A Novel Reversal Method to Estimate Horizontal Straightness/Yaw Error of a Linear Axis

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Abstract

The pose of a linear axis on machine tool can be modeled using the six geometric errors. The laser interferometer is used to estimate the geometric errors but this system has the limitation for accurate measurement due to high standard uncertainty and absence of identical reference coordinate. To overcome this limitation, reversal method is used to estimate geometric error. But conventional reversal method is designed without analyzing the standard uncertainty of estimated geometric error and also this method does not analyze the effect of set-up errors, obviously. For this reason, a novel reversal method is proposed to estimate the horizontal straightness error, δ_{yx} and yaw error, ε_{zx} of a linear axis simultaneously using the two capacitive sensors and one measurement target. To accurately estimate the geometric errors, the effect of standard uncertainty of sensors is minimized by determination of reference coordinate position. The set-up error of sensors and measurement target are eliminated by mathematical modeling.

1 The measurement principle of proposed method

The measurement configuration consists of the two capacitive sensors and one measurement target, as shown in Figure 1. The measurement data of capacitive sensors is m_{ij}. First subscript represents measurement order and second subscript represents respective capacitive sensor. In this case, the estimated geometric error has the set-up errors, which are error due to misalignment of the sensor $\triangle y_i$ (i=1, ···,4) and the relative pose between a linear axis and measurement target θ_i (i=1,2).

$$\delta_{yx} = \frac{1}{4}\left\{\left(m_{21}-m_{11}\right)+\left(m_{21}-m_{11}\right)\right\}+\frac{d_x\left(\tan\theta_1+\tan\theta_2\right)}{2}-\frac{1}{4}\left(\sum_{i=1}^{4}\Delta y_i+\sum_{i=1}^{2}m_{2i}\left(0\right)-\sum_{i=1}^{2}m_{1i}\left(0\right)\right)$$

$$\varepsilon_{zx} = \frac{1}{2l}\left\{\left(m_{11}-m_{21}\right)-\left(m_{12}-m_{22}\right)\right\}+\frac{\left(\tan\theta_1+\tan\theta_2\right)}{2}-\frac{1}{2l}\left(\sum_{i=1}^{4}\left(-1\right)^i\Delta y_i+\sum_{i=1}^{2}\left(-1\right)^i m_{2i}\left(0\right)-\sum_{i=1}^{2}\left(-1\right)^i m_{1i}\left(0\right)\right)$$

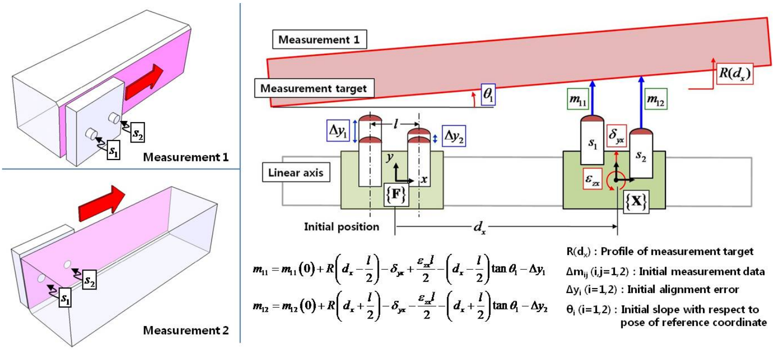


Figure 1: Measurement principle of novel reversal method

Here the misalignment of sensors $\triangle y_i$ (i=1, ···,4) can be defined as the relative distance between the ideal position and the actual position of the sensor at the initial setup. Similarly error of measurement target θ_i (i=1,2) is defined as the angle between the measurement target and measured linear axis. In order to separate the set-up errors, these errors are modeled as constant. Then geometric errors are modeled as the polynomial equation, estimated by the least square method. Through this mathematical approach geometric error can be estimated more accurately.

2 Standard uncertainty of capacitive sensor measurement data

The standard uncertainty of measurement data, u_{DEVICE} consists of uncertainty of both measurement target and sensor. Effect of standard uncertainty by the environment (temperature, humidity, pressure) is not considered, since it is relatively smaller than above mentioned.

