BASICS OF HIGHEST ACCURACY ROUNDNESS MEASUREMENT

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Abstract: A primary roundness measurement is independent of any standard due to the application of error separation techniques, and it is based on a complete characterization of all relevant influence quantities. The described roundness tester at METAS is based on a commercial instrument, but has undergone several modifications in order to achieve highest roundness measurement accuracy. It is equipped with a rotating spindle with an incremental encoder and an oil-hydrostatic bearing, driven by a vibration free DC motor with variable rotation speed. It further exhibits low noise amplifier electronics with selectable gain for the LVDT probe, new software for data acquisition and evaluation, and a heat protection shield. The software offers access to all relevant signals and allows for data manipulation such as averaging, noise analysis, drift monitoring, error separation with multi-step procedure, Gaussian filtering in the Fourier space, spectral analysis or mapping of the pre-determined spindle error. Experimental results on a standard sphere and on a multi-wavelength standard are presented and the uncertainty budget is discussed.

1. INTRODUCTION

The measurement of roundness deviation of work pieces is essential in mechanical production control. The terms, definitions, parameters of roundness and in particular the filtering of the measured profiles as well as the specification operators are defined in the ISO technical specifications 12181-1 and -2 [1]. Most roundness measurements are carried out with rotating spindle instruments. The accuracy requirements for roundness measurements range from a few 0.1 µm for work pieces down to below 10 nm for roundness standards such as precision spheres or hemispheres. The latter are used to verify and eventually correct the spindle run out errors of roundness testers.

For the traceable calibration of roundness standards primary roundness measuring machines are used, offering lowest possible measurement uncertainty. A primary roundness measuring machine is distinguished by the fact that the roundness measurement is independent of any standard due to the application of error separation techniques, by the possibility for a complete characterization of all relevant components and influence quantities and by the achievement of state of the art measurement capability. In the following, a highly accurate roundness instrument is described in detail where all relevant influence quantities are investigated [2]. Experimental results are reported and a measurement uncertainty budget is discussed.

2. EXTRACTING THE ROUNDNESS PROFILE

2.1. Multi-step error separation

It is common to all form measurements, that they are in fact not based on a primary standard, but on the mathematical definition of a perfect geometrical element, such as a straight line, a plane, a circle, a cylinder, or a sphere. A perfect independent form measurement is realized by exploiting the symmetry in an error separation method, such as the reversal method. For roundness the multi-step technique [3, 4] is most commonly used. A high quality roundness standard with small surface roughness and a low harmonic content is measured in n angular positions every $360/n°$. The spindle error is obtained from the average of the shifted profiles. By averaging in this way, the roundness deviation of the reference artefact is cancelled except all multiples of the n^{th} harmonic. The determination of the roundness deviation of the reference sphere is made by the same way, but shifting the measured profiles by the corresponding multiple of $360/n°$ before taking the average, and thus eliminating the run out error of the spindle, again except all multiples of the n^{th} harmonic of the spindle error. It has to be noted, that using a sphere as the artefact yields only the radial spindle error, whereas using a hemisphere, where the measurement is not taken in an equatorial plane, also an axial component of the spindle error is determined.

In practice, the number n of steps is often chosen to be 10, i.e. 36° steps, and each profile is measured several times in order to reduce noise and to detect any irreproducible peaks in the profile caused by dust or any other disturbance. Special attention has to be given to the alignment of the artefact with respect to the spindle and the indexing table. First the roundness standard is centred with respect to the indexing table by means of an x/y-translation stage (Fig.1), and then the indexing table together with the sphere is centred with respect to the spindle. The centring should be significantly better that 1 µm.

