

STRAIGHTNESS MEASUREMENT BASED ON KNIFE-EDGE SENSING

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INTRODUCTION

Straightness error is a parasitic translation along a perpendicular direction to the primary displacement axis of a linear stage. Its measurement and compensation are critical in the metrology, calibration, and manufacturing of multi-axis platforms. For example, the inverted XYZ platform in Figure 1 which is a stack of three mutually orthogonal linear stages. Although the linear stages are expected to move along perfect single axis trajectories, in practice they have two lateral straightness errors as shown in Figure 2. Thus, measuring and/or calibrating the straightness errors is important in precision engineering applications including semiconductor processing, printed circuit board (PCB) processing, micromachining, precision assembly processing, *etc.* [1].



FIGURE 1. Rocfish three-axis system

Several implementations for measuring straightness error have been presented, which are

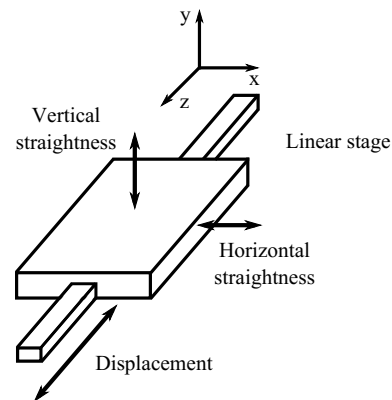


FIGURE 2. Three degrees of freedom of linear stage motion.

mostly based on three principles [2]. The first is an interferometric method, whose principle is similar to a displacement measuring interferometer. It measures the optical path change due to the movement of polarizing or non-polarizing straightness optics, and then converts the optical path change to the transverse displacement (straightness) [1, 3, 4]. The second is via light intensity detection. The straightness error produces a change of the optical power reaching a final photodetector. By monitoring and calibrating the power change, the straightness can be measured [2, 5, 6]. The third is a spot position detection method. It uses a laser as the reference location. The stage's straightness error leads to lateral motion of the laser and a final photodetector measures the position change of the incident beam [7, 8, 9, 10]. These solutions employ different configurations, components, detectors, and signal processing algorithms, and achieve varying levels of accuracy and resolution.

Our optical knife-edge method is a particularly simple configuration for light intensity detection

which builds on previous research [5, 6]. In this paper, we propose a new configuration of the knife-edge method, and explore its precision, resolution, linearity and feasibility to measure two-dimensional straightness errors.

OPERATING PRINCIPLE

The knife-edge method uses a sharp edge to block part of a laser and uses a photodetector to measure the transmitted and diffracted light. In previous studies, Fan, *et al.* presented a configuration whose experimental result showed that the accuracy is better than $\pm 0.2 \mu\text{m}$ [5]. Lee, *et al.* implemented a prototype 3-D printed stage which claims a 5.2 nm resolution with high linearity [6].

Lee's configuration (see Figure 3) splits a laser into two beams, and the two beams are partially blocked by two outward facing knife-edges. Two photodetectors measure the transmitted and diffracted light at a specified distance from the two knife-edges. When the knife-edges displace laterally, the two detected signals increase or decrease in a differential manner. Differential post-processing on two detected signals extracts the straightness error.

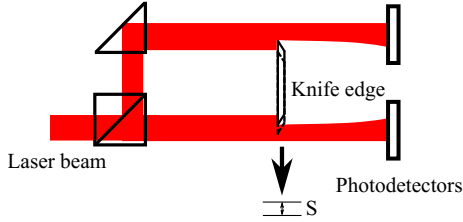


FIGURE 3. Lee's configuration based on knife-edge detection [6].

To extend the above configuration to a two-dimensional straightness measurement and reduce alignment drift errors, we propose a configuration that combines light intensity detection with spot position detection. It uses a two-dimensional knife-edge, which combines four inward facing knife-edges as a square aperture. When the single laser beam reaches the square aperture, the transmitted and diffracted light will be detected by a quadrant photodetector. When the aperture has a lateral displacement, the position of the spot on the detector will change (see Figure 4).

