High Precision Optical Sensors for Real-Time On-line Measurement of Straightness and Angular Errors for Smart Manufacturing

Hau-Wei Lee and Chien-Hung Liu

Abstract

A setup of two reflective-type optical sensors for the on-line real-time measurement of straightness and angular errors of a linear stage is presented. The arrangement is similar to that of a linear encoder and can make on-line measurements of stage errors for the analysis of automatic processes as well as real time monitoring. The reflector used as the sensor reference plane was a rectangular piece of commercial silicon wafer. The wafer fixed to the side of the slide was very flat and had good reflective properties. A silicon wafer is much cheaper than a long optically flat mirror of similar precision. The standard deviation of the straightness sensor and the angular error were verified as 0.06 μm and 0.08 arcsec. The accuracy of the two sensors was verified as ±0.25 μm and ±1 arcsec. The two sensors were integrated with a single axis PZT-based stage for real time straightness compensation experiments and the results showed straightness compensation from 3.5 μm down to 0.4 μm.
1. Introduction

The effect of the information technology (IT) revolution is being felt on factory floors all around the world. Manufacturing has already become highly automated and IT-driven, or more simply put, it has become smart. Furthermore, advances in modern manufacturing technologies are making factories smarter by the day, and at the same time, safer and more environmentally sustainable. To keep up with the pace of smart manufacturing, the use of on-line monitoring technology with automatic on-line measurement of process variation (with connection to the cloud) has become routine. For this purpose, many kinds of on-line measurement systems have been developed. This is especially the case for linear stages which are present in every kind of hi-tech manufacturing industry. The need for measuring straightness and angular error is increasing and doing this on-line is a logical development that allows the rapid accumulation of data and the correction of errors. The data can also be used to determine the useful lifetime of equipment. Geometric error measurement is very important for high precision manufacture which includes: geometric, form, directional, positioning, and run-out tolerance and so on. There are many alternatives to off-line error compensation of straightness in a moving stage. Typically, the geometric errors are measured off-line using a laser interferometer system and special mirror modules.[1] Each of the positioning errors, straightness, angularity, perpendicularity and so on, has to be measured individually. The laser interferometer system cannot measure these errors simultaneously. To solve this problem, many different laser based measurement systems with many degrees of freedom (DOF) have been developed.[2–8] These use corner cubes, or plane mirrors, or special prisms, or position sensitivity detectors, or quadrant photodiode detectors (PDs), or CCDs and multiple optical paths to measure multi-DOF errors simultaneously. Although, these systems can do the job, they cannot do it on-line and cannot be used to provide compensation either. Some research has been done on the development of a straightness measuring method. A Zeeman dual-frequency straightness laser interferometer was developed by Qianghua [9]. In 2009, Chen et al. used a heterodyne interferometry method to measure straightness error.[10] In the same year, Vekteris et al. used an optical meter to measure dual-axis straightness errors.[11] In addition to these optical methods, some non-optical straightness measurement systems were also developed. Hwang used three capacitive probes for measuring the parallelism and straightness of a pair of rails. [12] Fung used five proximity sensors to measure motion error in a linear guide.[13] Both these systems can also measure errors of straightness and yaw simultaneously. In a previous study, we developed a diffraction grating based sensor to measure linear displacement and three angular motion errors and also used it for measuring multi-DOF error in an indexing table.[14,15] For on-line and real-time measurement of multi-DOF motion error in a linear stage, we developed several reflective grating based multi-DOF laser linear encoder systems.[16–18] For real-time straightness compensation in a linear moving stage, we proposed a straightness self-compensating stage that used an optical straightness measuring system, an eddy current sensor, and a cross-roller compensation stage.[19] For another straightness measurement and compensation, we developed a system that used several right angle reflectors to increase sensitivity.[20] Multiple incident and reflected beams from several right angle reflectors provided a six times magnification of the error deflection. The straightness was then compensated using PZT actuated compensation stages. The previous two measuring systems did not measure angular error but utilized off-line straightness measurement to make real-time straightness compensation. However, an off-line measurement system has a degree of uncertainty and so in this paper two on-line measuring sensors have been used for straightness, as well as roll and yaw, and this allows both real-time measurement and straightness compensation. The arrangement of the two sensors and the reflector are similar to that used in a linear encoder for easy implementation.

