MACHINE TOOLS METROLOGY USING LASER SYSTEMS

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Abstract

The article presents in some detail two CNC machine tool metrology applications using laser systems. The first application concerns the measurement of position error of a linear axis of a turning center conducted with a laser Doppler interferometry system, according to the ISO-232-2 standard. This was followed by a compensation procedure on the controller of the machine resulting in an impressive reduction of the error. The second application concerns measurement of vertical straightness (alignment) error of the ram edge where the press-brake tools are seated by using a suitable quadrant light detector and a simple geometric model. This enables re-alignment of the tools by utilizing the press-brake's dedicated beam mounted on its ram.

Keywords: CNC machine tools, laser, linear positioning error, bending tools alignment

Περίληψη

Το άρθρο παρουσιάζει με λεπτομέρεια δύο εφαρμογές μετρολογίας εργαλειομηχανών CNC με χρήση συστημάτων laser. Η πρώτη αφορά τη μέτρηση του σφάλματος θέσης γραμμικών αξόνων κέντρου τόρνευσης με χρήση συστήματος laser Doppler, σύμφωνα με το πρότυπο ISO-232-2. Ακολούθησε αντιστάθμιση του σφάλματος στον ελεγκτή τα μηχανής, πράγμα που οδήγησε σε εντυπωσιακή μείωση του. Η δεύτερη εφαρμογή αφορά μέτρηση του σφάλματος ευθύτητας της ακμής στήριξης των εργαλείων κάμψης μιας υδραυλικής στράντζας με χρήση κατάλληλου φωτο-αισθητήρα τύπου 'τεταρτημορίων' σύμφωνα με απλό γεωμετρικό μοντέλο. Με βάση αυτή την καταγραφή γίνεται ευθυγράμμιση των εργαλείων με χρήση της δοκού της κινητής κεφαλής.

Λέξεις-Κλειδιά: εργαλειομηχανές cnc, laser, σφάλμα θέσης γραμμικού άξονα, ευθυγράμμιση εργαλείων

1. Introduction

Laser systems have established themselves in high-end machine tool metrology. Two of the most common examples are interferometers that measure axis position error along the laser beam direction and alignment systems that measure straightness error normal to the laser beam.

Positioning accuracy and repeatability of axes directly affect the machine tool's ability to produce parts within certain tolerance. Accuracy indicates deviation between the nominal and the actual manufactured dimension. Repeatability reflects how vulnerable a machine tool is against random error, thus affecting production variability. Machine tool accuracy contains both random and systematic error, Wu and Ni (1989). Since, systematic error is measurable, predictable and greater than random error it can be compensated via the machine tool controller, Sartori and Zhang (1995). This is a well-established strategy, provided by many CNC machine tool manufacturers, Zhang et al. (2016). Error compensation is proven to be more efficient than error avoidance strategy, which implies design and manufacturing of precise yet high-cost machine tools, Ramesh et al. (2000).

Precision alignment systems have been invariably based on a laser beam functioning as the straight line reference, Grafström et al. (1988). They are far superior in terms of accuracy to mechanical guides and gauges fixed, typically, on a linear bearing carriage. Many laser based alignment systems use a four quadrant detector, Capineri et al. (1999), the gap between quadrants being a known constraint to the size of the laser beam diameter, Ng et al. (2007). Detection of misalignment in the vertical and horizontal directions is usually sought in order to rectify it by appropriate counteraction using actuators that range from simple screws to sophisticated mechanisms, Schmitt et al. (2016).

Two typical application examples of the above are the subject of this paper, namely position error measurement and compensation of a CNC lathe linear axis and misalignment registration of press-brake tools which is connected to vertical straightness of the ram's edge where they sit. In Section 2 the measurement principles are briefly explained. In Section 3 the implementation methodology and equipment is explained and in Section 4 the respective results are outlined. Conclusions are presented in Section 5.

2. Error measurement principles

2.1 Axis position error

Laser Doppler Displacement Meter (LDDM™) is a patented "Michelson-type self-aligning interferometer" utilizing the same mirror, located exactly at laser output position, as reference and signal mirror simultaneously, Wang (1992). This is unlike typical Michelson interferometers which demand precise alignment of a separate reference mirror. Its operation principle is based on the Doppler effect, according to which the frequency f_s of a wave emitted from a stationary source towards a reflective target moving with velocity v, returns to its origin with shifted frequency f_0 as described in Eqn. (1), where c is the speed of light. Integration of Eqn. (1) with respect to time proves that measurement of phase change $\Delta\varphi$ determines displacement Δx, see Eqn. (2).

$$f_0=f_s(2v/c) \quad (1)$$

$$\Delta\varphi/2\pi=(2f_s/c)\Delta x \quad (2)$$

An installed phase detector traces the phase angle while a counter keeps track of phase changes every π. Both are input to a microprocessor and they are converted to travel length in mm, Wang (1987).

