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Digital Double-Pulse Holographic Interferometry for Vibration Analysis

Different arrangements for double-pulsed holographic and speckle interferometry for vibration analysis will be described. Experimental results obtained with films (classical holographic interferometry) and CCD cameras (digital holographic interferometry) as storage materials are presented. In digital holography, two separate holograms of an object under test are recorded within a few microseconds using a CCD camera and are stored in a frame grabber. The phases of the two reconstructed wave fields are calculated from the complex amplitudes. The deformation is obtained from the phase difference. In the case of electronic speckle pattern interferometry (or image plane hologram), the phase can be calculated by using the sinusoid-fitting method. In the case of digital holographic interferometry, the phase is obtained by digital reconstruction of the complex amplitudes of the wave fronts. Using three directions of illumination and one direction of observation, all the information necessary for the reconstruction of the 3-dimensional deformation vector can be recorded at the same time. Applications of the method for measuring rotating objects are discussed where a derotator needs to be used.

INTRODUCTION

Double-pulse holography is an important technique for vibration analysis of mechanically oscillating objects. Time average holographic and speckle techniques are appropriate for the analysis of harmonic vibrations, otherwise double-pulse techniques are needed. For the measurement of vibrations using double-pulse techniques, pulse separations in the range between 1 and 1000 μs are necessary. For the holographic recording a photographic plate or a thermoplastic camera is used. The hologram is usually reconstructed with a continuous laser and can be viewed with a CCD camera. The quantitative analysis can be carried out by using two reference beams. The process is time consuming, in particular if the development of a photographic film is needed.

The resolution of CCD cameras as well as computer capacity are increasing constantly. Schnars (1994) showed that it is now possible to record a hologram on a CCD camera and reconstruct it digitally. Pedrini et al. (1995) demonstrated the application of digital holographic interferometry to vibration measurements by using a double-pulse ruby laser. Two separate holograms of an object under test, which represent the undeformed and the deformed state, are recorded within a few microseconds using a CCD camera and are stored in a frame grabber. Different types

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of holograms can be recorded: Fresnel holograms, quasi-Fourier holograms, and image plane holograms. The Fresnel and the quasi-Fourier holograms need the reconstruction of the wave fronts by simulation of the Fresnel diffraction. The phases of the two reconstructed wave fronts are calculated from the complex amplitudes. The deformation is obtaned from the phase difference. In the case of the image plane hologram (this arrangement is known as the electronic speckle pattern interferometry or ESPI), the phase can be calculated without reconstruction of the wave front by using the sinusoid-fitting method (Macy, 1983; Pedrini et al., 1993).

In some cases a 2- or 3-dimensional (3-D) analysis of the deformation is necessary. Additional sensitivity vectors can be generated by illuminating the object from different directions (three directions of illumination and one direction of observation). The sensitivity vectors are given by the half-angle between the illumination and observation directions (Pedrini and Tiziani, 1994).

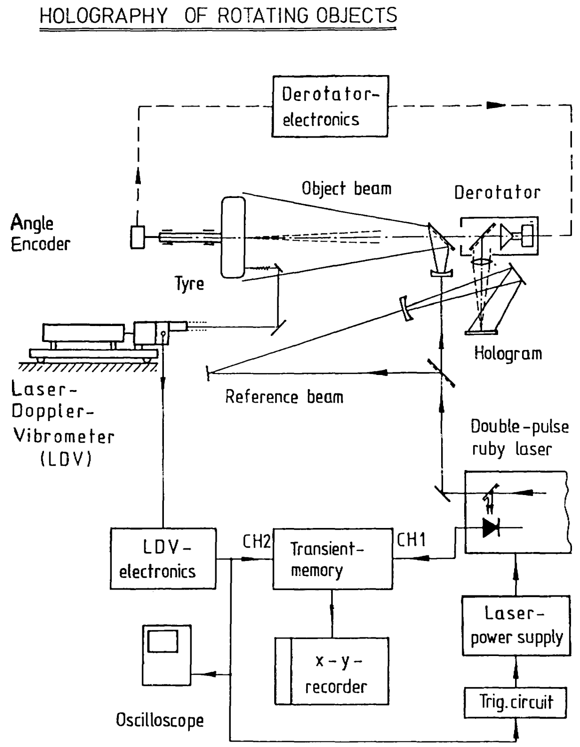


FIGURE 1 Setup for the noise analysis of rotating car tires.

