XX IMEKO World Congress
Metrology for Green Growth
September 9–14, 2012, Busan, Republic of Korea

THERMAL ERROR ANALYSIS OF PRECISION INTERFEROMETRIC LENGTH MEASUREMENT SYSTEMS

A. Jakstas[1], S. Kausinis[2], A. Kasparaitis[3], R. Barauskas[4], A. Barakauskas[5]

[1] Kaunas University of Technology, Kaunas, Lithuania, e-mail: aurimas.jakstas@ktu.lt
[2] Kaunas University of Technology, Kaunas, Lithuania, e-mail: saulius.kausinis@ktu.lt
[3] Vilnius Gediminas Technical University, Vilnius, Lithuania, e-mail: a.kasparaitis@precizika.lt
[4] Kaunas University of Technology, Kaunas, Lithuania, e-mail: rimantas.barauskas@ktu.lt
[5] Precizika-Metrology, Vilnius, Lithuania, e-mail: a.barakauskas@precizika.lt

Abstract: The paper describes the practical application of thermal error analysis for precision length measurement systems operating in non-ideal environments. Finite element analysis and experimental investigations are carried out to examine the essence of thermal process and to demonstrate the existence and feasibility of the thermal modal analysis in precision line scale calibration system.

Keywords: line scale calibration, thermal error analysis

1. INTRODUCTION

A fundamental problem that manufacturers of precision machines face most frequently is the control of elastic deformations induced by static or dynamic loads that allows obtaining geometrical deviations within a permissible range, as well as control of deviations caused by temperature variations. Due to the presence of sometimes changing internal and external heat/cold sources in precision machine tools and CMMs and the very often significant expansion coefficients and expansion coefficient differences of machine part materials, the resulting thermal distortion of the machine's structural loop often dominate the accuracy of the complete machine [1, 2].

While analyzing high precision calibration systems it is necessary to evaluate an average volume temperature of some parts of a mechanical comparator as well as the temperature of the scale. Under real calibration conditions, temperature measurement is possible only at certain points. The response time of temperature sensors is also rather long (from several seconds to several minutes). Therefore, fast temperature changes cannot be detected, and, consequently, the measurement uncertainty increases. Time-variant thermal errors are also more elusive to model than geometric errors.

Thermally induced error is a time-varying non-linear process caused by non-uniform temperature variation in the machine structure. The interaction between the heat source location, its intensity, thermal expansion coefficient and the machine system configuration creates complex thermal behavior [3], which respectively in the long-stroke measuring machine is even more significant because of their size and complexity. Due to high requirements for geometrical stability of calibration system, the temperature deformations caused by changes of several hundredth parts of Kelvin must be considered.

The cause-and-effect relationships can be calculated in considerable detail using modern FE analysis and empirical heat transfer formulas, but doing so requires considerable knowledge about the design and environment.

2. COMPENSATION OF THERMAL ERRORS

Precision length comparator is a complex mechanical system, the proper operation of which requires certain precision of geometrical dimensions [4]. To comply with these requirements the orders of gradient fractions of temperature fluctuations caused by temperature deformations are of great importance. Therefore the impact of ambient temperature fluctuations on the stability of machine geometry must be accurately estimated. Even with maximum elimination of mechanical disturbances influence and assurance of constant environmental temperature security, certain temperature disturbances and the resulting deformations are unavoidable due to the heat flows. Though such deformations are unavoidable, nevertheless proper structural solutions make it possible either to reduce their impact on the measuring process or to develop shading circuits if the extent of deformations can be estimated in advance, or to recalculate the measurement results removing systematic errors.

Thermal error identification is one of the crucial steps for a successful thermal error modelling and compensation. There are two basic error identification categories: workspace measurement approach where the required compensation values are determined by making direct measurements of the thermal errors between the main elements of a machine and error synthesis approach which comprise the computation of the resultant thermal errors by combining the measurement of the distortion of each individual machine element along the kinematic chain of a machine structure.

