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ANALYSIS OF THERMAL DEFORMATIONS OF AN OPTICAL ANGULAR ENCODER

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Abstract – The paper describes the practical application of thermal error analysis for an absolute angular encoder. 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 for improvement of the performance of an optical angular encoder.

Keywords: optical angular encoder, thermal errors, FE modelling

1. INTRODUCTION

The thermoelastic behaviour of a precision measurement system or machine is one of the most important factors in determining the accuracy capability. Due to inaccurate knowledge of the heat source, thermal boundary conditions, mechanism of heat transfer etc., precise prediction of the behaviour of a system, in particular at the design stage is very difficult. Overall, thermal errors and resulting deformations of the structural components amount to about 40 – 70 % of the total error budget of precision measurement systems.

Thermal errors are induced by thermo-elastic deformations due to internal and external heat sources of a machine. The internally generated heat and environment temperature gradient render the machine exposed to complex and changing temperature distributions. There are several main thermal error sources: heat generated during operating process, the system energy loss, cooling elements of a machine, and cooling systems, ambient environment, people, and thermal memory from previous environment. The thermal deformation errors thus caused are even more difficult to quantify and predict if the complicated geometry of a measurement system is taken into account [1].

Thermal error identification is one of the crucial steps for a successful thermal error modelling and compensation [2]. 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 [3-5].

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 [6-7].

Thermal modal analysis is exploited for the temperature sensor placement strategy and thermal error modelling. Finite element analysis is utilized to examine the essence of thermal process of the elements of an optical encoder.

The major contributions of this research include the practical application of an integrated thermal modal analysis to the elements of an optical encoder, development of a new numerical models and proposal of a generalized concept for minimization of thermal errors.

2. NUMERICAL ANALYSIS OF THE ANGULAR OPTICAL ENCODER

The resolution of an optical incremental encoder is mainly determined by the quality of the interfering periodic structures – the scale which implements the function of measuring standard and scanning reticle used to generate a particular form of the output signal. The form and precision of output signals depend on the scheme of the interaction of both structures.

Accuracy requirements for precision optical encoders are very tight so 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 [8].

A new numerical model has been developed which enables to determine mechanical deformations of the encoder structure resulting from inhomogeneity of thermal fields, heat transfer processes in the system and ambient environment. The influence of thermal deformations on the optical signal of the interfering gratings is determined employing the developed modelling software which simulates the interaction of two optical grating. The input data is geometry of both gratings as well as geometrical deviations governed by e.g. thermally induced deformations of the gratings and the output result is the transmittance function characterizing the changes of the light flux passed through the interfering gratings.

The sequence of modelling steps for calculation temperature measurement error is presented in Fig. 1.

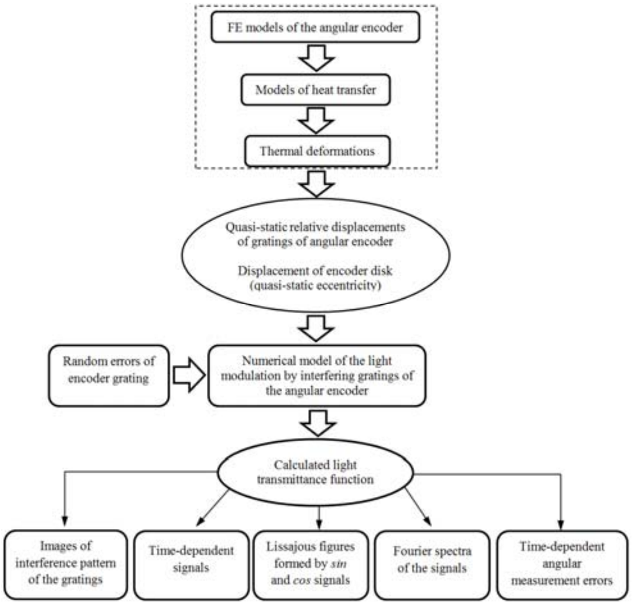

Fig. 1. Algorithm of numerical modelling of the influence of thermal deformations on interference signal of the gratings

We assume that these factors are slowly changing in time and their influence is regarded as quasi-static, i.e. for every particular mode we model static heat transfer process and elastic deformation and stress analysis is performed. Obtained results are treated as local relative displacement between scanning and measuring gratings i.e. zero offset error or relative quasi-static eccentricity. Relative quasi-static eccentricity is the distance between the actual axis of the bearings and the centre of the encoder disk when the structure is deformed due to inhomogeneous temperature field.