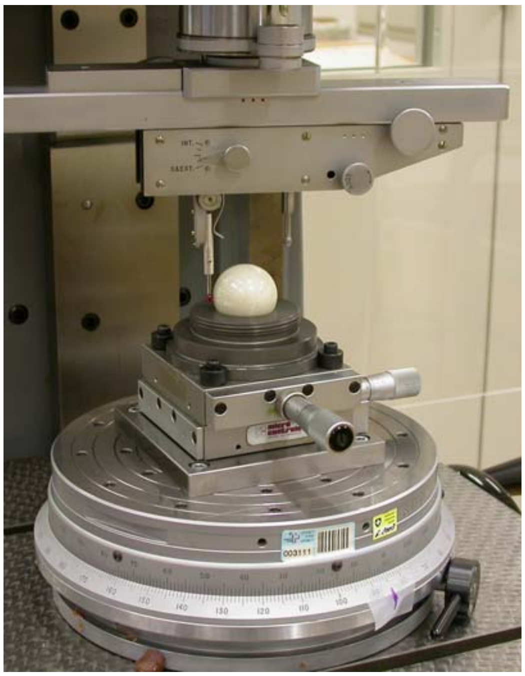

Fig. 1 *Set-up for multi-step spindle error correction.*

2.2. Profile filtering and roundness evaluation

The raw data of the roundness profile obtained after the error separation is essentially free from instrument errors and then has to be filtered and evaluated according to the standards' requirements [1]. By application of a discrete Fourier transformation, it is decomposed in its harmonic content. Profile filtering is realized by multiplying the Fourier coefficients with the Gaussian attenuation function [1]

$$e^{-\pi\left(\frac{\alpha\cdot f}{f_c}\right)^2} \quad \text{with} \quad \alpha = \sqrt{\frac{\ln(2)}{\pi}} = 0.4697 \quad . \tag{1}$$

f is the frequency of the harmonic in UPR (undulations/revolution) and f_c is the cut-off frequency of the filter, where the amplitude transmission is 50 %. After applying the filter function to the Fourier coefficients, the filtered profile is recomposed. The large number of sample points (2^{13} = 8192) in the recorded profile allows for filtering with high cut-off frequencies without under sampling. The profile is centred by setting the first Fourier coefficients to zero. It can be shown that this is equivalent to centring the profile with respect to the least squares reference circle (LSCI). From this, the peak-to-valley roundness deviation *RON*t is calculated.

3. DESCRIPTION OF THE INSTUMENT

The roundness measuring instrument used at METAS is basically a Talyrond 73 from Rank Taylor Hobson, but has undergone several modifications to improve accuracy and flexibility. It has a rotating spindle with an oil-hydrostatic bearing. The spindle is driven by a gearless DC-motor, which is completely free of vibration and allows to change the rotation speed of the spindle within adequate limits: the optimal speed according to the manufacturer is 6 rpm, whereas for parts with a high harmonic content in the profile, the rotation speed may be lowered to half in order to increase the bandwidth.
For reading the spindle position, which is necessary for separation and subsequent correction of the spindle error, an incremental rotary encoder has been built in (Heidenhain ERO 1225). It offers two TTL signals in quadrature with 2048 increments per revolution and an absolute index position signal. With a simple digital electronics we have multiplied these signals in order to obtain 8192 trigger signals per revolution and thus 8192 sample points per profile.

The instrument has a lever type probe with an inductive transducer (LVDT half bridge excited at nominally 10 kHz). For amplifying this signal we have two options. For highest accuracy applications, where lowest possible noise is more important than a high bandwidth, we use the analogue electronic length indicating instrument Tesatronic TTA20 from TESA SA, Switzerland. As a second option for higher bandwidth applications we have a 4-channel carrier frequency amplifier TFV8 from Messtechnik Sachs GmbH, Germany. The ranges can be software selected by an electronic switch. The analogue probe signal is recorded by the computer using a 16-bit A/D converter.

The entire instrument is protected against dust and radiation heat with a Plexiglas housing (Fig.2). The heat radiation shield is particularly important in order to minimize thermal drift of the roundness standard with respect to the spindle position during the measurement. The two large front doors around the corners allow for an easy access of the working volume.

Fig. 2 *Roundness measuring instrument protected with Plexiglas housing.*

4. CHARACTERIZATION OF INFLUENCE QUANTITIES

4.1. Stylus contact force

The lever type probe is bi-directional, i.e. for internal and external measurements. A button allows changing the force continuously from internal to external direction. The contact force of the stylus has been measured by a load cell. Usually the contact force is set in such a way that without contact the stylus is at the position of maximum deflection, which results in a contact force of approximately 20 mN at zero.

4.2. Probe calibration

The calibration of the probe is carried out statically in comparison with a high precision incremental length indicator. A translation stage with a differential screw is brought into contact with the probe, while the displacement of the stage is measured with an incremental length indicator with 2 nm digital resolution. The slope of the calibration curve gives the calibration factor and the residuals from the linear fit represent the non-linearity of the probe. Figure 3 shows, that the non-linearity of the ± 3 µm range which is normally used for precision measurements is only a few nm and thus within the uncertainty of the probe calibration.

