Precision Engineering xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Precision Engineering

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

# A multi-orientation error separation technique for spindle metrology of miniature ultra-high-speed spindles

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ARTICLE INFO

*Article history:*
Received 31 December 2014
Received in revised form 24 June 2015
Accepted 2 July 2015
Available online xxx

*Keywords:*
Ultra-high-speed spindles
Spindle metrology
Error separation
Multi-orientation method
Micro-manufacturing
Micromachining

ABSTRACT

This paper presents a multi-orientation error separation technique to remove the artifact form error from the radial measurements to obtain the radial spindle error motions of miniature ultra-high-speed (UHS) spindles. Unlike the existing approaches, the present technique neither relies on high-accuracy fixtures, nor necessitates measurements from specific orientations of the artifact. Rather, the spindle error motions are measured from a set of arbitrary artifact orientations using laser Doppler vibrometry (LDV). The angle of each artifact-setup orientation with respect to the spindle is determined with high precision through reflectivity measurement of the marks made on both the artifact and the spindle using another LDV. Although the presented approach can be applied by using different sensors (e.g., capacitance probes), we demonstrate the approach using LDVs. With the displacement measurement direction fixed, measurements are conducted from both LDVs for multiple orientations of the artifact. Using the unique implementation scheme developed in this paper, data from these orientations are post-processed to compute the artifact form error and further remove it from the radial motion measurements to obtain the synchronous radial spindle error motions. A thorough experimental evaluation is presented to quantify both the repeatability of the measured artifact form errors as well as the bandwidth of error separation for various number of artifact orientations. The spindle error motions measured from both the sphere and stem portions of a custom fabricated sphere-on-stem artifact mounted on a typical miniature UHS spindle, are seen to be similar in shape and within 5 nm in magnitude across the revolution, thus demonstrating the effectiveness of the technique. Using this technique, spindle error motions at ultra-high speeds up to 150 krpm were successfully quantified. Although the implementation scheme is demonstrated for miniature UHS spindles, it is readily applicable for error separation on macro-scale spindles without the need for any high-precision fixtures and precise setting of angles.

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## 1. Introduction

Among many other factors, dimensional and surface accuracy of precision machining operations depend on the accuracy of the rotary motions provided by the spindle. Miniature ultra-high-speed (UHS) spindles are widely used for micromachining and precision machining applications, and the strict tolerance and accuracy requirements of those processes impose limits on the unwanted axial and radial motions encountered when using the UHS spindles.

In spindle metrology, the motions of the spindle are measured from a precision artifact attached to the spindle. In addition to the synchronous and asynchronous spindle error motions, the measured radial motions also include the surface profile (form error or out-of-roundness) of the artifact around the circumferential measurement track. In order to isolate the spindle error motions from the form error of the artifact, and thus, to accurately determine the spindle error motions, error separation techniques are used. Various techniques that have been developed for error separation can be classified into (1) reversal techniques [4–9,18], (2) multi-probe techniques [8–12], and (3) multi-step techniques [9,13–15]. A thorough description of these techniques is provided in [6,4]. Common to all of the error separation techniques presented in the literature is the requirement of precise and rigid fixturing, with accurate and precise angular positioning of displacement sensors. Under ideal conditions, including perfect alignment, positioning, and fixturing, the reversal techniques allow for perfect separation of artifact and spindle errors. However, this is only true in theory since such ideal conditions cannot be obtained in reality. Even under ideal conditions, due to the finite number of indexing probes/angles, the multi-probe and multi-step techniques cannot completely separate certain harmonics of the spindle and artifact

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http://dx.doi.org/10.1016/j.precisioneng.2015.07.002
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errors. This issue is commonly referred to as *harmonic suppression* [6,14,17].

Many works in the literature have attempted to address the harmonic suppression problem. Gao et al. [16] showed that a method based on measuring the radial slope (using an angle probe) simultaneously with radial displacements could minimize the harmonic suppression problem and improve the accuracy of error motion measurement. Many researchers [8,13,6,15,25] have also shown that, while full separation of the artifact form and spindle error motion cannot be obtained using the multi-probe and multi-step techniques, sufficient number of harmonics can be effectively separated by a judicious choice of the angles and the number of probes/steps. Although these techniques have been successfully implemented to measure spindle error motions of ultra-precision spindles at sub-nanometer levels [8,9,25], their application imposes significant practical challenges during implementation due to the need for sophisticated measurement setups (as shown in [16]) or extremely precise fixturing to prescribe the chosen angles.

