Direct object-shape comparison by light-in-flight speckle interferometry

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A method is proposed for direct optical comparison of the three-dimensional shapes of objects by light-in-flight speckle holography. The basic idea of this technique is to use an ultrashort laser pulse with a short coherence length to produce interference patterns that present a single contouring of the object. A simple experiment using plane diffuse objects was performed to verify the method. © 1997 Optical Society of America

Since the introduction of the method of light-in-flight (LIF) recording by holography by Abramson in 1978,[1,2] LIF has been further developed for measuring the three-dimensional shapes of objects.[3] More recently, with the development of high-resolution CCD sensors, different methods of digitally recording LIF holograms have been proposed.[4,5] Further, holograms of small objects at large distances have been directly recorded in CCD arrays without the need for chemical development.[6] In this Letter we propose a new method of using the LIF technique for direct comparison of the three-dimensional shapes of objects.

The basic idea of LIF is to use an ultrashort laser pulse with a short coherence length to illuminate the object. In the hologram only the part of the object that is within the coherence length is recorded. When the coherence length of the pulse is short enough, the reconstructed object will be single-line contoured. By use of the proper strategy, the different object intersections can be recorded separately. As a result, the three-dimensional shape can be measured. In this Letter we use a similar setup with electronic speckle-pattern interferometry. As in general electronic holography, the mutual interference of the object and the reference field is recorded by a CCD camera. The irradiance distribution can then be described as

$$I = I_o(x, y) + I_r(x, y) + 2A_o(x, y)A_r(x, y)\cos[\varphi(x, y)]. \tag{1}$$

I_o and I_r denote the irradiance of the object and the reference fields, respectively, with amplitudes A_o and A_r, respectively, and φ is the phase difference between the two fields. When the reference mirror is moved, the phase will be changed and, at the same time, the irradiance distribution on the CCD will become

$$I' = I_o(x, y) + I_r(x, y) + 2A_o(x, y)A_r(x, y) \times \cos[\varphi(x, y) + \Delta\varphi], \tag{2}$$

where $\Delta\varphi$ is the phase change.

If Eq. (2) is subtracted from Eq. (1), then

$$\Delta I = I - I' = 4A_o(x, y)A_r(x, y)\sin[\varphi(x, y) + \Delta\varphi/2] \times \sin(\Delta\varphi/2). \tag{3}$$

Equation (3) is the standard formula for electronic holography.[7] But, unlike with the general method, we are interested in neither the phase nor the object amplitude distribution. With the LIF method, we are interested in only that part of the object that is within the coherence length, which will produce a suitable pattern to enable us to distinguish it from other object parts. The part within the coherence length will then represent the single-line contouring. Equation (3) represents the coherent part of the object field distribution. Changing the phase difference $\Delta\varphi$ will cause ΔI to vary between its minimum and maximum values.

The noncoherent part of the object is not affected by the change of phase, so it can be subtracted away as a background. As a result, on the computer screen we can clearly see the single-line contouring. By changing the reference optical path length (or changing the object position), we can achieve different intersectional contouring lines of the object, and with this change the three-dimensional object shape is measured, as we have previously shown.[8] The drawback to this method is the need for a long scanning range, as long as the object depth, and thus a long evaluation time.

However, often it is not necessary to have an absolute shape measurement, and only the deviation from the desired shape is of interest. This deviation can be obtained by replacement of the reference mirror with a reference object with the desired shape. In this case the resulting hologram will be a measure of the similarity between the true shape and the desired shape. This is possible because there is no need for the reference surface to be optically flat; a diffusely scattering reference surface works, too. To examine the method, we used the simple setup shown in Fig. 1.

The object is a circular plane plate placed at a 30° angle with respect to the reference surface. The reference is a painted white plane surface. The distance between the reference surface and the beam splitter is $L = 1000$ mm. The reference surface can be translated by a piezoelectric transducer to change the phase $\Delta\varphi$. A stepping motor moves the object to produce different intersectional contouring. The movement range of the reference mirror is roughly one wavelength (λ), and every step of movement is $\lambda/15$. During this process, a maximum and a minimum intensity image are recorded by the CCD camera, which is attached to a PC-based

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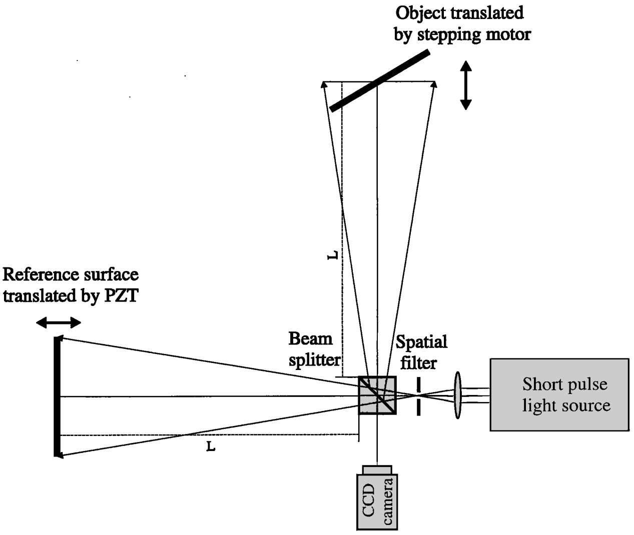

Fig. 1. Block diagram of the experimental setup. PZT, piezoelectric transducer.

