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USING MONTE CARLO SIMULATION FOR ESTIMATION OF UNCERTAINTY OF FOUR POINT ROUNDNESS MEASUREMENTS OF LARGE ROTORS

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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.

Index Terms – roundness, paper machine roll, harmonic amplitude, Monte Carlo, measurement uncertainty

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][4][5].

Fig. 1. Four point roll measuring device of a grinding machine.[1]

[1] Photo by RollResearch Int. Ltd.

In paper mills, roundness measurements are usually carried out with the roll placed on a lathe or grinding machine as shown in Fig. 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][9][10][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 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; and 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][15][16]. Its strength is that non-linearity in the measurement model is not a problem.

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 $n\geq2$ 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 $n\geq2$.

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 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. The two-point method has been used in, for example, calliper rules or measuring devices for conventional roll grinders and lathes. The three-point method can be used for roundness measurements [7]. The four-point method combines them in a more accurate way [19]. Fig. 2 illustrates the location and orientation of the probes and setup of a four-point device and Fig. 3 the analytic principle of the method. The idea of combining harmonics from different sets of measurements has also been used in the calibration of roundness standards [20].

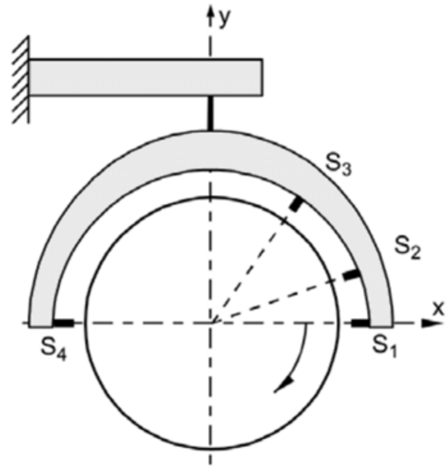

Fig. 2. Typical orientation of probes [S1-S4] in a four-point measurement system.

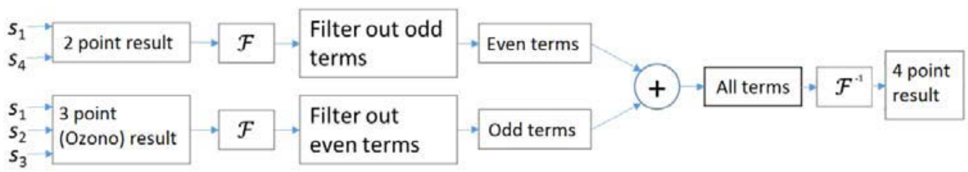

Fig. 3. Principle for the calculation of the hybrid four-point method ($\mathcal{F}$ = Fourier transform).

2.3. Measurement devices

There are several versions of the measurement device (one is in Fig. 1). All of them have four probes attached either directly to a frame or to four radially adjustable rods on a frame. The rods are used to bring the probes into the measurement position, if rotors with different diameters are measured. The simulations were based on the adjustable rod setup, which creates an additional source of error (rod alignment error, see Fig. 5).

The frame of the measurement device is made of carbon fibre due to its low thermal expansion coefficient and lightness. There are several alternatives for probes. Commonly used displacement probes are length gauges working internally with photoelectric scanning of a grating and a plunger with a ball touching the roll. For the chosen length gauge (Heidenhain MT 12) the measurement error was verified to be within ±0.2 µm when calibrated against a laser interferometer at the Finnish national metrology institute (VTT MIKES).

2.4. Test roundness profile

For testing and calibration of roundness measurement devices, discs with different roundness properties are used. In a previous work [21] calibration disc with a roundness profile containing 2-30 undulations per revolution (UPR) was designed and manufactured (Fig. 4). The roundness deviation of the profile was minimized by optimizing the phase angles of the individual harmonics. This roundness profile (Fig. 4) was used as the test roundness profile in this study.

2.5. Uncertainty evaluation by simulation

2.5.1. Probability distributions

In general, uncertainty evaluation or uncertainty budgets have been used to identify predominant uncertainty sources. In a typical "Classic Gum" approach, all uncertainty components are collected into one table together with sensitivity coefficients. As noted elsewhere [22], there is no counterpart to equivalent sensitivity coefficients in the Monte Carlo method. However, it is possible to run the Monte Carlo simulation with one uncertainty source at time while holding the other input quantities fixed at their best estimates [22]. A 'non-linear' sensitivity coefficient can be defined from the results [22].

