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A comparison of sensitivity standards in form metrology—final results of the EURAMET project 649

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Abstract
Results of an intercomparison measurement of sensitivity standards are presented. The standards circulated were a flick and two multi-wave standards (MWS). The measurands were form deviation and, for the MWS only, the height of the dominant spectral components. For the flick, influences from mechanical filtering and calibration are discussed. For the MWS several influencing quantities are identified and discussed. Some of these influencing quantities may dominate the result under certain circumstances. It can be shown that standard measurement uncertainties of smaller than 25 nm can be achieved for the amplitude heights of MWS, whereas the form deviation results disagree a little more than expected compared to standard uncertainties of the order of 50 nm.

Keywords: form metrology, flick, multi-wave standards, harmonic analysis

(Some figures in this article are in colour only in the electronic version)

1. Background of EURAMET project 649

Between 2004 and 2005 several European national metrology institutes (NMIs), namely PTB (1) (these numbers identify the individual NMIs in the result graphs of this paper), METAS (2), MIKES (3), INRIM (4) and NPL (5) ran the first comparison dealing with multi-wave standards (MWS) [1]. PTB acted as the pilot laboratory and evaluated the form deviations and spectra of the form profiles, from data supplied by the participants. MWS embody superimposed spatial harmonic waves on a cylindrical body. They represent an alternative realization of sensitivity standards used for the dissemination of the length unit to form measurement instruments. The term 'sensitivity standards' is used to identify embodiments that are used to perform the sensitivity calibration of form measurement instruments. This calibration was identified to be one of the most critical components in form metrology. Table 1 shows some typical error sources which may influence roundness measurements.

The main advantages of MWS compared to, e.g., flicks are the much better signal-to-noise ratio and low sensitivity to noise in their form measurement profiles. To compare the signal-to-noise ratios of MWS and flicks one could for example compare figure 3 (spectrum of MWS-1) and figure 6(*b*) (spectrum of a flick). Although the form deviation of the MWS is only 45% larger than that of the flick, the spectral lines are higher by 1500%. The noise background in the signal is approximately of the same order.

So far there is no standard procedure to exploit these properties within calibration procedures. However, it is obvious that they may be applied for checking the signal transmission chain of form measurement instruments. The transmission chain behaviour may be influenced, e.g., by the carrier frequency amplifier bandwidth and spectral

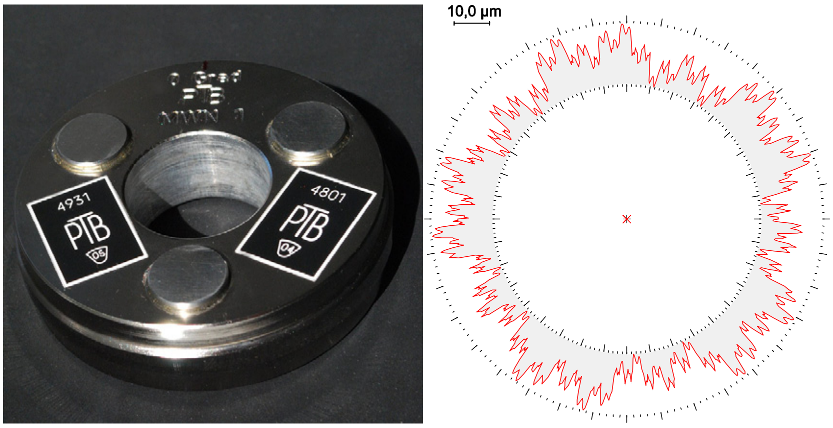

Figure 1. (*a*) Left: photograph; (*b*) right: form profile of MWS-1.

Table 1. Common error sources for tactile roundness measurements.

Sensitivity calibration (linearity, hysteresis, frequency dependence)
Alignment of artefact (levelling and centring)
Probe diameter/morphological filtering
Spindle (or rotary table) error
Contacting force influence (e.g. bending of thin work-pieces)
Closing error (thermal drift)
Electrical noise and mechanical vibration
Wear and stick–slip effects
Work-piece contamination

characteristics, the probe resonance frequency, and the friction parameters of the probe element and the work-piece. The potential broadband signal of MWS helps to check even the high frequency transmission of form measurement signals. Such a possible sensitivity calibration via MWS may utilize either the mean or even the individual heights of the spectral amplitudes as integral or frequency (wave number) dependent calibration factor.

