Good Practice guide to measure roundness on roller machines and to estimate their uncertainty

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We gratefully acknowledge the funding from the European Metrology Research Programme (EMRP). The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

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1 Introduction

Large scale rotors in the paper and steel industry are called rolls. These rolls are periodically reground and roundness measurements are made throughout the machining process. Dimensional measurement systems for large rolls (diameter < 2000 mm) are available on the market.

2 Determination of roundness measurement uncertainties using the R-MS

The measurement standards are intended to quantify error sources found in three point measurement systems and in four point measurement systems (Figure 1). The developed measurement standards are also useful for calibration of two-point and one-point measurement systems. The name “in process roundness measurement systems” will be used for these all categories in this guide.

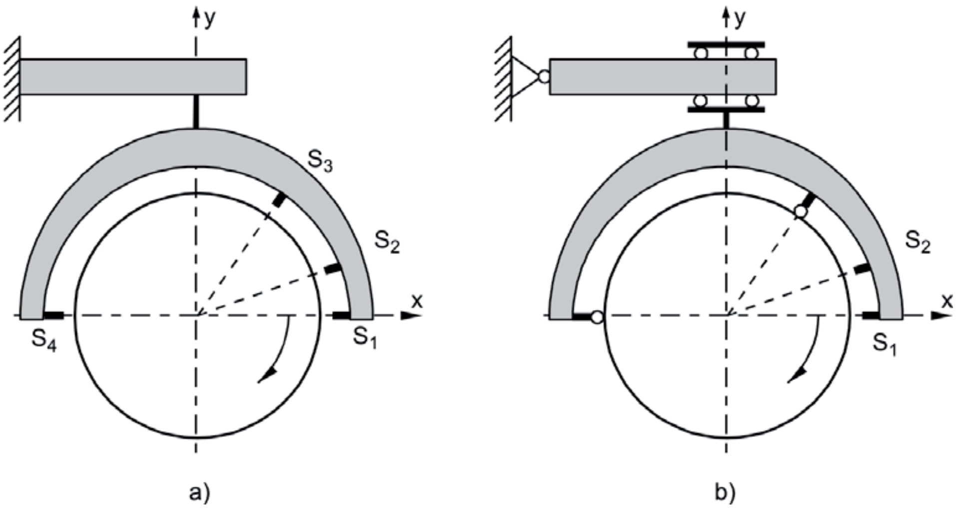


Figure 1. Typical orientation of probes in a four point measurement systems

All standards are discs with the diameter of 500 mm – 550 mm. This is the largest diameter that can be easily measured both in laboratories and not too small to be measured by in process roundness measurement systems in industry. The thickness of the discs will be 30 mm – 50 mm. The requirements are shown in table 1.

Table 1. Requirements for the measurement standards (R-MS).

Name	Form	Roundness error / µm
R-MS, type A	round	0 µm – 2 µm
R-MS, type B	21 UPR	20 µm – 25 µm
R-MS, type C	extended multiwave, 2 UPR – 30 UPR	10 µm / undulation

The type A standard is almost perfectly round, still not too expensive to manufacture. With a roundness error below 2 µm this standard helps to reveal errors like noise and thermal drift. Type B is selected as it has one characteristic form of a 21 UPR wave. The propagation of error of single probes at in process roundness measurement systems is expected to be revealed by this disc. The type C, extended multi wave, consists of several waves. Standards of this type have previously been used and they are expected to work as overall test standard. All standards are calibrated by roundness measuring instrument with rotary table. The measurement standards are intended to quantify error sources found in three point measurement systems and in four point measurement systems (see Figure 2).

Figure 2. Setup for the measurement of roundness, cylindricity and diameter using a multi-point measurement device.

In Figure 3 is shown a polar plot of disc C measured using a roundness instrument at MIKES. Additional tests with the manufactured calibration disc type C were carried out on three sites: with the four-point roll geometry measurement device (RollCal 3) at an industrial partner (IP), with the four-point measurement device (own model) at Aalto University and with the CMM (Legex 9106) at MIKES (Figure 4).

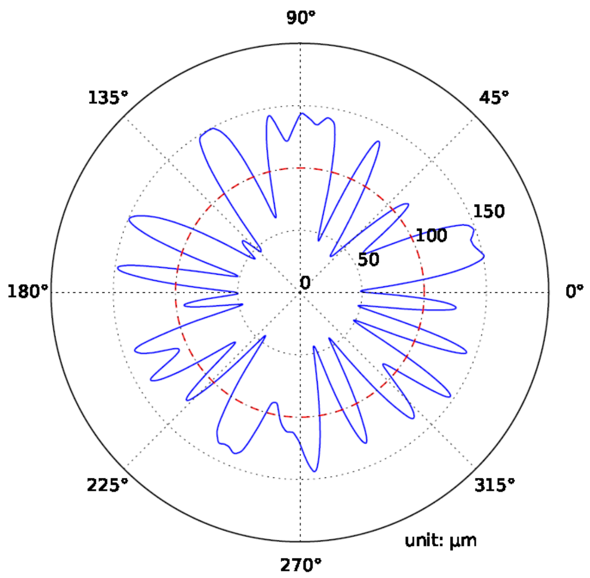


Figure 3. Polar plot of disc type C.

