XIX IMEKO World Congress
Fundamental and Applied Metrology
September 6–11, 2009, Lisbon, Portugal

POSIBILITIES OF IMPROOVING OF POSITIONAL PRECISION OF MACHINE TOOLS WITH LINEAR AXES

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Abstract – The positional deviation (difference between the actual and target position) belongs to the important criteria that describe the performance of numerically controlled axes. The procedure for determination of such deviation is described in the international standard ISO 230-2:1997. This standard provides calculation of the positional deviation only in several discrete (measuring) points. Moreover it does not consider effects of the measuring instrument on the obtained results. The new methodology is adopted and it is enables estimation of the positional deviation in any point of the axis travel, together with the uncertainty of such estimate. Obtained results can be incorporated into a control system in the form of corrections enhancing positioning possibilities of individual axes.

The paper introduces procedures that were verified by measurements for one linear axis. The more complicated situation occurs for testing the positioning accuracy in a plane or in a space. Paper also talks about possibilities of using such a measurement in process of controlling for compensation. Such compensation can bring great improvement in positional accuracy of machine tools.

Keywords: Machine tools, Positional deviation, Control system

1. INTRODUCTION

Machine tools became inseparable part of our world. In some advanced countries is production of machine tools 10% of total machine production. These machines allowed us, reached our high living standard. In nowadays we can't thing about living without this standard. Machine tools increase possibilities of product production and also the quality of products is increased by them. At the other side machine tools decrease the requests on the human work. They mainly remove monotone work in places where acquiring of new workers becoming bigger and bigger problem. These machines can replace these workers in great part. In nowadays became numerically controlled axes the inseparable part of machine tools.

The quality of the numerically controlled axis has great influence on quality of final products. Qualitative parameters of final product with influence of numerically controlled axis can be divided on surface quality and dimension precision quality. On dimension precision quality has great influence the precision of positioning of numerically controlled axis. From this reason is precision of positioning of linear axes of machine tools one of the most important parameters of the machine tools.

To precision of machine tools linear axes is dedicated international standard ISO 230-2:1997. Problem is that this standard is not very useful for creating of compensation line for the measured axe. To create suitable line is necessary to use another more mathematically complicated approach. With this approach is possible to create compensation line. This line is than possible to implement into the control system. This will decrease positional deviation of the linear axes.

2. EVALUATION ACCORDING TO THE STANDARD

Measuring according to the standard require several condition that should be met before start of the measuring. Main required conditions are environment temperature and condition of the Machine tool. The standard requires environment temperature of 20 degrees of Celsius. If this request can't be met it is necessary to compensate temperature difference in the evaluation of the results. Standard require also machine to be fully operational. Every type of correction mechanism in the control program of the line should be activated. If these conditions are met it is possible to start a measurement [1], [2].

For the measurement is necessary to use measuring cycle. It is possible to evaluate measured date after completing of this cycle. One of the possible measurement cycles is shown at Fig. 1.

For the evaluation of the measurement is necessary to evaluate few parameters [1], [2]. These parameters are:

Deviation of position x_{ij}

$$x_{ij} = P_{ij} - P_j \qquad (1)$$

where
P_{ij} – measured position,
P_i – desired position,
x_{ij} – positional deviation.

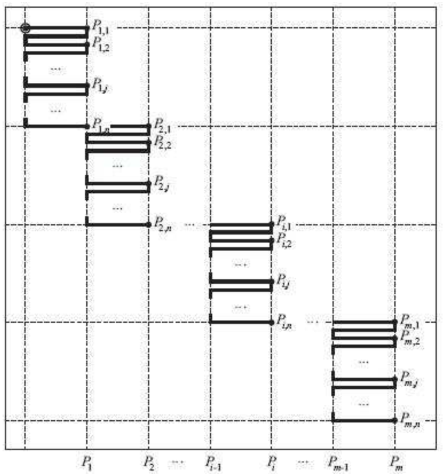

Fig. 1. Example of measuring cycle [1]

Mean unidirectional positional deviation at a position

$$\bar{x}_j \uparrow = \frac{1}{n}\sum_{i=1}^{n} x_{ij} \uparrow \qquad (2)$$

$$\bar{x}_j \downarrow = \frac{1}{n}\sum_{i=1}^{n} x_{ij} \downarrow \qquad (3)$$

where
$\bar{x}_j \downarrow$ – mean positional deviation,
n – number of measurement in point.

Estimator of the unidirectional standard uncertainty of positioning at position

$$s_j \uparrow = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(x_{ij} \uparrow - \bar{x}_j \uparrow\right)^2} \qquad (4)$$

$$s_j \downarrow = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(x_{ij} \downarrow - \bar{x}_j \downarrow\right)^2} \qquad (5)$$

where
s_j – unidirectional standard uncertainty.