Some NMIs have already applied MWS for analysis of their equipment [6].

The most common sensitivity standards are the so-called flick standards or ‘flicks’, i.e. cylinders with a ground flat. All participants were experienced in calibrating flicks, but only a few of them ever measured MWS before the project. Therefore it was decided to circulate a flick together with two different MWS. The comparison of sensitivity measurement intended to compare and verify the measurement capabilities of participating laboratories and to investigate the effect of systematic influences on the measurement process and ways for their elimination. In the case of the MWS it should in particular be examined whether better stability of the calibrated sensitivity could be achieved. One motivation of the comparison also was to broaden the data base for decisions about potential applications of MWS within the form measurement traceability chain, e.g. for NMIs and accredited laboratories.

Although the measurement results were available shortly after the measurements, the results were not published until 2011 [9]. One reason is that the measurements were not completely understood at that time. Recently there has been further progress in the understanding of measurements on multi-wave and flick standards. Therefore, it seemed worthwhile to discuss the measurement results on this new basis.

2. Circulated standards

2.1. Multi-wave standards

Two MWS were circulated, serial numbers MWS-1 and MWS-8. Their profiles contain a superposition of sinusoidal waves with the wave numbers 5, 15, 50, 150 and 500 UPR. MWS-1 is an outer cylinder (figure 1) and MWS-8 is an inner cylinder (figure 2). Both were manufactured at the Fraunhofer Institute for Production Technology (IPT)/WZL of the University of Aachen. Already the form profile of MWS-8 shows that it not only consists of the intended nominal harmonics, but also reveals unexpected additional asymmetry and high frequency content, which should not be confused with noise of the measurement. However, it should be mentioned that it was the first IPT prototype for inner MWS and the achieved quality is not on the same level as the outer standard MWS-1. For manufacturing the inner MWS, the fast-tool servo, which was used to turn the profile, had to penetrate the ring. This configuration may easily be exaggerated to vibrations. Recent measurements at PTB of newer inner MWS show much better manufacturing quality [2].

Since the time of the project the pilot laboratory has enhanced its form measurement capabilities. Therefore new reference measurements were made with a cylinder form measurement machine MarForm MFU110WP in 2011. This machine incorporates a variety of different probe systems, including an optical interferometer [3]. The reference measurements were made with tactile probing elements with radii 0.025 (single diamond surface measurement probe), 1 and 3 mm and an optical probe with a spot size of approximately 0.008 mm. No significant difference was found between the form profiles with 0.025 mm probe diameter and the optically acquired ones.

The reason for the application of different probe radii was to check possible influences from mechanical filtering by the contacting element. Figure 3 shows a comparison between the spectra of the MWS-1 form profile acquired

