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THERMAL DEFORMATION OF MEASURING MACHINES

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Abstract: The paper presents the system for temperature fields analysis of co-ordinate measuring machines. The system should allow the following operations: temperature measurements on the surface of selected CMM units and elements according to the adopted strategy, controlling the operations of the measurement systems, conducting the calibration and correction of measurement sensors, mathematical analysis with the finite element method and graphic presentation of results.

Keywords: temperature fields, analysis, finite element method, co-ordinate measuring machines, measurement

1 INTRODUCTION

The factors that bring about inaccuracies in measurements conducted on co-ordinate measuring machines (CMMs) can be divided into those that result from the apparatus applied and those that are independent of it. As far as the accuracy of the machines themselves is concerned, at present the manufacturing companies have attained such a level of execution precision at which further increase in CMM accuracy can bring about only marginal improvements in the measurement precision. In contrast, a great potential for increasing the accuracy of co-ordinate measurement precision lies in eliminating the interference of external factors on CMM measurements. One of the factors that largely influences the precision of the CMM measurements is the influence of the external thermal conditions. Temperature changes influence the measurements twofold. First, they bring about linear changes in the dimension of the specific CMM units, which are proportional to temperature increases. Secondly, they cause non-linear thermal distortions of the measuring equipment. Those result from the lack of balance in the distribution of temperatures at the different spots of CMM mechanic components, and lead inevitably to distortions in the displacement readings, which by definition should be straight-line. Those distortions can be to a certain extent limited by careful air-conditioning of the premises. However, a number of factors influencing the CMM's thermal condition remain [1,3]. The analysis of the scale of temperature changes and the degree of their unhomogeneity in CMM working conditions may be of capital importance for, at least partial, compensating for adverse thermal influence. In order for the results to be reliable, the methodology of CMM temperature measurement needed to be drawn. The literature in this field is vary scanty [6,7]. A fundamental difficulty in this respect is the minute scale of temperature changes in air-conditioned premises, and the resulting necessity of providing high-resolution measurements (in per cents of Celsius degrees). Apart from technological obstacles and those resulting from the methodology adopted, an important role had to be ascribed to the drawing of the analysis method and the interpretation of the results obtained. In the study described here, the finite elements method was selected as the basis for temperature analysis.

2 THE ANALYSIS OF THE THERMAL CONDITION OF CMM UNITS

CMM element's surface temperature distribution can be measured both by theoretical and by experimental methods [1,2,].

Theoretical methods apply different ways of solving equations describing temperature distribution and influence, taking into account appropriate initial and limiting conditions. Those methods include variable separation, integral transformation, numerical, approximate analytic, and diagrammatic methods. Due to rapid development of electronic calculation techniques, numerical methods are primarily used in engineering practice. They employ, among others, the finite difference method, and most importantly, finite and limiting element method.

In a number of cases the analytic solution may lead to obtaining specific formulas characterising the temperature field, depending on the shape of the analysed object, comportment of the material, and the method of determining thermal load.

Among the experimental methods of temperature field analysis, surface and point methods are distinguished. A basic surface method is that of thermovision which enables the determination of isotherms and temperature profiles in the surface areas of elements. In the point methods, thermoelements and thermistors are usually employed as sensors, and temperature values and changes are registered automatically.

In considering the problem of heat transmission in CMMs, the mechanical structure elements of the apparatus had to be focused upon. The most encountered of those is the so-called gantry unit. The present analysis concerned the bench, vertical columns and the horizontal beam of such a unit. Those are tree-dimensional elements, for which the equivalent minimum functional for a certain function (1) will be of the form:

$$J = \frac{1}{2}\int_V \left[lx\left(\frac{\partial q}{\partial x}\right)^2 + ly\left(\frac{\partial q}{\partial y}\right)^2 + lz\left(\frac{\partial q}{\partial z}\right)^2 \right] dV + \int_V q\, q_v\, dV + \int_S q^S q^S dS - \sum_i q_i\, Q_i \qquad (1)$$

where:
Q_i is the heat stream incoming at the p_i point with the x_i, y_i and z_i. co-ordinates,
λ_x, λ_y, λ_z, are the heat conduction coefficients for the different directions.

In considering the problem of heat conduction with the use of the finite element method, the considered *V* area needs to be subdivided into a finite number of V^e sub-areas, to be called *elements*. The elements are in contact in a number of points, to be called nodes, which are located at the surface of the elements.

