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Surface Profiling and Confocal Microscopy

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There is strong current interest in various approaches for measurement of surface profiles by non-contacting methods. These have application in a wide range of areas including non-destructive testing and industrial inspection. These approaches include various interferometric methods, confocal microscopy, and reconstruction by inverse scattering. The aim of this work is to examine by computer modelling various confocal and interferometric algorithms for surface profiling. In particular we have investigated three methods. The first is the confocal surface profiling method, in which the position of the peak in intensity during an axial scan is recorded (Hamilton and Wilson 1982, Cox and Sheppard 1983). In the second the position of the zero-order fringe in an interferometric image is tracked. This interferometric image can be produced by a range of different forms of interferometric microscope, including those of the Linnik or confocal geometry (Fig. 1). The third method, which is only applicable for surfaces of small RMS surface roughness, is the measurement of phase in a single in-focus image, again using an interferometric microscope.

In each case the two-dimensional image of a one-dimensional rough surface was calculated from scattering data generated using rigorous theory (Wombell and DeSanto 1991). The surfaces were generated to satisfy the statistics of a stationary Gaussian process with Gaussian correlation, and of various degrees of surface roughness. The aims of the study were to investigate the accuracy of the various profiling methods and the effects of system parameters.

The profiling methods can be regarded as nonlinear inverse methods for surface reconstruction based on the Kirchhoff approximation (Sheppard et al. 1993). Thus the methods are expected to tend to break down when the surface roughness is such that the Kirchhoff approximation does not hold. In particular the Kirchhoff approximation assumes that the surface can be taken as locally plane, so that the radius of curvature is large compared with the wavelength. In addition the Kirchhoff approximation neglects multiple scattering effects.

According to the Kirchhoff approximation, the scattering function for a surface of profile $\varsigma(x, y)$ can be expressed in terms of transverse and axial spatial frequencies by (Sheppard et al. 1993)

$$S(m,n,s)=\frac{m^2+n^2+s^2}{2s}\iint_{-\infty}^{+\infty}\exp\{-ik[mx+ny+s\varsigma(x,y)]\}dxdy \qquad (1)$$

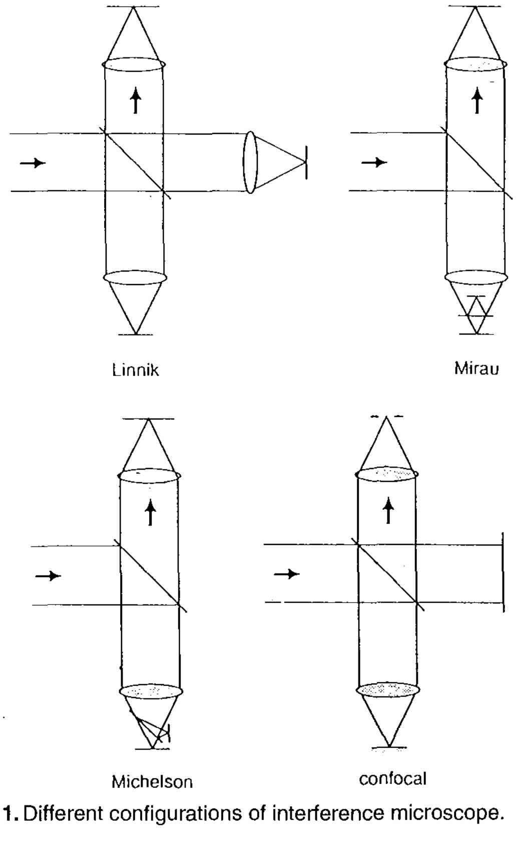


Fig. 1. Different configurations of interference microscope.

where m, n, s are related to the direction cosines of illumination and scattering m_1, n_1; $m_2 n_2$ by

$$m = m_2 - m_1$$

$$n = n_2 - n_1 \qquad (2)$$

$$s = (1 - m_1^2 - n_1^2)^{1/2} + (1 - m_2^2 - n_2^2)^{1/2}$$

Introducing the object function $\delta[z - \varsigma(x, y)]$ for the profile, this can be written in the form of a 3D Fourier transform

$$S(\mathbf{m}) = \frac{\mathbf{m}^2}{2\mathbf{m}\cdot\mathbf{k}} \iiint_{-\infty}^{+\infty} \delta[z-(x,y)] \exp\{-ik\mathbf{m}\cdot\mathbf{r}\} d\mathbf{r} \qquad (4)$$

