Recent advances in autocollimator calibration and optimisation at PTB

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An overview of the current status of autocollimator characterisation, calibration, and optimisation at the Physikalisch-Technische Bundesanstalt (PTB) and implications for practical applications are provided. The challenges associated with autocollimator use in profilometers for the precision measurement of the form of optical surfaces are emphasised and recent developments at PTB to approach them are highlighted.

1 Introduction

Autocollimators (AC) are versatile optical instruments for the contactless measurement of the inclination angle of reflecting optical surfaces. They are applied in optics, angle metrology, and precision engineering (form measurement of flat and aspherical optics, angular adjustment of components, calibration of angle encoders and artefacts). Beam-shaping optical surfaces in synchrotron beamlines and Free Electron Lasers are now routinely characterised by profilometers which are based on surface slope measurement by means of high-resolution electronic ACs. For a comprehensive overview of the use of ACs for this purpose and the specific challenges associated with this application, see [1].

2 Influences on AC angle response

Accurate and traceable angle metrology with ACs requires their precise characterisation and calibration, as their angle response depends sensitively on the measurement conditions. The AC's angle response depends on a large number of internal parameters – aberrations of the optical components, as well as their alignment, inter- and intra-pixel variations of the CCD, electronics and software algorithms, … – which are specific to the instrument and beyond user control, and on external parameters – reflectivity and curvature of the surface under test (SUT), its distance (beam path length) from the AC, the diameter and shape of the aperture stop, the position of the aperture stop along the AC's optical axis and perpendicular to it – which can be selected by the user or are given by the experimental set-up [2-4]. Therefore, the precise characterisation and calibration of ACs are central to making full use of their potential by correcting residual angle errors. In the following sections, specific challenges are highlighted and recent developments at PTB to meet them are presented.

3 Status of AC calibration

At PTB, the WMT 220 angle comparator [5] serves as the primary national standard for the plane angle in Germany and it is used for the most accurate calibrations of angle artefacts and angle measuring instruments. The systematic graduation errors of the grating can be determined by two independent methods: cross-calibration against a secondary angle encoder (built-in or external) and self-calibration [6,7]. The standard uncertainty of the calibration of the WMT 220 is of the order of u = 0.001 arcsec (5 nrad) and has been verified by various internal comparisons (of cross- and self-calibration) and by comparisons with independent, external partners, which all demonstrate consistency at the level of several nrad rms [8]. ACs can be calibrated, depending on the calibration parameters, down to a standard uncertainty of u = 0.005 arcsec (25 nrad).

4 AC performance at small apertures

Small AC apertures are desirable, e.g., for achieving a high lateral resolution with AC-based profilometers. To counter interference effects, PTB has developed novel Phase-Shifting Reticles (PSR) for ACs [9-11]. In collaboration with an AC manufacturer, the reticles have been included in a commercial AC. First results show a decrease in the feasible aperture and a strong suppression of angle deviations on an angular scale which corresponds to the pixel size of the AC's CCD detector.

5 Positioning of small apertures

We performed experimental investigations on the influence of the position of an aperture stop along the AC's optical axis and perpendicular to it on the AC's angle response [4]. This is an ongoing research topic and ray tracing modelling of an AC and calibrations are performed to characterise the influence of, e.g., optical aberrations of the AC's objective. The development of a device and a standardised procedure for the highly reproducible positioning of small apertures relative to the AC's optical axis during AC calibration and its subsequent use in a profilometer are also investigated.

6 Variability of beam path length

The characterization of the influence of the distance between the AC and the SUT (i.e., the optical path length of the AC beam) on its angular response is of major importance, as most AC-based profilometers use a movable pentaprism to scan the SUT, which induces large changes (in the range of 1-2 m) in this parameter [3]. This is an ongoing research topic which is addressed by AC ray tracing modelling and calibrations. We are also collaborating - together with the Helmholtz-Zentrum Berlin (HZB), Germany - with the Advanced Light Source (ALS), Berkeley, US, in the development of the Universal Test Mirror (UTM) to address this pressing problem [12].

