A REVIEW OF SPECKLE PHOTOGRAPHY AND INTERFEROMETRY

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INTRODUCTION

Speckling, a familiar phenomenon resulting from the high coherence of laser beams, is very often a nuisance in image formation with coherent light as well as in holography, but has practical applications sometimes superior to those of holography.

Speckling is an interference effect invariably present when highly coherent light is scattered by the different elements of an optically rough surface (roughness $\geq \lambda$, λ = wavelength). Speckle patterns appear everywhere in space, but interest centres on the image and Fourier transform planes. The lateral dimension of individual speckles is determined by the interference of waves from the edges of the limiting aperture and is of course the smallest detail to be resolved [1,2]. For large speckles the correlation becomes too small. Recording speckle patterns in the image, the size of individual speckles is governed by the numerical aperture of the lens (Fig.1 a). By contrast, the speckle size in the Fourier transform plane is limited by the angle of the interfering waves from the edge of the illuminated object field (Fig.1 b). The dimension of an individual speckle in the image plane is $\frac{\lambda 1'}{D}$. The speckle size in the Fourier transform plane is $\frac{\lambda}{b}$ L where λ = wavelength, D = dimension of pupil, 1' = distance from pupil to image plane, b = illuminated object field, L = distance from the object to the Fourier transform plane. Although there are other applications for speckling, two main ones only will be discussed.

ANALYSIS OF STRAIN

Speckle interferometry has become a powerful tool for the remote measurement of surface strain. It was shown by Leendertz [3] that two speckle fields can be derived from the same surface by illuminating it with two beams of light, one on each side of the normal (Fig.2). The lens forming the image of the optically rough surface superimposes two sets of coherent speckle patterns. Each illuminating beam generates, however, its own speckle pattern which combines coherently with the one generated by the complementary scattered beam. If the surface now moves in the ζ direction (normal to the object plane) the two interfering beams will undergo equal path length changes and the combined speckle pattern in the image formed by the lens will remain unchanged. Alterations only occur when the elementary part of the surface becomes displaced by a small distance in the ξ direction. The optical path will be increased by $\Delta\xi \sin\beta$ for the first illumination beam and decreased by the other. If the incident angles of the two beams are $\pm\beta$, the combined speckle pattern of the displaced object will correlate with the pre-displacement pattern when

$$2\Delta\xi \sin\beta = n\lambda$$

$n = 1,2 \ldots N$

λ = wave-length of light used

Different methods of speckle correlation to generate a fringe pattern for strain and displacement analysis exist [3,4].

ELECTRONIC ANALYSIS OF SPECKLE PATTERN INTERFEROGRAMS

The dimension of individual speckles can be chosen by altering the numerical aperture of the image forming system and can thus be matched to the resolving power of the detector. A TV pick-up tube, such as a vidicon, can therefore be used although the quality of the fringe pattern is necessarily poorer than for a photographic recording. The fringes are very often adequate for measuring purposes.

The TV speckle interferometer functions as follows:
The image of the optically rough surface is formed on a vidicon pick-up tube. A reference beam is superimposed. The interferometer is arranged to view the surface under examination. The amplified signal from the camera is recorded on a video-tape or disc. This corresponds to the recording of a photographic negative of the surface in the initial state. The signal from the video-store is then repetitively replayed into an electronic unit, where it is inverted and mixed with the "live" signal from the camera. The addition of these two signals is the equivalent of subtracting the two speckle fields from one another. The output signal from the subtractor is then enhanced and fed to a monitor or recorded on video-tape. The technique described leads to a useful method for analysing different movements in real time [4].

In Fig.3 an experimental arrangement for TV recording of speckle patterns is shown schematically. The speckle size is governed by the aperture of the lens which forms the image of the object. Alternatively, mechanical oscillations can be studied visually by observing the contrast of speckles. For moving parts of the object, the contrast of the speckles is reduced [5,6].

SPECKLE INTERFEROMETRY USING PHOTOGRAPHIC RECORDING FOR QUANTITATIVE ANALYSIS OF IN-PLANE MOVEMENTS

A promising technique applied so far compares identical but shifted speckle patterns [7,8,9,10].

Fig.4 shows an image of a paper surface recorded during an in-plane displacement. The stationary parts of this optically rough surface produce a stationary speckle pattern, but the pattern associated with the moving surface is displaced. The speckle patterns in the image before and after the movement are practically identical, but are displaced and the relative shift can be recorded, e.g. photographically.