DOUBLE-PULSE HOLOGRAPHIC INTERFEROMETRY FOR VIBRATION ANALYSIS OF ROTATING OBJECTS

For the vibration analysis of rotating objects, a derotator is needed to compensate for the rotation. Different techniques are useful for image derotation. Most appropriate are an image derotating prism or mirror systems, where the optical elements rotate at half the speed of the object rotation (Tiziani et al., 1981).

For the noise analysis of rotating car tires, double-pulse holography was used to measure the amplitudes of the mechanical vibration. The measuring setup is shown schematically in Fig. 1. A ruby laser was used (pulse width 20 ns) for the object illumination with double-pulse technique. To compensate the rotation (freeze the object) a derotator was used together with a grating encoder on the object for the syncronization. In particular the results of the front side of a car tire vibration occurring from tire contact with a road surface at a speed of 60 km/h was studied, for instance. The pulse separation was 40 μs. The fringes representing vibration amplitudes (lines of equal deformation) are superposed in the hologram reconstruction on the car tire as a fringe pattern. To obtain an absolute value of the vibration amplitude and frequency at a point, a heterodyne interferometer (vibrometer) was used. It turned out that for the analysis of the interference fringes the information at a point as obtained by the vibrometer was very useful. In the holographic setup in a car tire measuring arrangement, the pulse separation was adapted to the appropriate car speed. Of course, no beam derotation is needed for the reference beam (Fig. 1). The amplitude distribution (lines of equal amplitudes) are shown in Fig. 2.

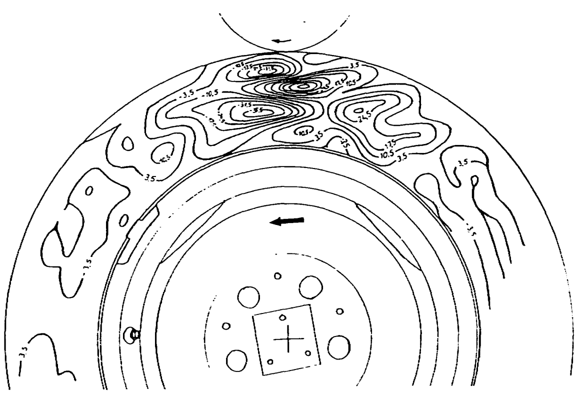


FIGURE 2 Mechanical deformation of a tire with the pulse separation of 40 μs, showing lines of equal deformation.

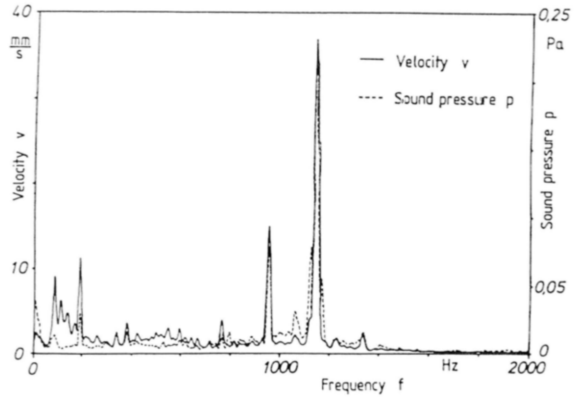


FIGURE 3 Absolute vibration amplitude and frequency obtained by means of the vibrometer.

The absolute vibration amplitude as well as the frequency obtained by means of the vibrometer are shown in Fig. 3 for one point leading to a reference for the fringe analysis of the double-pulse holographic technique. The frequency analysis at a speed of 60 km/h is shown by the solid line. For comparison the noise spectrum obtained with a microphone (dotted line) is shown; good agreement could be obtained.

In the arrangement for double-pulse holography, different storage materials, such as photographic emulsions, photothermoplastic materials, as well as photopolymer or photorefractive crystals can be used. As a photorefractive storage material for holographic interferometry and speckle techniques, $Bi_{12}SiO_2$ (BSO) crystals can be used (Tiziani, 1982).

The use of solid-state detectors is, however, very attractive for industrial applications even though the spatial resolution is limited. For CCD cameras the pixel size needs to be further reduced and the number of the pixels increased. However, a lot of progress has been made lately and will be made in the future. Some of the applications will be described here.

