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An intercomparison of roundness measurements between ten European national standards laboratories

A. Sacconi*, W. Pasin

Istituto di Metrologia "G. Colonnetti", IMGC, Strada delle Cacce 73, I-10135 Torino, Italy

Abstract

An intercomparison of high-accuracy roundness measurements has been carried out with the participation of the national standards laboratories of ten European countries. The circulated artefacts were a hemispherical glass standard and a steel disc. A total of eight roundness profiles were examined, two on the hemisphere and six on the disc. The eccentricity between external and internal surfaces of the disc was determined, and the effect of various measuring conditions evaluated. While the overall results show a satisfying agreement for almost all laboratories, room for further improvements still exists. The uncertainty limit was mainly due to the spindle errors of the roundness instruments used in each laboratory. These instruments were proven to be of a good quality at the 0.1 μm level. Below this limit, best results were reported by those laboratories where error separation techniques were available.

Key words: Form measurement; Interlaboratory comparison

1. Introduction

Roundness and form measurement are of increasing interest and directly influence precision engineering and quality control. However, due to insufficient standardization of measurement conditions and calibration procedures, significant discrepancies in roundness measurements occur.

In order to assess the mutual compatibility in this field, a collaborative project has been undertaken. This project consisted of two independent interlaboratory comparisons, one for primary laboratories (piloted by IMGC) and the other for both primary and industrial laboratories (piloted by PTB). This paper deals with the first of these exercises [1]. Both the intercomparisons have been made on behalf of the Commission of the European Communities under its Programme for Applied Metrology and Chemical Analysis (Community Bureau of Reference, BCR).

All the results presented in this paper were obtained at the time of the participation in the intercomparison. They may no longer represent the situation, nor the best measurement capability of each laboratory.

The national standards laboratories of ten European countries took part in this exercise. They are listed below with the name of the principal metrologists responsible for the work:

- EOLAS — The Irish Science and Technology Agency, Dublin, Ireland (M.A. Hines, S. Peyton)
- NPL — National Physical Laboratory, Teddington, UK (M. Stedman, D.R. Flack)
- VSL — Van Swinden Laboratorium, Nederlands Meetinstituut (NMi), Delft, The Netherlands (H. Haitjema)

* Corresponding author.

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ULg	Université de Liège, Liège, Belgium (A. Moës)
IPU	Instituttet for Produktudvikling, The Technical University of Denmark, Lyngby, Denmark (R.O. Sørensen, H.S. Nielsen)
LNE	Laboratoire National d'Essais, Paris, (R. Husse, J.P. Mathien)
PTB	Physikalisch-Technische Bundesanstalt, Braunschweig, Germany (F. Lüdicke, H. Bosse)
SP	Statens Provningsanstalt, Borås, Sweden (M. Frennberg)
OFM	Swiss Federal Office of Metrology, Wabern, Switzerland (R. Thalmann)
IMGC	Istituto di Metrologia "G. Colonnetti", Torino, Italy (A. Sacconi, W. Pasin)

2. Description of the intercomparison

The exercise was organized as an intercomparison of roundness measurements in the range from 0.05 μm to 0.5 μm, with simple-shaped artefacts. The package devised for this interchange consisted of two artefacts:
- *hemispherical glass roundness standard* of approximately 50 mm diameter, type 112/436, ser. no. 940D, made by RTH Ltd;
- *circular master*, steel disc of 20 mm internal diameter, 125.7 mm external diameter and 12 mm thick, ser. no. 125-39, made by Cary.

The hemisphere is one of the most widely used standards for testing the spindle accuracy of roundness instruments. Its surface finish is of optical quality and its departure from roundness is within 50 nm, or even less.

The steel disc represents a typical mid-level industrial standard with roundness deviations up to a few tenths of μm and its main application is for verification of coordinate measuring machines.

Participants were requested to use their normal measurement method to determine the peak-to-valley deviation (ΔR) from ideal roundness, evaluated with reference to the least-squares circle (LSC). Common filtering conditions of 50 upr (undulations per revolution) and 500 upr were suggested.

