Aust. J. Phys., 1980, **33**, 601–5

Velocity Measurement with Speckle and Speckle-like Photography

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Abstract

The criteria for image structure and film properties for velocity measurement by speckle-pattern photography are discussed. Even with low intensity light sources, holographic film is unnecessary, and Plus-X-Pan film will record sufficient detail (in multiple exposures if necessary) to form diffraction pattern fringes. Speckle photography techniques can also be applied to appropriately prepared, incoherently illuminated surfaces, so long as the camera image has the correct speckle-like granular structure. Experiments verifying these ideas are described.

Introduction

The photographic laser speckle technique for measuring displacements of surfaces involves essentially two steps:

(i) illuminating the moving surface with a laser beam and double exposing a film to the speckle pattern before and after displacement, and

(ii) observing the diffraction pattern of the developed negative. This will consist of Young's fringes whose separation allows the surface displacement to be determined; the normal to the fringes gives the direction of motion.

In this paper we wish to comment on two aspects of the process. Firstly, it is only necessary for the double exposure negative to have a speckle-like structure. For instance, if a rough surface is illuminated with *incoherent* light and focused onto film, it is possible, depending on the degree of surface roughness, the camera optics and the resolution of the film, to obtain a negative with a speckle-like character whose diffraction pattern also gives the displacement of the surface.

Secondly, the film used need only record sufficient detail to form diffraction fringes from the speckle-like pattern of the negative. If velocity measurements (Celaya *et al.* 1976; Dudderar and Simpkins 1977; Barker and Fourney 1977; Iwata *et al.* 1978) are required, the film speed is also a major consideration. The distance d between corresponding areas on a double exposure is $d = mvt$, where v is the surface velocity, t the time between exposures and m the magnification. To record pairs of speckle-like areas, d must be greater than the speckle size σ. In our experience, a practical minimum for the ratio $Q = d/\sigma$ is 3 or 4, otherwise no fringes can be seen. This gives

$$Q\sigma = mvt. \tag{1}$$

If a laser speckle pattern is used (Ennos 1975), we have

$$\sigma = 1\cdot 22(1+m)\lambda F, \tag{2}$$

where λ is the illuminating wavelength and F the f number of the camera. The distance then becomes

$$mvt = 1{\cdot}22(1+m)\lambda FQ. \tag{3}$$

The period p of each individual exposure must be such that the image is not unduly blurred. Thus mvp must be much less than σ. In practice this means

$$4mvp \lesssim \sigma. \tag{4}$$

These ideas are demonstrated in two velocity measurement experiments, using coherent and incoherent light of low intensity in combination with Kodak Plus-X-Pan film.

Experiments

Until now workers in laser speckle velocity measurement have used high intensity double pulsed ruby lasers or CW argon lasers in conjunction with holographic film (Celaya *et al.* 1976; Dudderar and Simpkins 1977; Barker and Fourney 1977; Iwata *et al.* 1978). A typical experiment with $\sigma = 10\ \mu$m, $m = 0{\cdot}2$, $v \approx 1$ cm s^{-1} and $Q = 4$ will require $t = 20$ ms and $p = 1{\cdot}2$ ms. Using a nominal 5 mW He–Ne laser, we found that Kodak S0-173 holographic film was not fast enough to record exposures of less than 18 ms. A higher speed film (with its consequent lower resolution) is required. Kodak Plus-X-Pan film rated at ASA-125 and an approximate resolution limit of 150 cycles mm^{-1} was chosen (Kodak Data Sheets 1970).

Double exposure photographs of a laser-illuminated white card translated perpendicular to the camera's line of sight were used to check the suitability of Plus-X-Pan film. After standard development, the fringe spacing of the diffraction pattern of the negative was measured. The smallest card displacement that could be measured corresponded to a speckle separation of 20 μm on the film ($\sigma = 5\ \mu$m). Although of low contrast, the fringes were adequate for measurement purposes.

In the following experiments, multiple exposures (Celaya *et al.* 1976; Dudderar and Simpkins 1977) were used because an improved average velocity measurement is obtained from the extra information recorded compared with a double exposure. The narrowing of the primary maxima reduces the error in measuring the fringe separation.