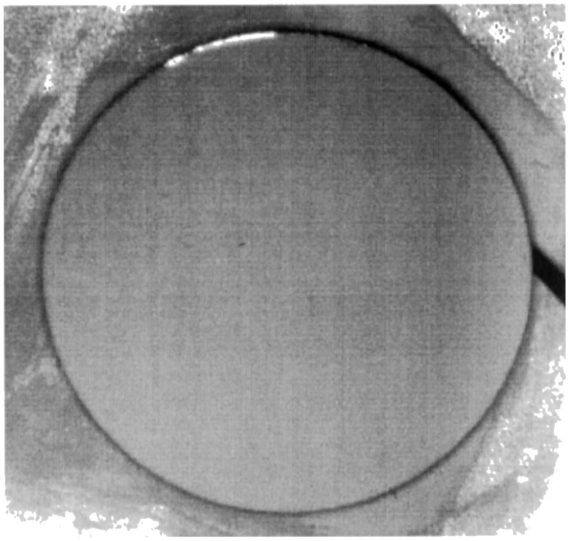

Fig. 2. Image of a real circular plane object.

image-processing system. By substracting the minimum intensity image from the maximum intensity image, we obtain a single contouring line. The resolution of the CCD camera used in this experiment was 768 × 572 pixels. The laser used was a mode-locked dye laser with a coherence length of ~1 mm and a wavelength $\lambda \approx 610\,\text{nm}$. Figure 2 shows the original object image. In Figs. 3a–3e, the contouring images of the object at different positions are shown. Figure 3f is the final gray image of the measurement that results when all the single contouring images are combined. When this final gray image of the measurement results is examined in three-dimensional coordinates, we can clearly see the three-dimensional shape of the object, as shown in Fig. 4.

Compared with other techniques, the method proposed here has some advantages for measuring the three-dimensional shapes of objects. First, it is a common-axis hologram-recording setup, and it can be used to record relatively large objects. Second, the depth resolution, in contrast to that of most other measuring techniques, is almost independent of the object size. There is no need for a long scanning range; the translated range of the reference mirror is within only λ. The measurement is absolute; no fringes have to be counted.

In conclusion, we have theoretically studied and experimentally tested the method of direct electronic holographic comparison of the three-dimensional shapes of objects with the LIF technique. Even though this prototype evaluation system also faces many shortcomings, such as low resolution of the CCD, it has proved the feasibility of the method.

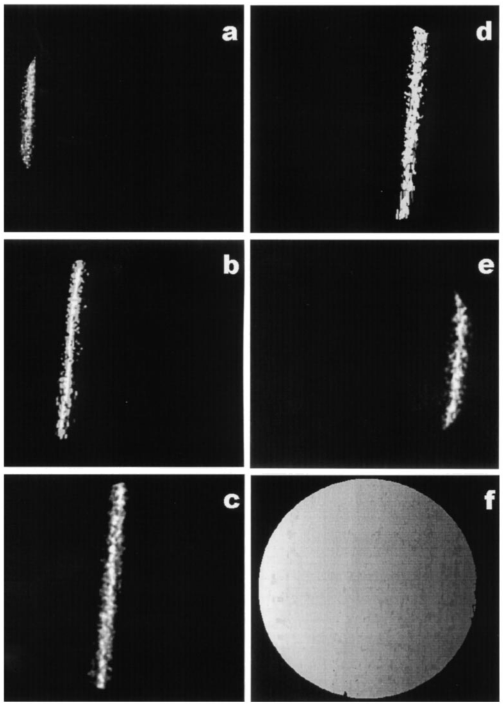

Fig. 3. When the object is translated by the stepping motor, the different intersectional contouring between the reference plane and the object is recorded. By combining all the single contouring images (a–e), we obtain the final gray image of the three-dimensional shape of the object (f).

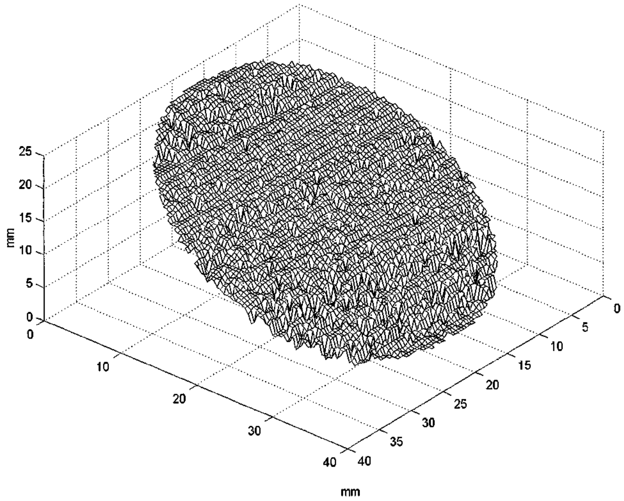

Fig. 4. Measured result shown in three-dimensional coordinates.

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