ISSN 1392 - 1207. MECHANIKA. 2011. 17(3): 279-283

Temperature fields, exchanges and deformations of a precise length comparator microscope

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crossref http://dx.doi.org/10.5755/j01.mech.17.3.503

1. Introduction

Precision of determining the real position of the calibrated scale depends highly on microscope stability [1]. To increase resolution power and sensitivity of a microscope, optical schema and structure of its precise length comparators are constantly improved by minimizing both the impact of external disturbances on repeated measurements and microscope drifts, especially those circumstanced by temperature fluctuations.

Thermal expansion is a significant error source in measuring systems which use lasers. Temperature gradients in optical and mechanical components emerge due to the environmental temperature. Stabilization of the instrument temperature at a constant environmental temperature may last for several hours. When calibrating scales under dynamic conditions, particularly at the fluctuating temperature in the environment, the instrument and ambient temperatures never achieve a good equilibrium. Instability of measurements lies mainly in unhomogeneity of temperature deformations. For this reason great attention is being given to modelling and experimental research into the properties of length calibration microscopes [2-4].

To reduce temperature errors of precise microscope structures both segmental structure and materials having a low thermal expansion coefficient are used. 2D and 3D modelling and experimental research into the prototype structures have indicated that sensitivity of such structure to the temperature impact is considerably lower than that of homogeneous structure since gaps between segments increase thermal resistance with an insignificant decrease in stiffness of the structure.

Elaborating the structure of an investigated comparator, a modern precise segmental microscope containing CCD camera and relay objectives has been developed, FE model has been made, modelling of microscope temperature deformations has been carried out and variation of temperature deflections in time and in the microscope CCD camera environment has been experimentally studied.

2. Problem formulation and solution methods

Precise length comparator (PLC) is a complex mechanical system, the proper operation of which requires precision of geometrical dimensions [5-7]. 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 contingent environmental temperature fluctuations on PLC geometry changes is to be accurately estimated. Even with maximum elimination of mechanical disturbances influence [8-10] and assurance of constant environmental temperature security, certain temperature disturbances and the deformations accompanying them are unavoidable due to the heat flows spread by PLC electrical equipment. 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 in advance estimated, or to recalculate the measurement results removing systematic errors [11-13].

One of precarious temperature disturbances is the heat spread by the measuring microscope CCD camera. As the steady-state temperature under the operating conditions is known, the process can be calculated by using the finite element simulation and the temperature values can be found at all points of the microscope structure. Having the temperature values obtained over the microscope structure, the displacements due to thermal expansion can be calculated at all points of the structure.

The analysis scheme is as follows [6, 11]: calculating the static or transient thermal field according to the assigned temperature values at some structure points (of CCD camera surface) and in accordance with the known conditions of convective heat exchange between the structure and the ambient air, the equation of the structure heat balance reads as follows

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

where $[C]$ is matrix of thermal capacity, $\{\dot{T}\}$ is vector with the time derivative of the nodal temperatures, $[K_{Th}]$ is matrix of thermal conductivity, $\{T\}$ is nodal temperatures vector, $\{S_{\infty}\}$ is nodal vector of heat sources of the element determined by the heat exchange over the surface of the body.

In the ANSYS system the heat exchange process is described by element SOLID70. The solution presents the nodal temperature values, which are further used as loads in the problem of thermal expansion of the structure as:

$$[K]\{U\}=\{Q\} \qquad (2)$$

where $[K]$ is stiffness matrix of the element, $\{U\}$ is nodal displacement matrix, $\{Q\}$ is vector of nodal forces determined by temperature loads.

The calculation scheme may be applied to the study of an impact of environment temperature fluctuations on the other PLC elements, e.g. a line scale, geometry changes. The finite element model of the structure has been set up, 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:

- heat transfer by the ambient air due to its thermal conductivity;
- convective heat transfer (due to the air fluctuation);
- heat exchange between the air and PLC structure;
- heat transfer by PLC structure due to its thermal conductivity;
- formation of deformations in PLC structure due to the nonhomogenous thermal field generated in it.

In the computational model phenomena 1-4 have been described by means of ANSYS (FLOTRAN) element FLUID142. The element can be used under two different conditions:

- liquid (gas) dynamics described by the continuity equation, the advection-diffusion equation and the ideal gas state equation;
- thermal conductivity in the solid described by the thermal conductivity equation.