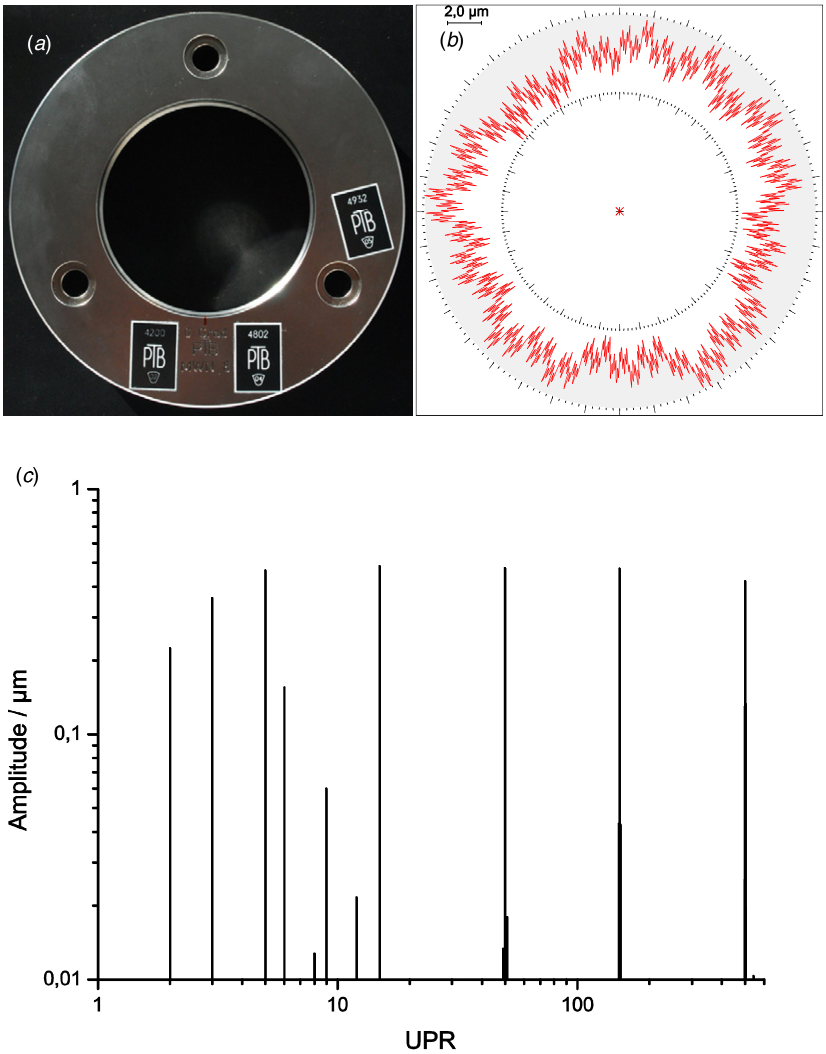

Figure 2. (*a*) Photograph; (*b*) form profile of MWS-8, (*c*) spectrum of the MWS-8 form profile (acquired with a 0.025 mm diameter probe).

with a probe diameter of 0.025 (for reference) and 3 mm, respectively. Indeed, some small spurious peaks are visible in the 3 mm spectrum, which are not present in the reference spectrum. These can be explained by mechanical filtering, i.e. convolution of the probing element geometry and the MWS surface profile during scanning [2]. The critical probe diameter, which is sufficient for full penetration into the valleys of a profile, can be calculated after [4]. It is approximately 7 mm for outer contacting of a 500 UPR wave with 1 μm amplitude and an MWS diameter of 80 mm. However, full penetration can still result in profile distortion. This is illustrated in figure 4 where an ideal sinusoidal profile is compared with the profile which a probe of critical size would acquire. The sharp corners of the distorted profile translate to new wave numbers in the spectrum. This is the reason why less than half the critical diameter should be chosen for the probing element when measuring MWS. This would be 3 mm in our case. But as previously shown, even a 3 mm stylus tip diameter results in a distorted spectrum. Morphological dilation may be applied to correct for these effects [2], but was not used throughout the project. Note that for the parameter form deviation RONt the critical size is already small enough.

The number of sampled data points was 9000. However, for the acquisition of the correct spectrum the required number of data points is little more than twice the largest wave number of the MWS. This fact was proven by a comparison of the spectra of the original 9000 point data file and a down sampled version with 1200 points (applied procedure: cubic interpolation). Figure 5 shows the spectral differences of the original from the down sampled one. Most differences are in a band of ±20 nm with some additional single peaks at larger, non-dominant wave numbers, which, however, were not further evaluated within the project. This fact is of importance, because some project participants could only acquire a relatively small number of data points.