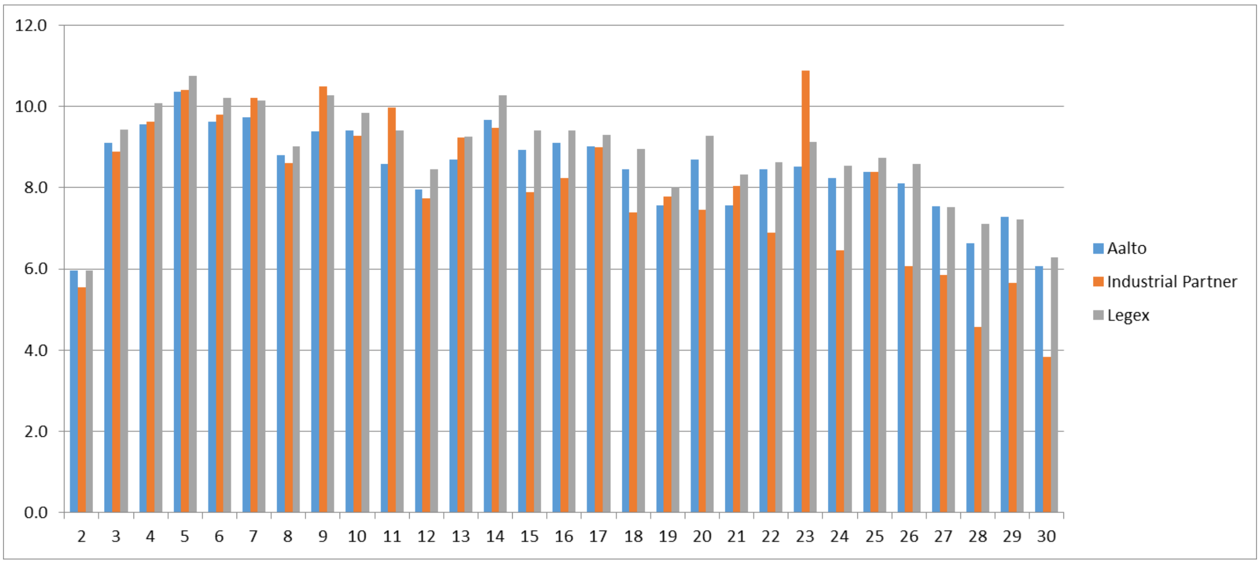


Figure 4. Comparison of the measurement results of the harmonics of the calibration disc type C made on three different sites.

In appendix 1 an Acceptance test for roll grinding machine is given.

3 Determination of roundness measurement uncertainties using Monte Carlo simulation

3.1 Four-point roll roundness measurement

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

3.1.1 Two-point method

The two-point method uses only two sensors. For some applications the other sensor can be replaced by a fixed point, see Figure 5 right hand side. Practical implementations of this kind of measurement devices are modified roll mikes or roll calipers, see Figure 6.

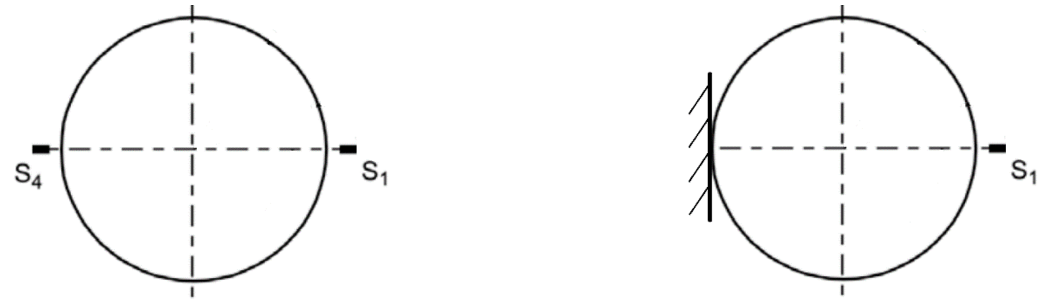


Figure 5. Two-point measurement transducer orientations and locations of a round workpiece.