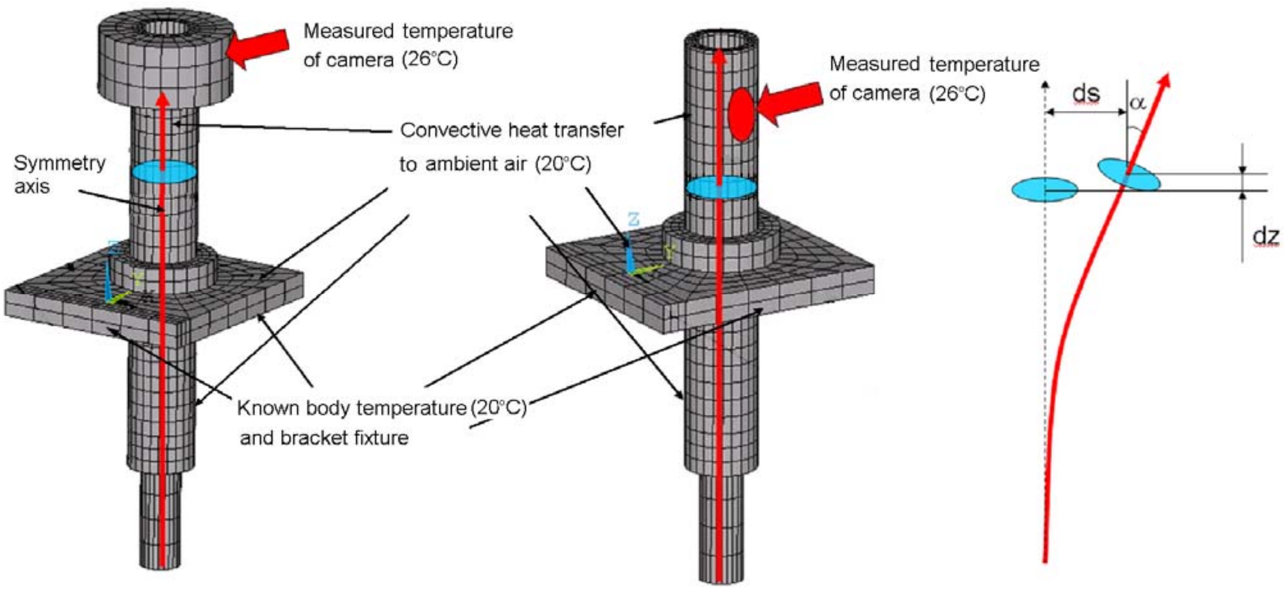


Fig. 1 Model of microscope structure: a) when CCD camera is fixed on the microscope side, b) when it is fixed in the symmetry axis, c) typical cross-section displacements under temperature deformations

3. Model of microscope temperature deformations and calculation results

The model of calculation of PLC microscope temperature deformations is used to analyze two different structures: (Fig. 1, a), when CCD camera is fixed onto the microscope side and (Fig. 1, b), when CCD camera is fixed onto the axis of microscope symmetry

In both cases the temperatures in the zone of the camera fixture are considered to be measured and known. The microscope is fixed on the bracket by means of which its position in the space is adjusted. The temperature at a certain distance from the bracket is assumed to be equal to that of the structure. It is logical to assume that in the rest of the structure surfaces the convectional heat exchanges with the ambient air are proceeding. The value of thermal conductivity of microscope material is assumed to be $\lambda_m = 54\dfrac{\text{W}}{\text{mK}}$, and that of the camera and objective washers - $\lambda_o = 27\dfrac{\text{W}}{\text{mK}}$. Convection coefficient over the surface is assumed to be everywhere - $\beta_c = 20\dfrac{\text{W}}{\text{m}^2\text{K}}$, and thermal expansion coefficient - $\alpha_{t.exp} = 65\times10^{-5}$.

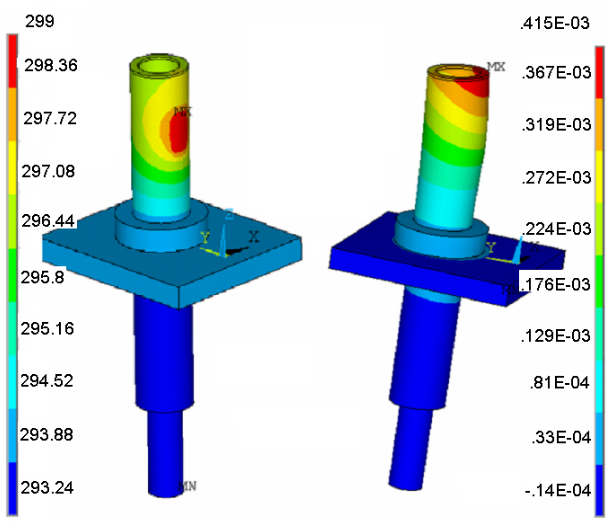
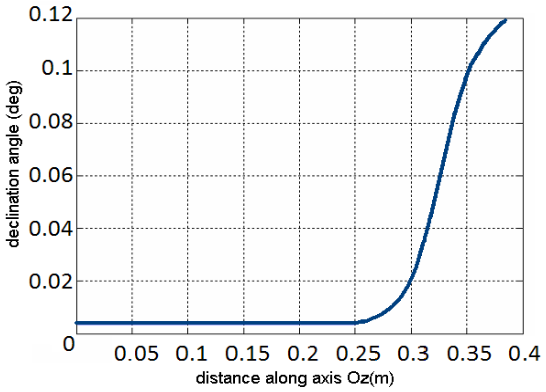


