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Deflectometric Measurement of Flat and Slightly Curved Optical Surfaces with Improved Lateral Resolution

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Abstract:

At the Physikalisch-Technische Bundesanstalt (PTB), a new Deflectometric Flatness Reference (DFR) for measuring the topography of flat or slightly curved optical surfaces has recently been installed [1-4]. With existing deflectometric procedures like the direct or difference mode, the spot size of the angle measuring system (autocollimator) is the limiting factor for the lateral resolution.

To reduce the spot size of the scanning beam, an additional measurement option, called Exact Autocollimation Deflectometric Scanning (EADS) is implemented. The surface under test is tilted at each measuring position to be perpendicular to the incoming light beam, and the tilt is measured by an additional autocollimator. The development of an angle measuring device with reduced spot size is explained. The development of the EADS system is detailed and the system will be compared with the classical deflectometric measurements.

Introduction

Highly accurate optical surfaces like mirrors or flatness references can be manufactured at the nanometre level. The size of the surfaces can be up to 1 metre or even more. To measure the form of such surfaces, interferometry has the drawback that a reference surface (of the same size) would be needed. Deflectometric surface form metrology using autocollimators or similar devices is easily extendable to long scan lengths and the accuracy of modern autocollimators – in combination with highly precise optical and mechanical components – allows for form uncertainties down to the sub-nanometre level. As a consequence, deflectometry is increasingly applied for highly accurate flatness metrology.

For the end users of the surfaces, two improvements are necessary: the spatial resolution, which is currently limited to a few millimetres by the autocollimator beams, needs to be improved and surface forms significantly deviating from a plane surface should also be measurable. For this, the Exact Autocollimation Deflectometric Scanning (EADS) principle has been developed and the proof of concept has been performed [5]. In the following, the classical deflectometric scanning and the EADS principle will be explained, measurements with this device and experience with the EADS setup will be reported and the system will be compared with the classical deflectometric procedures.

Principle of classical deflectometric scanning

The basic principle of deflectometric scanning combines an angle measuring device, for example an autocollimator, with a pentaprism or a corresponding double mirror unit that is scanned along the surface under test. The optical axis of the angle measuring device represents the straightness reference. The pentaprism eliminates in first order the tilt guidance errors of the scanning stage, which are always in the micron or arcsec range, and thus flatness measurements even with sub-nanometre uncertainties are possible.

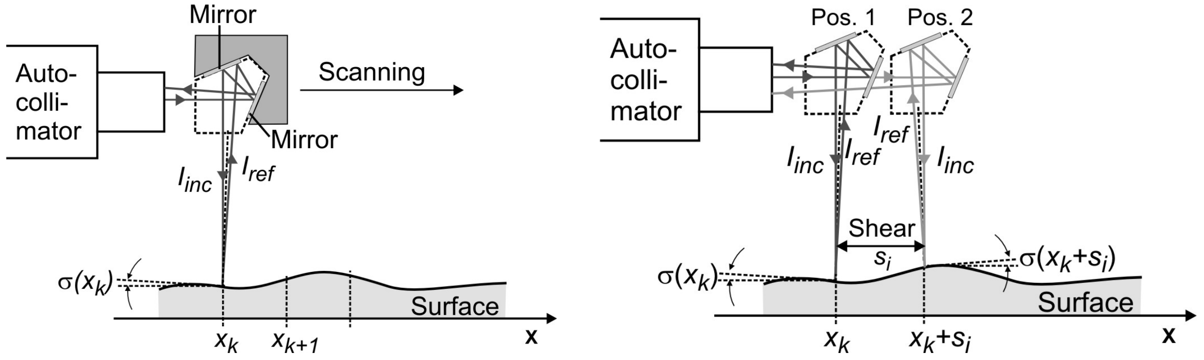

Fig. 1: Principle of conventional deflectometric scanning procedures: direct deflectometry (left) and difference deflectometry, also called ESAD (right).

