OPTICAL IMAGE SUBTRACTION THROUGH SPECKLE MODULATED BY YOUNG FRINGES

H.J. RABAL, N. BOLOGNINI *, E. SICRE and M. GARAVAGLIA
Centro de Investigaciones Opticas (CIOp) (CONICET - UNLP - LEMIT)
1900 La Plata, Argentina

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A new method for subtracting images is proposed. It is based on assigning complementary Young's fringes to the speckles of the common parts of two images. In this way, carrier frequency is cancelled, and "a-posteriori" spatial filtering shows only noncommon parts. Suggestions on applications of the method are briefly commented.

The importance is well known of developing simple and fast techniques for extracting the differences between two 2- and 3-dimensional scenes. In the last few years several methods have been proposed [1–4]. A review of the most important ones can be found in ref. [5].

The purpose of this paper is to propose a new approach, similar in some extent to the technique developed by Debrus et al. [3]. In its first step, the information contained in a transparency, modulated by a very fine speckle pattern, is photographically recorded. Afterwards, the photographic plate is slightly moved in-plane and then, a second transparency, modulated by the same speckle pattern, is recorded on the same plate. The developed plate contains pairs of equally spaced speckle grains for identical parts of the transparencies, and of unpaired speckles for different ones. If the transmittance of this plate is Fourier transformed in a conventional way [6], the paired speckles give raise to Young's fringes, while the spectrum of the unpaired ones spread all over the Fourier plane. If a slit filter is located in the nulls of the Young's fringes, it will only pass the light coming from the unpaired speckles, and the subsequent Fourier transform will depict a picture of the differences between the two transparencies.

The method we propose also has two steps. In the first one, a transparency modulated by speckles that are themselves modulated by Young's fringes, is recorded on a photographic plate. These speckles are obtained from the image of a diffuser by a lens whose pupil consists of two round holes, as suggested in ref. [7]. Then, Young's fringes are shifted by half a period, and the second transparency is recorded. If the two exposures are equal, the Young's fringes of the speckle of identical parts of both transparencies are added to a constant background, while the contrast of the Young's fringes of the speckle corresponding to non-identical parts increases in accordance with their mismatch. When the developed plate is Fourier transformed as before, the non-cancelled Young's fringes give raise to two diffracted orders in the Fourier plane. If a filter is placed in this plane, in order to observe only one diffracted order, and this order is again Fourier transformed, an image of the differences between the transparencies will be obtained.

The same principle can be applied for subtracting images of diffusing three-dimensional objects.

Young's fringe shifting can be performed by moving in-plane the photographic plate in the direction perpendicular to the fringes. In this case, the cancellation of Young's fringes is exact in the whole plane. However, in some cases it is more practical to produce the π-phase-shift by rotating a plane-parallel plate placed behind one of the holes, in spite of the fact that cancellation of Young's fringes is not complete all over the plane.

Fig. 1 shows the experimental set-up used for obtaining the differences between two scenes. The necessary

* Fellow of the Comisión de Investigaciones Científicas de la Provincia de Buenos Aires, Argentina (CIC).

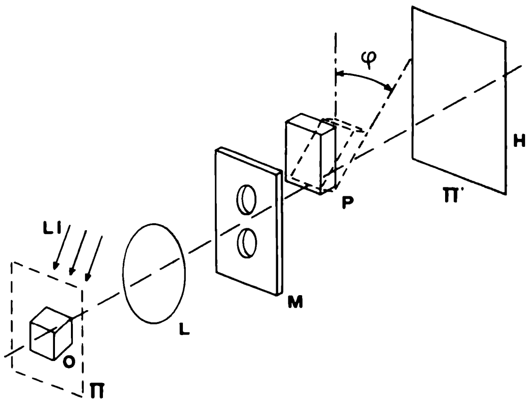

Fig. 1. Experimental set-up to record the double exposure plate as is described in the text. O, object, LI laser illumination; L, lens, M, mask; P, plane parallel glass plate and H, photographic plate. π and π' are the conjugate planes of the lens L.

angle ψ of rotation of the plate for producing the π-shift in Young's fringes, was previously determined with a microscope focused on the image plane. Fig. 2 shows the reconstruction procedure.

