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Optical profilometry and its application to mechanically inaccessible surfaces

Part I: Principles of focus error detection

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Optical profilometers can in principle be used to measure the roughness of surfaces that are not accessible for mechanical profilometers. Optical measurements can be performed through a transparent layer because of the noncontacting nature of the measuring principle. In this article the properties of a focus error detection system are given for the general case of scanning free surfaces and for the particular case of a glass plate lying on the scanned surface. Tests show that scanning through a glass plate is possible, but there are some limitations. The conditions under which proper measurements can be performed are described. Some examples of scanning through a transparent layer will be presented in part II of this paper.

Keywords: optical profilometry; surface roughness measurement; focus error detection; defect of focus system

Introduction

During the last decade optical profilometers have been developed for surface roughness measurements. Compared with mechanical profilometers, optical devices have the advantage of contactless scanning, thus avoiding deformation and possible damage of soft surfaces. Also, optical profilometers can in principle be used to scan surfaces that are not accessible for mechanical devices, e.g., profile measuring through a transparent layer, measuring on the backside of a transparent plate, or measuring the roughness texture of one surface in contact with another, transparent, surface (*Figure 1*). Such a measurement can be performed to determine the deformation of the roughness texture at different loads.

This article is divided into two parts. In part I the principles of optical profilometry will be presented, and the influence of the glass plate lying on the surface will be discussed. Measurements on a rough elastomer in contact with a smooth glass plate will be described in part II.¹

Optical profilometry

Two different principles are generally applied for optical profilometry: interferometry and focus error detection.

A profilometer based on interferometry has been described by Wyant et al.² Until recently, profilometers were only suitable for measuring relatively smooth surfaces (maximum peak to valley height $0.625\text{ }\mu\text{m}$, according to Dong et al.³; see also Sherrington and Smith⁴). In our experiments, measurements must be possible on surfaces with a roughness height on the order of $1\text{ }\mu\text{m}$. Therefore, application of interferometry was not considered.⁵

Figure 1 Scanning through a glass plate on the surface

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Recently, WYKO Corporation⁶ introduced an interferometric profilometer that is applicable to surfaces with a peak to valley height of up to 100 μm . However, its applicability for measurements through a glass plate on the surface has not yet been investigated.

Different kinds of focus error detection systems are available (see Mitsui,⁷ Struik and Chang,⁸ Sherrington and Smith,⁴ and Kagami et al.⁹) and an example of such a profilometer, based on the so-called pupil obscuration method (see Braat¹⁰), is shown in Figure 2. When the surface is in focus, all four photodiodes (B_1 , A_1 , A_2 , and B_2) receive the same amount of light. If the surface is in a higher position than the focus, the outer diodes (B_1 and B_2) receive more light than do the inner diodes (A_1 and A_2), and if the surface is in a lower position than the focus, B_1 and B_2 receive less light than do A_1 and A_2 . This difference is detected by the so-called focus error signal (fes):

$$\text{fes} = \frac{(A_1 + A_2) - (B_1 + B_2)}{(A_1 + A_2) + (B_1 + B_2)} \quad (1)$$

A_i and B_i being the signals from the diodes A_i and B_i , respectively.

Figure 3 shows the focus error signal as it is measured at varying distances between the surface and the focal point of the objective lens.

This focus error device was initially developed by Philips Research Laboratories for application in the compact disk player^{10,11} and was further developed for displacement measurements. Struik and Chang⁸ used it for shape and roughness measurements, and a commercial version was available from Rodenstock.

Figure 2 Optical profilometer

Figure 3 (a) Definition of surface height z relative to the focal point F . (b) Measured focus error signal fes versus surface height z .

In this study the test rig and sensor described by Struik and Chang is used. The optical characteristics are as follows: diode laser wavelength (λ) = 820 nm; collimator lens focal distance (f_{coll}) = 22.5 mm, numerical aperture (NA_{coll}) = 0.1; objective lens focal distance (f_{obj}) = 4.5 mm, numerical aperture (NA_{obj}) = 0.45.

Measurements can be performed in two ways. In the closed loop mode, the servo controller is used to focus the objective lens onto the surface, i.e., the lens is moved to the position where the focus error signal is zero. Scanning a rough surface, the height variations can be determined by continuous measurement of the lens position. In the open loop mode the servo controller is not used. Instead, the objective lens is fixed and the surface height is directly derived from the measured focus error signal.