On the hemisphere, the measurements were to be taken along two sections at 3 mm and 6 mm height from the base (Fig. 1(a)). Each section was to be measured along two different directions of measurement: one perpendicular to the axis of rotation (A) and the other perpendicular to the spherical surface (S).

On the steel disc, external and internal surfaces were to be measured (Fig. 1(b)). Profiles were to be taken along three sections (L = low, M = middle, H = high), 3 mm apart. The eccentricity between the two measured surfaces was also required.

The aims of this intercomparison were the following:
- to determine the present compatibility among European national laboratories;
- to assess the adequacy of the adopted transfer standards;
- to establish experimental evidence for a reliable traceability chain in Europe;
- to exchange information on measurement techniques and procedures and on problems encountered, in anticipation of possible standardisation of transfer standards and unification of calibration procedures.

Furthermore, this exercise gave some of the participants the first opportunity to test of very recently acquired equipment .

The round robin sequence of this exercise took about 15 months and was complete by June 1991.

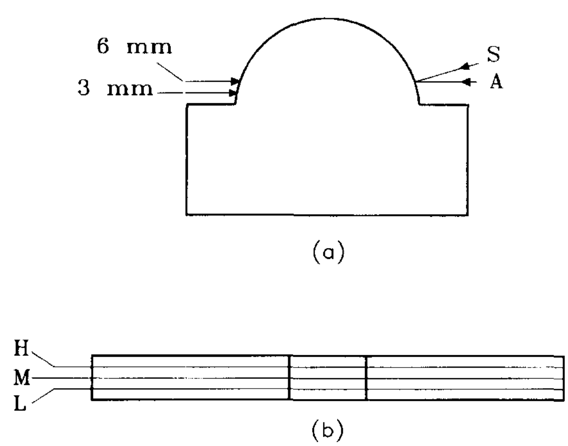

Fig. 1 Measuring directions (S, A) and measured sections of circulated artefacts: (a) hemisphere and (b) disc.

3. Stability of transfer standards

In order to get evidence of the stability of the artefacts, a number of independent measurements were made by the IMGC at the beginning and at the end of the intercomparison. To randomize any systematic effect depending on probe positioning and on surface quality, each measurement was taken after repositioning the artefact and/or the probe. Similarly, each filtering condition corresponded to an independent set of measurements rather than to a different software processing of the same data.

Initial and final results (ΔR) obtained by IMGC for both artefacts are summarized in Tables 1, 2 and 3. The overall (type A and type B) combined uncertainty (2σ) was ± 22 nm and ± 36 nm for the hemisphere and the disc, respectively. These results show that no significant change occurred to the standards during 15 months of circulation. However, as can be seen from the results of the internal surface of the disc, a greater deviation from roundness is generally accompanied by a worse repeatability.

Table 1
Hemisphere: IMGC initial and final results (nm)

Section height (mm)	3				6			
Measuring direction	S		A		S		A	
Prefiltering (upr)	50	500	50	500	50	500	50	500
Initial	45	51	49	55	38	46	40	46
Final	42	47	46	62	34	47	37	48

Table 2
Cary disc, external surface: IMGC initial and final results (nm)

Section	L		M		H	
upr	50	500	50	500	50	500
Initial	135	142	71	81	108	125
Final	135	139	74	81	106	110

Table 3
Cary disc, internal surface: IMGC initial and final results (nm)

Section	L		M		H	
upr	50	500	50	500	50	500
Initial	371	370	370	380	449	467
Final	394	405	379	382	446	446

The total (initial + final) number of independent measurements made at the IMGC was 26 (i.e. 12 + 14) for the hemisphere and 39 (i.e. 25 + 14) for the disc.

For the glass artefact, due to its low harmonic content, the influence of filtering conditions was extremely low. Also differences due to measuring direction and height of measured section proved to be almost negligible. In this case, even an apparently rough estimator like the overall average of roundness deviations, irrespective of measuring conditions, proved to be a very stable indicator of the stability and adequacy of this standard. In fact, this overall average was 46 nm at the beginning and 45 nm at the end of this exercise, whereas the corresponding estimated standard deviation of a single measurement was only 5 and 7 nm, respectively. Figs. 2 and 3 show examples of the reproducibility at 500 upr of initial and final measurements.

