Precision Engineering 41 (2015) 86–95

Contents lists available at ScienceDirect

Precision Engineering

journal homepage: www.elsevier.com/locate/precision

Stage error calibration for coordinates measuring machines based on self-calibration algorithm

Daodang Wang[a,b], Xixi Chen[a], Yangbo Xu[a], Tiantai Guo[a,*], Ming Kong[a], Jun Zhao[a], Baowu Zhang[a], Baohua Zhu[c,d,e]

[a] College of Metrology and Measurement Engineering, China Jiliang University, Hangzhou 310018, China
[b] State Key Laboratory of Precision Measuring Technology and Instrumentation, Tianjing University, Tianjing 300072, China
[c] Guilin University of Electronic Technology, Guilin 541004, China
[d] Guangxi Colleges and Universities Key Laboratory of Optoelectronic Information Processing, Guilin 541004, China
[e] Guangxi Key Laboratory of Automatic Detecting Technology and Instruments (Guilin University of Electronic Technology), Guilin 541004, China

ARTICLE INFO

Article history:
Received 25 June 2014
Received in revised form 5 January 2015
Accepted 27 February 2015
Available online 7 March 2015

Keywords:
Self-calibration
Coordinate measuring machines
Stage error
Grid plate
Least squares method

ABSTRACT

The stage error of coordinate measuring machines (CMM) can significantly influence the measurement results, and it places ultra-high requirement on the measurement and calibration tools. A calibration technique based on self-calibration algorithm is presented to calibrate the two-dimensional stage error of CMM, and it can be carried out with a grid plate of the accuracy no higher than test stage. With the proposed self-calibration algorithm based on least squares method, the measurements at various position combinations of rotation and translation are carried out to separate the stage error from measurement results. Both the accuracy and feasibility of the proposed calibration method have been demonstrated by computer simulation and experiments, and the measurement accuracy RMS better than 1 μm is achieved. The proposed calibration method has a good anti-noise ability and provides a feasible way to lower the accuracy requirement on standard parts. It is of great practicality for high-accuracy calibration of the stage error of CMM and manufacturing machines in the order of submicron.

1. Introduction

With the development of ultra-precise machining technique, coordinate measuring machines (CMM) have become a powerful measurement tool in the field of high-accuracy measurement. However, there is generally a deviation of measured stage position from the ideal position in Cartesian coordinates of CMM, which is mainly introduced by the errors including the systematic measurement error and random noise. The systematic measurement error, that is stage error, could introduce significant error in the measurement results [1,2]. Thus, it is necessary to measure and compensate the stage error to realize the high-accuracy measurement with CMM. Due to the limitation of practical problems such as technical and economic difficulties in the manufacture of precise test artifacts, the traditional CMM calibration method with an absolute standard artifact (with higher accuracy than the stage to be calibrated) is limited in application [3–5], especially not feasible in the case of high-accuracy measurement better than sub-microns. Though the high-accuracy method based with laser interferometer [2,6,7] has been widely applied in stage error calibration, it is high-cost and complex in the system.

The self-calibration method, which realizes the calibration of stage error with a grid plate of the accuracy no higher than test stage, has been proposed to overcome the accuracy limitation of standard parts and achieve the required accuracy. It is generally realized by measuring the grid plate at different positions on test stage, and the stage error map could be reconstructed by comparing different measurement positions, in which the unknown marker positioning errors cancel. Various self-calibration algorithms have been proposed to separate stage error from the measured systematic error [8–12], and they are mostly based on discrete Fourier Transform (FT) method. The self-calibration algorithms have been applied in the motion accuracy testing of two-dimensional stages [13–23], such as electron beam lithography. However, the existing algorithms are poor in noise suppression (the noise amplification factor is generally greater than 1) [9], and are difficult to be applied in practical measurement.

* Corresponding author at: College of Metrology and Measurement Engineering, China Jiliang University, Hangzhou 310018, China. Tel.: +86 571 86914563.
E-mail address: teampaper209@cjlu.edu.cn (T. Guo).

http://dx.doi.org/10.1016/j.precisioneng.2015.02.002
0141-6359/

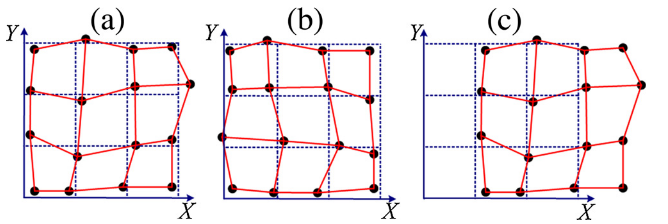

Fig. 1. Three ideal coordinate systems defined in self-calibration algorithm.

In this paper, a self-calibration algorithm based on least squares method is presented to calibrate the two-dimensional stage error of CMM. A grid plate with relatively lower accuracy than test stage, on which the markers are uniformly distributed in square array with the same spacing both in horizontal and vertical directions, is used as additional tool. The proposed method provides a feasible way to separate and calibrate the stage error of CMM, as well as those of ultra-precise stages, lens distortion and printing field distortion, etc. Section 2 presents the principle of self-calibration algorithm; Sections 3 and 4 show computer simulation and experimental results to demonstrate the feasibility and accuracy of the proposed calibration method, in which the effects of various factors such as position number, position combinations and deviations of rotation angle and translation distance are discussed in detail; and Section 5 draws some concluding remarks.

