I. M. Andrews
J. A. Leendertz

Speckle Pattern Interferometry of Vibration Modes

Abstract: An optical facility is described for the study of the vibrational behavior of engineering test pieces. Time-average holography and electronic speckle pattern methods of analysis are combined into one system. The speckle pattern method is used for the identification of resonances, frequency tuning, and object alignment, thereby optimizing the number of holographic exposures. An evaluation is made of the electronic speckle pattern method for the detection of vibration modes of three-dimensional objects. The method is shown to detect resonant vibration readily on object faces inclined at angles up to 60° to the viewing direction.

Introduction

Current design trends in computers include increased information density and reduced physical dimensions. The criteria for precision of movement and immunity to vibration therefore become increasingly significant and it becomes important to understand not only the frequencies of mechanical resonance but also the mode shapes in which a particular component exhibits resonance. From this knowledge, measures can be taken to minimize resonances at undesired frequencies.

To satisfy this requirement, it has been convenient to use the techniques of holographic interferometry. Holography is a versatile technique that has been successfully applied to many similar problems in vibration analysis [1–6].

The interference pattern in the image reconstructed from a hologram produced by either double or time-average exposure holography indicates the presence and shape of a vibration mode. A problem in conventional holographic analysis is that no result is available until after the development of a photographic plate, and so auxiliary means are needed prior to the holographic exposure to adjust a test object to a resonant condition. This is not always convenient, especially where the resonances are complex due to intercomponent coupling or when several different modes occur very close together in frequency. Another problem is that the shape of a resonance mode may well vary appreciably in symmetry as the excitation frequency is shifted slightly to either side of the peak resonant frequency. A new technique known as electronic speckle pattern interferometry [7] may be applied in such a way that the information density in the recording plane is within the resolution capability of a closed circuit television system [8]. The results from this method are equivalent to obtaining the results of time-average holography in real time. The loss in image quality, when compared to photographic results, is balanced by the ease and utility of the method. Resonant conditions may be identified and selected by use of the speckle television receiver method, and a high quality photographic hologram may be made subsequently to record just those conditions required for detailed analysis or for records.

The purpose of this communication is to describe an optical analysis facility in which both speckle pattern and photographic holography methods are combined into a single general-purpose system for vibration mode analysis. This approach represents, therefore, an advance over previous holographic system design.

To permit ready comparison of the two methods, we include some results of vibration mode studies obtained using the two techniques and an appraisal of the speckle pattern technique in the light of our experience with it to date.

General features of the optical system

The entire optical system, including the laser, is contained on a 2 × 1-meter steel surface plate which is isolated from ground-borne vibration by air mounts.

Since both optical techniques rely on a continuous-output laser, an argon-ion unit producing two watts total power was chosen and the component configuration built around it. For holographic recording, the component layout is traditional, spherical waves being used for both illumination and reference beams [9–11]. The interference pattern observed on the reconstructed image from a time-average hologram is, based on the deductions of Powell and Stetson [12], between images of the object in the peak positions of its probability density function.

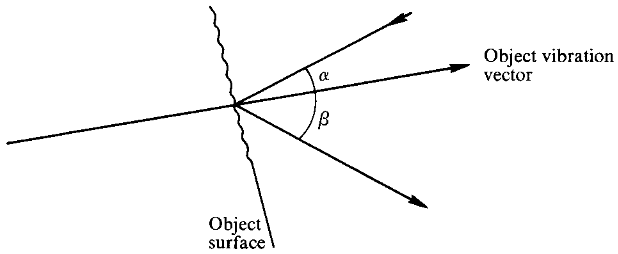


Figure 1 The relationships among object surface, object vibration vector, angle of incidence, and angle of reflection in speckle pattern interferometry.

The simultaneous reconstruction of these two correlated images produces a "moire-like" interference between them indicative of the extent and spatial variation of vibrational motion [13–15].

