Continuous measurement of optical surfaces using a line-scan interferometer with sinusoidal path length modulation

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Abstract: We present a fast approach to the continuous measurement of rotational symmetric optical surfaces. This approach is based on a line scanning interferometer with sinusoidal modulation of the optical path length. The specimen is positioned with respect to the sensor and both are moved during measurement by use of a five axes system comprising a high precision rotational table. The calibration of both the line sensor as well as the scanning and positioning system is discussed. As proof of principle of the measurement and stitching concept results of a scan of a rotational symmetric sinusoidal structure and a spherical lens with a moderate slope are shown.

OCIS codes: (110.0110) Imaging systems; (110.2650) Fringe analysis; (110.3175) Interferometric imaging; (110.5086) Phase unwrapping; (110.6880) Three-dimensional image acquisition; (120.0120) Instrumentation, measurement, and metrology; (120.2650) Fringe analysis; (120.2830) Height measurements; (120.3180) Interferometry; (120.3930) Metrological instrumentation; (120.3940) Metrology; (120.4640) Optical instruments; (120.4800) Optical standards and testing; (120.4820) Optical systems; (120.5050) Phase measurement; (120.5060) Phase modulation; (120.6650) Surface measurements, figure; (180.0180) Microscopy; (180.3170) Interference microscopy.

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Aspherical objects of rotational symmetry can be measured by shifting a conventional Fizeau
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1. Introduction

Fabrication of demanding optical components requires accurate measuring instruments in order to
fulfill geometrical tolerances. There are several well-established techniques to measure optical
surfaces of rotational symmetry. Probably the most common technique is the measurement of the
complete object using a Fizeau or Twyman-Green interferometer and to apply a linear
phase shifting technique to determine the phase information from a set of CCD camera images.
This requires costly reference surfaces or computer generated holograms of sufficient accuracy
adapting the wavefront to the geometry of the desired measurement object [1, 2]. The flexibility
of these full field phase shifting interferometers can be improved using adaptive optics to
shape the reference wavefront [3]. As an alternative different point-wise measuring sensors are
combined with appropriate scanning and positioning systems in order to measure the geometry
of an object in a sequential way. These systems for example use tactile, focus, confocal
chromatic, or interferometric measuring principles [4–9]. Because of the point-wise working
principle there is a lack of either speed or lateral resolution. Other methods rely on the stitching
of sub-apertures and require the specimen to be moved exactly to distinct positions, so that the
sub-apertures overlap appropriately. The measurement of sub-apertures usually uses methods
based on linear phase shifting interferometry (PSI) [10, 11] to gather the height information in
each sub-aperture. Depending on the measurement technique the acquisition of separate data
sets for each sub-aperture may be rather time consuming. Capturing four 90° phase shifted
sub-aperture images in a single shot is possible by using the pixelated phase mask technique re-
cently developed [12]. However, stitching single data sets together leads to additional measure-
ment uncertainty. Different methods to improve sub-aperture stitching have been employed:
Aspherical objects of rotational symmetry can be measured by shifting a conventional Fizeau
interferometer designed for spherical surfaces in well-known steps to different positions along

1 December 2014 | Vol. 22, No. 24 | DOI:10.1364/OE.22.029787 | OPTICS EXPRESS  29788
the optical axis and carrying out PSI measurements at each position [13]. This results in a set of circular surface sections, related to those regions of the measuring object, where the measured surface locally fits the spherical wavefront. Another promising idea is the so-called tilted wave interferometer (TWI) which illuminates the object with a set of tilted wavefronts [14,15]. This technique is similar to subaperture stitching but it does not require mechanical movement or scan axes. In this contribution we propose a novel approach to sub-aperture stitching. A line scanning interferometer [16,17] is used to measure ring shaped sub-apertures on a continuously rotating specimen. The interferometer consists of a microscope with a line scan camera and a Michelson setup which utilizes optical path length modulation (OPLM) in the reference arm to generate interference signals from which the surface topography can be obtained. Measurement systems based on OPLM were introduced first by Sasaki [18] and later by others [8,19,20]. Several ring shaped sections related to different radial positions of the surface topography are stitched together, so that the complete surface topography finally results. Compared to point-wise measurement this approach promises better accuracy because of the overlapping rings. Compared to sub-aperture techniques employing 2D-fields of view, the line scan technique is less demanding from the optical point of view. Furthermore, the mechanical axes needed are close to conventional configurations of tactile instruments used to measure objects of rotational symmetry, e.g. so-called form testers [4].