4. Measurement methods and techniques

Deviations from roundness are usually obtained by the displacements sensed by the tip of a probe held in contact with the workpiece to be measured when a relative motion (rotation) is maintained between the tip and the workpiece. This motion is realized with a high-accuracy spindle on which either the workpiece or the probe is mounted.

Since the measured displacements include the errors contributed by the artefact and by the spindle motion as well, the main difference in the measurement methods was given by the availability, or not, of an error separation technique [2,3] providing for a separation of the artefact errors from the spindle errors. Spindle errors are due to the component along the measuring direction of the displacement vector representing the path (in

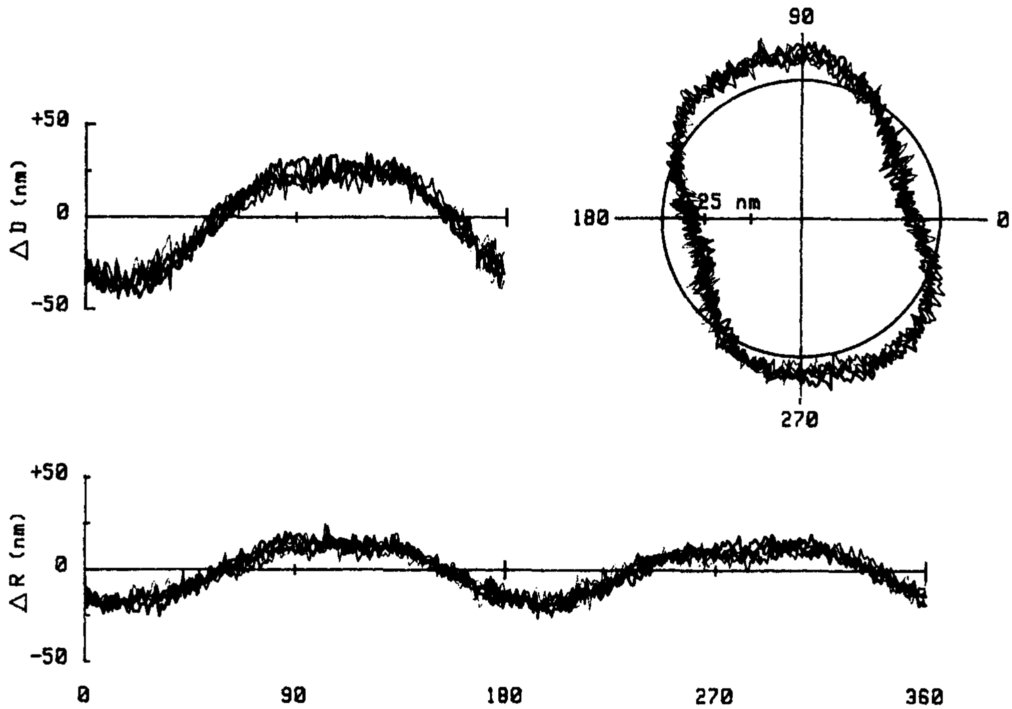

Fig. 2. Hemisphere profile at 6 mm height.

the plane of measurement) of the instantaneous axis of rotation of the reference spindle. Otherwise, when roundness measurements are made in the ordinary way, the errors of the reference spindle (even if usually small) are always included in the results. In this case, these errors are taken into account only in the uncertainty evaluation.

For this set of intercomparisons, only four out of ten laboratories (namely, IMGC, IPU, PTB and SP) were in a position to remove the spindle contributions from the roundness deviations of the artefacts by means of a direct application of the multistep technique.

This technique consists of taking n sets of measurements of the same profile at different mutual orientations (steps) between the artefact and the spindle. At each of these n steps, the initial orientation of the artefact changes by $360°/n$. If n is sufficiently large, it is possible, by averaging, to separate the artefact errors from the error motion of the spindle. In this exercise all four mentioned laboratories used ten steps.

A less precise technique has been applied in two other laboratories (VSL, OFM) where the error separation was obtained by subtracting the predetermined spindle errors by a semi-manual and a software method, respectively. At the OFM, two independent methods were used, hereafter referred as OFM1 and OFM2.

