Evaluation of the Positional Deviation by Calibration of CNC Machines

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Abstract. *CNC machines are required to produce accurate and high-quality products. It is only possible to produce accurate workpieces if we have an accurate machine. This contribution deals with the evaluation of calibration of CNC measuring systems and it simultaneously presents the solution of the problem from the metrological point of view, which is different from the common practice.*

Keywords: Calibration, Positional Deviation, Uncertainty in Measurement, Covariance

1. Introduction

CNC (**C**omputer **N**umerical **C**ontrol) machines can be defined as computer-controlled machines, which also meet the classification of the measurement system, because there are measuring systems in the axes of these machines. The capability of a machine to cope with rapidly changing operating conditions is an ultimate factor for its accuracy. A transition from roughing to finishing completely changes the mechanical and thermal load on the machine. Position control is important in this context. By indirect measuring (see Fig. 1) is monitored variable position of the servomotor monitored, which made movement. The position of an NC feed axis can be measured through the ball screw in combination with a rotary encoder. Changes in the driving mechanics due to wear or temperature cannot be compensated [1].

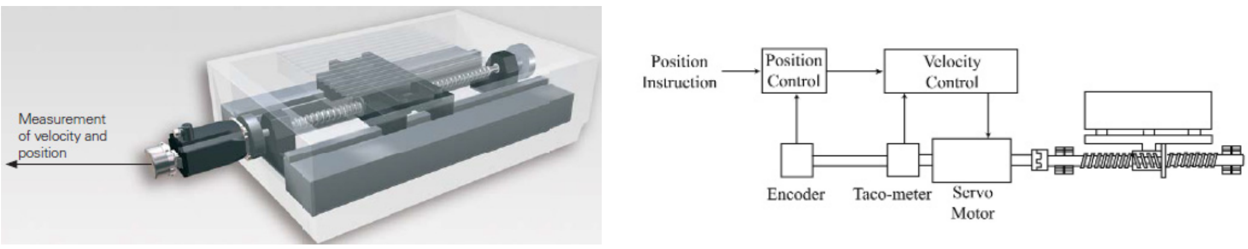

Fig. 1. The principle of indirect measuring (left) and its block diagram (right) [2]

Direct measuring systems are designed to immediately provide the information about the relative motion due to the machine frame. The target value is compared with the actual value as a result of feedback operation. The motion system of the CNC machine corrects the immediate value of the actuator of reading a linear encoder (see Fig. 2). Measurement accuracy depends solely on the precision and installation location of the linear encoder.

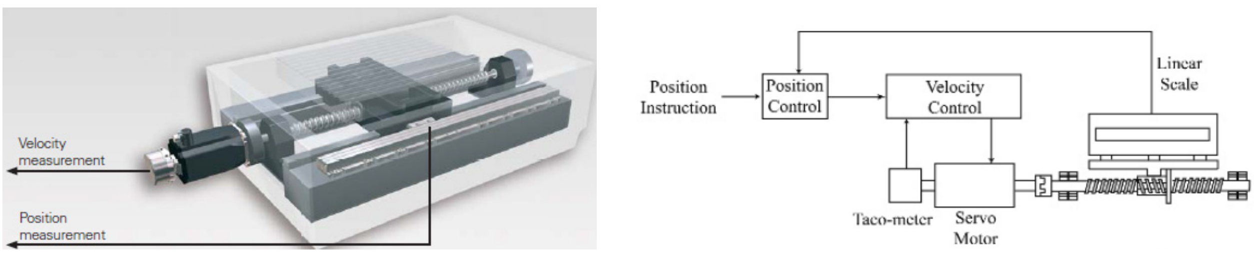

Fig. 2. The principle of direct measuring (left) and its block diagram (right) [2]

2. Calibration of the measuring systems of CNC machines

Calibration of the measuring systems of CNC machines and its evaluation is often carried out by ISO 230-2 in practise. Between the recommendations of this standard and conventional metrological approach could be found some discrepancies. According to definition of calibration by VIM 3 should be measured the measuring system of machine in first step. In the second step are measured data entered into the control system of the machine. This is subsequently used for determination of relationship for obtaining a measurement result from an indication [3]. In the metrological context we can talk about correction of systematic errors of positioning (in practice often called as compensation), which is awarded to control the CNC machine in the form of compensation map. By CNC machine calibration method called determination of accuracy and repeatability of positioning numerically controlled axes are evaluated nine standard parameters. After analysis of the above parameters and comparison with the definitions in metrological terminology is offered even easier possibility of expressing the results that characterize positioning of CNC machine. It is the expression of the average positional deviation in the axis and its uncertainty. This parameter is expressed in direct and reverse direction with the uncertainty of the measurement result, which includes the contribution of the uncertainty of determining the positional deviation of repeatability and other contributions, which appears systematically. This procedure also represents the intersection of the recommendations of the ISO 230-2 and metrological approach to the evaluation of the calibration of CNC machines. This solution corresponds to the evaluation method according to ISO GUM.

