OPTOELECTRONICS LETTERS Vol.4 No.2, 1 Mar. 2008

Advanced approaches to high precision MEMS metrology based on interferometric, confocal, and tactile techniques[*]

Peter Lehmann[**]
Mahr GmbH, 37073 Goettingen, Germany

(Received 21 August 2007)

Geometrical features of micro-systems can be determined by either tactile or optical profiling techniques, which show different non-linear transfer characteristics. This has to be considered especially, if the instruments operate close to their physical limitations. Depending on the specific measuring task either point-wise or areal optical measurement may be advantageous. Hence, examples for both approaches are discussed. Furthermore, systematic effects, which are related to the measuring principle have to be taken into account, e.g. if sharp edges or slopes are present on the measuring object. As it is shown, for white-light interferometry these difficulties can be solved by a two-wavelength technique.

CLC numbers: TN247 **Document code:** A **Article ID:** 1673-1905(2008)02-0143-4
DOI 10.1007/s11801-008-7100-0

Although optical and tactile techniques are widely used for micro-systems measurement, the comparability of the results is not always guaranteed, since the transfer characteristics of tactile and optical profiling are generally different. For example the lateral resolution of an optical imaging system is well defined based on Abbe's theory of image formation, whereas in tactile metrology the lateral resolution is generally given by the radius of a tactile stylus tip. However, characteristic features of a deterministic microstructure on a surface may be obtained correctly from tactile measurements where optical systems fail and vice versa. Therefore, a look at the transfer mechanisms facilitates a deeper understanding of the performance of either tactile or optical methods.

The tactile sampling process can be mathematically described in terms of morphological filtering. If a surface profile is given, the stylus sampled profile can be calculated by a dilation operation. The result is a filtered profile, which corresponds to the deflection of the centre point of a tactile stylus tip (see Fig.1). However, in practise this operation is performed by the sampling process itself. Hence, an important goal of the evaluation of tactile sampled profiles is the reconstruction of the profile as it was touched by the stylus tip, i.e. the reverse dilation operation, which is called erosion. The erosion process is displayed schematically in Fig.1. It is assumed, that the contour of the stylus tip is known either by measurement or by assuming an ideal e.g. spherical shape.

In summary, by erosion filtering all points on a sampled profile, which comes into contact with the stylus tip can be reconstructed with high resolution and high reliability in both, the lateral and the vertical direction. However, if concave edges with a smaller radius of curvature than the stylus tip radius are present on the measuring object, these points will not be reached by the tip. In these sections, the reconstructed profile resembles the corresponding section of the tip contour of the stylus. Consequently, a tactile profiler shows non-linear transfer characteristics.

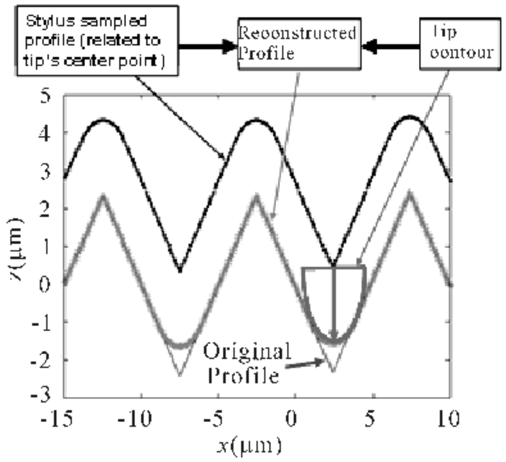

Fig.1 Reconstruction of the tactile sampled profile by morphological filtering: erosion

Some general limitations of tactile instruments abet the current trend towards optical measuring techniques:

Tactile sampling is time consuming, since a mechanical contact of stylus tip and measuring object is necessary and the contact forces must be small in order to avoid measuring

---

[*] Antrag GZ 398, Chinesisch-Deutsches Zentrum für Wissenschaftsförderung, 2006.

[**] E-mail:Gmb Hpeter.lehmann @ mahr.de.

uncertainties caused by deflection;

Tactile sampling may damage weak surfaces, e.g. scratches in polished glass surfaces caused by a diamond stylus;

Tactile instruments generally show a limited accuracy, which may be insufficient e.g. for roughness measurement on optical surfaces.

