HOLOGRAPHIC INTERFEROMETRY AND SPECKLE METROLOGY:

A REVIEW OF THE PRESENT STATE

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Abstract

The review paper will describe the present state of holographic and speckle techniques as applied to industrial measurement. The basic principles of both techniques will be outlined with special attention given to their advantages and limitations. Current developments in the field will then be described including the testing of rotating automobile tyres by holographic interferometry and a heterodyne technique to gain an insight into noise generation mechanism. Methods for real-time holographic and speckle recording to facilitate the use of the techniques in an industrial situation will be discussed.

Introduction and historical background

Holographic interferometry and speckle techniques are widely used; the major applications are not in optics but in measuring mechanical displacement, vibration, stress and deformation. The discovery of holographic interferometry in 1964 by R.L.Powell and K.A.Stetson[1] was a mile stone in the development of the application of the laser in metrology. Five years later J.Leendertz[2], at the ICO meeting in Reading, presented a paper on interferometry with diffusely reflecting objects by means of laser speckles. In 1968 Burch and Tokarski[3] published a paper in Optica Acta on multiple exposures of speckle patterns with equal displacements between, which led to the development of speckle photography techniques.

In the field of holographic interferometry, double exposure, multiple and time average exposure techniques were introduced, as well as beam modulation and stroboscopic exposures [4,5]. In addition, fringe localizations together with fringe pattern analyses in three dimensional space have been investigated. By 1970, published material was available predicting the object motion accurately from the fringe pattern. Methods were established to extract vectorial object displacement from the fringes, their parallax and their localization. The difficulty with these fringe analyses, however, was the amount of calculation required in their applications. The search for simpler techniques of describing fringes in holographic interferometry initiated various studies on fringe analysis. The theories developed so far simplify the analysis and make it easier for the engineer to understand and apply it. Very often, however, they are too difficult to be of practical value for many engineering problems, although they can be very useful for special applications.

In recent years, matrix methods and tensor calculus have been introduced for fringe analysis, leading to a number of strain analysis techniques. Phase detection has been significantly improved to one part in 1000 by heterodyne interferometry[6]. Now at last, holographic interferometry is beginning to show its true potential in structural metrology.

The field of speckle interferometry and photography has passed through an interesting development phase. The first of the techniques were described as speckle interferometry and are analogous to classical interferometry in that they use interference between two or more randomly speckled fields[2]. Detection of this random interference is based upon the cyclic repetition of the combined speckle pattern with every 2π phase change between the fields, leading to interferometric sensitivity. By contrast, speckle photography has extended the range of displacement measurements. It is based on the displacement of speckles in the image plane. Speckle photography fills the gap between holographic interferometry and Moiré techniques.

Speckle techniques are supplementary to holographic interferometry. Fringe localization is easier, some of the movements can be separated by taking the image-plane, Fourier-plane[10] or defocused[11] speckle pattern. Speckle correlation, however, is lost by greater surface tilt. By contrast, the analysis of general three dimensional speckle displacements is not unimportant. Some of the mathematical procedures of holographic strain analysis are applied in speckle metrology. Both speckle metrology and holographic interferometry depend on electronic data acquisition and processing for application to genuine problems that occur in practice.

For strain analysis a "grid" technique is used,applying high-frequency reflective crossed grids to the surface to be studied. The grids are illuminated and produce fringes corresponding to displacements relative to the original grid[16].
Photographic emulsions are generally used for holographic interferometry and speckle photography. For real-time recording, thermoplastic material or photorefractive crystals can also be used.

Holographic and speckle systems will be used more frequently in the future, when they can be integrated with data read-out and processing systems.

Holographic interferometry of rotating objects

Holographic interferometry has now progressed to a point where the main problem is that of improving the means of extracting the required information from the fringe pattern. However, the analysis of deformation, stress and vibration of rotating objects requires unwanted rigid body rotation to be eliminated while preserving the information about the elastic object deformation.

