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Tomáš PETÁK*, Eva KUREKOVÁ**

CALIBRATION OF BIAXIAL NC POSITIONING TABLE

KALIBRACE DVOUOSÉHO POLOHOVACÍHO NC STROJE

Abstract

This contribution describes procedures and interpretation techniques of calibration biaxial positioning table carried out in the Institution of automatization, measurement and applied informatics STU in Bratislava. Characteristics of table axes, which is installed as a part of information and control system laboratory are demonstrated by calibration. As method for calibration was used direct comparison method. The Aim of this work is to specify a calibration method, design of measurement model, execution of the measurement experiments, statistical evaluation of the measurements, specification of source of uncertainties and interpretation of the results of calibration in terms of the chosen methodology. As a standard was chosen laser interferometer XL 80 from Renishaw to fulfill requirements for high accuracy and repeatability measurements of NC table axes. Laser interferometer is used in the geometrical quantities measurement such as length, angle, straightness, flatness or perpendicularity. Advantage of this standard is the software, which allows evaluation of measurement according to ISO standards and the others. As a result of this work is to determine the positioning errors of NC table with application of corrections of these errors. Finally is made positioning control of table axes by re-execution of the measuring experiments.

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Abstrakt

Příspěvek popisuje postupy a techniky kalibrace dvouosého polohovacího stolu provedené v Ústavu automatizace, měření a aplikované informatiky STU v Bratislavě. Jako metoda pro kalibraci byla použita přímá srovnávací metoda. Cílem této práce je určit kalibrační metodu, návrh modelu měření, realizace měření experimentů, statistické vyhodnocování měření, specifikaci zdroje nejistot a interpretaci výsledků kalibrace z hlediska zvolené metodiky. Jako standard byl vybrán laserový interferometr XL 80 společnosti Renishaw pro splnění požadavků na vysokou přesnost a opakovatelnost měření NC stolních os. Laserový interferometr se používá při měření geometrických veličin jako je délka, úhel, přímost, rovina a kolmost. Výhodou tohoto standardu je software, který umožňuje vyhodnocení měření dle norem ISO a další. Na závěr se provádí řízení polohy os opětovným provedením měřicích experimentů.

* Ing. Tomáš PETÁK, STU Bratislava, ÚAMAI SjF, Námestie slobody 17, Bratislava 1, 812 31, tomas.petak@stuba.sk
** doc. Ing. Eva KUREKOVÁ, CSc., STU Bratislava, ÚAMAI SjF, Námestie slobody 17, Bratislava 1, 812 31, eva.kurekova@stuba.sk

1 NC POSITIONING TABLE

Micro-positioning device consists of two perpendicular and structurally identical axes X and Y. These two allow positioning in the horizontal plane and form basis of the positioning device. Linear movement axes of the two tracks are made up of rolling tracks with trackballs. Supporting structure is solved by the aluminum profiles. The biaxial positioning device is using position control without feedback. This is carried by SIMOSTEP stepper motors with incremental sensors connected to the trackball gear. The motor is connected to the screw shaft by clutch. Control system with FM-power units FM-SIMODRIVE is based on the programmable controller S7-300 with positioning module FM 357-2.

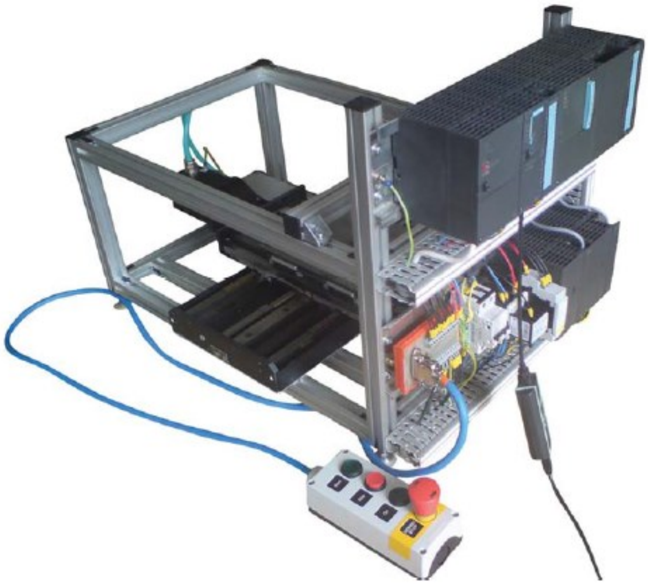

Fig. 1. Sample of biaxial NC positioning table.