Instrument errors derive from laser wavelength accuracy and electronic noise which dictates the minimum traceable $\Delta\varphi$ by the phase detector. Resolution is typically 0.01 μm. Changes in air temperature, humidity and pressure affect the speed of light hence they are captured by a sensor for compensation purposes. Similarly, a material temperature sensor is utilized to compensate for thermal expansion/contraction of the machine tool axis that is under measurement.

Measurement accuracy is affected by misalignment (cosine error), i.e. the angle between the axis under measurement and the laser beam, Abbé error and the dead-path error, i.e. the actual distance between laser output and the reference point, Optodyne (2006).

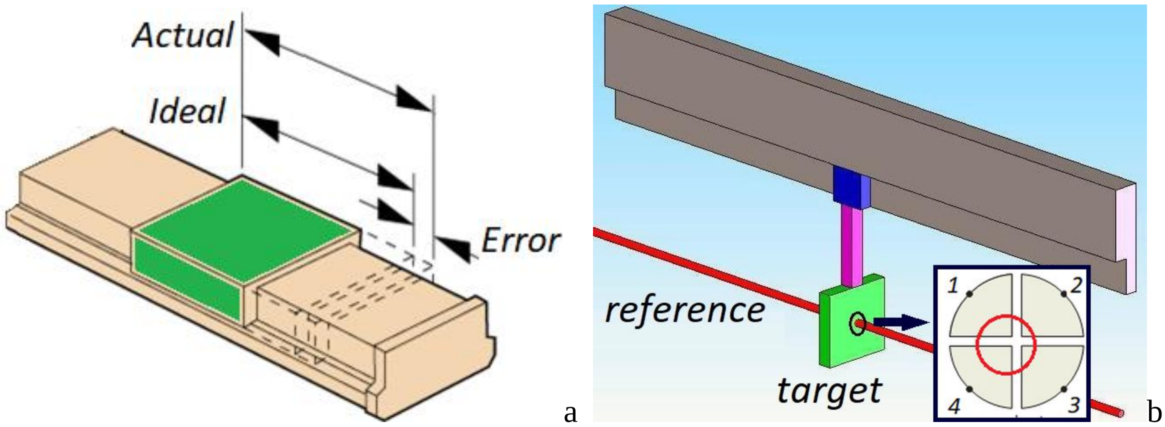

Figure 1: (a) CNC machine tool axis positioning error (b) Laser based alignment error of a tool

2.2 Vertical straightness (alignment) error

A special target is fixed on the part whose displacement is to be determined with respect to a reference line. The latter is a laser beam. Thus, the displacement (up-down, left-right) of the target with respect to the laser beam on a plane normal to the beam is sought, see Fig. 1(b). The target is often a quad-detector. This has four photocells in the form of the four quadrants of a circle, each of which outputs an electric current of intensity proportional to the area covered by the laser beam spot. The horizontal and vertical displacements of the beam with respect to the center of the sensor are given as:

$$\Delta x = ((I_1 + I_4) - (I_2 + I_3)) / (I_1 + I_2 + I_3 + I_4) \quad (3)$$

$$\Delta y = ((I_1 + I_2) - (I_3 + I_4)) / (I_1 + I_2 + I_3 + I_4) \quad (4)$$

where I_i is the output of quadrant I, see Fig. 1(b). When the target is perfectly centred on the beam the sum of the four currents is zero.

Note that initial linear and angular shifting of the laser beam is necessary so that the laser beam is reasonably aligned to the centreline of the target being at the two extreme positions. Yet, perfect alignment is not assumed, thus displacement at the two extreme positions needs to be recorded. Thus, skewed reference direction is acceptable, see Fig. 2. In addition, increase of the laser beam radius due to its inherent diversion angle characteristic needs to be taken into account.

