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Review

Thermal error analysis in precision length measurements

A. Jakstas [a,*], S. Kausinis [b], R. Barauskas [c], A. Kasparaitis [d], A. Barakauskas [e]

[a] *Department of Engineering Mechanics, Kaunas University of Technology, K. Donelaicio 73, LT-44244 Kaunas, Lithuania*
[b] *Department of Engineering Mechanics, Kaunas University of Technology, A. Mickeviciaus 37, LT-44244 Kaunas, Lithuania*
[c] *Department of System Analysis, Kaunas University of Technology Studentu 50-407, LT-51368 Kaunas, Lithuania*
[d] *Department of Machine Engineering, Vilnius Gediminas Technical University, J. Basanaviciaus g. 28, LT-03224 Vilnius, Lithuania*
[e] *Precizika-Metrology, Zirmunu g. 139, LT-09120 Vilnius, Lithuania*

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ABSTRACT

One of the most significant factors which determine the precision of a machine is elastic thermal deformations of the structural components. The paper describes the practical application of thermal error analysis that aims towards the reduction of thermally-induced errors for precision length measurement systems operating in non-ideal environments. Finite element analysis and experimental investigations were carried out to examine the core thermal processes and to demonstrate the existence and feasibility of the thermal modal analysis in precision line scale calibration system.

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1. Introduction

The thermo-elastic behaviour of a precision machine is one of the most important factors in determining its accuracy capability. With the improvement of machine accuracy, errors induced by thermo-elastic deformations due to internal and external heat sources become even more significant.

This issue is particularly relevant to the length measurement in non-ideal application environments, under the influence of many external factors that are not part of the desired measurement, namely, that are affected by a wide spectrum of seismic excitations, non-homogeneous temperature fields, electro-magnetic noise and other disturbances. Thermal effects here are still one of the largest sources of dimensional errors and apparent non-repeatability of measurement [1,2].

Nevertheless, compensation of machine tools should always deal with geometrical errors changing as a result of thermal changes and load effects. Thermal and

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[*] Corresponding author. Tel./fax: +370 37 323855.
E-mail address: aurimas.jakstas@ktu.lt (A. Jakstas).

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mechanical stiffness therefore remains a primary design criterion for high precision machines.

Although a lot of attention in the world has been paid to research of precision length calibration problems, the creation of new components and systems, and elevation of existing ones with the aim to meet the fast-growing scientific and industrial needs, many specific problems have been left unsolved. Precision systems often are too complex and different, so it is complicated or almost impossible to transfer and adapt the findings of such research directly for system perfection.

2. Thermal error analysis techniques

The numerous approaches and techniques to the assessment of thermo-elastic behaviour of precision machines have been systematically developed and reported over several decades. Significant work towards understanding and subsequent reducing of thermally induced errors was done in the CNC and CMM's arena [3].

Thermal error analysis techniques include series of passive to active methods to increase the thermal stability of a machine. These cover reducing the system sensitivity to the heat flow by structural design, management of the heat sources, control of the machine environment, and compensation for measured deviations.

A comprehensive review of the work carried out over the last decade in the estimation and compensation of temperature dependent errors in machine tools has been done in [1]. A generalised approach has been analysed that was proposed by many researchers towards handling the problem of non-uniform temperatures in the machine tools. The techniques in modelling the thermal behaviour have been considered, namely finite element analysis, coordinate transformation methods, and neural networks. The methods of measurement of the temperature and error components and correction of these errors in real-time have been described in [1].

An effort to develop a systematic methodology to improve the accuracy of a machine tools by applying the thermal modal analysis has been presented in [4]. The analysis was exploited for the temperature sensor placement strategy and thermal error modelling. Finite element analysis (FEA) is utilised to examine the essence of thermal process of machine tool elements. Numerical simulation and practical experiments are carried out to illustrate the existence and feasibility of the thermal modal analysis in reality [5–7].

In the aforementioned studies the numerous approaches and solutions have been considered to control the generation and flow of heat in precision machines. Although a lot of attention has been paid to research and develop a compensation strategies for thermal errors, many specific problems have been left unsolved. Precision systems often are too complex and different, so it is complicated or almost impossible to transfer and adapt the findings of such research forthrightly for the creation of new components and systems, and elevation of existing ones. New research activities and advanced modelling and simulation are still of relevance in order to provide "advisory service" for system perfection.

The paper describes the error-related problems specific to line scale calibration that are caused primarily by thermal deviations of the comparator components and the scale.

3. FE modelling for investigation of structural components

The structural components of the precision line scale comparator consist of four main parts, namely the body of the machine, a laser interferometer, a translating system and a detecting apparatus. The body of the machine, which is made of granite surface plate, is used as the base of the machine and as a guide for the moving carriage. Measurement of the displacement of the carriage is realised by laser interferometer that consist of Zygo ZMI 2000 laser head and interferometer with the single-pass arrangement. The interferometer provides a resolution of 0.62 nm [10].

The comparator is developed to calibrate line graduation scales and incremental linear encoders. A moving CCD microscope serves as structure localisation sensor for the measurements of line scales. The angular control loop – together with the numerical procedure – has been applied to compensate and reduce the Abbe uncertainty contribution. The comparator was designed to achieve expanded measurement uncertainties ($k = 2$) down to 7×10^{-7} m ($L = 1$ m) in dynamic regime. It enabled to trace the calibration of line scale of up to $L \leqslant 3.5$ m long to the wavelength standard. The magnification and numerical aperture of the NIKON objective lens used is 20× and 0.4 respectively. The microscope on the carriage guided on aerostatic bearings is moved with a controlled velocity of 1–10 mm/s.

Microscopes are now used for a wide variety of tasks in addition to imaging, requiring complex laser optics, metrology tools, and precision motion mechanisms in conjunction with the basic microscope structure.

Structural designs of current microscopes, which have retained similar cantilevered shapes for decades, make such advanced setups cumbersome and sensitive to thermal and mechanical disturbances. The mechanical performance of the microscope has become the limiting factor in particular for many high-resolution experiments.

Inhomogeneous thermal expansion of the body of the microscope is a major cause of instability during experiments. However, the optical train of the infinity-corrected microscope is not sensitive to motion in all directions. By using symmetry, the expansion of the mechanical structure can be channeled into directions which do not effect the optical measurement [8,9].

One of precarious temperature disturbances is the heat spread out by the CCD camera of the measuring microscope. As the steady-state temperature under the operating conditions is known, the thermal expansion process can be modelled by using the FE simulation, and the temperature values can be found at all points of the microscope structure. Having the temperature values

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