After evaluation it is possible to create graph of positional derivation. Such a graph is shown at the Fig. 2.

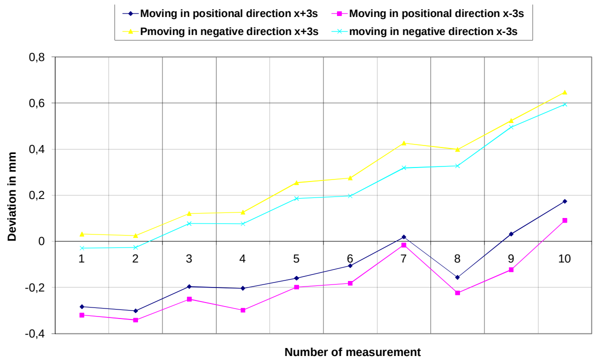

Fig. 2. Example of chart after evaluation

3. NEW APPROACH IN EVALUATION

Measurement according to standard doesn't describe uncertainty and deviation of position in any point of axis travel. Measurement according to standard describe deviation of position and it uncertainty only in measured points. Between points of measurement is deviation and uncertainty unknown. Standard predict these values to be linear. That's not correct prediction. (It may or may not be in that way.) Because of this is useful to use for evaluation of measurement regression analysis [4], [6].

If we want to obtain the estimates of the positional deviations also in other points than the measurement ones, we must approximate course of estimates. The least squares method is suitable for such approximation. The curve in a form of polynomial of n-th order will be placed over the points [3], [5], [7].

$$\Delta = b_0 + b_1 \cdot P + b_2 \cdot P^2 + \ldots + b_n \cdot P^n \qquad (6)$$

where
b_i, $i = 1, \ldots n$ – unknown parameters of the polynomial,
P – point of measurement,
Δ – positional deviation.

To the equation (6) are inserted measured points so it became to be a system of equations.

$$\begin{aligned} \bar{\Delta}_1 &= b_0 + b_1 \cdot P_1 + b_2 \cdot P_1^2 + \ldots + b_n \cdot P_1^n \\ \bar{\Delta}_2 &= b_0 + b_1 \cdot P_2 + b_2 \cdot P_2^2 + \ldots + b_n \cdot P_2^n \\ &\ldots \\ \bar{\Delta}_m &= b_0 + b_1 \cdot P_m + b_2 \cdot P_m^2 + \ldots + b_n \cdot P_m^n \end{aligned} \qquad (7)$$

$\bar{\Delta}_i$, $i = 1, \ldots m$ – mean positional deviation in point i.

Then for the estimation of the parameters of the regression line is applicable equation.

$$\hat{\boldsymbol{b}} = (\boldsymbol{x}^{\mathrm{T}}\boldsymbol{x})^{-1}\boldsymbol{x}^{\mathrm{T}}\boldsymbol{\Delta} \qquad (8)$$

where
$\hat{\boldsymbol{b}}$ – vector of estimates of polynomial parameters,
$\boldsymbol{x}$ – is a matrix of measured points.

But in this way there are not weights of measurement included in evaluation. From this reason is good to add to equation covariance matrix $\boldsymbol{U}(\varDelta)$.

$$\hat{\boldsymbol{b}} = (\boldsymbol{x}^{\mathrm{T}}\boldsymbol{U}^{-1}(\varDelta)\boldsymbol{x})^{-1}\boldsymbol{x}^{\mathrm{T}}\boldsymbol{U}^{-1}(\varDelta)\boldsymbol{\varDelta} \quad (9)$$

where $\hat{\boldsymbol{b}}$ has form:

$$\hat{\boldsymbol{b}} = \begin{pmatrix} b_0 \\ b_1 \\ \vdots \\ b_n \end{pmatrix} \quad (10)$$

$\boldsymbol{x}$ – has form:

$$\boldsymbol{x} = \begin{pmatrix} 1 & P_1 & \dots & P_1^n \\ 1 & P_2 & \dots & P_2^n \\ \vdots & \vdots & \vdots & \vdots \\ 1 & P_m & \dots & P_m^n \end{pmatrix} \quad (11)$$

$\boldsymbol{\varDelta}$ – has form:

$$\boldsymbol{\varDelta} = \begin{pmatrix} \varDelta_1 \\ \varDelta_2 \\ \vdots \\ \varDelta_m \end{pmatrix} \quad (12)$$