Three methods have been used to carry out holographic interferometry and speckle techniques on rotating objects. These are stroboscopic, rotating plate, and image derotated holographic interferometry.

The stroboscopic method consist in making a hologram of the object while stationary. For the second exposure with strobed light, the rotating object is illuminated, the illumination being at the same angular orientation to the object as for the first exposure.

Rotating-plate holographic interferometry uses the holographic plate fixed to the rotating axis of the object, but this is not always possible. In addition, the rotating hologram itself will be subject to vibration or rigid body motion, hence complicating fringe analysis.

Image derotation is the most promising approach for the study of rotating objects with holographic or speckle techniques. In this method, the image of the rotating object is passed through, or reflected by, a prism rotating at half the rotational speed of the object, thus cancelling out the rotational motion. A Q-switch double-pulsed ruby laser is then used to produce a double-exposure hologram of the rotating object[8,9].

An experimental set-up used for image-derotated holographic interferometry is shown in fig. 1. Light from the double-pulse ruby laser is divided by a beam splitter and illuminates the object via a second beam splitter. The reflection of the object passes through the derotator prism to interfere with the reference beam on the holographic plate and form an image-plane hologram. For the alignment it is important that the axis of the derotator is collinear with the rotation axis of the object, otherwise optical-path length differences will produce bias fringes between the two laser pulses. The exact 2:1 ratio between the object and prism speed is achieved by mounting an encoder disk on the drive shaft of the object and relaying its signals to an electronic unit controlling the speed of the servo motor.

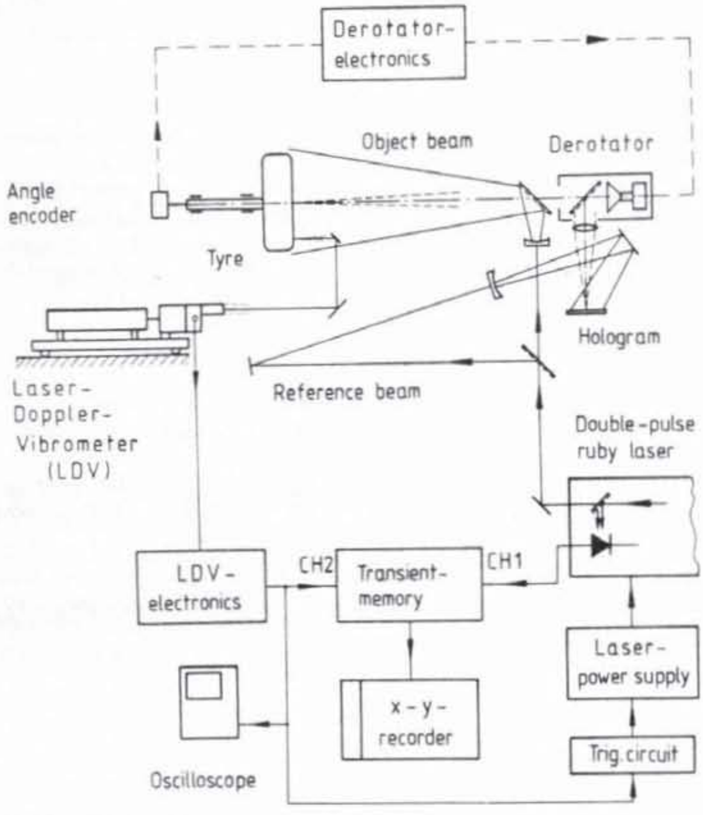


Fig. 1 Arrangement for double pulse holography with derotator for noise analysis of a rotating car tyre.

In addition, a laser Doppler vibrometer is used for the vibration analysis at a given point.

In our research we have studied the noise of rotating car tyres[10]. Fig. 1 shows the experimental arrangement with derotator and double pulse ruby laser. Fig. 2 shows the fringe pattern obtained by

a) pulse separations of 100 µs at $n = 320\ \text{min}^{-1}$ and a pulse width of 40 ns
and
b) by pulse separations of 50 µs.

