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Concept of metrological reference surfaces for asphere and freeform metrology

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Abstract
Within the framework of a European metrology research project, advanced reference surfaces, which will be used to characterize asphere and freeform metrology systems, are being developed. A so-called Metrological Reference Surface (MRS) consists of surface features, which are traceably measurable with low uncertainty.
This principle is, for example, realized in multispherical MRSs consisting – in the simplest case – of spherical segments with two different radii, arranged like sectors of a circle when projected onto a plane. The centre of the specimen is the common vertex of all spherical segments. Between the segments, well-designed transition zones are included.
The European project and the particular task of MRS development will be presented, and the metrology used to characterize the multispherical MRS will be explained in detail. In particular, the application of a modified interferometric radius measuring bench will be explained and improvements of the setup with regard to measurement uncertainty and traceability will be shown.
With these improvements, the multispherical MRSs represent a good possibility to verify asphere and freeform measuring instruments.

Calibration, measuring instrument, radius, uncertainty

1. The European "FreeFORM" project

Within the framework of EURAMET [1], the European association of National Metrology Institutes (NMIs), a three-year research project was launched in 2016 with nineteen international partners [2]. Because optics manufacturing, metrology and production are of high importance in Europe, the project focusses on reference algorithms and metrology on aspherical and freeform optical lenses.

Within the project, one work package is about innovative aspherical and freeform reference elements. Several comparisons of aspheres and freeform surfaces have already been conducted, for instance in [3]. Furthermore, various measuring instruments for optical surfaces of aspherical (with rotational symmetry) or freeform shape (without rotational symmetry) have been compared. As there is no real reference instrument, there is still a lack of absolute information in these comparisons.

As a solution, a new class of optical surfaces has been defined, which have a link to different measuring techniques delivering absolute values. These surfaces are called Metrological Reference Surfaces (MRSs) and exhibit surface features, which are traceably measurable with low uncertainty.

The most prominent example is a multispherical MRS [4]. Its concept will be presented in the following section. Further examples are MRSs with plateaus or chirp structures. The measurement of the "radius" surface feature will be described in section 3 and an outlook on the next developments will be given in section 4.

2. Concept of multispherical MRSs

A multispherical MRS consists of a combination of spherical sections with different radii of curvature. They can be arranged in different ways, whereby a very effective realization is to arrange spherical segments with two different radii, like sectors of a circle when projected onto a plane. The centre of the specimen is the common vertex of all spherical segments. Between the segments, well-designed transition zones are included.

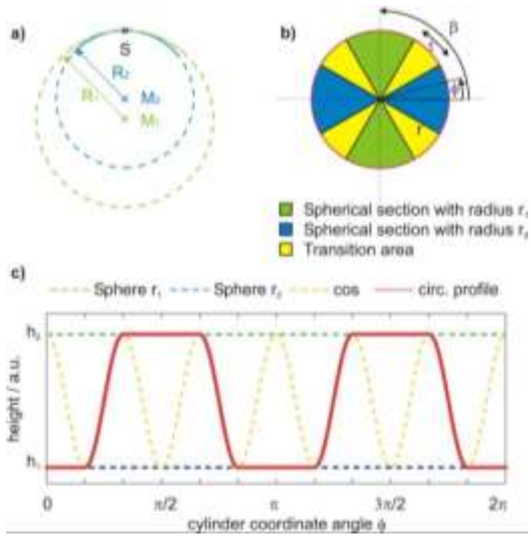

Figure 1. Example of a multispherical MRS. a) Sectional view showing the virtual arrangement of two spheres with common vertex S, b) different segments, c) circumferential profile for fixed radius coordinate r.

The functional description in a cylinder coordinate system $z(r,\phi)$ is characterized by the transition from the segment with a smaller radius R_1 (and height value h_1 at cylinder radius r) to a segment with a larger radius R_2 (and height value h_2 at cylinder radius r). For N spherical segments (N = 4 in figure 1), the functional relation from the middle of the first R_1-segment to the middle of the following R_2-segment is spread over the angular area of $0 \le \phi \le \beta$ with $\beta = 2 \cdot \pi / N$:

$$z(r,\phi) = h_1 \qquad \text{for } 0 \le \phi < (\beta - \tau)/2 \ ,$$

$$z(r,\phi) = h_2 \qquad \text{for } (\beta + \tau)/2 \le \phi < \beta \ ,$$

and in the transition area with $(\beta\text{-}\tau)/2 \le \phi < (\beta\text{+}\tau)/2$

$$z(r,\phi) = h_1 + \frac{h_2 - h_1}{2} \cdot \left(1 + \cos\left(\frac{\pi}{2\cdot\tau}(2\cdot\phi - \beta - \tau)\right)\right) \ . \qquad (1)$$

Here, the width of the transition area is τ with $\tau < \beta$.