In the following text, the performance of the profilometer will be presented for the general case and for the special case that measurements are performed through a transparent layer or through a glass plate lying on the surface (Figure 1). Some measurements will be presented in part II to demonstrate the potential of optical profilometry for the scanning of mechanically inaccessible surfaces.

Performance I: general case

In this section the performance of the focus error sensor, introduced in the former section, will be given for the general case, where there is no transparent layer or glass plate on or near the surface. Where

necessary the closed loop mode and the open loop mode will be distinguished.

Accuracy

The accuracy in the height measurements is better than 10 nm.⁸ According to Claesen¹² improvement to 1 nm is possible by increase of the laser power, use of a peltier element to stabilize the laser temperature, or new design of the electronic amplifier. Redesign of the electronic amplifier is in progress, including the possibility for temporarily increasing the laser power.

Lateral resolution

The lateral resolution is determined by the dimension of the focus spot, which is preferably diffraction limited because then it will be as small as possible. The dimension of a diffraction-spot size can be defined by the so-called 50% irradiance width ($d_{0.5}$), which is the diameter of the circle on which the irradiance is 50% of the maximum irradiance.⁵ It reads

$$d_{0.5} = \frac{\lambda}{2NA_{obj}} \quad (2)$$

and is 0.82 μm for the sensor introduced earlier in the optical profilometry section.

The focus spot will only be diffraction limited when two conditions are fulfilled: (a) the irradiance distribution of the incident beam on the objective lens is uniform and (b) the focused beam is free of aberrations. The former condition is sufficiently fulfilled when the collimator lens has a numerical aperture of 0.1.⁵ The latter condition will be discussed in more detail later because a transparent layer or glass plate introduces spherical aberration. Here we will only remind the reader that the used profilometer is derived from the compact disk sensor, which scans the disk surface through a protective layer of 1.2-mm thick polycarbonate. This layer obviously also introduces spherical aberration, and the objective lens was therefore specially designed to compensate for this. The same lens is used in the profilometer and, in the general case without a transparent layer on the surface, a 1.2-mm thick window is attached near the objective lens (as shown in *Figure 2*) to yield an aberration-free, diffraction-limited spot. The combination of this special lens and this window will appear to be helpful in the experiments presented in part II.

The measurement range

In the closed loop mode, the measurement range is determined by the maximum possible displacement of the objective lens, being 1 mm for the profilometer presented above.

In the open loop mode, the measurement range is limited by the fact that only the steep part of the focus error curve (between Z_1 and Z_2 in *Figure 3*) can be used for accurate measurements. The measurement range of the authors' scanning device is from -5 to $+5 \mu\text{m}$, but can be extended by reduction of the numerical aperture of the objective lens.⁵

The dynamic range

In the closed loop mode, the maximum measuring frequency is about 600 Hz because it is limited by the eigenfrequency of the objective lens and its suspension. Extension of the dynamic range is hardly possible due to the mechanical inertia of the objective lens.

In the open loop mode, the mechanical inertia is not a factor, and a dynamic range of 1 MHz is possible, depending on the electronic instrumentation.

Slope influence

In general, surface slopes are present in two directions: in the plane of drawing in *Figure 2* and perpendicular to the plane of drawing in *Figure 2*. In the latter case the focus error signal is not influenced by the surface slopes. In the former case, the slopes yield a shift of the light spots on the photodiodes in a vertical direction when the surface is out of focus. The spots are shifted relative to the photodiode boundaries; consequently, the slopes influence the focus error signal in the out-of-focus positions.⁵ Therefore, (a) in the closed loop mode the slopes have no influence because the surface remains in focus; and (b) in the open loop mode the slopes have a significant influence because the surface is out of focus and the height variations are directly derived from the measured focus error signal, which is shown in *Figure 4a* as a function of the surface slope. As shown by Visscher,⁵ the slope influence is larger when the numerical aperture of the objective lens is smaller. Elimination of the slope influence in the open loop mode is possible by simultaneous measurement of the so-called radial error signal* (res), which reads

$$\text{res} = \frac{(A_1 + B_1) - (A_2 + B_2)}{(A_1 + B_1) + (A_2 + B_2)} \quad (3)$$

It appears to be hardly influenced by the distance z between the surface and the focal point⁵ and is shown in *Figure 4b* as function of the surface slope.