2. Sensor design

2.1. Overall system

The arrangement of the real time straightness and angular error measurement and compensation system is shown in Figure 1. The system included two reflective-type optical sensors and a PZT-based straightness compensation stage. The compensation stage was placed under the linear stage and the straightness measurement system was fixed to one side of the compensation stage. An HP laser interferometer, used to verify measurements, is also shown in figure. When the linear stage moves, the straightness error is measured by both the proposed system and the interferometer, at the same time. The straightness measurement system can be adjusted by the three-axis adjustment mechanism to keep it parallel to the reflector to reduce system setup error.

2.2. Straightness sensor

Figure 2 shows the simple optical arrangement of the straightness sensor. The components include an LED with a collimating lens, a focusing lens (8 mm diameter, focal length 10 mm) and a one-dimensional PD. The sensor assembly is very inexpensive being made of cheap and readily available optical components. The collimated beam from the LED is focused by the lens, reflected by the wafer surface, and comes to a focus on the PD.
2.3. Angle sensor

The optical angle sensor serves two functions, one is to measure the roll and yaw of the linear stage and the other is to provide data used to separate and isolate the effect of roll and yaw on the linear straightness deviation data. By eliminating the effect of roll and yaw on the linear data error measurements, accuracy is greatly improved.

Figure 3 is a schematic layout of the angle sensor optical system. The expanded beam from the laser diode is reflected from the polarized beam splitter, passes through a $1/4\lambda$ plate and a collimator lens. The resulting parallel beam is reflected from the surface of the silicon wafer and returns along the same path through the collimator lens (which now focuses the beam), the $1/4\lambda$ plate and beam splitter to form a spot on the origin of the quadrant PD surface. Any change in the angle of the reflector surface $\theta$ will cause a $2\theta$ deflection of the reflected beam and move the position of the beam spot on the quadrant position sensor. This variation can be used to measure yaw and roll deviations on the linear stage.

2.4. Straightness compensating stage

The straightness compensation stage, shown in Figure 4, is driven by a piezoelectric actuator inside the flexure hinges.
2.5. Kinematic analysis of the straightness sensor

All rigid bodies have three rotational and three translation error components. For the linear moving stage, the HTM that describes the effects of errors on stage motion in series with error terms. Figure 6 shows the geometric relation of elements in the straightness sensor. The coordinate systems are defined as follows:

- \{R\}: the reference coordinate system
- \{L\}: the laser light source coordinate system
- \{Q\}: the coordinate system of PD
- \{M\}: the coordinate system of the silicon wafer.

The vector from \{R\} to \{M\} is \( \vec{m}_0 = \begin{bmatrix} 0 & 0 & m_{0z} \end{bmatrix}^T \);

the vector from the reference point to the laser light source is \( \vec{g}_0 = \begin{bmatrix} g_{0x} & g_{0y} & g_{0z} \end{bmatrix}^T \); the vector from the reference point to the zero point of the photodetector is \( \vec{q}_0 = \begin{bmatrix} q_{0x} & q_{0y} & q_{0z} \end{bmatrix}^T \).

