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High accurate squareness measurement squareness method for ultra-precision machine based on error separation

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ABSTRACT

Traditional measurement methods of squareness for ultra-precision motion stage have many limitations, especially the errors caused by the inaccuracy of standard specimens. On the basis of error separation, this paper presents a novel method to measure squareness with an optical square brick. The angles between the guideways and the four lines of brick section are measured based on the fact that sum of interior angle of a quadrilateral is 2π, and the squareness is obtained. A squareness measurement experiment was performed on a profilometer with a modified optical square brick. Experimental results show that the squareness accuracy between X and Y axes is not influenced by the accuracy of brick, and the measurement repeatability reaches 0.22 arcsec. Finally, a verification experiment to the proposed method was carried out with a high accurate standard specimen, and the error between the two methods is 1.06 arcsec. According to the error results and simulation analysis of the measurement system, the measurement error based on error separation is 0.06 arcsec. The proposed method is able to achieve a very high accurate squareness measurement with auxiliary components of normal accuracy, and can be applied to measure the accuracy class of sub-arcsec squareness.

1. Introduction

Squareness is the very susceptible factor to the profilometer, which accounts for more than 30% of all geometric errors, especially in ultra-precision motion stages [1]. Geometric error of a motion axis of general-precision motion stage and can be measured by laser interferometers. However, interferometers cannot be used to measure squareness of ultra-precision profilometers, such as Renishwa XL-80 interferometer. Therefore, other methods for squareness measurement are demanded.

The commonly used methods for squareness measurement can be divided into three categories. The first category includes parametric modeling methods, such as the integrated geometric error modeling method [2] and the product of exponential modeling method [3]. These models can predict the geometric errors on the condition that the basic geometric errors are measured and identified. Basic geometric errors can be acquired by 9-line method [4], 12-line method and step-diagonal measurement method [5] with an interferometer, but the limitations of the laser diagonal measurements are obvious [6]. Generally, the measuring instruments are developed at home and abroad, such as the 3D probe-ball [7,8], double-ball-bar and R-test [9,10]. Given a measurement point, the geometric error measurement methods make use of matrices to transform an array of every degree of freedom (DOF) into array at the point of interest. In this case, the accuracy class of estimating the errors greatly depends on the accuracy class of the kinematic model as well as the class of each DOF error. Because the first category belongs to comprehensive error measurement methods, this measurement is performed with special instruments, and the key factors are calibration of the instruments and error modeling. In addition, squareness measurement accuracy by the first category is lower than the following two categories.

The second category is a method uses standard specimen. This category is a very common, accurate and convenient method in markets currently. However, this method becomes expensive and inaccurate when measurement range is large because a specimen that exceeds commercially available dimensions must be custom-made and the cost is relevant to the required accuracy class. Principle of this method is given by the *GB/T 17421.1-1998 General Test Machine* [11]. Jie [12] and Wang [13] measured the squareness

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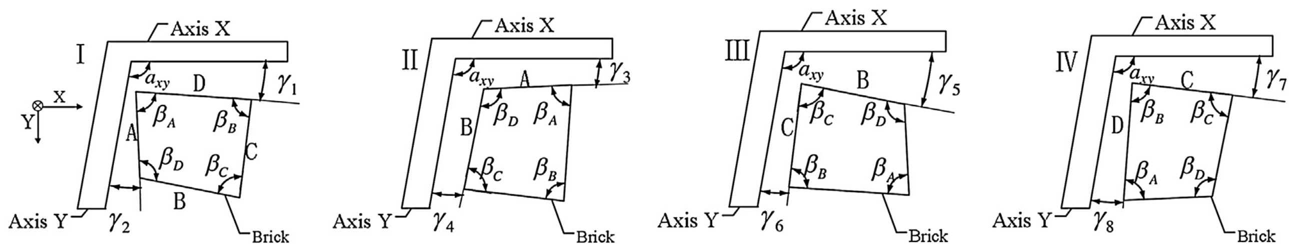

Fig. 1. Four positions of the brick.

of guideways with L-square and dial gauges. Additionally, squareness of CMM (Coordinate Measuring Machine) is measured with an interferometer and a pentagonal prism [14].

The third category is based on error separation. The basic idea and benefit of this method is that low-quality specimens can be used in this measurement because errors are separated from the error of interest. Therefore, error-separation method is the very cost-effective and large-range measurement method. In addition, if the procedure is executed well, the achievable accuracy can reach the class of system repeatability. Error-separation method is established for measuring the straightness of guideways, but is rarely used for measuring the squareness. This method is also known as reversal method or error separation technique in the literature. Hocken R J and Borchardt B R [15] used this method to measure the squareness, Lieberman [16] first introduced the concept of rotating a specimen in an earlier e-beam lithography system calibration, Ruijl [17] applied an error separation technique for the straightness calibration of a mirror, and Hume's angular measurement method [18] is used for measuring squareness, Evans [19] introduced several accurate feature measurements without reference to an externally calibrated artifact. An artifact reversal method usually belongs to a part of self-calibration. In this study, Ruijil and Evans' methods are improved and applied for measuring the squareness between the X and Y axis of the profilometer. Error analysis and simulation are used to verify the accuracy and validity of the method.

