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COMPARISON OF STATIC AND DYNAMIC LASER BASED POSITIONING METHODS FOR CHARACTERIZATION OF CNC MACHINES

In the paper we compare the laser based measurements of linear parameters of numerically controlled machines. A new dynamic method of measuring machine positioning is described and compared with the widely used static method. The algorithms of the dynamic method are presented and the comparison results of both methods are shown. It is proven that with the new method the measurement time of linear errors of the CNC machines can be reduced significantly. Additionally the machine wear-out in the linear axes can also be easily and efficiently monitored.

1. INTRODUCTION

High quality products manufactured with precision have always been in high demand. The production technology and machine tools for such products are being investigated for example in [1–5]. Together with the increase in requirements concerning the precision of manufactured goods, machine tools and manufacturing systems are faced with constantly higher requirements. The geometrical, kinematic and thermal errors of the machines need to be monitored and, usually, compensated for the machine to keep the accuracy on the required level [6]. As given in [7] the compensation of machine errors can be done with different methods, out of which the direct sensor-based method is the most commonly used in the industry. The reason for this is the simplicity of analysis of data obtained during measurements and the increasing capabilities of the available measurement equipment.

In the direct error compensation methods the machine tool error is measured periodically, with periods defined by the machine usage or by internal regulations of a company that is the machine owner. An important advantage of these methods is a direct error measurement and the possibility to use the results for machine compensation.

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As measurement systems, laser based devices or measurement probes are often applied [8, 9]. Out of various laser devices the best measurement precision and the widest number of available options is offered by laser interferometers [10–12]. The measurements of almost all important machine geometry error (beside the roll error) can be performed accurately and ably. Also the parameters of the measured machine as described in various international standards [13, 14] can be automatically calculated and printed.

In the paper we focus on a proposed improvement of the basic functionality of the laser interferometers i.e. the checking of machine positioning. The standard methods, described here as static positioning, usually require a significant measurement time [13]. In next chapters we will present an improved method of dynamic positioning, first described in [15]. The new method offers significantly shorter measurement time with additional information about the dynamic behavior of the measured machine.

2. BASICS OF LASER INTERFEROMETRY

Laser interferometry has been in use in machine tool geometry measurements for almost half a century now. The laser interferometer is currently the most convenient instrument for measuring many parameters of machine geometry. It allows measurements of such parameters as linear and angular positioning, axes straightness, perpendicularity and parallelism as well as vibrations or machine acceleration/deacceleration.

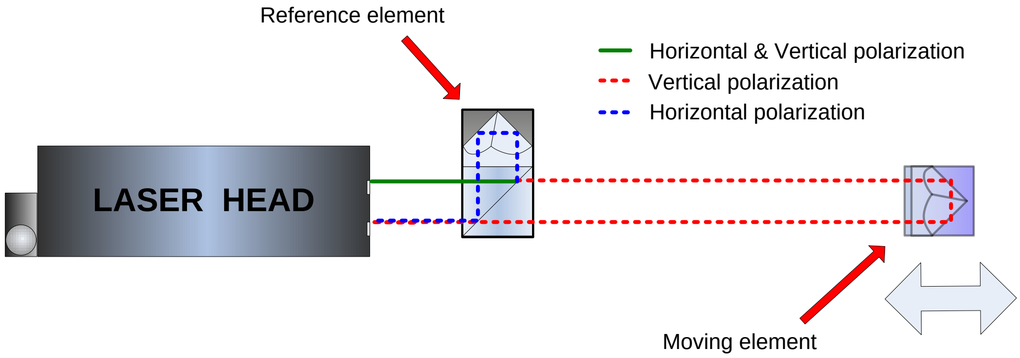

Fig. 1. Idea of a laser measurement

Most of the measurements are performed in the hardware configuration shown schematically in the Fig. 1. The necessary components are: laser head – an active element responsible for emitting and detecting laser light; optomechanical and passive components – reference and moving element. The laser head emits coherent beam of visible light which is split by the reference element into perpendicularly polarized beams. Horizontally polarized light is redirected back to the laser while the vertically polarized one is reflected from the moving component. The optical detector inside the laser head detects the difference in frequency between both returning beams f_D and calculates the shift of the moving element L according to the formula:

$$L = f_D \frac{\lambda}{2} \tag{1}$$

where: f_D – beam frequency difference, λ – laser light wavelength.