2. Sensor configuration

As stated before the sensor uses periodic OPLM of the reference arm of a Michelson interferometer to generate interference fringes on a line-scan camera from which a phase map of the specimen can be calculated. The configuration is shown in Fig. 1. The OPLM can be done by either changing the refractive index or the geometrical path length. In our case we use a piezoelectric disc actuator to move the reference surface of the interferometer with respect to the optical axis. The interference intensity $I(t)$ obtained from each pixel of the camera then takes the following form:

$$I(t) = I_0 \left( 1 + B \cos \left( \frac{4 \pi}{\lambda} z(t) + \varphi(t) \right) \right)$$

with the intensity offset $I_0$, the amplitude $B$ of the interference signal and the phase change $\varphi(t)$ introduced by the moving specimen. $z(t)$ describes the movement of the reference mirror and $\lambda$ is the wavelength of light.

A triangular shaped $z(t)$ leads to a constant fringe frequency and therefore, to an easy signal processing. However, harmonics of this signal due to the mechanical resonance of the actor may occur. We choose $z(t)$ to be a sinusoidal function leading to the simulated interference signal according to Fig. 2.

A changing height value is encoded in a phase change of the interference signal of the corresponding pixel within a single half cycle of the OPLM. This information can be extracted by phase detecting algorithms. Some of these algorithms are well known from phase shifting interferometry (for example the Hariharan algorithm [21]) or we can use the discrete Fourier transform (DFT). These algorithms usually result in two measurement values for each actuation cycle. In [17] we proposed some algorithms based on Hilbert transform or parameter estimation which enhance the density of measurement values. In this paper we use a single frequency DFT algorithm at a fixed frequency because this procedure is very robust against signal noise and there is no need to further increase the number of measurement values. A Gaussian shaped window function $W(n)$ is used to minimize low frequency components close to the turning points of the sinusoidal actor movement. $n$ is the number of the sampled CCD-line. For highly accurate measurement data a proper calibration of the sensor is crucial. Since the reference mirror is
fixed to a piezoelectric disc actuator, the actuation amplitude is not completely constant along the scan line of the sensor. Therefore, the fringe frequency $f_i(p)$ and the fringe phase offset $\phi_o(p)$ of the OPLM have to be calibrated for each pixel of the scan line before measurement. The resulting phase is $\phi_i(p)$. Here $p$ is an index related to the pixel number of the CCD line, i.e. $p \in \{1, \ldots, 1024\}$. While the fringe frequency can be measured on any static target, the fringe phase offset has to be measured on a known preferably flat surface. Both values depend on the amplitude and the frequency of the actuator signal as well as on the location of the reference surface corresponding to a given camera pixel. $\phi_o(p)$ consists of phase offsets from two different sources: the flatness deviation of the reference surface and the phase offset due to a position dependent actor amplitude. Assuming a sample frequency $f_s$ the DFT algorithm leads to the following equations to calculate the phase during a half cycle of the actuator signal:

Fig. 1: Michelson interferometer with oscillating reference mirror and light coupled directly into the interference beam splitter.

Fig. 2: Simulated interference signal of an OPLM interferometer and the corresponding path length modulation.
\[
\hat{I}_l(p) = \sum_{n=0}^{N/2-1} I(n,p)W(n) \cdot \exp \left( -2\pi i n \frac{f_l(p)}{f_s} \right)
\]  
(2)

\[
\phi_l(p) = \arctan \left( \frac{\text{Im} (\hat{I}_l(p))}{\text{Re} (\hat{I}_l(p))} \right) - \phi_o(p)
\]  
(3)

In order to obtain proper measurement results an additional calibration step is necessary: Due to the hysteresis of actor movement there is an additional phase offset between measurements on the upward and downward actor movement \(\phi_{ud}\). Furthermore, every second phase value has to be inverted because of the changing direction of actor movement. Using this calibration procedure a standard deviation \(\sigma\) below 0.8 nm could be achieved in repeatability measurements on a static surface as it is shown in Fig. 3.