Figure 1 shows the direct and difference deflectometric scanning mode. With the direct mode, the measured slopes $\sigma(x_k)$ will be integrated, which yields the topography $h(x_k)$. With the difference mode, slope differences, e.g., between position 1 and position 2 will be measured. If two slope differences are always measured, whereby the two lateral shears are relatively prime, an exact reconstruction of the slopes $\sigma(x_k)$ is possible by using natural extension and shearing transfer functions. The integration of the reconstructed slopes $\sigma(x_k)$ yields the surface topography $h(x_k)$. The difference mode is also called the Extended Shear Angle Difference (ESAD) [6, 7] and has been developed at PTB. The autocollimators used in deflectometric setups typically have a spot size of a few millimetres.

Principle of Exact Autocollimation Deflectometric Scanning (EADS)

For the DFR, an additional measurement option, called Exact Autocollimation Deflectometric Scanning (EADS) is implemented that is capable of achieving smaller spot sizes and thus a better lateral resolution.

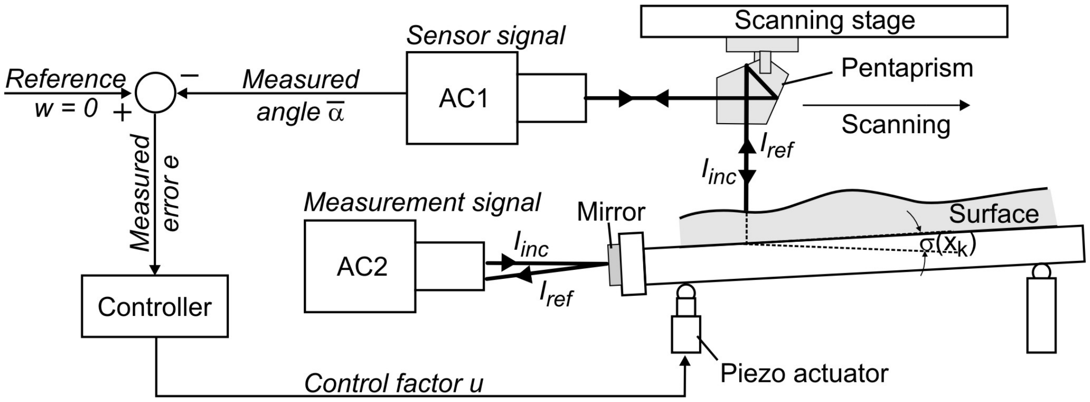

Fig. 2: Principle of operation of the EADS system according to [5]. AC1: straightness representation and null instrument, AC2: angle measurement.

In the EADS principle (see Fig. 2), the scanning operation is the same as for conventional deflectometric principles, but the surface under test is tilted at each measuring position with a digital controller to be perpendicular to the incoming light beam, i.e. realizing an exact autocollimation for the angle measuring device in the scanning unit. Thus, this angle measuring device is operated as a null instrument. As a consequence, the spot size can be reduced and a deformation of the measuring beam profile by a local curvature of the specimen is tolerable. The null instrument only has to detect the state of symmetry. Additionally, this leads to a reduction of possible distance dependent effects. A second angle measuring device is applied to measure the surface tilt, which is the angle measuring signal.

The controller was realized by a software controller using the graphical development environment LabVIEW. The autocollimator AC1 acts as a sensor and measures the angle α with a measurement frequency of 25 values per second. The mean value $\overline{\alpha}$ over one second is used as the controller input. During the first loop of the feedback control, the controller uses the value $\overline{\alpha}(t_1)$ and calculates the control factor for the piezo actuator by $u(t_1) = K_I \cdot \overline{\alpha}(t_1)$. For the experiments which we are showing in this paper, we use a pure integral controller. The amplification factor K_I was determined experimentally. During the second loop, the mean values of the autocollimator at t_1 and t_2 are added resulting in a new control factor $u(t_2) = K_I \cdot \left[\overline{\alpha}(t_1) + \overline{\alpha}(t_1)\right]$. The control loop is repeated until the angle $\overline{\alpha}$ is approximately zero. The control factor for the actuator is computed as follows:

$$u(t_n) = K_I \cdot \sum_{i=1}^{n} \overline{\alpha}(t_i)$$

where $\overline{\alpha}(t_i)$ is the mean value of 25 angle values at time t_i, $u(t_n)$ is the control factor for the actuator at time t_n, and K_I is the amplification factor of the integral controller.