Positioning of the table is provided by the limit switches. These are located in the axes frame. Selected parameters of the axes are shown in Table 1.

Table 1: Basic technical parameters of the NC positioning table.

Parameter	Parameter value	
	axis X	**axis Y**
Stroke	160 mm	160 mm
Length of the positioning platform	640 mm	585 mm
Width of the positioning platform	250 mm	210 mm
Max. positioning speed	80 mm/s	80 mm/s
Min. positioning step	0.0004 mm	0.0004 mm
Directness of movement	0.004 mm	0.004 mm
Perpendicularity of movement	0.005 mm/stroke	0.005 mm/stroke
Maximum load	100 N	100 N
Climb of screw	4 mm/rev.	4 mm/rev.

2 STANDARD – LASER INTERFEROMETER RENISHAW XL 80

For NC positioning table calibration was chosen the laser interferometer XL 80 from Renishaw as a standard. Laser interferometer is measuring device that is used in the geometrical quantities measurement such as length, angle, straightness, flatness or perpendicularity. As a light source is used He-Ne laser (Helium-Neon) methane CH_4 stabilized. Frequency is sufficiently stable to be able measure the frequency and wavelength with high accuracy. Wavelength of stabilized He-Ne laser of the measuring system XL 80 is therefore suitable to the device could be used as a length measure with declared precision and inclusion. Laser interferometer Renishaw XL 80 is based on heterodyne principle. It is therefore a dual frequency interferometer.

Table 2: Basic metrological parameters of the laser interferometer Renishaw XL 80.

System performance	**Renishaw XL 80**
Linear measurement range	0 to 40 m
Linear measurement accuracy	± 0.5 µm/m
Linear frequency accuracy	± 0.05 µm/m
Resolution	1 nm
Maximum travel velocity	4 m/s
Dynamic capture rate	10 Hz to 50 kHz
Preheat time	< 6 minutes
Specifies accuracy temperature range	(0 to 40) °C

The Laser interferometer is using physical principle of the interference comparator. The light source is dual frequency gas laser. The laser emits light radiation at two very close frequencies. Both beams are orthogonal polarized. This allows their separation by polarizing filter. This provides reference and measurement beams. Reference beams f_1 and f_2 fall on a photosensitive element, the measuring beams continue to half mirror. The measuring beams are divided into two parts here. One part of the frequency f_2 is reflected by the corner reflector and after reflection from the semi-permeable mirror returns to the photosensitive element. The second part of the frequency f_1 moves through the half mirror and turns to the corner reflector mounted on the measured object. There is a frequency shift of the beam on value $f_1 + \Delta f$. The beam turns on a photosensitive element. There is an output signal proportional to the frequency change Δf on the output of evaluation unit [1].

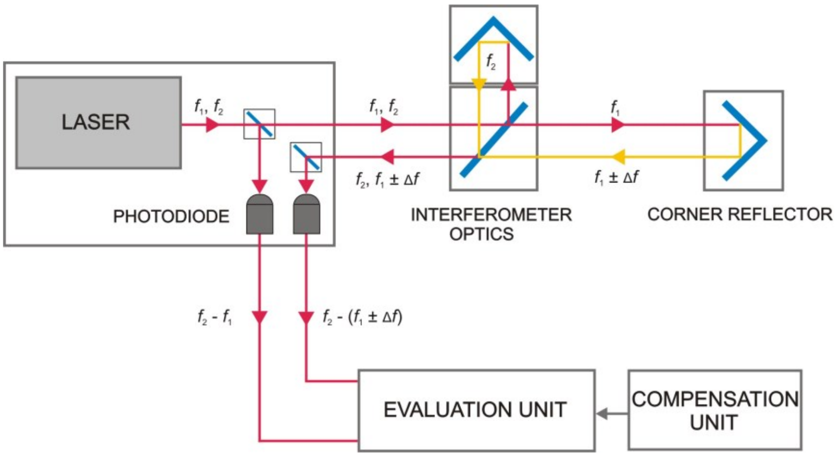

Fig. 2. Schematic sample of the heterodyne laser interferometer.