Application of the well-established spindle metrology techniques to miniature UHS spindles poses important challenges arising from (1) the smaller size of the spindle and the artifact (typical artifact size is $\phi$3 mm or $\phi$0.125 in.); (2) the curvature effect due to the small artifact diameter; and (3) the requirement for performing measurements at higher spindle speeds (e.g., >40 krpm), since majority of the UHS spindles cannot be operated below a specific speed. Furthermore, the sphere-on-stem artifacts typically used for these measurements in the macro-scale are not commercially available for the $\phi$3 mm size and are very expensive to fabricate. To address those challenges, the authors recently developed a laser Doppler vibrometer (LDV)-based measurement approach for measuring axial and radial spindle *motions* of ultra-high-speed spindles [1,2]. In those works, however, the form error of the artifact was not removed, but rather considered as a source of uncertainty in the synchronous component of the radial error, thus leading to relatively high uncertainties in the measurement of radial synchronous spindle error motions. This approach was followed since, due to the aforementioned challenges, error separation techniques presented in the literature were either impossible or impractical to apply to UHS spindles. Therefore, an effective error separation technique that will enable accurate measurement of error motions of miniature UHS spindles at operational speeds is critically needed. Ideally, this technique will alleviate the need for custom designed high precision artifacts, and will capture many harmonics (e.g., >50) to enable high precision measurement of the synchronous spindle error motions of miniature UHS spindles.

In this work, we have implemented a single-probe multi-orientation technique to remove the artifact form error from the radial measurements to obtain the radial spindle errors of miniature UHS spindles. The approach involves measurements of radial motions using a single LDV by keeping it stationary, and conducting measurements at multiple *orientations* of the artifact (i.e., by removing the artifact, changing its relative angular position with respect to the spindle, and re-attaching the artifact in its re-oriented configuration). While the idea of multi-orientation error separation (MOES) is not new [9,13–15], we have established an unique implementation approach that eliminates the need for measuring at specific orientations, but rather uses measurements from multiple *arbitrary* orientations of the artifact, thereby circumventing the need for extra precision fixtures. This is enabled by accurate determination of the relative orientation between the artifact and the spindle by monitoring the reflectivity signal of another laser in-situ. We demonstrate the use of MOES technique for the measurement of the spindle error motions of a typical miniature UHS spindle across its operational speeds. Furthermore, the effectiveness of the technique is evaluated by comparing spindle error motions determined from measurements from two artifact surfaces with drastically different form errors. It is noted here that, although the implementation scheme has been demonstrated for miniature UHS spindles, the same approach can be readily used for error separation on macro-scale and conventional spindles.

This paper is organized as follows: First, a brief introduction of the MOES technique is provided. Then, the details of the implementation scheme developed in this work are described, with a focus on measuring spindle error motions of UHS spindles. Next, using a typical UHS spindle, measurements are conducted to (a) demonstrate the functionality of the implementation scheme by measuring spindle error motions from the sphere and stem portions of the sphere-on-stem artifact, and (b) study the effect of the number of orientations (used for error separation) on both the repeatability and bandwidth of error separation. Finally, to demonstrate the effectiveness of the implementation scheme across a wide range of speeds, radial spindle error motions of the tested UHS spindle are obtained at four speeds (40 krpm, 90 krpm, 120 krpm, and 150 krpm) that span the entire operating range of the spindle along both the fixed- and rotating-sensitive directions.

## 2. Description of the single-probe multi-orientation technique

The theory for single-probe multi-orientation technique was first described in [6]. This technique requires measurements from at least two orientations of the artifact. It involves using a single displacement sensor to measure the radial motions from the surface of an artifact that is attached to an axis of rotation provided by the spindle. The motions measured when the spindle is run at the operating speeds can be decomposed into motions at the fundamental frequency, synchronous motions and asynchronous motions [19,20]. The synchronous motions consist of the artifact form error and the speed-dependent synchronous spindle error motions [19,20]. In order to obtain the true synchronous spindle error motions, the synchronous radial motion measurements from multiple orientations of the artifact are combined to calculate and separate the artifact form error.

A description of the steps involved in the multi-orientation technique is shown in Fig. 1 for an implementation along the fixed-sensitive *Y*-direction. After conducting the first measurement, the artifact is re-oriented by removing it from the spindle, rotating by a certain angle about its axis, and re-attaching it to the spindle for the second measurement. This step is repeated until all the measurements from the desired number of orientations are completed. The measured displacement data from each orientation is post-processed to obtain the synchronous radial motions at certain fixed angular positions of the spindle.

Denoting the spindle error motions and artifact form error measured along the fixed-sensitive *Y*-direction as $S(\theta)$ and $A(\theta)$, respectively, the synchronous radial motions for the three orientations $M_1(\theta)$, $M_2(\theta)$, $M_3(\theta)$ can be related to $S(\theta)$ and $A(\theta)$ as

$$
\begin{aligned}
M_1(\theta) &= A(\theta) + S(\theta) \\
M_2(\theta) &= A(\theta - \alpha_1) + S(\theta) \\
M_3(\theta) &= A(\theta - \alpha_2) + S(\theta),
\end{aligned}
\tag{1}
$$

where $\alpha_1$ and $\alpha_2$ are the rotation angles of the artifact (with respect to the first orientation) in the second and third orientations, respectively, as shown in Fig. 1. It is important to note that the angular reference ($\theta = 0$) between different orientations corresponds to the same physical angular orientation of the spindle.

Mathematically, we can eliminate the spindle error motions $S(\theta)$ from the three measurements and obtain a relationship for the

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