2.1. Finite element (FE) model

FE computational model represents exact geometry but simplified configuration of an optical encoder including main structural elements like shaft, housing, bearings, measurement and scanning gratings etc. which geometry basically influence substantial variations of a measurement chain of an encoder. Thermally induced geometrical deviations of the gratings will be translated into relative eccentricity and angular variations of the grating line in respect of reference line of the scanning window.

The FE model takes into account the following physical phenomena:

- heat conduction in ambient air due to its heat conductivity;
- convective heat transfer between the air and the encoder structure;
- heat conduction within the encoder structure;
- deformations of the encoder structure due to inhomogeneous temperature field within the structure.

Thermal analysis problem is presented in the form of the structural heat conductivity equation as

$$\left\lfloor \mathbf{C}^e_{th} \right\rfloor \left\{ \dot{\mathbf{T}}^e \right\} + \left\lfloor \mathbf{K}^e_{th} \right\rfloor \left\{ \mathbf{T}^e \right\} = \left\{ \mathbf{S}^e_\infty \right\} + \left\{ \mathbf{Q}^e_{th} \right\} \tag{1}$$

where $\left\lfloor \mathbf{C}^e_{th} \right\rfloor$- matrix of thermal capacity of the element, $\left\lfloor \mathbf{K}^e_{th} \right\rfloor$ - matrix of thermal conductivity of the element, $\left\{ \mathbf{S}^e_\infty \right\}$ - nodal vector of heat sources of the element determined by the heat exchange over the surface of the body, $\left\{ \mathbf{T}^e \right\}$ - nodal temperature vector of the element and $\left\{ \mathbf{Q}^e_{th} \right\}$ - nodal vector of heat sources of the element determined by adjacent elements [9].

FE models are unanimous as they are describing different physical phenomena in a particular structure. Calculation of thermal deformations is based on the impact of equivalent nodal load vector $\left\{ \mathbf{Q}^e_{th} \right\}$ that depends on the nascent temperature field. Thus the structure is deformed by the applied loads (forces) as if it has been influenced under the temperature load.

2.2. Calculation results of thermal deformations

Thermal load is modelled by indicating thermal boundary conditions of the model. We assume that at a certain distance from the encoder the temperature of the support is equal to the temperature of the overall structure (~20 °C). At all other surfaces of the structure the convective heat exchange with ambient air (~20 °C) is assumed. The following material constants have been employed: heat conduction coefficients of the encoder material are λ=54W/m K and of the zones illustrating bearing elements and the gaskets λ=27 W/m K. Surface convection coefficient is α=20 W/m^2 K, and thermal expansion coefficient is κ=12×10^{-6}. However it is assumed that the built-up numerical models are linear and the stated magnitudes of physical constants and temperature deviations are not substantial here.

Calculated displacements are presented in dimensionless form as

$$\bar{u} = u \big/ \Delta T \cdot \kappa \cdot R \tag{2}$$

where R is the distance from the disk axis to the centre of the scanning window, ΔT – temperature deviation.

The solution of the model equations provides information about physical behaviour of the structure and displacement data of every node of the investigated model.

Relative displacement of interfering gratings is determined from the analysis of displacement vectors as presented in Fig. 2a and 2b where initial (unloaded) and deformed positions of the particular nodes are displayed respectively.

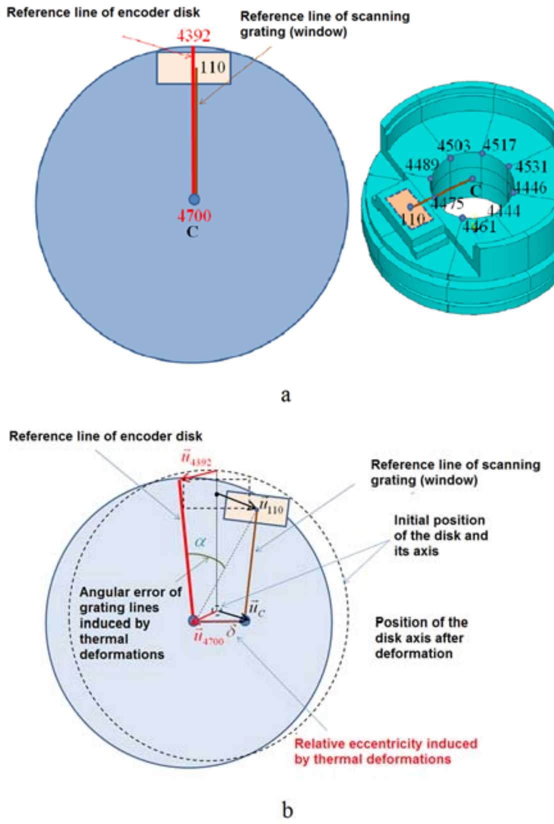

Fig. 2. Principal schemes for determination of relative displacements: a – unloaded configuration and the main nodes in FE model (right), b – thermally loaded configuration