The accuracy of measurement of using the laser interferometer affects the refractive effect index of environment, usually air.

Wavelength of the laser beam varies according the formula:

$$\lambda = \frac{\lambda_0}{n} \tag{1}$$

where:

λ – wavelength of laser light in air,
λ_0 – wavelength of laser light in vacuum,
n – refraction index of air.

The value of the refractive index varies according to changes in temperature, pressure relative humidity and chemical composition of air. Contamination of optical path of laser between interferometer and corner reflector also affects the measurement. Great advantage of application of laser interferometer is using of metrological station for measurement and follow compensation ambient parameters given to the reference values.

Fig. 3. Laser interferometer Renishaw XL 80 [2].

3 CONDITIONS OF THE EXPERIMENT

ISO standard 230-2 is possible to use for calibration of the NC positioning table. It is aimed on testing and evaluation of the accuracy and repeatability of positioning numerically controlled axes in machine tools, using direct measurement of the machine axes. The method is applicable for linear and rotary axes. The aim of measurements under that methodology is to create compensatory curve to compensate for positioning errors in numerically controlled machines tool axes. The measurement is performed on the device steady-state temperature. It must be preceded a suitable heating process. Positioning table must stop in the measured position for long enough to allow a capturing of actual position. Device must be steady in horizontally position and moved by balanced speed. Direct to the nature of measurement is chosen as a measuring step the linear bi-directional measuring cycle, which is described in Figure 4. It refers to a series of measurement, where setting to the specified position in given axis is performed in both directions of movement [3].