2.2. *Flick standard*

Flick standards are widely used in NMIs, accredited laboratories and industry. Although a flick principally embodies a length—the deepness of the flick with respect to the base cylinder—it is common to filter flick profiles. Generally, a table of a filtering series is displayed in calibration certificates. These data are frequently used by users of form

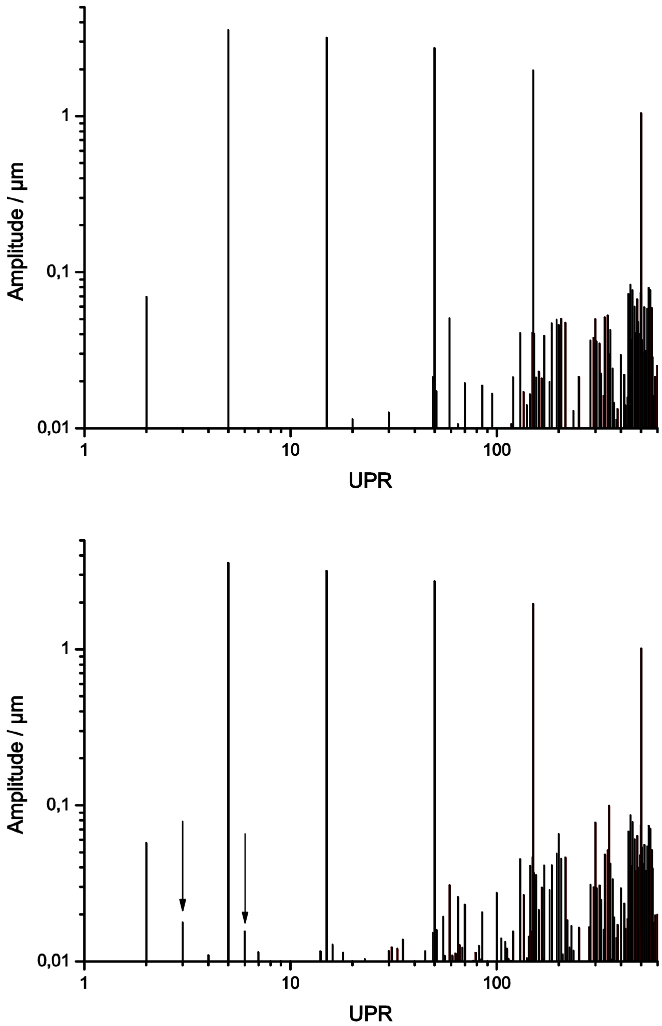

Figure 3. Spectra of MWS-1 form profiles. Top: probe diameter during acquisition: 0.025 μm; bottom: probe diameter during acquisition: 3 mm. Spurious peaks are visible (marked with arrows) due to mechanical filtering.

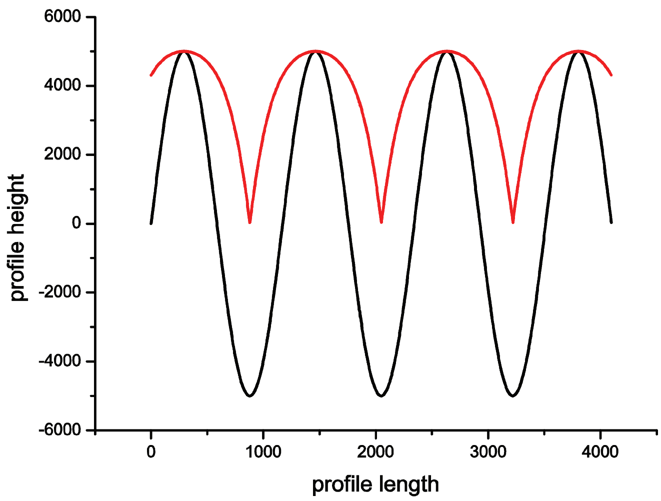

Figure 4. Comparison of an ideal sinusoidal profile and a distorted profile due to mechanical filtering.

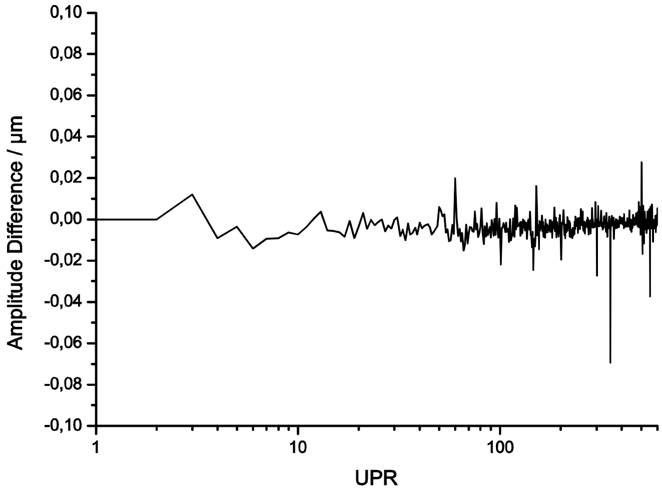

Figure 5. Spectral amplitude difference between 9000 data point form profile file of MWS-1 and a 1200 point down sampled version.