Depending on the configuration of the optomechanical components, the measured shift L is used for calculation of appropriate machine parameters. The accuracy of the laser interferometer measurements results from very high stability of the wavelength. The instruments currently available on the market claim wavelength stability of 0.01 ppm or better [12].

3. IDEA OF DYNAMIC POSITIONING

The standard measurement type performed with laser interferometers is the test of linear positioning. In [13] there are defined procedures for measuring positioning of machines both in the linear and in the pendulum mode. Schematically the machine movement in the linear procedure is shown in the Fig. 2. The machine starts in point **S**, moves backwards by more than 1mm and returns to point **1**. This part is done for compensating of the backlash. Next the measured machine shall move in steps to point **n**, stopping at each point for at least 1 second (usually 2–3 seconds). Afterwards the machine makes the movement in the backward direction, stopping at the same positions like in the forward direction.

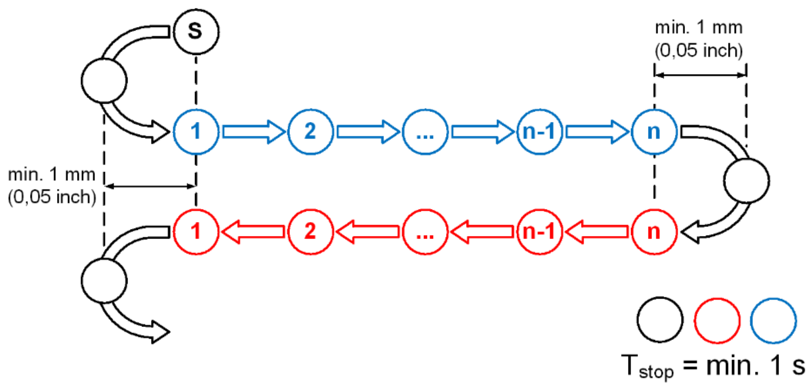

Fig. 2. Schematic diagram of the static positioning

The position of the machine at the measurement points is compared with the reading of the distance from the laser head and the differences, treated as errors, are gathered in a table for further analysis and for machine compensation. An example static positioning error chart is shown in the Fig. 3 with two series of forward and two series of backward measurements. Main limitation of the static positioning is the time required to perform he measurement. The time is dependent on the feed rate of the machine, the number of measurement points and the number of measurement cycles. For example for a 5 m long machine axis moving with feed rate of 1000 mm/min, with 100 measurement points, 2 seconds machine stop time and 3 measurement cycles the whole measurement would take more than an hour.

