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Calibration of circular apertures using an optical CMM

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Abstract
The calibration of circular apertures with the aid of an optical CMM is described. This method is fast and economical. The relative uncertainties of optical area calibrations estimated for an aperture 5 mm in diameter amount to $3 \cdot 10^{-4}$ but depend strongly on the form deviation of the aperture itself. The optical calibration results were verified with tactile calibration results obtained with a micro-CMM.

Keywords: Apertures, Calibration, Optical CMM, Micro-CMM

1. Introduction

Apertures are essential components of photometric and thermographic measuring devices. At PTB, a large number of apertures of different type, size and material have to be calibrated. The measurand is the effective area and the required relative uncertainty is in the order of a few 10^{-4} [1].

Different methods for the calibration of apertures are described using optical methods, given in [2, 3], and a special fibre probe, given in [4], respectively. However, these methods require very special and unique devices. Our goal, therefore, is to calibrate apertures using a commercial optical CMM to reduce time and effort considerably. The optical calibration results are to be verified by comparison with tactile calibration results obtained with a micro-CMM.

2. Reference aperture

Most of the apertures to be calibrated are made of aluminium or copper and, therefore, cannot be probed with tactile sensors. We used a reference aperture which can be probed tactilely without damaging the surface. The aperture was made of tungsten carbide (RGS 50) by Rotodur AG (CH). It has a diameter of 5 mm at the upper part of a 60° cone, cf. Figure 1. The nominal height of the cylindrical part below the top, the so-called land, is less than 20 µm, cf. Figure 2.

3. Optical measurements with Werth VideoCheck®

For the optical measurements two different CMMs were used: a Werth VideoCheck VC-HA (High Accuracy) and a Werth VideoCheck VC-UA (Ultra Accuracy). The measurements were carried out with transmitted light using objectives with 10x / 12x magnification and NA = 0.2. The threshold of the optical measurements was traced back using two chromium standards, an opaque and a transparent circle of 200 µm in diameter, respectively. The aperture was set up upside-down and measured in different positions and orientations on these CMMs. The influence of the illumination level and focusing was investigated. The repeatability of the diameter measurements was better than 0.2 µm. The form deviations amount to about 1.4 µm, cf. Figure 3.

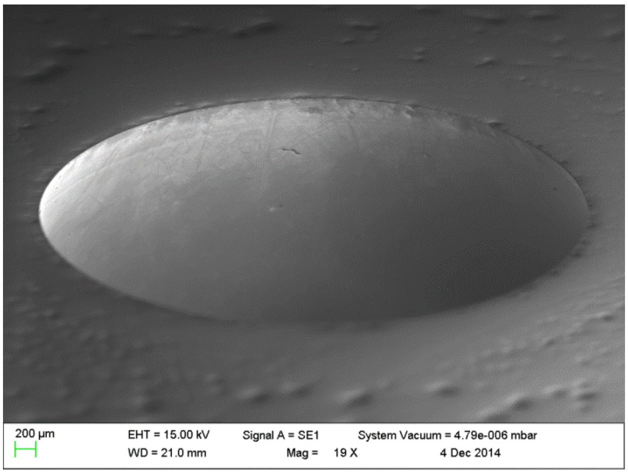

Figure 1. SEM image of the aperture, diameter 5 mm

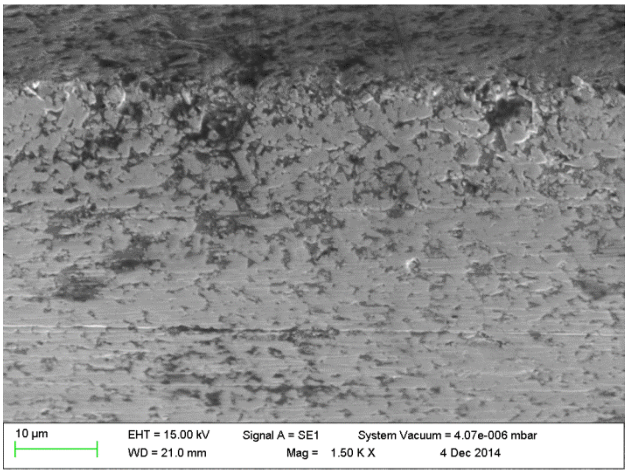

Figure 2. SEM image of the aperture, detail of land

4. Tactile measurements with Zeiss F25

For the tactile measurements a micro-CMM Zeiss F25 was used. The aperture was probed with a micro-probe with a ruby sphere (diameter 0.12 mm). The probing force was about 1 mN. To determine the smallest diameter of the land a number of circular profiles was measured at different heights below the top. 360 points were measured on the circumference using single point probing. The form deviations amount to about 1.1 µm, cf. Figure 3.