There are a number of general approaches pertaining to the thermal error avoidance that include: reducing and relocating heat sources, rearranging the machine structure to achieve thermal robustness, the use materials that have strong thermal stiffness as well as monitoring and control of the environmental temperature since ambient temperature fluctuation is one of the major heat disturbances [5-7].

3. MODELING OF THERMAL ERRORS

The impact of temperature on the mechanical deformation of the line scale can be simulated in several ways:

1. temperature values at certain points of the construction can be detected experimentally and used for calculation;
2. temperature field can be calculated depending on the assigned non-homogeneity of the environment temperature by taking into account heat convection processes between the parts of the structure and its surrounding.

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 modeled by using the FE simulation, and the temperature values can be found at all points of the microscope structure. Having the temperature values obtained, the displacements due to thermal expansion can be calculated at any point of the structure.

The equation of the structure heat balance reads as follows:

$$[C]\{\dot{T}\}+[K_{Th}]\{T\}=\{S_{\infty}\} \tag{1}$$

where $[C]$ - matrix of thermal capacity, $[K_{Th}]$ - matrix of thermal conductivity, $\{S_{\infty}\}$ - nodal vector of heat sources of the element determined by the heat exchange over the surface of the body.

The FE computational model of the structure was set up, shown in Fig. 1, in which the temperatures of the structure and the ambient air could be calculated. The model is based on the coupling of the following physical phenomena:

1. Heat transfer by the ambient air due to its thermal conductivity;
2. Convective heat transfer (due to the motion of the air);
3. Heat exchange between the air and comparator structure;
4. Heat transfer by comparator structure due to its thermal conductivity;
5. Formation of deformations in comparator structure due to the non-homogenous thermal field generated in it.

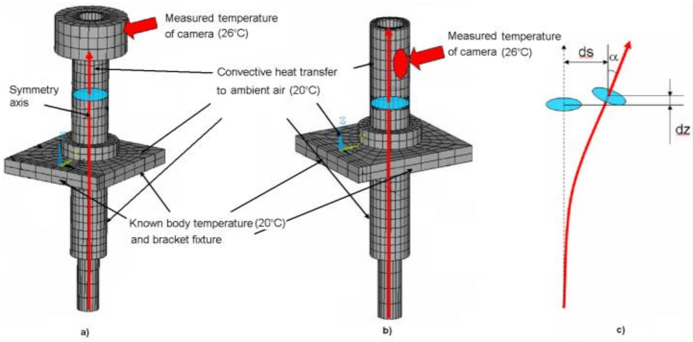
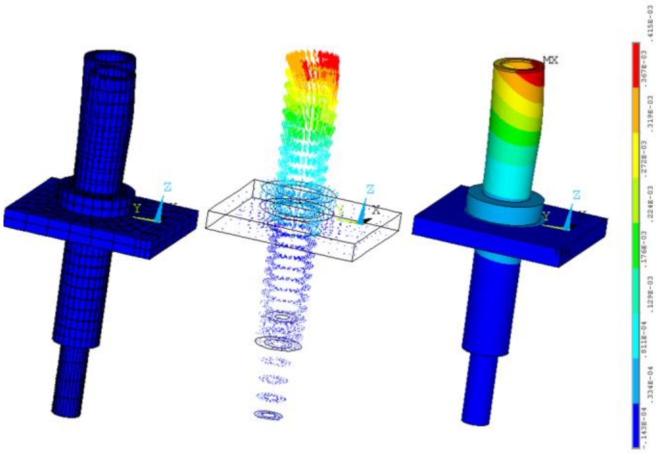


Fig. 1 Model of microscope structure when CCD camera is fixed on the microscope side (a), when it is fixed in the symmetry axis (b), typical cross-section displacements under temperature deformations (c)

The model is capable to predict the system's behavior under thermal load and enables us to investigate thermo-mechanical processes in the system and facilitates finding proper structural solutions to reduce the impact of thermal load on the calibration accuracy.

Displacements in the structure caused by the calculated temperatures field are depicted in Fig. 2.