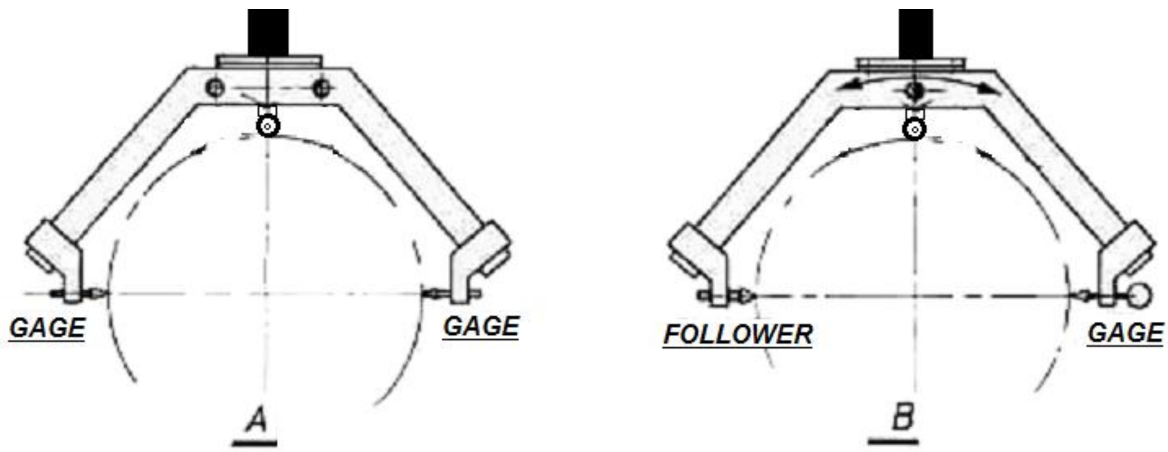


Figure 6. Modified saddle-type roll calipers for two-point measurement. A) With fixed arms. B) With swing arms.

This method measures the diameter profile or diameter variation profile. In principle, the only difference between the diameter variation profile and diameter profile is that the from the variation profile the average or the minimum diameter value has been subtracted. The diameter variation measurement is commonly used in large roll grinding machine. There the measured profile is often called “roundness profile”, although two-point measuring method cannot measure the true roundness profile, because it suffers from a harmonic filtration, as shown in Figure 7, where a Relaux triangle is illustrated. 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 geometry error of the cross-section from the error motion of the rotating axis.

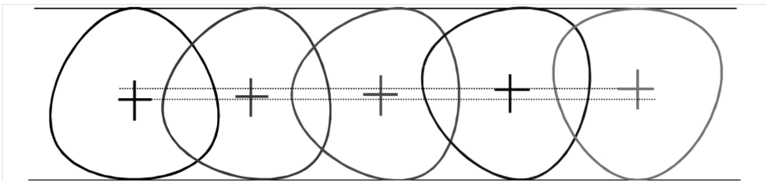


Figure 7. Two point measurement cannot be used to measure odd lobe geometry errors, because the method suffers from harmonic filtration, i.e., the method cannot separate the odd lobe geometry error from the error motion of the rotating axis.

The calculation of the measured value is straight forward and includes only addition or subtraction, depending on the orientation of the transducers. If the values of the used transducers increase in the direction of the increasing diameter, then the measured diameter variation value is:

$$\Delta d(\theta) = s_1(\theta) + s_4(\theta). \tag{1}$$

3.1.2 Three-point Ozono roundness measurement method

In the literature one of the first numerical methods for assessing roundness is presented by Ozono.The method is complex and only basic principles are presented here. The roundness profile is determined by measuring run-out $s_1(\theta)$, $s_2(\theta)$ and $s_3(\theta)$ from three different angles denoted γ_1, γ_2 and γ_3. In practice, the first angle is set as γ_1=0, see Figure 8.

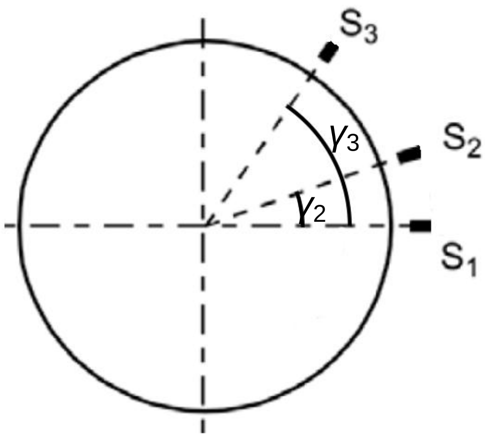


Figure 8. Orientation and location of the three run-out measurement transducers of the Ozono method.

A sampling function $m(k)$ is introduced and denoted as

$$m(k) = s_1(\theta) + w_2 s_1(\theta) + w_3 s_1(\theta) \tag{2}$$

where k = 0, 1, 2, …, N-1.

The idea is to eliminate centre point motion by using eq. (6) with appropriate weighting factors w_2 and w_3. The weighting factors w_2 and w_3 are derived from conditions

$$\sin\gamma_1 + w_2 \sin\gamma_2 + w_3 \sin\gamma_3 = 0 \text{ and} \tag{3}$$

$$\cos\gamma_1 + w_2 \cos\gamma_2 + w_3 \cos\gamma_3 = 0. \tag{4}$$

Kato et al. have developed a numerical method to optimize the measuring angles resulting in

$$\gamma_1 = 0°,$$
$$\gamma_2 = 38° \quad \text{and}$$
$$\gamma_3 = 67°.$$

As a function of observation angles the weighting factors w_2 and w_3 can be expressed

$$w_2 = \frac{-\sin\gamma_3}{\sin(\gamma_3 - \gamma_2)} \text{ and} \tag{5}$$

$$w_3 = \frac{\sin\gamma_2}{\sin(\gamma_3 - \gamma_2)}. \tag{6}$$

Previous studies show that the sensitivity of the algorithm is at the best with no major harmonic filtration when the number of lobes per revolution is below 35.