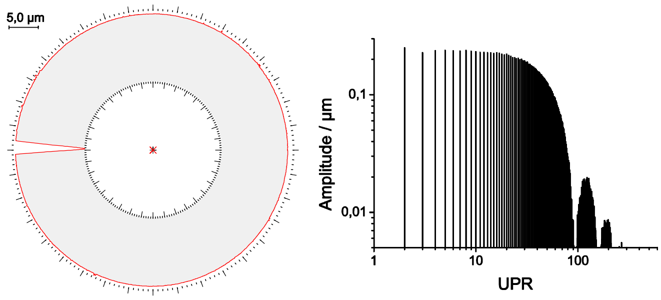

Figure 6. (*a*) Left: form profile; (*b*) right: spectrum of the circulated flick.

measurement instruments for testing their signal transmission chain components such as, e.g., their software filter algorithms. However, it is well known that flick calibration is non-trivial and often results in insufficient measurement uncertainties. Again, mechanical filtering is one of main influencing factors [5]. One part of the EURAMET project 649 therefore was to clarify the state of the art in flick measurement at the NMI level.

Flicks exist in various sizes and technical realizations. For the project it was decided to use a common 12 μm flick at a 20 mm base cylinder. Figure 6 shows its form profile and spectrum. The spectrum of flicks is of smaller bandwidth and amplitude height than often assumed. Figure 6 shows that it decays rapidly, shows zero crossings and carries no higher amplitude than 0.2 μm.

To check the influence of mechanical filtering on flick measurement, the pilot has measured the circulated flick in 2011 with the MFU110WP with 9000 data points by utilizing the three probe diameters 25 μm, 1 mm and 3 mm. Table 2 shows the results as a function of the filter parameters in absolute values and as differences to the 25 μm reference measurement. Please note that the last line differs from the earlier published version in [9], because a calculation error was corrected. Although there is little or no difference for the unfiltered and 500 UPR values, the differences for the 15 UPR values are 0.086 μm and 0.153 μm, respectively.

Table 2. Roundness deviation RONt of the flick for different probe diameters and filter settings. The lower two lines show the difference from the 25 μm measurement.

	Probe	Gaussian filtering/UPR				
	dia.	None	500	150	50	15
	25 μm	11.930	11.875	11.587	9.405	3.874
RONt (μm)	1 mm	11.969	11.875	11.574	9.306	3.788
	3 mm	11.982	11.875	11.523	9.092	3.635
Diff. from	1 mm	0.039	0.000	−0.013	−0.099	−0.086
25 μm	3 mm	0.052	0.000	−0.064	−0.313	−0.239

This result may be unexpected. However, it can be understood quite easily. All probes detect the flick depth in the same way. However, the convolution of the probe geometry with the sharp flick boundary is very different for the three probes. Therefore these high wave-number components get significantly mechanically filtered in very different ways. Consequently, the Gaussian filter shows different impact in table 2. Therefore, it is strongly recommended to only compare flick calibration results that stem from measurements with the same probe diameter. As ISO 12181 recommends a default 1 mm probe diameter, this should be the value of choice [8].

Unfortunately, the probe radius was not fixed for the EURAMET project 649. Therefore deviating results were to be expected.