$\boldsymbol{U}(\varDelta)$ – has form:

$$\boldsymbol{U}(\varDelta) = \begin{pmatrix} u^2(\varDelta_1) & u(\varDelta_1,\varDelta_2) & u(\varDelta_1,\varDelta_3) & \cdots & u(\varDelta_1,\varDelta_m) \\ u(\varDelta_2,\varDelta_1) & u^2(\varDelta_2) & u(\varDelta_2,\varDelta_3) & \cdots & u(\varDelta_2,\varDelta_m) \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ . & . & . & . & u(\varDelta_{m-1},\varDelta_m) \\ u(\varDelta_m,\varDelta_1) & . & . & u(\varDelta_m,\varDelta_{m-1}) & u^2(\varDelta_m) \end{pmatrix} \quad (13)$$

where

$u(\varDelta_1), u(\varDelta_2), \ldots u(\varDelta_m)$ – are uncertainties of individual positional deviations. These uncertainties are determined by the type A method in this case,

$u(\varDelta_1,\varDelta_2)$ is the covariance between positional deviations in position $\varDelta_1$ and position $\varDelta_2$, …

$u(\varDelta_{m-1},\varDelta_m)$ is the covariance between positional deviations in position $\varDelta_{m-1}$ and position $\varDelta_m$.

Covariance matrix $\boldsymbol{U}(\hat{b})$ of unknown parameters of polynomial can be evaluated according to equation:

$$\boldsymbol{U}(\hat{\boldsymbol{b}}) = (\boldsymbol{x}^{\mathrm{T}}\boldsymbol{U}^{-1}(\varDelta)\boldsymbol{x})^{-1} \quad (14)$$

$\boldsymbol{U}(\hat{b})$ - has form:

$$\boldsymbol{U}(\hat{b}) = \begin{pmatrix} u^2(\hat{b}_1) & u(\hat{b}_1,\hat{b}_2) & u(\hat{b}_1,\hat{b}_3) & \cdots & u(\hat{b}_1,\hat{b}_m) \\ u(\hat{b}_2,\hat{b}_1) & u^2(\hat{b}_2) & u(\hat{b}_2,\hat{b}_3) & \cdots & u(\hat{b}_2,\hat{b}_m) \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ . & . & . & . & u(\hat{b}_{m-1},\hat{b}_m) \\ u(\hat{b}_m,\hat{b}_1) & . & . & u(\hat{b}_m,\hat{b}_{m-1}) & u^2(\hat{b}_m) \end{pmatrix} \quad (15)$$

Covariance matrix of estimation of deviation $\boldsymbol{U}(\hat{\boldsymbol{\varDelta}})$ can be evaluated as

$$\boldsymbol{U}(\hat{\boldsymbol{\varDelta}}) = \boldsymbol{x}\boldsymbol{U}(\hat{\boldsymbol{b}})\boldsymbol{x}^T \quad (16)$$

$\boldsymbol{U}(\hat{\boldsymbol{\varDelta}})$ - has form:

$$\boldsymbol{U}(\hat{\varDelta}) = \begin{pmatrix} u^2(\hat{\varDelta}_1) & u(\hat{\varDelta}_1,\hat{\varDelta}_2) & u(\hat{\varDelta}_1,\hat{\varDelta}_3) & \cdots & u(\hat{\varDelta}_1,\hat{\varDelta}_m) \\ u(\hat{\varDelta}_2,\hat{\varDelta}_1) & u^2(\hat{\varDelta}_2) & u(\hat{\varDelta}_2,\hat{\varDelta}_3) & \cdots & u(\hat{\varDelta}_2,\hat{\varDelta}_m) \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ . & . & . & . & u(\hat{\varDelta}_{m-1},\hat{\varDelta}_m) \\ u(\hat{\varDelta}_m,\hat{\varDelta}_1) & . & . & u(\hat{\varDelta}_m,\hat{\varDelta}_{m-1}) & u^2(\hat{\varDelta}_m) \end{pmatrix} \quad (17)$$

The result of this analysis is regression curve which represent deviation and uncertainty of positioning in any point of axes travel. Such a curve can be used as input parameter for correction of positioning of linear axes. Example of such a curve is at the Fig. 3.

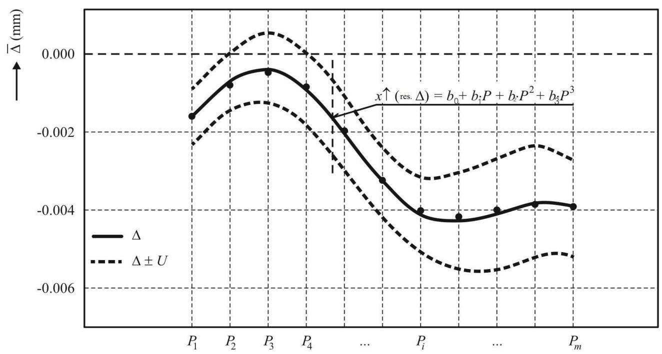

Fig. 3. Example of curve after evaluation

In very similar way can be analysis applied also on system with two axes. In that case is result from analysis surface not a curve.