All laboratories adopted a contact measurement method based on the use of inductive type transducers with spherical or hatched tips. The various individual aspects of each laboratory's contribution are compared in Table 4, where H and D stand for hemisphere and disc, respectively

The calibration of probing systems was made by each laboratory with its usual method. These methods were based either on laser interferometry or on calibrated artifacts such as gauge blocks or flick standards.

5. Results and discussion

In the following, underlined acronyms and filled or dotted symbols (as for VSL) in the graphs

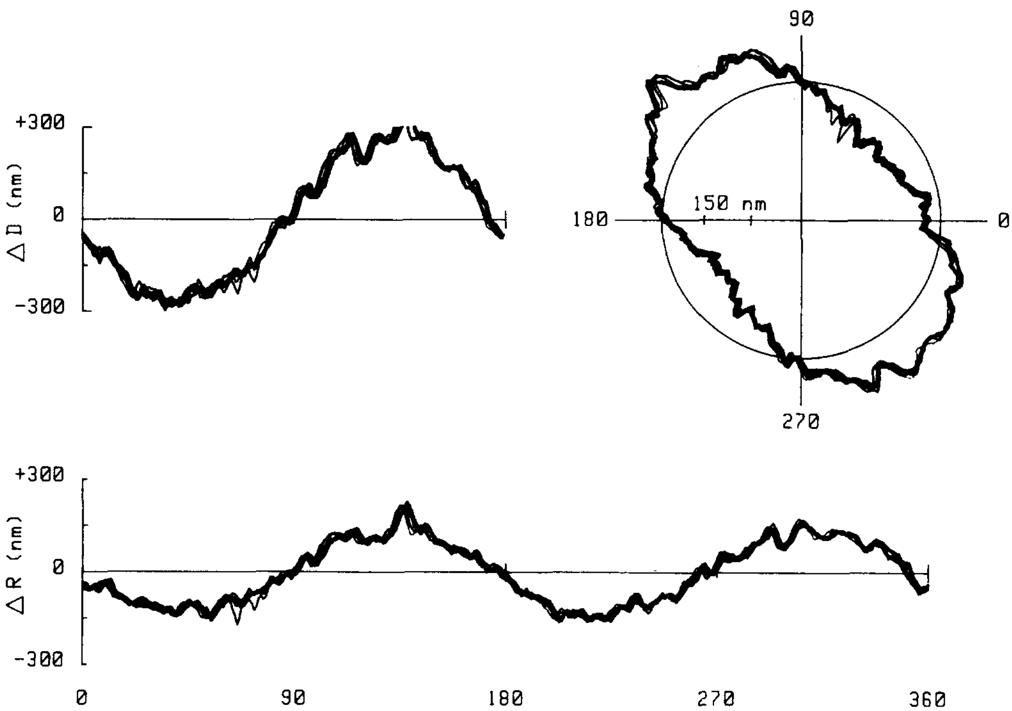

Fig. 3. Disc profile: internal section, mid height.

correspond to the results obtained by using error separation methods (either multistep or subtraction).

In the tables, all the submitted results have been reported with the exception of ULg results, which seem to be affected by some problem in the transducer calibration. The values are even lower than those obtained with error separation and, as a consequence, have been excluded from the computation of the means.

OFM 1 results indicate that the software compensation of the spindle error was effective at 50 upr only. At 500 upr, this compensation clearly failed because of noise problems. For this reason, the OFM1 results at 500 upr were considered as corresponding to measurements without separation of spindle errors.

5.1. Hemispherical glass standard

The results and uncertainties (2σ), as reported by the participating laboratories are given in chronological order in Tables 5 and 6.

In general, as can be seen by comparing the resulting standard deviations given in these tables with the uncertainties stated by each laboratory, the overall agreement is rather good. On the other hand, these uncertainties are strictly dependent on the measurement method. In particular, when the standard method (i.e. without error separation) is adopted, any quantitative statement of the systematic uncertainty is mainly based on the manufacturers' specifications. These have to be regarded as a very safe upper limit, when compared with the uncertainties estimated on the basis of the experimental results.