where

$$\mathbf{m} = m\mathbf{i} + n\mathbf{j} + s\mathbf{k} \qquad (5)$$

and

$$\mathbf{r} = x\mathbf{i} + y\mathbf{j} + z\mathbf{k} \qquad (6)$$

The amplitude of the 3D image of the surface in the Kirchhoff approximation is then

$$U(\mathbf{r}) = \iint_{-\infty}^{+\infty} c(\mathbf{m}) S(\mathbf{m}) \exp(ik\mathbf{m}\cdot\mathbf{r}) d\mathbf{m} \qquad (7)$$

where $c(\mathbf{m})$ is the 3D coherent transfer function. The form of the coherent transfer function for a confocal microscope has been described elsewhere (Sheppard et al. 1994). However, in practice it is possible to control the value of the transfer function within is passband by apodization or digital image processing. Thus in the following we assume a transfer function

$$c(\mathbf{m}) = \frac{2\mathbf{m}\cdot\mathbf{k}}{\mathbf{m}^2}, \quad \mathbf{m}^2 < 4 \text{ and } \mathbf{m}\cdot\mathbf{k} > 2\cos\alpha$$

$$= 0, \text{ otherwise} \qquad (8)$$

where α is the angular semiaperture of the lens, which expression is chosen to exactly cancel the premultiplying factor of Eq.4.

We have investigated surfaces with a correlation lenghth of 1λ, and of RMS surface height, σ, in the range from 0.05 to 0.20 λ.

As examples, in Fig. 2. we show profiles reconstructed using the confocal profiling method for α=60°. It is seen that, although the reconstructions are reasonably good, the reconstruction becomes