Speckle pattern interferometry

As in holographic imaging, when a microscopically rough object is illuminated with coherent light from a laser it has a speckled appearance. If the illuminated object is viewed through an aperture, the size of the individual speckles increases as the aperture is reduced. This type of speckle has been called "subjective," as its precise characteristics are determined primarily by the viewing system [16]. One of the attributes of this type of speckle is that it is associated with the position and texture of the scattering surface and may therefore be considered as being a function of the surface [17, 18].

The significant feature of speckle is that information is carried at the speckle spatial frequency which, since it depends on the choice of the imaging aperture, is controllable and may be made compatible with the resolving power of standard television systems [8, 19]. The television camera thus converts the coded speckle information from a three-dimensional object field into two dimensions. In this format, it is available as an electrical waveform which may be treated in any manner desired, e.g., it may be filtered, stored, or strobed.

In practice it is necessary to employ a reference wave to sample the light scattered by the test object. Light from the object is collected by a lens, in our case a Dallmeyer oscilloscope 3″ anastigmat, and an image is formed in a plane convenient for the location of the television camera photocathode. Between this lens and the camera tube, a beam splitter is mounted so as to introduce a reference beam expanded from a spatial filter. Interference is obtained in the plane of the beam splitter and the phase front of the object beam is visible as an amplitude variation in the image plane. Without the reference wave, the phase information in the object wave would have been lost.

At small apertures of the "object" lens, the display on the television monitor of a static object exhibits a speckled appearance but at low contrast. To optimize speckle visibility the iris of the Dallmeyer lens was modified to obtain apertures down to about *f* 44. When the object is vibrating, the time integral of speckle motion is seen as an interference pattern on the monitor screen. As will be shown, the profile of the pattern resembles that of time-average holography. To increase the low contrast of the screen image, in which only the bright zero-order fringe can be observed, an electronic signal enhancement unit was introduced between the camera and monitor.

- *Theory of speckle pattern interferometry*

Consider a diffusely reflecting object surface in the x-y plane to be receiving dispersed illumination from a laser such that the light scattered in the observing direction may be denoted by $A(x,y)$. Derived from the same laser source, a reference wave is filtered and expanded so as to produce a brightness amplitude $B(x, y)$ at a position where it is made to interfere with the object scatter. The intensity resulting from the interference of these two beams, at any point in the light field is given by

$$1(x, y) = A^2 + B^2 + 2AB \cos\theta\ (x, y), \tag{1}$$

with

$$\theta = \theta_0 + (2\pi/\lambda)\ (\cos\alpha + \cos\beta)\ a \sin \omega t, \tag{2}$$

where α and β are respectively the angles of incidence and reflection of light at the object surface. This surface is shown in relation to the objective vibration vector in Fig. 1. The variable a is the semi-amplitude of object vibration displacement, ω is its angular frequency, θ can θ_0 are the instantaneous and static phase angles between the light vectors.

The resulting interference fringe pattern is obtained by integrating Eq. (1) over one vibration cycle, the value of θ having been expanded to the form given by Eq. 2, i.e.,

$$I(x, y) = A^2 + B^2 + 2AB \cos \theta_0, J_0\left(\frac{2\pi a G}{\lambda}\right). \tag{3}$$