As expected, the results are somewhat clustered, depending on the adopted method. In fact, results for the ordinary measurement method are generally higher and more scattered than those obtained from the error separation method, because of the inherent bias due to the inclusion of spindle errors. As a consequence, any refined assessment of the interlaboratory agreement must be made by sorting the results according to which method was adopted. In this case, due to the small

Table 4
Summary of measurement facilities and conditions (a) Measurement facilities

Laboratory	Instrument	Rotating element	Direction	Speed (rpm)	Error separation (Yes/No)	
					H	D
IMGC	Modified Formscan 3000	workpiece	ccw	4	Y	Y
EOLAS	Talyrond 210	workpiece	cw	6	N	N
NPL	Talycenta	workpiece	cw	6	N	N
VSL	Talyrond 200	workpiece	cw	6	Y	N
ULg	Talyrond 50	probe	cw	3	N	N
PTB	Modified Moore n.3	probe	ccw	2 (H) 0.5 (D)	Y	N
IPU	Talyrond 73P	probe	ccw	6	Y	Y
LNE	LNE-design	workpiece	ccw	2	N	N
SP	Talyrond 73P	probe	ccw	6	Y	Y
OFM1	Talyrond 300	workpiece	ccw	6	Y	Y
OFM2	Talyrond 73	probe	ccw	6	N	N

(b) Measurement conditions

Laboratory	Measuring force (mN)	Stylus tip material	Tip diameter (mm)	Points per revolution	Ambient temperature (°C)
IMGC	27	ruby	3	360	20.6 ± 0.1
EOLAS	60	ruby	2	2000	25 ± 1
NPL	35	tungsten carbide	1.6	512	20 ± 0.25
VSL	100	tungsten carbide	6.3/0.4[a]	continuous	20 ± 0.5
ULg	150	steel	1.6	continuous	20 ± 0.5
PTB	28	tungsten carbide	1.6(H) 3.2(D)	1024(H) 4096(D)	20.4 ± 0.2
IPU	50	steel	1.6	512/50	19.8 ± 0.1
LNE	50	ruby	2	360	20 ± 0.2
SP	100	tungsten carbide	6.3/0.4[a]	512/50	20.4 ± 0.2
OFM1	50	ruby	3	2000	20 ± 0.2
OFM2	50	ruby	4	2000	20 ± 0.2

[a] Hatched tip.

roundness error of the hemisphere, a meaningful comparison may be based only on the error separation technique. For the other method, the value of this exercise consisted in giving experimental evidence of the magnitude of the spindle errors involved.

By assuming as reference values the means of only those results based on error separation, a more significant assessment of the overall compatibility may be given. This is shown in Fig. 4, where the deviations from these reference values, at 500 upr, are plotted. Also for laboratories with error separation techniques some problems of compatibility were evidenced, even if an agreement within about ± 25 nm is considered to be satisfactory.

In addition to VSL results, where spindle errors were only partially compensated, PTB results appear to be slightly biased toward higher values. A temporary instability of the hemispherical standard cannot be excluded, because some previous measurements, not reported here, made by this laboratory were very close to the other results. A conclusive explanation of these results has not yet been found.

Table 5
Hemisphere, 500 upr: LSC deviations from roundness and estimated uncertainties (nm)

Section height	3 mm		6 mm		$u_{2\sigma}$
Measuring direction	S	A	S	A	
IMGC	49	58	46	47	22
EOLAS	107	109	98	104	46
NPL	70	84	74	109	87
VSL	80	–	60	–	90
ULg	17	20	22	20	60
IPU	40	45	34	35	10
LNE	100	100	100	100	47
PTB	86	90	72	79	20
SP	36	–	27	–	8
OFM1	–	120	–	150	120
OFM2	–	80	–	80	64
Mean	71	86	64	88	
Std. dev.	27	25	27	36	

Table 6
Hemisphere, 50 upr: LSC deviations from roundness and estimated uncertainties (nm)

