High Precision Algorithms for Shadow Inspection of 3D Objects in Partially Coherent Light

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Abstract. *The peculiarities of 3D object's image formation in a diffraction-limited system using quasi-monochromatic source with finite angular width are presented. The algorithms to determine the geometric parameters of the 3D objects by shadow optical method inspection are proposed. The theoretical results obtained have been experimentally verified.*

Keywords: 3D Diffraction, Shadow Method, Dimensional Inspection, Partially Coherent Source

1. Introduction

The shadow systems due to their high precision and operation speed as well as broad measurement range are widely used among optical means of noncontact dimensional inspection in industry [1]. The essence of the measurement shadow method consists in finding of the position of object's true boundary. It allows us to determine its different geometrical dimensions, including width, length, holes diameter, etc. In case of flat objects (zero thickness), the true boundary is determined using shadow image thresholding, either at 25 % of light intensity illuminating the object (coherent illumination) or at 50% of intensity (noncoherent illumination) [2]. Under inspection of the extended objects in coherent light the threshold shift takes place [3], which is proportional to Fresnel zone.

Because of known difficulties occurring under the use of coherent illumination (first of all, speckle noises) the more perspective is the partially coherent illumination for inspected 3D objects using, for instance, small-size LED.

The peculiarities of 3D object images formation in a diffraction-limited system under their illumination by partially coherent light are examined. The methods for analytical determination of shift of 3D object image shadow boundary and its correction depending on the object thickness and the optical system parameters are proposed. These algorithms allow us to considerably increase the measurement precision of 3D objects by the shadow method.

2. The Shadow Mearsurements for 3D Objects in Partially Coherent Light

The optical scheme of the system to realize the shadow inspection method for 3D objects can be seen in Fig. 1a. Source 1 with angular sizes $2\theta_s$ is illuminating 3D object 3 as an extended (thick) edge with width *d* through objective of lens 2. Projection lenses 4 and 6 are forming its shadow image on photodetector matrix 7. Aperture diaphragm 5 with angular sizes $2\theta_{ap}$ is situated at focal distance 4 from the lens. The image profile of the 3D object's edge can be seen in Fig. 1b.

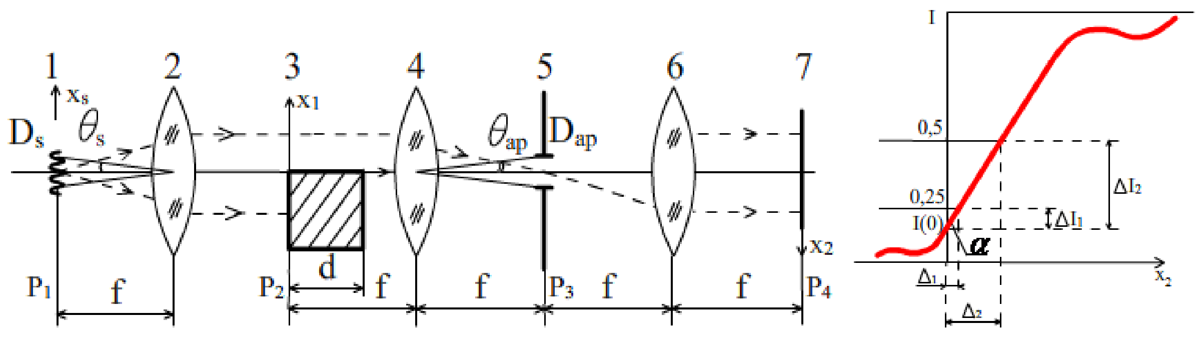

Fig. 1. Formation of 3D object's image in a diffraction-limited system: optical scheme (a); image profile of the 3D object's edge (b).

The value of threshold $I_{thr} = I(0)$ depends on many parameters, including angular size of the light source and the aperture diaphragm, as well as the object's volumetricity. In case of flat objects (*d=0*) illuminated by coherent light the threshold is equal to $I_{thr}^{(1)} = 0{,}25$ ($\theta_s \to 0\ rad$), and by noncoherent light the threshold equals $I_{thr}^{(2)} = 0{,}5$ ($\theta_s \to \pi/2\ rad$). Under partially coherent illumination the threshold becomes within the limits of $0{,}25 < I_{thr} < 0{,}5$ ($0\ rad < \theta_s < \pi/2\ rad$) [2].

The influences of 3D object extension on the structure of the field in its image is determined by the ratio of critical diffraction angle $\theta_{cr} = \sqrt{\lambda/d}$ (under which the volume effects become significant) to the angular aperture size $2\theta_{ap}$ [3] (λ is wavelength). If at $\theta_{cr} >> \theta_{ap}$ the weak volume effects occur, so at $\theta_{cr} << \theta_{ap}$ their effects are sufficiently significant. For further calculations one has limited by weak volume effects taking place in practical applications.