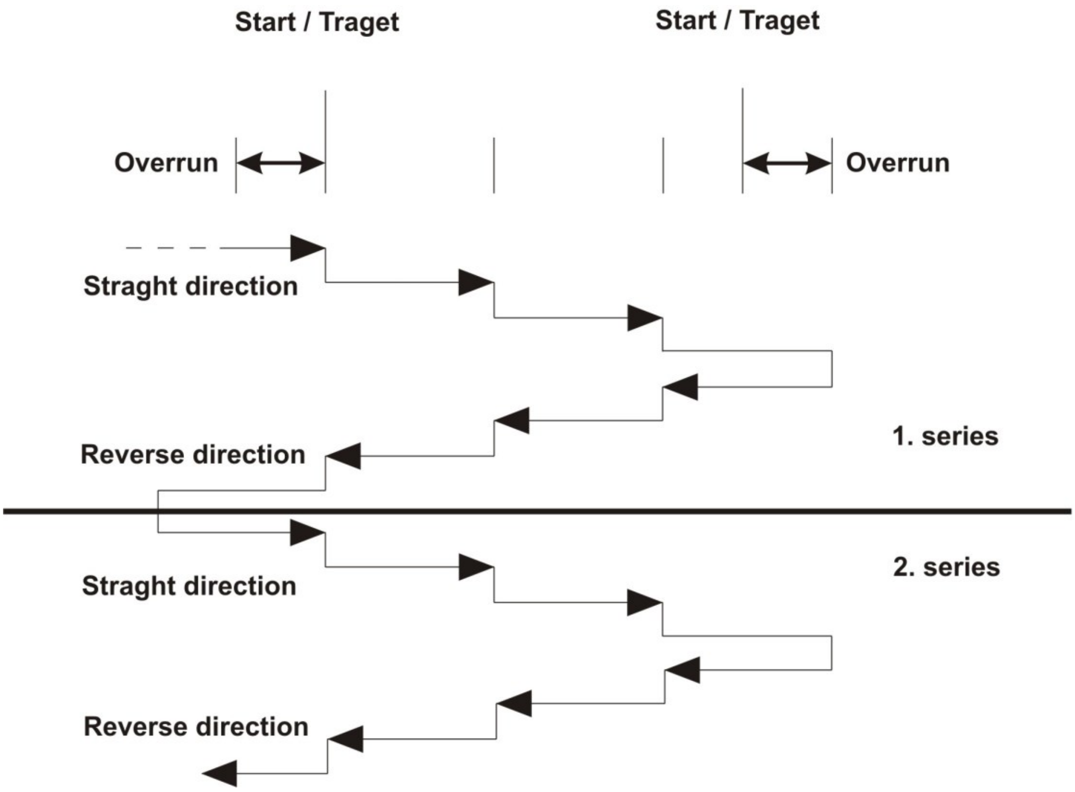

Fig. 4. Linear bi-directional measuring cycle.

In accordance with requirements of ISO 230-2 the range of calibration of linear axes is restricted to -70 mm to 70 mm. Foray into the extreme positions of stroke of NC table could not be realized by reverse direction of measurement.

The following parameters are evaluated according to ISO 230-2:

Target position

$$P_i(i = 1 \text{ až } m) \tag{2}$$

Actual position

$$P_{ij}(i = 1 \text{ až } m,\ j = 1 \text{ až } n) \tag{3}$$

Deviation of position, positional deviation

$$x_{ij} = P_{ij} - P_i \tag{4}$$

Mean unidirectional positional deviation at a position

Straight direction:

$$\bar{x}_i \uparrow = \frac{1}{n}\sum_{j=1}^{n} x_{ij} \uparrow \tag{5}$$

Reverse direction:

$$\bar{x}_i \downarrow = \frac{1}{n}\sum_{j=1}^{n} x_{ij} \downarrow \tag{6}$$

Mean bi-directional positional deviation at a position

$$\bar{x}_i = \frac{\bar{x}_i \uparrow + \bar{x}_i \downarrow}{2} \tag{7}$$

Reversal value at a position

$$B_i = \bar{x}_i \uparrow - \bar{x}_i \downarrow \tag{8}$$

Reversal value of an axis

$$B = \max.\left[|B_i| \right] \tag{9}$$

Mean reversal value of an axis

$$\bar{B} = \frac{1}{m}\sum_{i=1}^{m} B_i \tag{10}$$

Estimator of the unidirectional axis repeatability of positioning at a position

Straight direction:

$$s_i \uparrow = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}\left(x_{ij} \uparrow - \bar{x}_i \uparrow\right)^2} \tag{11}$$

Reverse direction:

$$s_i \uparrow = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}\left(x_{ij} \downarrow - \bar{x}_i \uparrow\right)^2} \tag{12}$$

Unidirectional repeatability of positioning at a position

Straight direction:

$$R_i \uparrow = 4 s_i \uparrow \tag{13}$$

Reverse direction:

$$R_i \downarrow = 4 s_i \uparrow \tag{14}$$

Bi-directional repeatability of positioning at a position

$$R_i = \max.\left[2 s_i \uparrow + 2 s_i \downarrow + |B_i|; R_i \uparrow; R_i \downarrow\right] \tag{15}$$

Unidirectional repeatability of positioning

Straight direction:

$$R \uparrow = \max.\left[R_i \uparrow\right] \tag{16}$$

Reverse direction:

$$R \downarrow = \max.\left[R_i \downarrow\right] \tag{17}$$

Bi-directional repeatability of positioning

$$R = \max.\left[R_i\right] \tag{18}$$

Unidirectional systematic positional deviation of an axis

Straight direction:

$$E \uparrow = \max.\left[\bar{x}_i \uparrow\right] - \min.\left[\bar{x}_i \uparrow\right] \tag{19}$$

Reverse direction:

$$E\downarrow = \max.\left[\bar{x}_i\downarrow\right] - \min.\left[\bar{x}_i\downarrow\right] \quad (20)$$

Bi-directional systematic positional deviation of an axis

$$E = \max.\left[\bar{x}_i\uparrow;\bar{x}_i\downarrow\right] - \min.\left[\bar{x}_i\uparrow;\bar{x}_i\downarrow\right] \quad (21)$$