Calculated relative eccentricity δ and angular deviation α of the reference lines of the gratings are global estimates of the structural deformations resultant due to settled thermal effects. Local estimate is a vector that defines relative deflections of the grating lines in the scanning window.

Modelled temperature fields and resulting displacements when particular temperature increment is added for 4 different surface zones of the housing of the encoder are presented in Fig 3.

In simulation, it is possible to compare the effects of the temperature collected at different locations based on certain mathematical model. Compared to thermal deformations induced by heating of the housing of the encoder the influence of the frictional effects in the bearings for displacements in the interaction zone of both gratings is much less significant.

3. EXPERIMENTAL SETUP

Comprehensive FE analysis conducted gave approximate values and locations of the expected high- and low-temperature zones, along with expected deformations, e.g. at the scanning unit of the encoder. Further, detailed experiments on the physical setup of the angular encoder were conducted to provide a more accurate characterization of the thermal gradients in the structural components of the encoder and the resultant mechanical deformations in free air due to internal and external disturbances like friction at the sealant and shaft – bearing unit, electronic components and the light source.

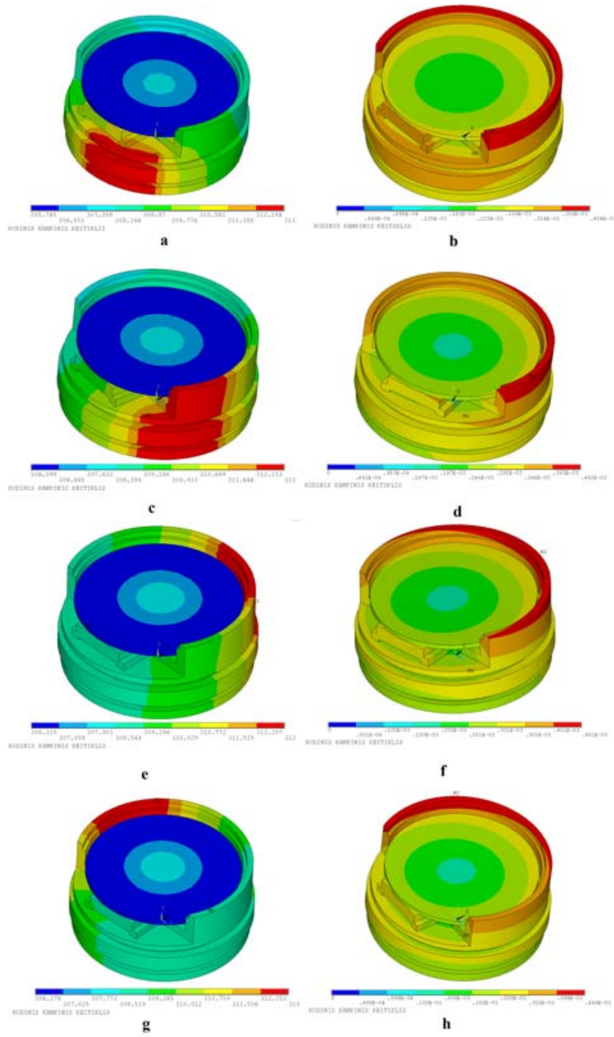

Fig. 3. Calculated temperature profiles (a, c, e g) of the encoder structure and corresponding displacements (b, d, f, h) due to temperature deviations

Multiple contact temperature measurements have been conducted (sensors 1, 3 were placed on the electronic board, sensor was attached 5 near the light source, sensor 4 placed on the mount of the encoder and of the sensor 2 and 6 were positioned on the body of the encoder) as well as monitoring of ambient thermal fluctuations near the encoder (sensor 7) was performed in order to determine variation of temperature errors in time at warming up (when electronics is switched on and shaft of the encoder is not rotating), steady operating (when electronics is on and shaft is rotating at max. speed of 13 000 rev/min) and cut-off conditions. The sensors were placed on the encoder structure or at equivalent locations for both evaluation of thermal stability of the optical encoder and monitoring of temperature near the system. The scatter of temperatures in three transition phases is depicted in Fig. 4.