Section height	3 mm		6 mm		$u_{2\sigma}$
Measuring direction	S	A	S	A	
IMGC	44	48	36	38	22
NPL	57	57	50	50	87
VSL	60	–	50	–	40
PTB	74	78	60	69	20
SP	36	–	28	–	8
OFM1	–	40	–	40	40
OFM2	–	60	–	60	50
Mean	54	57	45	51	
Std. dev.	15	14	13	13	

Finally, roundness deviations are generally higher at 3 mm than at 6 mm section height, independent of measuring direction (S or A). Similarly, roundness deviations are higher along direction A than along S, independent of the section height. These small differences (of about 10 nm or less), being almost constant in all laboratories, indicate on the one hand that the effect of measuring direction (in addition to the section height) is not negligible and, on the other hand, that resolution and transducer repositioning do not seriously affect the results.

5.2. Steel disc

For the external and internal surface of the disc, the results and uncertainties at 500 and 50 upr are given from Table 7 to Table 10. For this artefact, as the ratio of component error to spindle error increases from the external to the internal surface, the systematic difference between measurement methods with and without error separation is correspondingly less.

Nevertheless, the results based on the multistep method take advantage of the noise reduction resulting from averaging over a number of repeated measurements (steps). This is particularly apparent at 500 upr, where noise problems prevail.

Fig. 5 presents a graphical representation of the 500 upr deviations from the means of error separation results, taken as the reference values. In conclusion, the overall agreement between the results is rather good, especially at 50 upr. The interlaboratory standard deviations are generally consistent with the uncertainties estimated by each laboratory.

The eccentricity between external and internal surfaces of the steel disc was also measured by almost all the participants. The results at 50 upr are listed in Table 11. In the mid-height section, the standard deviation from eight laboratories out of nine was only 0.02 μm, i.e. definitely lower than the estimated uncertainty. This result, which could not be obtained without good stability of the instrumentation, may also be regarded as a first test for validating the software.

6. Supplementary results

Minimum zone center (MZC) evaluation of roundness deviations was obtained by various laboratories. This evaluation was mostly made by software or, in a few cases, semi-manually with a template. In both cases the MZC evaluations were constantly lower than LSC results, by about 10%,

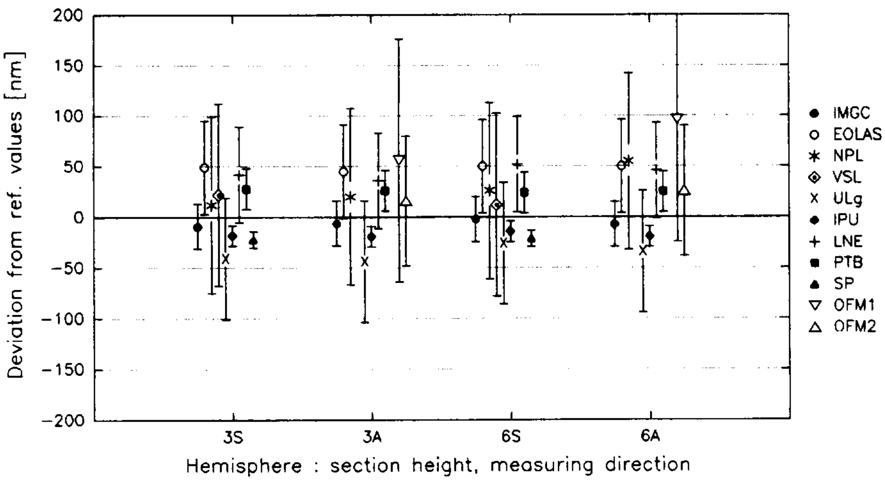

Fig. 4. Hemisphere: deviations from reference values at 500 upr.