3. Measurement results

The participants were free in their selection of the measurement instrument to be used. Most participants selected instruments of the Taylor Hobson Talyrond 73 series, as this device class was utilized by most participants and other NMIs for their roundness reference calibrations. The Talyrond 73 is a form measurement instrument with a rotating spindle with high reproducibility (approx. 1 nm) and low spindle error (e.g. 30 nm @ 50 UPR). The construction principle of the spindle, which is based on a hydrodynamic bearing, leads to constraints for the rotating speed (e.g. 6 rpm). Therefore most participants used the same acquisition speed. The data were gained by single scans of the circumference. No averaging was applied. The sensitivity calibration of the probe systems was performed by the usual procedures of the participants. No special procedure was defined for the comparison. Most participants either calibrate their form measurement instrument by measuring an otherwise calibrated flick standard or end gauge step or directly use scales or laser interferometry.

No error separation was applied during the measurements. However, for MWS error separation does not play a major role, because as long as the harmonic content of the spindle error does not interfere with the intentional harmonic content of the MWS, the spectral analysis will not be influenced significantly. If the amplitude of the spindle error is low enough, it will also be a second-order effect for the form deviation. Most influence of the spindle error could be eliminated by subtracting a reference file before evaluation. However, this was not applied for the analysed data. Error separation is generally not applied for flick calibrations by the participants. Therefore this was also the case for the comparison.

Table 3. Roundness deviation RONt of MWS-1 evaluated from the mean value of the participant results.

	Gaussian filtering/UPR				
	15	50	150	500	Unfiltered
RONt (μm)	7.179	12.206	15.229	17.377	18.390

Table 4. Roundness deviation RONt of MWS-8 evaluated from the mean value of the participant results.

	Gaussian filtering/UPR				
	15	50	150	500	Unfiltered
RONt (μm)	1.811	2.658	3.308	4.055	4.635

The evaluation of the raw measurement files was performed by each individual participant and additionally by the pilot with the custom-made form profile analysis software ‘FormCalc’, written in IDL [7]. The parameter roundness deviation RONt was evaluated for the reference circle LSCI [8]. In this case RONt is the peak-to-valley distance of a form profile after fitting of a best fit and (optionally) applying a digital filter. The calculation was repeated for the Gaussian filter cut-off wave numbers 15, 50, 150, 500 UPR, and for no filtering applied.

The spectral analysis of the MWS profiles was performed by the pilot using FormCalc with an embedded FFT algorithm which can deal with any number of data points, and not multiples of 2^n only. No filtering was applied to the files. Only the dominant amplitudes 5, 15, 50, 150 and 500 UPR were compared.

All results are displayed with 1 nm resolution, although the measurement uncertainties did not always match such high resolution.

The results of PTB (1) stem from the original data of the comparison—not from the measurements in 2011.

3.1. MWS—form deviation RONt

The mean results for the roundness deviation of MWS-1 are summarized in table 3.

Figure 7 shows the deviations from mean of the RONt results of MWS-1. Surprisingly, the unfiltered values agree a little better than the filtered results. Table 4 and figure 8 show the corresponding results for MWS-8.

3.2. MWS—dominant amplitudes

The mean results for the height of the dominant amplitudes in the spectrum of MWS-1 are summarized in table 5.

Figure 9 shows the deviations from mean of the spectral results of MWS-1. Again, the unfiltered values agree a little better than the filtered results. Table 6 and figure 10 show the corresponding results for MWS-8.

The agreement is very good, less than 10 nm for the lower wave numbers. Some of the participants only disagree a little

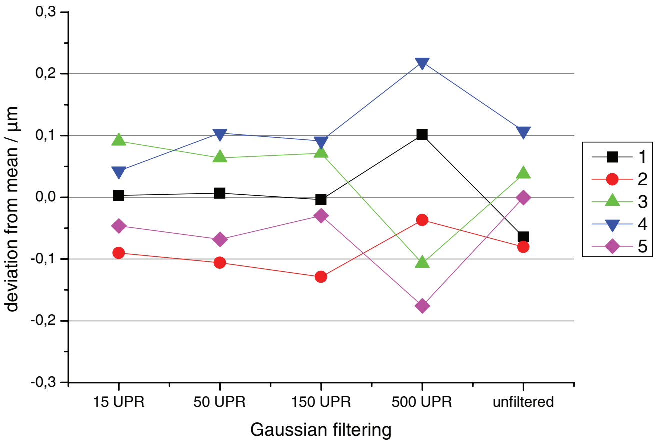

Figure 7. Deviations from mean of the RONt results of MWS-1.