3.1.3 Hybrid four-point roundness measurement

One of the multi-point methods commonly used in the roll geometry measurement devices of the roll grinding machines is the so called Hybrid four-point method. The method behind the Hybrid four-point measurement device is based on the three-point Ozono method, but in a combination with the two-point (diameter) measurement method. The two-point measurement method suffers, as mentioned before, from a harmonic filtration, and thus making it unsuitable for the measurement of the odd numbered harmonic lobes of a roundness profile, but the even numbered harmonic lopes are measured accurately. The Hybrid four-point method presented originally by Väänänen[1] uses the Ozono method to measure the odd numbered harmonic lopes and combines the result with the even numbered lopes measured with the two-point method.

The principle is shown in Figure 10 and the roundness profile S can be expressed as

[1] Väänänen P. (1993). Turning of flexible rotor by high precision circularity profile measurement and active chatter compensation. Licentiate's thesis. Helsinki University of Technology, Espoo, Finland. 104 p.

$$s = f(s_1, s_4) + g(s_1, s_2, s_3) \tag{11}$$

where f is the function for the two point method and g is the function for the Ozono method. In theory the Hybrid four-point method ensures an overall better accuracy compared with Ozono or two-point method alone.

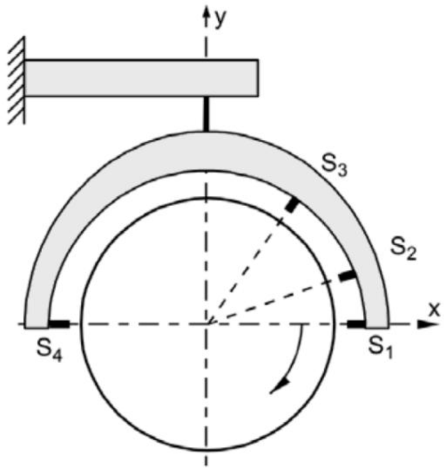


Figure 9. Orientation of probes [S1-S4] in a four-point measurement system when measuring a round workpiece.

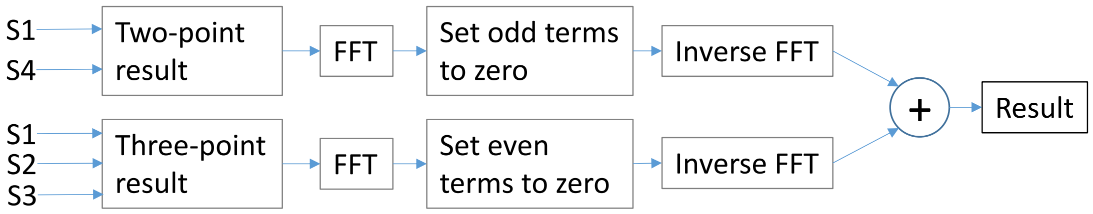


Figure 10. Principle of the hybrid four-point method.

3.1.4 Probes

There are several alternatives for probes. Commonly used displacement probes are length gauges internally working with photoelectric scanning of a grating and using a plunger with a ball contacting the roll. For a chosen length gauge (Heidenhain MT 12) the error was verified to be within ±0.2 µm when calibrated against laser interferometer at the Finnish national metrology institute MIKES (Calibration Certificate M-08L056, 2008). The probes are mounted on measurement rods which are attached the measurement frame. Different versions with different measurement heads exist.

Figure 11. Measurement rod with MT12 probe.

3.2 Uncertainty evaluation by simulation

3.2.1 Roundness profile used in simulation

For testing and calibration of roundness measurement devices discs with different roundness properties are used. An example of such a disc is shown in Figure 12. In previous work a roundness profile containing 2-30 UPR was designed and manufactured (Figure 13). The roundness deviation of the profile was minimized by optimizing the phase angles of the individual harmonics.

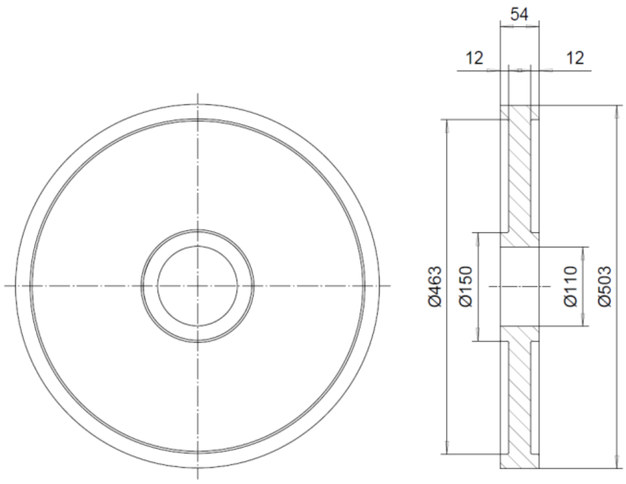
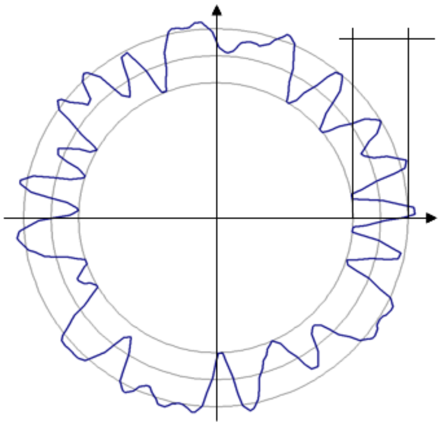