When the stage is moved with straightness error at \( \theta_y \) and \( \delta_z \), the vector between \{R\} is:

\[
\vec{m}_1 = \begin{bmatrix} 0 & 0 & m_{0z} + \delta_z \end{bmatrix}^T
\]

(1)

When the stage is moved with angular displacement, the vectors which are from \{R\} to \{L\} and from \{R\} to \{Q\} are:

\[
\vec{g}_1 = \begin{bmatrix} g_{1x} & g_{1y} & g_{1z} \end{bmatrix}^T = \mathbf{M} \cdot \vec{g}_0
\]

(2)

\[
\vec{q}_1 = \begin{bmatrix} q_{1x} & q_{1y} & q_{1z} \end{bmatrix}^T = \mathbf{M} \cdot \vec{q}_0
\]

(3)

\[
\mathbf{M} = \begin{bmatrix}
\cos \theta_y & -\sin \theta_y & 0 \\
\sin \theta_y & \cos \theta_y & 0 \\
0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
\cos \theta_z & 0 & \sin \theta_z \\
\sin \theta_z & \cos \theta_z & 0 \\
0 & 0 & 1
\end{bmatrix} = \begin{bmatrix}
\cos \theta_z & -\sin \theta_z & 0 \\
\sin \theta_z & \cos \theta_z & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

(4)

where \( \theta_x \), \( \theta_y \), and \( \theta_z \) represent the angular displacement of the stage on the \( x \)-, \( y \)-, and \( z \)-axis, respectively. Since, only \( \theta_y \) effects the measurement result, Equation (4) can be simplified as below:

\[
\mathbf{M} = \begin{bmatrix}
\cos \theta_y & 0 & \sin \theta_y \\
0 & 1 & 0 \\
-\sin \theta_y & 0 & \cos \theta_y
\end{bmatrix}
\]

(5)

The vector of the laser light reflected by the wafer is:

\[
\vec{r}_0 = \begin{bmatrix} r_{0x} & r_{0y} & r_{0z} \end{bmatrix}^T
\]

\[
= \begin{bmatrix} u_{0x} & -u_{0y} & -u_{0z} \end{bmatrix}^T
\]

(10)

Note that, \( \vec{r}_0 \) is measured by the proposed angle sensor in this study, which means that \( \theta_y \) is known. The vector of light from laser projected onto the wafer is:

\[
\vec{l}_0 = \begin{bmatrix} l_{0x} & l_{0y} & l_{0z} \end{bmatrix}^T
\]

in which \( \vec{u}_{00} = \begin{bmatrix} u_{0x} & u_{0y} & u_{0z} \end{bmatrix}^T \) is the unity vector of \( l_0 \). When the stage moves with straightness error (including linear straightness and angular straightness), the vector of the incident light is changed:

\[
\vec{l}_1 = \begin{bmatrix} l_{1x} & l_{1y} & l_{1z} \end{bmatrix}^T = \vec{l}_0 \times \vec{u}_{00} = \vec{l}_0 \times \mathbf{M} \cdot \vec{u}_{00}
\]

(6)

where \( \vec{l}_1 \) is the unity vector of \( l_1 \) as seen in Figure 6, since \( z \)-axis displacement of \( \vec{g}_1 \) is absolutely equal to \( \vec{m}_1 - \vec{l}_0 \) thus:

\[
l_{1z} = g_{1z} - m_{0z} - \delta_z
\]

(8)

From Equations (7)–(8), \( |l_1| \) can be computed by the following equation:

\[
|l_1| = \frac{l_{1z}}{u_{11z}} = \frac{g_{1z} - m_{0z} - \delta_z}{u_{11z}}
\]

(9)

The vector of the laser light reflected by the wafer is:

\[
\vec{r}_1 = \begin{bmatrix} r_{0x} & r_{0y} & r_{0z} \end{bmatrix}^T
\]

\[
= \begin{bmatrix} u_{0x} & -u_{0y} & -u_{0z} \end{bmatrix}^T
\]
where $|\vec{r}_0|$ is the length of $\vec{r}_0$. Similarly, the vector of the reflected light when the stage moves with a straightness error is:

$$\vec{r}_1 = \begin{bmatrix} r_{1x} & r_{1y} & r_{1z} \end{bmatrix}^T = |\vec{r}_1| \times \begin{bmatrix} u_{1lx} & -u_{1ly} & -u_{1lz} \end{bmatrix}^T,$$