DOUBLE-PULSE ELECTRONIC SPECKLE PATTERN INTERFEROMETRY (DP-ESPI) FOR VIBRATION ANALYSIS

Electronic Recording of Two Speckle Patterns of a Vibrating Object

The system used is shown in Fig. 4. The beam coming from the ruby laser is separated into two beams, the object beam and the reference beam. The object beam is enlarged by a diverging lens and illuminates the object (O). The object is imaged on the CCD camera by the lens L. With the aperture in front of the lens, it is possible to choose the mean dimension of the speckle in the sensor plane. The CCD camera records the interference between the light coming from the object and a reference. When the object vibrates, the interference pattern changes. The first image was recorded with the first pulse and the second image with the second pulse. The two images are then subtracted one from the other and correlation fringes corresponding to the object deformation appear. For the experiments a ruby laser (wavelength 694 nm), which can emit two high energy pulses separated by a few microseconds, was used. The problem is to record two images corresponding to the two pulses by using a CCD camera. To perform this task an interline transfer CCD camera was used. This camera consists of an array of photosensors each connected to a tap on a vertical shift register. When illuminated, the photosensors generate charges that, after a period of time, are transferred in the shift register that is covered to prevent generation of new charges. The time necessary to transfer the charges from the photosensors to the shift register is short (2 or 3 μs for the camera used in the reported experiment) because it involves only a parallel transfer from each photosensor to the adjacent one. After the charge transfer the photosensors of the camera are ready to capture a new image. The first pulse was recorded and the charges transferred to the shift register; after this transfer the second pulse was recorded. The two images (first image in the shift register and second image in the photosensors) can be read in two normal readout cycles, digitalized, and stored in the frame memory. Because the two laser pulses usually do not have the same energy, a normalization of the two re-

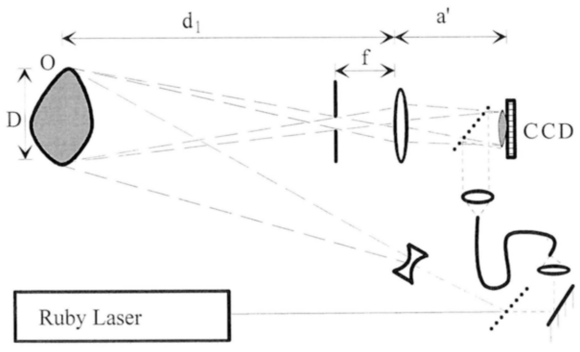


FIGURE 4 Optical setup.

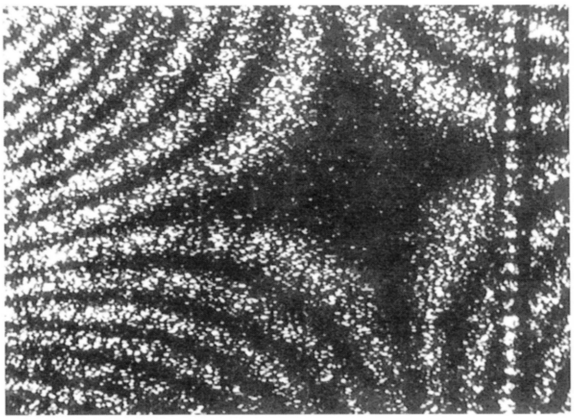


FIGURE 5 Speckle interferogram of a vibrating plate.

corded speckle images is necessary. The images are then substracted one from the other and the absolute value is taken and stored in the frame grabber. Figure 5 shows the result for a vibrating plate after the subtraction between the two speckle pattern. The pulse separation was 100 μs. It was even possible to record two separated images using pulse separation of 5 μs.