The road contact was simulated by a toothed wheel. Fig. 3 shows a typical picture of the fringe analysis of the side wall (fig. 2b) of a rotating car tyre.

For noise analysis, a frequency analysis of vibration is required. A heterodyne technique can be used for the analysis of the amplitude and for the frequency of vibration at one or several points. In addition this facilitates fringe analysis of holographic interferometry . The two methods are therefore frequently used in parallel in our laboratory (fig. 1), the heterodyne technique for the analysis of the vibrations at a given point and the holographic or speckle techniques

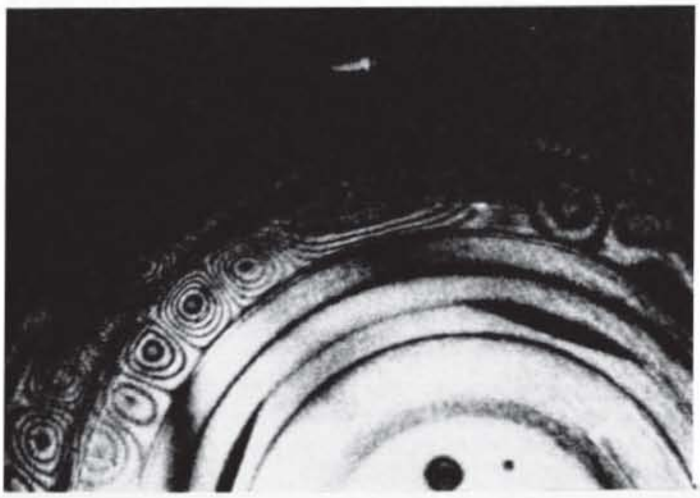


Fig. 2a Fringe pattern obtained by double pulse holography of a rotating car tyre using an image derotator. The rotation is counter clock-wise at a speed of $n = 320\ \text{min}^{-1}$.
Pulse separation 100 µs;
pulse width 40 ns

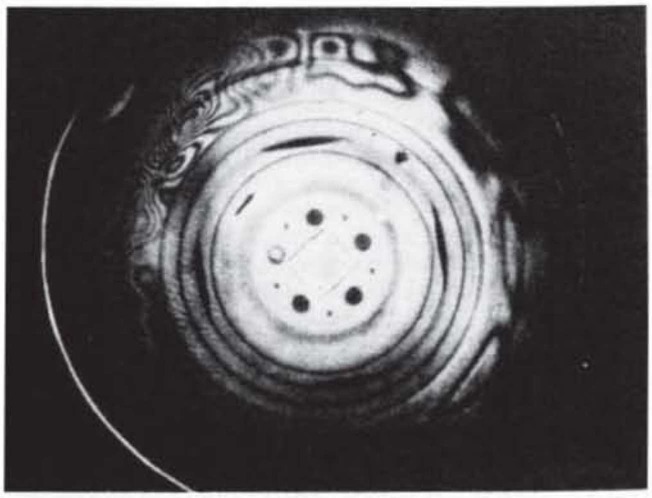


Fig. 2b Fringe pattern similar to fig. 2a, but with pulse separation of 50 µs at $n = 320\ \text{min}^{-1}$ in order to resolve the fringes near the contact zone.
The rotation is clockwise.

for the analysis of the spatial distribution of the vibration with reference to the movements of a single point, measured by using the Doppler frequency shift technique.