7 Spatial Angle Autocollimator Calibrator

In AC-based profilometers, the AC beam is reflected simultaneously in two orthogonal angular directions (i.e., both measurement axes of the AC are engaged). For extending traceable angle calibration from the plane to spatial angles, a novel calibration device (Spatial Angle Autocollimator Calibrator – SAAC) is currently being set-up. It makes use of an innovative Cartesian arrangement of three ACs (two reference ACs and the AC to be calibrated), which allows a precise measurement of the angular orientation of a reflector cube in space. Each reference AC is sensitive primarily to changes in one of the two relevant tilt angles and can thus be calibrated and traced back to our national primary angle standard in a conventional manner. In contrast, the AC to be calibrated is sensitive to both angles. In addition, the optical path length between the reflector cube and the AC to be calibrated can be varied flexibly.

8 In-situ profilometer alignment

In AC-based profilometers, the pentaprism / optical square needs to be aligned with respect to the AC's measuring axes and its optical axis. Additionally, the reflective surfaces of the optical square need to be aligned with respect to each other. Together with collaborators from the ALS, US, and the HZB, Germany, we have developed in-situ alignment procedures for an in-depth solving of these problems [13-15].

9 Novel approaches to AC calibration

We are investigating advanced error-separating shearing techniques for the cross-calibration of angle measuring devices. AC calibration usually relies on comparison with a calibrated angle reference standard (rotary table with an angle encoder, sine bar with a displacement sensor or interferometer). Shearing techniques, by applying defined angular offsets between both systems, offer a unique opportunity to separate the errors of the AC and of the second system and, therefore, to calibrate both without recourse to any external standard. First experimental tests show very promising results.

10 EURAMET.L-K3.2009 Key Comparison

PTB has initiated and is heading the first European Association of National Metrology Institutes (EURAMET) Key Comparison on AC calibration to provide information on the capabilities and limits of independent calibration methods and devices (EURAMET.L-K3.2009 [16]). A total of 27 international National Metrology Institutes (NMI) are participating, including seven form Asian-pacific countries, and data acquisition (scheduled between 12/2009 – 08/2013) is under way.

References

[1] R.D. Geckeler, A. Just, M. Krause, V.V. Yashchuk, Nucl. Instrum. Meth. A 616 (2010), 140-146

[2] A. Just, M. Krause, R. Probst, R. Wittekopf, Metrologia 40 (2003), 288-294

[3] R.D. Geckeler, A. Just, Proc. SPIE 7077 (2008), 70770B, 12 p.

[4] R.D. Geckeler, A. Just, Proc. SPIE 6704 (2007), 670407, 12 p.

[5] R. Probst, R. Wittekopf, M. Krause, H. Dangschat, A. Ernst, Meas. Sci. Technol. 9 (1998), 1059-1066

[6] R. Probst, Meas. Sci. Technol. 19 (2008), 015101, 11 p.

[7] R.D. Geckeler, A. Fricke, C. Elster, Meas. Sci. Technol. 17(10) (2006), 2811-2818

[8] A. Just, M. Krause, R. Probst, H. Bosse, H. Haunerdinger, C. Spaeth, G. Metz, W. Israel, Precis. Eng. 33(4) (2009), 530-533

[9] G. Fütterer, Proc. SPIE 6617 (2007), 661703, 8 p.

[10] G. Fütterer, Proc. SPIE 5856 (2005), 950-959

[11] G. Fütterer, patent DE102005018983, 26.10.2006

[12] V.V. Yashchuk, W. McKinney, T. Warwick, T. Noll, F. Siewert, T. Zeschke, R.D. Geckeler, Proc. SPIE 6704 (2007), 67040A, 12 p.

[13] S.K. Barber, R.D. Geckeler, V.V. Yashchuk, M.V. Gubarev, J. Buchheim, F. Siewert , T. Zeschke, Opt. Eng. 50(7) (2011), 073602, 8 p.

[14] S.K. Barber, G.Y. Morrison, V.V. Yashchuk, M.V. Gubarev, R.D. Geckeler, J. Buchheim, F. Siewert, T. Zeschke, Opt. Eng. 50(5) (2011), 053601, 10 p.

[15] R.D. Geckeler, Meas. Sci. Technol. 18(1) (2007), 115-125

[16] http://kcdb.bipm.org/appendixb/appbresults/EURAMET.L-K3.2009/EURAMET.L-K3.2009_Techical_Protocol.pdf