A Miniature Three-angle Sensor for the Accuracy Improvement of Machine Tools

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Abstract – **Machine tool accuracy is always largely influenced by the Abbé error that the scale measuring axis is not in line with the cutting axis. Any angular motion of the carriage will yield to positioning error amplified by the Abbé offset. In this paper a developed miniature three-angle sensor module is presented. This module is composed of pitch and yaw angles based on the interferometry, and the roll angle based on the spot shift. This three-angle module is small in size and cheap in cost. It is possible to embed in the machine tool as a feedback sensor to adjust the cutting position in real-time. Experiments show that the machine tool accuracy can be significantly improved after Abbé error compensation.**

Keywords - Three-angle sensor, Abbé error, machine tool, positioning accuracy

1 INTRODUCTION

Abbé error is the inherent systematic error in all numerically controlled (NC) machine tools. Since it was proposed by Professor Ernest Abbé in 1890 [1], the Abbé principle is regarded as the first principle in the design of precision positioning stages, machine tools, and measuring instruments. It defines that the measuring apparatus is to be arranged in such a way that the distance to be measured is a straight-line extension of the graduation used as a scale. Bryan further made a generalized interpretation with that if the Abbé principle is not possible in the system design, either the slideway that transfer the displacement must be free of angular motion or the angular motion data must be obtained to compensate the Abbé error by software [2, 3]. Zhang revised the definition to suit for other geometrical measurements, such as roundness, straightness, etc. [4].

Nowadays, most commercial machine tools and CMMs still cannot comply with Abbé principle because the scale axis is always parallel to the moving axis. A very popular way to improve the accuracy is to store the positioning or volumetric errors through prior calibration process and then compensate for the error budget with software, which is called the feed-forward compensation. It, however, can only compensate for the mean systematic errors. The angular errors are subjected to the temperature changes. It is known that if the Abbé principle is not possible in the system design, one effective method is to obtain the real time angular data and compensate for the Abbé error in software or hardware.

Techniques of non-contact angle measurement find applications in many fields. Autocollimators are commonly used optical tools for straightness calibration [5]. It is based on the spot shift of the reflected beam at the focus target due to angle motion of the moving mirror. An improved method is to employ a grating for position sensing to enlarge the measuring range [6, 7]. The resolution and accuracy of both these methods, however, are limited by the spot shift detection. Another approach for small angle measurement is based on the effect of total internal reflection [8, 9]. In the vicinity of critical angle with the angle movement a notable change of polarization can be detected, but the output has obvious nonlinearity. Laser interferometer, with its superiority in accuracy and resolution, also has been applied for angle measurement [10, 11]. By counting interference fringes the tiny displacement of objective point can be detected and converted into angle value. The resolution can be improved by techniques of phase subdivision to very fine [12-14]. The author's group has developed a miniature interferometer system for holographic gratings with good performance in measuring uncertainty and signal quality [15].

This paper presents a new approach for real-time Abbé error compensation on the machine tools. A low-cost three-angle sensor is developed that can embed in each axis of the machine tool. With an appropriate interface connection with the NC controller, this system can successfully compensate for the Abbé error during machine running condition. Experimental results show that the positioning errors within the working volume can be significantly reduced.

2 ABBE ERROR IN MACHINE TOOL

Current NC controller in the machine tool feeds back the scale reading position, which is offset from the real commanded position, as shown in Fig. 1. The straightness error of the slideway will cause angular motion (θ) of the moving table yielding inevitable positioning error (δ) at the cutting point, which is offset from the scale reading position by L.

$$\delta = L\tan(\theta) \tag{1}$$

From the 3D point of view, the moving table has three angular errors, namely pitch, yaw, and roll. Any of these angles will induce positioning errors at the cutting points in three dimensions, as shown in Fig. 2. The corresponding errors can be expressed by the following equation.

$$\begin{bmatrix}\delta_X\\ \delta_Y\\ \delta_Z\end{bmatrix}=\begin{bmatrix}-\theta_Z\cdot L_Y+\theta_Y\cdot L_Z\\ \theta_Z\cdot L_X-\theta_X\cdot L_Z\\ -\theta_Y\cdot L_X+\theta_X\cdot L_Y\end{bmatrix} \tag{2}$$

