the spindles and electro spindles which include:

-determine the amount of heat generated in the rolling bearings, depending on the type of bearing, the rotational speed, the load, the lubrication, the material properties, the assembly tolerances, the ambient conditions and running clearances;

-model the flow of heat in the spindle assembly, taking into account the interactions between the above factors;

-model the forced cooling of the spindle bearings and the other elements, depending on the type and velocity of the flow of the cooling medium;

-determine the amount of heat generated in the spindle motor, depending on the rotational speed and the load;

-model the distribution of the heat generated in the stator and in the rotor;

and model the motor cooling system.

Much attention is also puts in the case of machine tools for modeling thermal errors in the linear axes, in which for example, in ball screws are more significant influences because of the large cutting forces, which causing friction and generating significant amounts of heat. Similarly intensively are analyzed thermal processes in the axes with linear motor which can generate significant temperature gradients. In these cases, it leads to the use of the cooling process which is unusual in terms of measuring machines.

4.Reduction of thermal errors

The data obtained through measurements and computer calculations can be in the final effect used to compensate for thermal errors. And that's where there is a significant difference between machine tools and measuring machines. In machine tools during the cutting process if we want to improve the machining parameters, we need to make corrections in time immediately in real time. However, the effect of the measurement process is the data that could be corrected (based on specific thermal errors) after the measurement process. As you can see thermal error compensation on machine tools is a much more difficult task. It is most often done through the use of drive systems, sometimes by uses a special compensation axes.

It is based at the different methods including:

-analytical models

-Estimation based on heat source information with use of transfer function model

-Estimation of thermal deformation based on temperature distribution information with use of a neural network model

-Estimation of thermal deformation based on strain distribution information with use of a neural network model

-Estimation of thermal deformation based on temperature measurements

-Estimation of thermal deformation based on computational models

Work on this last method has been initiated in relation to measuring machines in the work of the author [3].

Despite the differences in the approach to thermal error compensation on machine tools and measuring machines, there are methods that can be applied in both cases. For example, through the use of advanced materials. Thermal displacement resulting from the positive coefficient of linear expansion of component of the device, (for example, aluminum spindle housing) may be compensated (reduced) generating a thermal load in the opposite direction using the material with a negative coefficient of linear expansion (e.g. CFRP), but keep in mind their strong anisotropy. The thermal deformations due to local temperature gradients of a polymer concrete machine tool bed can be reduced by 30% by casting in steel fixings for linear guide ways to improve heat conduction.

5.Methods for increasing the thermal resistance of measuring machines

Apart from above described approach to thermal error compensation are currently being used by many manufacturers preventive methods to reduce the impact of thermal effects on the quality of work of measuring machines. For some time now is marked a strong trend towards to placing measuring machines in the production process. The existing common practice users of CMM was to use them in a strict laboratory conditions, demanding high requirements of stable temperature (20ºC), humidity, high purity environment. It was connected with high capital costs for the construction of laboratory facilities, installation of air conditioning, provide adequate means of transport for inter-operational control, thermal stability of the workpiece, vibration isolation, etc.

Measuring machines that can take measurements in the production environment without significant loss of the precision, has become an attractive and desirable alternative. Therefore, for some time carried out intensive research and design of such solutions.

An interesting approach to this issue represent Zeiss manufacturers of measuring machines. In some designs their resigned almost entirely from the software temperature compensation methods. And despite that in its offer are a number of types of machines which can be included directly in the production cycle.

These machines according to catalog data can be used in a wide range of variable temperature (from 20°C up to 40°C), without significantly compromising the accuracy of the measurement.

A good example of such a structure is universal coordinate measuring machine Center Max navigator able to work directly on the production hall. All issues related to thermal stability according to the manufacturer have been resolved through design and by careful selection of materials. The entire structure already in the conceptual phase subordinated to the purpose of reducing the thermal influences on the measurement accuracy. Below (Figure 3) shows a schematic construction with the basic structural elements.

Figure 3 (1) Invar carriers, (2) Bearing and scale covers, (3) Active anti-vibration system, (4) Dynamic and thermal damping thru TRF, (5) Liquids drainage, (6) Raised guideways, and the (7) Mineral cast

In this design abandoned the classical conception of driving gate, removing two supports of beam axis X , by raising the same beam and the Y-axis rails on top of the machine body. Eliminated by this errors of stiffness of the supports and their sensitivity to varying temperature and significantly increased the dynamics. Supporting structure was made of TRF (Temperature Resistant Frame) that is, heat-resistant frame fixed to the bracket made of Invar material having a low coefficient of thermal expansion, the whole surrounded by a body of mineral concrete with good vibration damping, constituting an additional thermal insulation. Beam thermally sensitive components X and Z axes blanketed with covers with good insulating properties. Also the elements of measurement systems and guides have been tightly covered. The machine is equipped with an active pneumatic vibration isolation. This design provides good resistance to most harmful interference present in the environment of working machines. The only elements of the thermal compensation system are temperature sensors of environment and on measured object. As regards the Zeiss machine protection against varying thermal conditions, should also be mentioned about specially designed glass scales made from Zerodur material with close to zero coefficient of linear expansion.

Another element which has a significant impact on the operation of machines under varying thermal conditions is used by Zeiss technology, precision coating of guide elements made of aluminum by temperature barrier named CARAT.

CONCLUSIONS

As you can see from presented above analysis thermal approach to the design of machine tools and measuring machines in many points overlapping. The main difference is the implementation of the data obtained from measurements, experiments and simulations, which in machine tools must be implemented in real time. Differences also appear in placing more emphasis on some typical machine tool units like the spindle and kinematic axis due to the generation of a significant amount of heat, and cutting parameters (machining force and the propagation of heat during processing). Also different is the approach to minimize the effect of heat, in the case of machine tools commonly is used cooling by different cooling media (machining fluids, air, oil mist), in the case of measuring machines by covers, thermal barriers, special dedicated design. Work on machine tools are connected with intense internal heat sources. In measuring machines this phenomena (if exist) are characterized by much lower intensity. Therefore, the most important CMM thermal problems are those associated with the direct influence of the environment surrounding the machine and its working space.

A separate issue is compensation of machining error of a workpiece (the measured object) is the case of a composite element composed of materials with different coefficients of CTE, even in the case of homogeneous (but changing) temperature, may lead to nonlinear thermal deformation (bimetallic effect), which greatly complicates the issue.

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