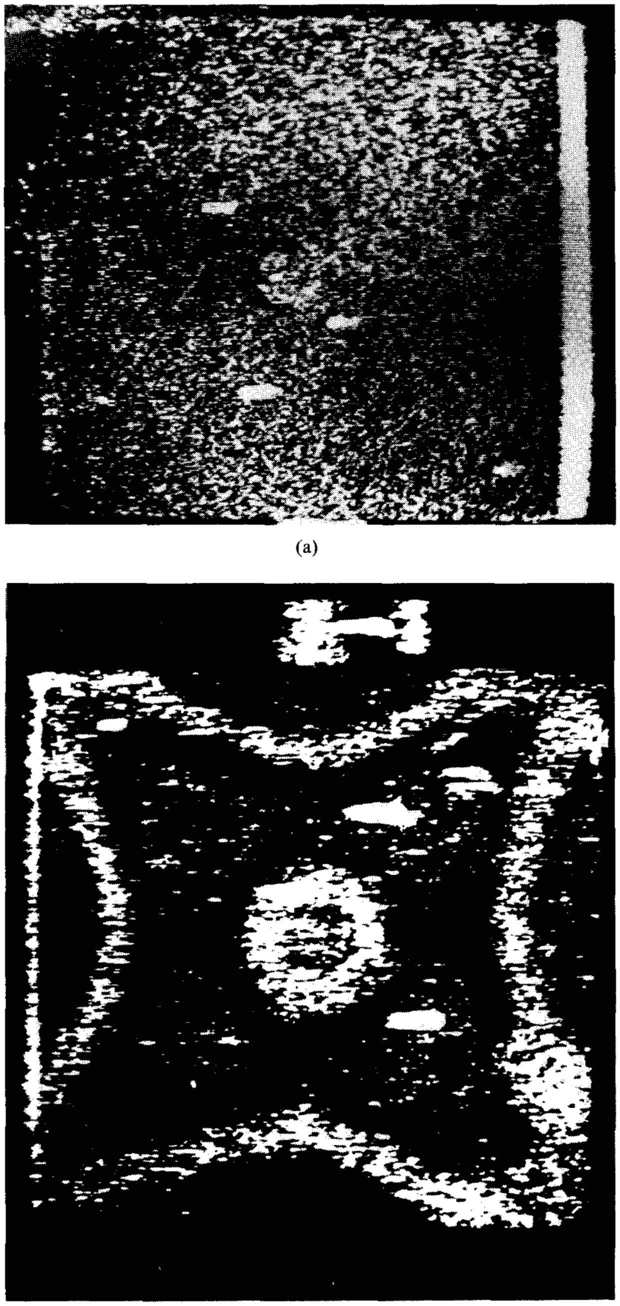
By arranging that the reference beam intensity exceeds that of the object beam, ($B^2 > A^2$ and $2AB > A^2$) the interference term becomes dominant.

The interference term is thus left as an intensity modulation on an overall screen illumination. Appreciable enhancement of the interference term is achieved by electronically filtering out the dc and high-frequency speckle twinkling and then differentiating and rectifying the interference term. As a result, each individual speckle is brightened up at its edges and displayed against a dark background. With this greatly enhanced contrast, the visibility of the speckle pattern is improved such that the time integral of the vibration interference pattern becomes readily apparent. This effect is illustrated in Fig. 2.

Appraisal of the technique for vibration mode analysis

The speckle pattern technique operating under precisely the same conditions as are used subsequently for time-average holography, is a valuable means for identifying conditions of object resonance. It introduces no more object response degradation than does the holographic process because it requires identical conditions of optical reflectance. As such, it is the ideal partner to photographic time-average holography. By means of the speckle technique alone, object stability may be verified and resonant frequencies determined. In most cases, especially if the excitation level of the object is kept low so that only one or two fringe orders are present, the shape of a resonant mode can be ascertained directly and immediately from the cathode-ray screen. These benefits alone are valuable. Under favorable conditions, a record of the mode pattern can be obtained by merely photographing the monitor screen, but for complex object shapes, mode visibility is usually much better on the screen than on the photograph. This is true generally because of the dynamic awareness associated with the use of the television screen. For example, if the object excitation frequency is repetitively scanned across a resonance, the variation in fringe pattern is much more readily apparent to the eye than is the static pattern, even at the peak of resonance. For this reason it is more practical to use videotape for record purposes than photography. Also, the mixing beam splitter is at an extremely critical position in the viewing system, with the result that any defect or dust on its surface is manifest, much magnified by diffraction, in the image. Further degradation to the image quality can occur because of the dimensions of the beam splitter and the presence of a rear subsidiary surface duplicate image is inevitable. This is most pronounced when the object has an intricate geometrical shape. If the images can be separated by the use of a thick beamsplitter (Fig. 3) then a measure of alleviation can be achieved by the use of an auxiliary aperture between the beam splitter and television camera. The thicker the beam splitter, the better the image separation, and a wedge plate attached to its rear surface can further eliminate the redundant image.

