Precision Engineering 38 (2014) 458–471

Contents lists available at ScienceDirect

Precision Engineering

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

A sub-nanometre spindle error motion separation technique

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ARTICLE INFO

Article history:
Received 18 January 2013
Received in revised form
22 December 2013
Accepted 31 December 2013
Available online 24 January 2014

Keywords:
Spindle error motion separation technique
Donaldson reversal
Grejda reversal
Multiprobe technique
Spindle metrology
Air bearing
Measurement uncertainty
Error budgeting
Optimisation
Fractal set

ABSTRACT

This work designs and validates a spindle error motion separation technique having a sub-nanometre measurement uncertainty. This technique overcomes typical measurement error sources arising from sensor, indexing or the repositioning of the artifact. We compare and assess various known reversal and multiprobe techniques by means of a novel error analysis method. From this, we develop an improved implementation of the multiprobe technique, which by-passes accurate indexing of the artifact and sensor(s) during testing, as well as unequal sensor sensitivities, in case multiple sensors are used. This is achieved by measuring the error motion consecutively under three different orientations by rotating the stator of the spindle utilising a high-precision indexing table. These modifications result in a measurement uncertainty that is four times smaller than the conventional multiprobe technique. Furthermore, the suppression of the low-order harmonics is reduced by an optimisation of measurement angles. Finally, several experimental tests are performed to quantify the measurement uncertainty and the influence of the measurement angles on the error separation. Repeatability tests on the radial error motion of an aerostatic rotary table show a measurement uncertainty of 0.455 nm.

1. Introduction

Today, nanometre-level form error and sub-nanometre surface finish are required for the production of aspheric lenses, free form surfaces and micro-structured optics, to mention but a few. The axis-of-rotation error motion[1] of a machine spindle is crucial in achieving these levels as any deviation from pure rotation reduces the machining performances. As a result, ultra-precision machines for single point diamond turning, fly cutting and precision grinding are more and more being equipped with aerostatic spindles as conventional bearing spindles cannot produce mirror surface finish [1]. Aerostatic machine tool spindles with a rotational speed of 60,000 rpm and axial and radial error motion below 25 nm are already commercially available on the market. Nevertheless, new application fields urge for ultra-precision machine tool spindles capable of achieving yet lower error motions. In order to achieve this, one needs a reliable method to calibrate the machine tool spindle with a measurement uncertainty of sub-nanometre level. Throughout the years, several researchers proposed different methods in the literature because improvements in DAQ, signal processing and sensors made it possible to measure on such an excessively small scale.

Generally, the error motion of an ultra-precision machine tool spindle is measured by means of a capacitive sensor targeting a lapped spherical artifact (master ball), which is mounted on top of the rotor. However, as a result, the measurement data includes both the effect of the error motion of the spindle and the out-of-roundness (form error) of the artifact. For most types of spindles is the form accuracy of a precision artifact is at least 10–100 times better than the spindle error motion. In this case, the form error of the artifact, i.e. between 10 nm and 30 nm, is neglected and the measurand is treated as the error motion of the spindle. However, ultra-precision aerostatic spindles approach or even surpass these precision artifacts in accuracy. This necessitates the use of a spindle error motion separation technique to extract the error motion and artifact form error from the raw measurement data as no method relies upon a calibrated artifact. For decades, many spindle error motion separation techniques have been described in the literature such as Donaldson and Estler reversal. However, most of them are still prone to measurement errors and uncertainties because of poor hardware design and not careful implementation of the separation technique.

This paper will analyse three of the most well-known error separation techniques, namely Donaldson reversal, Grejda

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[1] The axis-of-rotation error motion is from this point forward designated as error motion.

0141-6359/$ – see front matter © 2014 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.precisioneng.2013.12.011

reversal and the multiprobe technique. This is carried out because the measurement accuracy of each of these methods may be degraded by imperfectly indexing the sensor(s) and/or artifact, as well as unequal sensor sensitivities. Hereto, we will identify and observe the error components or error sources of the Donaldson reversal, Grejda reversal and multiprobe technique based on a theoretical error analysis method. With their shortcomings identified, this finally leads to the design and validation of a modified multiprobe method, ensuring sub-nanometre measurement uncertainty.

Section 2 overviews the background of error separation techniques relevant to the present study. Section 3 describes the principle of the Donaldson reversal, Grejda reversal and the multiprobe technique. Thereafter, the error sources and measurement uncertainty are studied in Section 4. In Section 5, the principle of the modified multiprobe technique is proposed and the test setup, used for the experimental validation in Section 6, is described. Moreover, the optimal measurement angles are determined reducing harmonic suppression. Section 6 continues with the experimental validation of the proposed error separation technique. Finally, Section 7 ends with a conclusion.

