Precision Engineering 48 (2017) 181–190

Contents lists available at ScienceDirect

Precision Engineering

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

# Application of Monte Carlo simulation for estimation of uncertainty of four-point roundness measurements of rolls

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ARTICLE INFO

*Article history:*
Received 15 July 2016
Received in revised form
18 November 2016
Accepted 1 December 2016
Available online 5 December 2016

*Keywords:*
Roundness
Paper machine roll
Harmonic amplitude
Monte Carlo
Measurement uncertainty

ABSTRACT

Large-scale rotors in the paper and steel industry are called rolls. Rolls are reground at regular intervals and roundness measurements are made throughout the machining process. Measurement systems for roundness and diameter variation of large rolls (diameter <2000 mm) are available on the market, and generally use two to four sensors and a roundness measurement algorithm. These methods are intended to separate roundness of the rotor from its movement. The hybrid four-point method has improved accuracy, even for harmonic component amplitudes. For reliable measurement results, every measurement should be traceable with an estimation of measurement uncertainty. In this paper, the Monte-Carlo method is used for uncertainty evaluation of the harmonic components of the measured roundness profile under typical industrial conditions. According to the evaluation, the standard uncertainties for the harmonic amplitudes with the hybrid method are below 0.5 μm for the even harmonics and from 1.5 μm to 2.5 μm for the odd harmonics, when the standard uncertainty for the four probes is 0.3 μm each. The standard uncertainty for roundness deviation is 3.3 μm.



## 1. Introduction

Roundness is defined by ISO 12181-1 [1] and ISO 12181-2 [2] as a geometrical property of a cross-section of a piece intended to be round. Roundness is an important feature of all rotating machines where smooth rotation of the rotors or even surface quality and even thickness of the end product are needed, such as paper machines, steel strip or sheet production, printing machines, engines and generators etc. In length metrology, diameter is often measured as a two-point measurement that is affected by out-of-roundness of the part. Measurements of roundness profiles are also useful when a specific harmonic component is critical or important, e.g. for vibration excitation. In laboratories, roundness measuring machines can measure deviation from roundness using a single sensor, as high-accuracy bearing assembly ensures that there is only a small rotational error in the radial direction [3–5].

In paper mills, roundness measurements are usually carried out with the roll placed on a lathe or grinding machine as shown in Fig. 1[1]. Heavy rolls rotate with their own bearings or are supported by sliding pads. With these measurement setups it is difficult to avoid a rotational error of the roll's centreline; thus one- or two-point measurement methods cannot properly separate this rotational error from the geometry of the workpiece – hence the usage of multi-point measurement devices in the paper industry [6]. Most of these devices are based on the Ozono method, where the roundness is calculated from weighted sensor signals in a given configuration around the rotor [7]. In the steel industry the roundness tolerances of the rolls are not as tight as in the paper industry, thus a two-point measurement device is used, which is well suited for diameter variation profile measurement. Generally, in steel strip and paper production the diameter and the diameter variation profiles are more important than the roundness [8–11].

The reliability of the measurement is naturally important for machined workpieces in production. Competitive production needs reliable information about the geometry of the workpiece or some specific dimension or feature of the workpiece, e.g. roundness profile. In modern machine tools for large scale rotors, i.e. in paper

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[1] Photo by RollResearch Int. Ltd.

http://dx.doi.org/10.1016/j.precisioneng.2016.12.001


**Fig. 1.** Four-point roll measuring device of a grinding machine.

or steel mills, the reliability of the onsite measurement device is important also for the error compensation of the roll grinder or lathe. The control systems of the machine tools use the geometry information provided by the measurement device for error compensation; thus the measured geometry must be accurate for the compensation to be correct [8,10,11].

Uncertainty of a measurement can be evaluated using the "GUM" method, which uses a linear Taylor expansion of the measurement model with sensitivity coefficients [12]. If the measurement model is simple, this method is straightforward and used extensively. However, once the measurement model becomes complex, as with measurement of rolls, the sensitivity coefficients are difficult to evaluate.

In 2008, "Supplements to the GUM" were published describing the use of the Monte-Carlo method for uncertainty evaluation [13]. Using the Monte Carlo method the measurement is simulated using input quantities which are random, but follows probability density functions relevant to each uncertainty contribution to the measurement [14–16]. Its strength is that non-linearity in the measurement model is not a problem.