Quantitative Analysis of Fringes

For a quantitative analysis in the case of a pulsed laser, all the information necessary to reduce an interferogram to a phase map should be recorded simultaneously. For this purpose the spatial-carrier phase-shifting method was used. In the spatial-carrier phase-shifting method the reference beam is tilted by an angle θ with respect to the optical axis. In the image plane (where the CCD sensor is located) the speckle image of the object to be tested is then modulated with a carrier frequency having a period $p_M = 1/f_0 = \lambda/\sin\theta$. The angle is chosen such that the phase difference between the reference and object beam changes by a constant $\alpha = 2\pi\Delta x f_0$ (e.g., $\pi/2$) from one pixel of the CCD camera to the other (where the pixel separation is Δx). To apply this method it is necessary that the speckles are still correlated after the image shift of one pixel; this involves the pixel size being greater than the period p_M. The first speckle pattern $I_1(x, y)$ with the object in position O1 and the second $I_2(x, y)$ with the object in position O2 are recorded and stored in the frame grabber. Each recorded pattern can be seen as a carrier wave whose spatial frequency is modulated by the object information. This can be described mathematically by the relation

$$I_1(x, y) = |r(x, y)|^2 + |u(x, y)|^2 + |r(x, y)||u(x, y)|\{\cos[\phi_1(x, y) + 2\pi f_0 x]\} \tag{1a}$$

$$I_2(x, y) = |r(x, y)|^2 + |u(x, y)|^2 + |r(x, y)||u(x, y)|\{\cos[\phi_2(x, y) + 2\pi f_0 x]\} \tag{1b}$$

which describes a set of carrier interference fringes of spatial frequencies f_0 that are modulated in amplitude by $|u(x, y)|$ and in phase by $\phi(x, y)$. Three adjacent pixels can be used to calculate the phases $\phi_1(x, y)$ and $\phi_2(x, y)$, according to the standard phase shifting algorithm:

$$\phi(x, y) = \arctan\left(\frac{I(x - \Delta x, y) - I(x + \Delta x, y)}{I(x - \Delta x, y) + I(x + \Delta x, y) - 2I(x, y)} \tan\frac{\alpha}{2}\right). \tag{2}$$

Experimental Results

Figure 6 shows a result obtained using the spatial-carrier phase-shifting method or sinusoid fitting. The object was a plate that was excited using a pendulum and the two pulses were fired about 1 ms after the impact of the pendulum with the plate. The pulse separation was 100 μs. The two images of the vibrating object were recorded with a CCD camera, digitalized, and stored in the frame memory. The filtered phase map is shown in Fig. 6(a). Figure 6(b) shows a pseudo-3-D representation of the deformation of the central part of the plate.

2- and 3-D Vibration Measurements

The results presented are only 1-D, meaning that they give only the deformation of the object along one sensitivity vector. In some cases a 2- or 3-D analysis of the deformation is necessary. More sensitivity vectors can be generated by observing the object from different directions or by illuminating the object from different directions (three directions of illumination and one direction of observation). The second possibility was chosen because it has the advantage that it does not need rectifications due to the distortion by different observation directions. Figure 7 shows the arrangement used for the measurement of 2-D deformations. The sensitivity vectors are given by

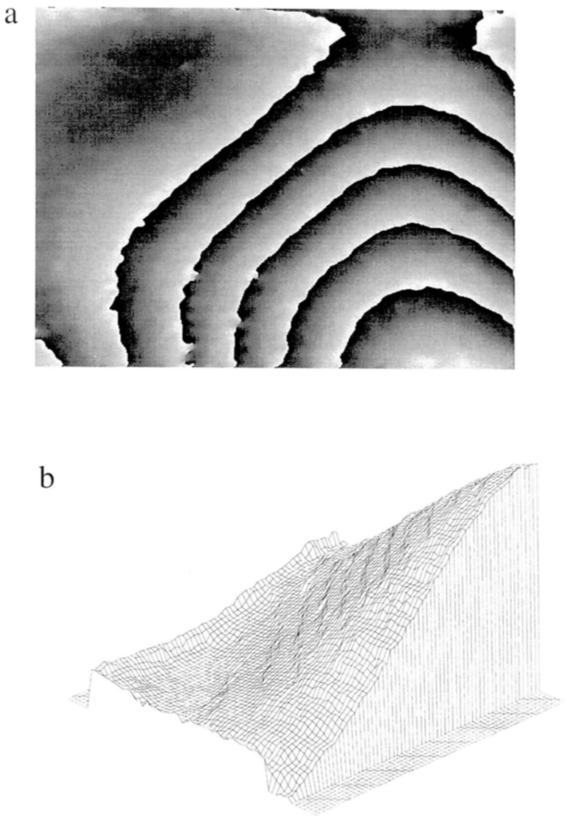


FIGURE 6 Deformation of a plate between 150 and 250 μs after the impact of a pendulum on the plate: (a) phase map and (b) pseudo-3-D representation of the deformation.