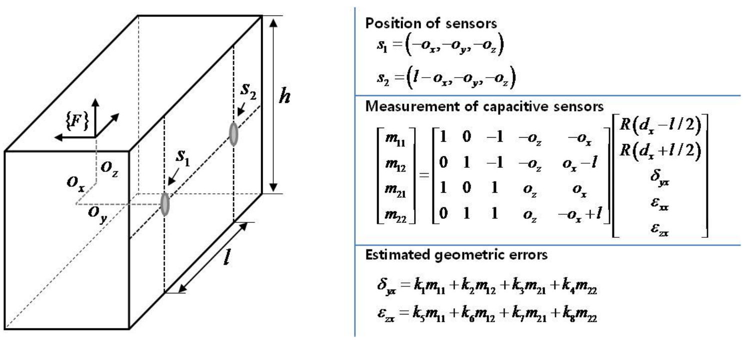


Figure 2: Reference coordinate and sensors

The uncertainty of measurement target is governed by uncertainty of measurement target flatness, but it can be eliminated based on the reversal method objectives. Standard uncertainty of sensor is determined by the uncertainty of linearity and resolution, mainly. These factors are assumed as uniform distribution [1].

$$u_{DEVICE} = \sqrt{\left(u_{MIRROR}\right)^2 + \left(u_{SENSOR}\right)^2} \quad u_{SENSOR} = \frac{1}{2\sqrt{3}}\sqrt{\left(s^{+}_{LINEARITY} - s^{-}_{LINEARITY}\right)^2 + \left(m_{RESOLUTION}\right)^2}$$

3 The optimization design of reference coordinate position

As shown in above equation, the standard uncertainty, u_{DEVICE} would adversely affect the standard uncertainty of estimated geometric errors, $u(\delta_{xy})$ and $u(\varepsilon_{xy})$. These standard uncertainties are affected by the relative position between reference coordinate and sensors because of Abbe's error. To minimize this effect, the position of reference coordinate is modeled using offset (o_x ,o_y ,o_z), as shown in Figure 2. Using the proposed algorithm, the geometric error is defined using the constant k_i (i=1,···,8), which is consist of offset and parameter *d*. For minimization of standard uncertainty of estimated geometric error, offset o_x is calculated using the partial differential equation.

4 Experiment result

By using proposed method, the horizontal straightness error and yaw error are estimated along the X-axis in a three axis high precision machine tool. At the experiment, two capacitive sensors (4810 module, 2805 probe, ADE Technology) and stainless steel as measurement target are used. And the estimated geometric errors are compared with the measured data using the laser interferometer (XL80, Renishaw).

Standard uncertainty of estimated geometric errors

$$u(\delta_{yx}) = \sqrt{k_1^2 + k_2^2 + k_3^2 + k_4^2}\,u_{DEVICE}$$

$$u(\varepsilon_{zx}) = \sqrt{k_5^2 + k_6^2 + k_7^2 + k_8^2}\,u_{DEVICE}$$

Differential equation

$$\frac{\partial}{\partial o_x}\left(u^2\left(\delta_{yx}\right)\right) = 0$$

$$o_x = \frac{l}{2}$$

Calculation of standard uncertainty

$$u(\delta_{yx}) = \frac{1}{2}u_{DEVICE}$$

$$u(\varepsilon_{zx}) = \frac{1}{l}u_{DEVICE}$$

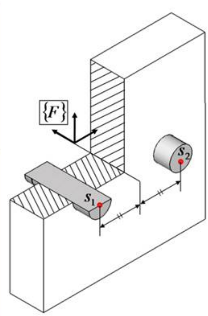
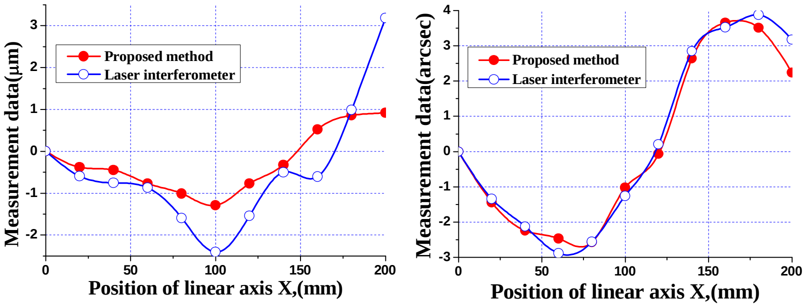


Figure 3: Proposed positions of reference coordinate and sensors



(a) Horizontal straightness error, δ_{yx} (b) yaw error, ε_{zx}

Figure 4: Comparison of estimated geometric errors

The two measured geometric errors between proposed method and laser interferometer are presented as shown in Figure 4. As expected, estimated horizontal straightness error, δ_{yx} using proposed method is more reasonable in the aspect of smoothness when compared with the result of laser interferometer.

5 Conclusions

In this paper, a novel reversal method is proposed to estimate the horizontal straightness error and yaw error in a linear axis and designed to minimize the effect of standard uncertainty. The conclusions are summarized as follows:

1. Reference coordinate position is optimized to minimize the effect of standard uncertainty at estimated geomeric errors.
2. Set-up errors are eliminated through mathmatical modeling.
3. The proposed method is validated on high precision machine tool.

Acknowledgements

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References:

[1] ISO/TR 230-9, "Test Code for Machine Tool-Part 9: Estimation of Measurement Uncertainty for Machine Tool Tests according to Series ISO 230, Basic Equation," ISO, 2005.