(11)

where $|\vec{r}_1|$ now is unknown. As seen in Figure 6, if the spot deviation vector is $\vec{s}_1 = \begin{bmatrix} s_x & s_y & 0 \end{bmatrix}^T$, the following equation can be derived:

$$\vec{s}_1 = \mathbf{R}_{\psi d}^{-1} (\vec{g}_1 + \vec{l}_1 + \vec{r}_1 - \vec{q}_1),$$

(12)

$$\mathbf{R}_{\psi d} = \begin{bmatrix} \cos (\beta + \theta_y) & 0 & \sin (\beta + \theta_y) \\ 0 & 1 & 0 \\ -\sin (\beta + \theta_y) & 0 & \cos (\beta + \theta_y) \end{bmatrix},$$

(13)

where $\beta$ is the installation angle of the photodetector that rotates on the $y$-axis. Since $s_{1z} = 0$, we have:

$$\left( \mathbf{R}_{\psi d}^{-1} \vec{r}_1 \right)_{z} = \left( \mathbf{R}_{\psi d}^{-1} (\vec{q}_1 - \vec{g}_1 - \vec{l}_1) \right)_{z}. \tag{14}$$

Then the length of $|\vec{r}_1|$ can be calculated by the following equation:

$$|\vec{r}_1| = \frac{|(g_{lx} - q_{lx} + |l_i| \times u_{1lx}) \cos (\beta + \theta_y) + (g_{ly} - q_{ly} + |l_i| \times u_{1ly}) \sin (\beta + \theta_y)|}{u_{1lz} \cos (\beta + \theta_y) - u_{1lx} \sin (\beta + \theta_y)} \tag{15}.$$
straightness compensation system as shown in Figure 15. It consists of a linear moving stage, a straightness compensation stage, straightness and angle sensors and a laser interferometer measurement system used only for verification. The measurement results were compared with the HP laser interferometer results in real time. The linear stage was moved over a distance of 80 mm and the straightness error was measured at 2 mm intervals. The straightness of the linear stage was measured and the results before compensation are shown in Figure 16.
The measurement difference showed that the straightness error of the linear stage is within 3500 nm and the measurement difference was within ±400 nm. The observed STDEVs from the laser interferometer and straightness sensor are about 300 and 200 nm, respectively, as shown in Figure 17. The straightness compensation process is a position to position method with 2 mm steps. Five on-line and real-time compensation tests using the PZT compensation stage (see the control block diagram in Figure 5) were carried out and the compensated straightness error measured by the laser interferometer are shown in Figure 18. Comparison of Figures 16 and 18 showed the straightness error had been improved by 89%. The above results showed that our proposed on-line and real-time system was useful for improving the accuracy of a linear stage.

4. Conclusion

An on-line real-time straightness and angle measurement system using two inexpensive sensors and a few other simple components has been developed. The experiments showed both high resolution and precision. The arrangement of the two sensors, which provide real-time measurement, is very like that of a linear encoder. They can be set up on one side of a linear stage in a straightforward and simple way. To increase the measuring range over a greater distance, the reflective grating scale of an existing linear encoder can be used with these sensors. Their output can also be fed into a cloud computation system via an

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**Figure 14.** STDEV of the angle sensor.

**Figure 15.** The on-line and real-time straightness compensation system.

**Figure 16.** Straightness measurements: HP laser interferometer and straightness sensor.

**Figure 17.** Comparison of STDEV.

**Figure 18.** Five time results of straightness compensation: (a) average result and (b) STDEV.
Internet connection where the data can be captured, monitored and analyzed by a smart manufacturing application.

**Disclosure statement**

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**ORCID**

Hau-Wei Lee http://orcid.org/0000-0002-9692-224X
Chien-Hung Liu http://orcid.org/0000-0001-8918-5627

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