Figure 12. Calibration disc.



b)

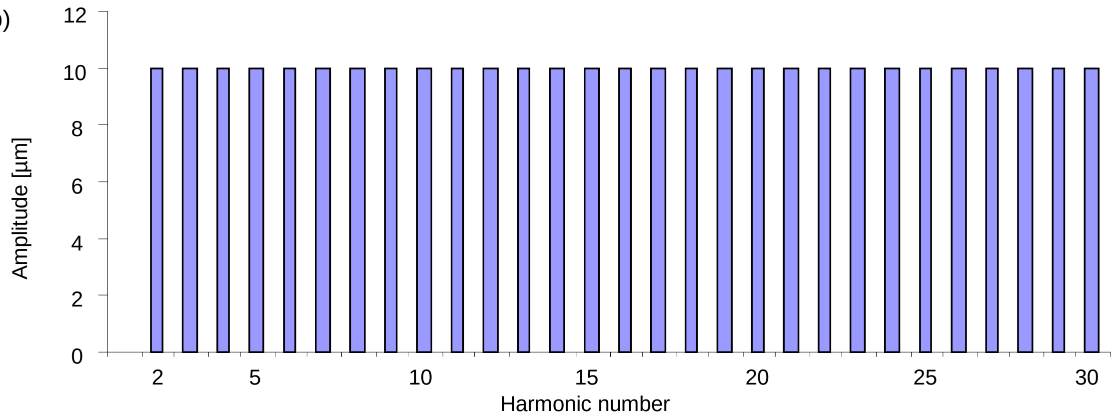


Figure 13. a) Designed test profile with 2 –30 UPR. b) Designed wave amplitudes of the test profile.

3.2.2 Probability distributions

Typically uncertainty evaluation or uncertainty budgets have been used to identify the dominating uncertainty sources. In a "Classic Gum" approach all uncertainty components are collected in one table together with sensitivity coefficients. There is no counterpart to equivalent sensitivity coefficients' in Monte Carlo method. However, it is possible to run the Monte Carlo simulation with one uncertainty source at time and holding the other input quantities fixed at their best estimates Hence, a 'non-linear' sensitivity coefficient can be defined.

The algorithm doing the calculations for the four point method (eq. 11) was acquired as an executable program. This program takes measured data as input file and calculates the harmonic amplitudes as 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 inputs for uncertainty evaluation for four point measurement system in industrial use are presented. The assumed uncertainty contributions are based on experiences made 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.

The error sources which are expected to be found are errors of the transducers, angular orientation error and positioning error of transducers. Thermal expansion and vibration of the measurement frame are other possible error sources. The position of a length transducer in the Ozono method should be at either 0°, 38°, 67° or 180° in polar co-ordinates. It is assumed that these positions differ from the nominal angular values with a standard uncertainty of 0.5° (Figure 14).

A standard uncertainty of 0.3 µm for scale error of length transducers is assumed, based on specification from manufacturer. This might be a pessimistic assumption as experience from calibration indicate better accuracy (see section 3.1.4).

The temperature of the instrument is assumed to be 20 °C and a standard uncertainty of 0.5 °C for temperature is assumed. One measurement takes typically 10 to 30 s to complete. The effect of temperature is taken as a linear expansion of the whole measurement device during the measurements. Much more complex temperature effects may occur in different industrial environments, e.g., when measuring warm workpieces. These should be based on real measurements and different scenarios and is not in the scope of this paper.

For length transducers an assumed alignment error with standard uncertainty of one degree can be assumed. The resulting cosine error for an effective length of 1 mm is about half of the scale error of the transducer and can be omitted as preliminary analysis showed that also the scale error is of minor significance.

The significant error sources with their probability density functions (PDF) are shown in Table 2. As there are four rods with transducers the number of separately simulated error sources is nine.

Table 2. Selected significant error sources. The PDF's have normal distribution with expectation μ and standard deviation σ.

Quantity	PDF	μ	σ
Alignment/position of the rods	$N(\mu, \sigma^2)$	0 °	0.5 °
Scale errors of the transducers	$N(\mu, \sigma^2)$	0°	0.3 μm
Temperature of the instrument	$N(\mu, \sigma^2)$	20 °	0.5 °C

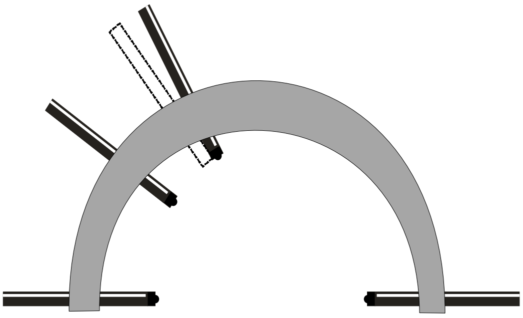


Figure 14. Alignment/position error of a rod.