(*a*) (*b*) (*c*)

Fig. 2 Displacements in the structure caused by the calculated temperatures field; CCD camera is fixed to a side of the microscope: (*a*) deformation of the construction; (*b*) vectors of nodal displacements; (*c*) deformation of the structure

Inhomogeneous thermal expansion of the body of the microscope is a major cause of instability during experiments. However, the optical layout of the infinity-corrected microscope is not sensitive to motion in all directions. By using design symmetry, the expansion of the mechanical structure can be channeled into directions which do not affect the optical measurement. The geometrical deviations of the structure in axial and lateral direction are presented in Fig. 3.

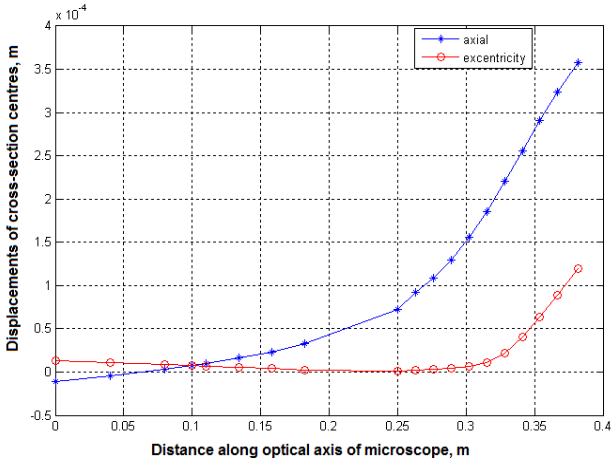


Fig. 3 Axial and lateral displacements of the microscope along the optical axis

The most sensitive degrees of freedom for the microscope optics are the two axes of tilt perpendicular to the optical axis, which respectively result in deviations of the focal spot. The influence of a more uniform temperature distribution on the tilt error depends on the type of disturbance, the dimensions of the segment as well as the material properties of the segment. The results of calculations have proven that microscope structure layout with the camera on top is more favourable respectively lateral deviations. The FE model predicted about 1 arcsec tilt of the structure.

Axial thermal expansion of a tube structure due to a temperature gradient around the circumference of the tube causes the tilt error motion. The magnitude of displacement of the focal spot will directly depend on magnification of the objective, focal length of the tube lens and the tilt angle [5].

4. EXPERIMENTAL ANALYSIS

The previously conducted FE analysis gave approximate values and locations of the expected high- and low-temperature zones, along with expected deformations, e.g. at the tip of CCD microscope. However, detailed experiments with the physical setup were conducted to develop a more accurate characterization of the thermal profile of the structural components of the comparator and the resultant deformations in free air.

The temperature distribution on the comparator components and in the surrounding air was monitored using PP2 temperature measurement system with max. 22 temperature detectors Pt100. Within the calibration range from 19 °C to 21 °C the measurement uncertainty of the temperature detectors is below 0,022 °C.

For evaluation of thermal stability of the microscope the sensors were distributed on CCD microscope structure (or at equivalent locations for monitoring of temperature fields around the system) at CCD cut-off, warming up, and steady operating conditions. The scatter of temperatures in transition phase around the microscope is displayed in Fig. 4. It clearly indicates temperature inhomogeneity at different locations and the speed of transitional processes.

Under operating conditions the heat is withdrawn from the camera by both the ambient air flux and the microscope frame. The significant amount of heat is dispersed by the camera mandrel due to high ratio of its surface area to mass. The camera emits heat mostly through its couplings with cables on the camera surface which was intended for data acquisition and transmission. The upper segment of the camera can warm up to 27,5 °C during the operation.