Table 7
Disc, external surface, 500 upr: LSC deviations from roundness and estimated uncertainties (μm)

Section	L	M	H	$u_{2\sigma}$
IMGC	0.14	0.08	0.12	0.04
EOLAS	0.19	0.21	0.28	0.05
NPL	0.12	0.11	0.15	0.09
VSL	0.18	0.11	0.09	0.12
ULg	0.09	0.03	0.10	0.06
PTB	0.20	0.17	0.20	0.10
IPU	0.10	0.07	0.10	0.03
LNE	0.14	0.10	0.11	0.05
SP	0.12	0.09	0.13	0.04
OFM1	–	0.16	–	0.12
OFM2	0.17	0.16	0.18	0.06
Mean	0.15	0.13	0.15	
Std. dev.	0.04	0.05	0.06	

Table 8
Disc, internal surface, 500 upr: LSC deviations from roundness and estimated uncertainties (μm)

Section	L	M	H	$u_{2\sigma}$
IMGC	0.39	0.38	0.46	0.04
EOLAS	0.43	0.47	0.60	0.05
NPL	0.49	0.40	0.39	0.09
VSL	0.39	0.47	0.46	0.14
ULg	0.27	0.28	0.24	0.06
PTB	0.42	0.40	0.46	0.10
IPU	0.34	0.35	0.40	0.05
LNE	0.43	0.39	0.52	0.05
SP	0.38	0.38	4	0.04
OFM1	–	0.45	–	0.12
OFM2	0.43	0.39	0.44	0.06
Mean	0.41	0.41	0.46	
Std. dev.	0.04	0.04	0.06	

independent of the laboratory and of the measured roundness deviations as well.

In addition to IMGC, only three other laboratories, IPU, OFM and SP, supplied their results on the harmonic analysis of the measured profiles. These results, summarised in Table 12, confirm well the agreement among these laboratories, taking into account the resolution and uncertainty limits of the original data and also that the peak-to-valley value is twice the amplitude of the harmonics.

7. Conclusions and recommendations

For the hemisphere, the findings of this interlaboratory comparison may be summarized as follows.

(i) To be strictly meaningful, the calibration of a hemispherical glass standard requires the availability of error separation techniques. This is the condition to be met for getting a measurement uncertainty lower than the measurand.

(ii) Where separation techniques were not

Table 9
Disc, external surface, 50 upr: LSC deviations from roundness and estimated uncertainties (μm)

Section	L	M	H	$u_{2\sigma}$
IMGC	0.14	0.07	0.11	0.04
NPL	0.10	0.08	0.13	0.09
VSL	0.16	0.08	0.07	0.06
PTB	0.14	0.10	0.14	0.06
SP	–	0.07	–	0.04
OFM1	0.12	0.09	0.11	0.04
OFM2	0.12	0.12	0.13	0.05
Mean	0.13	0.09	0.12	
Std. dev.	0.02	0.02	0.03	

Table 10
Disc, internal surface, 50 upr: LSC deviations from roundness and estimated uncertainties (μm)

Section	L	M	H	$u_{2\sigma}$
IMGC	0.38	0.37	0.45	0.04
NPL	0.39	0.36	0.38	0.09
VSL	0.36	0.42	0.44	0.10
PTB	0.36	0.36	0.42	0.06
OFM1	0.38	0.39	0.44	0.04
OFM2	0.36	0.35	0.40	0.05
Mean	0.37	0.38	0.42	
Std. dev.	0.01	0.03	0.03	

Table 11
Disc eccentricity between external and internal surface (μm)

Section	L	M	H	$u_{2\sigma}$
IMGC	0.36	0	0.22	0.10
EOLAS	0.34	0.28	0.21	0.05
NPL	–	0.33	–	0.09
VSL	–	0.26	–	0.12
ULg	–	0.28	–	0.10
PTB	0.34	0.29	0.22	0.10
IPU	–	0.26	–	0.06
LNE	0.35	0.45	0.55	0.13
OFM1	–	0.29	–	0.10

Table 12
Harmonic analysis: Amplitude (nm)

	Hemisphere			Disc—external			Disc—internal		
Harmonics	II	III	IV	II	III	IV	II	III	IV
IMGC	16	3	4	26	6	4	138	10	8
IPU	17	–	–	15	8	0	126	6	6
SP	–	–	–	27	6	–	–	–	–
OFM	–	–	–	20	10	10	130	0	10

available, the results verify that spindle errors had an influence generally not larger than expected and that the measurement process was under control.