Performance II: measurement through a transparent layer

Now we will consider the particular situation that the roughness profile is scanned through a transparent layer, e.g., when a (possibly deformed) roughness texture is measured through a smooth glass plate pressed onto the rough surface (*Figure 1*). The presence of such a glass plate will influence the measurement due to (a) spherical aberration caused by the refraction on the glass surfaces (this aberration reduces the focus spot quality) and (b) introduction of two additional reflecting surfaces (i.e., both surfaces of the glass plate).

Now it will be shown how the influence of these factors can be reduced to obtain proper measurements.

* The term originates from the compact disk technique, where the radial error signal is used to position the transducer properly in the radial direction of the disk.¹⁰

Figure 4 (a) Measured focus error signal and (b) radial error signal versus surface slope. These measurements were performed with a slightly different focus error sensor than the one introduced in the optical profilometry section (see Visscher³ for the details)

Spherical aberration

When aberration-free lenses are used, the wave front of the focused beam is spherical and the resulting focus spot is diffraction limited. However, the wave front of the beam transmitted through the window is not spherical due to light refraction on the window surface (Figure 5). Consequently, the focus spot diameter is larger than for the spherical wave front, and the resolving power of the profilometer is reduced. A criterion for the maximum spherical aberration is derived by Visscher,⁵ regarding the spot still diffraction limited, when the aberration reduces the maximum in the irradiance distribution by more than 20% (Maréchal's criterion). Then the criterion for the maximum spherical aberration reads

$$\frac{n^2 - 1}{8n^3} t (NA_{\text{obj}})^4 \leq 0.95\lambda, \quad (4)$$

Figure 5 Spherical aberration due to refraction on the window surface

n being the index of refraction of the window (—), t the window thickness (m), NA_{obj} the numerical aperture of the objective lens (—), and λ the wavelength of the radiation (m). In practice, n is in the range of roughly 1.4 to 1.7 and λ is about 800 nm (diode lasers). Therefore the aberration criterion can be written as

$$NA_{\text{obj}} \leq 2t^{-1/4} \quad (t \text{ in } \mu\text{m}). \quad (5)$$

The focus error device shown in Figure 2 is derived from a compact disk transducer⁸ in which a special objective lens ($NA_{\text{obj}} = 0.45$) is applied that compensates for the aberration of the 1.2-mm thick protective layer of the compact disk ($n = 1.56$). In normal roughness measurements, such a layer does not exist on the scanned surface. Therefore, a 1.2-mm thick window is fixed near the objective lens to substitute the protective layer optically. In part of our experiments (presented in part II of this paper), an elastomeric surface will be scanned through a 1.2-mm thick glass plate on the surface. Then the window near the objective lens will be removed in order for the spot to remain diffraction limited.

Reflection on the glass surfaces

Scanning a surface through a glass plate (Figure 1), the light from the diode laser reflects on three surfaces: the upper glass surface; the lower, contacting glass surface; and the elastomeric surface. This last reflection is needed for the surface scanning. Visscher⁵ found that the reflection on the upper glass surface, which is a relatively large distance from the focus, has no influence on the measurement. When discussing the influence of reflection on the lower glass surface, we must consider the closed loop mode and the open loop mode separately.

In the closed loop mode the reflection on the lower glass surface has a large influence. It was initially expected that the measured roughness height would be smaller than the real roughness height because the objective lens would be focused between both reflecting surfaces.⁵ However, experiments showed larger rather than smaller height variations in

Figure 6 Surface roughness measurements on a metallic sinus profile: (a) without glass plate on the surface, (b) with glass plate on the surface, and (c) with glass plate on the surface and liquid in the contact area

the roughness profiles, as is illustrated by comparison of *Figure 6a* and *b*. *Figure 6a* shows the measured shape of a metallic sinus profile as it appears in a normal roughness measurement (i.e., without a glass plate on it). *Figure 6b* shows the resulting shape from a measurement on the same profile, but now measured through a smooth 1.2-mm thick glass plate on the surface (the window nearby the objective lens, shown in *Figure 2*, is now removed to avoid spherical aberration).

The origin of this result is not understood at the moment; therefore, a liquid is needed in the contact area for proper measurements. No reflection occurs on the lower window surface when the index of refraction of the liquid equals the index of refraction of the glass plate. The reflection influence is then eliminated, as shown by comparing *Figure 6c* with *6a*. *Figure 6c* shows the measured shape when a liquid is present in the contact area, which has an equal index of refraction as the glass plate. Now the measured height variations are smaller, due to refraction, which yields a measured height variation of $1/n$ times the real height variation (n is the index of refraction of the glass and the liquid = 1.47).