Optical measurement systems may be a capable solution if these limitations become relevant. Areal interferometric methods allow an efficient topography measurement with a nanometre or sub-nanometre height resolution and are therefore well established for MEMs or MOEMs measurement. On the other hand, there may be geometrical features on a measuring object, which cannot be obtained by an areal measuring system, e.g. the shape and roughness of walls of bore holes or grooves, for instance. In order to satisfy these requirements by optical means special microprobes are necessary. Consequently, in the following sections both concepts of optical measurement will be discussed.

According to E. Abbe the optical image formation can be understood as a twofold diffraction process, where the interception of certain diffracted components due to the numerical aperture of the imaging system corresponds to an inherent low-pass filtering process. If an object is characterized by a sinusoidal transmittance function in one dimension, the diffraction pattern is given by three intense lines. Under the assumption, that the objective's pupil intercepts these lines the period length of the sinusoid will be resolved and a sinusoidal intensity pattern results in the image plane. However, with respect to optical profiling the measuring object may not be treated as an amplitude but as a phase object. Thus, according to Fourier optics, the diffraction pattern of a sinusoidal phase grating can be calculated by the Fourier transform

$$U(k_x) = \int_{-\infty}^{+\infty} r(x)\exp(-ik_x x)\mathrm{d}x \quad \text{with}$$
$$r(x) = \exp\left(i\frac{4\pi h_0}{\lambda}\sin(2\pi x/\Lambda)\right), \quad k_x = \frac{2\pi}{\lambda}\sin(\theta_x) \tag{1}$$

where $U(k_x)$ is the electric field strength in the Fourier domain, $r(x)$ is called reflectance function, k_x is the spatial frequency in terms of the angular deviation θ_x from the optical axis, and λ is the wavelength of light. The intensity in the Fourier plane is given by:

$$I(k_x) = |U(k_x)|^2 \tag{2}$$

In contrast to a sinusoidal amplitude grating, in the case of a phase grating the number of Fourier components depends on the amplitude of the sine wave. For an amplitude of approximately 10 λ and a period of three times the amplitude numerous Fourier components contribute as it can be seen in Fig.2(a). Due to the phase object, a constant intensity results in the image plane and the sinusoidal surface can be reconstructed from the phase of the wave in the image plane. However, if the numerical aperture of the optical system is limited, only the lower frequency components pass the optical system. For the limitation according to Fig.2(a) the intensity distribution of Fig.2(b) (upper curve) results from a second Fourier transform, where the intensity falls down to zero for the profile sections, which correspond to the steepest flanks of the sine wave. This can be seen by comparison with the lower curve of Fig.2(b), which shows the original profile and the profile reconstructed from the phase values. Even if the intensity is not vanishing, deviations between the original and the reconstructed profile remain as a consequence of the filtering in the Fourier domain. This limita-

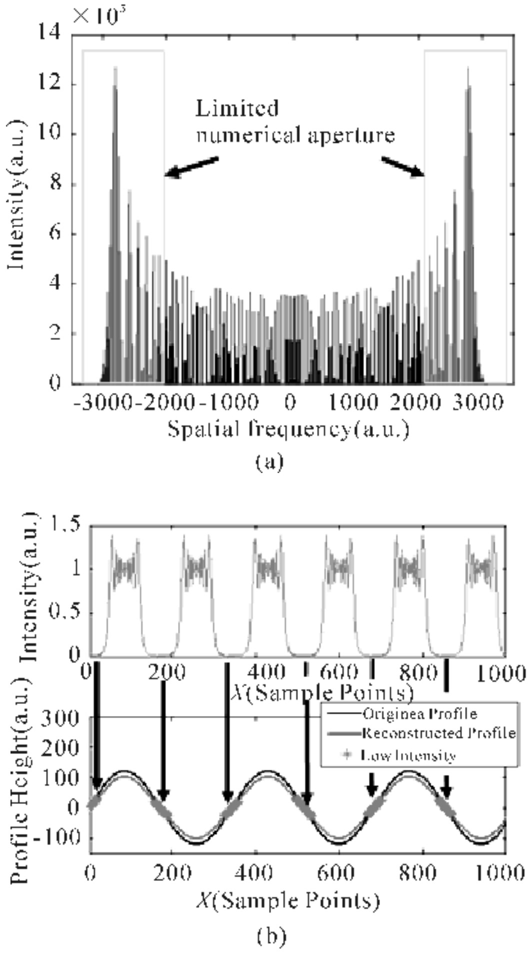

Fig.2 a) Intensity distribution of a sinusoidal phase grating in the Fourier plane, b) top: calculated image plane intensity after optical low pass filtering, bottom: profile reconstructed from phase values

tion applies to all optical profilers, which are working on the basis of microscopic imaging, and it finally leads to non-linear transfer characteristics, since in certain cases the output to a sinusoidal input signal is no longer a sinusoidal function [1].