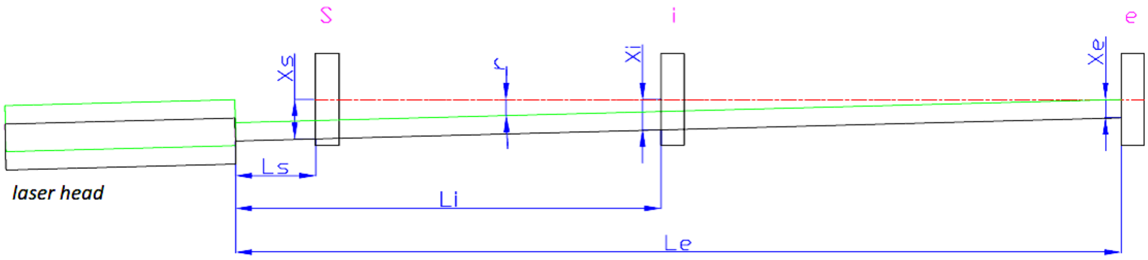

Figure 2: Calculation of theoretical displacement and radius of laser beam

At a known point *i*, the radius of the beam and the point's displacement theoretical displacement due to reference line skewness are calculated as follows, see Fig. 2:

$$R_i = R_o + L_i \tan(\alpha/2) \tag{5}$$

$$X_i = X_e + (X_s - X_e)(L_e - L_i) / (L_e - L_s) \tag{6}$$

where R_o is the nominal beam diameter at the exit from the laser head, L_i is the distance of point i from the laser head exit, α the diversion cone angle, indices s, e symbolising the left-most and right-most points respectively, and X_s, X_e the respective displacements. The difference of the theoretical displacement X_i see Eqn. (6) from the actually measured displacement is the alignment error in the vertical direction. An analogous calculation holds for the horizontal direction, if needed.

3 Implementation

3.1 Positioning error of a CNC axis

A Haas TL-1 CNC turning center was the subject of this case study. A ball screw actuates displacement along Z-axis within a travel range of 762 mm. To measure accuracy and repeatability international standard ISO 230-2 (1997) is followed. The ISO 230-2 guidelines dictate definition of at least five target points, either equidistant or randomly scattered, each measurement being taken five times along both directions.

The Optodyne MCV500 LDDM™ system was used, employing a HeNe laser of 632.8 nm wavelength, see Fig. 3. Laser head was fixed by a magnetic base on the tailstock, see Fig. 3, and was adjustable with respect to three rotations. For setup, the laser base is rotated around Y and Z axes until its misalignment is below 0.03 mm, measured with a dial indicator of 0.01 mm resolution. The retroflector was fixed on the toolpost by a similar magnetic base. To align the retroflector, the nearest and the most distant target point from the laser source are checked with a beam intensity diagnostic tool, included in the system's software.

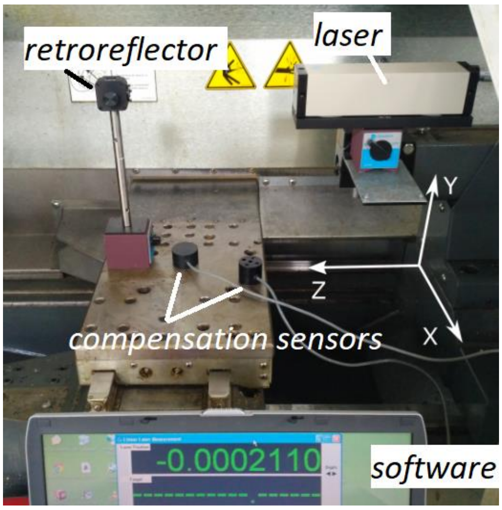

Figure 3: Positioning error measurement rig for Z axis of CNC lathe

The target points were set at 137.5 mm intervals starting from position -50.00 mm to position -600.00 mm on Z axis. The measurement process was automated by synchronizing laser system operation with a user-defined G-code routine that commands the CNC axis to move towards each of the target points successively at a feed rate of 1 m/min. Time-dwell commands of 5 seconds are used during which the laser system is triggered to record measurements, thanks to a pertinent software feature.

The error results for each target point are used to create a positioning error map for Z axis. The lathe's controller accepts compensation values for equidistant positions every 10.00 mm along Z-axis. Since error measurements were obtained for five target points, linear interpolation was applied in order to retrieve error values at intermediate points. Compensation values for the entire axis length were input and, then, the measurement process was repeated. Systematic positioning error (E), positioning repeatability (R) and positioning error (A) are automatically calculated by the system's software.

3.2 Straightness error of press brake ram edge

Acquisition of an off-the-shelf dedicated alignment measurement system was rejected for cost reasons. Therefore a custom defined system was put together by selecting and matching a suitable laser source and sensor to achieve a position (displacement) accuracy of 0.01mm.

For each press-brake 15 equidistant positions of measurement are defined along the ram edge in addition to the two extreme points of the ram edge. At each measurement point the mean of 5 values taken over a time period of 30 sec is taken to account for mechanical noise in industrial environment as well as for instrument noise.