3. Evaluation of the calibration of CNC machines

Model of the measurement consists of the system of equations where number of equations is greater than number of unknown parameters of the deviation function [4]. In the model are including other influence quantities of the measurements. Therefore the right side of model will be:

$$\begin{aligned}
\overline{P}_1 - P_{\mathrm{nv}_1} + P_{\mathrm{nv}_1}\cdot\alpha\cdot\Delta t + \delta_{\mathrm{cos}} + \delta_{\mathrm{cc}} + \delta_{\mathrm{res}} &= a + b\overline{x}_1 + c\overline{x}_1^{2} + d\overline{x}_1^{3} \\
\overline{P}_2 - P_{\mathrm{nv}_2} + P_{\mathrm{nv}_2}\cdot\alpha\cdot\Delta t + \delta_{\mathrm{cos}} + \delta_{\mathrm{cc}} + \delta_{\mathrm{res}} &= a + b\overline{x}_2 + c\overline{x}_2^{2} + d\overline{x}_2^{3} \\
&\vdots \\
\underbrace{\overline{P}_n - P_{\mathrm{nv}_n} + P_{\mathrm{nv}_n}\cdot\alpha\cdot\Delta t + \delta_{\mathrm{cos}} + \delta_{\mathrm{cc}} + \delta_{\mathrm{res}}}_{\boldsymbol{W}=\boldsymbol{P}+\boldsymbol{C\Delta}} &= \underbrace{a + b\overline{x}_n + c\overline{x}_n^{2} + d\overline{x}_n^{3}}_{\boldsymbol{A}\cdot\boldsymbol{y}}
\end{aligned} \tag{1}$$

where

$\overline{x}_1, \overline{x}_2 \ldots \overline{x}_n$ mean positional deviation in position

$\overline{P}_1, \overline{P}_2 \ldots \overline{P}_n$ position determined from the series of measurements (n = 5).

$P_{\mathrm{nv}_1}, P_{\mathrm{nv}_1}, \ldots P_{\mathrm{nv}_n}$ nominal value of length – position set by control unit of CNC machine

α coefficient of the thermal expansion

δ_{cos} correction of the cosine error

δ_{cc} correction of the indication of the standard from the calibration certificate

δ_{res} correction of the resolution of the standard

$\Delta t = (t_{\mathrm{CNC}} - t_{20})$ difference between temperature of CNC machines t_{CNC} and reference temperature t_{20} 20 °C.

The left side of the model is deviation function which represents mean positional deviation in given position. Deviation functions are polynomial. Degree of polynoms is depended from the characteristics of measured values, in our cases polynomial of third degree. Third degree polynomial was chosen after iterative estimations, where we found that it best follows the process of the measured values.

where *a*, *b*, *c*, *d* are parameters of polynoms.

Now model of measurement is described in matrix notation:

$$\underbrace{\underbrace{\begin{pmatrix} \bar{P}_1 - P_{\mathrm{nv}_1} \\ \bar{P}_2 - P_{\mathrm{nv}_2} \\ \vdots \\ \bar{P}_n - P_{\mathrm{nv}_n} \end{pmatrix}}_{\boldsymbol{P}} + \underbrace{\begin{pmatrix} P_{\mathrm{nv}_1} & 1 & 1 & 1 \\ P_{\mathrm{nv}_2} & 1 & 1 & 1 \\ \vdots & & & \\ P_{\mathrm{nv}_n} & 1 & 1 & 1 \end{pmatrix}}_{\boldsymbol{C}} \cdot \underbrace{\begin{pmatrix} \alpha\Delta t \\ \delta_{\mathrm{cos}} \\ \delta_{\mathrm{cc}} \\ \delta_{\mathrm{res}} \end{pmatrix}}_{\boldsymbol{\Delta}}}_{\boldsymbol{W}} = \underbrace{\begin{pmatrix} 1 & \bar{x}_1 & \bar{x}_1^2 & \bar{x}_1^3 \\ 1 & \bar{x}_2 & \bar{x}_2^2 & \bar{x}_2^3 \\ \vdots & \vdots & \vdots & \vdots \\ 1 & \bar{x}_n & \bar{x}_n^2 & \bar{x}_n^3 \end{pmatrix}}_{\boldsymbol{A}} \cdot \underbrace{\begin{pmatrix} a \\ b \\ c \\ d \end{pmatrix}}_{\boldsymbol{y}} \tag{2}$$

where

$\boldsymbol{W}$	observation vector
$\boldsymbol{P}$	vector of the mean positional deviations
$\boldsymbol{C}$	matrix of the sensitivity coefficients
$\boldsymbol{\Delta}$	vector of corrections
$\boldsymbol{A}$	Vandermonde matrix
$\boldsymbol{y}$	vector of the output quantities, in our case vector of unknown parameters for polynomial of third degree.