A script written in Python and using Scipy mathematical package generates input data files representing simulated measurement data with containing desired PDF's and calls the executable analysis program for the four point method. From a test run with no error contributions from the transducers etc. the result shows that the algorithm works well. The Monte Carlo simulation with the PDF's of Table 2 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 sensitivity for each uncertainty source simulations with one source at time shown in Table 3 was also done. These results are relative to selected σ value and serve to illustrate virtual sensitivity discussed earlier.

Table 3. Error sources for sensitivity analysis evaluated with one error source at time.

Quantity	PDF	μ	σ
Alignment/position of the rods	$N(\mu, \sigma^2)$	0 °	1 °
Scale errors of the transducers	$N(\mu, \sigma^2)$	0 μm	1 μm
Thermal expansion during a measurement	$N(\mu, \sigma^2)$	0 °C	1 °C

The output from the Monte Carlo simulation is shown in Figure 15 to Figure 19 where the different standard uncertainties are shown as error bars. A simulation with 10 000 runs took 5 hours on a windows PC with Intel i7 processor. In Figure 15 the output from a simulation run without error sources is shown. This simulation demonstrates the method in ideal conditions where the σ values of all PDF's are set to zero.

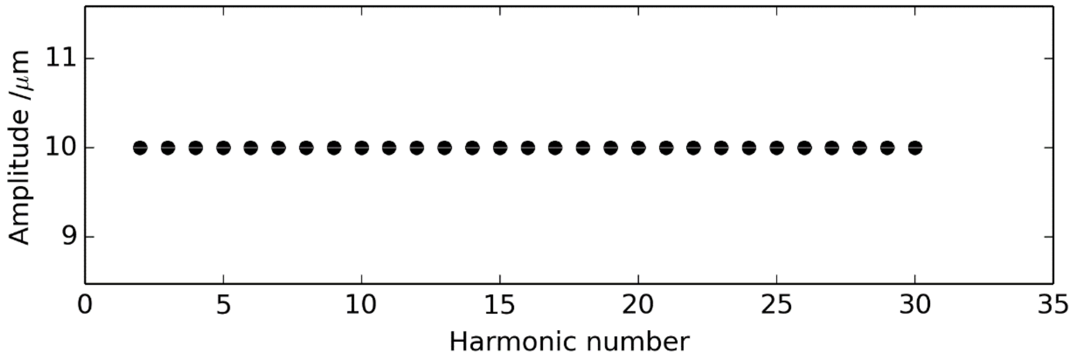


Figure 15. Output from Monte Carlo simulation (N = 10 000) where the different standard uncertainties are shown as error bars. This simulation was run without any error sources to get a result about the ideal amplitude values.

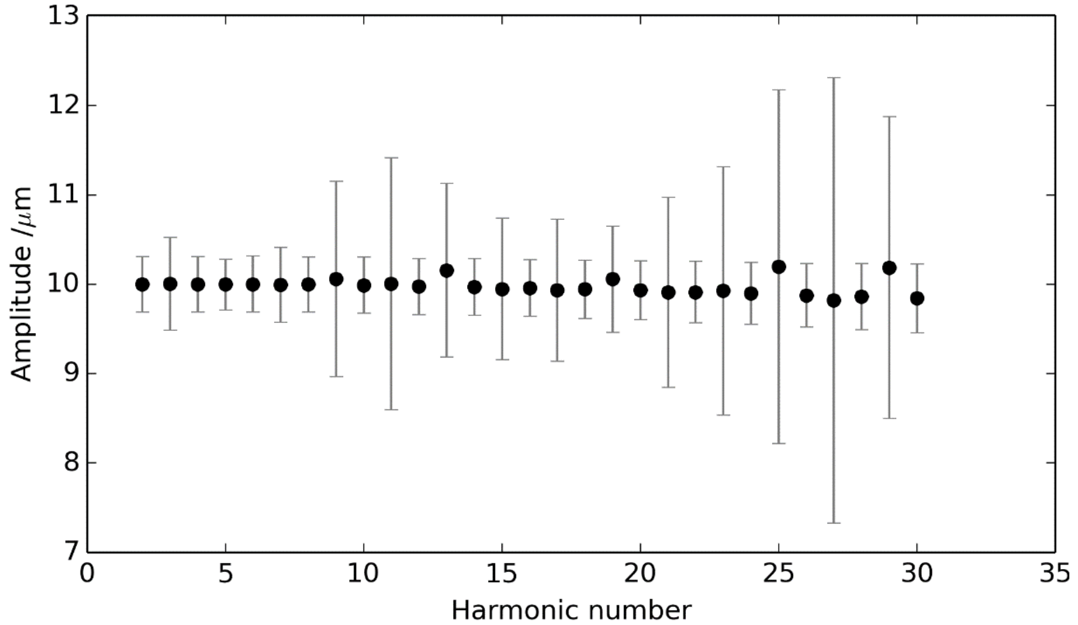


Figure 16. Output from Monte Carlo simulation (N = 10 000) where the different standard uncertainties are shown as error bars. This simulation was run with all the specified error sources from Table 1.

The result in Figure 16 is the simulation run with all the error sources from Table 1. This represents measurement uncertainty of the method under assumed typical measurement conditions in the industry. The uncertainties of the odd harmonic amplitudes are generally higher than of the even harmonics. This is a feature of the Hybrid measurement method, where the odd harmonics are calculated with the Ozono method and the even harmonics with 2-point method.