3. Algorithms for High Precision Determination of 3D Object's Boundaries

Two algorithms to determine the position of the geometric boundary of thick (extended) edge which plane perfectly absorption surface coincides with optical axis ($x_1 = 0$) have been developed. The first one is based on the use of threshold $I_{thr} = I(0)$ (Fig. 1b) that takes into account the angular source size $2\theta_s$ and object's thickness *d*. For calculation we used the constructive theory of image formation for extended objects with sharp shadow projection [3]. One has shown that normalized light intensity in the thick edge image in point $x_2 = 0$ that coincides with boundary geometric position, under $\theta_s << \theta_{ap}$ is equal to:

$$I_{thr} = I(0) = \frac{1}{4} + \frac{1}{3\pi^2}\frac{\theta_s^2}{\theta_{ap}^2} - \frac{\theta_{ap}}{\sqrt{2}\pi\theta_{cr}} . \quad (1)$$

It is seen that value $I(0)$ is determined by the three components. The first corresponds to the case when a flat object is being illuminated with point axial light source (coherent illumination). The second one refers to the influence of the final angular source size that is quadric and results in increase of $I(0)$. At last the third component is determined by the object volumetricity with decreases the threshold of $I(0)$. Thus, at given parameters of *d* and θ_{ap} one has had an opportunity, by choosing the angular source size $2\theta_s$, to compensate the effect of the object's volumetricity on the change of light intensity at the point of geometric position of the thick edge boundary ($x_2 = 0$).

Computer modeling has allowed obtaining the dependency of the level of threshold on the light source diameter (Fig. 2). According to the obtained results (Eq. 1) the threshold levels for the thick and flat edges illuminated by light source of different size are differed by the third component. Under $\theta_s = \theta_{ap}$ threshold level jump is observed. The theoretical results as well as computer modeling ones are in good agreement.

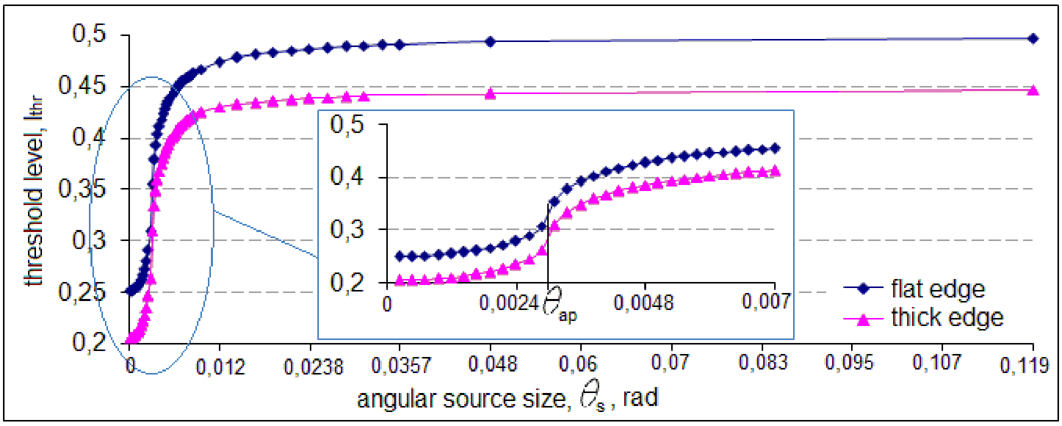

Fig. 2. The threshold level for shadow image vs. the light source diameter.

The second algorithm developed envisages the determination of the position of the 3D edge's boundary using the two standard thresholds: $I_{thr}^{(1)} = 0{,}5$ and $I_{thr}^{(2)} = 0{,}25$. It is important that high precise determination of the boundaries requires introduction of two corrections Δ_1 and Δ_2 that are determined by the following (Fig. 1b):

$$\Delta_1 = \frac{0{,}5 - I(0)}{I'(0)} = \frac{\Delta I_1}{tg\alpha}, \qquad \Delta_2 = \frac{0{,}25 - I(0)}{I'(0)} = \frac{\Delta I_2}{tg\alpha}, \tag{2}$$

where $tg\alpha = I'(0)$ is the slope angle of the 3D edge's image profile under selected level. In this case one has to know the value of $I'(0)$. It's established that at $\theta_s << \theta_{ap}$

$$I'(0) = \frac{2\theta_{ap}}{\lambda} + \frac{4}{\sqrt{2\pi\lambda\theta_{cr}}}\left(\frac{1}{3}\theta_s^2 - \theta_{ap}^2\right) \tag{3}$$

