Optical flatness metrology: 40 years of progress

Metrología óptica de superficies planas: 40 años de progreso

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ABSTRACT:
Optical flatness metrology has improved significantly in the last decades due to novel measurement tools and new math-based methods. An overview is given summarizing the most important optical techniques for flatness metrology at the nanometer level. The capabilities of modern methods such as the interferometric three-flat test accompanied by a computer-aided evaluation, the Traceable Multi Sensor method as an improved stitching method, and difference deflectometry represented by the Extended Shear Angle Difference method are reviewed.

Key words: Metrology, Optical inspection, Interferometry, Deflectometry, Mathematical methods.

RESUMEN:
La metrología de superficies planas ha avanzado considerablemente en las últimas décadas gracias a nuevas herramientas de medida y a nuevos métodos basados en nuevos enfoques matemáticos. En este artículo se da un repaso a las técnicas ópticas más importantes dedicadas a la medida óptica de superficies planas con incertidumbres nanométricas. Así se revisan las capacidades que ofrecen métodos modernos tales como el test interferométrico basado en tres planos (three flat test) acompañado de una evaluación asistida por ordenador, el método de múltiples sensores con trazabilidad (Traceable Multi Sensor method) como un método de stitching mejorado, y la deflectometría diferencial representada por el método de Extended Shear Angle Difference.

Palabras clave: Metrología, Inspección óptica, Interferometría, Deflectometría, Métodos matemáticos.

REFERENCES AND LINKS


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1. Introduction: forty years of flatness measurement

The publication of this special issue gives us the opportunity to look back at the development of flatness measurements during the past forty years. In the field of optical flatness metrology for optical surfaces at the nanometer level, remarkable improvements have been achieved by virtue of novel measurement tools and new math-based methods.

In the 1960s, interferometry against a liquid mirror [1] or the three-flat test [2] represented the state-of-the-art in optical flatness metrology. These methods were able to reach an uncertainty of a few nanometers for surfaces with typically up to 250 mm diameter. While the liquid mirror method according to [1] yielded two-dimensional surface measurements, the three-flat test provided only a one-dimensional profile measurement. These methods have constituted the state-of-the-art for many years, and they were by far sufficient for the technical applications of that time. In the recent past, the demands on flatness metrology have become more challenging as the surfaces required in such fields of applications as astronomy, synchrotrons or photolithography have become larger and because the lateral and the height resolution of production tools have improved [3]. As an answer to these needs, new methods in optical flatness metrology were developed.

Technical resources have improved significantly in the past decades. The availability of the laser [4] as a radiation source was of help for many techniques that require a large coherence length, such as flatness- or length-measuring interferometers [5]. In flatness metrology, the laser became the typical radiation source and made it possible to realize for the first time longer path differences [6] and higher light intensities.

Electronic detectors were invented and nowadays, two-dimensional data with array sizes of several thousand pixels in each direction are state-of-the-art, as well as computers capable of handling this amount of data. Beyond this, the resolution of the signals has increased by several magnitudes. While in former times the readings of typical analogue instruments could have a relative resolution of not much better than $10^{-2}$, modern analogue-to-digital converters have a resolution of $10^{-4}$, which can even be improved by averaging. Besides these general developments in measurement tools, also developments of particular measurement principles for flatness measurements have taken place.

2. Three-flat test

The mathematical analysis of interferometric fringe patterns for optical flatness measurements has continuously been improved. A big step forward was the development of phase-shifting techniques [7]. These methods allow the calculation of the topography for every single pixel. Afterwards, the complete topography can be reconstructed with phase-unwrapping algorithms [8]. However, these techniques lead to relative topography measurement results between a reference surface and the specimen under test, i.e. it cannot be distinguished between errors of the reference surface and the specimen’s topography.

As an absolute method and an alternative to liquid mirror methods [1], the three-flat test was developed. It is based on the reversal principle, which means (in the simplest case) that for the two surface height values $a$ and $b$, the value of $a$ can be determined as $a = ((a + b) - (b - a)) / 2$ from two measurements of a combination of $a$ and $b$ [9]. In optical flatness metrology, it is fundamental for this principle that the measurement responds linearly to distance variations and that the light propagation in the measurements is rectilinear. Besides this, no physical flatness reference is needed. In the early stages, data evaluation was done by fringe position analysis, and it delivered information along single diameters of the flats [2].

There have been many improvements in the last decades (see [10] and ref. therein) and today the state-of-the-art is a version that uses four measurements, with one being the rotational average when rotating one flat (see Fig. 1). The results can be calculated with a relatively high lateral resolution which depends on the pixel number across the aperture. This is possible today with the full amount of data (typical spatial resolution of 1000 pixel $\times$ 1000 pixel) requiring extensive matrix calculations. The accuracy attainable is in the range of 0.5 nm when gravity effects by the rotation are taken into account [10].

