Measurement 47 (2014) 627–632

Contents lists available at ScienceDirect

Measurement

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

Investigation of error separation for three dimensional profile rotary measuring system

Bo Chen, Xiangchao Zhang *, Hao Zhang, Xiaoying He, Min Xu

Shanghai Ultra-Precision Optical Manufacturing Engineering Center, Fudan University, Shanghai 200438, China

A R T I C L E I N F O

Article history:
Received 3 December 2012
Received in revised form 17 September 2013
Accepted 19 September 2013
Available online 2 October 2013

Keywords:
Rotary profile measuring system
Error separation
Systematic error
Two-probe-two-step method
Orthogonal distance least-squares fitting

A B S T R A C T

High precision 3D profile rotary measuring systems for large diameter workpieces are urgently needed in precision engineering. Error separation is critical for improving the accuracy of the system. In order to obtain higher accuracy for 3D profile rotary measuring systems, the random and systematic errors are analyzed and separated in this paper. In the measuring system, roll and pitch caused by the probe tilt violate the Abbe principle. Roll is removed by using two probes and pitch is separated by the interferometer method. The radial run-out and the perpendicularity error between the probe and the spindle axis are compensated by a two-probe-two-step method carried out on a standard hemisphere artifact. As the form error of the artifact is mixed with the perpendicularity error, the least-squares method is applied to fit the hemisphere and work out the perpendicularity error and the profile error of the hemisphere. Finally, numerical validation is presented using Matlab program to demonstrate the effectiveness and correctness of the proposed method.

1. Introduction

Nowadays, advancements in the high precision manufacturing and metrology are making increasing demands on higher accuracy of the 3D profile rotary measuring systems. However, existing systems and techniques are not satisfactory for measuring the complicated rotary workpieces with large diameters. The widely used coordinate measuring machines (CMMs) can be used to measure various geometrical features of workpieces such as form, size, position, angle, etc. However, the design of the conventional CMMs violating the Abbe principle [1,2] leads to low measuring accuracy. Some high precision 3D form measuring instruments have been developed [2,3], but the measuring ranges are not large enough for some applications.

Error separation techniques are important for reducing the measurement errors. The existing error separation techniques of rotary workpieces can be classified into roundness error separation techniques and cylindricity error separation techniques. Roundness error separation techniques [4] merely focus on a single circular profile section [5]. And the cylindricity error separation techniques mainly concentrate on the straightness error of the guide and the radial errors of the sections perpendicular to the spindle [6,7], but these techniques cannot help to separate the probe motion errors along the radial direction. Although the aforementioned techniques can improve the accuracy, they are not suitable for measuring the profiles of complicated shapes.

This paper proposes a scheme to separate the measurement errors based on a self-built 3D profile rotary measuring instrument. The errors of the measuring system can be divided into systematic errors and random errors. Among the systematic errors the roll and pitch errors caused by the probe tilt are separated during the measurement. For the multi-probe method, matching the frequency responses, linearity and temperature coefficients of the multiple probes is very important. Consequently, using the fewest possible probes is desirable, especially when ultra high accuracy is required. For one-probe reversal

---

* Corresponding author. Tel.: +86 21 51630347; fax: +86 21 65641344.
E-mail address: zxchao@fudan.edu.cn (X. Zhang).

0263-2241/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.measurement.2013.09.043

method, reinstallation of the probe brings extra errors into the signal and makes the measurement very complicated. Taking these issues into consideration, this paper adopts a two-probe-two-step method [8] which combines a two-probe method and a two-step method.

2. Random errors of the measuring system

2.1. The measuring system

The built 3D profile rotary measuring system is shown in Fig. 1. A right-handed Cartesian coordinate system is established. The *XOY* plane is parallel to the rotary table, and the *Y* axis is parallel to the guide. The measuring range is 60 mm × 60 mm × 25 mm, as limited by the probes. The rotary table is ABTech AT150, a precision air bearing index rotary system with resolution of 0.0001°. There are three probes in the system, and probe 1 is Heidenhain CT2502 with measuring range of 25 mm, and both probe 2 and probe 3 are CT6002 with measuring range of 60 mm. The maximum positioning error of the three probes is within 50 nm after calibration. Probe 1 whose measuring rod is retractable along the *Z* direction can move along the guide to measure the *Z* coordinate of the workpiece. While probe 2 and probe 3 are also retractable to measure the radial coordinates of the rotary workpiece.

