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MODELING OF THE THERMAL INFLUENCES ON THE CMM KINEMATIC SYSTEM

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Abstract–This paper presents new method of modeling of the thermal influences on the Coordinate Measuring Machine kinematic system. The model is based on the residual kinematic errors distributions that are determined for different temperature ranges. It can be used in simulative methods of uncertainty determination in order to make them more sensitive on temperature changes. The example of utilization of such a model and the verification of its proper functioning were also presented.

Keywords: CMM, geometrical errors, thermal influences

1. INTRODUCTION

The influence of temperature on widely understood production engineering cannot be omitted. The temperature influences parts of machines that are used for performing various tasks connected with machining, assembling, transporting, positioning, etc. Also handled workpieces are vulnerable for temperature influences what has to be taken into account during planning of manufacturing processes.

This problem is extremely important during coordinate measurements of geometric quantities as the level of measurement accuracy has to be significantly better than the production tolerances assumed for manufactured products. To understand the importance of this issue one should listen to the saying of experienced metrologists, who used to mention: "when you measure with micron or submicron accuracy, it is not about measuring the lengths but the temperature".

Because of it, in recent years we can observe the trend of installing the machines in strictly air-conditioned rooms. This demeanour is of course a proper one, but also an expensive one. Considering the economical determinants of present production engineering it is impossible to ensure the high stability of thermal conditions in all rooms in which the coordinate measuring machines are used. This is why the thermal influences has to be dealt in some other way. The methods of minimizing the temperature influences include usage of the materials that has low coefficient of thermal expansion (CTE), using the structure of materials in which the thermal influences are self compensating and incorporating the models of thermal influences in order to compensate or forecast them [1-3].

Regarding the temperature influence on the kinematic system of the CMM, some attempts was made to take it into account in the measurement result. The model that include the thermal influences on positioning errors of the machine are commonly known and they are used nowadays in great number of machine's CAA matrices. In some of CMM models also the influence of temperature on other translational errors of the machine are included in CAA matrix. A very small number of machines uses the full geometrical errors compensation in dependence of actual temperature.

This is why the authors has started the research on this subject. Basing on the first experiences regarding the modeling of the residual kinematic errors at the temperature close to 20 °C [4] the authors have decided to perform experiments aiming in finding out whether the temperature changes influence the distributions of residual errors. The results of these investigations along with the way of their practical implementation in the form of novel method of modeling of the thermal influences on the CMM kinematic system were presented in this paper.

2. CHANGES IN RESIDUAL ERRORS DISTRIBUTIONS CAUSED BY THERMAL INFLUENCES

The model of CMM residual kinematic errors that was presented in [4] was used. As a residual kinematic errors the authors understand the parts of machine's geometric errors that remained uncompensated after usage of CAA matrix. The determination of residual errors distributions is performed experimentally, using the LaserTracer interferometric system. The machine's measuring volume has to be described by the grid of reference points. After determining the structure of this grid, the measurement ought to be proceeded. The machine with retroreflector mounted instead of the probe head performs 14 approaches from different directions to each node of the grid (after doing it for one reference point, the machine goes to another and perform 14 approaches again). The entire sequence is repeated four times for different LaserTracer positions. As a result of measurement and the representation of residual errors, the standard deviations of reproduction of point coordinates x, y, z are obtained. It is important to note that during described measurement, the machine's CAA matrix has to be switched on.

In order to check the temperature influence on the distributions of residual errors the experiment was performed in 5 different temperatures: 18±0,2 °C, 19±0,2 °C, 20±0,2 °C, 21±0,2 °C, 22±0,2 °C. There were 36 reference points set in measuring volume of the machine. As the modeled machine, the bridge CMM with measuring volume of 1000:1200:500 mm was chosen. The distribution of reference points in machine's volume was presented in Tab. 1.

Table 1. Nominal values of reference points coordinates given in mm.

No.	x	y	z	No.	x	y	z
1	180	242	64	19	180	242	338
2	180	627	64	20	180	627	338
3	180	1012	64	21	180	1012	338
4	440	242	64	22	440	242	338
5	440	627	64	23	440	627	338
6	440	1012	64	24	440	1012	338
7	700	242	64	25	700	242	338
8	700	627	64	26	700	627	338
9	700	1012	64	27	700	1012	338
10	180	242	201	28	180	242	475
11	180	627	201	29	180	627	475
12	180	1012	201	30	180	1012	475
13	440	242	201	31	440	242	475
14	440	627	201	32	440	627	475
15	440	1012	201	33	440	1012	475
16	700	242	201	34	700	242	475
17	700	627	201	35	700	627	475
18	700	1012	201	36	700	1012	475

The results of performed analysis was presented in Fig. 1-3 and Tab. 2. They show that the temperature influence the values of residual errors significantly. The differences are visible the most for the temperatures that diverges from the reference temperature considerably (for 18 and 22 °C).