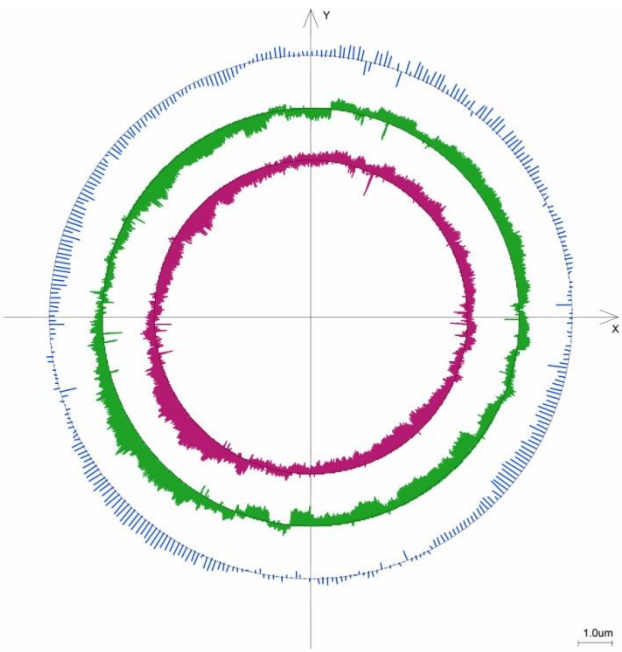

Figure 3. Profiles measured tactilely with F25 (360 points, blue) and optically with VC-HA (14000 points, green) and VC-UA (16000 points, red)

Figure 4 shows the diameter differences obtained at the aperture with the F25. The symbols represent the deviations from the minimum diameter. The repeatability of the diameter measurements was better than 0.05 µm. The minimum diameter of the aperture can be found about 3.5 µm below the top.

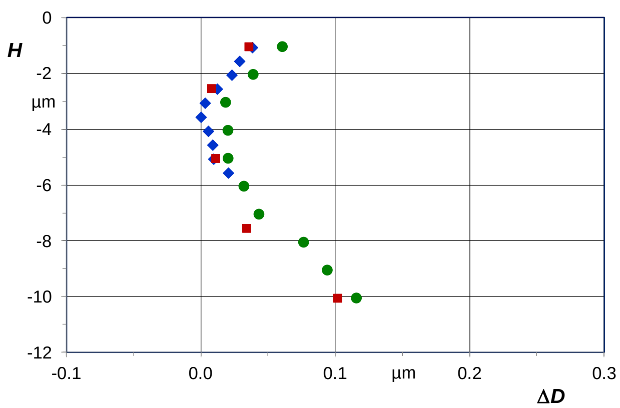

Figure 4. Deviations from minimum diameter of the land in different heights below the top, ■◆● different measurement series with varying distances between the circular profiles, minimum diameter in height -3.5 µm.

5. Measurement uncertainty

To estimate the measurement uncertainty the following influences were considered:

1. Temperature deviation from 20°C,
2. Threshold of optical measurement / diameter of probing sphere,
3. Length measurement deviation of the CMM,
4. Defocusing / variation in height for tactile probing,
5. Misalignment and determination of basis system,
6. Form deviations in horizontal direction,
7. Form deviations in vertical direction.

The expanded uncertainties estimated for the optical and for the tactile measurements are given in Table 1. The main uncertainty influences are the length measurement deviation of the CMM, the threshold of optical measurement / diameter of the probing sphere and the influence of form deviations of the aperture, respectively. The influence of form deviations in horizontal direction, as can be seen in Figure 3, on the uncertainty of the area calculation from the points measured was estimated with a method described in [5].

6. Comparison results

The results for the tactile and for the optical measurements are summarized in Table 1 with D diameter, A area, U expanded uncertainty for k = 2, Δ deviation from F25 results. The results of the tactile and of the optical measurements agree within the estimated uncertainties.

Table 1. Results of aperture measurements, expanded uncertainties (k = 2) and deviations from tactile reference measurements

CMM	$U(D)$ µm	ΔD µm	$U(A)/A$	$\Delta A/A$
F25	0.3	-	$1.5{\cdot}10^{-4}$	-
VC-UA	0.5	-0.13	$2.5{\cdot}10^{-4}$	$-0.1{\cdot}10^{-4}$
VC-HA	0.7	-0.30	$3.0{\cdot}10^{-4}$	$-0.8{\cdot}10^{-4}$

7. Summary and outlook

A procedure for the calibration of circular apertures using commercial optical CMMs was investigated. This calibration procedure reduces time and effort compared to special and unique devices. The relative uncertainties of optical area calibration at a reference aperture 5 mm in diameter was estimated to be $U(A)/A \approx 3{\cdot}10^{-4}$. However, this uncertainty is strongly influenced by the form deviations of the aperture itself. The results were verified by comparison with tactile calibration results obtained with a micro-CMM with a relative uncertainty of $U(A)/A = 1.5{\cdot}10^{-4}$. The results agree within the uncertainties. The next step is the investigation of a calibration procedure for rectangular apertures with the aid of appropriate reference apertures.

Acknowledgement

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