2. Background

Since 1960, a considerable amount of literature has been published on error separation techniques, each with the objective of improving the accuracy of error motion measurements. Evans et al. [2] and Whitehouse [3] provide an in-depth analysis of several methods, describing their limitations and applications. Donaldson [4] and Estler [2] reversal are widely preferred since both methods completely separate the artifact form error from the spindle error motion. These reversal techniques require only two measurements, with the sensor and artifact orientation rotated by 180° between measurements. Alternatives to Donaldson and Estler reversal are the multi-position techniques, i.e. the multiprobe and the multistep method. The conventional multiprobe method, proposed by Whitehouse [3], uses three (or more) asymmetrical positioned probes, simultaneously measuring the error motion of the spindle while neither the probes nor the artifact are moved. The multistep method, on the other hand, requires many measurements targeting an artifact at equally spaced angular orientations. These multi-position techniques are, however, not true reversals as pointed out by Whitehouse. Depending on the number of probes and their positioning (multiprobe) or the number of steps (multistep) these multi-position techniques are insensitive to some harmonic components of the error motion. This phenomenon is also known as harmonic suppression. Although, with a clear understanding of their limitations, these multi-position techniques prove to be very useful [5]. As stated by Whitehouse, the multiprobe method is less sensitive to this problem if the number of probes and their angular positions are well-considered. Estler [6], in turn, showed that the harmonics *kN*, with *N* the number of measurements, become mixed in the multistep method. In this instance, the spindle error motion cannot be distinguished from the artifact form error. However, increasing the number of measurements *N* shifts the harmonic suppression to higher, meaningless, harmonics.

Several works are published in the literature wherein the above-mentioned separation techniques are validated and compared with each other. Marsh et al. [7] compared the Donaldson reversal and multiprobe technique using two different test rigs. Their results matched within 1 nm for both methods measured at the same test rig and within 3 nm when measured at two different test rigs. In addition, Marsh et al. compared the Donaldson reversal, multistep and multiprobe technique in [8], showing an agreement better than 1 nm. In [8], Marsh et al. also demonstrated the Grejda reversal technique, highlighting a measurement uncertainty of 0.1 nm.

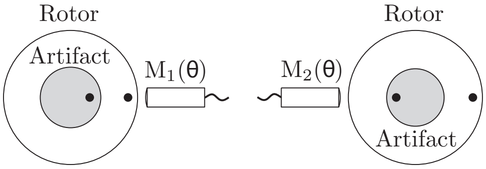

Fig. 1. Schematic representation of the Donaldson reversal technique.

Grejda et al. [9], in turn, tested the multistep, multiprobe and Donaldson reversal technique. Their results agree within 1.5 nm with each other. With a slight modification to the Donaldson reversal technique, Grejda et al. [9,10] achieved error and roundness measurements with sub-nanometre repeatability. To this end, they placed the test spindle on an indexing table rotating the stator of the spindle relative to the sensor rather than moving the sensor relative to the stator. The artifact, however, must still be indexed by 180°. Zhang et al. [11] modified the customary multiprobe method by using four probes instead of three probes, reducing the effect of harmonic suppression. However, they were not able to examine the uncertainty because the error motion value changed too much from run to run.

Further, reversal methods are also used for measuring the surface profile and the roundness of shafts, as demonstrated by Al-Bender and Van Brussel in [12].

3. Error separation techniques

At first, the error separation techniques compared in this study will be analysed and discussed in more detail. Their specific advantages and shortcomings, as well as their mathematics, are given for the completeness and to evaluate and analyse the measurement uncertainty in the following section. A more extensive review, together with an introduction to the fundamental issues of spindles and spindle metrology, can be found in [5]. For a description of relevant terms and techniques in spindle metrology, the interested reader is referred to the B89.3.4M standard [13].

3.1. Donaldson reversal

Donaldson reversal is the rotational equivalent of the straight-edge reversal and requires two measurements, i.e. $M_1(\theta)$ and $M_2(\theta)$ as illustrated schematically in Fig. 1. The measurement data $M_1(\theta)$ and $M_2(\theta)$ are a combination of the artifact's form error $A(\theta)$ and the radial error motion of the spindle $X(\theta)$ respectively:

$$M_1(\theta) = A(\theta) + X(\theta) \tag{1}$$

$$M_2(\theta) = A(\theta) - X(\theta) \tag{2}$$

Between two measurements, the artifact and sensor orientation is rotated by 180°, reversing the sign of the spindle error motion $X(\theta)$ in Eq. (2) (note the alignment of the marks in Fig. 1). Hence, by adding and subtracting Eqs. (1) and (2), the spindle error motion $X(\theta)$ can be separated from the artifact form error $A(\theta)$, namely:

$$A(\theta) = \frac{M_1(\theta) + M_2(\theta)}{2} \tag{3}$$

$$X(\theta) = \frac{M_1(\theta) - M_2(\theta)}{2} \tag{4}$$

However, to achieve nanometre level repeatability and accuracy, sensor and artifact must be indexed with nearly perfect orientation and fixturing to measure at precisely the correct radial and axial locations. It is apparent that there are practical difficulties involved in this process that make this method less than perfect. This has been demonstrated experimentally in [14].