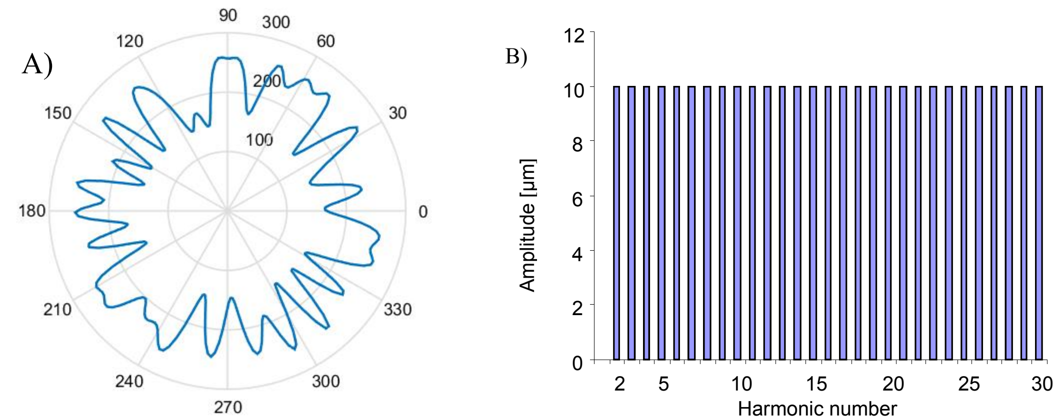

Fig. 4. A) Test roundness profile with harmonics 2 –30 UPR. B) Designed lobe amplitudes of the roundness profile.

The profile used in the simulation was the profile used for calibration disc as discussed previously and shown in Fig. 4. The algorithm doing the calculations for the four-point method was acquired as an executable program, which takes measured data as an input file and calculates the harmonic amplitudes as a result of roundness. The principle for the Monte Carlo simulation is to generate synthetic data representing a roundness measurement, distorted with suitable distributions for error contributions. Next, uncertainty evaluation inputs are presented for a four-point measurement system in industrial use. The assumed uncertainty contributions are based on experience in typical industrial environments. The probability distribution functions (PDF) are assumed to follow a normal distribution where the standard deviation is a property of the variation of input values.

Expected error sources are the probes themselves and their angular orientation and positioning. Thermal expansion and vibration of the measurement frame and movement of the centreline are other possible sources. The position of a length probe in the Ozono method should be at either 0°, 38°, 67° or 180° in polar co-ordinates (see Fig. 2). It is assumed that these positions differ from the nominal angular values with a standard uncertainty of 0.5° (Fig. 5).

A standard uncertainty of 0.3 µm for the scale error of length probes is assumed based on calibrations and experience. The temperature of the instrument is assumed 20°C, with a standard uncertainty of 0.5°C. One measurement typically takes 10 to 30 s to complete. The effect of temperature is taken as a linear expansion of the whole measurement device during the measurements. Far more complex temperature effects may occur in different industrial environments, e.g., when measuring hot or warm workpieces. Modelling of these should be based on real temperature measurements and different scenarios and is outside the scope of this paper.

For length probes, an assumed alignment error with standard uncertainty of one degree is estimated. The resulting cosine error for an effective length of 1 mm is about half of the scale error of the probes and can be omitted, as preliminary analysis showed that also the scale error is of minor significance. In all roundness measurements of rolls, there is also some movement of the centreline of the roll, but this is not studied in this paper.

Significant error sources with their probability density functions are shown in Table 1. As there are four rods with probes, the number of separately simulated quantities is ten.

Table 1. Selected significant error sources. The notation of the PDFs follows specific guidelines [13].

Quantity	**PDF**	**Parameters**			
		μ	σ	a	b
Alignment of the rods	$N(\mu, \sigma^2)$	0°	0.5°		
Scale error of the probe	$N(\mu, \sigma^2)$	0°	0.3 µm		
Temperature change	$N(\mu, \sigma^2)$	20°C	0.5°C		

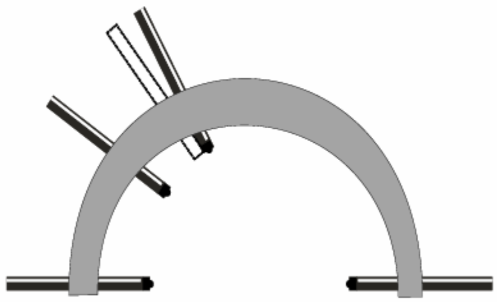

Fig. 5. Alignment/position error of a rod.

A script, written in Python and using the SciPy mathematical package, generates input data files representing simulated measurement data containing the desired PDFs and calls the executable analysis program for the four-point method. From a test run with no error contributions from the probes etc., the result shows that the algorithm works well. The Monte Carlo simulation with the PDFs of Table 1 is done with a large number of test runs, and from the results the mean and standard deviations of the outputted harmonic components is calculated. To evaluate the sensitivity for each uncertainty source, simulations are done with one error source at a time for alignment, probe error and temperature change. The standard deviation << was set to 1.0° for alignment, 1.0 µm for scale error and 1.0°C for temperature change. These results are relative to the selected << value and serve to illustrate virtual sensitivity as discussed earlier.

