Overcoming the diffractive limit of lateral resolution under 3D nanorelief measurements

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Abstract

The method of overcoming the diffractive limit of lateral resolution of 3D nanorelief measurement is proposed. Algorithm for digital processing of measurement data based on deconvolution operation using Wiener filtration is presented. Results of theoretical researches, numerical and optical experiments are given.

Keywords: Nanorelief measurement, lateral resolution, deconvolution

1. Introduction

Methods of low-coherent interferometry are widely used for 3D nanorelief measurement. High longitudinal resolution is achieved due to measuring the phase of the autocorrelation function of the interfering waves at each measurement point.

In phase-shift interferometers the relief height measurements are carried out either by moving the entire interferometer relative to the surface being measured, or by changing the position of the reference mirror along the optical axis of the interferometer. Wherein the scanning step can be significantly less than the wavelength of light used in the interference measurements.

Modern interference microscopes allow measuring the surface topography with longitudinal resolution of less than 0.1 nm and using atomically smooth surfaces as a reference mirror – less than 0.03 nm [1].

Lateral resolution, as well as longitudinal one, is determined by mutual influence of the phase of scattered waves of nearby points of the measured surface. This effect is determined by the instrumental phase function of the interferometer.

With the advent of the possibility of digitizing images and computer processing of large information volumes an opportunity for taking into account the effect of the instrumental function on the resulting images is appeared. This led to significant increase of resolution in applications of 2D microscopy, photos, astronomy, medicine [2–4].

In this paper it is proposed to increase the lateral resolution of 3D nanorelief measurement by preprocessing of interferograms set using deconvolution algorithms.

2. Reducing of the instrumental function effect

Way of accounting for the instrumental function $G$ of the optical system based on the fact that the result image $I$ of the measurement object $I_0$ is defined as the result of convolution:

$$I(x, y) = G(x, y) \otimes I_0(x, y).$$

Then $I_0$ can be restored using the inverse operation convolution – deconvolution:
where $F$ is Fourier transform, $F^{-1}$ is the inverse Fourier transform, and the division of the spectra $I$ and $G$ is made frequency by frequency.

When measuring a surface nanorelief by interference methods the phase of the interfering waves scattered by each point of the surface being measured is calculated. Calculation is based on the amplitude of the recorded intensity $I$, the amount of which affected by the function $G$.

Obviously, to get the resolution is better than it is allowed by function $G$, it is necessary to perform its measurement with high resolution. In addition, cross-sampling image of the object must also be made with a resolution much greater than the transverse dimension of the function $G$.

In practice, for sampling images CCD matrix are often used. High resolution of capturing an image for subsequent digital processing is achieved by making the optical projection of CCD pixel into the observation area much smaller than the function $G$.

In actual measuring systems the noise component $N$ is also added to optical distortion:

$$I(x, y) = I_0(x, y) \otimes G(x, y) + N(x, y).$$

To reduce the effect of noise in the interferograms it was made a filtration of interferograms spectra based on Wiener filter [5]:

$$I_1(x, y) = F^{-1} \left( \frac{F(I(x, y))}{F(G(x, y))} \left[ \frac{\left| F(G(x, y)) \right|^2}{\left| F(G(x, y)) \right|^2 + C} \right] \right),$$

where $I_1$ is an approximation of $I_0$, $C$ is constant depending on signal-to-noise ratio.

Figure 1 shows the results of numerical experiment to restoration of blurred and noisy images. Original image (Fig. 1, a) contains targets with lines width of 3 (top line), 6 (middle line) and 9 pixels (bottom line). Transverse dimension of the function $G$ used in convolution and deconvolution is equal to 10 pixels. After convolution of original image and $G$ the noise at level 0.1% was added (Fig. 1, b). The result of deconvolution without filtration (1) shows that high frequencies in image spectra have been disproportionately increased (Fig. 1, c). Deconvolution using filtration (2) with $C$ that is equal to 0.01 allows resolving the smallest targets (Fig. 1, d).

3. Optical experiment

To test this technique as the object of measurement it was selected the sample of silicon with structure having a sharp edge. Measurement of the relief was performed by low-coherent microscope “MNP-1” [6], with optical scheme shown in Fig. 2.
Fig. 2. Scheme of low-coherent interferometer: 1 – source of partially coherent light (LED), 2 – light source objective, 3 – beamsplitter, 4 and 7 – microobjectives with magnification 20x and numerical aperture 0.4, 5 – reference plane mirror, 6 – piezo actuator, 8 – measurement object, 9 – CCD camera.

Effectiveness of the proposed method was evaluated by the technique described in [7], in which the lateral resolution is measured by half-width of the derivative height of nanorelief along lateral direction in the region of sharp edge.

Approximation of $G$ was chosen as the Airy function whose parameters were determined by numerical aperture of the optical system as well as the wavelength of light:

$$G(x, y) = \frac{\sin^2(r(x, y))}{(r(x, y))^2},$$

where $r$ is determined by equation:

$$r(x, y) = \pi \cdot \frac{2NA \cdot \sqrt{x^2 + y^2}}{\lambda},$$

where $\lambda = 630 \text{ nm}$ is the wavelength of light, $NA = 0.4$ is the numerical aperture of the objective 7 (see Fig. 2). Projection of pixel in the measurement area has a size of $300 \times 300 \text{ nm}^2$. Cross-section of $G$ in scale grid tied to the size of the pixel projection is shown in Fig. 3.

Comparison of the results of nanorelief measurement in the region of the sharp edge without and with use of the proposed method is shown in Fig. 4. Value of constant $C$ was set to 0.1 in according to noise level.
Fig. 4. Height of the measured relief of the sharp edge. Using the deconvolution of interferograms (solid line) and without using one (dashed line).

Figure 5 shows graphs of derivative height of the measured relief.

Fig. 5. Module of derivative height of the measured relief of the sharp edge. Using the deconvolution of interferograms (solid line) and without using one (dashed line).

Figure 5 shows that the application of the proposed method can improve the lateral resolution more than 20%.

4. Conclusion

It is shown that the use of deconvolution algorithms to interferograms can overcome the diffraction limit of the lateral resolution in the measurement of 3D nanorelief. To improve obtained results it is necessary to achieve interferograms registration with better signal-to-noise ratio and to measure instrumental function with higher precision.

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References