As an example of an areal measuring optical profiler, a vertical scanning white-light interferometer (SWLI) will be discussed, which is based on a Mirau interference objective in order to keep the dimensions of the instrument small. One advantage of SWLI is that a sub-nanometre height resolution is reached independently of the size of the field of view. This is achieved by a signal processing procedure, which takes the phase of the high-frequency interference component of the SWLI signals obtained from each pixel of the camera into account. First, the position of the maximum of the envelope is obtained from the evaluation of the maximum contrast. This gives a raw estimation of the height position, which may be used to determine the fringe order of the signal. In a second step the phase of the signal is calculated. Together with the correct fringe order a second height value can be obtained from the phase value with a very high precision. However, in certain applications of SWLI, especially in those relevant to MEMs metrology, steeper flanks and sharp edges are present on the measuring objects. In these situations disturbing effects arise in the results of the envelope evaluation, namely batwings and the slope effect. Batwings occur if height steps are to be measured and the step height is smaller than the coherence length of the light used for illumination. Close to the height step contributions coming from the upper and the lower level interfere on a single camera pixel, so that the position of maximum contrast shifts away from the correct height position. However, the phase evaluation is less affected. Unfortunately, in certain situations an erroneous fringe order determination may result from the envelope evaluation procedure, which finally leads to phase jumps [2].

Furthermore, in the presence of local tilts on the measuring object the light cones of the object and the reference rays in the interferometer are no longer the same. As a consequence, the shadowing caused by the reference mirror in the Mirau set-up is different for measuring and reference rays as well as the illumination in the pupil plane of the objective and the mean travelling lengths in the coplanar glass plates, i.e. the beam splitter and the reference mirror holder. Hence, if the optical system is sensitive to dispersion differences, a shift of the envelope position with respect to the phase value of the signal results [3], which may be diminished by a proper correction of lateral colour errors. However, if this shift exceeds $\lambda/4$, phase jumps corresponding to height steps of $\lambda/2$ arise.

A novel approach to overcome these difficulties is to use light of a second centre wavelength λ_2 and to obtain a second height profile from the phase evaluation for this wavelength. Such profiles are plotted in Fig.3(a) and Fig.3(b). If we calculate the difference of the two profiles obtained from phase evaluation curves like those shown in Fig.4(a) and 4(b) In these curves the positions, where phase jumps occur can be easily obtained as virtual height steps. The step height depends on whether a phase jump arises for both wavelengths or only for a single wavelength. If the results for both wavelengths show a 2π=phase jump a virtual height step of $(\lambda_1-\lambda_2)/2$ occurs. Otherwise, if a phase jump is observed only for one of the two wavelengths virtual height steps of $\lambda_1/2$ or $\lambda_2/2$ result, whereas for a real height step on the measuring object a nearly constant height difference can be found, if the two results of phase evaluation are subtracted. This finally allows a correct measurement of typical surfaces structures with steep edges and curvatures as they are typical for MEMs and MOEMs. For further details of the method it is referred to Ref. [4].

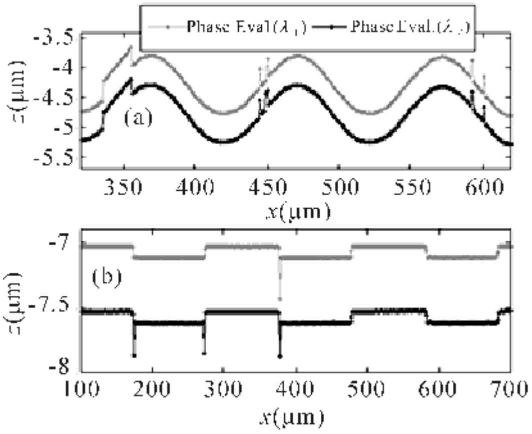

Fig.3 SWLI phase evaluation results for two different wavelengths a) for a sinusoidal test surface, b) for a rectangular grid