![Fig. 3: Repeatability measurements on a static target for one single pixel, standard deviation is \(\sigma = 0.77\) nm.](image)

For the optical setup of the sensor we use an infinity corrected apochromatic microscope objective with 5x magnification, \(NA = 0.14\), working distance 34 mm and a tube lens. For the interferometer two configurations are possible. The first configuration is aimed at OPLM using a narrow band light source with an actuated reference mirror as mentioned above. Here, the light source is a green high power single emitter LED with an additional interference band pass filter in the afocal region of the illumination path. The filter bandwidth is FWHM = 9.7 nm with a center wavelength of \(\lambda_c = 531\) nm leading to a coherence length of \(l_c = 29\) \(\mu\)m. This spectral characteristic is a compromise allowing fairly large measuring range and avoiding the occurrence of speckles and parasitic interferences. Since the intensity of the light source is largely reduced by the band pass filter, the illuminating light is directly coupled into the beam splitter cube of the Michelson interferometer as shown in Fig. 1 in order to reduce any further loss. A polished silicon plate is used as reference mirror. This is a compromise between satisfying reflectivity and a low mass of the reference mirror leading to a high enough amplitude of sinusoidal excitation. The sensor is designed to work with the maximum acquisition rate of the line scan camera of roughly \(f_c = 50\) kHz. Taking \(N = 128\) discrete samples during each actuation period this results in an actuator frequency of \(f_m = 390\) Hz at an amplitude of \(A \approx 1\) \(\mu\)m of the actor movement \(z(t) = A \cdot \sin \left( 2\pi f_m t \right)\). If the sampling and actor frequency will be lowered an increased SNR of the interference signal can be achieved. To be able to measure distance changes with high accuracy, the signal acquisition has to be perfectly synchronous to the OPLM. The easiest way to guarantee this is to derive the actuator signal from the same clock
source as the signal triggering the camera. In our arrangement both signals are generated by a single microcontroller. However, still the clock jitter has to be taken into account, when quantifying measurement uncertainties. From Eq. (1) we can derive the maximum fringe frequency for constant distance: \( f_{\text{max}} = \frac{4\pi A f_m}{\lambda} \). This results in a jitter based phase error of:

\[
\Delta \phi_j = 2\pi f_{\text{max}} \Delta t_j
\]  

For a jitter of \( \Delta t_j = 127\,\text{ns} \) we calculate \( \Delta \phi_j = 74\,\text{mrad} \) resulting in a measurement error of about \( \pm 0.3\,\text{nm} \) which can be neglected. In the second configuration we built a dispersion compensated Michelson interferometer that can be used as a white light interferometer (WLI). Since the microscope objective is not designed for putting a beam splitter cube underneath (see Fig. 1) reduction of the resulting aberration is necessary. This is achieved by a plano-convex lens above the beam splitter cube and two plano-concave lenses between the beam splitter cube and either the measurement object or the reference mirror of the interferometer. The curvatures of the lenses are adapted to the wave front in a way that refraction is avoided for the light cone focused on the optical axis. This requires that the illuminating light passes the microscope objective [22].

3. Concept based on line-scan sensor

The objective is to measure rotational symmetric specimens with a moderate slope using the interferometric line sensor. The maximum dimensions of the specimen depend solely on the positioning system. In the current system specimens with a maximum diameter of 80 mm can be measured. The whole configuration is based on a polar coordinate system. The first step is to scan a ring shaped section as shown in Fig. 4. To ensure overlap in the scanning direction and to utilize this overlap to eliminate possible drifts or run outs of the rotational axis, the object is rotated by 370°. If one circular scan is finished, the line sensor is moved in x-direction by 1 mm (see Figure 4), before the next circular scan starts. This ensures an overlap of half of the line width of the sensor in the radial direction.

![Fig. 4: Schematic of the measurement process: in step (1) the specimen is rotated by 370° and in step (2) the sensor is translated by 1 mm relative to the specimen.](image)

To test the stitching algorithm a simulated topography is generated. In radial direction the test topography shows a sinusoidal shape with period of \( \Lambda_r = 2.048 \, \text{mm} \). In the angular direction a sine function with an angular period of \( \Lambda_\phi = 2.56° \) is assumed. The amplitude is characterized by a peak-to-valley value of \( a_{\text{pv}} = 1 \, \mu\text{m} \). The data set consists of two sub-aperture rings of 2 mm in radial extension and an overlap of 1 mm. Before stitching the second ring is tilted in x and y
direction and an offset is added to test if the stitching procedure works correctly. The result of the stitching algorithm shows deviations from the originally simulated topography in the range of the numerical accuracy. After the ring shaped sections are stitched together, the data given in polar coordinates is transformed to Cartesian coordinates and corrected by a best fit plane to correct for misalignment of the specimen.