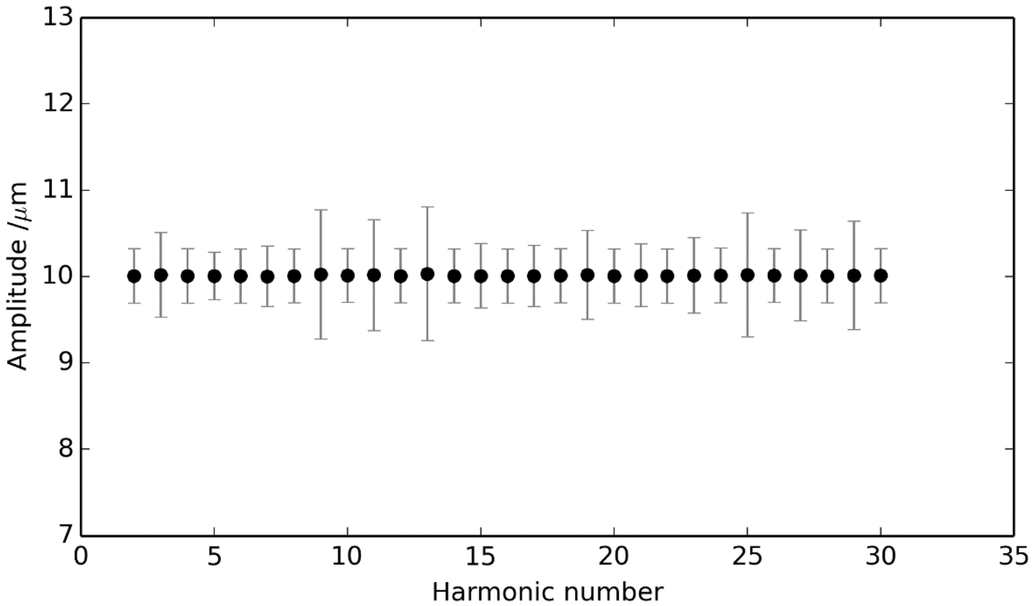


Figure 17. Output from Monte Carlo simulation (N = 10 000) where the different standard uncertainties are shown as error bars. This simulation was run with thermal error sources from Table 2 (σ=1 °C).

The sensitivity results with the thermal error source show similar increase in the uncertainties of the odd harmonic amplitudes (Figure 17) and the reason for this is also the same: the different calculation method for odd and even harmonics.

The sensitivity results with the four different probe error sources show very small uncertainties for all of probes (Figure 18). It seems that the Hybrid four-point roundness measurement method is robust and not sensitive to probing error. However with Monte Carlo uncertainty evaluation there is always a danger that the errors are averaged out too much. This happens if the error source in reality is not as random as it is assumed with normal distribution and zero expectation value μ. Some experiments are required before the low sensitivity for probing error can be finally concluded. These studies would include autocorrelation of points measured with one probe and cross correlation for data between several probes. The probes are insensitive to small alignment errors (cosine error) because their magnitude is negligible compared to other error sources.

The rod alignment error sensitivity simulations produced clear uncertainties for the odd harmonic amplitudes for the rods S1 to S3. S1 and S4 have very small uncertainties for the even harmonic amplitudes. The results are presented in Figure 19.

The Hybrid four-point roundness measurement method is similar to the Ozono method sensitive to the errors in the S2 and S3 run-out signals, which is natural because the Ozono method used as part of the roundness calculation. Temperature variation affect the measurement result noticeably, but the short measurement time decreases the effect and there is normally no need to measure hot or warm workpieces, because their geometry changes with the temperature change.

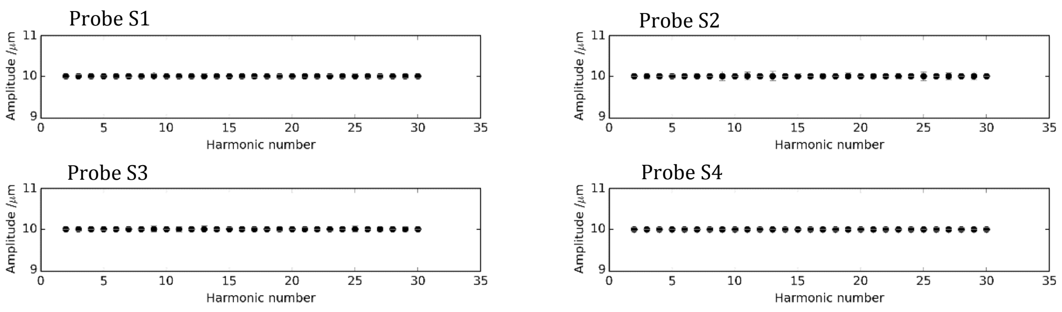


Figure 18. Outputs from four Monte Carlo simulations (N = 10 000) where the different standard uncertainties are shown as error bars. These simulations were run with the probe error value from Table 2 (σ=1 μm).