In this paper, the principle of the four-point method is described first. The application of the Monte-Carlo method for an uncertainty evaluation is presented next, and finally the simulation results are reported and discussed.

## 2. Material and methods

### 2.1. Roundness and Fourier series

The roundness profile is typically presented in polar coordinates, but for analytical purposes a more relevant presentation is the use of Fourier series terms. For roundness profile characterization only terms with $n \geq 2$ are significant, because the term $n = 0$ denotes the offset of the signal, i.e. the DC value, and the term $n = 1$ stands for the eccentricity of the roundness profile. Therefore, our results include only the terms $n \geq 2$.

One of the most common Fourier analyses is done with the fast Fourier transform (FFT) algorithm developed originally by Cooley & Tukey [17]. The inverse FFT algorithm can be used to compose the original measurement signal in the time domain from these complex numbers. Filtering of some unwanted frequencies or components is straightforward. The complex number representing the unwanted frequency or component is set to zero before the inverse FFT, an example of which is shown by Mosier-Boss et al. [18]. In the analysed measurement signals of our research, the FFT algorithm

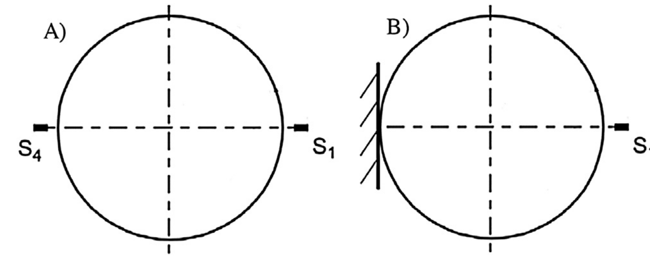


**Fig. 2.** Two-point measurement probes orientations with A) two sensors and B) one sensor.

is used both for identifying certain harmonic components and for filtering purposes.

### 2.2. Four-point roll roundness measurement

The studied four-point roundness measurement method is a combination of the two-point method and the Ozono three-point method. Both are briefly discussed here.

#### 2.2.1. Two-point method

The two-point method uses only two probes (Fig. 2A). In some applications, one of the probes can be replaced with a fixed point (Fig. 2B). Practical implementations of this type of device include modified roll callipers (see Fig. 3). These devices can also be used for absolute diameter measurements, if the distance between the probe and the follower or the distance between the two probes is known. Otherwise it can only measure the variation in the diameter when measuring a rotating object.

This method measures the diameter profile or diameter variation profile. In principle, the only difference between the two is that in variation profile, the average or minimum diameter value has been subtracted. The diameter variation measurement is commonly used for large roll grinding machines. There, the measured profile is inaccurately called the "roundness profile", although a two-point measuring method cannot measure the true roundness profile because it suffers from harmonic filtration. Using this type of diameter-measuring device one cannot measure odd lobe shapes like triangular, 5-lobe, 7-lobe etc. geometries, because the method is unable to separate the form error of the cross-section from the error motion of the rotating axis [8,19,20].

Calculation of the measured diameter variation profile of a workpiece with the two-point method is straightforward, and includes only addition or subtraction depending on the orientation of the probes. If the values of the probes increase in the direction of the increasing diameter, the measured diameter variation $\Delta d$ is:

$$\Delta d\left(\theta\right) = s_1\left(\theta\right) + s_4\left(\theta\right), \tag{1}$$

where $s_1$ and $s_4$ are measured sensor signals (see Fig. 3). Variation for radius $\Delta r$ is:

$$\Delta r\left(\theta\right) = \frac{s_1\left(\theta\right) + s_4\left(\theta\right)}{2}. \tag{2}$$

The harmonic amplitudes $D_n$ are then calculated by Fourier transform of the roundness profile

$$D_n = \mathcal{F}\left(\Delta r\left(\theta\right)\right), \tag{3}$$

where $n = 2,4.N/2$.

#### 2.2.2. Three-point Ozono roundness measurement method

One of the first numerical methods in the literature for assessing roundness is that by Ozono [7]. The method is complex, thus only the basic principles are presented here. The roundness profile is determined by measuring run-out $s_1(\theta)$, $s_2(\theta)$ and $s_3(\theta)$ at three