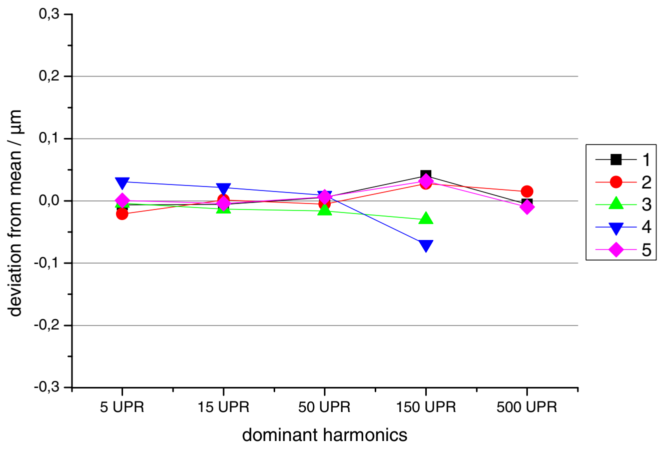

Figure 9. Deviations from mean of the spectral analysis results of MWS-1.

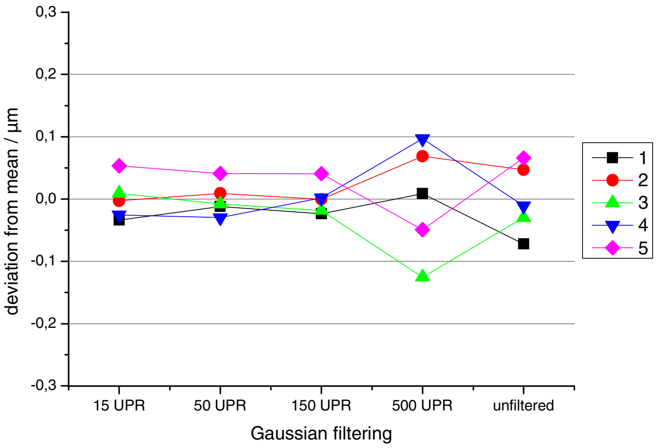

Figure 8. Deviations from mean of the RONt results of MWS-8.

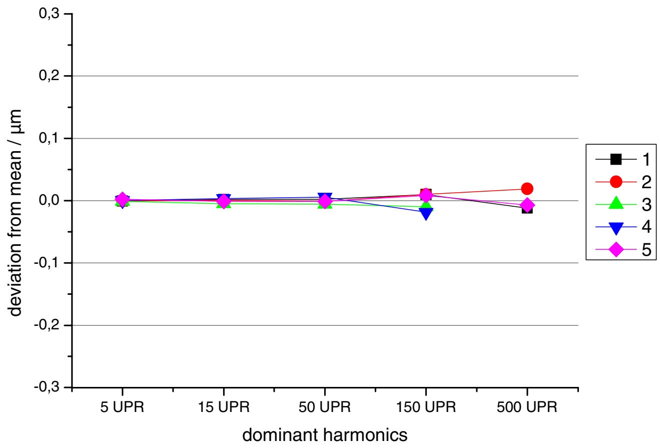

Figure 10. Deviations from mean of the spectral analysis results of MWS-8.

Table 5. Mean results of the amplitude heights of the dominant amplitudes of MWS-1.

	Spectral wave number/UPR				
	5	15	50	150	500
Amplitude height (μm)	3.583	3.196	2.725	1.909	0.910

Table 6. Mean results of the amplitude heights of the dominant amplitudes of MWS-8.

	Spectral wave number/UPR				
	5	15	50	150	500
Amplitude height (μm)	0.464	0.485	0.480	0.473	0.475

more at the wave number 500 UPR. Although the reason is unknown, it may be supposed that the deviations are caused by uneven data sampling and limited bandwidth of the signal amplifiers.

The relative deviation looks more modulated. However, this is mainly caused by the low absolute deviation of the results, which shows up in the denominators of the relative deviations.

Table 7. Roundness deviation RONt of the flick evaluated from the mean value of the participant results.