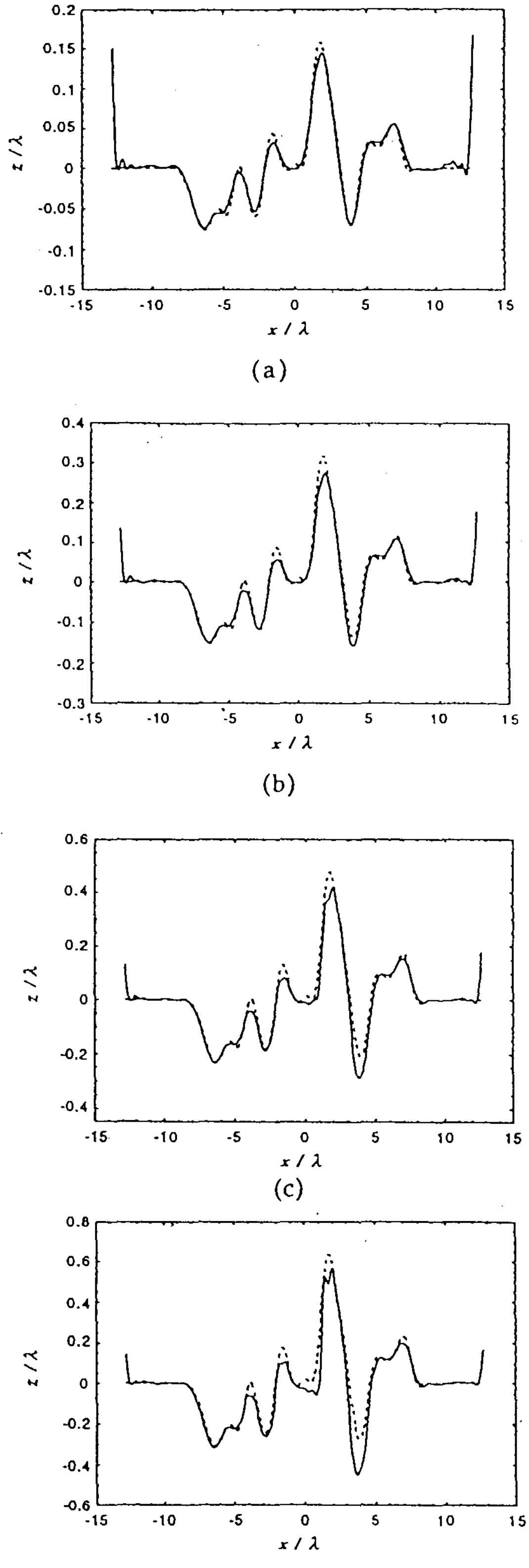
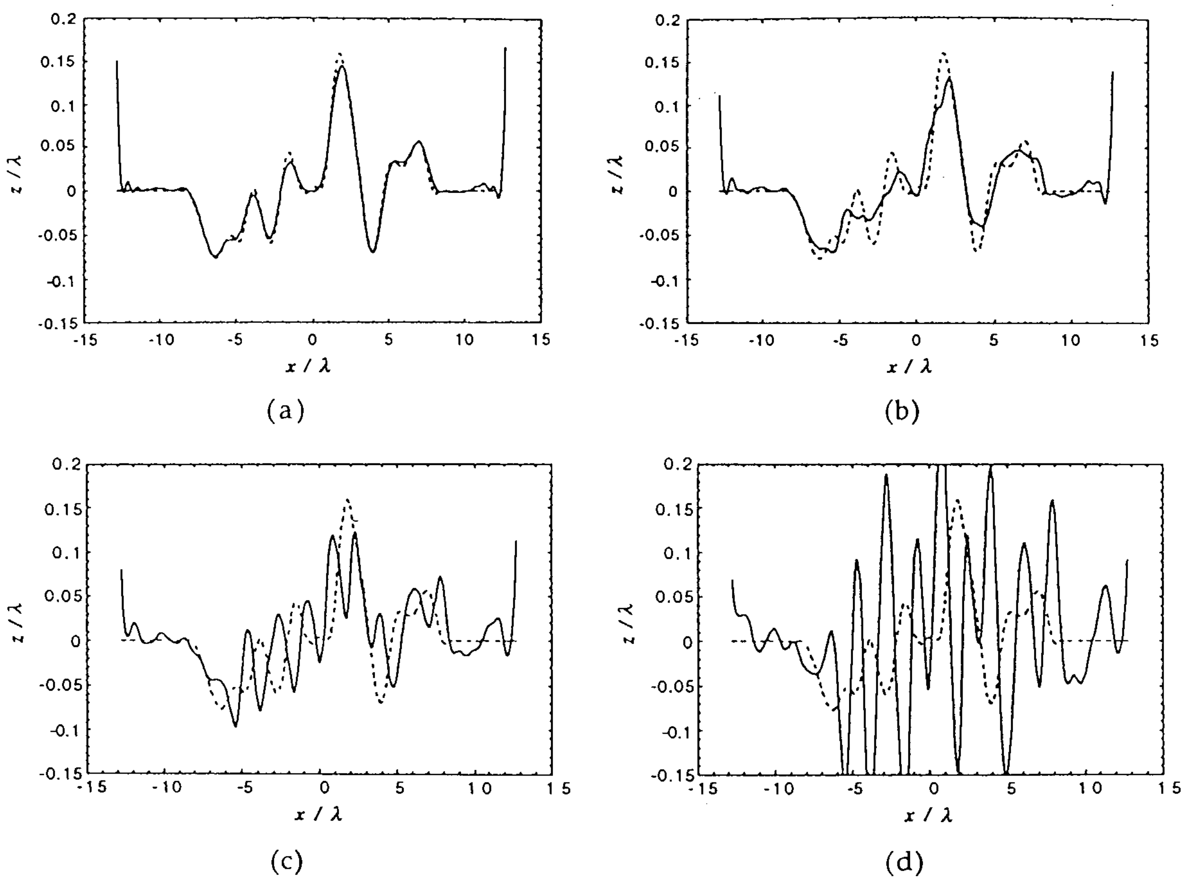


Fig. 2. Profile reconstructions (solid curves) using the confocal profiling method with α=60°. The surfaces (dashed curves) have (a) σ=0.05λ, (b) σ=0.10λ (c) σ=0.15λ (d) σ=0.20λ.



(a) (b)

(c) (d)

Fig. 3. Profile reconstructions (solid curves) using the confocal profiling method on the surface (dashed curves) $\sigma=0.05\lambda$. (a) $\alpha=60°$, (b) $\alpha=50°$, (c) $\alpha=40°$, (d) $\alpha=30°$.

poorer as the roughness is increased, with the peaks and troughs, where the curvature is greatest, the most likely regions for errors.

In Fig. 3. we show the effect of altering the numerical aperture for a particular surface. It is seen that the reconstruction is poor for α less then about 50°, when the optical system cannot image adequately the transverse spatial frequencies.

Studies of this type can determine the relative performance and limitations in accuracy of the various profiling methods.

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