While modern interferometers (see Fig. 2) are highly efficient, enable large numbers of averages and can even resolve multiple cavities [11], the three-flat test for the calibration of the instruments requires three flats as large as the interferometer or specimen aperture to be procured. For large specimens, this can be rather expensive. Furthermore, for horizontally [12] or vertically [10] oriented flats, gravity effects influence the method in different steps of the procedure. This influence can arise to the order of several nanometers.
In conclusion, the three-flat test method has been developed further in the past and is now thanks to optimized algorithms, high-resolution detectors and powerful computers capable of delivering flatness measurements with an uncertainty slightly below the single nanometer with high lateral resolution.

Fig. 1: Principle of the three-flat test similar to [10]. The flats A, B, C are measured against each other in four combinations: 1. A and B, 2. A and C, 3. B (which has to be turned around and, as a consequence, has to be optically transmissive) and C, 4. A and C, with C being averaged under rotation.

Fig. 2. Modern wavelength shifting interferometer for calibrating customer specimens at PTB.

3. Deflectometry and extended shear angle difference method

As an alternative to interferometry, the deflectometric scanning method was found to be useful for optical flatness measurement [13]. While the use of autocollimators for straightness measurements was established earlier, for optical flatness measurement only the use of penta prisms allowed high-accuracy non-contact measurements [14]. Improvements in electronic autocollimators have led to resolution and precision values of 0.005 arcsec [15,16], and an uncertainty of 0.0035 arcsec has been reported for a calibration of the autocollimator Elcomat 3000 (Möller-Wedel Optical) [17].

The principle of deflectometry by means of a penta prism is shown in Fig. 3. The straightness of the light propagation from the optical angle measuring instrument, typically an autocollimator, represents the straightness reference. The light is then deflected at a right angle by the penta prism and propagates to the surface under test. When reflected from the surface, it propagates back, and the deviation from the original direction is measured by the angle measuring instrument. From the tilt values, the topography of the specimen is calculated by integration with appropriate algorithms [18].

The improvements in electronic autocollimators have made it possible to achieve uncertainties in the nanometer and even sub-nanometer regime. The measurement yields surface profiles of the specimen, for which reason such profilers - with a long scanning range (see Fig. 4) - are often used for the measurement of synchrotron mirrors. In this field, it is also of help that the primary information is an angle signal and that surfaces are often characterized by their angular function rather than by their height function. Two-dimensional topographies can be combined from profiles in different directions. In contrast to interferometry (see Section 2), the lateral resolution is limited by the beam diameter used for scanning the surface. It can be as low as 1 mm [19]. In contrast to interferometers, the costs of the measuring system increase only moderately with the specimen dimensions, as only the scanning unit has to be larger.

If an ultimate accuracy is aimed at, the Extended Shear Angle Difference (ESAD) method can be used. This method utilizes angle difference information as a primary measurement property. The angle difference for two points on the surface – separated by the shear distance - is not influenced by height shifts or tilts of the specimen. This makes the method useful for systems which require a long measurement time. In the ESAD realization used at the Physikalisch-Technische Bundesanstalt (PTB), the shearing and the scanning movement are separated, thereby allowing a constant optical path length for all measurement points on the surface.
The ESAD method has been developed during the last decade with three major improvements: The first is the idea of using multiple shears and processing the data in Fourier space using transfer functions [20]. This avoids the lack of information at the periodicity of a single shear. The second is the mathematical solution of the shearing problem [21,22], allowing application of the transfer function approach also for non-periodic surface topographies. The third is minimizing the influence of a non-perfect penta prism by using the same prism and shifting it between the two positions corresponding to the shear [23]. In addition, the adjustment of the setup resulted in procedures with an optimized accuracy [24]. Details of the ESAD method can be found, for example, in [25].

While the present setup (Fig. 5) was built for testing the method and measuring horizontally mounted specimens, a second-generation universal ESAD measuring system for horizontal and vertical operation with optimized components is presently being constructed and realized at PTB. With this new system, two-dimensional topography measurements with uncertainties in the sub-nanometer range should be possible within acceptably short measurement times.

To summarize, the development of reliable and highly accurate sensors, especially autocollimators, and the development of new math-based methods (ESAD, solution to the shearing problem, transfer function concept) has led to remarkable improvements in deflectometric form measurement methods in the recent decades, and deflectometry has now established itself as a high-accuracy form measuring technique.

4. Traceable Multi Sensor technique

For the highly accurate measurement of surface topographies that deviate strongly from a plane, conventional interferometers and deflectometric scanning systems are no longer sufficient, since their measurement range is exceeded. For interferometry, stitching techniques can be applied in such cases [26]. Stitching methods, however suffer from the accumulation of (small) systematic interferometer errors, and when the ratio between the aperture and the specimen diameter is small compared to 1, this can result in extremely high measurement errors. The systematic interferometer errors can, in principle, not be eliminated by means of the stitching method [27]. Although multiple sensor techniques can make use of redundant information and large amounts of data can easily be evaluated by modern computers, this drawback of stitching cannot be avoided.

