Calibration of CMM Reference Spheres Using Stitching Interferometry

M. Jansen[1], M. te Voert[2], H. Haitjema[1],
[1]*Mitutoyo RCE, The Netherlands*
[2]*Universiteit van Utrecht, The Netherlands*

m.jansen@mitutoyo.nl

Abstract

In the ISO 10360 series on acceptance and verification of CMMs it is stated that the form of the test sphere shall be calibrated. It is common to do this with a roundness measurement, however from the probe performance test it is clear that the sphericity is the relevant parameter. We built a system that can calibrate the sphericity of CMM test spheres on a routine base. A Fizeau interferometer is used together with mechanical stages to rotate and orient the sphere and software to stitch the measurements into a full sphericity map. Both ceramic and steel test spheres with a diameter in the 10-50 mm range can be calibrated within 20 minutes with an uncertainty of typically 30 nm. The measurement uncertainty of this system has been validated using a Monte-Carlo approach.

1 Relevance of reference sphere sphericity for CMM acceptance tests

The performance evaluation of CMM's, as far as the probe performance is concerned, is defined in ISO 10360-2(2001) for probes taking discrete points and ISO 10360-4 (2000) for scanning probes.

As these procedures must determine the probing error, the influence of the geometry of the sphere should be known and reduced to a minimum. Therefore the standards describe that the form of the sphere should be calibrated. In practice this is commonly interpreted as carrying one or more roundness measurements at equatorial planes that give an indication of the form errors present. However, from the nature of the test carried out it is obvious that the sphericity is decisive for the form error of the standard that influences the test result. Another issue is that it is common to filter roundness profiles while from the nature and evaluation method of the CMM-data taken it is obvious that no kind of filtering is – or usefully can be – applied.

2 Sphere stitching Fizeau interferometer system

For measuring the sphericity of a sphere, a calibration setup is constructed that consists of a Fizeau interferometer with a transmission sphere (*figure 1*).

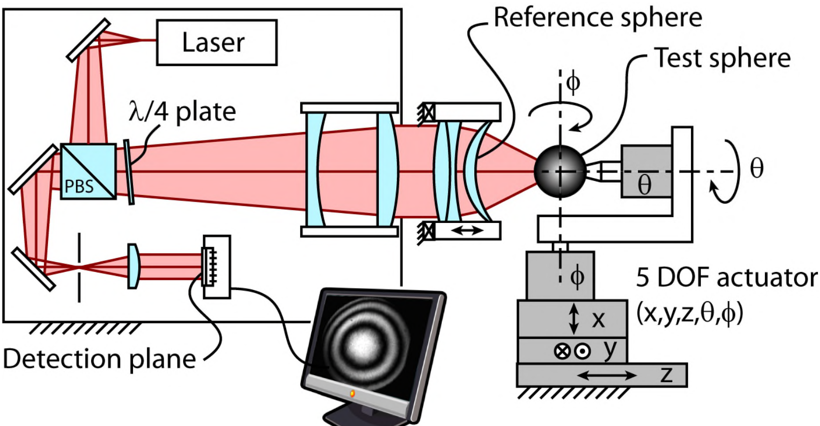

Figure 1: Schematic layout of Fizeau type ball sphericity measurement setup.

The test sphere can be positioned in the field of view with 5 degrees of freedom. The *(θ,ϕ)* rotary stages are used to select a spherical measurement position on the surface of the test sphere. The x,y,z stages are used to align the sphere such that a (almost) normal incidence measurement beam is obtained for each subaperture measurement.

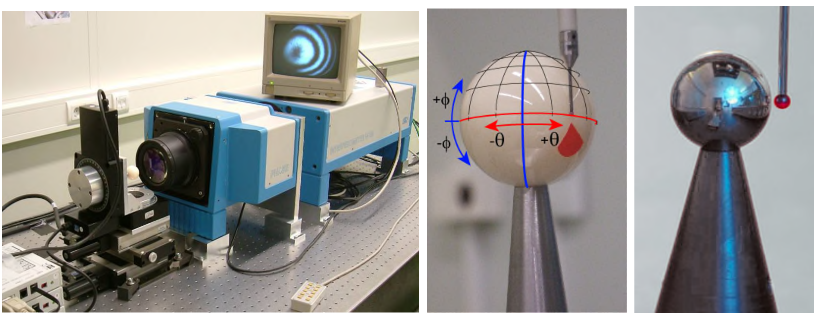

Figure 2: Ball sphericity measurement setup and typical test spheres. Both ceramic and steel master balls can be measured.