Due to the fact that non-axial rays suffer different phase delays, non exact cancellation will be obtained for common object points far enough from the axis. If the phase-delay is not π but $(\pi + \epsilon)$, then the intensity addition in the recording plate will contain a certain amount of undesirable a.c. component:

$$I = A[\cos(px) + \cos(px + \pi + \epsilon)] + C$$

$$= C - 2A \sin(\epsilon/2)\cos(px + \pi/2 + \epsilon/2)\,,$$

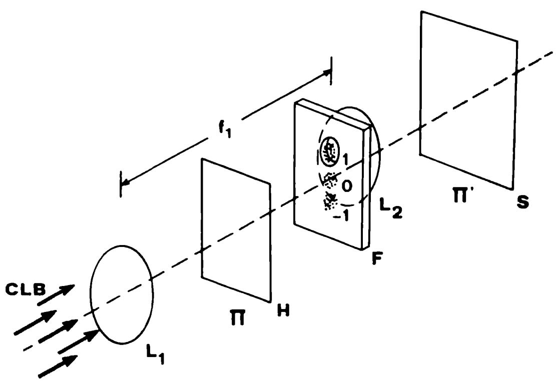

Fig. 2. Reconstructing experimental set-up. CLB, collimated laser beam; L_1 and L_2, transforming lenses; H, developed photographic plate; F, spatial filter and S, observing screen. π and π' are conjugate planes of the L_2 transforming lens.

where p is the spatial frequency of Young's fringes, and A and C are constants.

If the recording of the two exposures is done in the linear region of the $t-E$ curve of the photographic plate, the fraction of intensity transmitted to the image is:

$$[2\sin(\epsilon/2)]^2 \sim \epsilon^2\,, \quad \text{if } \epsilon \text{ is small enough.}$$

Then, the subtraction quality is given by the smallness of ϵ^2, for the maximum value of the incidence angle.

A straightforward geometrical calculation shows that the phase delay shift $\Delta\delta$ between two angular positions of the plate, for a ray making an angle θ_i with the normal to the glass plate, is:

$$\Delta\delta = \frac{2\pi e}{\lambda}\left\{\frac{n}{\cos[\sin^{-1}(n^{-1}\sin(\psi+\theta_i))]} + \frac{1}{\cos\theta_i} - \frac{\cos[\sin^{-1}(n^{-1}\sin(\psi+\theta_i)) - \psi]}{\cos\theta_i \cos[\sin^{-1}(n^{-1}\sin(\psi+\theta_i))]} - \frac{n}{\cos[\sin^{-1}(n^{-1}\sin\theta_i)]}\right\}\dots, \tag{1}$$

where λ is the wavelength of the incident light, n the refractive index of the plate and e its thickness, and ψ is the necessary angle of rotation of the plate for producing a π-shift for axial rays. The angle ψ can be calculated solving the following equation by iterative methods:

Table 1

n	e (mm)	$[2\sin(\epsilon/2)]^2 = 0.01$ $\theta_{i\,max}$	$[2\sin(\epsilon/2)]^2 = 0.001$ $\theta_{i\,max}$
1.3	0.01	6°	4°
1.3	0.1	5°	3°
1.3	1	4°	2°
1.3	10	3°	2°
1.5	0.01	7°	4°
1.5	0.1	5°	3°
1.5	1	4°	3°
1.5	10	3°	2°
1.7	0.01	8°	4°
1.7	0.1	6°	4°
1.7	1	4°	3°
1.7	10	3°	2°
1.9	0.01	9°	5°
1.9	0.1	7°	4°
1.9	1	5°	3°
1.9	10	3°	2°