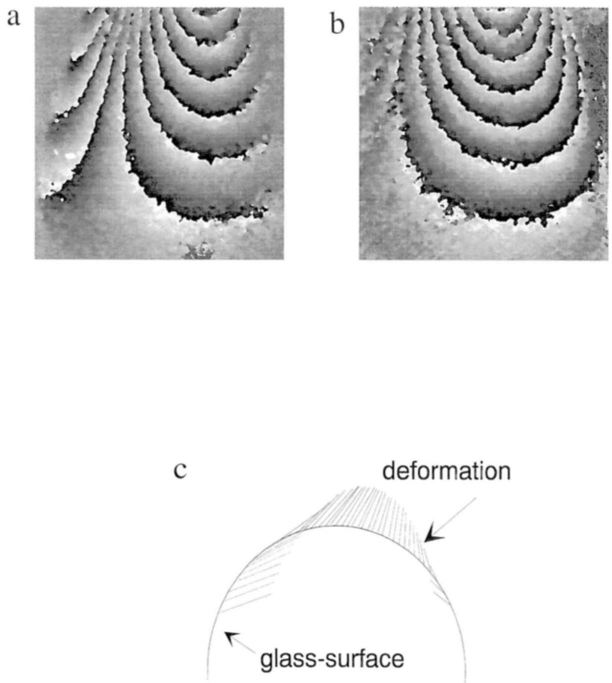


FIGURE 8 2-D measurement of a cognac glass: (a) phase map recorded with camera 1 leading to the deformation along the sensitivity vector s_1; (b) phase map recorded with camera 2 resulting in the deformation along the sensitivity vector s_2; (c) deformation along a line at the height h of the glass, obtained by combination of the deformations along the sensitivity vectors s_1 and s_2.

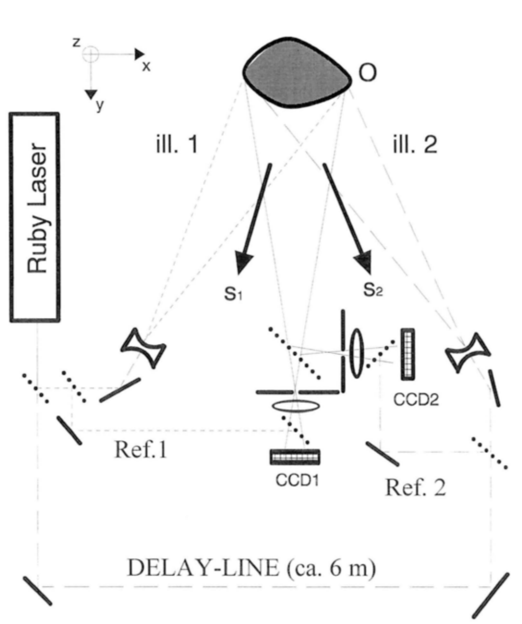


FIGURE 7 Optical setup for 2-D speckle interferometry.

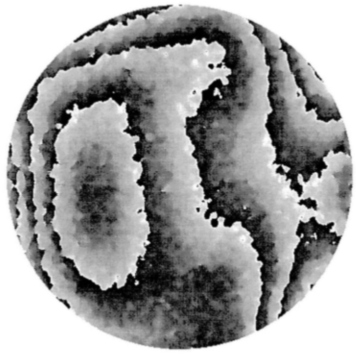
the half-angle between the illumination and observation directions. Camera 1 records the interference between reference 1 and illumination 1. It also gives the information of the deformation along the sensitivity vector **s1**, and analogously camera 2 measures the deformation along the vector **s2**. To avoid unwanted interference, the second reference/illumination beam pair is delayed by 6 m (coherence length of the ruby laser). For the 3-D case we use the same principle but with three cameras and three illumination directions. Figure 8 shows the results of the measurement of a vibrating cognac glass using the 2-D arrangement.