4. REAL EXPERIMENT EVALUATION

Measurement according the standard was made in company Microstep at their experimental laser cutting machine tool. This machine tool has some specific features. The most important of its feature is using of linear motors for its linear axes. This feature ensures very quick movements of the linear axes along their guide ways. It also ensures smaller friction forces and better dynamics than classic driving system with thread shaft. On the other hand it is more sensitive to the quality of steering system.

Linear axes of this machine tool are equipped with linear incremental sensor. This sensor works on optical principle. Precision of this sensor is 2 µm. For measurement of error of positioning was used laser interferometer ML 10 from company Renishaw. In Table 1 are basic information about this laser interferometer.

Table 1. Laser interferometer ML 10

Measuring range	40 m may be extended to 80 m
Laser source	Helium neon (HeNe) laser tube
Laser power	< 1 mW
Differentiability	1,2 nm
Vacuum wavelength	632,990577 nm
Precision of linear measurement	±0,7 ppm
Long term frequency accuracy	±0,05 ppm
Working temperature	0 °C – 40 °C
Humidity	0 – 95 %

Results of the measurement evaluated according to the standard are shown at the Table 2. This is result for the approach in direction from left.

Table 2. Results of measurement, approach from left

Measured point (mm)	Positional deviation (µm)	+ 3s (µm)	- 3s (µm)
10	0,9	1,528	-1,348
250	44,57	45,04	44,1
500,2	64,85	65,303	64,697
749,9	80,51	81,877	79,143
1001	95,02	97,791	92,249
1248,5	104,96	107,599	102,321
1500	113,7	116,759	110,641
1749,3	114,55	117,439	111,661
2000,8	121,12	124,487	117,753
2250,1	125,52	127,64	123,4
2498,3	122,79	124,636	120,944

Results are very hard to read from the table. Far better is to show them at the graph. At Fig. 4 is result.

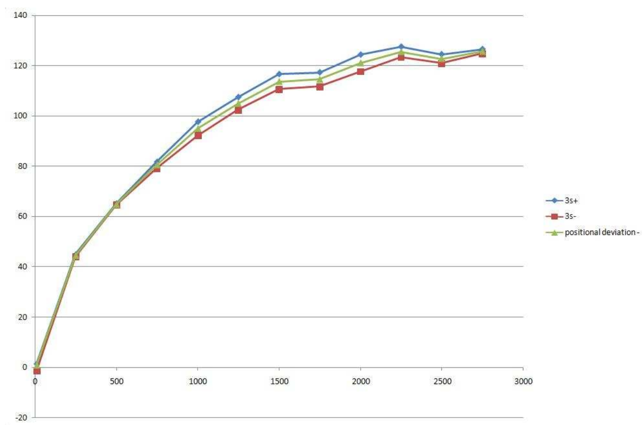

Fig. 4. Graph of results according to standard, approach from left

At the Table 3 and Fig. 5 are results for approach in direction from right.

Table 3. Results of measurement, approach from right

Measured point (mm)	Positional deviation (µm)	+ 3s (µm)	- 3s (µm)
10	0,97	1,909	0,031
250	46,67	47,254	46,086
500,2	67,79	68,667	66,913
749,9	87,61	88,863	86,357
1001	104,8	105,905	103,695
1248,5	117,26	119,11	115,41
1500	124,09	125,542	122,638
1749,3	124,54	126,768	122,312
2000,8	131,38	133,217	129,543
2250,1	135,03	136,553	133,507
2498,3	134,88	136,792	132,968

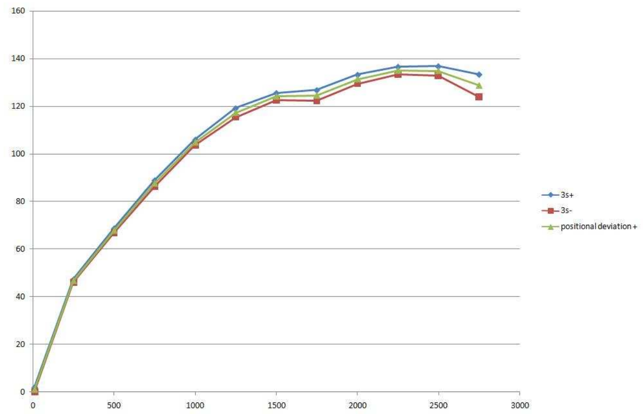

Fig. 5. Graph of results according to standard, approach from right

At the results graph can be seen the tendency of system to have bigger deviation at the end of the axe. These results are good for comparing of two axes or for comparing of axes precision after time period. But unfortunately it is not very useful as a compensation line. We can obtain such a line by using of linear regression method. The result graph is at the Fig. 6. for approach in direction from left.