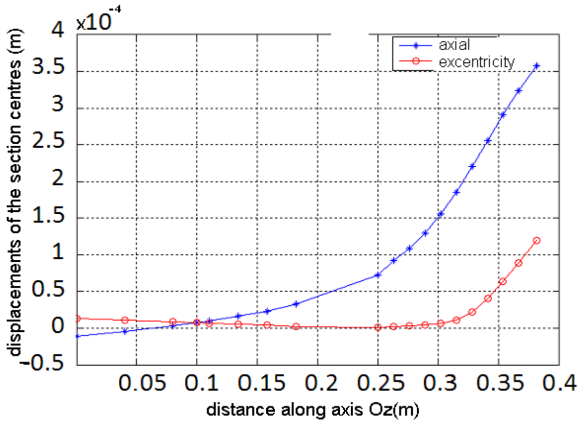
Fig. 2 Displacements in the structure caused by the calculated temperatures field: a) steady-state temperature in the structure, b) distribution of heat flux

Calculation results when CCD camera fixed on a microscope side presented in Fig. 2, a and b. It should be noted that the temperature of microscope beneath the bracket fixture rises insignificantly, and there should be a good microscope bracket thermal contact (it is assumed in the model).

Deviations are the magnitudes explained in Fig. 1, c. It is angle α of the deformed axis with the vertical, as well as displacement of cross-section center dz along the axis, as well as side displacement ds. All three deviation types are observed: axis declination angle α, defocusing deviation dz and eccentric deviation ds.



a



b

Fig. 3 Microscope with CCD camera fixed on its side: declination angle of simmey axis (a), displacements of sectio centres (b)

To evaluate distribution of displacements not only visually but in the context of the system functionality, deviation values of microscope tube cross-sections position and shape in different cuts along the axis are presented in Fig. 3.

In the structure when CCD camera is fixed on the symmetry axis, axial deviations dominate which may affect only the quality of CCD ray focusing, while less affecting its projection in the line scale. The axis course remains unchanged.

4. Temperature fields in the microscope camera environment

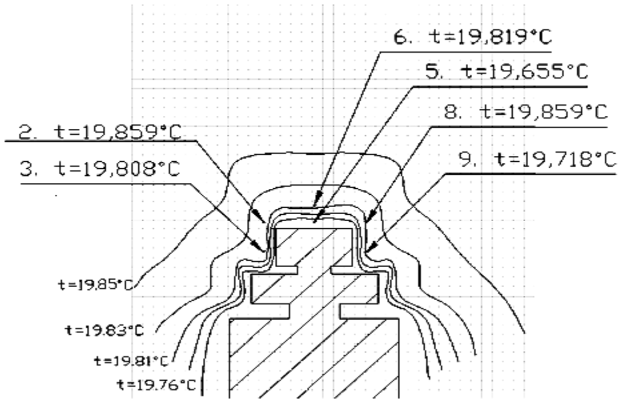
4.1. Experimental research into temperature gradients in the space

In order to determine distribution of the temperature fields around the microscope camera, temperature sensors were arranged in the way that constant temperature curves (isotherms) could be represented in certain cuts. To measure the temperature around the microscope camera, 21 sensors were used: four sensors were glued onto the microscope frame, one – onto the flashbulb, one onto the camera and one onto the camera setting device, the rest of them were layed out in the air.

