ARTICLE IN PRESS

Precision Engineering xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Precision Engineering

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

Uncertainty analysis of phase and amplitude of harmonic components of bearing inner ring four-point roundness measurement

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ARTICLE INFO

Keywords:
Monte-Carlo simulation
Phase uncertainty
Harmonic component uncertainty
Uncertainty evaluation
Bearing excitation
Odd and even harmonic components
Four-point method
Three-point method

ABSTRACT

The four-point roundness measurement method enables the measurement of roundness without a requirement for a precise rotating motion of the workpiece or a measurement sensor. The four-point roundness measurement method can separate the roundness profile and the motion of the rotating axis of the workpiece. In the present study, the uncertainty of the four-point roundness measurement of a bearing inner ring was analysed. The bearing inner ring was installed in its operating position on the shaft of a large rotor during the measurement in order to investigate the bearing inner ring roundness profile in operating conditions. Since the measurement evaluation using the four-point method is complex, the uncertainty analysis was conducted through a Monte-Carlo simulation, using realistic error sources in typical measurement conditions. The uncertainty of both the amplitude and phase of the harmonic components of the roundness profile was analysed for the 2nd till the 30th harmonic component. Attention was directed especially towards the phase of the harmonic components, since the uncertainty of the phase is analysed very little in existing research studies. In addition, the phase of the harmonic components of the roundness profile is important when considering compensative precision grinding applications of round workpieces. The results show that below the 10th harmonic component, the maximum amplitude standard uncertainty was circa 0.5 µm, and the maximum phase standard uncertainty was circa 5°. The standard uncertainties of the amplitudes for the complete harmonic component range were below 1.3 µm for odd components and 0.2 µm for even components. The maximum standard uncertainties of the phases for the complete harmonic component range were circa 15° for odd components and circa 5° for even components. The measured roundness profile itself did not have an effect on the uncertainty of the method.

1. Introduction

Roundness is a key quality measure of rotating components (i.e., rotors) in many fields of machinery, such as turbines, electric motors and rolls in the paper, steel and non-ferrous metal manufacturing industries. The rotational accuracy of a rotor is greatly affected by the bearings, which are core components of a rotor system. The bearings support the rotor during rotation and sustain the forces exerted by the rotor and external loads. Additional rotational error sources can be unbalance, bending stiffness variation and roundness errors of the rotor itself. Bearings are typically not tailored for a specific rotor, but they are considered as replaceable separate components. The roundness errors of the bearing components can deviate the motion of the rotor central axis as well as cause undesired subcritical resonance vibration of the rotor [1,2].

Typical bearing arrangement is a rolling element bearing with an outer ring connected to the foundation through the bearing housing, balls or rollers as rolling elements and an inner ring attached to the rotor shaft. The bearings excite vibrations into the rotor: the inner ring, outer ring and rolling elements have geometrical errors, which cause harmful vibration with a frequency proportional to the rotating frequency of the rotor. The most remarkable bearing element excitations are caused by the roundness profile of the bearing inner ring, which is attached to the rotor and rotates at the same frequency. The inner ring roundness profile is a sum of the inner ring and the possible conical adapter sleeve thickness variations and the roundness of the shaft (Fig. 1), on which the bearing is attached. Thus, the final bearing inner ring roundness profile is a property of the bearing assembly on the rotor shaft. The roundness errors are commonly presented as harmonic components of the Fourier series.

ISO standard 12181 [3,4] defines roundness as a feature of a circular cross-section of an object. Moreover, the diameter of a round object is typically measured as a two-point measurement, which is sensitive to the out-of-roundness of the measured object. If knowledge

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https://doi.org/10.1016/j.precisioneng.2018.05.008
Received 20 April 2018; Received in revised form 14 May 2018; Accepted 22 May 2018
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Nomenclature

A	Amplitude
c	circa, approximately
D	Even harmonic components of the roundness profile
E	Odd harmonic components of the roundness profile
FFT	$\mathscr{F}$ Fast Fourier Transform
G	Combined harmonic components from two-point and three-point methods
GUM	Guide to the expression of uncertainty in measurement
m	Roundness profile measured with Ozono three-point method
n	Lobe number, harmonic component number
N	Normal distribution
P	Phase
PDF	Probability distribution function
STD	Standard deviation
S1 – S4	Sensors S1, S2, S3 and S4 in four-point roundness measurement method
U	Uncertainty
UPR	Undulations per revolution
Δr	Diameter variation profile measured with two-point method
μ	Mean
σ	Standard deviation