Measurement cycle is repeated three times after temperature had been settled before each measurement cycle. The temperature distribution was monitored using PP2 temperature measurement system with 7 (max. 22) temperature detectors Pt100. Due to inertia of Pt100 detectors the reading time of the detector signal was 6 seconds (accuracy approx. 1 mK) and the readings of all sensors were taken in intervals of 120 s and averaged values of individual temperature sensors for three realizations are calculated as well as their standard deviations. The obtained experimental data is further used for calculations of temperatures and displacements at all points of the designed encoder geometry.

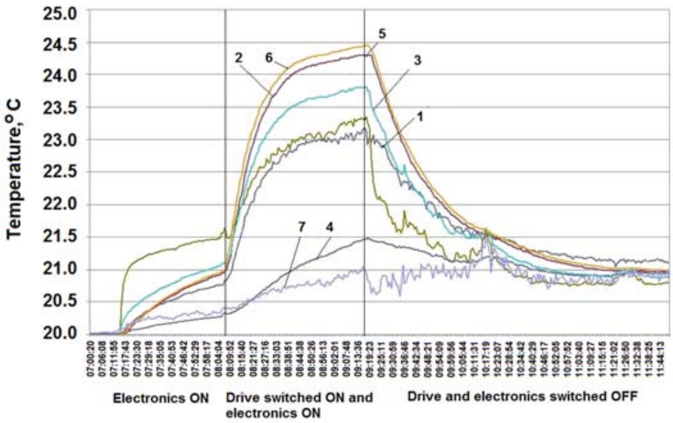

Fig. 4. Temperature variations of the components of an optical encoder and ambient environment

Adequacy between numerical analysis and experimental data is set by matching the temperatures obtained by sensors 2 and 6. Since thermal load cannot be unambiguously determined from the measurement data, equivalent values of thermal power must be adjusted in order to achieve good correspondence of temperatures at measurement points.

For thermal error models with temperature as inputs, the locations of temperature sensors are of major importance in determining the accuracy, efficiency and robustness of the derived models. Taking into account locations of potential heat sources (electronics and bearings) and analysis of calculated and experimentally obtained temperature data equivalent time-depended heat capacity pattern has been developed. Heat capacity changes provided by encoder electronics are assumed as linearly varying in heating and cooling phases. On the contrary, bearings are generating heat only during the rotation and cooling phase is taking place by losing accumulated heat capacity.

Validation of the numerical model is accomplished by comparing the calculated temperatures and measured data for the rest positions of temperature detectors. Good agreement between numerical and experimental data proved that the constructed model of heat transfer is very close to reality and heat generation zones (heat sources) have been estimated correctly.

Knowing the exact temperature profiles the underlying displacements of specific points of the encoder structure are estimated alike thermal deformations in section 2.2. Recalculated results of the temperature induced time-depended deformations are displayed in Fig. 5a and b. Such intermediate results are obtained for particular time moments through the whole investigate time period.