3. RESULTS AND DISCUSSION

The output from the Monte Carlo simulations with 10 000 runs is shown in Figs. 6 and 7, where the different standard uncertainties are shown as error bars. Each simulation with 10 000 runs took half an hour on a Windows PC with Intel i7 processor. Fig. 6 shows the output from a simulation run with no error sources. This simulation demonstrates the method in conditions where the σ values of PDFs of the measurement instrument are set to zero. The result shows that the method measures under ideal conditions the roundness well.

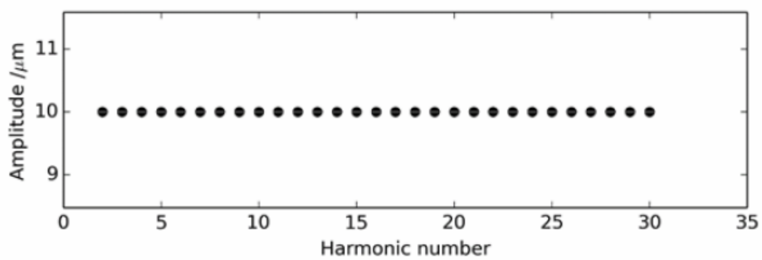

Fig. 6. Output from Monte Carlo simulation with no error sources.

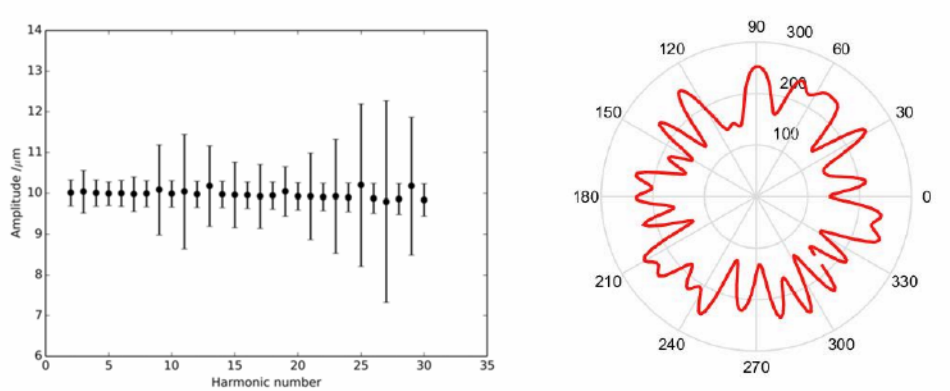

Fig. 7. Output from Monte Carlo simulation where the standard uncertainties are shown as error bars for the harmonics (left) and the average of simulated results as a polar plot (right).

The result shown in Fig. 7 is from a simulation run with all the error sources listed in Table 1. This represents the measurement uncertainty of the method under assumed typical measurement conditions in the industry. The uncertainties of the odd harmonic amplitudes are generally higher than for the even harmonics. This is a feature of the hybrid measurement method, where odd harmonics are calculated with the Ozono method and even harmonics with the two-point method. The deviation was also analysed from the simulated roundness. Fig. 7 also shows the average roundness curve, and from the results the standard uncertainty for roundness deviation was evaluated at 3.3 µm when filtered with a Gaussian filter with cut-off UPR 30.

4. CONCLUSIONS

Knowledge of measurement uncertainty is a fundamental requirement arising from both practical problems, scientific issues and quality systems. Measurement of rolls in an industrial environment using a four-point measurement device is an example of a measurement with large economic impact where knowledge of measurement uncertainty has been weak or non-existent. The influence of several uncertainty components is analysed and discussed. The results are characteristic of the hybrid four-point method, although unstable temperature conditions or the presence of vibrations may make additional uncertainty contributions in a very rough industrial environment.

With the present assumptions, the four-point hybrid algorithm works well. This in conformance with the good experience from industrial use. We also conclude that the predominant uncertainty contribution for a four-point measurement instrument is the positioning of rods of the probes S2 and S3. According to our evaluation, the standard uncertainties for harmonic amplitudes with the hybrid method are below 0.5 µm for even harmonics, and from 1.5 µm to 2.5 µm for odd harmonics. The uncertainties of the odd harmonic amplitudes are generally higher than for the even harmonics. The evaluated uncertainties are in line with measurements using a calibration disc.