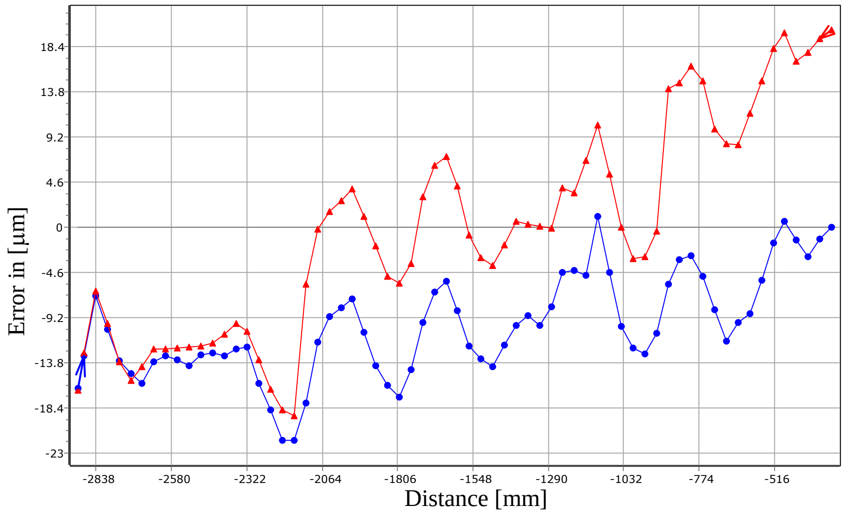

Fig. 3. Example results of the static positioning

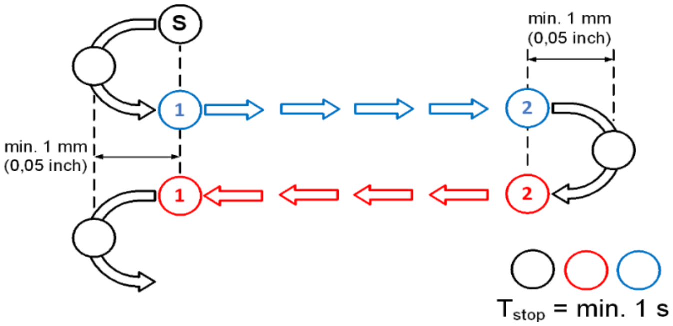

Fig. 4. Schematic diagram of the dynamic positioning

The remedy for the long measurement time is the dynamic version of the positioning. In the proposed version the stopping points are eliminated (see Fig. 4). The machine, after reducing the backlash is only to move with a constant velocity from point **1** to point **2**. Returning back to point **1** finishes the measurement cycle. The laser head together with the accompanying PC software detects and registers the real position of points **1** and **2** and calculates the machine feed rate between those two points. The calculated feed rate v_{ref} is treated as the constant reference value. The actual error $\varepsilon(n)$ is then calculated according to the formula:

$$\varepsilon(n) = (v_{\mathrm{ref}} - v_{\mathrm{meas}}) \cdot n \cdot \tau \tag{2}$$

where: v_{meas} – actual reading from the laser interferometer, v_{ref}– machine feed rate,
n – sample number, τ – time between registered samples.

The time between samples τ should as short as possible for the high-fidelity registration of dynamic behavior of the machine. In the experiments described in this paper the value of τ was set to 1 millisecond making it possible to notice any machine vibrations with frequencies up to 500 Hz. The reference feed rate v_{ref} is calculated in the PC software with automatic detection and negligence of machine acceleration (ramping) and machine deceleration (breaking).

The machine mentioned earlier would be measured within 30 minutes if three measurement cycles are performed. In the next chapter there are shown measurement results proving that the dynamic method is not only faster but also that it delivers additional information. Moreover, in order to characterize the tested machine or prepare the axis compensation table it is usually enough to make just one measurement series. In such a case the required measurement time can be reduced on the example machine to just 10 minutes, i.e. six times shorter than in the case of the static positioning.

4. MEASUREMENTS

The important point during the development of new measurement methods is the comparison of results with the existing standard. The comparison has been performed during tests of more than twenty different machines with similar results given by both methods. In the Fig. 5a and 5b there are shown example results from the same machine axis of 170 mm length. In both measurements the machine feed rate was set to 1000 mm/min, which means that the sample in the dynamic measurement was taken every 16.7 μm. Thanks to this the chart delivers very exact information about the machine – see the magnified fragment of the Fig. 5a. The registered spikes are most probably coming from the imperfections of the ball screw bearing. The sinusoidal changes of the error with period of 10 mm are on the other hand the imperfections of the ball screw itself.

In order to obtain similar number of information, the static positioning must had been done with a very fine step of 1mm and three measurement cycles had to performed. The real measurement time was in this case almost ten times longer, while the visible number of details still noticeably smaller.

The advantages of the proposed method are even more visible for longer axes. In the Fig. 6 there are shown results from the tests of a 8500 mm long axis. Beside the significant error trend and substantial value of the backlash, the measurement revealed uncompensatable and harmful in day-to-day use “sharp” positioning errors. Those error spikes were physically caused by the construction of the linear scales mounted on the machine – the scale was constructed of a 1m long parts assembled together with improper precision. The measurements were performed with machine feed rate of 4000 mm/min, i.e. the whole measurement lasted only 4 minutes. Control measurements performed at lower feed rate delivered the same results like shown in the Fig. 6.