The quadrant photodiode consists of a 2×2 photodiode array with a small (several micrometers) gap separating adjacent elements. Due to the position of the incident beam change, the optical

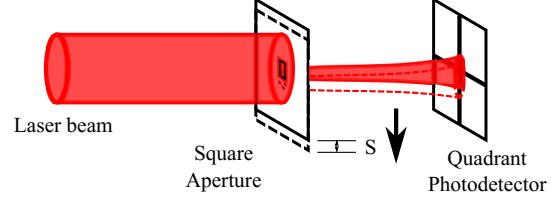


FIGURE 4. The configuration of proposed 2D straightness measurement system based on 2D knife-edge (square aperture).

power distributes differently on each element (see Figure 5). Each single photodiode converts the incident optical power to a photocurrent. By tracking these four photocurrents, the position of the spot can be derived according to [9, 11]

$$S_x = k_x \frac{(I_A + I_B) - (I_C + I_D)}{I_A + I_B + I_C + I_D} \quad \text{and} \quad (1)$$

$$S_y = k_y \frac{(I_A + I_C) - (I_B + I_D)}{I_A + I_B + I_C + I_D}, \quad (2)$$

where S_x and S_y are the straightness errors in the x- and y-directions respectively, I_A , I_B , I_C , and I_D are the photocurrents generated by the four elements, and k_x and k_y are scaling factors that convert the current measurement to its corresponding length (straightness).

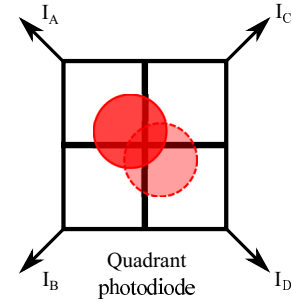


FIGURE 5. The relative position change makes the optical power distribution on the detector change, thus leading to a change in photocurrent.

The variation in the laser intensity is eliminated by dividing the sum of four elements, and the common mode noise is also eliminated by the differential post-processing (numerator part). However, the intensity distribution of the beam is not uniform because the knife edge clips the beam. It leads to the relationship in (1) and (2) which are nonlinear, thus, k_x and k_y are non-constant values, which must be calibrated carefully. The size of the aperture also leads to a trade-off between measuring range and resolution [8, 11]. However, this tradeoff can be critical in extending the range of this sensing architecture to the mesoscale, which has limited low cost, high

precision options.

IMPLEMENTATION

In this work, we utilize a one-dimensional piezo-stage with a calibrated internal capacitance sensor for closed loop control to simulate a horizontal straightness error. Thus, we designed a configuration to verify the one-dimensional measuring capability of the proposed sensor only. Figure 6 shows the configuration to measure one-dimensional straightness error. Unlike Lee's configuration, it uses a single beam, two inward-facing knife-edges, and a quadrant photodetector. This makes the configuration more compact and easier to align.

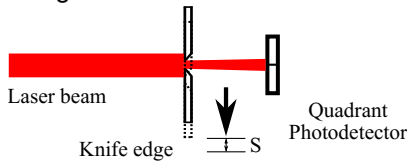


FIGURE 6. The proposed configuration to measure one-dimensional straightness error.

SIMULATIONS

Simulations were performed to determine the theoretical relationship between the straightness and photocurrents generated by the detector. When the laser reaches the aperture, part of the light passes the aperture, and part of the light is blocked. Due to diffraction, some transmitted light "bends" into the region of the geometrical shadow of the aperture. The size of the spot on the detector is not exactly the same as the aperture. To obtain the relationship between lateral displacement and the photocurrents, the distribution of the transmitted light must be identified.