The *J* functional will be identical in form for each of the V^e subareas, and its value will be identified as J^e. The value of the *J* functional in the entire *V* area is the sum total of the J^e functionals in all the elements:

$$J = \sum_e J^e \qquad (2)$$

The temperature $q = q\ (x, y, z)$ inside each of the elements described in the rectangular axis *x, y, z* system is expresses through its T_i value determined at the element's nodes and certain interpolative F_i (x, y, z) functions:

$$q(x,y,z) = \sum_{i=1}^{m} \Phi_i(x,y,z) T_i \qquad (3)$$

where:
m - is the number of nodes in the element
For longer periods of time, the temperature$F$ is a function of the time *t*, which can be expressed as follows:

$$\theta = \theta\ (x, y, z, t) = \Phi\ (x, y, z)\ T\ (t) \qquad (4)$$

while its derivative of time will amount to:

$$\frac{\partial q}{\partial t} = \Phi \frac{\partial}{\partial t} T(t) = \Phi \dot{T}(t) \qquad (5)$$

In the analysis of the heat conduction problems the following limiting conditions need to be taken into account:

1. The limiting condition of type I - the temperature T is known for the part S_1 of the surface S, and it can be in general treated as a function of spatial co-ordinates and time. The temperature at any moment is known for the nodes of the element net, located at the S_1 surface. In particular cases, the S_1 surface can be located in the infinity in regard to the centre of the co-ordinate system.
2. The limiting condition of type II - the derivative of the temperature T, in the normal direction of the surface, is given for the part S_2 of the surface S. The amount of heat flowing at any moment through every node of the element net, located at the S_2 surface, is also known. When the S_2 surface is heat insulated or is the plane of symmetry, there is no heat flow through this surface and the temperature derivative value in the normal direction for this plane amounts to zero.
3. The limiting condition of type III - the convection derivative according to Newton's formula is given for the part S_2 of the surface S:

$$l\,\frac{\partial q}{\partial n}\Big|_{S_2} = a\,(T^0 - T^S) \tag{6}$$

where:

a is the heat take-up coefficient
T^s is the temperature of the body at the S_2 surface
T^0 is the temperature of medium that touches the body at the S_2 surface

The surface on which the heat convection exchange occurs is treated as the contact point of two bodies: the analysed body and its surroundings. The surface is described with the help of double nodes of identical co-ordinates. One of these nodes is attributed the body temperature, and the other the ambient temperature. Those double nodes designate the spatial elements on the body surface which have a zero dimension in the normal direction of the surface.

If we are to consider a broader sope of the flow of the heat generated by the CMM units (e.g. electric drives) and the surroundings in which it is operating (lighting, computers and peripherals, as well as the servicing personnel), the equations describing the conduction, convection and radiation processes need to be given.

The conduction process is expressed as follows:

$$rc\left(\frac{\partial T}{\partial t} + v_x\frac{\partial T}{\partial x} + v_v\frac{\partial T}{\partial y} + v_z\frac{\partial T}{\partial z}\right) = \dddot{q} + \frac{\partial}{\partial x}\left(K_x\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z\frac{\partial T}{\partial z}\right) \tag{7}$$

where:

r is the body density
V_x, V_y, V_z are the vectors of heat flow along the z, y, and z axes of the CMM co-ordinate system.
c is the specific heat
T is the temperature
K_x, K_y, K_z are the coefficients of heat flow along the z, y, and z axes of the CMM co-ordinate system.

The radiation process is described by the Stefan-Boltzmann law:

$$Q_i = s e_i F_{ij} A_i (T_i^4 - T_j^4) \tag{8}$$

where:

Q_i is the speed of heat flow from the *i* surface
s is the Stefan-Boltzmann constant
e_i is the transmission efficiency
F_{ij} is the surface of transmission between the *i* and *j* surfaces
F_i is the size of the *i* surface
T_i, T_j are the overall temperature at the *i* and *j* surfaces

The above presentations demonstrate the it is possible to describe the analysed problem in theoretical terms. However, this description is to a very limited extent applicable to industrial uses. In order to employ the described model in practice, it is necessary to use special computer software and research the actual temperature distributions on the analysed CMM sets.

3 THE IDENTIFICATION SYSTEM

The system should allow the following operations:

- temperature measurements on the surface of selected CMM units and elements according to the adopted strategy
- controlling the operations of the measurement systems
- conducting the calibration and correction of measurement sensors
- analysis and graphic presentation of results

The block diagram of the system is presented in Fig. 1.

The analysis unit was constructed at the co-ordinate measuring machine. The measurement points, in accordance with the adopted measurement strategy [3,4], were placed on the bench guides, the basis, the measurement bench, the gantry columns and the horizontal beam. Additionally, the temperature of the CMM surroundings and working space was measured.