Another interesting case is shown in the Fig. 7. The machine axis was 10000 mm long, the feed rate was set to 5000 mm/min and just one measurement cycle was performed. Beside the expected positioning errors, the measurement revealed various mechanical problems of the wore-out machine guide rails marked in the figure with circles.

Like in the case of the static positioning, the results obtained after dynamic positioning can be reported in a printable version with all parameters calculated according to the formulas found for example in the ISO230 standards family. The difference is the increased number of calculation points and thus more accurate overall result. The dynamic positioning results can also be used for the compensation of the encoder errors. The result of the example axis compensation is shown in the Figs 8a and 8b.

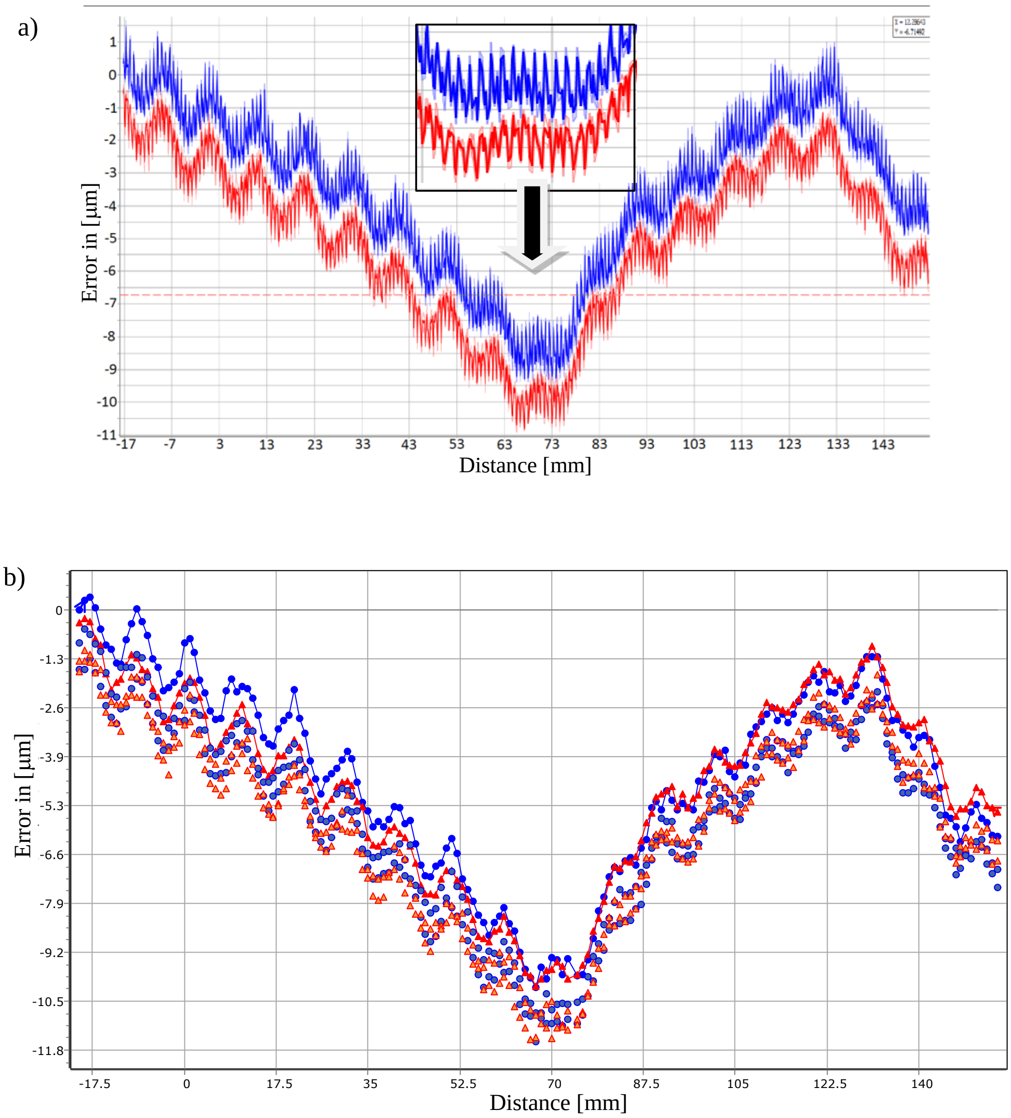

Fig. 5. Measurement results of positioning of a 170 mm long axis: a) Dynamic Positioning, b) Static Positioning