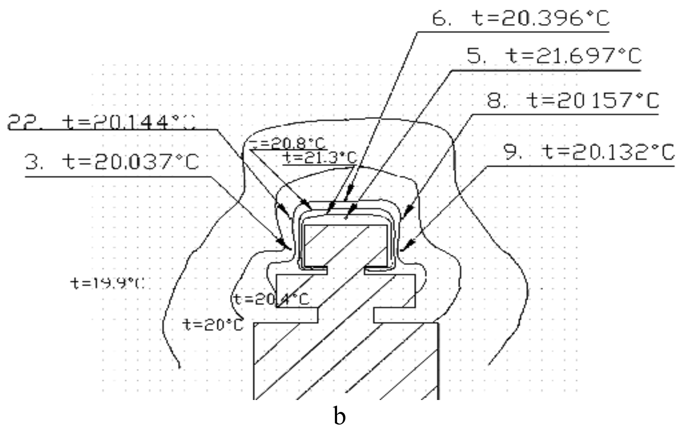
The measurement process was divided into three phases:

- cut-off conditions, when the equipment is switched off for a long time and acquires the ambient temperature;
- warming up, when the camera is switched on and warms up, but the flashbulb does not operate;
- operating conditions, when the thermal balance between the camera and the ambient air flux settles down.

Measurements have been performed three times under similar conditions. Results of the first phase evaluated in terms of the averages of three measurements indicate that the microscope temperature is 0.15°C lower than that of the ambient air. This difference in temperatures has emerged because before the experimental measuring of the temperature fields the premises air-conditioner was switched off. Temperatures around the microscope are uniformly distributed. Microscope is slowly warming-up achieving the air flux temperature. In half an hour its temperature increases by 0.04°C. A similar change is noticed in the read-outs of sensors located closer to the microscope. The closely spaced temperature field, Fig. 4, a, repeats the outline of the microscope and camera frames. The shape of the farther field is cast off.



a



b

Fig. 4 Temperature fields on the vertical cut: a) when the camera is switched off, b) camera switched on

When the camera is switched on, all sensors are recording heat. Temperature dispersion rises. The temperature of sensors fixed onto the frames of microscope and camera uniformly rises. Its least change occurs in the sensors glued on the microscope frame farther from the camera. The temperatures of the sensors which are closer to the camera rise a little faster. A temperature change of the sensor fixed onto a flashbulb is slight. The fastest rise in the temperature is indicated by the sensor fixed onto a camera mandrel. It is evident that the camera achieves thermal equilibrium in about 15 minutes.

Under operating conditions heat is withdrawn from the camera by both the ambient air flux and microscope frame. The camera mandrel disperses heat exceptionally well due to a big ratio of its surface area to mass. Camera emits heat mostly through its couplings with cables on the camera surface intended for data reading check-up and transmission. The camera frame top warms up to 27.5°C. At a spot where camera is connected to the bracket the temperature is only 24.7°C, while that of camera sides is some fractions of a degree lower than on the top. The bracket edge warms up to 22.5°C and after half an hour of operation the sensors fixed onto microscope do not indicate any difference. The temperature fields of horizontal cuts differ very little from each other, whereas when comparing with the same cuts at a switched off camera the distant field is drifting off.

In a vertical cut (Fig. 4) the visible field repeats the camera and microscope outline. Its temperature from the camera to the top changes according to the law which is approximate to the exponential one. Conclusion may be drawn that the camera frame emits heat to the air through both a holder and a mandrel – to microscope. Though the microscope temperature change at the camera is negligible and no change is recorded on the farther frame points, the camera emits the thermal flux which affects temperature deformations of a microscope and a calibrated scale.

4.2. Temperature gradients depending on time

To determine the change of temperature errors the contact temperature measurements have been made on the top of the microscope camera, on the camera setting device, on the camera flashbulb and the air was measured at the line scale. Distribution of temperature sensors is shown in Fig. 5. Temperature measurements have been made at some time before scale calibration and during three calibrations, during the whole measuring period the microscope camera was switched on.

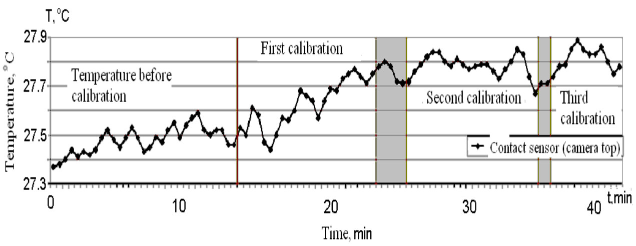


Fig. 5 Temperature change of microscope camera top

The obtained results indicate that the temperature on the camera top before calibration fluctuated by 0.2°C within the range of 27.4°C and 27.6°C (Fig. 5). During the first calibration the temperature rose up to 27.8°C, and during the following two calibrations it fluctuated within 27.7°C and 27.9°C. This temperature fluctuation is stimulated by Peltier element present in the camera which ensures its cooling.

Temperature change of the camera flashbulb frame is also clear. Before calibration the temperature was stable and close to that of the ambient air. From the start of the first calibration the temperature of a flashbulb frame was continually increasing and at the end of the third calibration the temperature change from the initial value reached +0.6°C.