2. Principle

The calibration of stage error is realized with self-calibration algorithm, in which the measurement error is mainly introduced by the grid plate error, stage error and random noise. Considering the fact that the grid plate error and stage error are dominant in magnitude, the main goal in the self-calibration is the separation of grid plate error and stage error, by which the calibration of stage error can be realized.

2.1. Principle of self-calibration algorithm

According to the characteristics of systematic error in CMM, the following assumptions about stage positioning error are made: (1) high repeatability and (2) low frequency (which means the positioning error remain unchanged in a small range). Fig. 1 shows the ideal coordinate systems established for error analysis, including the stage coordinate system $X_AO_AY_A$, grid plate coordinate system $X_GO_GY_G$ and defined absolute coordinate system XOY, where (V_A, W_A) and (V_G, W_G) represent the deviations of the origins on stage and grid plate coordinate systems from that on defined absolute system XOY, respectively, θ_A and θ_G are the corresponding tilt angles. Thus, the systematic error of the markers on grid plate can be written as

$$\begin{bmatrix} Q_x \\ Q_y \end{bmatrix} = \begin{bmatrix} M_x \\ M_y \end{bmatrix} - \begin{bmatrix} N_x \\ N_y \end{bmatrix} = \begin{bmatrix} A_x \\ A_y \end{bmatrix} + \begin{bmatrix} G_x \\ G_y \end{bmatrix} + \begin{bmatrix} -N_y \cdot \theta \\ N_x \cdot \theta \end{bmatrix} + \begin{bmatrix} V \\ W \end{bmatrix}, \quad (1)$$

where $\begin{bmatrix} V \\ W \end{bmatrix} = \begin{bmatrix} V_A + V_G \\ W_A + W_G \end{bmatrix}$ and $\theta = \theta_A + \theta_G$, (M_x, M_y) and (N_x, N_y) refer to the measured and nominal coordinate values of the markers on grid plate, respectively, (A_x, A_y) and (G_x, G_y) represent the corresponding stage error and grid plate error.

In addition, five assumptions [13] are made in the definition of three ideal coordinate systems, those are: (1) no translation components in stage error; (2) no tilt components in stage error; (3) no scaling components in stage error; (4) no translation components in grid plate error; (5) no tilt components in grid plate error, which can be written as

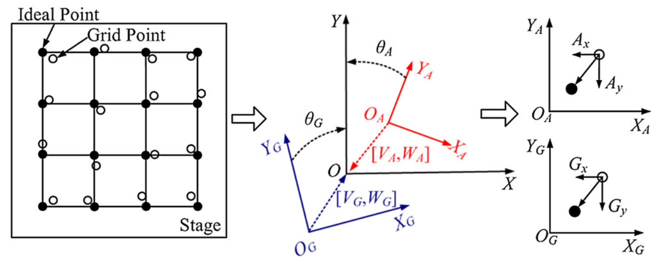

Fig. 2. Various positions in 3-position self-calibration, (a) original position, (b) after 90° counterclockwise rotation and (c) after one-grid translation.

$$\begin{cases} \sum A_x = \sum A_y = 0, \\ \dfrac{\partial}{\partial \theta} \sum [(A_x - \theta \cdot N_y)^2 + (A_y + \theta \cdot N_x)^2] = \sum (A_x \cdot N_y - A_y \cdot N_x) = 0, \\ \dfrac{\partial}{\partial M} \sum [(A_x - M \cdot N_x)^2 + (A_y - M \cdot N_y)^2] = \sum (A_x \cdot N_x + A_y \cdot N_y) = 0, \\ \sum G_x = \sum G_y = 0, \\ \dfrac{\partial}{\partial \theta} \sum [(G_x - \theta \cdot N_y)^2 + (G_y + \theta \cdot N_x)^2] = \sum (G_x \cdot N_y - G_y \cdot N_x) = 0, \end{cases} \quad (2)$$

where M represents magnification. According to the five assumptions mentioned above and the measurement result of each marker on grid plate at the original measurement position, the measurement error of the markers can be written as

$$\begin{bmatrix} Q_{1x} \\ Q_{1y} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} I & 0 & I & 0 & E & 0 & -[N_y]^T \\ 0 & I & 0 & I & 0 & E & [N_x]^T \\ E^T & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & E^T & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & E^T & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & E^T & 0 & 0 & 0 \\ [N_y] & -[N_x] & 0 & 0 & 0 & 0 & 0 \\ [N_x] & [N_y] & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & [N_y] & -[N_x] & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} A_x \\ A_y \\ G_x \\ G_y \\ V_1 \\ W_1 \\ \theta_1 \end{bmatrix}, \quad (3)$$

where (Q_{1x}, Q_{1y}) is the measurement error of the markers on grid plate, $[\cdot]^T$ represents a matrix transpose, I and E are the identity matrix and the column vector with all the elements being 1, respectively.

Assume that n^2 denotes the number of the points on grid plate, the corresponding numbers of unknowns and equations in Eq. (3) are $4n^2+3$ and $2n^2+7$, respectively, and there are infinite solutions in the case of equation number less than that of unknowns. The numbers of unknowns and equations would be $4n^2+9$ and $6n^2-2n+7$ when the measurements are carried out in three various positions (as shown in Fig. 2), and the single solution to the equations can be determined with the least squares method. With the increase of measurement position number, the solution accuracy with least squares method can be further promoted. Considering the fact that the increase of measurement position number could also reduce the efficiency in calibration, the number of measurement positions ranging from 3 to 8 is chosen for the study of self-calibration algorithm in this paper.

2.2. Self-calibration algorithm with eight positions

In the case of 8-position self-calibration method, the measurements at 8 various positions of grid plate are carried out to realize