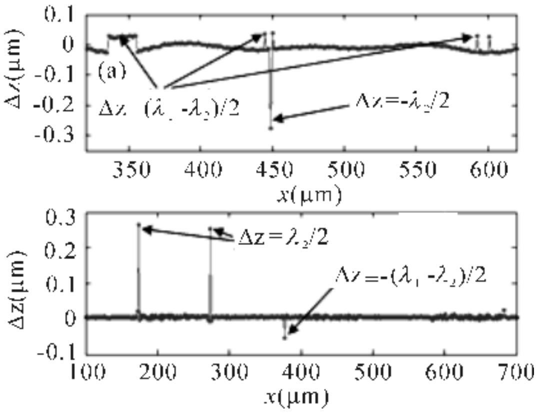

Fig.4 Differences of results according to Fig. 3

However, a problem, which is still to be solved is the measurement of in small cavities, e.g. bore holes of diameters < 2 mm of automotive fuel injectors, where the cylindricity is to be evaluated. Special micro-optical sensors are necessary for these requirements. A first approach based on a confocal chromatic measuring principle is shown in Fig.5 [5]. A fiber-coupled broadband light source is used and an optical probe at the end of the fiber focuses the light onto the wall of the bore hole. A micro-prism with a diffractive lens structure is used in order to realize a 90° direction change of the optical output beam. The focal length of the diffractive lens depends strongly on the wavelength of light. Consequently, the light, which is reflected from the measuring object and is again coupled into the fiber after passing through the optical probe, is spectrally analysed. From the wavelength position of the spectral peak the actual distance between measuring object and probe can be obtained with a very high accuracy. This is demonstrated in Fig.6, where the distance between probe head and measuring object was changed in small steps of 20 nm. The stair-like response of the sensor to distance changes can be clearly observed in Fig.6. Although the overall diameter of the micro-optical probe shown in Fig.5 is 1.2 mm ahich can be regarded as a first step of miniaturization. For MEMS and MOEMS applications the diameter of such micro-optical probes should be much smaller. However, this is a subject of future research work.

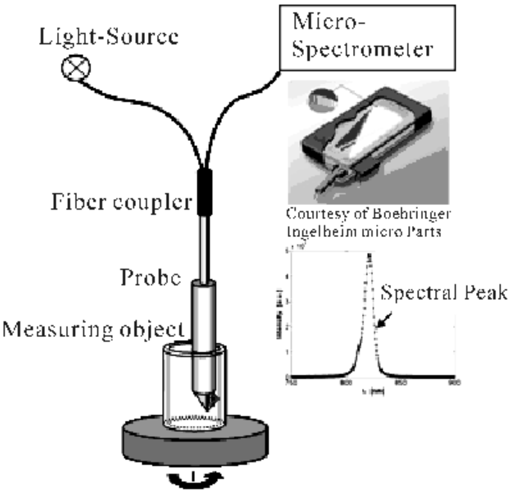

Fig.5 Microoptical confocal chromatic sensor for measurement in small cavities

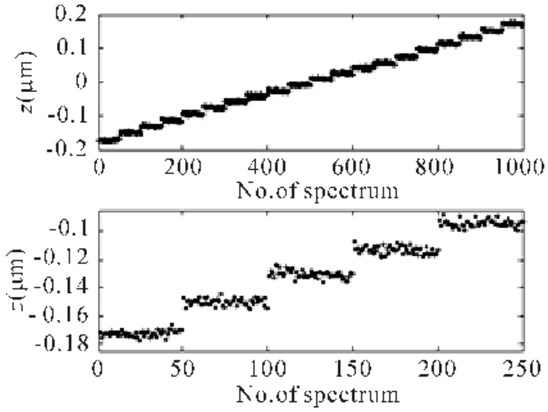

Fig.6 Response of the sensor output signal to distance changes in steps of 20 nm (bottom: section of top diagram)

References

[1] P. de Groot and X. C. de Lega, 5th International Workshop on Automatic Processing of Fringe Patterns, W. Osten ed., Springer, (2005), 30.

[2] A. Harasaki and James C. Wyant, Appl. Opt., **39** (2000), 2101

[3] P. Lehmann, SPIE Proc., **6188** (2006), 11-1.

[4] J. Niehues, P. Lehmann, in Optical Measurement Systems for Industrial Inspection V, W.Osten, C. Gorecki, and E.L. Novak eds., SPIE Proc., **6616** (2007), 661606-1.

[5] Lücke, P.; Last, A.; Mohr, J.; Ruprecht, A.K.; Pruss, C.; Tiziani, H.J.; Osten, W.; Lehmann, P.; Schönfelder, S., "Design and realization of a confocal micro optical distance sensor, " Proc. 11th Microoptics Conf. (MOC'05), Tokyo 2005.