By differentiation, the angular slope along the circumference results in:

$$z'(r,\phi) = \frac{(h_1 - h_2)\cdot\pi}{2\cdot\tau} \cdot \sin\left(\frac{\pi}{2\cdot\tau}(2\cdot\phi - \beta - \tau)\right) \qquad (2)$$

and is zero for $\phi = (\beta\text{-}\tau)/2$ and $\phi = (\beta\text{+}\tau)/2$, which is necessary for a smooth transition.

The maximum angular slope, together with the radius of the circumference line, determines the maximum slope of the surface when imaged by an interferometer. To start with not too steep slopes in the transition areas, it was decided to choose the radii R_1 = 40 mm and R_2 = 39.5 mm as nominal values for the first fabrication of the multispherical MRS. The MRS was manufactured with an ultraprecision diamond turning machine (Nanotech 250 UPL). The measurement results (Fig. 3) demonstrate the manufacturability of such a specimen.

3. Radius metrology for multispherical MRSs

The extended radius measuring bench (figure 2) determines the radii from the difference of the respective confocal positions to the cat's eye position. The concept of using radius measurement to trace back the multispherical MRS implies measuring the radii for all segments. For a multispherical MRS, the adjustment, in particular, has to be performed carefully to have the common vertex on the optical axis.

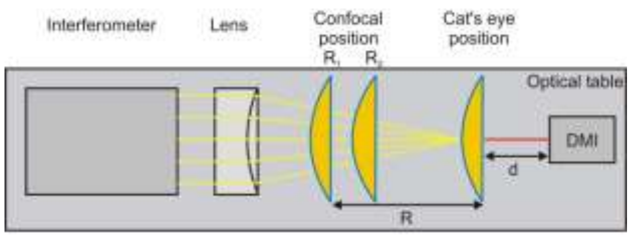

Figure 2. Extended radius measuring bench for multispherical MRS. The distance is measured by a distance measuring interferometer (DMI). The interferometer on the left, in combination with the lens, measures the sphericity of the resulting wavefront.

A result is calculated from the difference of the respective confocal position and the cat's eye position along with averaging a time series of these measurements (figure 3). Table 1 shows the main uncertainty influences [5], which are higher than for classical spherical specimens because the evaluable area in the interferometer images is smaller.

The highest uncertainty contribution results from temperature changes, which influence the length of the optical bench.

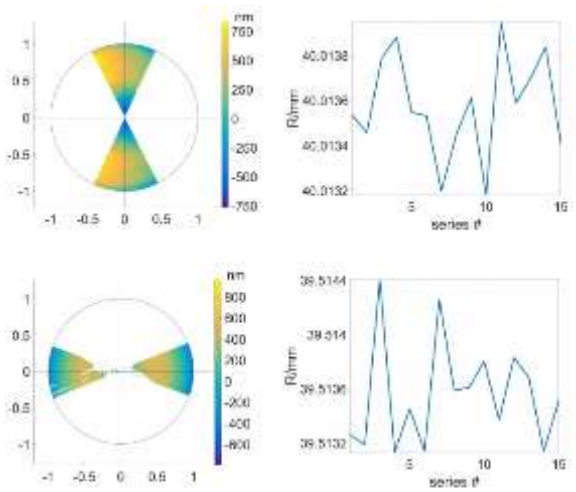

Figure 3. Typical section topographies in relative aperture coordinates (specimen diameter 36 mm) after removal of the defocus contribution (left) and corresponding radius measurement time series (right).

Table 1. Main **u**ncertainty contributions for the radius measurements for the multispherical MRS. The values are given with an expansion factor of *k* = 2 according to [6].

Uncertainty contribution from	**Value**
Stage height error	20 nm
Temperature	210 nm
Abbe offset	1.5 nm
DMI dead path	80 nm
DMI (general uncertainty)	18 nm
Air turbulence	1 nm
Confocal/cat's eye position	118 nm
Sphericity measurement	13 nm
Resulting uncertainty	**512 nm**

4. Outlook

Two improvements are intended within this European project. First, the radius measuring bench will be equipped with a DMI measuring the distance from the interferometer side. This will eliminate most of the temperature influence of the length measurement. Second, it is intended to manufacture the MRSs from thermo-invariant material. This will reduce effects from temperature on the specimens themselves.

5. Acknowledgements

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