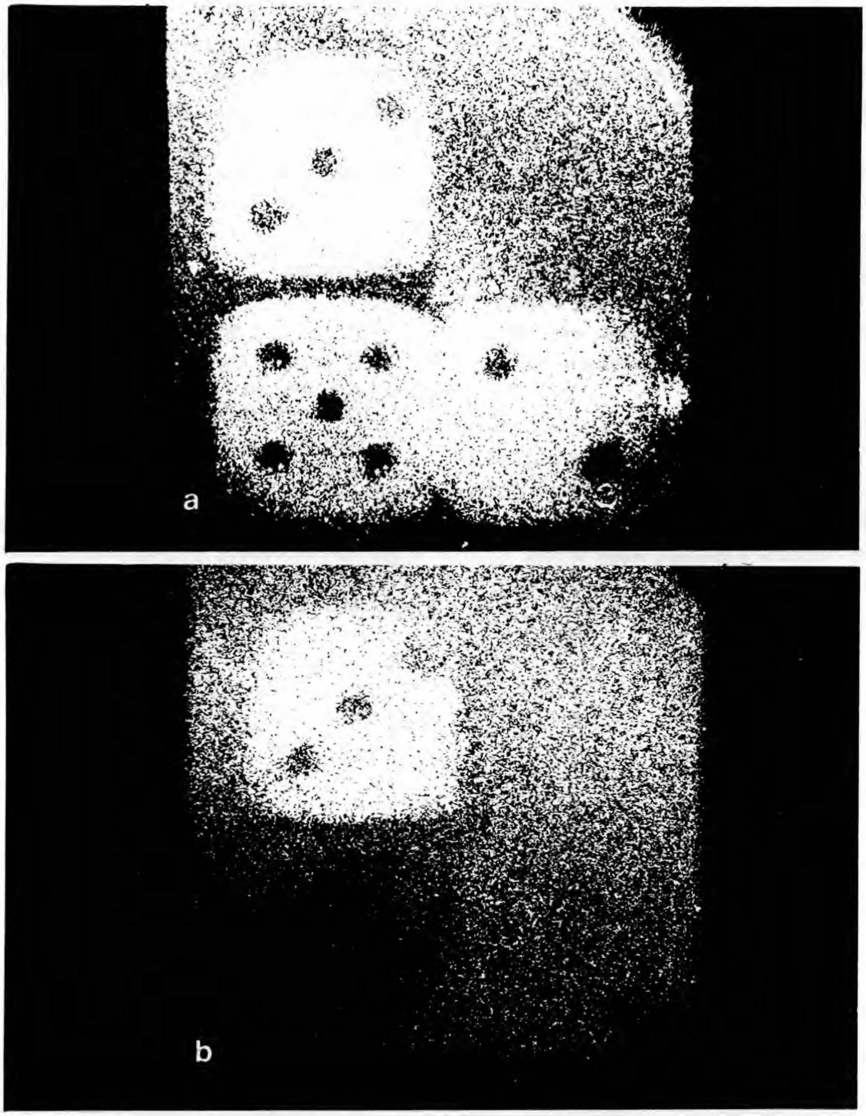

Fig. 3. Experimental results. A) Direct reconstruction of the object scene composed by three dice, and B) Reconstruction of the same scene where two dice have been subtracted. To record H Ilford FP4 film was used.

$$\frac{2e}{\lambda \cos[\sin^{-1}(n^{-1} \sin \psi)]}$$

$$\times \{\cos[\sin^{-1}(n^{-1} \sin \psi)] (1 - n - \cos \psi) + n - n^{-1} \sin^2 \psi\} = 1 .$$

So, using eq. (1), we can find

$$\epsilon = \Delta\delta - \pi .$$

Some calculations for feasible values of the parameters are listed in table 1. For example, it shows that, when the plate thickness is 0.1 mm and the refractive index is 1.7, $(2 \sin \epsilon/2)^2$ can be kept below 0.001 for angles θ_i up to 4°. In general, the acceptable angle θ_i for a given value of $(2 \sin \epsilon/2)^2$ increases as e decreases and as n increases. These numerical results mean that non-exact cancellation can be good enough for small angular field of view.

Fig. 3 shows the experimental results. In this case, the separation between holes was 10 mm and their diameter 6 mm. The focal length of the lens was 500 mm, and the maximum value of θ_i was near 1.2°. A λ = 632.8 nm, 2 mW, He-Ne laser was employed. Common film was used, resulting in very speckly images.

The spatial filtering operation is easily done, because all the light coming from the differences between the images is concentrated in two orders.

By using holographic plates, it could be possible to record higher carrier frequencies resulting in wider separations of the diffracted orders. Then, larger spatial filter diameters could be used, resulting in finer speckles.

Spatial derivatives and contrast reversals were obtained with this method. We are intending to implement this same technique, but using a half wave plate and an electro-optical polarization rotator, for the π-shift, *with no mechanical motions*, what seems promising for ultra-fast subtraction in time-evolving phenomena.

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