Precision Engineering 38 (2014) 969–978

Contents lists available at ScienceDirect

Precision Engineering

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

Technical note

Exact reconstruction method for on-machine measurement of profile

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ARTICLE INFO

Article history:
Received 12 January 2014
Received in revised form 20 May 2014
Accepted 31 May 2014
Available online 11 June 2014

Keywords:
Interferometry
Scanning
Error separation
On-machine measurement

ABSTRACT

We present a new reconstruction method for measuring profile of large, ultraprecise absolute optical surfaces with a compact interferometer. The profile of workpiece can be reconstructed exactly with high lateral resolution and large non-equidistant scanning step. Both systematic errors of the interferometer and height offsets of the scanning stage can be eliminated. Additional angular measurement can be used to measure pitching angles of the scanning stage. The exact reconstruction method is verified by computer simulation and on-machine measurement experiment.

1. Introduction

The highly accurate measurement of workpiece's topography is an important task in many fields of industry. Interferometry with high accuracy is a widely used method for measuring optical flats and spherical surfaces. And when measuring an aspheric surface, accessories such as null lenses and computer-generated holograms (CGH) are applied. However, as for freeform surface or the surface departed largely from the fitting spherical surface, this kind of method does not work. Stitching interferometry which combining the advantages of a high resolution and a large field of view can be applied in such cases or large flats. However, a disadvantage of stitching methods in general is that the accumulation of small systematic interferometer errors of a sub-aperture measurement. Due to this error propagation the measurement uncertainty of large scale features may increase. The systematic interferometer errors which resulting in a parabolic topography error can, in principle, not be eliminated by means of the stitching method even using modern computers [1].

Scanning measurement besides sub-aperture stitching interferometry can measure large size and complicated surfaces with high lateral resolution, but the motion errors of stage include height offsets and pitch will affect the measurement results. In order to eliminate the motion errors of stage, multi-sensor method with errors separation is employed.

Ultra precision straightness measurement generally uses multiply non-contact probes to separate straightness of workpiece from motion errors of stage [2–10]. When using multi-probe, such as capacitance probes, for straightness measurement, probe spacing cannot be too small due to the limitations of the physical dimensions of the probes. Reconstruction distance, equal to scanning step, is usually smaller than the probe spacing in order to get high lateral resolution. There are many methods for reconstruction of straightness profile with reconstruction distance smaller than the probe spacing, such as combined method [3] and mix method [4]. However, the difference between the zero-values of each probe introduces a parabolic error in the measurement value. It is similar to systematic errors in interferometry. Many studies have addressed the problem of evaluating zero-adjustment error [5–8], but it is still difficult to calculate it directly. In order to reconstruct the straightness profile in each sampling point exactly, two exact reconstruction methods including frequency-domain method and time-domain method have been developed previously [9,10]. Both these methods, which can calculate the relative zero-adjustment error exactly instead of zero-adjustment error, employ the large non-equidistant probe spacing and small equidistant scanning step. These algorithms can also be used in lateral shearing interferometer [11].

Schulz et al. of PTB have proposed a Traceable Multi Sensor (TMS) technique to use a compact interferometer as multi-sensor system for form measurement [12]. There are many sensors for measuring when each pixel of interferometer (such as μphase1000 interferometer with 1020 × 1024 pixels) is regarded as a displacement sensor, and the pixel distance, i.e. the sensor distance is very small (about 2 μm when using Φ2 mm transmission flat). The previous methods of straightness reconstruction in [2–10] cannot be employed directly in this case, as they all deal with large probe spacing and small reconstruction distance. As we know,

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http://dx.doi.org/10.1016/j.precisioneng.2014.05.008
0141-6359/

straightness profile can be reconstructed exactly by sequential two-point (STP) method with only two sensors when scanning step is equal to sensor distance and pitching angle of stage is detected [13]. However, this kind of method will bring following disadvantages in the case of compact interferometer for form measurement: Firstly, the signal-to-noise ratio is low when sensor distance is too small [14], secondly, quite a number of scanning positions will lead to a long measuring time when using interferometer for measuring, and thirdly, straightness profile is reconstructed by only two pixels (sensors), the information of many other sensors is not used. Wiegmann et al. have developed a method to reconstruct straightness profiles by combination of sub-profile measurements and used non-equidistant sensor spacing to improve the lateral resolution [15]. The scanning step in their method must be less than or equal to the reconstruction distance, which will result in a long measuring and computing time. A new method with high lateral resolution and large scanning step for reconstructing straightness profile exactly is developed in this paper. Both scanning stage error and systemic interferometer errors can be eliminated.

2. Measurement principles

Straightness profile can be reconstructed exactly up to an unknown straight line by STP method, i.e. the translation and tilt of straightness profile cannot be determined. Interferometer have many pixels, each can be used as a distance sensor. We can choose any two distance sensors to reconstruct straightness profile by STP method. Large sensor spacing is desirable in order to obtain high signal-to-noise ratio. A group of two-sensors with the same sensor spacing can be used to reconstruct a group of curves of straightness profile. The lateral resolution of each curve is now equal to the chosen large sensor spacing. If we combine these curves into one curve when lateral spacing between them is equal to the reconstruction distance, the straightness profile of all reconstruction points with high lateral resolution can be obtained. The relative position, which includes both vertical translation and tilt, between these curves should be determined before combining. So, the key problem is how to determine these relative positions.