In order to employ scanning systems using multiple sensors for high-accuracy topography measurement, an additional measurement quantity is needed. This led to a principle called the Traceable Multi Sensor (TMS) technique. The additional measurement quantity here is the tilt of

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Fig. 3. Deflectometric scanning system.

Fig. 4. The Nanometer Optic Measuring Machine NOM at BESSY.

Fig. 5. Current ESAD setup at PTB.
the multiple distance sensor during the scanning of the surface under test. The tilt can easily be measured by a rigidly mounted autocollimator, cp. Fig. 6. For the analysis proposed in [27,28], the distance between the sensors has to be a multiple of the scanning step. As a sensor array, the pixels of a small interferometer may be used, either directly or in combinations. By using an interferometer with a small aperture (typically in the range of 1 mm) large surface slopes and curvatures can be measured.

Fig. 6. TMS measuring system. An autocollimator (AC) measures the tilt angle of a small mirror attached to the multiple distance sensor (MDS) which is scanned over the specimen.

The distance $d_{ij}$ between the $j$-th sensor at the $i$-th scanning position and the surface may be modeled according to

$$d_{ij} = f(p_i + s(j)) + \varepsilon_j + a_i + b_i s(j).$$

(1)

Here, $f(\cdot)$ is the topography profile of the specimen, $p_i$ is the position of the first sensor of the multiple distance sensor array at scanning step $i$, $s(j)$ is the relative position of the $j$-th sensor, $\varepsilon_j$ is the sensor offset error, and $a_i, b_i$ are the positioning offset and tilt errors of the scanning stage at scanning step $i$.

This setup is often referred to as “Linear TMS” because – due to the linear scanning stage – (1) is linear with respect to all unknowns.

From Eq. (1), topography profiles can be reconstructed up to an arbitrary straight line. When the specimen is mounted approximately in parallel to the scanning direction, this non-uniqueness raises no concerns. The reason for this is that a small error in the tilt of this straight line is well described by a rotation (around a small angle) for which the topography remains invariant. In addition, the sensor offset errors $\varepsilon_j$, which represent the systematic errors of the multi distance sensor (e.g. the interferometer) employed, are determined (also up to a straight line). This makes it possible to calibrate even large interferometers directly [29].

An analysis of the uncertainty reached requires, among other things, that the uncertainties of the measurement positions during scanning are taken into account. As a consequence, the uncertainty of the surface profile measurements depends not only on the setup used, but also on the topography height of the specimen. While for nearly flat surfaces, uncertainties in the nanometer range can be achieved, for topographies with larger peak-to-valley heights, the uncertainty will increase.

The latest developments have extended TMS to continuous lateral coordinates [30], for which lateral positions have no longer to be adjusted for by the scanning stage. For this extension it is sufficient to measure the position, typically with a displacement interferometer. This result in an improvement of the accuracy if positioning errors of the stage are present (cp. Fig. 7).

Fig. 7. Influence of positioning errors on the reconstruction error for different spatial surface wavelengths for TMS (left) and extended TMS (right).
The improvement can be demonstrated by a simulation of a TMS measurement with and without additional lateral distance measurements (see Fig. 7). A realistic simulation (100 sensor pixels, pixel distance: 18.9 µm, positioning uncertainty: 5 µm) shows, that the influence of the lateral positioning measurement error on the obtained resolution is significantly reduced by the extended TMS method. The practical realization of TMS measuring systems requires modern computer techniques for data analysis. For a measurement of 750 points on the topography, the extended TMS procedure needs about 40 minutes to evaluate the measured data on a typical PC.

In conclusion, TMS combines the high lateral resolution of a small interferometer with the straightness reference given by the light of an autocollimator. It is a typical computer- and math-based measurement method based on newly developed algorithms. This method also has a large potential to be developed further, e.g. by applying the ideas of the principle to rotational scanning geometries. A new TMS-based measurement setup for two-dimensional form measurements is at the moment under construction at PTB (Fig. 8).

5. Conclusions
In the last decades, impressive progress has been made in optical flatness metrology, due to improvements having been achieved in measuring systems, electronics and computers, in combination with newly developed mathematical methods and physical measurement concepts. For the three-flat test, new methods with optimized algorithms, high-resolution detectors and powerful computers have improved the measurement capabilities to uncertainties slightly below the single nanometer. In deflectometric form measurement, reliable and highly accurate sensors and the development of new methods such as ESAD have led to remarkable improvements. Meanwhile, deflectometry has established itself as a high-accuracy form measuring technique with uncertainties in the sub-nanometer range. TMS is an example of recent computer- and math-based measurement methods whose practical realizations require the large computational power available today.

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