The laser source was a class IIIa Melles Griot^{TM} 25 LHR 171-230 HeNe system with wavelength 532.8 nm, minimum beam diameter 1.02 mm and divergence cone angle 0.79rad. A Melles Griot^{TM} 13PSQ003 quad-detector was selected, having a quadrant gap of 1mm, which is less than the minimum laser beam diameter, excellent accuracy (1μm or 0.25% of the beam diameter), and resolution (0.5μm) and PCMCIA connectivity to any computer. A mounting post and magnetic holder of length close to that of the bending tool holds the sensor in place, thereby avoiding Abbe type error. The pertinent rig is shown in Fig. 4.

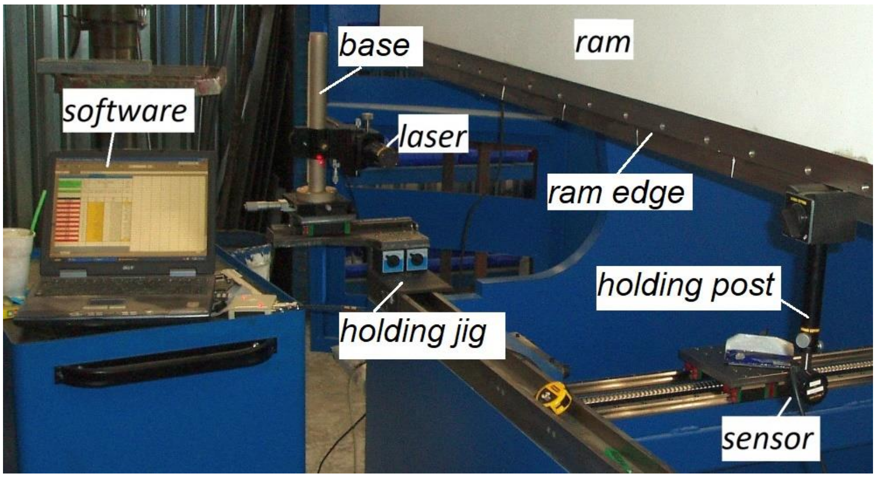

Figure 4: Vertical straightness measurement rig of press-brake ram edge

By simple calculation, the laser beam at 5m distance from the head exit has a diameter of 3.95mm thus yielding an accuracy of 0.01mm at the sensor. A neutral-density optical filter, 13 PSA 001 by Melles Griot™ was employed for attenuating laser power from 7.00 to 1.75 mW in order to avoid saturation effect on the quad detector.

The laser head was fixed on a special base (Melles Griot™ 07 HLA 535) enabling linear vertical and angular adjustment (azimuth and elevation), as well as micro-adjustment vertically and horizontally. A special holding jig was designed and manufactured to accommodate the laser base, see Fig. 4. It is magnetically clamped on the press-brake and enables horizontal movement of the base, which was a missing feature of the latter.

Special software SpotOn™ depicts the divergence of the laser beam spot with respect to the centre of the quad detector sensor in horizontal and vertical direction, according to Eqns. (3) (4). A pertinent spreadsheet template has been prepared and was used reflecting the calculations of these equations.

4 Results and Discussion

4.1 Positioning error of CNC axis

The results before and after compensation are shown in Fig. 5 and Table 1. Before compensation input, the bi-directional positioning error (A) of the axis was 36.3 μm and the bi-directional repeatability (R) 6.9 μm. The error compensation procedure resulted in an impressive improvement in bi-directional positioning error of 61.70%. Besides, systematic positioning error E was drastically reduced by an order of magnitude. Repeatability was slightly affected by the compensation process, yet being of the same order of magnitude as before and below positioning accuracy, too.

After compensation the machine tool approached its maximum capability regarding the specifications provided by machine tool manufacturer, being positioning accuracy at 10.0 μm and positioning repeatability at 5.0 μm. Uncertainty values are also calculated and presented in parentheses in Table 1 to enhance validity of the results.