4. Positioning system

The setup of the positioning system is shown in Fig. 5 together with the specimen used for testing. The three linear axes x, y and z are mounted at the top of the setup and two rotational stages at the bottom of the system. An additional manual rotational stage is mounted on the z-axis. This stage is needed to tilt the sensor until it is nearly perpendicular to the specimen. As mentioned above, the idea of the scanning process is to scan concentric ring-shaped surface sections and to stitch these together to a complete surface.

Fig. 5: Five axes movement system with line sensor (left) and the specimen used for testing (right).

4.1. Alignment of the specimen

The first task is to adjust the object under test nearly perpendicular to the optical axis of the interferometer. For this purpose the illumination module is removed from the interferometer and an autocollimator is coupled to the beam splitter of the interferometer. The autocollimator projects a reticle onto the object that moves on the CCD images acquired during the object is rotating. By iteratively tilting and tipping the object one can achieve that the reticle is always imaged on the same position in the image plane. If the crosshair is no longer moving on the image sensor the optical axis of the interferometer and the measurement object are almost perpendicular to each other. Based on this adjustment, it can be ensured that the interference fringes stay within the measurement range of approximately 29 \( \mu \text{m} \) when rotating the object. If the specimen leaves the measurement range of the sensor due to the translation in between two
circular measurements, only the z-axis has to be readjusted. The second task is to align the specimen with respect to the rotational axis. The interferometric sensor is positioned at the flank of the specimen and the position of the flank is observed during rotation. The centering process is iteratively done with micrometer accuracy by two linear stages mounted on the rotational stage, until the distance change observed during rotation is at a minimum.

4.2. Accuracy estimation of the movement axes

To test the accuracy of the axes a laser distance interferometer is used that measures the relative distance of the movement of the system. As an example the x-axis is moved 140 mm in 140 steps of 1 mm. In each position 1200 distance values are obtained by the laser interferometer. The result of such a repeatability measurement at one position is shown in Fig. 6. The positioning accuracy of the axis is close to the digitization error of the laser interferometer. This procedure is repeated for all steps and the standard deviation on each of the 140 steps is shown in Fig. 7. The standard deviation for the step width is about 19.9 nm. This is good enough so that the stitching algorithm will work, because one pixel of the camera is related to 2 µm length on the radial axis in the object plane. Further researches regarding the run out are currently under investigation.

![Fig. 6: Deviation of the position value from the median of the repeatability measurement for one step of the x-axis](image1)

![Fig. 7: Deviation of the step width from the intended step width of 1 mm for 140 consecutive steps.](image2)
4.3. Calibration

The calibration can be done using a highly accurate flat surface as a calibration object. The line sensor can be calibrated by one or two or more positions on the object as described before in Sec. 2 and the median of the measurement results corresponds to the topography of the reference mirror. Measurement results show maximum deviations of about 60 nm from the ideal straight profile. However, once these deviations are known they can be eliminated during measurement. In addition the object can be rotated and the run out of the rotational stage can be measured and corrected because the surface of the calibration object can be seen as an ideal flat for our purpose. The flatness can be measured with sub-nm accuracy at PTB [23]. So it can be traced back to the meter.

5. Measurement results

For testing and verification of the complete system we have designed a test specimen which consists of a flat disc with a 15 mm wide sinusoidal structure in radial direction as it is shown in Fig. 5. The sinusoidal structure starts at a radius of 15 mm, while the whole specimen has a radius of 40 mm. The period length of the structure is 50 µm and the amplitude is 250 nm. The specimen is specifically designed and manufactured by diamond turning at PTB. It shows a well defined surface which allows to test the lateral as well as the height resolution of the sensor and provides a structure on which stitching algorithms can be checked. An exemplary measurement is taken at the transition from the plane surface to the sinusoidal structure. The interference data of a measured area corresponding to 0.3° of rotation is shown in Fig. 8 and Fig. 9. Along the ordinate of Fig. 8 the interference fringes resulting from the OPLM can be observed whereas the sinusoidal surface structure is related to the horizontal axis. Accordingly Fig. 9a) represents a line of Fig. 8 whereas Fig. 9b) represents a single column. Due to the flatness of the surface the signal in Fig. 9b) corresponds to the time-dependent OPLM signal accordingly to Fig. 2. The unwrapped phase data and resulting height values along the scan line are shown in Fig. 10 and 11 a). Figure 11b) shows a reference measurement of the specimen with the measurement system described in [9]. The low frequency oscillation in the reference measurement is due to the straightness deviation of the linear stage used to move the specimen.