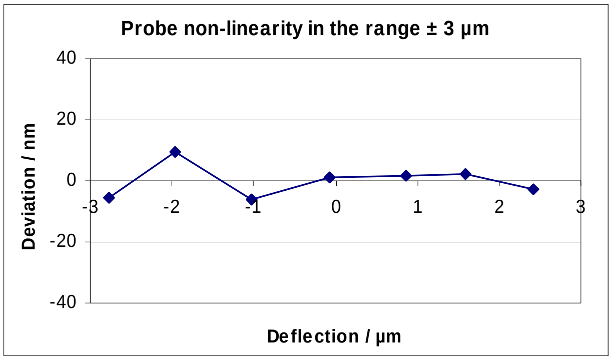

Fig. 3 *Linearity of the probe calibrated statically with a linear encoder.*

4.3. Transfer function

The transfer function of the probe including the amplifier and the A/D conversion has been measured with the help of a vibrating digital piezo-electric transducer. The latter is controlled by a capacitive sensor sufficiently fast to ensure a flat response over the used range. Figure 4 shows the transfer function measured for the TFV4 amplifier. The 50% cut-off frequency is roughly 125 Hz corresponding to a cut-off in the roundness profile harmonics of 1250 UPR.

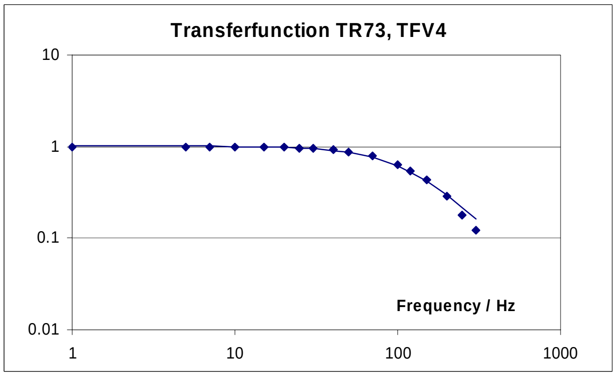

Fig. 4 *Linearity of the probe calibrated statically with a linear encoder.*

4.4. Noise in the recorded profile

The noise is one of the limiting factors in high precision roundness measurement. It has been measured in the digitally recorded signal for the entire measurement chain, i.e. with the rotating spindle by clamping the probe to a fixed value without contact to a surface. Thus also the noise produced by the sliding contact on the spindle for the probe signal is included. Table 1 shows the rms-noise evaluated from the unfiltered and filtered roundness profiles with clamped probe.

	rms-noise/nm	
Filter	TTA20	TFV4
unfiltered	0.9	1.5
500 UPR	0.7	1.0
150 UPR	0.6	0.8
50 UPR	0.4	0.6
15 UPR	0.2	0.4

Table 1 *rms-noise level in the filtered roundness profiles for the two amplifiers.*

4.5 Profile repeatability

The short term repeatability of the roundness profile measurement is possibly not only determined by the instrumental noise, but also by vibrations, thermal effects and the probe/surface interaction. This repeatability has been determined from five successive roundness measurements on a ceramic spherical standard. The average of the standard deviation of the five profile values in each point is 0.9 nm, i.e. exactly the same value as obtained from the noise of a null measurement (Table 1).

4.6 Profile drift

One of the major problems in roundness measurement is the thermal drift of the measured object with respect to the spindle during the measurement. The mechanical loop between object and probe is always rather large: it comprises the measurement table with positioning stages for adjusting the object, the instrument's column, the spindle and finally the probe with again some adjustments. For high precision roundness measurements, all this is required to be stable within about 1 nm during the measurement time of typically 10 s. Most of commercial software artificially close the beginning and the end of the measured profile and thus distort the roundness. A better way is to monitor the eccentricity continuously during successive measurements and to take the profile data only once the drift of the eccentricity per revolution is below a preset value. The Plexiglas housing (Fig.2) helps to improve the thermal stability. Thus, drifts well below 1 nm between successive roundness measurements can be obtained.

4.7 Stability of the spindle error

In most measurements of high precision roundness standards, the spindle error is eliminated by the multi-step procedure as described in section 2.1. For less demanding measurements, however, a pre-stored spindle error is taken into account. The long term stability of the spindle error must therefore be known. Successive measurements of the spindle error in several months interval have resulted in a standard deviation of differences between the measurements of about 1 nm with a maximum difference below 3 nm.

4.8 Spindle error harmonic content

The n^{th} harmonics of the spindle error, which are not taken into account correctly by the application of a n-step error separation procedure, will show up as an artefact in the roundness profile. The harmonic content of the spindle error at 10 UPR, 20 UPR and eventually 30 UPR has been estimated from a harmonic analysis to be below 0.2 nm [2].