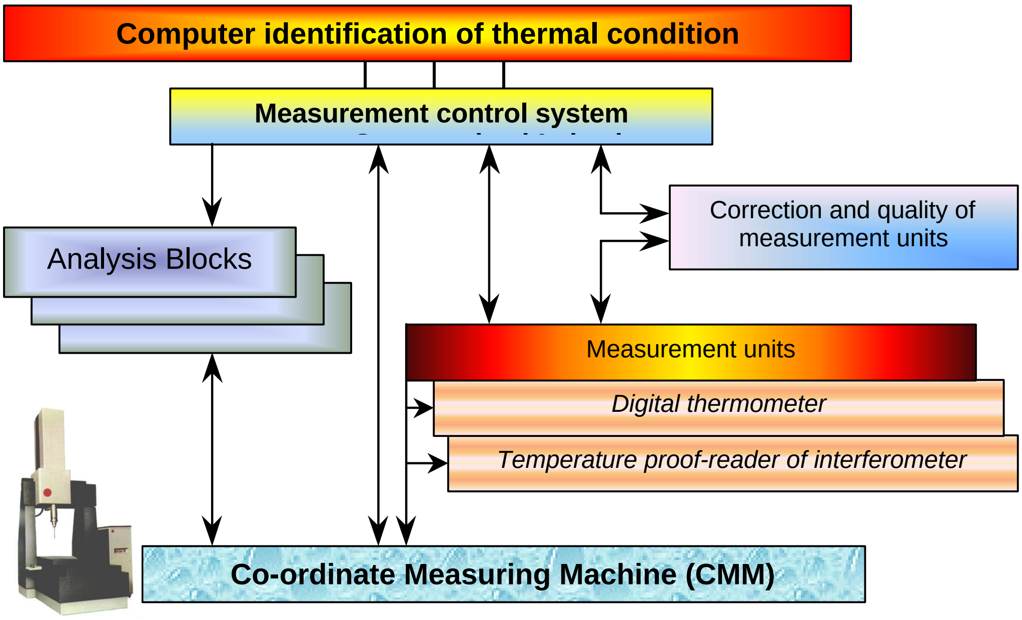


Figure 1. The block diagram of the system

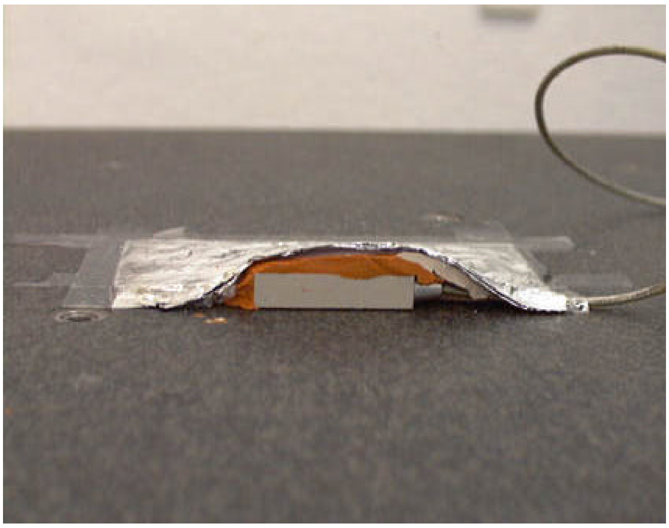


Figure 2. The cross-section of the temperature measurement point

An electronic thermometer equipped with four PT-1000 measurement probes, along with a laser interferometer corrector measurement set, were used in the capacity of temperature measurement units. Both units were plugged into a controlling computer, where all the measurement results were recorded. The temperature measurement was conducted by contact sensors which touched the surface of the analysed element and were protected from the external temperature influence with anti-thermal foil. The cross-section of the temperature measurement point is presented in Fig. 2.

The finite element method requires measuring temperature at the nodes. However, due to equipment limitations (the number of precise temperature sensors in possession) and research costs the number of the measurement points cannot be excessive.

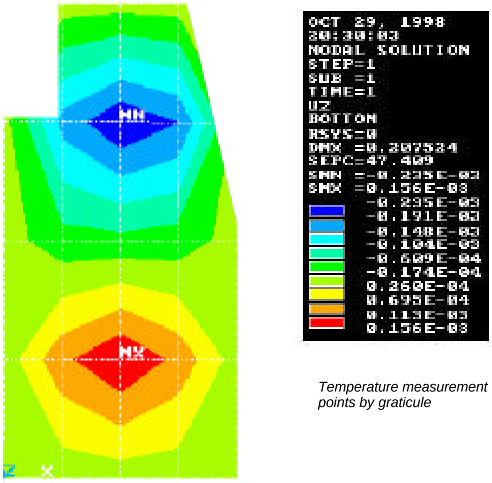
Therefore the following number of measurement points was set:

- 40 points on the machine bench
- 18 points on each column of the gantry
- 12 points on the horizontal beam

In the present work, all the temperature measurement points were duly numbered for each CMM element and attributed appropriate measuring sensors.