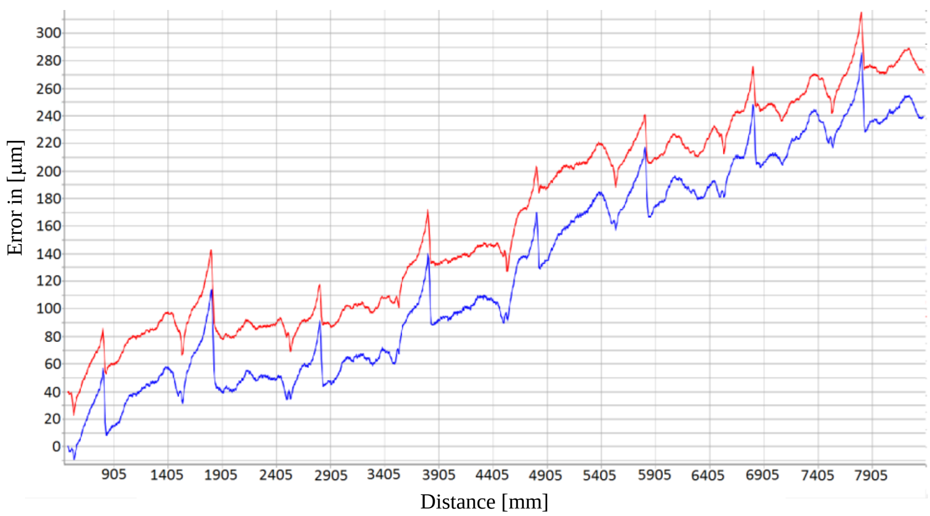

Fig. 6. Measurement results of dynamic positioning of a 8500 mm long axis

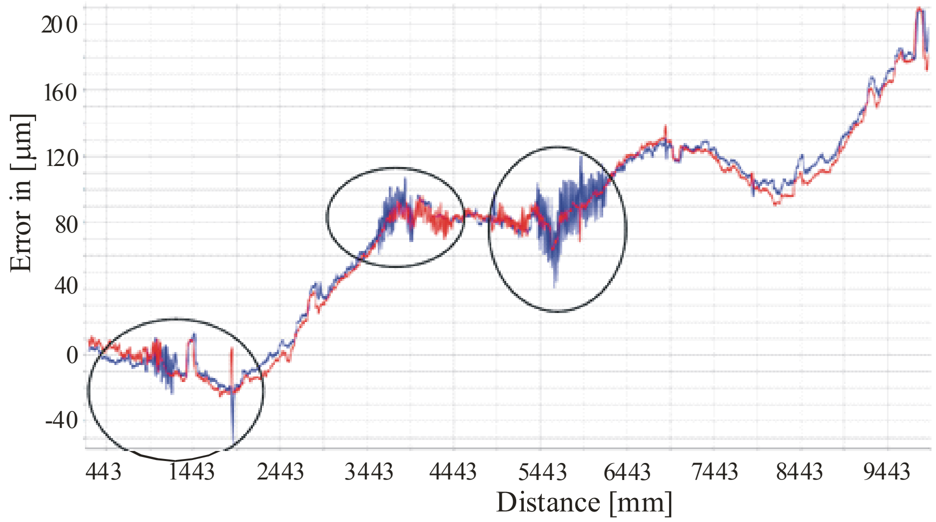

Fig. 7. Measurement results of dynamic positioning of a 10000 mm long axis

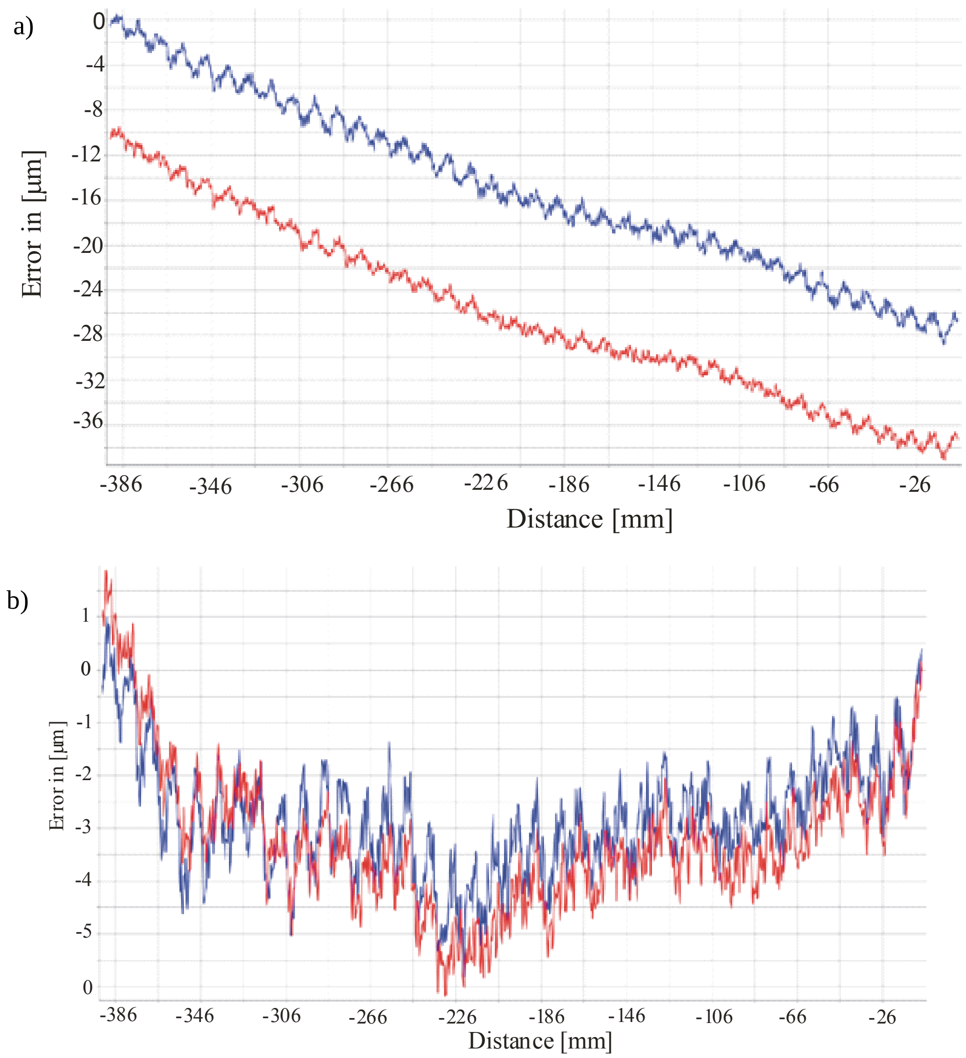

Fig. 8. Measurement results of dynamic positioning of a 400 mm long axis: a) before compensation, b) after compensation

The vertical scale of the charts is different – Fig. 8a scale is 40 μm, while Fig. 8b scale is 7 μm. Because of the large number of available measurement points, it is possible to decide about the length of the compensation table after the measurements – unlike in the static positioning. Moreover the length of the compensation table is only limited by the amount of the memory in the machine controller.

5. CONCLUSIONS

The ability of fast estimation and compensation of machine errors plays an important role in todays world. The method of dynamic machine positioning, described in the paper, gives significant advantages against the classic, static, method. The proposed solution is suitable for industrial applications of laser interferometers because of its simplicity and convenience in operation. With the use of the dynamic positioning the time required for machine servicing can be significantly reduced leading to noticeable cost saving. Moreover in the reduced measurement time the user can obtain additional information about dynamic characteristics of the machine.

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