Despite these effects, speckle pattern interferometry does provide a simple means for obtaining time-average interference patterns indicative of object vibration. Previous work using this technique had been restricted to the study of flat objects [8, 20, 21], so it was of considerable interest to investigate the visibility of speckle pattern interference on three-dimensional objects. The simple expedient of rotating a vibrating plate showed convincingly that, notwithstanding the incurred sensitivity variation, the speckle pattern technique would show up normal vibration behavior on surfaces inclined at angles well in excess of 60 degrees to the viewing direction. In general, this is beyond the range normally required. For most purposes, viewing angles will not be expected to



(a)

(b)

Figure 2 Speckle patterns for a flat plate as viewed on closed circuit television display screen. (a) Image enhanced electronically, using small viewing aperture, with no vibration. (b) Vibration interference pattern. Viewing conditions same as (a).

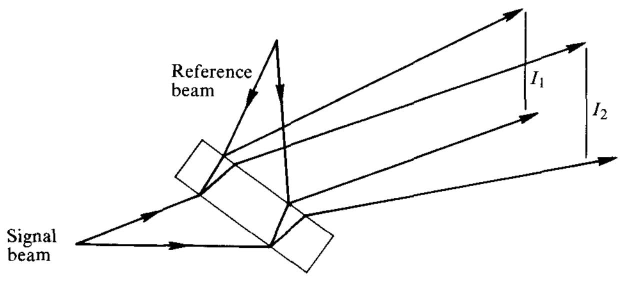
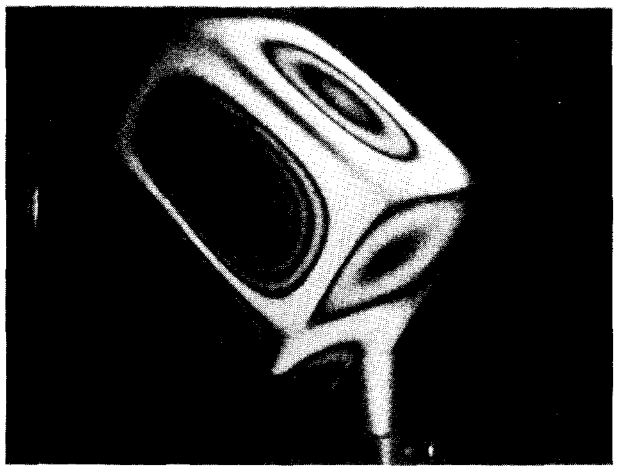


Figure 3 Beam splitter configuration used in the speckle pattern technique.

Figure 4 Vibration patterns, at 45° to the viewing direction, for a small rectangular metal box. (a) Speckle pattern interferometry. (b) Time-average holography.

(a)



(b)

exceed 45 degrees. To illustrate the visibility of vibration patterns at 45 degrees, a resonant condition of a small rectangular metal box was recorded using both speckle pattern interferometry and time-average holography (Fig. 4), each face being oriented at 45 degrees to the viewing axis. The excitation is clearly visible in both cases.

Conclusion

A composite optical facility has been devised and constructed, in which conventional photographic time-average holography was combined with the real-time method of speckle pattern interferometry. It has been shown that, whereas the speckle method is not capable of yielding pictorial results of the same high quality as that of the photographic emulsion, it is nevertheless of value in identifying resonant conditions and for preliminary analysis.

The vibration analysis facility has been employed in many investigations since it became operational, thereby permitting measurements during equipment design phases which would otherwise not have been possible. In these studies, the speckle pattern method has proved most useful and since the additional cost involved to add the speckle pattern function to an existing time-average holography facility is scarcely more than that of a closed-circuit television system, it is to be recommended whenever vibration or strain measurement are being undertaken.

In addition, the speckle method offers the possibilities for stroboscopic analysis, contour fringing, strain measurement, and similarity studies.

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Mr. Andrews is located at the IBM United Kingdom Laboratory, Hursley, Winchester, England; Mr. Leendertz, formerly an IBM consultant, is located at the University of Bristol, England.