Precision Engineering 45 (2016) 403–413

Contents lists available at ScienceDirect

Precision Engineering

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

A hybrid three-probe method for measuring the roundness error and the spindle error

Shengyu Shi[a], Jing Lin[b,*], Xiufeng Wang[a], Ming Zhao[a]

[a] Shaanxi Key Laboratory of Mechanical Product Quality Assurance and Diagnostics, School of Mechanical Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi Province 710049, PR China
[b] State Key Laboratory for Manufacturing System Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, PR China

ARTICLE INFO

Article history:
Received 11 December 2015
Received in revised form 17 February 2016
Accepted 27 March 2016
Available online 29 March 2016

Keywords:
Roundness error
Spindle error
Hybrid three-probe method
Suppressed harmonics
Susceptible harmonics

ABSTRACT

The three-probe method is the most widely used technique for separating the artifact roundness error from the spindle error, with the superiority available for *in situ* measurement. For further improving the measurement accuracy of the three-probe method, in this paper, the harmonic measurement errors are investigated analytically and experimentally. To achieve this aim, firstly, according to the transfer matrices $W(k)$, the harmonics are classified into two types: the suppressed harmonics with *zero* $W(k)$ and the unsuppressed harmonics with *no-zero* $W(k)$. Then, on one hand, through mathematical deduction, the formulation for determining the suppressed harmonics is derived; on the other hand, the measurement errors to the unsuppressed harmonics are experimentally acquired, and the experimental results demonstrate that the measurement errors to the unsuppressed harmonics are greatly related to the determinant of the transfer matrix $|W(k)|$, but not rigorously in inverse proportion to $|W(k)|$. Based on the conclusions drawn from the investigations, a hybrid three-probe method is constructed, where several conventional three-probe measurements are performed for optimizing individual harmonic coefficients. Experiments verify that the hybrid three-probe method is more robust to the error sources than the conventional method.

1. Introduction

Motion error of a spindle affects the surface finish and the roundness of the machined parts directly (ISO 230- 7: 2006). Therefore, to guarantee the manufacturing accuracy, there are growing demands for quantifying the spindle error accurately. On the other hand, rotary workpieces, like shafts, bearings, are common machine elements, whose out-of-roundness can greatly deteriorate the performance of the machinery. Thereby, to ensure the performance of the machines, there are increasing needs for precise measurement of the roundness error of the rotary workpieces. In manufacturing industry, identifications of these two types of errors are two fundamental but complicated tasks. In general, the spindle error measurement is carried out by attaching a ball or cylindrical mandrel to the spindle as the reference. While in the roundness measurement, the spindle of the instrument is used as the reference. As a result, the raw probe signals are always superposition of the spindle error and the roundness error. Hence, to obtain accurate final results, it is required to remove the reference error.

Donaldson and Estler reversal (Donaldson, 1972; Salsbury, 2003), multi-orientation (Whitehouse, 1976), and three-probe (Whitehouse, 1976; Marsh et al., 2010) methods are the most commonly used techniques for separating the roundness error from the spindle error, which have been reviewed in Evans et al. (1996) and Marsh et al. (2006). The reversal and multi-orientation methods require several consecutive measurements with the artifact rotated at different angular positions. Consequently, two correlated errors sources arise: the imperfect rotation of the artifact and the non-repeatability of the spindle error during the several consecutive measurements. What is worse, on-machine measurement is not feasible. These disadvantages have limited the extensive uses of the two methods. Comparatively, only the three-probe method is available for *in situ* measurement.