In the open loop mode, the focus error signal, and therefore the measurement, is influenced by the reflection on the lower glass surface. This influence is

derived theoretically from measured curves of the photodiode signals⁵ and is shown in *Figure 7* for the case that both the lower glass surface and the scanned rough surface have a low and nearly equal reflectance

Figure 7 Focus error signal for different values of gap height h between a glass plate ("window") and a test surface with nearly equal reflectance: (a) calculated for $h = 1, 10$, and $25 \mu\text{m}$; (b) calculated and measured for $h = 50 \mu\text{m}$; (c) calculated and measured for $h = 120 \mu\text{m}$

of about 4%. Figure 7b and c also shows a measured curve for comparison.

Figure 7 shows that the focus error curve is hardly affected at a gap height h of $1\text{ }\mu\text{m}$ between the reflecting surfaces. The curve seems only to be shifted to the right due to the fact that the focus error signal will now be zero for a focus spot position somewhere between both surfaces (in Figure 7 the in-focus position of the scanned surface is given by $z = 0$; the in-focus position of the lower glass surface is then given by $z = h$). Increase of the gap height h yields a part in the focus error curve, around $fes = 0$, where the slope in the curve is small (e.g., for $h = 25\text{ }\mu\text{m}$ and $h = 50\text{ }\mu\text{m}$). Consequently, the measurement will not be very sensitive. Finally, at a gap height h of $120\text{ }\mu\text{m}$, both surfaces are found separately in the focus error curve. As a consequence, measurements in the open loop can be useful at a larger distance between the glass plate and the rough surface (gap height h larger than about $100\text{ }\mu\text{m}$), because the influence of the lower glass surface reflectance is small when measurements are performed with the focus spot near the rough surface (around $z = 0$). When the gap height is small (e.g., $h < 10\text{ }\mu\text{m}$) measurements in the open loop mode are also useful because the focus error curve is not changed much by the presence of the glass plate, but proper calibration will be needed. In the middle region (roughly $10\text{ }\mu\text{m} < h < 100\text{ }\mu\text{m}$), measurements in the open loop mode can be a problem because of the small slope in the focus error curve around $fes = 0$, which extends over a larger range of height z .

When the reflectance on the rough surface is significantly higher than that on the glass surface (e.g., a glass plate on a metallic surface), the influence of reflection on the glass surface will be much smaller, as shown in Figure 8. The focus error curve is hardly influenced by the presence of the glass plate, whereas the influence was large in the situation of a glass plate on a low reflecting surface (Figure 7).

Figure 8 Focus error signal measured for a gap height $h = 5\text{ }\mu\text{m}$ between a glass plate and a silicon surface

Conclusions

Optical profilometers, based on focus error detection, can be used to scan surfaces that are mechanically inaccessible when measures are taken to prevent too much spherical aberration and to prevent influence of reflection on the window surface near the scanned surface. Some examples of a measurement through a transparent layer (e.g., glass plate or window) will be presented in part II of this article.

The performance of the profilometer, which is partly different for the closed loop and for the open loop mode, will be summarized now.

Both closed and open loop mode

Accuracy, 10 nm or better; lateral resolution of about $1\text{ }\mu\text{m}$ is possible (depending on the numerical aperture and on the wavelength) when the spot is diffraction limited. When measurements are performed through a transparent layer, the spherical aberration, introduced by the layer, must be limited to remain a diffraction limited spot. This requires reduction of the numerical aperture of the objective lens, depending on the layer thickness, or the use of a specially designed objective lens to compensate for the aberration introduced by the layer.

Closed loop mode only

The measurement range depends on the maximum possible displacement of the objective lens only and can be 1 mm . The dynamic range is limited by mechanical inertia to 600 Hz . The surface slopes have no influence. The measurement is disturbed by a reflecting surface (e.g., of a window) close to the scanned surface. Therefore, a liquid with an index of refraction equal to that of the window is needed in the contact area to eliminate this reflection.

Open loop mode only

The measurement range is limited to micrometers, depending on the numerical aperture of the objective lens. The dynamic range depends on the electronics only and can be 1 MHz . The surface slopes have a significant influence on the measurement, and simultaneous measurement of the radial error signal is therefore required. Reflection on a surface close to the scanned surface is in general not severe, and elimination of this reflection will therefore be necessary in some cases.

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