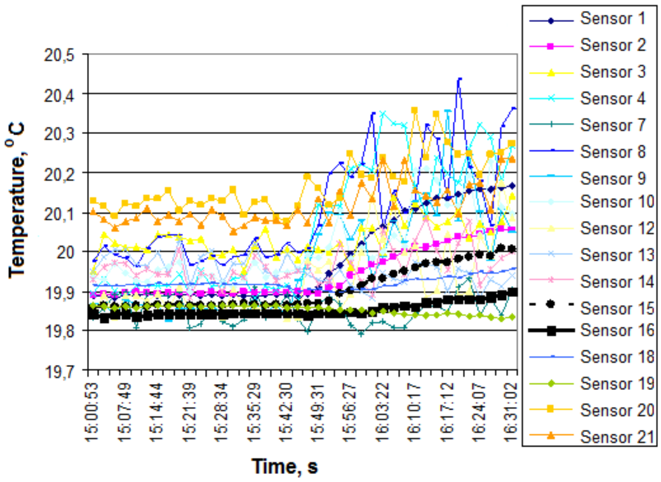


Fig. 4 Temperature variations measured by 17 sensors located on the microscope structure

For example sensor 1 represents temperature shift of the support of the optical microscope, sensors 2, 15, 16 and 19 are measuring temperature distributions on microscope housing away from the camera. These changes could be approximated by an exponential law similar to one obtained in FE calculations and shown in Fig. 1c. Although temperature variations on the camera setting device is less significant compared to ones at the top or the flashbulb frame, the above mentioned factors have an influence on the temperature drift up to 0,2 °C that subsequently results in temperature deformations of the camera setting device and contributes to measurement uncertainty budget. Calibration error caused by a thermal CCD camera impact under steady-state calibration conditions is of a random character and in real-time it cannot be compensated by numerical compensation techniques.

Before calibration and during three subsequent calibrations air temperature around the calibrated scale has been measured. Temperature measurement results are depicted in Fig. 5. Temperature variations of 0,1 ^{o}C have been observed and that could be influenced by a number of factors such as sources of the increased heat amount in the calibrated scale environment, instability of air fluxes in the laboratory, etc. A typical method for improving the positioning accuracy is stabilization of air in the laboratory. But even with an ideal air conditioning system, by the time the stabilized air reaches the laser beam, it is turbulent and riddled with temperature variations. Despite the stabilized conditions, a variation of tens of mK can be observed as shown in Fig. 6. With a conventional environmental compensation system the amount of variation seen in the picture would result about ±10 nm positioning error with laser beam path length of 600 mm.

