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Measurement device for diameter variation of ultraprecise silicon spheres

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Abstract
To control the sensitive polishing process of silicon spheres with form deviations in the range of 20 nm and below, it is reasonable to characterise the variation of the diameter of the spheres in time intervals of some hours. A novel device is presented, which uses an interferometric non-contact sensor and a simple mechanical setup. A direct measurement reveals the variation of the actual diameter at three orthogonal equators on a silicon sphere, which can be acquired within a measurement time of some minutes. The compact and stable measurement loop of the setup enables a repeatability of a few nanometres.

ultra precision, measuring instrument, production, interferometry

1. Introduction

For the international Avogadro project, ultraprecise silicon spheres have been manufactured at PTB [1]. The final polishing step of the manufacturing chain of the spheres with form errors around 20 nm needs continuous control by means of daily dimensional measurements. Even though the national metrology institute of Germany, PTB, has appropriate traceable measurement devices, legal tasks do not permit the continuous use of these outstanding instruments for daily measurements of currently up to four spheres in polishing processes. Besides this, the measurement times are also too long. Thus, a highly specialized device has been designed for short measurement times below 5 minutes along one equator and with a repeatability of some single nanometres.

2. Design

The design and principle of the purpose-built device is based on the basic properties of the objects to be measured – ultraprecise silicon spheres:

1. high reflectivity of almost perfect spherical surfaces with average roughness values of approx. 0.2 nm
2. very low form error with wavelengths of several millimetres and amplitudes around 10 nm.

These preconditions allow a tailored approach.
Firstly, interferometry was chosen as the measurement principle. Due to the very good reflectivity of the surfaces with the lowest roughness, no further mirrors or optical components are necessary. The non-contact measurement furthermore allows a sufficient distance of some millimetres between the mechanical setup and the very expensive spheres and thus prevents damage to the spheres due to mechanical contact. The wavelength in the two interferometrical devices is 632.8 nm with a resolution of the displacement signal of 5 pm.

Secondly, table 1 shows the influence of the misalignment of a sphere on the measurement result. With the ideal centre in the collinear beams, an eccentricity *e* of the position off the centre leads to a cosine error of 2Δ. This error is smaller than 1 nm, if the eccentricity *e* of the rotating sphere is less than 10 µm.

Table 1. Eccentricity *e* of sphere and resulting cosine error 2Δ

***e* / µm**	**2Δ /nm**
1	0.01
10	1
100	100

In combination with the large wavelengths of form errors of the spheres of several millimetres, the positioning of the sphere in the rotational axis is not critical. Relative movements between the object and the sensor plate however must be detected by the measurement system. Thus, the bandwidth of signal acquirement must reliably map the mechanical noise frequencies in the moving parts of the system.

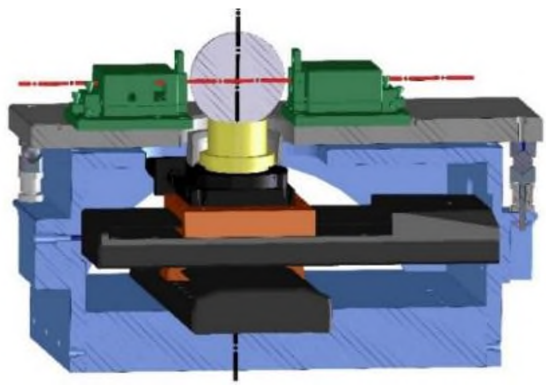

Figure 1. Partial sectional view of the setup. Interferometer heads are green, the laser beam axis is red, the rotational axis is dotted

black. Kinematic couplings are left and right.