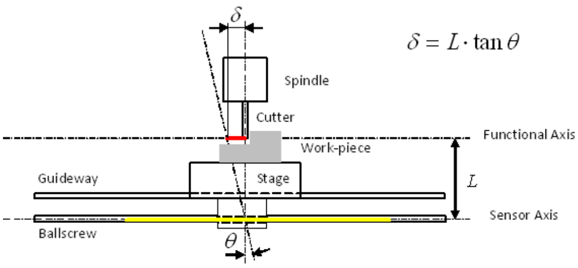

Fig 1. Abbé error in 1D stage

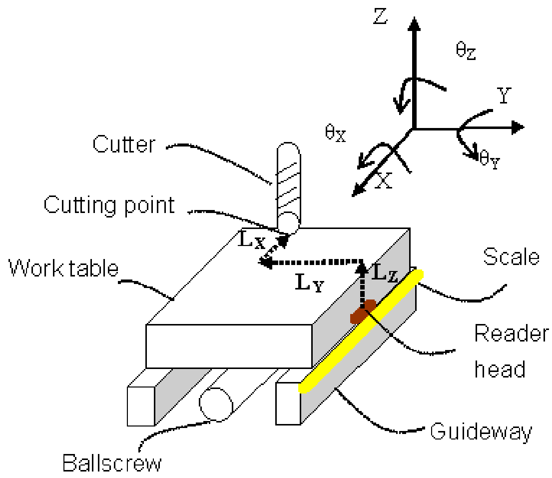

Fig 2. Abbé error in the 3D space of a linear stage

It is known that to eliminate δ by letting L or θ zero is impossible. The only way is to compensate for the positioning errors by sensing both L and θ and correct the cutting position through the controller. The design of low cost three-angle sensor is necessary.

3 PRINCIPLE OF THE ANGLE INTERFEROMETER

The optical structure of the proposed system is shown in Fig.3a. The principle is based on the classic model of Michelson interferometer. The approximately linear polarized beam from the laser diode is split by the polarization beam splitter PBS1. The P-polarized beam passes through and the S-polarized beam is reflected to the left. With careful rotation of the PBS1 these two beams will have equal intensity. Then, the reflective mirrors M1, M2 and M3 guide these two beams to the object mirror in parallel and equal path distance. When the object mirror has an angle displacement, the change of the optical path difference will cause interference of two returned beams after joining together, which can be converted into corresponding angle value. After passing through the quarter waveplate Q1 twice, the left-arm beam will be converted into P-polarized beam and pass through PBS1. The right-arm beam has the similar feature. This design is to avoid the beam returning back to the laser diode. After passing through Q3 the left-arm beam and right-arm beam will be converted into right-circularly and left-circularly polarized beams, respectively. The NPBS divides both beams into two split beams of equal intensity. These four beams will be separated by 0-90-180-270 degrees by PBS2 and PBS3 (set fast axis to 45 degrees) and interfere with each other. Four photo detectors (PD) will convert the beam intensity to corresponding current. A proper sinusoidal signal processing circuit can reach 0.1 arc-sec resolution. Fig. 3b is the compact size of this developed yaw angle sensor.

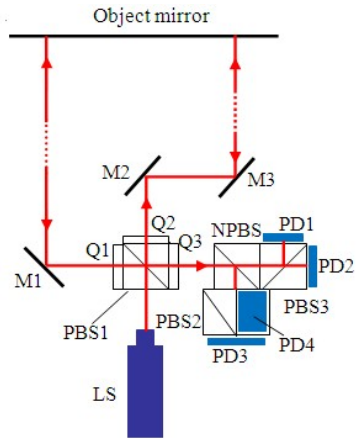

Fig.3a. Optical configuration of angle interferometer

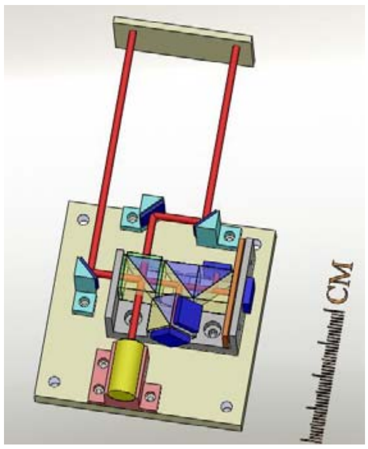

Fig.3b. the design drawing

4 THE THREE-ANGLE SENSOR DESIGN

A miniature three-angle sensor has been developed for this purpose, as shown the schematic diagram in Fig. 4. One laser diode splits the beam into two angle interferometer modules set in orthogonal directions, one for the yaw and another for the pitch measurements. The second laser diode also splits the beams to two paths and each one is reflected by a corner cube reflector (CCR) and collected by a quadrant detector. The relative up/down motion of two CCRs reflects the roll angle motion of the stage. After calibration, the pitch and yaw sensors can reach ±0.3 sec accuracy for the range of ±100 sec, and for roll angle it is ±1 sec accuracy for the range of ±150 sec. These performances are good enough for machine tool use.

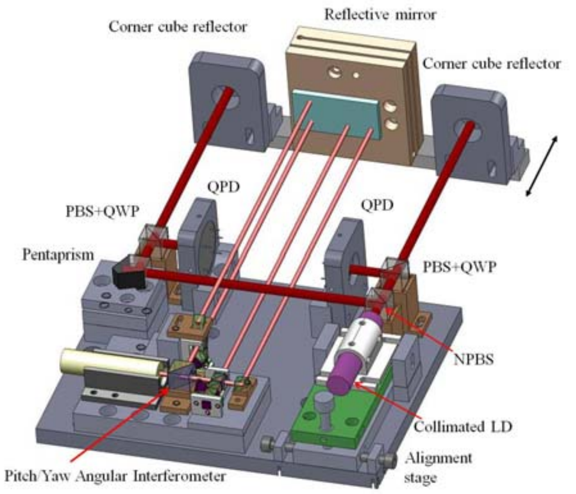

Fig.4. the integrated structure of a three-angle sensor

5 EXPERIMENTS

The three-angle sensor features small size (about 160× 130 mm of mounting area) and low cost. It is able to install in any machine tool and connect to the NC controller, as schematically shown in Fig.5. A microprocessor that processes the angle signals and calculates Eq. (2) is called the Abbé error compensator, which can dynamically acquire the current three coordinate positions from the NC controller and, after processing, send the compensated command into the controller. By this way, the cutting point can be automatically adjusted in real-time with the amount of Abbé errors in space.