4.9 Software

The software has been checked with simulated data in the framework of an EUROMET comparison [5]. The data files comprised simulations of

- an ideal Flick standard;
- a multi-wavelength profile with five distinct harmonics up to 500 UPR all of the same amplitude;
- idem, but slightly modulated in angle to simulate a harmonic distortion of the angular encoder;
- a multi-wavelength profile with two distinct harmonics very close together (149 UPR and 151 UPR);
- a multi-wavelength profile with three distinct harmonics and additional noise.

The values compared were LSC roundness deviation for different filter cut-off frequencies and a harmonic analysis. The results of this software comparison show excellent agreement between METAS and PTB.

5. MEASUREMENTS

5.1 Spherical roundness standard

A ceramic sphere of 30 mm diameter (Fig.1) serves as roundness standard. It has been calibrated three times using the multi-step procedure, as described in section 2.1. Fig. 5 shows the reproducibility of three measurements with filter cut-off at 50 UPR. The sphere has – unlike glass hemispheres – a relatively large content of higher harmonics and a roundness deviation of 19 nm. The standard deviation of differences between the measurements in February and June 2005, i.e. 4 months apart, is 3.8 nm, the maximum difference amounts to 10 nm, whereas these two values reduce to 0.6 nm and 1.6 nm, respectively, for the difference between the two measurements in June 2005, 4 days apart. It has to be noted, that the second and third measurement have been carried out with the same mechanical setting of the standard, therefore the much better reproducibility.

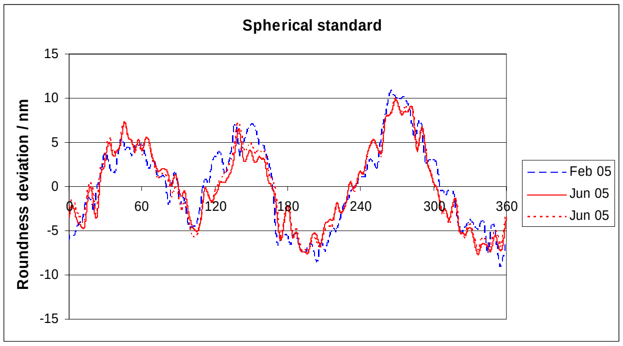

Fig. 5 *Roundness profile of ceramic sphere measured three times with the multi-step procedure, filtered with a cut-off of 50 UPR.*

5.2 Multi-wavelength standard

Further test measurements were carried out on a multi-wavelength standard, developed at PTB and manufactured by IPT [6]. The artefact (Fig.6) is manufactured such, that it has only distinct harmonics (at 15 UPR, 50 UPR, 150 UPR and 500 UPR) of all approximately the same amplitude and is thus best suited for testing roundness measuring machines including their dynamic response and their filtering. Fig. 7 shows the measured roundness profile and the harmonic analysis of the profile with the above mentioned distinct harmonics.

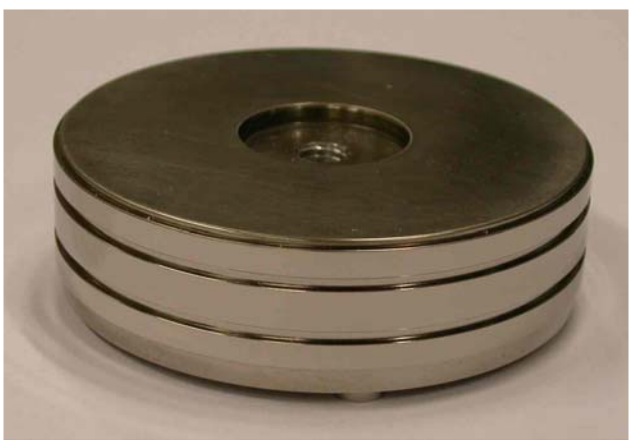

Fig. 6 *Multi-wavelength standard, having two cylindrical parts (low and high) for alignment and a structured part (centre) with only distinct harmonics.*

It is expected, that the higher harmonics are attenuated due to the limited bandwidth of the transfer function of the measurement system. This can be checked from measurements of the multi-wavelength standard at different rotation speed of the spindle and thus different bandwidth of the roundness measurement in terms of undulations per revolution. Excellent agreement between the predicted and the measured attenuation has been shown [2].