Fig. 1*a* shows the experimental configuration used for laser illumination. An aluminium target was lightly sandblasted with 100 μm diameter particles to give a depth variation of $20\pm10\ \mu$m (as measured by a microscope). (The depth variation determination is not critical to the experimental results.) The target was rotated at 4·00 r.p.m. by a synchronous motor. The 35 mm camera had a lens of focal length 24 mm with an f number of 4·4. The 5 mW He–Ne laser beam was chopped by a perforated rotating disc into light pulses 0·4 ms long (p) separated by 7·8 ms (t). These were calculated from equations (3) and (4) using the estimates $v = 2{\cdot}5$ mm s^{-1}, $m = 2{\cdot}5$, $Q = 4$, $F = 4{\cdot}4$ and $\lambda = 633$ nm. From equation (2) we find $\sigma \approx 12\ \mu$m. The chopped beam was reflected onto the target from a front-surfaced mirror next to the camera.

A multiple exposure photograph was taken at a shutter speed of 1/30 s. After standard development with D-76 for 5 min at 20°C the diffraction pattern of the negative was analysed using the apparatus illustrated in Fig. 1*b*. The negative was illuminated over an area of about 2 mm^2 at a radius R from the centre of revolution of the image. The velocity corresponding to R was calculated from

$$v = \lambda D/mt\Delta x, \tag{5}$$

where D is the distance from the film to the Fraunhofer plane, λ is the illuminating wavelength, Δx is the fringe separation, and m and t are the magnification and time between exposures, as before (Iwata *et al.* 1978).

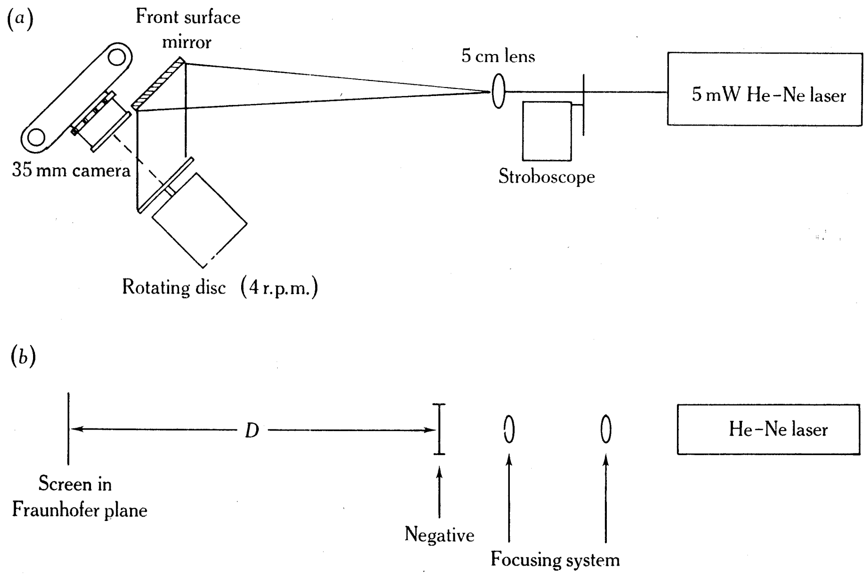

Fig. 1. Experimental configurations for (*a*) laser speckle photography and (*b*) analysis of the diffraction pattern.

The velocity v was compared with the velocity w computed from

$$w = 2\pi R\omega/60\,m, \tag{6}$$

where ω is the angular speed in r.p.m. The magnification m was determined by comparing corresponding distances on the disc and the negative. Typical results were $v = 3{\cdot}23 \pm 0{\cdot}07$ mm s^{-1} compared with $w = 3{\cdot}25 \pm 0{\cdot}02$ mm s^{-1} (when $R = 1{\cdot}75$ cm, $D = 215$ cm, $\lambda = 633$ nm, $t = 7{\cdot}8$ ms, $m = 2{\cdot}25$, $\Delta x = 2{\cdot}4$ cm and $\omega = 4{\cdot}00$ r.p.m.).