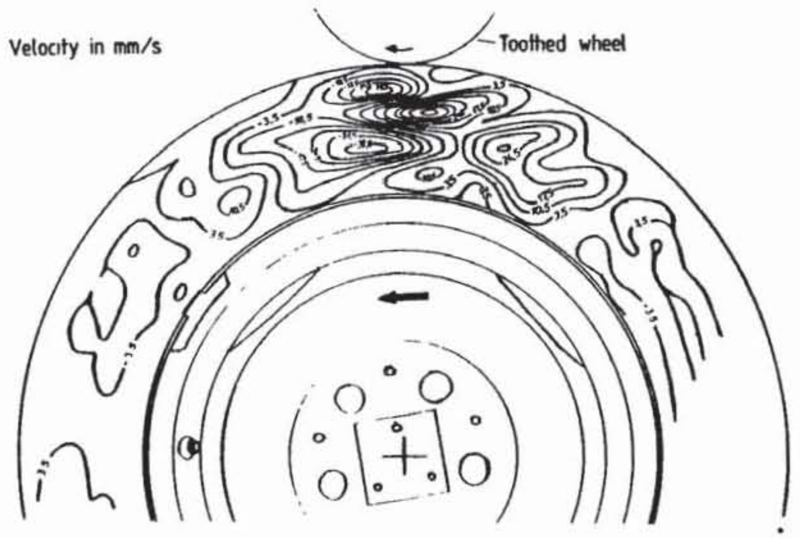


Fig. 3 Fringe pattern analysis of fig. 2b of a typical rotating car tyre; contour separations Δv = 7 mm/s.

Heterodyne techniques applied to vibration analysis

The laser Doppler velocimeter is used to measure flow velocities of gases and liquids, using the light scattered from small particles suspended in the flowing medium. The speed of optically rough surfaces can be determined by similar methods.

The heterodyne interference or speckle techniques measure in-plane and out-of-plane displacements and vibrations of objects with diffusely scattering surfaces at high local and temporal resolution. We have been concerned primarily with out-of-plane vibration analysis.

A) Classical interferometry

In classical interferometry, phase differences of optical fields are transformed into detectable intensity variations. For two-beam interference, the two light fields are assumed to be

$$A_1 = a_1 \cos(\omega_1 t + \phi_1) \qquad A_2 = a_2 \cos(\omega_2 t + \phi_2)$$

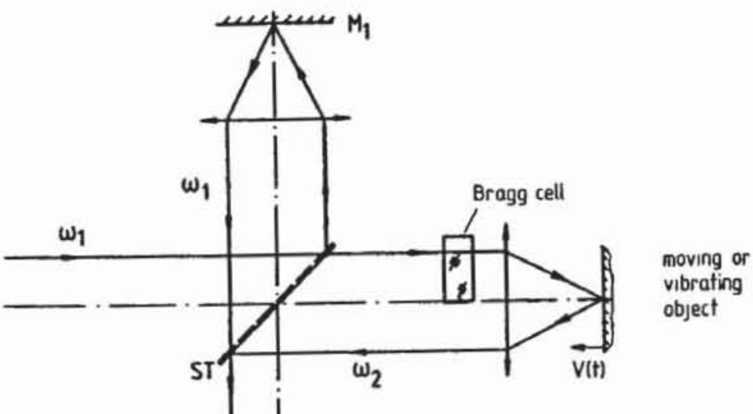


Fig. 4 Principle of a heterodyne interference technique.

In classical interferometry the two optical frequencies ω_1 and ω_2 are identical ($\omega_1 = \omega_2$). Therefore, the intensity after the superposition is:

$$I_1 = |A_1 + A_2|^2 = |a_1|^2 + |a_2|^2 + 2a_1a_2 \cos(\phi_2 - \phi_1)$$

The analysis of the phase difference $\phi_1 - \phi_2$ is not very accurate.

B) Heterodyne interferometry

In heterodyne interferometry, the two optical frequencies arechosen to differ by a small amount $\Delta\omega = \omega_2 - \omega_1$, say 40 MHz, for ease of electronic analysis. Superposition then yields a time dependent intensity. If the object point is moving at a speed of $v(t)$, the interference phase change is proportional to the displacement, namely $4\pi/\lambda\ v(t)\cdot t$. Hence, for $\omega_1 \neq \omega_2$ we find the intensity of the two interfering beams (fig. 4) to be

$$I = |a_1|^2 + |a_2|^2 + 2a_1a_2 \cos(\Delta\omega t \pm 4\pi/\lambda\ v(t)t + \phi_2 - \phi_1)$$

and the frequency shift

$$\delta f(t) = 2/\lambda\ v(t)$$

which is proportional to the velocity v (parallel to optical axis) and can be regarded as a Doppler shift. For a vibrating object such as a car tyre the instantaneous velocity is measured.