Illuminating the recorded speckle patterns by converging monochromatic waves, for instance, leads to the well-known Young's interference fringes in the Fraunhofer plane. The fringes are due to interference of the waves from the two sets of near-identical but displaced speckle patterns. Fringes can also be seen in white light.

A simple analysis of the phenomenon will now be given. The speckle pattern in the image can be described as

$$B'(\xi',\eta') * \delta(\xi'\,\eta')$$

and the displaced speckle pattern as

$$B'(\xi'\,\eta') * \delta(\xi'+\Delta\xi',\eta')$$

where the displacement is $\Delta\xi'$, $*$ = convolution

ξ', η' are the rectangular coordinates in the image space.

The recorded intensity in the image is therefore the sum of the intensities of the two sets of speckle patterns

$$B'(\xi',\eta') * \{\delta(\xi',\eta') + \delta(\xi'+\Delta\xi',\eta')\}$$

These speckle patterns are recorded by double exposure techniques utilizing the integration properties of the photographic emulsion. It is assumed that the amplitude transmission of the recording medium is proportional to the intensity recorded. In the Fraunhofer diffraction plane we record the intensity of the Fourier transform, namely

$$|a(X,Y)|^2 = \left| FT\left[B'(\xi',\eta')\right] \left\{1+\exp\left[\frac{i2\pi X\Delta\xi'}{\lambda f_1}\right]\right\}\right|^2$$

which can be written as

$$|a(X,Y)|^2 = \left| FT\left[B'(\xi',\eta')\right]\right|^2 2\left(1+\cos\frac{2\pi X\Delta\xi'}{\lambda f_1}\right)$$

f_1 is a focal length of the lens displaying the diffraction pattern; if the plate is illuminated by a converging spherical wave, f_1 is the distance of the plate to the Fraunhofer plane (Fig.5). The lateral in-plane displacement $\Delta\xi'$ in the image or $\Delta\xi$ in the object is found to be

$$\Delta\xi' = \frac{\lambda f_1}{p}$$

where $\Delta\xi' = M\Delta\xi$
λ = wave-length of the light
p = fringe spacing
M = magnification of the lens

A typical configuration for measurements of in-plane movements is shown schematically in Fig.5.

For the analysis of mechanical, harmonic oscillation the speckle patterns are recorded in the time average, i.e. exposures during a number of oscillations. To understand the phenomenon the probability of the speckle density can be considered. The probability density of oscillating speckles is expressed graphically in Fig.$6._2$. It reveals that the minimum occurs for the highest velocity, i.e. at the origin of oscillation, and the maxima at the extreme positions. This is the intensity distribution detected. The Fourier transform of the speckle pattern recorded in the time average leads to Bessel functions of zero order and first kind and no longer to cosine fringes. Cosine fringes can, however, be obtained again by stroboscopic illumination of the harmonically oscillating object as shown in Fig.$6._1$ where the object is supposed to be illuminated at the extreme positions of oscillation only. The speckles appear to be shifted between the exposures.

In Fig.7 the corresponding fringes obtained from a harmonically oscillating object are shown for stroboscopic illumination and time-averaged exposure.

TILT ANALYSIS - APPLYING PHOTOGRAPHIC RECORDING OF SPECKLE PATTERNS

Holography has proved very useful for some applications, but the resulting fringes are rather difficult to interpret, especially for superimposed movements. Speckle methods, on the other hand, produce useful, easily-interpreted fringes.

Tilt, i.e. movement out of an object plane, can be studied in the presence of in-plane movements by recording the speckle patterns in the Fourier transform plane instead of in the image plane, as shown schematically in Fig.8. Tilt in the object leads to a lateral shift proportional to the tilt of the identical speckle pattern in the Fourier transform plane - P_1 moves to P_2.

Double exposure techniques or time-averaged recording for an oscillating object can be applied in the Fourier transform plane in the same way as discussed previously for the image plane.