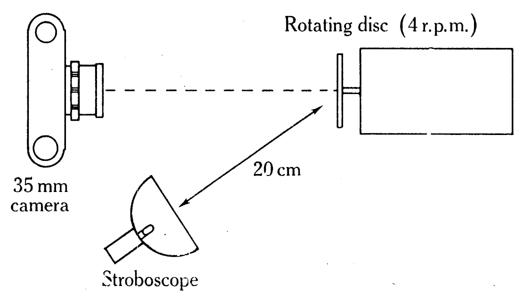

Fig. 2. Experimental configuration for photography with incoherent light.

A similar experiment was performed with the laser replaced by a stroboscope as depicted in Fig. 2. The 35 mm camera had a lens of focal length 50 mm with an f number of $4 \cdot 5$.

The first estimate of exposure separation t was made by assuming the average size of the speckle-like areas of the sandblasted disc to be equal to the resolution limit of the camera. This corresponds to the speckle size when a laser is the light source, and thus equation (3) can be used. From the data $v = 4\ \mathrm{mm\ s^{-1}}$, $Q = 4$, $m = 0 \cdot 1$, $F = 4 \cdot 5$ and $\lambda = 633$ nm, t was calculated to be about 8 ms. During the experiment a range of separations corresponding to multiples of t were used.

A better estimate is made from estimating σ by microscopic inspection of the surface. Alternatively, σ is given approximately by (Baker *et al.* 1979)

$$\sigma \approx 2 \cdot 44\, D\lambda / A\,, \tag{7}$$

where A is the diffraction halo diameter of a trial photograph analysed by the apparatus shown in Fig. 1*b*. For this experiment, A has a maximum value of 10 cm when $D = 220$ cm. Thus $\sigma \approx 35\ \mu\mathrm{m}$ and $t \approx 50$ ms as calculated from equation (3).

The stroboscope utilized a Ferranti NSP2 valve which gives a 15 μs pulse with a peak intensity of approximately 700 cd in the wavelength region 580–630 nm. A range of frequencies from 20 to 250 Hz were used to record two, four or eight multiple exposures, when the appropriate camera shutter speed was chosen. After development the negatives were analysed as above using the configuration in Fig. 1*b* and equations (5) and (6). Typical results from an exposure of 1/15 s were $v = 1 \cdot 04 \pm 0 \cdot 03\ \mathrm{cm\ s^{-1}}$ and $w = 1 \cdot 06 \pm 0 \cdot 01\ \mathrm{cm\ s^{-1}}$ (when $R = 1 \cdot 7$ cm, $D = 220$ cm, $m = 0 \cdot 67$, $\lambda = 633$ nm, $t = 15$ ms, $\Delta x = 1 \cdot 33$ cm and $\omega = 4 \cdot 00$ r.p.m.).

As shown previously by its use in laser interferometry (Elomag Data Sheets; Hariharan 1978), Polaroid positive/negative films (55 P/N, 655 P/N) produce a negative with similar characteristics to Plus-X-Pan film. Consequently, they have also been successfully used for velocity measurements. With more intense light sources and shorter exposure separations t, the range of velocities that can be measured using Plus-X-Pan film will be much greater than with holographic film. While lasers have the advantages of high intensity well-collimated beams and control of the speckle size through a suitable choice of optics, incoherent light sources are adequate for velocity measurements with suitably prepared surfaces.

We have also been able to make measurements of the protoplasmic streaming velocity in such biological samples as *Nitella*, using a nominal 5 mW He–Ne laser and Plus-X-Pan film. Despite the presence of Brownian motion, sufficient fringe definition was obtained with multiple exposures to obtain values of the average streaming velocity within $\pm 10\%$ of that measured using optical microscopy. A fuller account of this aspect of the work will be published elsewhere.

Conclusions

There will be many situations where low intensity lasers can be used with suitable optics to give accurate speckle-pattern measurements of velocity with Plus-X-Pan film. Even when multiple exposure techniques might smear out the information, as in the case of protoplasmic streaming in biological specimens, useful estimates of velocity can be made by the double exposure technique. The apparatus required is obviously inexpensive and simple when compared for example with an argon-ion laser and photon correlator. Suitably prepared surfaces can also yield velocity measurements with incoherent sources, provided the camera image has a speckle-like structure with average speckle size greater than or equal to the resolution limits of both camera and film. Intense incoherent sources can be less expensive than intense laser sources, so once again comparatively simple and less expensive apparatus can be used.

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Manuscript received 25 September 1979, accepted 12 December 1979