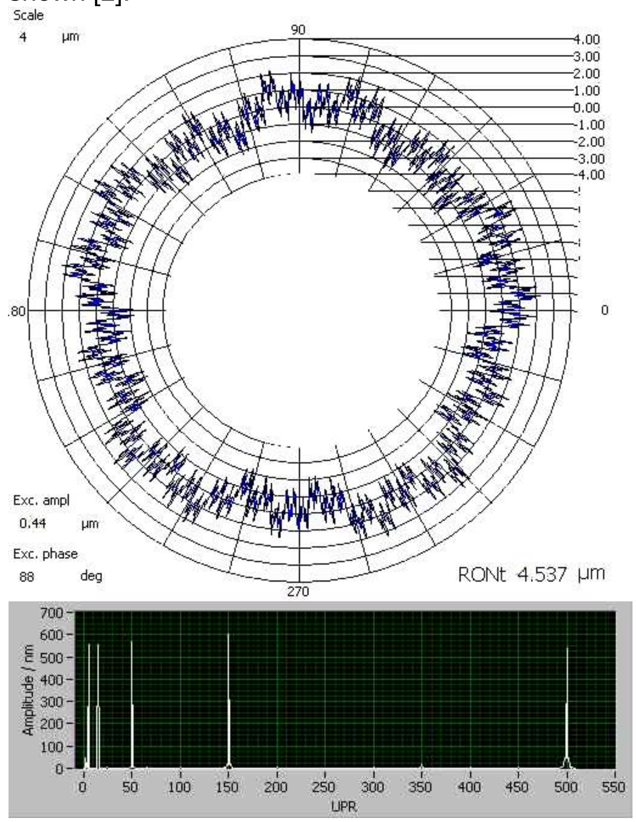

Fig. 7 *Roundness plot of the multi- wavelength standard and measured harmonic content.*

6. UNCERTAINTY OF MEASUREMENT

The estimation of the measurement uncertainty for roundness measurement is extremely difficult and cannot be based on an analytical model without some simplifying assumptions. The mathematical modelling of the effect of different influence quantities and the combination of the distribution functions to the resulting uncertainty of the individual profile point and the peak to valley roundness deviation should in fact be carried out rather by numerical simulation, taking into account the actual spindle error and the roundness deviation of the measured artefact. In the following, we will follow the simplified approach outlined by Neugebauer [7]. This procedure essentially distinguishes between short waved contributions, considered to be uncorrelated and thus reduced by filtering, and correlated long waved contributions. Correlation means, that the uncertainty of a profile point is correlated to the uncertainty of the points in the neighbourhood of the profile. We shall hereafter estimate the uncertainty of measurement of a perfectly round ideal artefact, no influence from the actual roundness will therefore be considered.

The effect of filtering on uncorrelated influence quantities is discussed theoretically in [7] and experimentally in [2]. Hereafter, the experimental values from table 1 will be used.

In Table 2 the contributions to the roundness measurement uncertainty discussed above are summarized.

Quantity	**Description**	**Std. uncert.**
Noise	Noise expressed as standard deviation in the roundness profile at 500 UPR	0.7 nm
Probe calibration	Repeatability of probe calibration factor: 1% (not significant for artefacts with very small roundness deviation)	-
Probe linearity	Probe non-linearity: < 0.1%. Assuming a maximum artefact eccentricity of 1 µm produces an apparent roundness error < 0.001·1 µm = 1 nm, rectangular distribution	0.6 nm
Thermal drift	Thermal drift of the artefact position with respect to spindle during 1 revolution: < 1 nm, produces a maximum profile distortion of 0.5 nm, rectangular distribution	0.3 nm
Spindle error stability	Reproducibility or short term stability of the spindle error: 0.7 nm, standard deviation	0.7 nm
Spindle harmonics	The 10^{th} harmonics of the spindle error not corrected by the error separation: < 0.3 nm	0.3 nm
	Combined standard uncertainty	**1.3 nm**

Table 2 *Uncertainty budget of a roundness measurement, without taking into account the influence of the measured artefact and its actual roundness profile.*

The expanded (k = 2) measurement uncertainty for a single point of the profile amounts to U = 2.5 nm. According to [7], the uncertainty of the peak to valley roundness deviation can be estimated to twice the single point uncertainty, which is certainly a worst case estimation, thus U(*RON*t) = 5 nm. It has to be noted, that this represents a best measurement capability under ideal conditions and that on artefacts with a relatively fine structured surface, such as the ceramic sphere reported in Sect. 5.1, this uncertainty has to be increased by a contribution reflecting the ability to reproduce exactly the same profile location.

7. CONCLUSION

By upgrading an existing high precision roundness measuring instrument with some hardware modifications such as amplifier electronics or an angular encoder and with new software, as well as by a complete characterization of the entire measurement process, an expanded measurement uncertainty for a single profile point of 2.5 nm in the very best case can be achieved.

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