	Gaussian filtering/UPR				
	15	50	150	500	Unfiltered
RONt (μm)	3.794	9.295	11.619	11.932	11.964

3.3. Flick—form deviation RONt

The mean results of the participants for the roundness deviation of the flick are summarized in table 7. The individual deviations of the participants are shown in figure 11. The results of participant #2 seem to reveal a wave-number (frequency) dependence. This is most probably caused by the large probe diameter (4 mm), as shown in table 2.

4. Some remarks about measurement uncertainty

Most participants claim standard uncertainties below 50 nm for RONt with a RONt-dependent term. This seems reasonable at least for smaller roundness deviations. However, the absolute RONt deviations of MWS-1 and the flick seem to lie partly outside this band. The challenge might be a broadband and

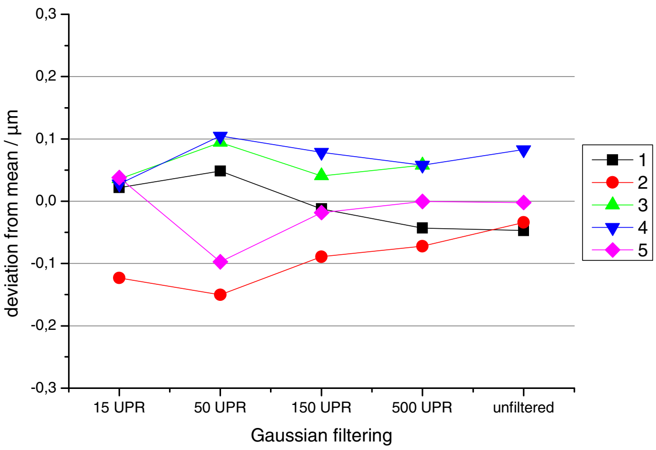

Figure 11. Deviations from mean of RONt results of the flick.

at the same time large deflection probe calibration. Generally, some participants estimated 0.1%–0.25% for this uncertainty contribution. But such small values might only be achievable if the probe system is calibrated by precise external references such as interferometers. Often only flicks or end gauges are used for the calibration of probe systems. However, these methods are sufficient for probes which will only be applied for the low RONt values of hemispheres.

As already mentioned, flick results depend on the diameter of the probe. The variety of the results of the flick can therefore partly be explained by this influence. Another influence might stem from the very different flick data sampling densities of the participants, which varied between 2000 and 4096 data points. It is obvious that the flick boundary shape gets better resolved with higher sampling density.

With the exception of the pilot laboratory, no uncertainty claims were made by participants for the spectral analysis. This was to be expected, as only the pilot offered calibration services for these standards at the time of the project. There was no formal uncertainty calculation scheme for the spectral amplitudes of form profiles available. Therefore the project results could serve as input for future uncertainty estimations.

The pilot laboratory claimed standard uncertainties below 25 nm for the amplitude heights and zero uncertainty for the wave number.

The first value seems reasonable as the low deviations of the spectral values show. However, the data of some participants showed decreasing agreement with increasing wave number.

The latter claim is a consequence of the closed nature of roundness profiles, where closed sinusoidal waves will show up in the FFT only as integer wave numbers with no uncertainty. This would not be as easy for pseudo harmonics (e.g. for twist analysis of technical shafts) or open profiles.

5. Conclusions

The results showed that the measurement of form profiles of standards with larger roundness deviations is a challenge, even for NMIs. It was shown that spectral analysis of MWS profiles leads to much better agreement and stability than the RONt evaluation. This may be no surprise, because spectral analysis is an integral method, which is based on all data points, where RONt is a measurand which only relies on two data points for the LSCI and four data points for the MZCI reference circles. Furthermore, background noise is nearly completely suppressed by the concentration on the dominant amplitudes, whereas noise has a direct influence on the RONt evaluation. In addition, it was noted that the spectral evaluation is less sensitive to small probe calibration errors. Therefore MWS may be a valuable replacement for flicks for special applications. However, because there is no mass production so far, their widespread application will be limited by the manufacturing costs of several 1000 € (depending on the individual design). The uncertainty calculation of the spectral analysis needs further theoretical input.

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