Unfortunately, the three-probe method is also subject to a critical problem: the harmonic suppression. In 1976, Whitehouse put forward the problem of harmonic suppression occurred in different error separation methods (Whitehouse, 1976). Since then, enormous amount of research effort has been paid regarding the

* Corresponding author. Fax: +86 29 83395041.
E-mail addresses: shi.shengyu@stu.xjtu.edu.cn (S. Shi), jinglin@mail.xjtu.edu.cn, jing_lin00@sina.com (J. Lin), wangxiufeng@mail.xjtu.edu.cn (X. Wang), zhaomingxjtu@mail.xjtu.edu.cn (M. Zhao).

http://dx.doi.org/10.1016/j.precisioneng.2016.03.020

harmonic suppression in three-probe method. Zhang and Wang (1993) and Zhang et al. (1997) stated that when the transfer coefficients are very small, a small measurement error source might cause quite large measurement error. To solve this problem, he modified the conventional three-probe method by using four or more probes instead of three. Gao et al. (1996) found that some high-frequency harmonics (*i.e.*, the suppressed harmonics) could not be observed and measured absolutely by the three-probe method. To overcome this drawback, Gao et al. developed the mixed multi-probe method for roundness measurement, where two displacement probes and one angle probe were used. Jansen et al. (2001) presented a general and convenient algorithm applicable to all types of multi-probe measurements, in which the least-square solutions of the harmonic coefficients were directly solved from an over-determined system of equations. Recently, to alleviate the problem of harmonic suppression, the optimization of the probe angles has been discussed extensively, and the common way to optimize the probe angles is by maximizing the minimal $|W(k)|$ (Hale et al., 2011; Hench, 2013; Cappa et al., 2014).

It can be seen that many techniques have be proposed to reduce the adverse effects of harmonic suppression. However, the problem of harmonic suppression itself has never been rigorously studied, or in the other words, the harmonic measurement error has never been thoroughly investigated.

Therefore, to establish a reliable foundation for further improving the measurement accuracy of the three-probe method, the harmonic measurement errors will be analytically and experimentally investigated in this paper. To achieve this aim, first of all, the harmonics will be classified into two types according to the transfer matrices $W(k)$: the suppressed harmonics with *zero* $W(k)$ and the unsuppressed harmonics with *no-zero* $W(k)$. Subsequently, the formulation for determining the suppressed harmonics will be mathematically derived. Then, the measurement errors to the unsuppressed harmonics will be analytically and experimentally investigated.

Based on the conclusions drawn from these investigations, a hybrid three-probe method will be proposed. Then, experiments will be carried out to check the robustness of the hybrid three-probe method.

The rest of this paper is organized as follow. In Section 2, the conventional three-probe method is analytically investigated. In Section 3, the measurement setup is described firstly, and then, experiments are carried out to investigate the harmonic measurement errors. In Section 4, a hybrid three-probe method is developed, and experiments are performed to validate this method. In Section 5, the hybrid method is compared with the multi-probe method, and besides, some unsolved problems worthy of studying are also discussed. Section 6 gives the conclusions.

2. Theoretical analysis of the conventional three-probe method

2.1. The three-probe method

In the three-probe method, a spherical or cylindrical artifact is affixed to the end of the spindle. Then, three displacement probes are oriented respectively at 0°, ϕ, and φ to inspect the same cross section of the artifact, as shown in Fig. 1. Thus, the raw probe signals are summations of the artifact roundness error $r(\theta)$, including a phase shift caused by probe angles, and the X- and Y-component of the radial motion of the artifact center $\varepsilon_{Px}(\theta)$ and $\varepsilon_{Py}(\theta)$:

$$m_1(\theta) = r(\theta) + \varepsilon_{Px}(\theta) \tag{1}$$

$$m_2(\theta) = r(\theta - \phi) + \varepsilon_{Px}(\theta)\cos(\phi) + \varepsilon_{Py}(\theta)\sin(\phi) \tag{2}$$

$$m_3(\theta) = r(\theta - \varphi) + \varepsilon_{Px}(\theta)\cos(\varphi) + \varepsilon_{Py}(\theta)\sin(\varphi) \tag{3}$$