To identify the distribution of the transmitted light on the detector, we use angular spectrum propagation to calculate the spot distribution on the detector plane at distance z [12],

$$U(x, y, z) = F_{f_x f_y}^{-1} (F_{f_x f_y} (U(x, y, 0)) \cdot e^{j \frac{2\pi}{\lambda} \sqrt{1 - \lambda^2 f_x^2 - \lambda^2 f_y^2} z}), \quad (3)$$

where $U(x, y, 0)$ is the distribution across the aperture plane at distance $z = 0$, $U(x, y, z)$ is the distribution across the detector plane, $F_{f_x f_y}$ and $F_{f_x f_y}^{-1}$ are the two-dimensional Fourier transform and its inverse transform, and f_x and f_y are the spatial frequency variables.

After obtaining the complex field $U(x, y, z)$, the intensity at the detector plane is calculated as the

modulus squared,

$$I(x, y, z) = |U(x, y, z)|^2. \quad (4)$$

The intensity pattern is detected by the photodetector, which converts the optical power to photocurrent. When using a quadrant photodetector, the photocurrent generated by each element is related to the integration of the intensity pattern on that element,

$$I_i = \int_{A=i} R_\lambda I(x, y) dA, \quad (5)$$

where I_i is the photocurrent generated by the i th element, R_λ is the responsivity or photosensitivity of the photodiode, measuring the effectiveness of the conversion of optical power into photocurrent, expressed in units *amps/watt*.

Figure 7 shows the simulated power distribution of the original beam and the power distribution on the photodetector after the beam passes the two knife-edges (MATLAB simulation). The knife-edges reshape the beam through diffraction.

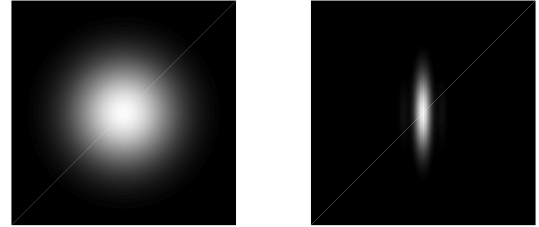


FIGURE 7. The left figure simulates a Gaussian laser with a 2.6 mm beam diameter, and the right figure simulates the laser beam after passing a 0.2 mm-width slit and being received by a detector 40 mm away.

As the relative positions of the knife-edge and detector change, the quadrant photodetector generates varied photocurrents. Figure 8 shows the relationship between straightness error and photocurrents. The middle linear part is an active area, where differential processing (1) can be applied to determine the one-dimensional straightness error.

EXPERIMENTS

Experiments were performed to compare the measurement accuracy and resolution with and without the knife-edge, and explore whether the setup with knife-edges is superior to that without knife-edges. Figure 9 shows the setup of the measurement system with knife-edges. The green frame holds the two razor blades

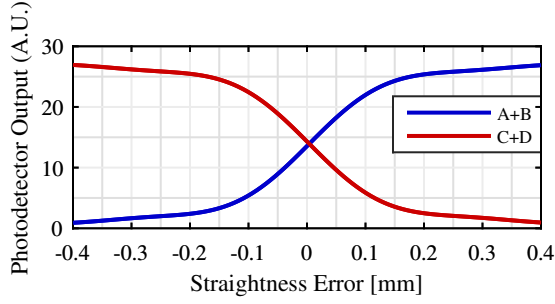


FIGURE 8. The photocurrents generated by the left two elements and right two elements change in opposite directions when the aperture and detector have a relative lateral displacement.

as two inward-facing knife-edges. A quadrant photodetector is placed on a piezo-stage, which produces a lateral displacement imitating the straightness error. The alternative setup removes the knife-edge, so that the beam is directly incident on the quadrant photodetector.

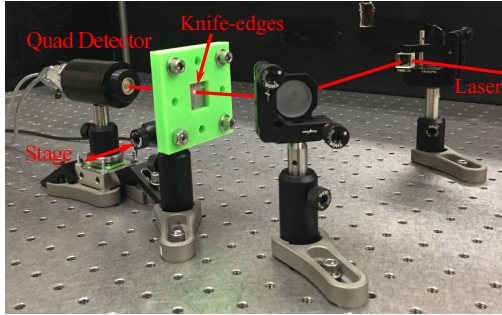


FIGURE 9. The setup of the 1D straightness error measurement system with two inward-facing knife-edges.