After a few cycles, the measured error $e(t)$ is less than 0.01 arcsecond. Typically, we use seven cycles.

Spot size reduction for the null sensor of EADS

To increase the lateral resolution of the topography measurement, the spot size of the scanning beam must be reduced. This requires a collimated beam, whose beam diameter is almost constant over a scanlength of one metre. A beam width of less than 0.1 mm is aimed at.

With a Gaussian beam this cannot be realized, since the beam width will increase too much. Figure 3 shows a Gaussian beam at *z* = 0 m, *z*= 0.1 m and *z* = 0.5 m. The beam width of a Gaussian beam starting with 50 µm at z = 0 m will increase to approx. 0.63 mm at *z* = 0.5 m. In contrast, a Bessel beam is theoretically diffraction-free and, thus, it will not change its beam width along the propagation axis [8]. Figure 3 shows the profile of a Bessel beam. A disadvantage of Bessel beams is that only a part of the light intensity will be in the main maximum. A Bessel beam can be generated with diffractive optics [8]. This approach and its application to the EADS setup are present topics of research.

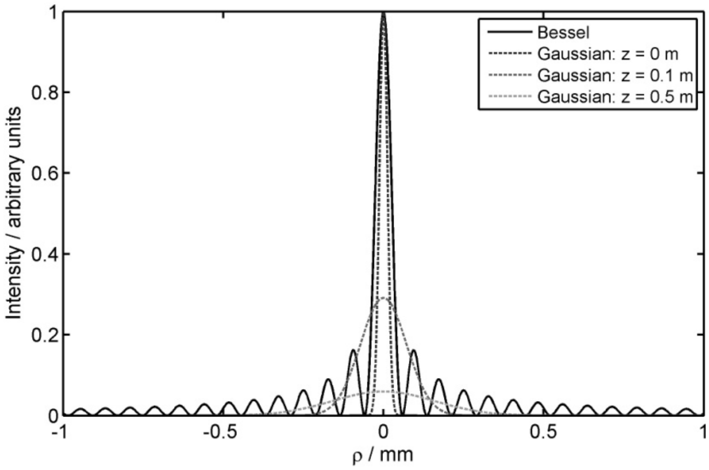

Fig. 3: Beam profile of a Bessel and a Gaussian beam (λ=632 nm) with similar beam width of approx. 50 µm at z=0. Theoretically, the beam width of the Bessel beam does not change along the propagation axis, the beam width of the Gaussian beam has increased to approx. 0.28 mm at z = 0.1 m and to 0.63 mm at z = 0.5 m. The Gaussian intensities at z = 0.1 m and z = 0.5 m have been multiplied by a factor of 10 to allow for a better visibility.

Measurements

Figure 4 shows a photo of the EADS setup. For AC1 (null sensor) as well as for AC2 (measurement of the specimen's tilt), an autocollimator ELCOMAT 3000 from Moeller-Wedel Optical GmbH is used. As actuators, low voltage piezo actuators from Physik Instrumente GmbH & Co.KG with travel ranges of 15 µm are applied. The first measurements were accomplished with this setup.

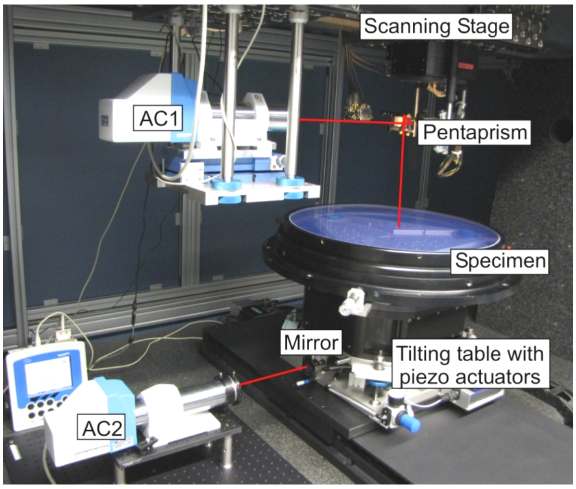

Fig. 4: Experimental setup of the EADS in the new DFR system 1.