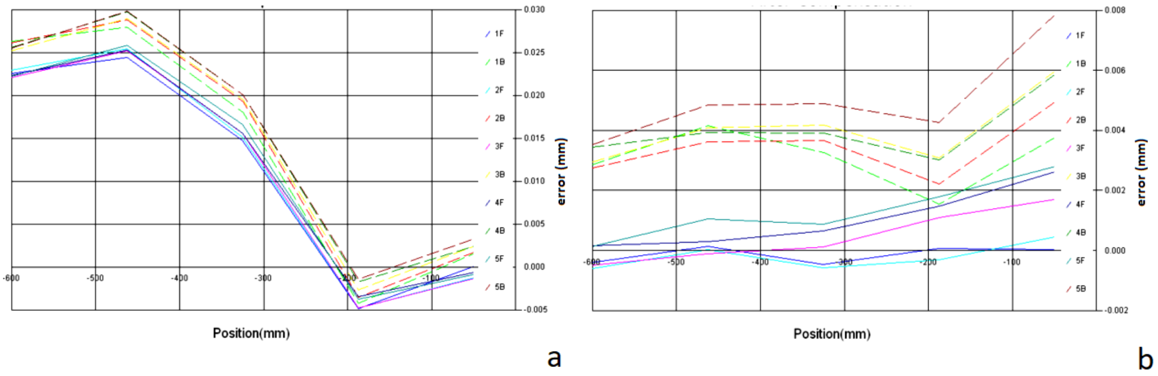

Figure 5: Positioning error recorded (a) before compensation (b) after compensation

Table 1: Results for linear axis positioning error and repeatability in μm

	Before compensation			**After compensation**		
Direction	*Forward*	*Backward*	*Bi-directional*	*Forward*	*Backward*	*Bi-directional*
Systematic positioning error E	29.6	31.8	33.4 (±3.7)	2.3	9.8	9.8 (±3.7)
Positioning Repeatability R	2.8	4.7	6.9 (±2.2)	5.0	6.0	9.7 (±2.2)
Positioning error A	32.0	35.7	36.3 (±4.2)	6.7	13.9	13.9 (±4.2)

4.2 Straightness error of press brake ram edge

At each position (points 0 to 16) along the ram edge the vertical distance between the ram edge and the laser reference line is measured, see Fig. 6(a). The laser reference line is, in the general case, not parallel to the ram edge, see Fig. 6(b), thus the actual deviation is not the measured one, but its difference from the (skewed) reference, see Fig. 6(b).

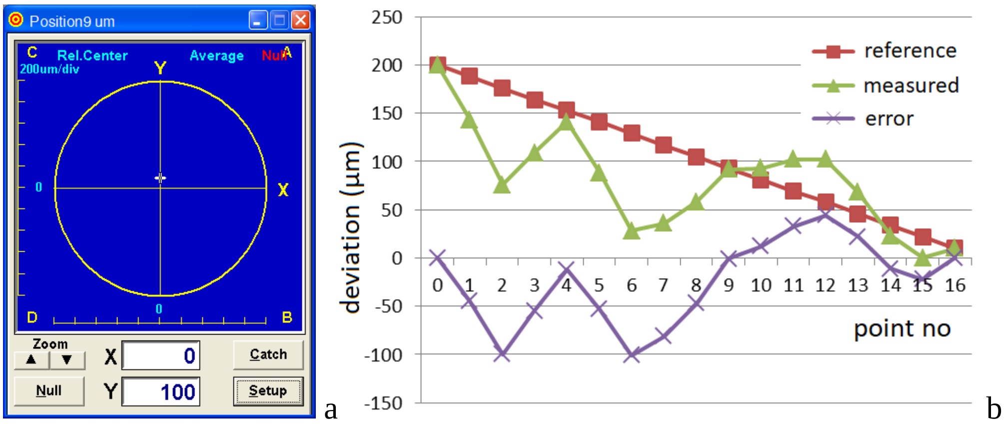

Figure 6: (a) Measurement display at one position (b) typical error for a 3m long press-brake

Having obtained the misalignment error map of the bending tools due to the straightness error of the ram edge it is possible to correct such error by operating on the screws provided on the special beam that is fixed on the back side of the press ram, see Fig. 7.

Figure 7: Misalignment rectification

5 Conclusions

Laser systems do provide the necessary features for high-end machine tool metrology.

Positioning error of CNC axes is most conveniently measured by a laser interferometer, in this case a special type exploiting the Doppler effect. The measurement process is efficiently supported by automated data collection in connection to G-code programmed movement of the axis under evaluation. Compensation applied to the axis, at least in the case study presented, improved the error impressively worsening repeatability only marginally.

Vertical straightness of a press brake ram edge on which bending tools are clamped is conveniently measured by a quad-detector and a laser beam as reference over several meters of ram length. The laser reference line does not need to pass from the ram edge ends or, indeed, any other points, since this is dealt with by a simple trigonometry model. Such measurements allow corrections by operating on the straightening screws of a special beam fixed on the ram.

Further applications can be sought along the lines of (a) measuring the other components constituting the volumetric error of a CNC machine by interferometry as well as (b) measuring straightness of the back gauge of press-brakes.

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