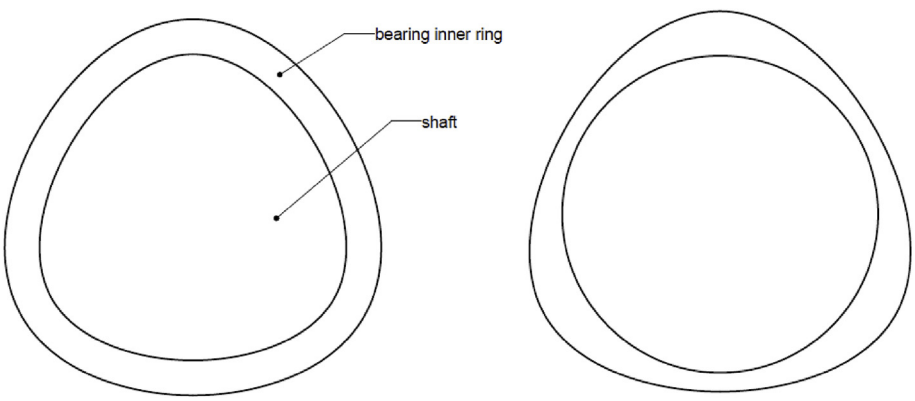

Fig. 1. Schematic visualizing the formation of the roundness error of an installed bearing inner ring. On the left hand side, the roundness error (in this case the 3rd harmonic component, triangularity) is caused by the roundness error of the shaft, on which the relatively thin inner ring has been tightened and thus deformed. On the right hand side, the roundness error is caused by the triangular thickness variation of the bearing inner ring. In reality, the roundness error is a composition of both these error types.

of the shape of the roundness error or the harmonic components of the roundness profile are needed for the application, roundness profile measurements are essential [5–7].

Certain harmonic components of the roundness profile of a bearing inner ring can cause harmful subcritical resonance vibration in the operating range of a large rotor. The harmful subcritical resonances are observed, when the bearing inner ring excites the rotor at its natural frequency. For example, triangular (3rd harmonic) roundness error in the bearing inner ring excites the rotor three times per revolution leading to subcritical resonance at 1/3 of the natural frequency, with quadrangular (4th harmonic) roundness error at ¼ of the natural frequency etc. The amplitude of the harmonic components of the roundness error has a substantial effect on the vibration amplitudes [1,2].

Commercial roundness measuring machines are available for laboratory-scale measurements (diameter typically below 500 mm, length typically below 1000 mm). They typically utilize only one sensor for measuring the roundness profile, since the high-accuracy bearing of the roundness measuring machine confirms the accurate rotating motion of the workpiece. However, these machines cannot be used for large-scale rotor and bearing measurements due to the size of the objects. For example, rotors in the paper industry have diameters of over 1000 mm and a length of several meters up to 12 m. The roundness of slightly larger components can be measured with coordinate measuring machines, but the measurement uncertainty is larger than with roundness instruments.

Multipoint roundness measurement devices are typical in the paper and in the steel industry, where the roundness of the rolls is important for the quality of the end product. The measurement setup cannot prevent the rotational error of the centreline of the roll, and thus multipoint methods have to be used. Most of these roll roundness measurement applications rest on a three-point Ozono method, which uses three weighted sensor signals to calculate the roundness [8]. The control systems of the modern roll grinding machines enable the usage of the measured roundness profile for error compensation in the grinding process, where the roundness error has to be minimized [9–13]. Another multipoint method for spindle run-out separation is presented by Ref. [14]. In their study, the measurement system is implemented to measure the run-out of the spindle of a high precision turning lathe, and finally the roundness of the achieved workpiece.

The reliability of the measurement revealing the harmonic components of the roundness profile of an installed bearing inner ring is important for the manufacturing and quality control process of rotors with excellent dynamic properties.

Measurement uncertainty can be estimated with the GUM (Guide to the expression of uncertainty in measurement) method using a linear Taylor series [15]. The GUM method is fairly unambiguous and used commonly if the measurement method and model is simple, linear and well defined. However, for more complex measurements models, it is challenging to establish the sensitivity coefficients.

The GUM method was extended by applying Monte-Carlo simulations to evaluate the uncertainty [16]. The Monte-Carlo simulations enabled the introduction of randomised input quantities and the evaluation of their contributions to the measurement uncertainty. The benefit of the method is in using the true measurement model to evaluate the uncertainty, and thus a non-linear measurement model can be used [17–19].

The phase of the harmonic components of the roundness profile, or the uncertainty of the phase, has received little attention in previous research. However, the phase of the harmonic components is significant, when considering, for example, applications, where the roundness profile measurement data is used as a feedback for the precision manufacturing procedure (such as 3D predictive grinding for round workpieces, presented, e.g., by Kuosmanen [12]. The phase error of the harmonic component can affect the interpreted roundness profile in a way, which essentially doubles the error, when used as feedback data for the precision manufacturing process.

This paper presents a method to measure the roundness profile of a bearing inner ring, which is installed on a rotor shaft during the

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