The developed method is to choose another group of two-sensors with different sensor spacing, which can also be used to reconstruct another group of curves of straightness profile. The subsequent sensor spacing should be chosen appropriately so as to obtain the same sampling positions as the previous group of sensors. At the same sampling positions of two groups, the height of profile should be the same too. If a curve of the first group (previous group) has the same two sampling positions as one of the second group (subsequent group), the relative translation and tilt between them can be calculated. And then, these two curves can be combined into one curve. So, all curves of first group can be combined into one curve after the relative translation and tilt of each curve with the same one curve of second group are determined. Now, straightness profile can be reconstructed exactly at all sampling points with high lateral resolution and large scanning step.

Sometimes, not every curve of first group can be determined by only one curve of second group because of insufficient length of workpiece. We can determine firstly the relative position between each curve of first group with more than one curves of second group. Then the relative position of these curves of second group can be determined after the relative position between them and one curve of first group determined. Finally, the relative position of each curve of first group can be determined. This case is not discussed here because it is seldom and complicated.

3. Exact reconstruction algorithms

All sampling points are fall into two groups according to sensor spacing. The curves in each group are reconstructed by STP method firstly. And then, we combine the curves of the first group into one curve, which is the exact straightness profile of workpiece. Reconstructed procedure is as followings.

(1) As shown in Fig. 1, assume the reconstruction distance is δ. Sensor spacing and scanning step of the first group is chosen as $d_1 = s_1 = \vartheta_1\delta$ and the second is $d_2 = s_2 = \vartheta_2\delta$ ($s_1 < s_2$), where, d_1 and d_2 are scanning step, s_1 and s_2 are sensor spacing, and ϑ_1 and ϑ_2 are coprime numbers. So, the scanning step is non-equidistant when a straightness profile is measured by scanning once time. The reconstruction length of workpiece is p, and the total number of reconstruction points is N, $N = p/\delta$.

(2) Assume that the surface is described by function $f(x)$. To simplify expression, we let

$$f(m) = f(x_m), \quad m = 0, \ldots, N-1$$

Given the systemic error of each sensor is e_k ($k = 1, 2, \ldots, k$ is the number of sensor), pitching angle errors of both groups are $\theta_{1,i}$ ($i = 1, 2, \ldots$) and $\theta_{2,j}$ ($j = 1, 2, \ldots$), respectively. When the sensor spacing is s_1, the measurement value $p_{a,j}$ of the front distance sensor j in the stage position i is given by

$$p_{a,j} = f(j + i \cdot \vartheta_1) + e_{1,j} + c_{1,i} \tag{1}$$

The measurement value of back distance sensor is

$$p_{b,j} = f(j + (i+1) \cdot \vartheta_1) + e_{1,j+\vartheta_1} + c_{1,i} + s_1 \cdot \tan(\theta_{1,i}) \tag{2}$$

where $i = 0, \ldots, [N/\vartheta_1]$, $j = 0, \ldots, \vartheta_1 - 1$, $e_{1,j}$ is the systemic error of the distance sensor j in the first group (sensor spacing is s_1). In measurement position i, the scanning stage introduces a height offset $c_{1,i}$ and a pitching angle $\theta_{1,i}$.

(3) We can get follow equation from Eqs. (1) and (2) by STP method.

$$\Delta p_j = p_{a,j} - p_{b,j} = \Delta f_{1,j}(i) + \Delta e_{1,j} + s_1 \cdot \tan(\theta_{1,i}) \tag{3}$$

where $\Delta f_{1,j}(i) = f(j + (i+1) \cdot \vartheta_1) - f(j + i \cdot \vartheta_1)$, $\Delta e_{1,j} = e_{1,j+\vartheta_1} - e_{1,j}$. The left of Eq. (3) is the difference measurement of front and back sensor, which is a known quantity. $s_1 \cdot \tan(\theta_{1,i})$ is also a known quantity when pitching angle $\theta_{1,i}$ is measured by angle sensor. Let

$$\Delta\tilde{f}_{1,j} = \frac{\Delta f_{1,j}(i) + \Delta e_{1,j}}{s_1} = \frac{\Delta p_j - s_1 \cdot \tan(\theta_{1,i})}{s_1} \tag{4}$$

After making integral of Eq. (4) and assuming the first point of each straightness profile is zero, we get the straightness profile j

$$\begin{aligned}\tilde{f}_{1,j} &= f(j + i \cdot \vartheta_1) - f(j) + i \cdot \vartheta_1 \cdot \delta \cdot \left(\frac{\Delta e_{1,j}}{s_1}\right) \\ &= f(j + i \cdot \vartheta_1) - f(j) + i \cdot \Delta e_{1,j}\end{aligned} \tag{5}$$

There are ϑ_1 ($j = 0, \ldots, \vartheta_1 - 1$) curves in all. Reconstructing straightness profile is to determine the relative position of these ϑ_1 curves exactly and then combine them into one curve. We fix one of these curves as a base curve and calculate its relative translation and tilt with anyone of other curves, and then the straightness profile of workpiece can be obtained. The relative translation and tilt between them can be determined by the second group curves with sensor spacing s_2.