(iii) As expected from the low harmonic content of this standard, the results from error separation methods were depending on the filtering

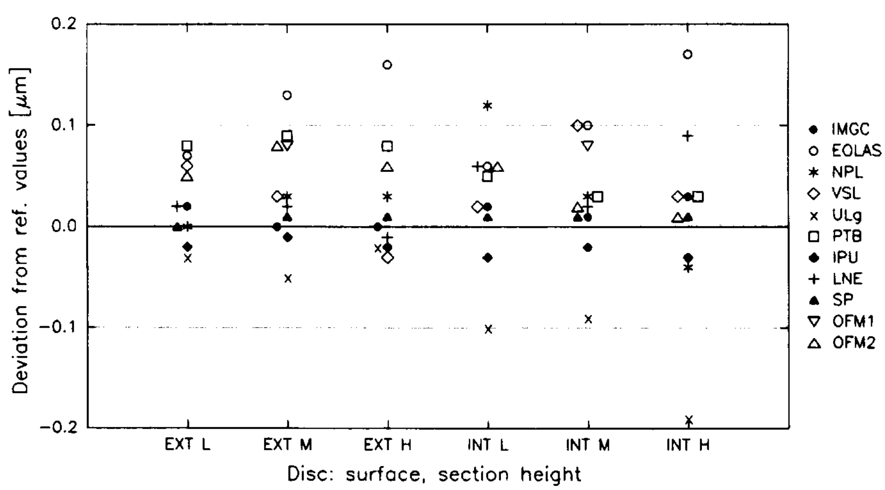

Fig. 5. Disc: deviations from reference values at 500 upr.

conditions by no more than a few nanometers. On the contrary, by comparing the overall mean results at 500 upr and at 50 upr, their ratio is very close to the ratio of the corresponding standard deviations. This suggests that, in the absence of error separation, the results at 500 upr are seriously affected by the noise of measuring systems.

(iv) Among the results with spindle error separation, with a single exception due to a slight unexplained anomaly, the agreement obtained among the participants resulted in an interlaboratory standard deviation of 10 nm or less.

(v) Differences of about 10 nm were found relating to section height and measuring direction (higher values at 3 mm and along the A direction). As a consequence, these conditions have to be explicitly indicated in any calibration report on hemispheres.

(vi) For those laboratories where results are given for a reduced set of points (e.g. 50 vs 512), a tiny bias toward lower values may be present. Minor measurement details, such as rotating element, direction and speed of rotation, tip material and radius, produced no detectable influence on the results.

(vi) Instruments where the maximum plotting magnification was 20,000 × ought to be modified to allow higher magnification, when used with hemispheres.

(vii) Caution is to be taken when spindle error separation is obtained by subtraction of pre-stored deviations. Noise problems may nullify the advantage of this technique.

Even though these results are satisfactory for the first intercomparison in this field, room for further improvements still exists, in order to solve the following problems:
- a systematic trend in the within-laboratories deviation from the means;
- large differences in the stated uncertainty;
- instrumentation noise at high upr;
- the inclusion of hemisphere instability.

For the disc the following conclusions may be drawn.

(i) As the roundness deviations increase, the benefit of using error separation methods becomes less apparent, mainly at 50 upr. Nevertheless at 500 upr, where with the ordinary method the system noise contribution becomes more critical than the systematic spindle error, the error separation method has a clear advantage due to the random noise reduction consequent to the number of replications involved.

(ii) The results at 500 upr without error separation are appreciably affected by the system noise, whereas, due to the low harmonic content of the disc, no systematic difference should be expected.

(iii) In general, almost all the measurement results were consistent with the uncertainties claimed by each laboratory. By excluding a few anomalous results, the overall agreement, independent of the method, was within 200 nm at 500 upr and within 100 nm at 50 upr.

(iv) A very good agreement was also found in the measurements of the eccentricity between external and internal surfaces. The interlaboratory standard deviation was 0.06 μm. A further improvement may be achievable by considering that in eight out of nine laboratories the resulting standard deviation was 0.02 μm.

Finally, for both artefacts there is a supplementary finding given from the comparison made by a number of participants of MZC and LSC evaluation. MZC results were consistently lower than those based on LSC of about 10%.

In conclusion, the experiences drawn by the participants in this set of intercomparisons resulted in a better understanding of the different aspects (problems and limits) involved in these measurements.

Acknowledgements

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