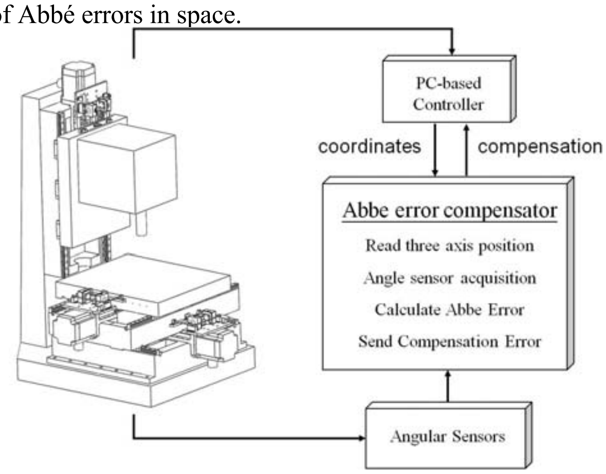

Fig.5. System integration of the Abbé error compensator

A test trial has been carried out on a small table top NC machine tool. The experimental setup is shown in Fig. 6 for the X-axis motion. A laser interferometer of HP5529 was amounted at different Z heights of the spindle head as a calibration reference. Same procedure can also be conducted for the Y-motion. Fig. 7 shows the comparison of positioning errors with and without the Abbé error compensation in X-axis. The kinematic error of the table can be regarded as a rigid body motion. It is clearly seen that the positioning errors can be significantly reduced with the use of Abbé error compensation scheme at any height position.

The stability of the laser diode (Thorlabs CPS180) has been investigated by pointing the spot on a four-quadrant photo detector, which is placed about 500 mm far. The spot shift during 10 minutes was found only about ±0.15 μm after a moving average data processing, as shown in Fig. 8. The corresponding laser beam drift is less than 0.1 arc-second. Its influence to measured angle can be neglected.

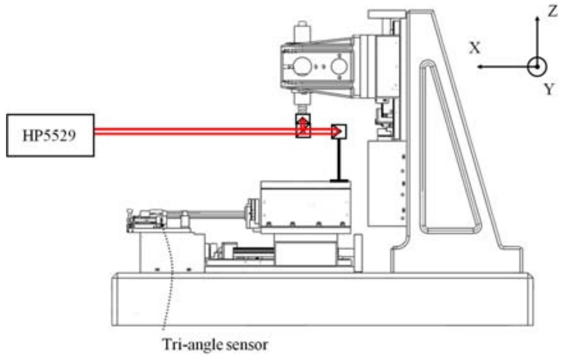

Fig.6. Experimental setup for positioning test

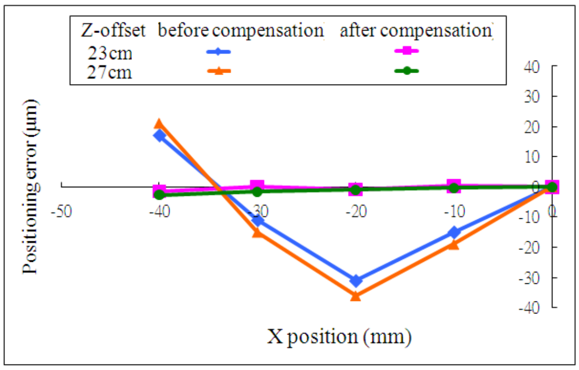

Fig. 7. Experimental results of X-positioning error calibration

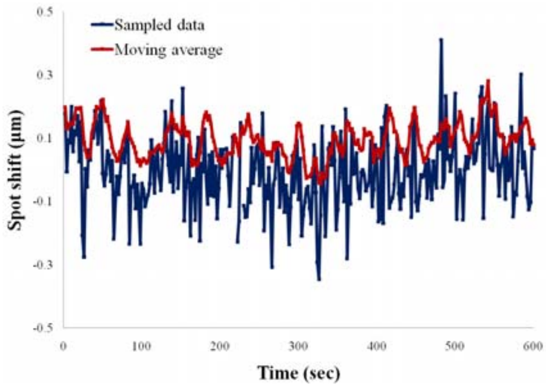

Fig. 8. Experiment of the laser beam stability

6 CONCLUSIONS

In this paper, a developed low cost miniature three-angle sensor module is presented. It is able to embed in the machine tool structure and compensate for the positioning errors within the working zone. The developed Abbé error compensator can be equipped to any machine tool for real-time Abbé error compensation. Experimental results show the effectiveness of this system.

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