Adopting the principle of common form measurement devices, one single sensor and a well-rotating spindle would be necessary. Unfortunately, the amplitudes of typical form errors of the spheres to be measured are in the order of the non-repeatable error motion of commercially available ultraprecision spindles and would thus influence the result significantly. Multiple separation techniques for spindle errors are known [2], but all these demand a large amount of calculation or modelling, or simply measurement runs and time. This applies to some multiple sensor approaches too [3].
Thus, as a third special feature, the direct determination of the variation of the diameter of a sphere around its equator is realised by means of the double-probe method. The distance signals of two opposite collinear sensors relative to the sphere are added, see figure 1. Very short optical paths reduce the influence of air pressure variations and density gradients. Applied in an appropriate mechanical design, this feature strictly reduces the influence of the error motion of the driving spindle on the measurement result.
Furthermore, the mechanical part for centring and rotating the sphere and the plate for the measurement devices is separated and a kinematic coupling is used to combine these. Thus, the thermal influence and potential forces of the mechanical base onto the plate with the two interferometer heads are reduced. To compensate for different coefficients of thermal expansion, the same material is used for the plate and the interferometer heads. The interferometrical part works very stably during measurements. The prototype setup is shown in figure 2. A further setup was designed and built at SIOS Meßtechnik GmbH. This setup is shielded thermally, the interferometers are optimised for the lower reflectivity of the spherical objects and software was added.

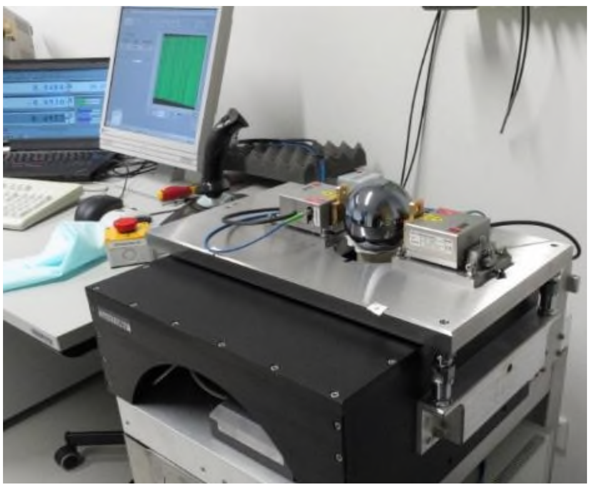

Figure 2. Photo of first setup with optical sensors without enclosure

The final calculation of the results is processed with additional software, which uses the primary measurement data. In the numerical results of two turns, each piece of geometrical information of opposite points appears four times due to symmetry. Four sets of data are thus overlaid, correlated by the encoder's angular information, to average the results as shown in figure 3. Thermal drift can be compensated for linearly in time by means of several algorithms or manually to the best fit.
After half an hour of acclimatisation, the thermal drift due to the temperature of a processed silicon sphere is in the range of some single nanometres within the measurement time.

3. Results

A typical plot of a measurement result is shown in figure 3. The variation of the diameter is 13 nm p-v here. The apparatus has excellent repeatability and reliability. Due to the crystal structure and the resulting symmetry, the detected form error is expected to be half the value of the peak valley values of the diameter variation. This was proved with measurements in PTB's spherical interferometer.

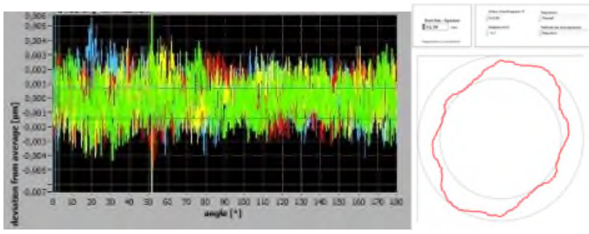

Figure 3. Typical result. Left: deviations of captured diameter variation signals (in µm) from average of 4 measurements, right resulting polar plot of diameter variation with 13 nm p-v

4. Summary and outlook

A novel device for the determination of the variation of the diameter of a ultraprecise silicon sphere is presented. Because mass is the primary target of the processed spheres, the actual absolute diameter values are of lower interest during manufacturing. Thus a fast and effective setup for measuring the diameter variation is developed. Due to the unique design, a repeatability of measurements within some nanometres can be achieved. In a next step, the instrument will be characterised in a metrological manner. Due to the principal blindness to orbiform curves and odd harmonics, the instrument will be optimised to be able to capture form deviations. A new spindle with sufficient non-repeatable error motion will be installed.

References

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