Taking into account the Eq. 3, the Eq. 2 for corrections Δ_1 and Δ_2 is as follows:

$$\Delta_1 = \frac{\lambda}{\theta_{ap}}\left[0{,}25 + \frac{3}{2\sqrt{2\pi}}\frac{\theta_{ap}}{\theta_{cr}} - \frac{1}{3\pi^2}\frac{\theta_s^2}{\theta_{ap}^2}\right], \qquad \Delta_2 = \frac{\lambda}{\theta_{ap}}\left[\frac{3}{2\sqrt{2\pi}}\frac{\theta_{ap}}{\theta_{cr}} - \frac{1}{3\pi^2}\frac{\theta_s^2}{\theta_{ap}^2}\right] \tag{4}$$

It is seen that the values of the corrections depend on the angular aperture size, the angular light source size and the critical angle. The corrections can be minimized through choice of the parameters system due to the different signs of the components in the Eq. 4.

4. Experimental Results and Discussion

The theoretical results obtained have been experimentally verified. The scheme of experimental optical system is presented in Fig. 1a. As light source 1 one used LED with effective wavelength $\lambda = 628$ nm and spectral width $\Delta\lambda = 15$ nm. Necessary angular light source size was set using a diaphragm. The homogeneity illumination of the inspected object is reached by mat diffuser. The extended object 3 was projected by lenses 4 and 6 on photodetector camera with 2210×3002 pixel matrix (size of the pixel was 3.5 µm). The angular size of aperture diaphragm 5 had been set on the assumption that $\theta_{ap} > \theta_s$.

In experiments we used ceramic isolations rings with thickness of 0.8-80 mm, outer diameter of 28 – 80 mm and inner diameter of 23 – 62 mm as the extended objects. The position of thick edge was determined at level $I_{thr}^{(1)} = 0{,}5$.

It has been experimentally established and confirmed theoretically the influence of the object's thickness and of the optical system parameters on the image position profile. For example, when measuring thicknesses of the three-dimensional edge is varied from 2 to 10 mm, the position boundary shift was 4,77 µm. The results of the experiment and computer modeling are presented in Fig. 3, which shows the dependence of ring edge's shift from the thickness. One can see that deviation of the experimental and theoretical data in average has not exceeded a few microns that can be explained by non accuracy precision in calibration of the initial objects (instrument error was about 2 µm).

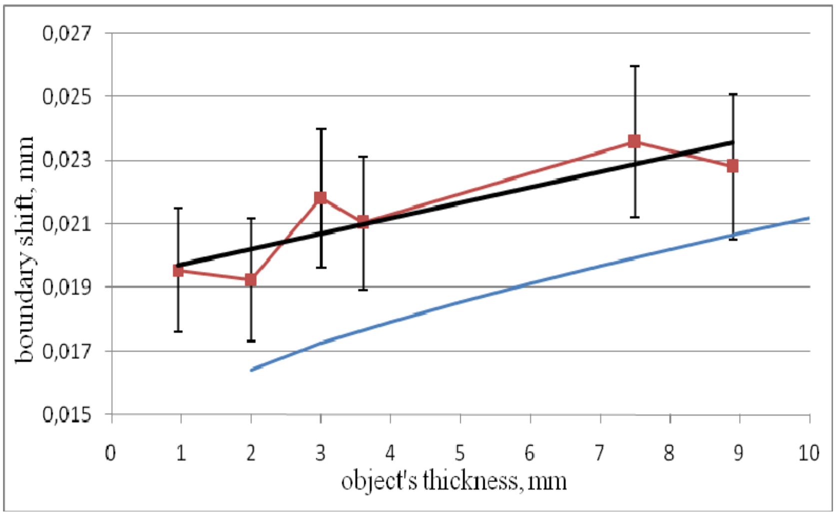

Fig. 3. Shift of the position of 3D object's edge vs. the object's thickness: jogged line – experimental data; thick line – averaged experimental curve; the curve below – calculation data.

Using the second algorithm one has been able to decrease the systematic error of the inspection system by 10 times: from 20 µm to 2 µm.

5. Conclusion

We have studied the peculiarities of image formation for 3D object as a thick edge with sharp shadow projection illuminated by partially coherent light applied to dimensional inspection. The developed algorithms for processing the measurement information allow one by choosing the angular light source size to increase significantly the precision of 3D objects geometrical parameters measurement. The results obtained can be used for development of precision measurement systems for 3D objects inspection with sharp shadow projection.

References

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