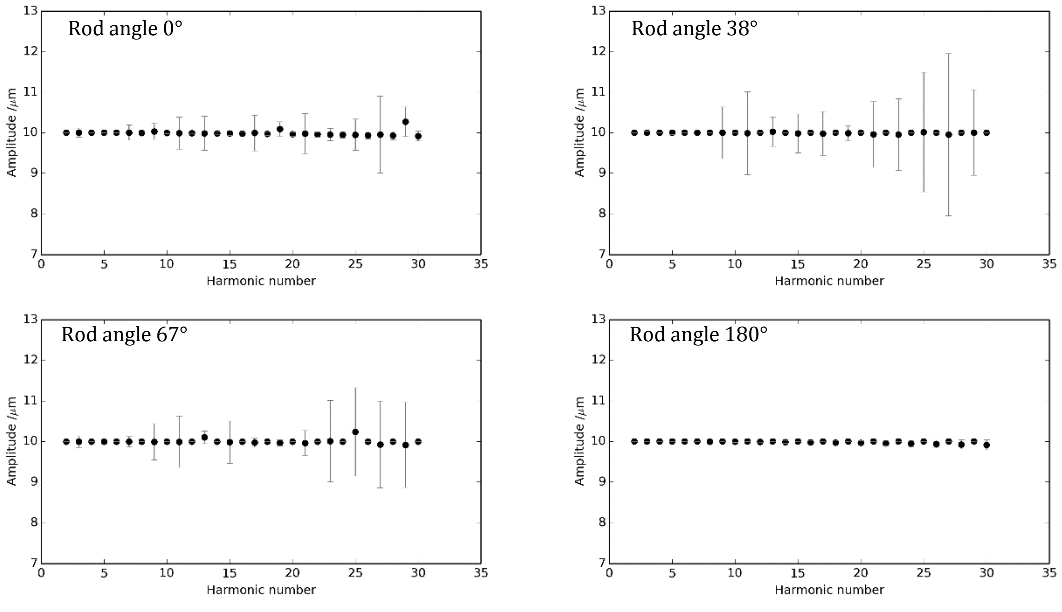


Figure 19. Outputs from four Monte Carlo simulations (N = 10 000) where the different standard uncertainties are shown as error bars. These simulations were run with the rod alignment error (σ=1°).

4 Conclusion

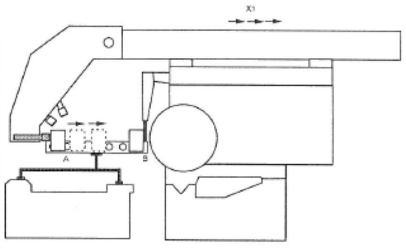
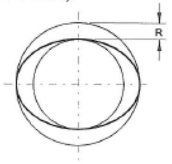
Using Monte Carlo simulation the uncertainties can be calculated. Naturally the any end-user may adjust the input values for the simulation according to actual environmental conditions.

Using material standards the uncertainties should be checked for validity.

5 References

[1] ISO 15530-3: 2004, *Geometrical Product Specifications (GPS) – Coordinate measuring machines (CMM): Technique for determining the uncertainty of measurements – Part 3: Use of calibrated workpieces or measurement standards*

6 Appendix 1. Acceptance test.

Acceptance Test *for CNC Roll Grinding Machine (paper industry type)*			Machine Type: Serial No.:		Sheet: 3 (8)	Revision: 1.4
No.	**Subject of check**	**Diagram**	**Tolerance**	**Measured deviation**	**Measuring Instruments**	**Method of check**
6 6.1	**Measurements** **Absolute diameter measurement** a) Repeatability b) Accuracy Measurement of abs. diameter calibration curve table		a) 0.02 mm b) 0.1 mm		For calibration: • Calibration instrument: linear scale and straight edge • Grinding machine's own measuring system a) Grinding machine's own measuring system b) • Calibration instrument: large micrometer • Grinding machine's own measuring system	Calibration curve: • Set calibration instrument between sensor arms S1 and S4. • Set calibration instrument at maximum diameter • Displace X1 by CNC handwheel by approx. 30-50 mm steps. Set S1 in same value each time. • Write down values of both measuring devices or use program • Store calibration curve in CNC program. a) • Use CNC program for the repeatability measurements • Measurements at roll center • Run program 5 x consecutively, time: max. 15 min. b) • Select test roll, same as in Item 6.3 • Measure diameter value by micrometer • Measure diameter value by grinding machine • Compare results
6.2	**Roundness measurement** ***Measurement of roundness profile from a test disc*** a) Repeatability b) Accuracy	**Definition of roundness R:** The tolerance zone, in the considered cross-section, is limited by two concentric circles with a difference in radii of R (ISO 1101: 2004):  R = Roundness	a) 0.001 mm b) 0.003 mm		• Calibration disc with certain measured roundness profile A, measured in accredited calibration laboratory • Grinding machine's own 4-point measuring system	• Set calibration disc on the end of test roll's shaft or use a separate shaft • Run program 5 x consecutively, time: max. 15 min. • Rotational speed 3-6 r/min a) • Repeatability: max variation between test results. b) • Accuracy: Compare results with profile A • Add accuracy of measurement **A** to tolerance.