In the Fraunhofer diffraction pattern, fringes of the doubly-exposed, near-identical speckle patterns recorded before and after a tilt are obtained. Tilt measurements γ are derived from the fringe spacing p_1.

$$\gamma = \frac{f_1}{f} \quad \frac{\lambda}{(1 + \cos\beta)\, p_1}$$

λ = wave-length of the light
β = incident angle of the illuminating plane wave
f = focal length of the lens used to perform the Fourier transform of the object
f_1 = focal length of the lens used to display the fringes in the Fraunhofer diffraction plane; f_1 will be considered to be the distance of the photographic plate to the Fraunhofer plane when the plate is illuminated by a converging spherical wave

Small tilts can also be measured in the presence of small in-plane displacements. This will be illustrated in Fig.9, showing Fraunhofer fringes of recorded speckle patterns of two superimposed movements, one in-plane and the other a tilt perpendicular to it. The speckle patterns were recorded in different planes including the image and Fourier transform planes ($Z=0$). The two movements can only be separated accurately by recording speckle patterns for tilt measurements in the Fourier transform plane and for the study of in-plane movements in the image plane. Combined movements are only observed in other recording planes, manifested in the spacing and orientation of the fringes obtained (Fig.9).

SOME LIMITATIONS IN THE TECHNIQUE OF SPECKLE PHOTOGRAPHY

Superimposed movements can be measured very easily by recording the speckle pattern in the appropriate plane. However, large tilts or movements in the line of sight reduce the correlation of the speckles and hence the contrast of the Young's interference fringes obtained in the Fraunhofer diffraction plane. In this technique we rely on the shift of identical speckle patterns. Large tilts, for instance, lead to a phase change of individual speckles, therefore white speckle could turn into dark and vice versa. We are no longer able to record sets of correlated identical but shifted speckle patterns.

Fig.10 shows the influence of the tilt (in the presence of an in-plane movement) on the contrast of fringes obtained in the

Fraunhofer diffraction pattern. For the analysis of in-plane movements in the presence of tilts the contrast of fringes decreases with increasing tilt. The contrast depends further on the amount of in-plane displacement. Movements $\Delta \zeta$ parallel to the line of sight, i.e. change of focus of doubly-exposed speckle patterns recorded in the image plane, should be small between exposures to maintain good speckle correlation, hence

$$|\Delta \zeta| \leq \frac{\lambda}{2 \sin^2 \alpha'} \quad \text{(Rayleigh limit)}$$

where λ = wavelength
α' = aperture angle in image space

Furthermore, the smallest detectable in-plane displacement needs to be at least equal to the size of an individual speckle in the appropriate plane.

SOME APPLICATIONS OF LASER PHOTOGRAPHY

Laser photography has been found to be a very useful and powerful tool for many applications. The interpretation of the fringes obtained is very much easier than for holography.

In Fig.11, for example, the fringes obtained from the doubly-exposed speckle pattern of a lever recorded before and after bending are shown. Fringes were obtained by a point-by-point illumination of the speckle patterns.

Fig.12 depicts Fraunhofer interference fringes obtained from speckle patterns recorded in the image plane as time-averaged exposure . The oscillating object was a tuning fork vibrating at 1050 Hz, which was used in an electronic watch and needed to be adjusted. The amplitude of oscillation was found to be ϱ = 9.5 μm. The region of the tuning fork studied is marked in Fig.12. By contrast, for the same portion of the tuning fork the time-averaged speckle patterns were recorded in the Fourier transform plane. The corresponding fringes of the time-averaged recording in the Fourier transform plane of the tuning fork are shown in Fig.13.

In Fig.14 the amplitude of oscillation, both in-plane and for tilts, is plotted against voltages applied.

Speckle techniques for strain, displacement and vibration analysis were found to be very powerful aids. The requirements on coherence of the light source used are moderate. High-resolution, low-scatter film or plates can be used to record the speckle patterns (Kodak or Agfa Scientia).

REFERENCES

(1) L.I. Goldfischer, J. opt. Soc. Am. 55, 247 (1965).

(2) H.H. Hopkins and H.J. Tiziani, Proc. of the Int. Symposium on Holography, Besançon (1970).

(3) J.A. Leendertz, J. Phys. E (Sci. Instrum.) 3, 214 (1970).

(4) J.N. Butters and J.A. Leendertz, J. scient. Instrum. 4, 277 (1971).

(5) L.Ek., N-E. Molin, Opt. Commun. 2, 419 (1971).

(6) B. Eliasson and F.M. Mottier, J. opt. Soc. Am. 61, 559 (1971).

(7) E. Archbold and A.E. Ennos, Opt. Acta 19, 253 (1972).

(8) H.J. Tiziani, Opt. Acta 18, 891 (1971).

(9) H.J. Tiziani, Appl. Opt. 11, 2911 (1972).

(10) G. Cloud, Appl. Opt. 14, 878 (1975).

(11) J.C. Dainty, "Laser speckle and related Phenomena", chapter 5 + 6, Springer (1975).