For a harmonically oscillating object the phase change parallel to the optical axis is given by $4\pi/\lambda\ \rho \cos \Omega t$, which produces a frequency modulated output signal at the detector, with a carrier frequency of $\Delta\omega$ and frequency modulation of Ω; ρ is the amplitude of oscillation. The signal can be evaluated by the well-known frequency analysis techniques.

Fig. 5a shows the velocity for a single point of the side wall of the rotating tyre, obtained by using the derotator. Fig. 5b shows the corresponding frequency spectrum of fig. 5a. Such an arrangement is used for vibration analysis. Fig. 6 shows a comparison of results obtained with the Doppler-vibrometer (LDV) and independent measurements obtained by a microphone. Very close agreement is obtained between the noise detected with the microphone and the optical vibration analysis. No derotator was used for fig. 6 to avoid the Doppler effect due to the relative movement between the measured point and the source of vibration.

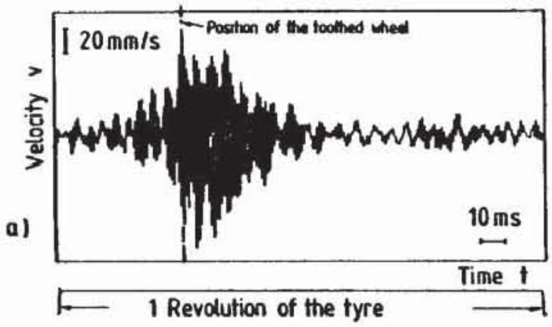


Fig. 5a Velocity of a single point of the side wall for one tyre revolution measured with the laser-Doppler--vibrometer through the image derotator

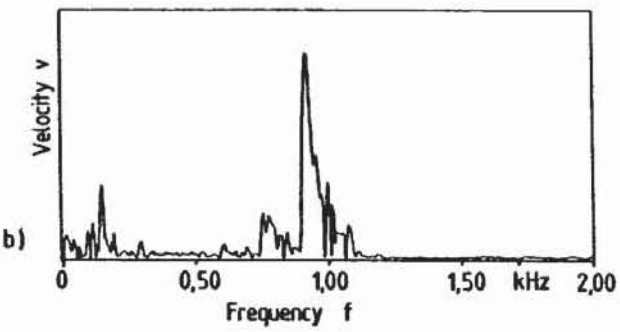


Fig. 5b Frequency spectrum of Fig. 5a

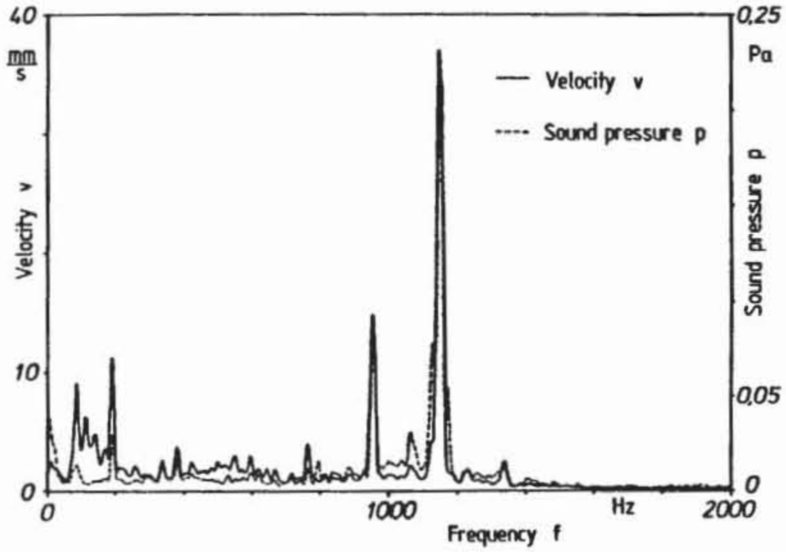


Fig. 6 Comparison of the analysis of a rotating car tyre and a microphone placed appropriately. It shows that the airborne sound is due to the structureborne sound.