The temperature change on the camera setting device is not so much significant as that on its top or on the flashbulb frame, nevertheless the above mentioned factors have an influence on the temperature drift up to 0.2°C (Fig. 6). This temperature drift affects temperature deformations of the camera setting device and influences the general uncertainty budget.

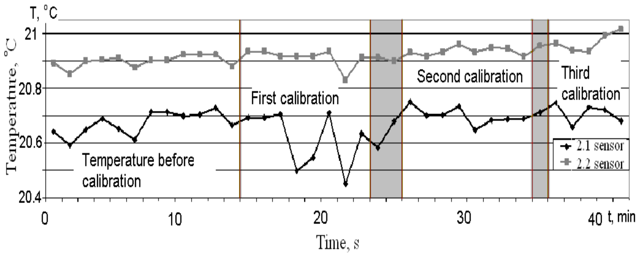


Fig. 6 Temperature change of top setting device of camera

Before calibration and during three calibrations the temperature of the air around the calibrated scale was being measured. During that measurement time the air temperature was falling down within a certain interval. This fall is influenced by a number of factors such as sources of the increased amount of heat in the calibrated scale environment, instability of air fluxes in the calibration laboratory, etc. All these factors have an impact on the calibration results dispersion due to thermal deformations.

5. Conclusions

1. CCD camera of the precise length comparator microscope for determining the dash position of length measures is a source of temperature calibration errors having an essential impact on calibration process precision.
2. As a result of a camera direct temperature impact by means of heat exchange the microscope frame thermally deforms yielding parasite scale picture displacements formed in the microscope coming out as calibration error constituents. Due to this temperature impact the elements connecting the microscope calibrator to the laser interferometer and also coming out as calibration error constituents undergo thermal deformation. An additional error springs up due to both a picture defocusing and a decrease in its distinctness.
3. Thermal emission of the camera violates standard temperature conditions of calibration space of thermo-constant premises and brings about temperature deformations of the measure being calibrated and the comparator elements, thus also causing bigger calibration errors.
4. 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 mathematical methods.

5. In an investigated structure an estimate of the dispersion field of this error at the 95% reliance interval is +/-0.23 μm.

6. To minimize this calibration error sand it is expedient to use the cameras of lower power, symmetric structures made of low thermal expansion materials and to isolate CCD cameras thermally.

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PRECIZINIO ILGIO KOMPARATORIAUS MIKROSKOPO TEMPERATŪRINIAI LAUKAI IR DEFORMACIJOS

R e z i u m ė

Straipsnyje nagrinėjama brūkšnių padėčiai nustatyti skirta mikroskopo vidinių šilumos šaltinių įtaka skalių paklaidų kalibravimo tikslumui. Trumpai pateikiama mikroskopo temperatūrinių laukų ir deformacijų modeliavimo metodika, įvertinanti vidinius mikroskopų šilumos šaltinius. Grafiškai iliustruojami modeliavimo rezultatai, rodantys šilumos šaltinių poveikį mikroskopų temperatūriniams laukams, bei dėl to atsirandančios temperatūrinės deformacijos. Pateikiamos išvados apie nagrinėjamų procesų įtaką skalių kalibravimo tikslumui.

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TEMPERATURE FIELDS EXCHANGES AND DEFORMATIONS OF A PRECISE LENGTH COMPARATOR MICROSCOPE

S u m m a r y

In this article the influence of internal thermal sources of line position detection microscope onto scale error calibration accuracy is analyzed. Short description of the microscope temperature fields and thermal body deformation modelling methodology is proposed, eva-luating internal heat sources of microscope. The modelling results graphs showing the influence heat sources onto microscope temperature field. The resulting temperature deformations are given. Draw conclusions about the processes in question affect the scale calibration accuracy.

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ТЕМПЕРАТУРНЫЕ ПОЛЯ И ДЕФОРМАЦИИ МИКРОСКОПА КОМПАРАТОРА ПРЕЦИЗИОННЫХ ЛИНЕЙНЫХ ШКАЛ

Р е з ю м е

В статье рассматривается влияние внутренних источников теплоты микроскопа, предназначенного для определения положения штрихов. Коротко представлена методика моделирования температурных полей и деформаций микроскопа, учитывая внутренние источники теплоты микроскопа. Графически иллюстрируются результаты моделирования, показывающие воздействие источников теплоты на температурные поля и возникающие от этого температурные деформации. Делаются выводы о влиянии исследованных процессов на точность калибровки шкал.

Received February 02, 2011
Accepted June 15, 2011