![Fig. 8: Measured interference data of the sinusoidal structure and the plane structure of the test surface](image)

A single sub-aperture measured at an angular speed of 40°/s consists of around 476 million intensity values, which result in 7.4 million height measurements. To evaluate the capability of the stitching algorithm for the measured data, two overlapping ring-shaped sub-aperture topographies are shown in Fig. 12 where the angular axis is plotted as a Cartesian axis. The
Fig. 9: Intensity values of Fig. 8 at 0.15° rotation along scan line (a) and for radial position 14.5 mm during rotation (b).

Fig. 10: Unwrapped phase data of one ring measurement of the sinusoidal specimen.

Fig. 11: Height values at a rotation angle of 0° calculated from the phase data in Fig. 10 (b) and reference measurement (a). The tilt of the specimen has been removed.
topography data in the overlapping area is cut out and the second topography is corrected with respect to tip, tilt and offset. The result of this stitching procedure is shown in Fig. 13. From the measurement result it can be seen, that the specimen is tilted by a few micrometers in both, radial and angular direction. From the measurements of the axis accuracy and the sensor standard deviation it can be concluded that the overall measurement uncertainty is dominated by the axis errors. Digitization errors are neglectable due to the averaging property of the DFT phase detection as it is described in [24].

Fig. 12: Two overlapping topography data sets of neighboring ring measurements in cylindrical coordinates

For further improvement of the stitching process residual errors have to be removed. The movement distance of the x-axis has to be measured accurately or the algorithm detecting the overlap region has to be optimized at this point. A first proof of principle with sub-topographies of a spherical lens is shown in Fig. 14. The topography consists of number of four ring shaped sub-topographies, which where combined by the stitching algorithm and afterward corrected by a best fit plane to correct for alignment errors of the specimen. From the topography shown in Fig. 14 a radius of curvature of the spherical lens of 730.5 mm is obtained by least square fit. For reference a commercial confocal chromatic distance sensor was used to scan a profile over the complete diameter of 50 mm of the lens. From this profile a radius of curvature of the lens of 733.7 mm was obtained. Taking into account that in both cases the measured surface section is very small compared to the radius of curvature of the lens the results are in a good agreement.
6. Conclusion and outlook

A line scanning interferometer with optical path length modulation has been developed which is well suited for the measurement of optical surfaces. The height information is derived from phase modulated interference signals. The calibration and behavior of the sensor are characterized. The sensor can be calibrated using a known reference surface to obtain high accuracy measurements. We also present a strategy for the measurement of rotational symmetric surfaces with moderate slope and show that a complete surface can be measured by stitching of circular sub-apertures.

For the measurement of aspheres with high slope angles we developed a concept which has to be tested in the future. To keep the number of interference fringes along the CCD-line limited the sensor needs to be tilted by an appropriate rotational fixture. In addition, the calibration approach assumes that the line scanning interferometer is capable of absolute distance measurement. With this calibration and measurement procedure we want to overcome the limitation of the microscope NA, which limits the maximum slope angle between the surface of the measurement object and the sensor that can be tolerated. Hence, in case of aspheres, the calibration and measurement procedure shall consist of the following steps:

1. A calibration sphere of known radius is adjusted with its center to the rotational axis. The height position is calibrated

2. The sphere is tilted in the XZ plane to calculate the height position of the pivot point and the length of the rotatable arm by a second measurement determining the position of the center of the sphere.

3. The specimen (asphere) is positioned at the symmetry axis and the height position of the vertex is measured. Now the length of the rotatable arm can be calculated.

4. The specimen can now be tilted by a well defined angle because coordinates after tilt can be calculated and related to the base coordinate system.

Based on this calibration, measurements of the complete aspheric surface should be possible even if it shows large slope.

Acknowledgment

The financial support of this research work (LE 992/7-1, EH 400/4-1) by Deutsche Forschungsgemeinschaft (DFG) is gratefully acknowledged.