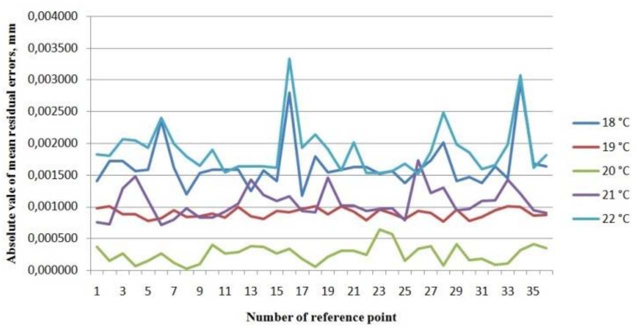

Fig. 1. Absolute values of mean residual errors of coordinate reproduction for *x* coordinate, determined in different temperatures. Numbers of reference points and their positions are consistent with Tab. 1.

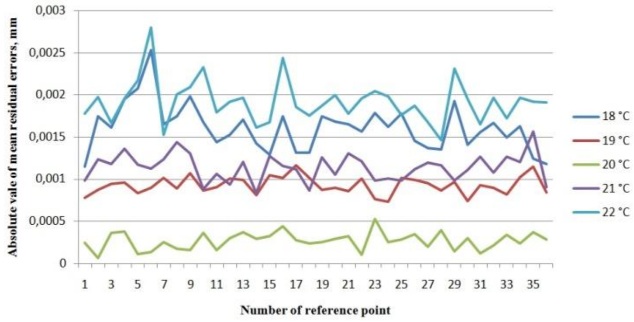

Fig. 2. Absolute values of mean residual errors of coordinate reproduction for *y* coordinate, determined in different temperatures. Numbers of reference points and their positions are consistent with Tab. 1.

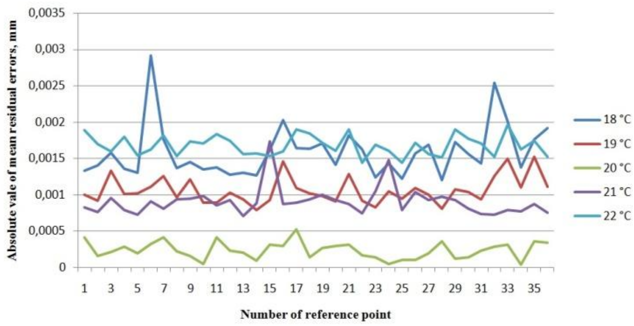

Fig. 3. Absolute values of mean residual errors of coordinate reproduction for *z* coordinate, determined in different temperatures. Numbers of reference points and their positions are consistent with Tab. 1.

Table 2. Values of mean absolute value of coordinate reproduction errors for *x*, *y* and *z* coordinates, determined in different temperatures. Values given in mm for points 1-7 from Tab. 1.

Mean absolute value of	No. of point	18°C	19°C	20°C	21°C	22°C
x coordinate reproduction error	1	0,0014	0,0010	0,0004	0,0007	0,0018
	2	0,0017	0,0010	0,0002	0,0007	0,0018
	3	0,0017	0,0009	0,0003	0,0013	0,0021
	4	0,0016	0,0009	0,0001	0,0015	0,0020
	5	0,0016	0,0008	0,0001	0,0011	0,0019
	6	0,0024	0,0008	0,0003	0,0007	0,0024
	7	0,0016	0,0009	0,0001	0,0008	0,0020
y coordinate reproduction error	1	0,0011	0,0008	0,0002	0,0010	0,0018
	2	0,0017	0,0009	0,0001	0,0012	0,0020
	3	0,0016	0,0009	0,0004	0,0012	0,0017
	4	0,0019	0,0010	0,0004	0,0014	0,0020
	5	0,0021	0,0008	0,0001	0,0012	0,0022
	6	0,0025	0,0009	0,0001	0,0011	0,0028
	7	0,0017	0,0010	0,0002	0,0012	0,0015
z coordinate reproduction error	1	0,0013	0,0010	0,0004	0,0008	0,0019
	2	0,0014	0,0009	0,0002	0,0008	0,0017
	3	0,0016	0,0013	0,0002	0,0010	0,0016
	4	0,0014	0,0010	0,0003	0,0008	0,0018
	5	0,0013	0,0010	0,0002	0,0007	0,0015
	6	0,0029	0,0011	0,0003	0,0009	0,0016
	7	0,0018	0,0013	0,0004	0,0008	0,0018

3. MODELING OF THE THERMAL INFLUECES ON THE CMM KINEMATIC SYSTEM

Basing on the results of experiments presented in section 2 the authors decided to create the model of thermal influences on the CMM kinematic system. The model is based on the active monitoring of the temperature in the measuring volume of the machine and using of the different distributions of residual errors (presented in section 2), determined for different temperature ranges.