Mean bi-directional positional deviation of an axis

$$M = \max.\left[\bar{x}_i\right] - \min.\left[\bar{x}_i\right] \quad (22)$$

Unidirectional accuracy of positioning of an axis

Straight direction:

$$A\uparrow = \max.\left[\bar{x}_i\uparrow + 2s_i\uparrow\right] - \min.\left[\bar{x}_i\uparrow - 2s_i\uparrow\right] \quad (23)$$

Reverse direction:

$$A\downarrow = \max.\left[\bar{x}_i\downarrow + 2s_i\downarrow\right] - \min.\left[\bar{x}_i\downarrow - 2s_i\downarrow\right] \quad (24)$$

Bi-directional accuracy of positioning of an axis

$$A = \max.\left[\bar{x}_i\uparrow + 2s_i\uparrow;\bar{x}_i\downarrow + 2s_i\downarrow\right] - \min.\left[\bar{x}_i\uparrow + 2s_i\uparrow;\bar{x}_i\downarrow + 2s_i\downarrow\right] \quad (25)$$

4 DETERMINATION OF ACCURACY AND REPEATABILITY OF POSITIONING NC TABLE AXES

Figure 5 and 6 are graphical representations of the results of accuracy and repeatability analysis of positioning axes X and axes Y. Additional parameters that are described in the ISO 230-2 are evaluated by calibration of the NC positioning table.

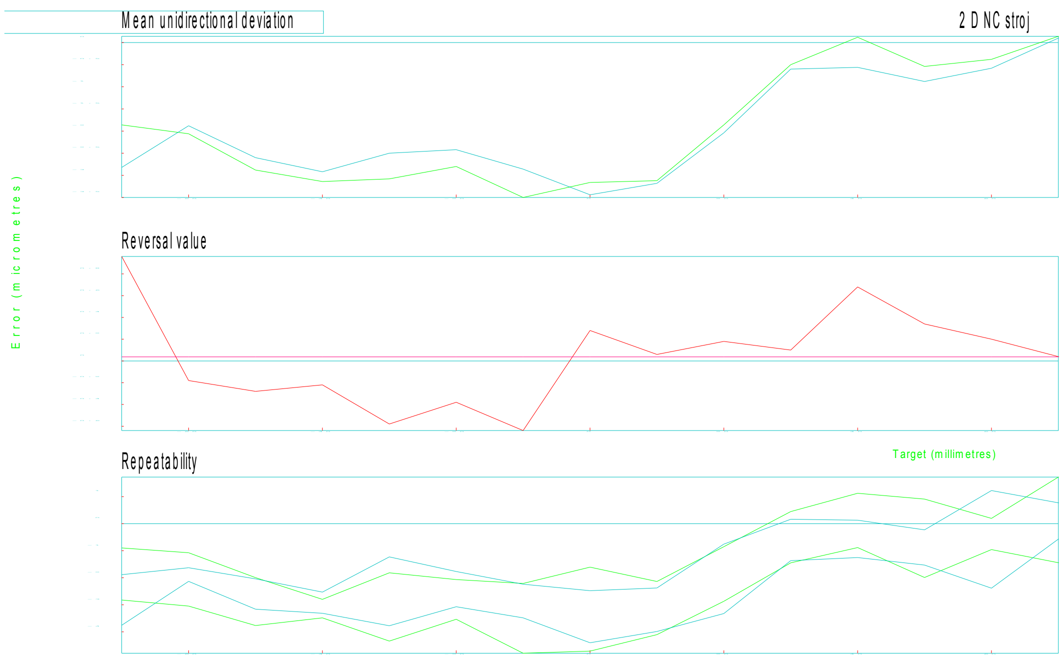

Fig. 5. Analysis of the results of the axis X according to ISO 230-2.