The categorization of the measuring errors of this system is illustrated in details in Fig. 2. The random errors can be reduced by averaging with repeated experiments, and other variable errors should be suppressed by well-controlled conditions. While systematic errors should be compensated by suitable calibration techniques.

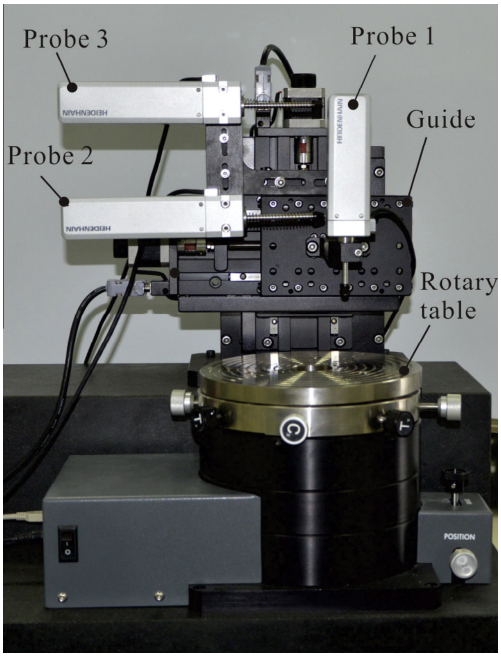

Fig. 1. The self-built 3D profile rotary measuring system.

2.2. Suppression of random errors

The primary random errors depicted in Fig. 2 include the spindle rotation random error, the probe motion random error along the *Y* direction, the spindle drift, the thermal drift, the probing system error and the deformation errors. The spindle rotation random errors and the probe 1 motion random errors along the guide are caused by fluctuations and environmental disturbances. These two errors are very small compared with the systematic spindle and probe motion errors. The spindle drift describes the change of the spindle orientation and the thermal drift of the workpiece position with respect to the spindle. These two error are related, both affected by the measurement time, vibration and rotation speed of the rotary table.

The three probes measure the workpiece in a contact manner. The probing system causes random errors due to contact forces, thermal expansion, indicating errors, etc. Controlling the environment temperature in a suitable range and averaging multiple measurements are effective to reduce this type of errors. Deformation of the instrument arises from finite stiffness of the instrument, external forces, inertia and temperature changes. For example, the gravities of the guide and the probes make the column deform slightly. The rotary table also has deformation, because of the gravity.

3. Compensation of systematic errors

The systematic errors are summarized in Fig. 2. These errors can be divided into two types, one associated with probe 1 and the other associated with the spindle.

3.1. Errors related to probe 1

(1) As the guide is not absolutely straight, the measured *Z* coordinates of probe 1 will be affected when moving along the guide. This error can be calibrated by interferometer. More about straightness error separation techniques can be found in Ref. [9].

(2) Roll, pitch and yaw motions are angular errors of the probe 1 about the *Y*, *X* and *Z* axes, respectively. Yaw motion does not affect the measuring results, but roll and pitch cause Abbe tilt and they affect the radial value of the workpiece directly. Thus roll and pitch must be measured and separated [3,10].

Roll error is calibrated by the reading difference of the probe 2 and the probe 3 as illustrated in Fig. 1. The pitch error is calibrated as follows. Set a laser source on the left side of the probe, and mount a mirror to reflect the light to the optical detector (Fig. 3). Take point *O* as the reference point. If the probe has a tilt of angle δ, the light reflects to point *P*. The angle δ can be obtained by

$$\delta \approx \frac{1}{2}\arctan\left(\frac{OP}{AO}\right) \approx \frac{OP}{2AO}. \tag{1}$$

The Abbe error in *Y* direction is

$$\Delta R = d\sin\delta = d\sin\left(\frac{OP}{2AO}\right) = \frac{d \times OP}{2AO}, \tag{2}$$