Applications of speckle-techniques

A) Speckle photography

Speckle techniques are a useful tool for determining displacements, vibrations, deformations and contours of a wide range of optically rough surfaces. For speckle photography, an optically rough surface is illuminated with coherent light and photographed either in the image plane, in Fourier plane[11] or a defocused plane[12], depending on the application. The recorded image will have a speckled appearance. Exposing the image on photographic film before and after a small object movement (double exposure), pairs of practically identical speckles are recorded. Illuminating the developed double-exposed speckle pattern with a

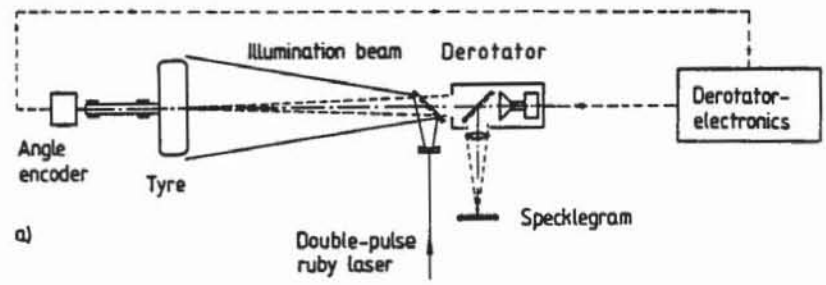
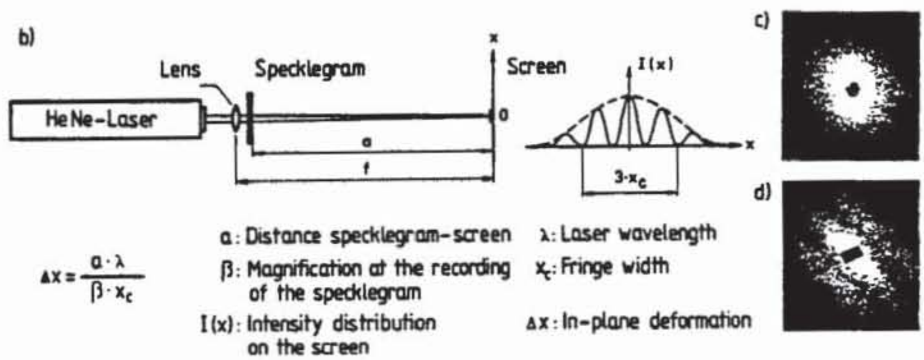


Fig. 7a Arrangement for image-plane speckle photography with double-pulse ruby laser through the derotator.



$$\Delta x = \frac{a \cdot \lambda}{\beta \cdot x_c}$$

Fig. 7b Indicates schematically the display of the Young's fringes. The diffraction pattern in the Fraunhofer plane is shown without fringes in fig. 7c and with fringes in fig. 7d.

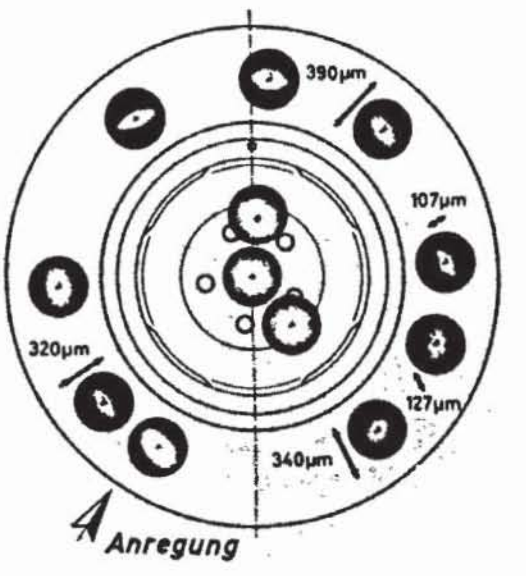


Fig. 8 Young's fringes obtained from the speckle pattern of the rotating car tyre, recording through the image derotator, $n = 850 \text{ min}^{-1}$