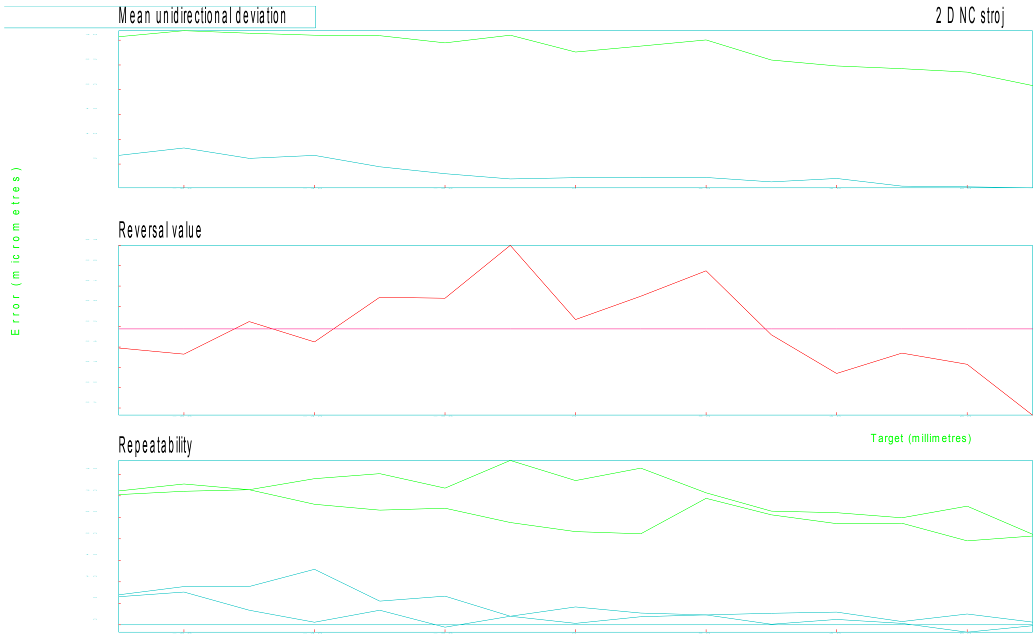

Fig. 6. Analysis of the results of the axis Y according to ISO 230-2.

Figure 7 is graphical representation of the results of analysis corrected axis Y in accordance to ISO 230-2. It is possible to apply corrections because control software allows entering corrections to twist of screw shaft. The relevant corrections were obtained by expressing the results from the first measurement of the axis Y of positioning table.

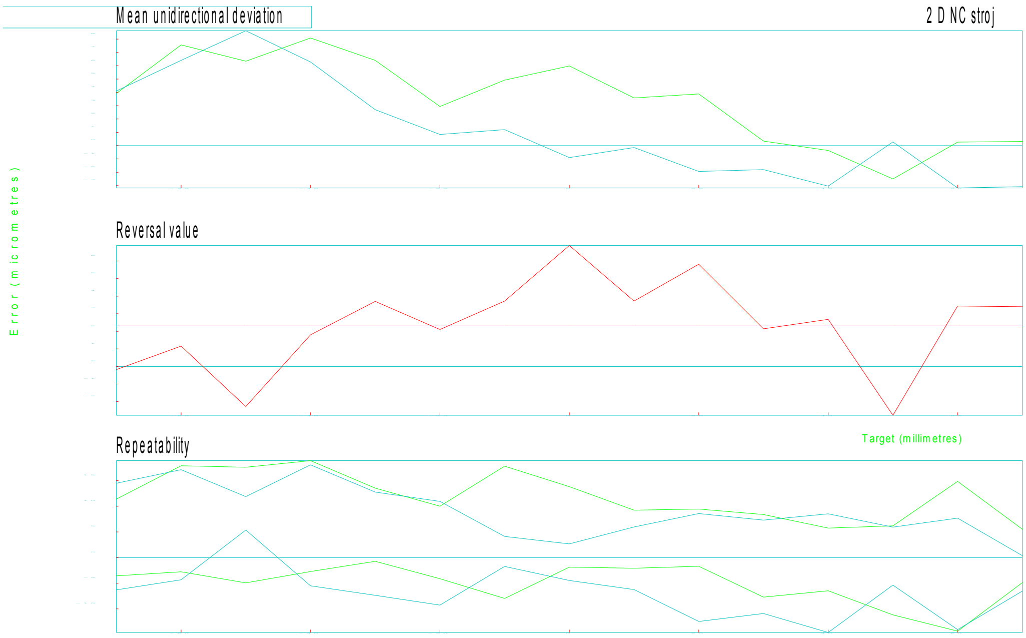

Fig. 7. Analysis of the results of the corrected axis Y according to ISO 230-2.