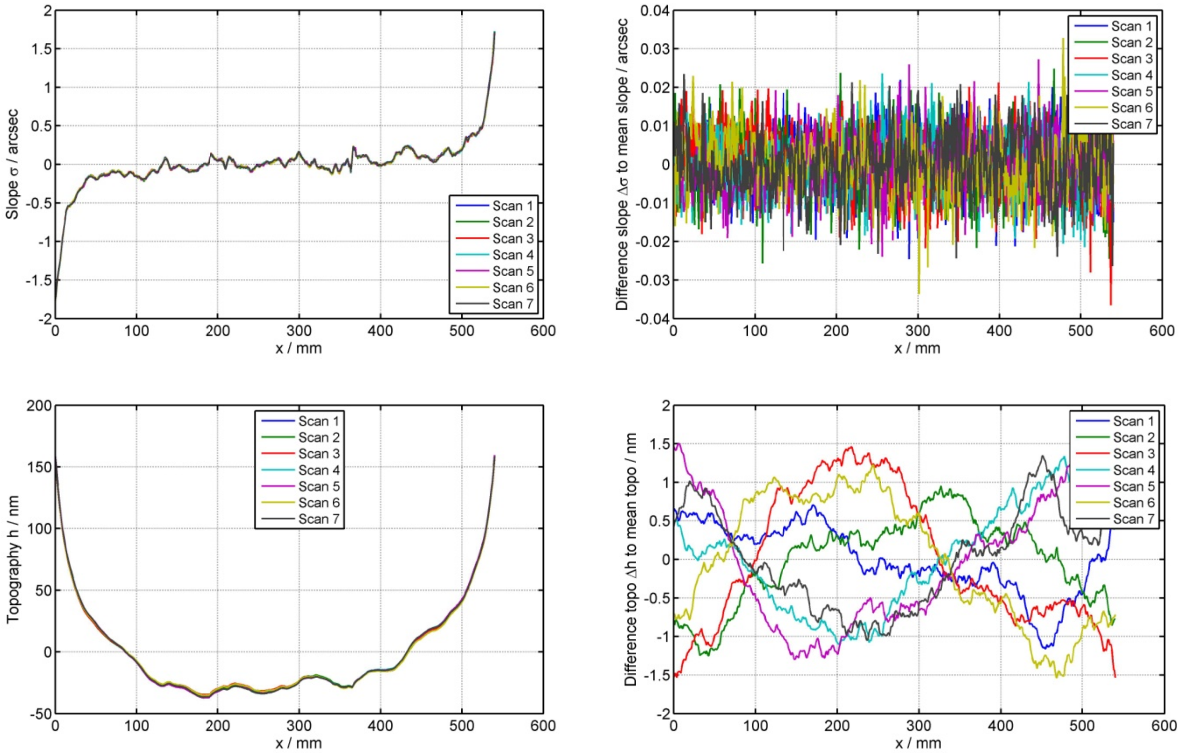

Fig. 5: Experimental EADS results of seven scans with a scan length of 540 mm for the glass specimen shown in Fig. 4.

Figure 5 shows seven scans for the glass specimen shown in Fig. 4. The differences in the measured slopes are in the range of +/- 0.02 arcsec (pv), which leads to differences for the topography of +/- 1.5 nm (pv). Measurements for the same specimen with the direct deflectometric mode yield similar repeatabilities.

Summary / Outlook

Besides the classical deflectometric procedures (direct and difference mode), also the new EADS procedure has been implemented in the Deflectometric Flatness Reference. The first experiments for a 540 mm specimen show good repeatabilities for the EADS mode and thus it will be possible to improve the lateral resolution in future. Further work will be done to design a customized null sensor with apertures of a few tens of microns.

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