laser beam, Young's fringes are obtained in the Fraunhofer diffraction plane, with a separation inversely proportional to the object displacement. Young's interference fringes occur only if the displaced speckles remain correlated. A point-by-point analysis of the in-plane motion of the displacement vector field can be carried out even in the presence of small out-of-plane movements (fig. 7). In fig. 8 Young's fringes of speckle patterns recorded through the derotator are shown for a simulated disturbance of the car tyre. For tilt analysis speckle recording in the Fourier plane or out-of-plane speckle recording is suitable[5,11,12]. For applications where out-of-plane deformation of a surface is to be measured, two methods can be used, i.e. double-exposure holography or double exposure speckle photography with the camera deliberately defocused. In the latter case the local surface tilt is measured and the profile change can subsequently be obtained by integration. Errors can occur in speckle photography due to focusing the camera incorrectly. The sensitivity of out-of-plane measurements with defocused speckles can approach that of holographic interferometry, but without requiring interferometric stability of the recording apparatus. In addition it covers a wider measurement range than the holographic technique[13], but additional data processing is needed. The accuracy of the measurements is dependent upon instrumental setting and lens performance. Additional complications occur for data processing if the surface under examination is not flat. Finally, the speckle shearing interferometry of Hung (chapter 4 in[5]) permits the direct measurement of the surface deformations.

Speckle photography is by now well understood and can be a useful tool in optical metrology. The limitations are those due to strong deformations (strain), rotation and tilt. For example, deformation and tilt in the presence of translations lead to a limitation of speckle photography due to loss of speckle correlation.

B) Analysis of double exposure speckle photographs

By measurements of the spacing and the direction of the Young's fringe patterns (fig. 7b) for points on a square-mesh lattice, the two-dimensional strain field can be evaluated. Visual methods for the fringe analysis are time consuming and limited to small sample regions and are heavily dependent on the skill of the operator. For these reasons electro-optical read-out systems for automatic fringe analysis have been studied recently. Kaufmann[15] et al. used the one-dimensional Fourier transformation of a small area of the speckle photograph and formed Young's fringes on a self-scanning linear photodiode array. The output of the array is transfered to a computer where the displacement and strain fields are calculated. For good contrast fringes speckle displacements were obtained to 0,1 µm standard deviation.

Bruhn and Felske[16] developed a fast two dimensional Fourier transform analysis of Young's fringes using TV techniques together with image analysis methods in order to construct an automatic fringe analysis system.

C) Electronic speckle pattern interferometric system

For recording interference pattern of diffuse reflecting objects, different names are found in the literature, namely electronic speckle pattern interferometry (ESPI), TV speckle interferometry, TV holography. ESPI is a holographic method usually employing a specular reference beam as in conventional holography superimposed on the speckled object beam onto a TV camera (see Butters & al. in reference 5, ch. 6). For a moving object, the intensity on the photosurface varies cyclically, corresponding to a path-length change between reference and object beam by λ(λ beeing the wavelength of the laser). The video signal is processed, high pass filtered, rectified and displayed on the TV monitor. This electronic processing can be considered to correspond to the reconstruction in conventional holography.

On the monitor, fringe pattern occur depending on the subtraction of double-exposed speckle patterns or time-average fringes are produced of a harmonically oscillating object. Movements parallel to the line of sight are measured. The lateral shifts must be kept smaller than the mean speckle size. For in-plane strain measurements the object can be illuminated obliquely with two plane waves (reference 5, ch. 6). Fig. 9 shows a typical time-averaged fringe pattern of an oscillating membrane photographed from the TV monitor.

