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The influence of tilt on surface roughness measurement using the focus variation microscope

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Abstract

In a recent publication it was shown that surface roughness measurements made using a focus variation microscope (FVM) are influenced by surface tilt. The effect appears to be most significant when the surface has micro-scale roughness that is sufficient to provide a diffusely scattered signal that is comparable in magnitude to the specular component (Ra ≈ 50nm). This paper explores, from first principles, image formation using the focus variation method. With the assumption of incoherent scattering, it is shown that the process is linear and the 3D point spread characteristics and transfer characteristics of instrument are well defined. It is argued that, for the case of micro-scale roughness and through the objective illumination, the assumption of incoherence cannot be justified and more rigorous analysis is required. Using a boundary element method the scattered fields and output of FVM has been calculated. It is shown that for small tilt angles, which fall within the acceptance angle of the objective, the signal quality is degraded in a systematic manner. This is attributed to the mixing of specular and diffusely reflected components and leads to an asymmetry in the k-space representation of the output signals. At tilt angles that are greater than the acceptance angle of aperture, the specular component is lost and the incoherent assumption can be justified once again.

Focus variation microscope, tilt sensitivity, point spread function, transfer function

1. Introduction

The focus variation microscope (FVM) is an increasingly popular means to measure the surface geometry of micro-components that compares favourably to the more established techniques of confocal microscopy (CM) and coherence scanning interferometry (CSI) [1]. The focus variation method exploits the limited depth of focus of a vertical scanning microscope and consequently is suited to the measurement of steep surfaces provided that they are optically rough. Like other optical methods, however, FVM measurements can be influenced by surface tilt and tilt-dependent surface roughness measurements have been recently reported [2]. In this paper we explore this concept further.

2. Basic Theory

According to linear systems theory an imaging system can be characterised by way of its coherent or incoherent point spread function (PSF) [3]. The coherent PSF describes the phase and amplitude of the image of a point scatterer and is particularly useful when coherent detection is used (i.e. digital holography). The incoherent PSF describes the intensity of this image and mathematically is the squared modulus of its coherent counterpart. Providing that the field scattered by the surface is incoherent, the image recorded by FVM can be characterised by the incoherent PSF.

In a previous publication [4] we have found it useful to characterise CSI and CM in terms of their 3D PSF characteristics or equivalently, in the frequency domain (k-space) by the Transfer Function (TF). With the assumption of incoherent illumination the TF, $\widetilde{H}_B(\boldsymbol{k})$, that characterises the intensity of the 3D field output (i.e. the image stack) by a quassi-monochromatic FVM with a numerical aperture N_A can be written [4],

$$\widetilde{H}_B(\boldsymbol{k}) = k_0^2 \int \tilde{G}_{NA}(\boldsymbol{k}', k_0)\tilde{G}_{NA}(\boldsymbol{k}' - \boldsymbol{k}, k_0)\, d^3k',$$

where $k_0 = 1/\lambda$ and $\tilde{G}_{NA}(\mathbf{k}, k_0)$, is the coherent transfer function given by,

$$\tilde{G}_{NA}(\boldsymbol{k}, k_0) = \frac{j}{4\pi k_0}\delta(|\boldsymbol{k}| - k_0)\, step\left(\frac{\boldsymbol{k}.\hat{\boldsymbol{o}}}{k_0} - \sqrt{1 - N_A^2}\right),$$

where *step* (x) is the Heaviside step function and $\hat{\boldsymbol{o}}$ is a unit vector in the direction of observation (i.e. along the optical axis of the instrument).

Sections through the TF and PSF for the case of an instrument with $N_A = 0.5$; λ = 0.5 μm are shown in figures 1(a) and 1(b).

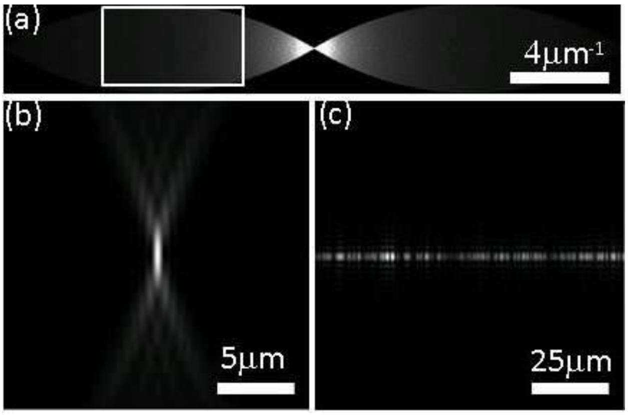

Figure 1. (a) TF (b) PSF (c) filtered final image.