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6. REFERENCES

[1] ISO 12181-1:2011 Geometrical product specifications (GPS) -- Roundness -- Part 1: Vocabulary and parameters of roundness (International Organization of Standardization). 13p

[2] ISO 12181-2:2011 Geometrical product specifications (GPS) -- Roundness -- Part 2: Specification operators (International Organization of Standardization). 9 p

[3] Neugebauer M. Uncertainty analysis for roundness measurements by theexample of measurements on a glass hemisphere. Meas Sci Technol2000;12:68-76.

[4] Thalmann R, Spiller J, Küng A, Jusko O. Calibration of Flick standards. Meas SciTechnol 2012;23(9):7p.

[5] Haitjema H, Bosse H, Frennberg M, Sacconi A, Thalmann R. Internationalcomparison of roundness profiles with nanometric accuracy. Metrologia1996;33(1):67-73. [4] Ozono S. (1974). On A New Method Of Roundness Measurement On The Three Point Method, Proceeding of the ICPE, pp 457-462, Tokyo, Japan, 1974

[6] Kiviluoma P. Method and device for in situ runout measurement of calenderthermo rolls. Doctoral dissertation. Espoo: Helsinki University of Technology;2009. ISBN 978-952-248-259-4.

[7] Ozono S. On a new method of roundness measurement on the three pointmethod. Proceeding of the ICPE, vol. 1974. 1974. p. 457-62.

[8] T. Widmaier, 2012. Optimisation of the roll geometry for productionconditions. Aalto University Publication Series Doctoral Dissertations156/2012. 184 p. ISBN 978-952-60-4878-9.

[9] J. Juhanko, 2011. Dynamic Geometry of a Rotating Paper Machine Roll,Doctoral Dissertations. Aalto University Publication Series 117/2011. 172 p.ISBN 978-952-60-4363-0.

[10] Kotamäki M. In-situ measurement and compensation control in externalgrinding of large cylinders. Helsinki: Acta Polytechnica Scandinavica; 1996.Mechanical Engineering Series No. 121, 123 p.

[11] Kuosmanen P. Predictive 3D roll grinding method for reducing paper qualityvariations in coating machines. Espoo: Helsinki University of Technology;2004. Publications in Machine Design 2/2004, ISBN 951-22-7014-5.

[12] BIPMIEC, IFCCISO, IUPACIUPAP, OIML. Guide to the expression of uncertaintyin measurement, vol. 100. International Organization for Standardization,JCGM; 2008. GUM 1995 with minor corrections. Corrected version 2010.

[13] BIPMIEC, IFCCISO, IUPACIUPAP, OIML. Evaluation of measurement data -supplement 1 to the Guide to the expression of uncertainty in measurement -Propagation of distributions using a Monte Carlo method, vol. 101. JCGM;2008.

[14] Brizard M, Megharfi M, Verdier C. Absolute falling-ball viscometer: evaluationof measurement uncertainty. Metrologia 2005;42(4):298-303.

[15] Wübbeler G, Krystek M, Elster C. Evaluation of measurement uncertainty andits numerical calculation by a Monte Carlo method. Meas Sci Technol2008;19(8):4p.

[16] MAA Morel, H. Haitjema;, Task-specific uncertainty estimation for roundnessmeasurement, 3rd International Euspen Conference, Eindhoven, Netherlands,513-516, 2002 Proc. of the 3rd euspen International Conference, Eindhoven,The Netherlands, May 26th-30th, 2002.

[17] Cooley JW, Tukey JW. An algorithm for the machine calculation of complexFourier series. Math Comput 1965;19:297-301.

[18] Mosier-Boss PA, Liebermann SH, Newbery R. Fluorescence rejection in ramanspectroscopy by shifted-spectra, edge detection, and FFT filtering techniques.Appl Spectrosc 1995;49(5):630-8.

[19] Väänänen P. Turning of flexible rotor by high precision circularity profilemeasurement and active chatter compensation. Licentiate's thesis. Espoo,Finland: Helsinki University of Technology; 1993, 104 p.

[20] Hemming B, Widmaier T, Palosuo I, V.-P- Esala, Laukkanen P, Lillepea L, et al.Traceability for roundness measurements. DAAAM Conference, vol. 2014.2014.

[21] Widmaier T, Hemming B, Palosuo I, Esala V-P, Laukkanen P, Brabandt D, et al.New material standards for traceability of roundness measurements of largescale rotors. 9 p. Proceedings of the 58th Ilmenau Scientific Colloquium, vol.2012. 2014.

[22] Harris PM, Cox MG. On a Monte Carlo method for measurement uncertaintyevaluation and its implementation? Metrologia 2014;51(4):S176-82.

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