The temperature monitoring system is based on the Arduino Nano board, two digital temperature sensors and an Python based application used for recording the sensors indications (Fig. 4) and deciding which distribution of residual errors should be used. The Arduino platform was chosen because in the future it would be easy to expand the temperature monitoring system with another sensors that uses wireless communication technology. It is also possible to enhance the system by the measurements of air pressure and humidity. Currently, the indications from the system are obtained by averaging 10 measurements of temperature from both digital sensors. The precision of temperature measurement was assessed by comparing the system indications with the calibrated thermal sensor. The correction to developed system indications was determined as 0,08 °C and it is currently used in the application that support the system.

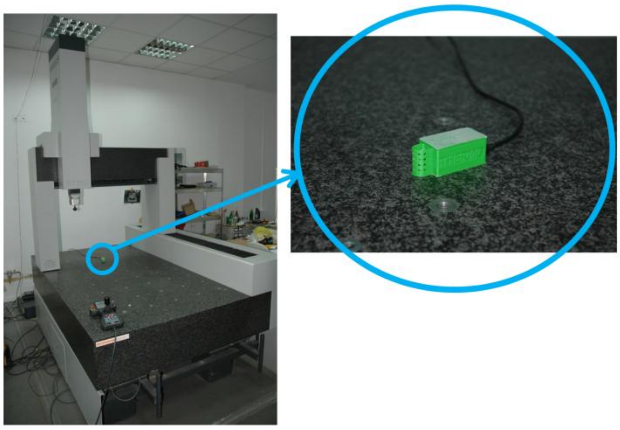

Fig. 4. Digital temperature sensor located in the machine's measuring volume.

Knowing the residual errors distributions determined for five different temperatures also the five temperature ranges could be defined. The temperatures at which residual errors were determined should be the centers of these ranges. So defined ranges in the case of presented experiments were: (17,5°C;18,5°C), (18,5°C;19,5°C), (19,5°C;20,5°C), (20,5°C;21,5°C) and (21,5°C;22,5°C). Each time the actual temperature changes from one range to another the different residual errors distribution is loaded and used for simulating the kinematic system errors.

Developed model can be used as a module of Virtual CMM model used for simulation of CMM kinematic system errors. It can be used instead of the popular modules based on knowledge about the values of 21 components of geometrical errors known from [5,6].

4. VERIFICATION OF DEVELOPED MODEL

Developed model was verified experimentally in one of its possible usages, it was utilized as a part of Virtual CMM model. The verification of its functioning was based on minimizing of any other influences than temperature, that may cause the increase of measurement uncertainty. So the machine and probe head configuration, sampling strategy and localizations of measured workpiece were the same during all performed measurements. The only condition that was changing was the temperature.

As a measured workpiece, the multi-feature standard presented in fig. 5 was used. The popular measuring tasks were performed. They included the measurement of plane-plane distance, diameter of a circle, form deviations for a plane and a cylinder. The measurements were repeated in different temperatures. There were 6 measuring cycles performed. In the first five the temperature was set to stay within one of the ranges described in section 3. In the last cycle the temperature was oscillating near the border between two ranges, so that it was for some time in the first range and then in the second one.

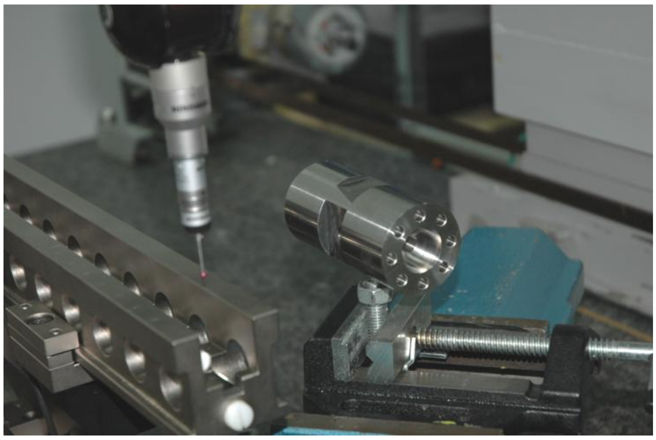

Fig. 5. Verification measurements using multi-feature standard.

The verification was based on the comparison of the uncertainties determined using Virtual CMM that utilizes verified model of thermal influences and the uncertainties determined using substitution method and multiple measurement method - the methods that are commonly used and are treated as validated ones.