Estimation of the parameters is possible to find out by application of the least squares method. Because of corrections are considered as zeros, their influence taking into the uncertainties is described by input covariance matrix $\boldsymbol{U_W}$.

$$\hat{\boldsymbol{y}} = \left(\boldsymbol{A}^T \cdot \left(\boldsymbol{U}_A + \boldsymbol{C} \cdot \boldsymbol{U}_B \cdot \boldsymbol{C}^T\right) \cdot \boldsymbol{A}\right)^{-1} \cdot \boldsymbol{A}^T \cdot \underbrace{\left(\boldsymbol{U}_A + \boldsymbol{C} \cdot \boldsymbol{U}_B \cdot \boldsymbol{C}^T\right)^{-1}}_{\boldsymbol{U_W}} \cdot \boldsymbol{W} \tag{3}$$

where

$\boldsymbol{U}_{\mathrm{A}} = \boldsymbol{U}_{\mathrm{A}}(\boldsymbol{P}) = \mathrm{diag}(u_{\mathrm{A}}(\boldsymbol{P}_1); u_{\mathrm{A}}(\boldsymbol{P}_2) \ldots u_{\mathrm{A}}(\boldsymbol{P}_n))$, where $\boldsymbol{P}_i = \bar{\boldsymbol{P}}_i - \boldsymbol{P}_{nv_i}$ are contributions of the repeatability in given position

$\boldsymbol{U}_{\mathrm{B}} = \boldsymbol{U}_{\mathrm{B}}(\boldsymbol{\Delta}) = \mathrm{diag}(u_{\mathrm{B}}(\Delta_1); u_{\mathrm{B}}(\Delta_2) \ldots u_{\mathrm{B}}(\Delta_4))$ is matrix contains uncertainty determined by method type B.

After multiplication of the covariance matrix $\boldsymbol{U}_{\mathrm{B}}$ with matrix $\boldsymbol{C}$ from right and left, we get covariance matrix $\boldsymbol{U}_{W\mathrm{B}}$, where out of the diagonal are covariances of influence quantities.

Uncertainty of the estimations of parameters of deviation function calculates by applying law of propagation uncertainties:

$$\boldsymbol{U}_y = \left(\boldsymbol{A}^{\mathrm{T}} \cdot \boldsymbol{U}_W \cdot \boldsymbol{A}\right)^{-1} \tag{4}$$

Uncertainty of the deviations in given position is evaluated by following expression:

$$\boldsymbol{U}_{\mathrm{A}}(\hat{\boldsymbol{W}}) = \left(\boldsymbol{A} \cdot \boldsymbol{U}_y \cdot \boldsymbol{A}^{\mathrm{T}}\right), \text{ where } \hat{\boldsymbol{W}} = \boldsymbol{A} \cdot \hat{\boldsymbol{y}} \tag{5}$$

Evaluation with designed algorithm allows estimating the parameters of the deviation function and their uncertainties when are considered covariances between influence quantities in the whole range of the positioning in given axes. For verification of this algorithm was carried out the measurements on the CNC turning machine. On the Figure 3 are displayed deviation functions and their expanded uncertainties *U* when are considering covariance or not. Erratic function is because there are not thought the covariances, where the source of the covariance is temperature. Conversely, where we considered the covariances, it caused that the function is smoothed.

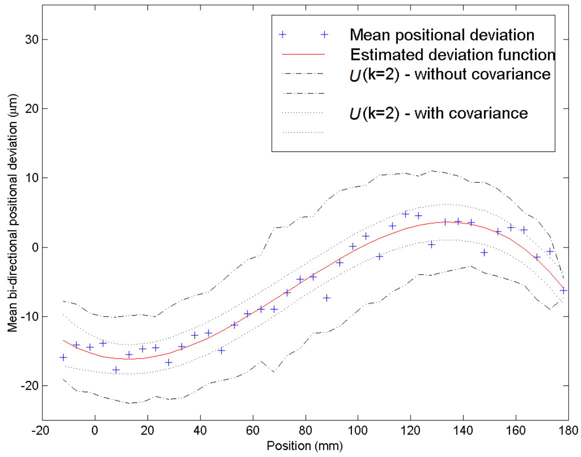

Fig. 3. Mean positional deviation of the CNC machine before compensation

When we considered covariance in evaluation, value of the expanded uncertainty *U* is markedly smaller. The reason is right application of the law of propagation uncertainties. By this way of evaluation is possible to uncover and quantify mutual resources of uncertainties.

4. Conclusions

By procedure described in this paper we have obtained not only a function describing the dependence of the positional deviation from the position, but also the covariance matrix of output quantities. If we know the confidence interval of the deviation function, i.e. we are able to determine the uncertainty for each one point, respectively position [4]. The evaluation procedure is applied for determination the equation or measurement function in direct and reverse direction.

Acknowledgements

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