In the 2008 conference of "Collège e International pour la Recherché Productique" (CIRP), measurement effective of error was considered as the important study fields within the foreseeable 10 years. Therefore, the methods of improving the measurement accuracy have great practical significance to ultra-precision motion stage.

2. Principle

The basic idea of error separation in this paper is that the sum of interior angle of a quadrilateral is 2π, which is applied to squareness measurement of guidways. No matter what value of every interior angle is, the suqareness of guidways can be obtained accurately. In order to obtain the squareness between X and Y axes, an optical brick with four faces is used. Specific geometric principle is shown in Fig. 1. In position I, angle a_{xy} is the squareness between X and Y axes. Interior angles β_A, γ_1 and γ_2 satisfy the following relationship

$$\text{PositionI}: \beta_A + \gamma_1 + \gamma_2 = a_{xy} \tag{1}$$

where β_A is bounded by the peripheral face D and face A of the brick, γ_1 is an angle bounded by axis X and face D, γ_2 is an angle bounded by axis Y and face A.

After continuously rotating the brick at an angle of approximately 90° along Z axis, three positions II, III and IV are acquired, and the following equations can be obtained

$$\text{PositionII}: \beta_D + \gamma_3 + \gamma_4 = a_{xy} \tag{2}$$

$$\text{PositionIII}: \beta_C + \gamma_5 + \gamma_6 = a_{xy} \tag{3}$$

$$\text{PositionIV}: \beta_B + \gamma_7 + \gamma_8 = a_{xy} \tag{4}$$

where β_D is bounded by peripheral face A and face B of the brick, γ_3 is the angle bounded by axis X and face A, γ_4 is an angle bounded by axis Y and face B. β_C is bounded by the peripheral face B and face C of the brick, γ_5 is an angle bounded by axis X and face B, γ_6 is an angle bounded by axis Y and face C. β_B is bounded by the peripheral face C and face D, γ_7 is an angle bounded by axis X and face C, γ_4 is the angle bounded by axis Y and face D.

The angles of the brick meet the following requirement:

$$\beta_A + \beta_B + \beta_C + \beta_D = 2\pi \tag{5}$$

Summation of (1) to (4) and substitution of (5) yields:

$$a_{xy} = \frac{2\pi + \sum_{k=1}^{8} \gamma_k}{4} \tag{6}$$

Eq. (6) shows that angles γ_i (i = 1, 2, 3, 4, 5, 6, 7, 8) between faces and guideways are measured before getting the squareness a_{xy} of X and Y axes. In order to obtain γ_i (i = 1, 2, 3, 4, 5, 6, 7, 8), displacement transducers and corresponding displacement jig transducers are used. When the brick is located in position I, an actual measurement model for measuring γ_1 and γ_2 is built and shown in Fig. 2. Brick angle β_A is bounded by the peripheral face D and face A. Accordingly, γ_1 is determined by measuring the brick face D. Specifically, the brick face D at any point satisfies the following equation:

$$e_D(t_i) + p_1 t_i + \Delta_1 = m_1(t_i) - e_Y(t_i) \tag{7}$$

where, the deviation of the straightness of the brick face D is denoted as $e_D(t_i)$; $e_Y(t_i)$ is the deviation of the flatness; $m_1(t_i)$ measured by the displacement transducer is the distance between face D and the guideway; t_i is a step distance value, which is an independent variable in the whole measurement procedure; the wedge between the reference line and the reference plane is defined by parameters p_1 and Δ_1. Angle γ_1 is determined by p_1 which is calculated based on the following equation:

$$\gamma_1 = \tan^{-1}(p_1) \tag{8}$$

Definition of the reference lines and planes leads to be less susceptible to random measurement errors by a least squares definition [20]. Solution of this least squares definition can be obtained from a linear operation according to a simple matrix equation. A useful least squares definition is as follows:

$$\sum_{i=-n}^{n} t_i e_{j(j=A,B,C,D)}(t_i) = \sum_{i=-n}^{n} e_{j(j=A,B,C,D)}(t_i) = 0 \tag{9}$$

Therefore, all the points along the reference line of face D which is measured at Δt can be expressed using a matrix as:

$$\mathbf{e_D} + \mathbf{P_1 k_1} = \mathbf{m_1} - \mathbf{e_Y} \tag{10}$$

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