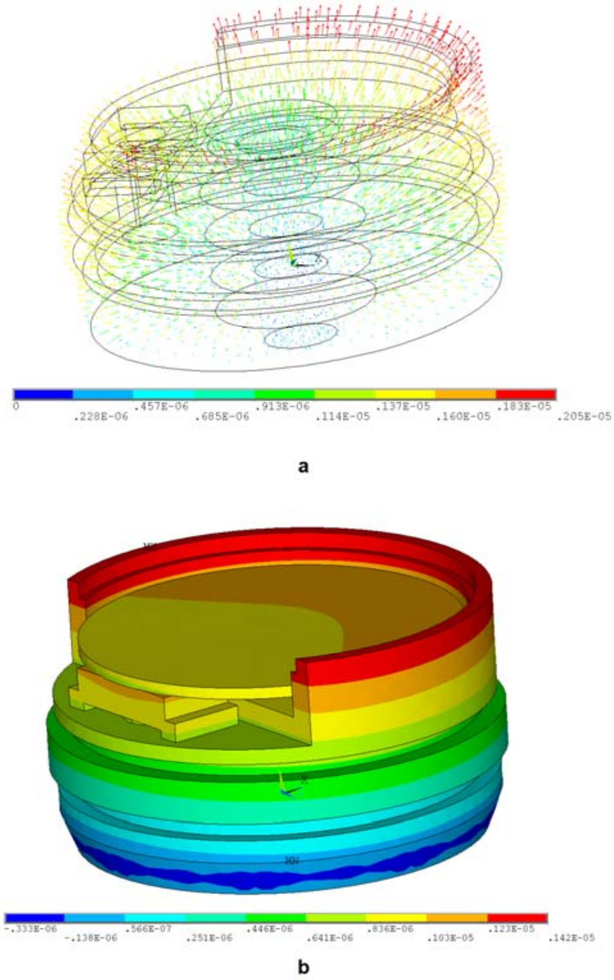

Fig. 5. Temperature induced displacement vectors (a) and coextensive displacement zones (b) in vertical direction (Oy) at time t=6000 s

Calculated local displacements of the grating lines and eccentricity values are presented in Fig. 6 and variations of the gap between the encoder disk and scanning window are depicted in Fig. 7 respectively.

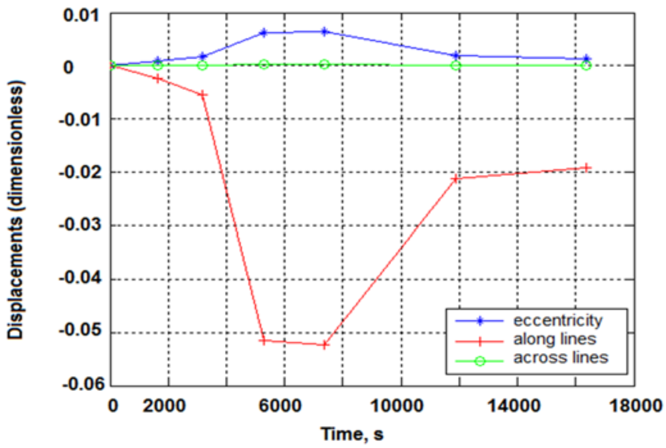

Fig. 6. Local displacements (dimensionless) of the gratings and eccentricity induced by thermal deformations

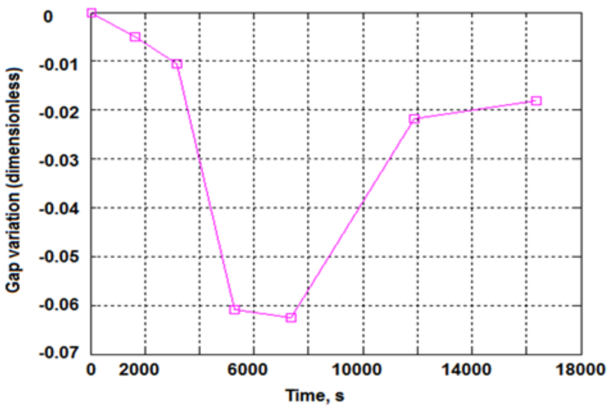

Fig. 7. Gap variation (dimensionless) between the gratings induced by thermal deformations

In all thermal load cases the least displacements are observed across the interfering lines, longitudinal deviations are 4 to 5 times higher. Herewith the resulting gap variations between the disk and scanning window are influenced by thermal gradients more significantly and may exceed relative displacements of the grating lines up to 10 times. Through the generalized thermal error analysis strategy, most of the geometric and thermal errors are accurately predicted and accounted for, the encoder accuracy, therefore, can be significantly improved.

4. CONCLUSIONS

Systematic methodology to quantify the thermal errors through a new numerical modelling approach based on FE models and simulation techniques for interaction of optical gratings of an angular encoder has been developed. The models enable thorough estimation of measurement errors caused by relative displacements and mechanical deformations of the structural components of a precision encoder due to thermal inhomogeneity of the encoder structure and time variant thermal gradients.

Thermal errors are determined by the global and local estimates. Global estimate allows to quantify relative displacements of the axis and disk of the encoder and to define the angular measurement error of the grating lines. Although angular deviations of the grating lines are practically insignificant, eccentricity errors induced by thermo-elastic deformations of the main structural components may amount up to few microns. Local estimate characterises the relative (biased) shifts of interfering grating lines in the centre of the scanning window.

Presented methodology and complex investigations of the optical schemes and interfering gratings enabled us to optimize the performance of an infrared light source and to adjust the design of major components of the encoder.

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