4 THE ANALYSIS OF THE OBTAINED RESULTS

The results obtained from the measurements were computed with the help of the ANSYS software, which was adapted to the calculation of the values of the deformation resulting from the temperature influence. [4,5,7]



Temperature measurement points by graticule

Figure 3. The thermal deformations of the surface of CMM column [mm]

The application of appropriate sub-softwares has allowed to model the deformations of indivudual CMM mechanical units arising in the course of the measurements due to the changing temperature.
The results obtained from the measurements were computed with the help of the ANSYS software. The samples of thermal deformations of the surface of column and gantry horizontal beam of CMM are presented in Fig. 3, 4, & 5.

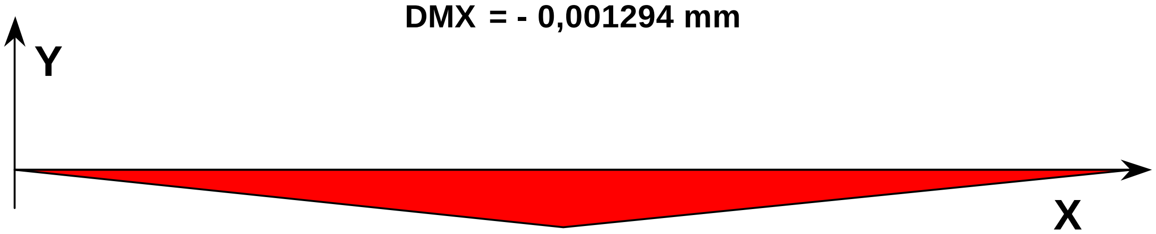


Figure 4. The side view of the gantry horizontal beam before operation

The deformation values are given below:

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    THE FOLLOWING DEGREE OF FREEDOM RESULTS ARE IN GLOBAL COORDINATES
        NODE             UX               UY              UZ
          1          0.00000E+00     0.00000E+00    0.00000E+00
          2         -0.12127E-02    -0.61716E-03    0.54497E-03
          3          0.11336E-02     0.00000E+00    0.00000E+00
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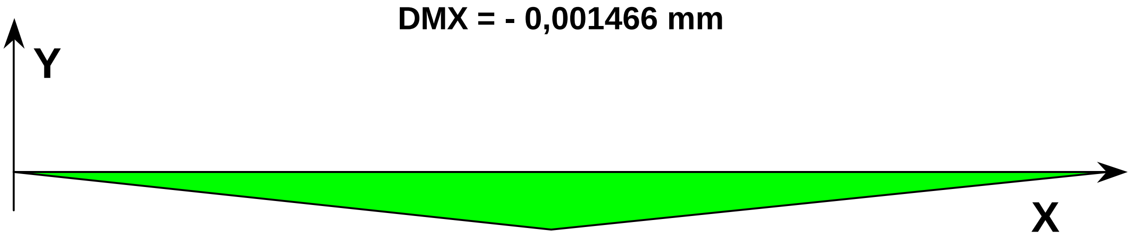

Figure 5. The top view of the gantry horizontal beam after operation

5 CONCLUSIONS

1. The work presents the methodology that was created for precise temperature measurements of individual CMM units.
2. The methodology was specially selected for the use in accordance with the finite element method.
3. The result analysis and graphic presentation was conducted by means of a compurter method based on the ANSYS software.
4. The maximum deformations obtained from the analysis of the measure temperatures were as follows:
    - 1.80 ÷2.00 µm for the bench surface (along the Z axis)
    - 1.50÷2.08 µm for the columns (depending on the surface analysed)
    - 1.20 ÷2.50 µm for the horizontal beam (depending on the surface analysed)
5. The computer identification method presented here may be applied both for scientific and industrial purposes in determining the range of temperature variability in technical or measurement apparatus units.
6. The conducted measurements allow for the determination of the temperature distribution on the analysed surfaces, also as a function of time.
7. The temperature gradients changes that were observed are due, among others, to the operation of the measuring machine and the presence of the personnel.
8. The system is prepared as an open entity which allows the use of any number of measurement sensors and the application of various analysing software.

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