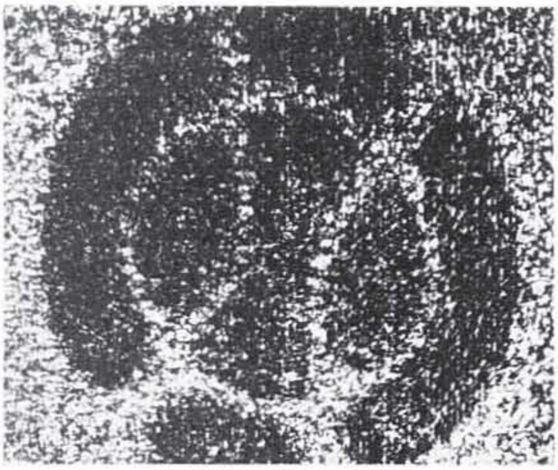


Fig. 9 Vibration analysis of the oscillating membrane, using an ESPI. Oscillation frequency 5,1 kHz.

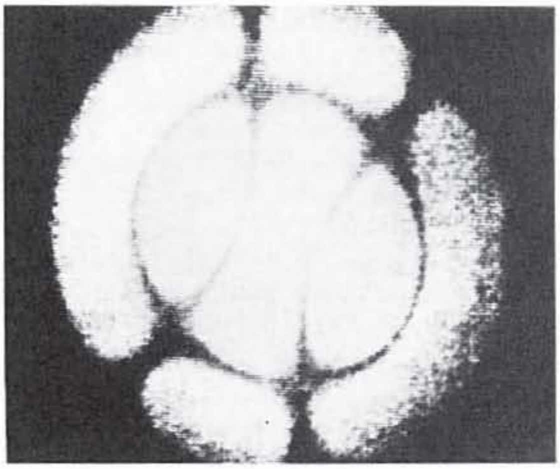


Fig. 10 Vibration analasis of the oscillating membrane analysed in fig. 9 but using a BSO crystal for recording. The fringes were photographed from the monitor.

Real-time holography and speckle recording

The storage media used for holographic interferometry and speckle photography are mainly photographic materials based on silver halide. Alternatves are photoresist, dichromated gelatin,photochromic- or thermoplastic materials, or photorefractive electro-optical crystals. Thermoplastic material is frequently used in holographic interferometry.

The most promising electro-optical materials are bismuth silicon oxide $Bi_{12}SiO_{20}$ (BSO) and bismuth germanium oxide $Bi_{12}GeO_{20}$ (BGO). In our laboratory we mainly used BSO for real-time holography and holographic interferometry and also for speckle techniques[17,18]. For BSO, the writing energy for a diffraction efficiency of 1 per cent is 0,3 mJ/cm² as compared with 30 mJ/cm² for $LiNbO_3$ (lithium niobate). The sensitivity is therefore comparable to that of the fine-grain Kodak 649 F spectroscopic emulsion, but less than for thermoplastic materials.

The physical mechanism for holography and speckle pattern recording and erasure in electro-optical crystals are drift and trapping of photoelectrons under illumination. The photo-induced space charge field changes the refractive index of the crystal via the linear electro-optic effect, leading to a refractive index variation in the crystal volume. Flooding with uniform illumination leads to erasure of the stored information by space charge relaxation. Consequently, reading out with the recording wavelength is destructive. For the analysis of the fringe pattern from holographic interferometry or speckle applications, TV techniques are useful. Fig. 10 shows the reconstructed time averaged fringe pattern of the oscillating membrane used for fig. 9 recorded with the BSO crystal and photographed from the TV monitor. The contrast and spatial resolution obtained with the BSO storage device are superior to that of the ESPI although the experimental arrangement was found to be simpler. Real-time recording and fringe displacement, together with a real-time fringe analysis technique for holography and holographic interferometry and speckle techniques can become a useful tool for the engineer.

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