Comparing the results of calibration axis Y of positioning table in Table 3, the differences between the results of calibration of axis Y before and after corrections are observed. In axis X was not necessary to apply corrections to the axis. The results of accuracy and repeatability of positioning table in axis X are in relation to the requirements of a pointing device.

Table 3. Comparison of the results of axis Y before/after correction

Axis Y	**Accuracy**	**Mean reversal value of an axis**	**Bi-directional repeatability of positioning at a position**
Before corrections	39.934 μm	24.890 μm	36.212 μm
After corrections	33.489 μm	2.355 μm	29.196 μm

5 EVALUATION OF THE EXPERIMENT

By calibration of the NC positioning table there are several potential sources of error. Their classification and estimation is important in determination the measurement uncertainties in term of qualitative indicator of its quality. Full knowledge of uncertainty in measurement requires a lot of information. Phenomena that contribute to the uncertainty and the fact that the result of measurement can not be characterized by a single value are called sources of uncertainty [4].

Mathematical model of the positional deviation of the NC positioning table is expressed as follows:

$$\Delta L = L_{\mathrm{NC}} - \underbrace{[1+\alpha(20-t_{\mathrm{m}})]\cdot L_{\mathrm{LI}}}_{L_{\mathrm{k}}} + \delta L_{\mathrm{cos}} + \delta L_{\mathrm{Abbe}} + \delta L_{\mathrm{dp}} \quad (26)$$

where:

ΔL - deviation of position in axis of positioning table,
L_{NC} - measured length value indicated by positioning table,
L_{k} - corrected value of the measured length of the laser interferometer (conventionally true value).

Further corrections in the model will be considered zero and their impact is transferred to the uncertainty of measurement. These corrections will be presented in the next evaluation as sources of measurement uncertainties.

Other influencing parameters in the model are:
α - coefficient of thermal expansion of the mechanical part of the positioning table,
t_m - temperature of material,
L_{LI} – length measured by the laser interferometer expressed as:

$$L_{\mathrm{LI}} = \left(\frac{\lambda_0}{64 n_{\mathrm{tph}}}\right)\cdot \mathrm{N} \quad (27)$$

where:

λ_0 - wavelegth of laser radiation in vacuum,
64 - constant of polarization splitter,
n_{tph} - index of refraction of air at a temperature t, pressure p, relative humidity h,
N - number of laser pulses.

The refractive index n_{tph} can be expressed by Edlens equation or using the calculator on the website: http://emtoolbox.nist.gov/Wavelength/Edlen.asp.

Edlens equation:

$$n_{tph} = n_0\left[1 + K_\mathrm{t}(t-20) + K_\mathrm{p}(p-101{,}325) + K_\mathrm{h}(h-50)\right] \tag{28}$$

Errors that are specified as mechanical sources of uncertainties which are added to overall measurement model are follows:

δL_cos - cosine error,

δL_Abbe - Abbe error,

δL_dp - dead path error.

These errors in the mathematical model are known as mechanical errors. In the evaluation of calibration of the NC positioning table were these acquired from similar applications of laser interferometer.

6 CONCLUSIONS

Contribution deals with the calibration of the NC positioning table using method of determination of accuracy and repeatability of positioning numerically controlled axes by the laser interferometer. In continuity of this are published some brief knowledges from the physics, namely laser interferometry. Calibration of the NC positioning table is in relation with right designing of mathematical model and specification of the errors caused by measurement. In contribution are designed operation process of calibration of the NC positioning table, conditions of measurement are described and example of evaluation of calibration is expressed. Given the topicality of the issue is this work stated too for using in the metrological practice.

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