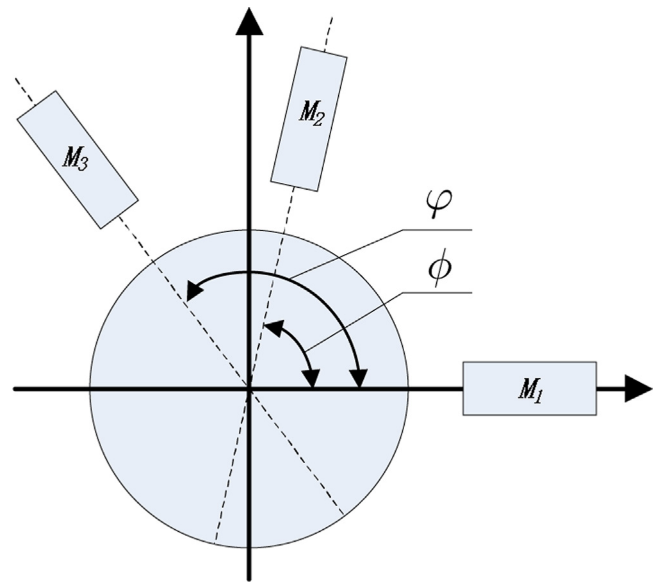

Fig. 1. The schematic diagram of the three-probe method.

The probe signals could be divided into two parts: the synchronous components m_{1s}, m_{2s}, m_{3s} that occur at integer multiples of rotation frequency, and the asynchronous components m_{1a}, m_{2a}, m_{3a} that occur at frequencies other than integer multiples of rotation frequency. The synchronous components could be derived by averaging M revolutions of the probe signals:

$$\begin{aligned} m_{1s}(\theta) &= \frac{1}{M}\sum_{i=0}^{M-1} m_1(\theta + 2\pi i) \\ m_{2s}(\theta) &= \frac{1}{M}\sum_{i=0}^{M-1} m_2(\theta + 2\pi i)\theta \in [0, 2\pi) \\ m_{3s}(\theta) &= \frac{1}{M}\sum_{i=0}^{M-1} m_3(\theta + 2\pi i) \end{aligned} \tag{4}$$

Since the artifact roundness error repeats in each revolution, it has no effect on the asynchronous probe signals m_{1a}, m_{2a}, m_{3a}. Hence, the asynchronous radial motion ε_{Pxa} and ε_{Pya} could be directly derived from the asynchronous probe signals:

$$\varepsilon_{Pxa} = m_{1a} \tag{5}$$

$$\varepsilon_{Pya} = \frac{m_{2a} - m_{1a}\cos(\phi)}{\sin(\phi)} \tag{6}$$

Unfortunately, the synchronous probe signals m_{1s}, m_{2s}, m_{3s} are still superposition of the roundness error $r(\theta)$ and the synchronous radial motion of the artifact center $\varepsilon_{Pxs}(\theta)$, $\varepsilon_{Pys}(\theta)$. Therefore, the separation algorithm should be applied to the synchronous probe signals to extract $r(\theta)$, $\varepsilon_{Pxs}(\theta)$, and $\varepsilon_{Pys}(\theta)$. To realize this, a weighed function $m(\theta)$ is built as a weighed combination of the synchronous probe signals m_{1s}, m_{2s}, m_{3s}, using weighted coefficients of *unity*, a, and b:

$$\begin{aligned} & m(\theta) = m_{1s}(\theta) + am_{2s}(\theta) + bm_{3s}(\theta) = \\ & r(\theta) + ar(\theta - \phi) + br(\theta - \varphi) + \varepsilon_{Pxs}[1 + a\cos(\phi) + b\cos(\varphi)] \\ & \quad + \varepsilon_{Pys}[a\sin(\phi) + b\sin(\varphi)] \end{aligned} \tag{7}$$

To remove the contribution of ε_{Pxs} and ε_{Pys} in $m(\theta)$, the weighted coefficients a and b must satisfy the following two equations:

$$1 + a\cos(\phi) + b\cos(\varphi) = 0 \tag{8}$$

$$a\sin(\phi) + b\sin(\varphi) = 0 \tag{9}$$