It is interesting to note that the vertical extent of the TF is inversely proportional to the depth resolution of the instrument (the Nyquist resolution) and, for quassi-monochromatic systems this is exactly the resolution provided by CSI (or half the resolution of incoherent CM) [4]. There are several ways to deduce the position of surface of interest [1,5,6]. For the purposes of illustration we will not concern ourselves with the details but merely note that the information that defines the position of the surface is found in the high frequency part of the transfer function (i.e. within the box in figure 1a)). Modelling the surface as a set of random amplitude, incoherent scattering sources, a typical surface image using the proposed filtering method is shown in figure 1c). It can be seen that the individual scattering sources behave like beacons in 3D space which define the position of the surface.

The assumption that the scattered field is incoherent (on the scale of the PSF) is only strictly true if the illumination is incoherent and/or the surface is sufficiently rough that multiple scattering dominates. It is noted that illumination which propagates through the objective does not fulfil the former condition, while the latter is strictly only satisfied when the Ra >> λ. Consequently many of the illumination conditions used in practice and typical surfaces of interest do satisfy this assumption and, consequently, a more detailed analysis is required.

3. Modelling

In order to model scattering from rough surfaces we have developed a rigorous boundary element code based on the work of Simonsen [7]. We have used this model to calculate the fields obtained using FVM when light is scattered from different tilted surfaces. We have found that the most significant deviation from the theory outlined above appears when the surface has micro-scale roughness that is sufficient to provide a diffusely scattered signal that is comparable in magnitude to the specular component (Ra ≈ 50nm). Some results of this analysis are shown in figure 2 for the case of an instrument with through lens illumination and N_A = 0.5.

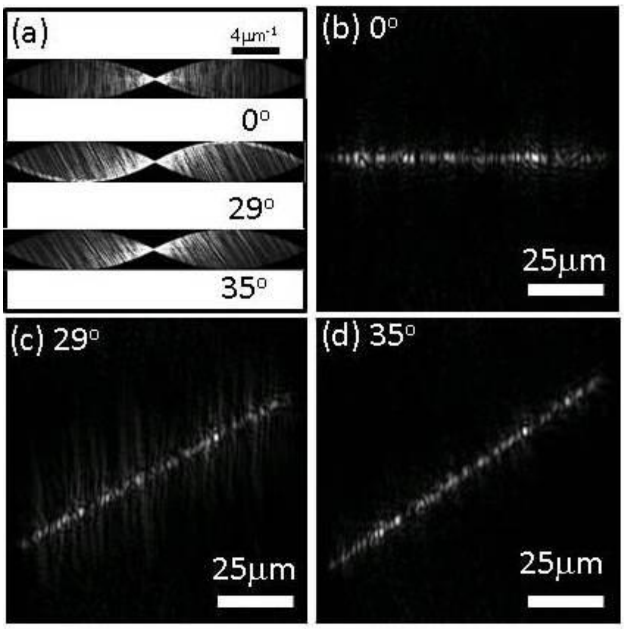

Figure 2. (a) Frequency domain responses and filtered final images obtained for (b) 0° (c) 29° (d) 35° surface tilt.

It can be seen that in the frequency domain (figure 2(a)) the scattered field is bounded by the same region of k-space where the incoherent TF is non-zero (figure 1(a)). It is also noted that the filtered final images, figures 2(a) and 2(d), are similar to those obtained under the assumption of incoherence. At a tilt angle of 29°, however, the form of the filtered final image, figure 2(c), differs significantly. It appears that at this angle the axial extent of the PSF has increased considerably. Inspection of the corresponding frequency domain output shows that spectrum now differs from the TF with additional signal above and below the lobes to the left and right of the image respectively. Further analysis shows that these additional features are due to the mixing of specular and diffusely reflected components. As the objective has a numerical aperture N_A = 0.5 its acceptance angle is 30° and consequently the majority of the specular reflection is not collected by the reflection. The part of the specular reflection that is collected by the objective is responsible for the change in output. Interestingly a similar (but opposite) result is obtained when the surface tilt is 1°. At tilt angles between 1° and 29° varying degrees of asymmetry are observed, while at tilt angles above 30° the results resemble those of the incoherent theory.

4. Conclusions

In this paper we have proposed a linear model of the FVM based on the assumption of incoherent scattering. We have argued that this assumption is not valid for surfaces with micro-scale roughness and/or through the lens illumination such that the scattered field has specular and diffuse components of comparable magnitude. Using rigorous scattering methods we have shown that in these cases the FVM output is strongly influenced by surface tilt. This is attributed to the mixing of specular and diffusely reflected components and leads to an asymmetry in the k-space representation of the output signals. At tilt angles that are greater than the acceptance angle of aperture, the specular component is lost and the incoherent assumption can be justified once again.

Further work is necessary to test this hypothesis in practice.

Acknowledgements

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