As previously mentioned, the scaling factor k_x in (1) is not a constant value because the relationship between the left and right terms is nonlinear. Thus, before using this system to measure straightness error, it must be carefully calibrated. There is an embedded capacitive sensor in the piezo-stage, whose output can be used as the reference. We drive the piezo-stage to sweep in a sawtooth path within $\pm 40 \mu\text{m}$, and then curve fit the photodetector's readout to the reference. In this way, the scaling factor k_x can be determined. Figure 10 shows the relationship between the knife-edge system readout and the reference. The slope of the curve is the scaling factor k_x .

After obtaining the scaling factor k_x as a function of knife-edge system readout, the measurement result can be derived. We test both setups

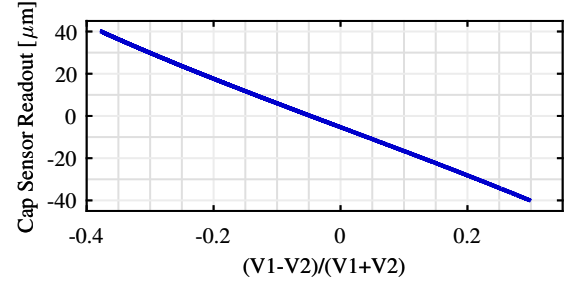


FIGURE 10. The proposed measurement system readout with respect to the embedded capacitive sensor readout. The stage is driven to linearly move within $\pm 40 \mu\text{m}$.

with and without knife-edges. Figure 11 shows the comparison. From the figure, we can see the setup with knife-edges can achieve a 10X improvement in sensitivity and noise than that without knife-edges. To generate the figure, the piezo-stage was driven in a sawtooth path within $\pm 40 \mu\text{m}$.

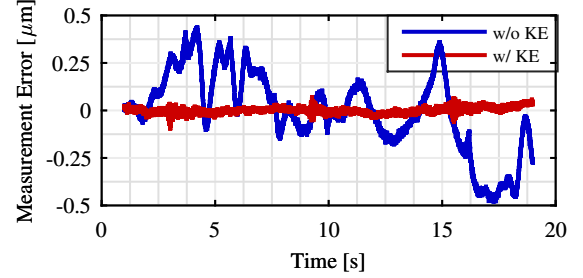


FIGURE 11. The red curve is from a measurement using knife-edges, whose measurement error is within $\pm 40 \text{ nm}$. The blue curve is from a measurement setup without knife-edges, whose measurement error is within $\pm 400 \text{ nm}$.

The knife-edges block a portion of the beam and narrow the spot size, which increases the measurement sensitivity, but decreases the measurement range. The accuracy of this method relies on the power stabilization of the laser source. Experiments have observed small intensity drifts of the incident beam. Therefore, a robust system will need to compensate the drift through better intensity stabilization, laser power monitoring, or AC modulation of the incoming light.

CONCLUSION

We have presented a simple and compact configuration to measure the straightness error of a linear stage which uses inward-facing knife-edges, a single laser beam, and a single quadrant detector. Currently, we have tested its performance to measure one-dimensional

straightness error, and it can achieve an accuracy of ± 40 nm. It is also feasible to extend this sensor to a two-dimensional straightness error measurement setup.

FUTURE WORK

It has been shown that the inward-facing knife-edge configuration is feasible to measure a one-dimensional straightness error with a ± 40 nm noise level. In the future, we will extend this configuration to a two-dimensional straightness measurement (Figure 4). To minimize the effect of laser power instability, we plan to monitor the laser power during the measurement, and compensate the measured signal in processing. Lastly, we will investigate the theory of the aperture design and how it affects range versus sensitivity tradeoffs.

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