3 Stitched measurement

A stitching algorithm combines overlapped subaperture datamaps and minimizes the data discrepancy in the overlapped regions. Before stitching, all datamaps are accurately mapped onto a global (θ,ϕ) sphere coordinate system. The equation that is to be solved to obtain a stitched datamap $r_{stitched}$ for each subaperture is then defined:

$$r_{stitched}(\theta,\phi) = r_{measured}(\theta,\phi) + \underbrace{\left[\Delta x \cdot \sin(\theta)\cos(\phi) + \Delta y \cdot \sin(\phi) + \Delta z \cdot \cos(\theta)\cos(\phi) + \Delta R\right]}_{stitching} \quad \text{(eq.1)}$$

In our setup the parameters Δx, Δy, Δz and sphere radius ΔR are considered to be free compensators that have to be determined for each subaperture datamap $r_{measured}$. For the overlapping coordinates between any two partially overlapping datamaps $r_m(\theta,\phi)$ and $r_n(\theta,\phi)$ the following linear equation can be written for a selected set of overlapping coordinates to minimize the mismatch in the overlap regions:

$$\begin{aligned} r_m(\theta,\phi) + \left(\Delta x_m \sin(\theta)\cos(\phi) + \Delta y_m \sin(\phi) + \Delta z_m \cos(\theta)\cos(\phi) + \Delta R_m\right) &= \\ r_n(\theta,\phi) + \left(\Delta x_n \sin(\theta)\cos(\phi) + \Delta y_n \sin(\phi) + \Delta z_n \cos(\theta)\cos(\phi) + \Delta R_n\right) & \end{aligned} \quad \text{(eq.2)}$$

After solving the linear stitch equations of all selected overlap coordinates simultaneously by a weighted minimum-least-square solving method, and applying the result, the stitched measurement result is obtained (*figure 3*).

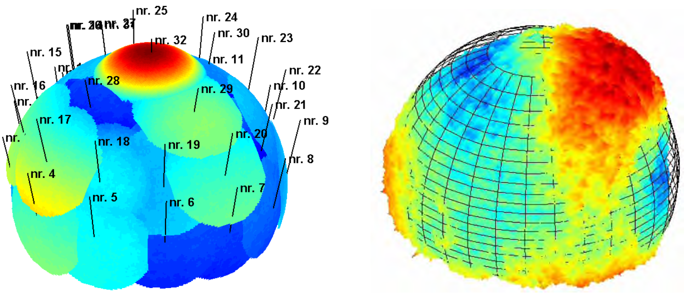

Figure 3 Measurement of a∅30 mm CMM calibration sphere. Left: 32 partially overlapping measurements before stitching (40% overlap), Right: Stitched measurement result: RMS 23± 2 nm, PV 142 ± 26 nm.

Systematic measurement errors related to the optical design of the interferometer can be determined separately and must be compensated before stitching. These errors include retrace errors, field distortion, mapping errors and reference sphere form errors. The form error of the λ/10 reference sphere is calibrated with an RMS uncertainty of 2 nm by using an averaging random ball test measurement [1].

4 Validation and uncertainty evaluation

We have found agreement between the stitched interferometric measurement and a stylus contour measurement within the uncertainty of both instruments (*figure 4*).

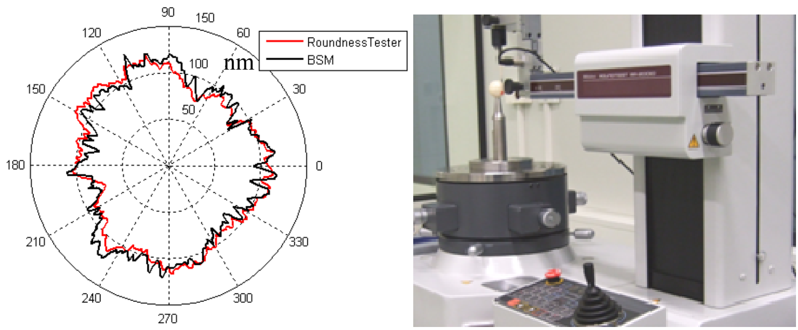

Figure 4 Comparison between an interferometric contour measurement (BSM) and a stylus contour measurement taken with a Mitutoyo Roundtest RA–2100.

The uncertainty contribution of noise, mapping errors, positioning errors and calibration errors to the stitched sphericity measurement result are estimated by applying a Monte Carlo method. With this we can derive a sample and measurement strategy dependent uncertainty for various measurement conditions.

For measuring the CMM calibration sphere a typical sphericity measurement uncertainty of 26 nm is obtained for the PV sphericity (k=2).

References:

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