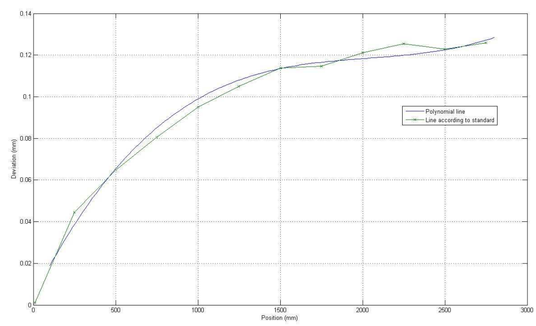

Fig. 6. Graph of results according to new methodology, approach from left

Linear regression gives us also parameters of such a line in this case is line represented by function:

$$\varDelta = 3,7662 + 0,1574.P - 7,4442.10^{-5}.P^2 + 1,2192.10^{-8}.P^3 \quad (18)$$

At Fig. 7 is result graph for approach in direction from right.

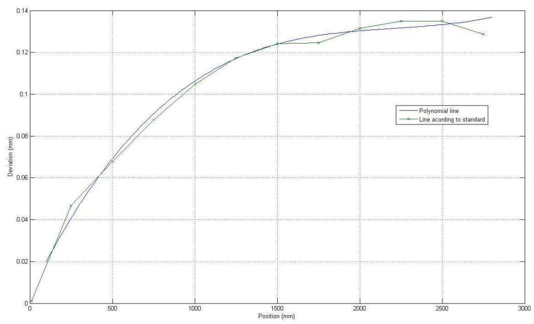

Fig. 7. Graph of results according to new methodology, approach from right

And the function of this polynomial line is:

$$\varDelta = 4,544 + 0,162.P - 7,0945.10^{-5}.P^2 + 1,0704.10^{-8}.P^3 \quad (19)$$

Because after this evaluation we have the parameters of function which represent the polynomial line it is possible to use these functions as a parameter for the compensation program.

5. IMPLEMENTING OF RESULTS TO THE CONTROL SYSTEM

There are several ways how it is possible to implement results of measurement in to the control system [8], [9]. Each of this way has some advantages and some disadvantages.

First way how it is possible to implement correction curve is to implement correction curve directly to the control system. Then control system itself can make a correction of desired points. Advantage of this approach is that control system will make correction every time we want position axes somewhere. Problem of this approach is that in this way is necessary to use some of computing power of system for computing of correction. This may cause serious problem because if system has not enough computing power it can cause that system will be position worst then before correcting. On the another hand if system have enough computing power it is one of the best way how to make correction of positioning of linear axes of machine tools.

Another way is to implement correction mechanism at point of creating of the curve for the machine tools. In this way all computing is made outside the control system. Disadvantage is that correction is done only for the programmed curve not for other operations.

There is also way that combine both these approaches. In this way is used second computer outside the control system. This second computer produce correction signal and control system does correction according to this signal. In this way main control computer do not use computing power for computation of the desired point location. All this computations are made at the secondary computer.

6. CONCLUSION

Machine tools are very important part of our lives. They produce many things without which will not be possible for industry to run and supply us with all necessary things for our living. From this reason is very important to improve machine tools in any possible way.

In this paper was described way how to improve machine tools capabilities by measurement. There is also description of this measurement and its evaluation.

This approach in combination with other approaches which compensate temperature influence, geometrical defects etc. can significantly improve quality of machine tools. Every improvement of machine tools will be advantage for our industries and at the end also for us.

As we see from the result of measurement there is quite big deviation of positioning at this concrete machine tool. But we can also see that uncertainty of positioning is very small. If we use calculated function as a compensation curve it will be possible to decrease the deviation of positioning at significant level. In ideal scenario it is possible to decrease the deviation of positioning at the level of uncertainty of measurement. But that’s possible only at ideal conditions.

ACKNOWLEDGMENTS

The research work described in the paper was performed by a financial support of the Slovak Scientific Agency (VEGA), grant No. 1/0265/08 and grant No. 1/0310/09.

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