The results of performed verifications were presented in Tab. 3-6.

The thermal influences on workpiece were compensated using external temperature sensor. The maximum differences in uncertainty values for one feature evaluated in different temperatures equalled to 0,0012 mm for cylindricity. This result lead to conclusion that the differences in obtained uncertainties are relatively small (considering that the uncertainties was determined for temperature changing in range 18,0 -21,7 °C) so the model of thermal influences should be treated as working properly.

Table 3. Results of performed verifications. The numbers given as columns' captions are the ranges of temperature values (given in °C) for which considered results (y) with corresponding expanded uncertainties (U(y)) were obtained. y and U(y) given in mm. PNT-PNT denotes point-point distance, PLA-PLA plane-plane distance, OUT DIAM - external diameter and IN DIAM - internal diameter.

Feature	18,0-18,4		18,9-19,3		20,1-20,5		20,8-21,2		21,6-22,0		21,3-21,7	
	y	U(y)	y	U(y)	y	U(y)	y	U(y)	y	U(y)	y	U(y)
PLA-PLA	99,9654	0,0043	99,9657	0,0044	99,9662	0,0034	99,9668	0,0037	99,9671	0,0039	99,9667	0,0044
OUT DIAM	35,0175	0,0029	35,0176	0,0027	35,0189	0,0031	35,0191	0,0032	35,0202	0,0034	35,0200	0,0038
IN DIAM	24,9823	0,0037	24,9826	0,0035	24,9845	0,0038	24,9848	0,0035	24,9808	0,0036	24,9804	0,0039
FLATNESS	0,0045	0,0014	0,0044	0,0016	0,0047	0,0015	0,0044	0,0013	0,0048	0,0016	0,0047	0,0021
CYLINDRICITY	0,0072	0,0015	0,0075	0,0013	0,0057	0,0021	0,0059	0,0020	0,0067	0,0023	0,0069	0,0025

Table 4. Comparison of results obtained for temperature range 18,0 - 18,4 °C using different methods. y and U(y) given in mm.

Feature	Calibrated Object		Multiple measurement		Virtual CMM	
	y	U(y)	y	U(y)	y	U(y)
PLA-PLA	99,9624	0,0009	99,9619	0,0024	99,9654	0,0043
OUT DIAM	35,0162	0,0011	35,0158	0,0018	35,0175	0,0029
IN DIAM	24,9811	0,0009	24,9811	0,0016	24,9823	0,0037
FLAT	0,0042	0,0010	0,0040	0,0011	0,0045	0,0014
CYL	0,0083	0,0016	0,0076	0,0021	0,0072	0,0015

Table 5. Comparison of results obtained for temperature range 20,1 - 20,5 °C using different methods. y and U(y) given in mm.

Feature	Calibrated Object		Multiple measurement		Virtual CMM	
	y	U(y)	y	U(y)	y	U(y)
PLA-PLA	99,9637	0,0010	99,9634	0,0014	99,9662	0,0034
OUT DIAM	35,0178	0,0012	35,0183	0,0015	35,0189	0,0031
IN DIAM	24,9823	0,0011	24,9818	0,0012	24,9845	0,0038
FLAT	0,0045	0,0010	0,0041	0,0013	0,0047	0,0015
CYL	0,0068	0,0012	0,0059	0,0018	0,0057	0,0021

Table 6. Comparison of results obtained for temperature range 21,6 - 22,0 °C using different methods. y and U(y) given in mm.

Feature	Calibrated Object		Multiple measurement		Virtual CMM	
	y	U(y)	y	U(y)	y	U(y)
PLA-PLA	99,9650	0,0009	99,9649	0,0018	99,9671	0,0039
OUT DIAM	35,0192	0,0011	35,0190	0,0016	35,0202	0,0034
IN DIAM	24,9829	0,0011	24,9832	0,0015	24,9808	0,0036
FLAT	0,0042	0,0010	0,0041	0,0011	0,0048	0,0016
CYL	0,0074	0,0017	0,0075	0,0021	0,0067	0,0023

5. CONCLUSIONS

The paper presents novel method of modeling the thermal influences on the CMM kinematic system. The model was verified and its proper functioning was shown. The presented model can be a milestone in broadening the range of applications of Virtual CMM models. Their usage was limited to laboratories in which the thermal stability was a necessary condition. Thanks to developed model the thermal stability should be no longer a barrier for Virtual CMM usage. It was shown in this paper that the virtual model based on developed solution is capable of faithful uncertainty assessment in the wide range of temperature changes spanning from 17,5 to 22,5 °C. The bigger temperature variations are barely met in the measuring laboratories.

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