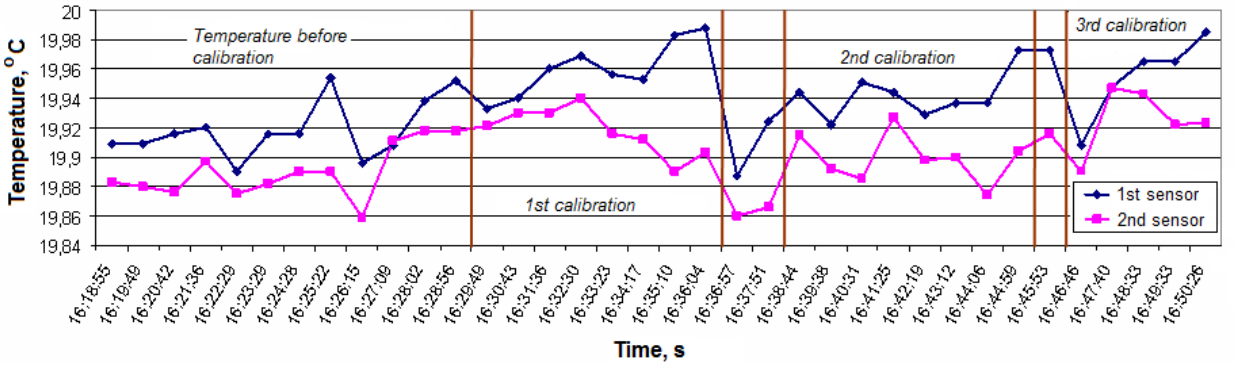


Fig. 5 Temperature variations around the measured scale

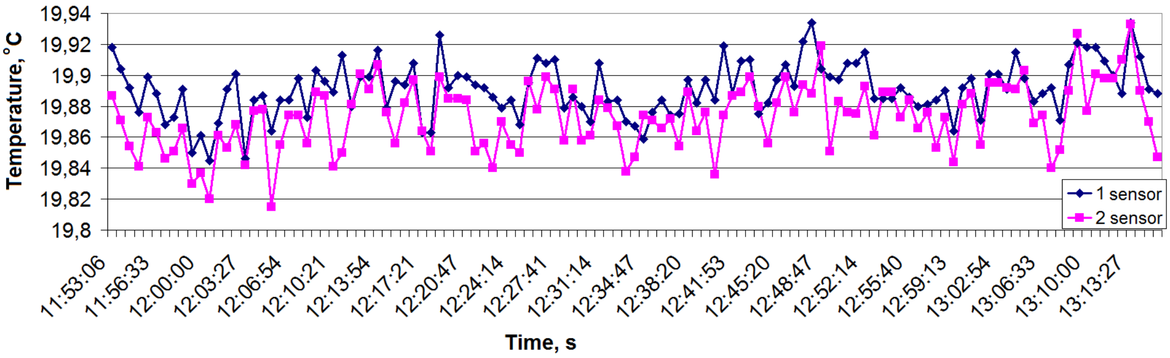


Fig. 6 Temperature variations along the path of laser beam, 600 mm away from the laser

The direct outcome of thermal deformations of the microscope frame structure is line detection errors originated due to geometrical instability of metrology loop. Additionally the measurement error is increasing due to microscope defocusing which leads to reduced quality of line profile images obtained by line detection system. Suppression of high frequency components in the image due to defocusing leads to a certain misrepresentation of the amplitude of optical signal.

Within the experiments conducted an estimate of the variance of this error amounts to +/- 0.23 µm at the 95% probability level.

4. CONCLUSIONS

The performance of a thermal error compensation system strongly depends on the accuracy and robustness of the thermal error model.

Thermal emission of the heat sources in the machine environment violates standard temperature conditions of calibration space of thermo-constant premises and brings about temperature deformations of the calibrated measure and the comparator elements, thus also causing bigger calibration errors.

Measurement errors caused by a thermal inhomogeneity of CCD microscope structure under steady-state calibration conditions is of a random character and in it cannot be compensated by mathematical methods real-time.

5. REFERENCES

[1] H. Schwenke, W. Knapp, H. Haitjema, A. Weckenmann, R. Schmitt, F. Delbressine “Geometric error measurement and compensation of machines-An update”, CIRP Annals - Manufacturing Technology, vol. 57, pp. 660–675, 2008.

[2] E. Creighton, A. Honegger, A. Tulsian, D. Mukhopadhyay “Analysis of thermal errors in a high-speed micro-milling spindle”, International Journal of Machine Tools & Manufacture, vol. 50, pp. 386–393, 2010.

[3] R. Ramesh, M.A. Mannan, A.N. Poo, “Error compensation in machine tools - a review Part II: thermal errors” International Journal of Machine Tools & Manufacture, vol. 40, pp. 1257–1284, 2000.

[4] A. Jakstas, S. Kausinis, R. Barauskas, A. Kasparaitis, A. Barakauskas, “Investigation of dynamics-induced errors of long line scale calibration systems”, Measurement vol. 44, pp. 976–987, 2011.

[5] A. J. Hart, A. Slocum, J. Sutin, “Segmented and shielded structures for reduction of thermal expansion-induced tilt errors”, Precision Engineering vol. 28, pp. 443–458, 2004.

[6] K. C. Wang, P. C. Tseng and K. M. Lin, “Thermal error modelling of a machining center using grey system theory and adaptive network-based fuzzy interference system”, JSME International Journal, vol. 49, no. 4, 2006.

[7] J. W. Li, W. J. Zhang, G. S. Yang, S. D. Tu, X. B. Chen “Thermal-error modeling for complex physical systems: the-state-of-arts review”, The International Journal of Advanced Manufacturing Technology, 2009, v.42., no. 1-2, p.168-179.