ESPI for Vibration Measurements of Rotating Objects

It is difficult to measure the vibration of rotating objects because the objects rotate between the two exposures too. To eliminate the object rotation, an image derotator was used. The image derotator is a device by which the rotational motion of the object is compensated optically. A roof edge prism rotating at half the speed of the object produces a stationary image. For this purpose an angular encoder measures the rotation of the object; a derotator control unit drives a motor that rotates the prism. The arrangement used is shown schematically in Fig. 9. It should be mentioned that the axes of rotation of the object and derotator need to be collinear and that the observation and illumination direction coincide and are parallel to the rotation axis of the object and of the derotator. These two conditions are needed to obtain correlation fringes of good contrast corresponding to the out of plane (parallel to the rotation axis) deformation. To satisfy these conditions, it is necessary to use beam splitter BS1 and BS2 in front of the rotating prism of the derotator to convey the derotated image to the CCD camera. The lens L_2 images the object onto the CCD camera and another beam splitter is used to introduce the reference wave.

For the experiment a thin plate (thickness 0.5 mm) with a diameter of 12 cm was used. This plate was driven by a small electric motor. For alignment of the system we adjusted at first the two rotating axes (object and derotator axis) so that they were parallel. This can be achieved easily by illuminating the object (it can, for instance, be illuminated with white light not collinear to the axis of rotation) and by adjusting the derotator until a stable image of the object is observed (it can be observed, for example, by a CCD camera). In order to have the virtual point source of divergence on the rotation axis, the rotating object can be illuminated with a He-Ne laser that is collinear with the ruby laser. At the output of the derotator we observed the illuminated object. The direction and the virtual diverging point of the illumination beam were adjusted until a stable speckle pattern was obtained. That means, the derotator compensates the in-plane rotation of the object and the virtual point of the illumination source lies on the rotation axis.

a



b

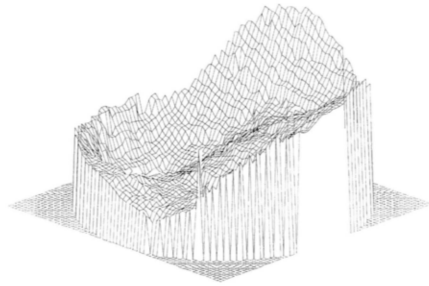


FIGURE 10 Double-pulse speckle interferometry with a plate rotating at 3000 rpm, pulse separation 200 μs: (a) phase map and (b) pseudo-3-D representation of the deformation.

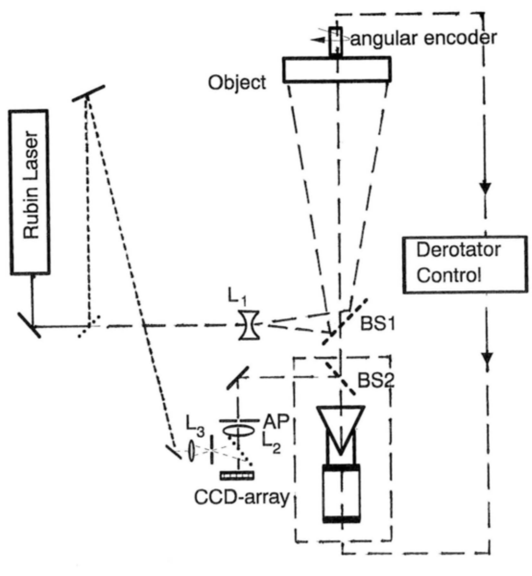


FIGURE 9 Optical setup for double-pulse speckle interferometry with rotating object.

Figure 10(a) shows a phase map obtained with this arrangement and object as pointed out. In this case the frequency of rotation was 3000 rpm and the pulse separation 200 μs. It was observed that the contrast of the fringes after the subtraction was worse than in the case of stationary objects. This is probably due to the fact that our illumination beam was not uniform, and thus a certain part of the object (because it rotates) was illuminated differently between the two exposures. Hence the speckle correlation decreased and the fringe contrast after subtraction was poor.

For this reason the phase map contains quite a lot of noise, but an analysis is still possible as shown in Fig. 10 (b) in a pseudo-3-D representation of the deformation. The phase map does not contain straight fringes that are generated from in-plane rotations; this means that the system is quite well aligned and only the out of plane deformations are obtained.

DIGITAL HOLOGRAPHY USING FRESNEL AND IMAGE-PLANE HOLOGRAMS

Digital Fresnel Hologram

Recording. Figure 11(a) shows an arrangement for the recording of an off-axis hologram using a plane wave as a reference. Recording a hologram using the arrangement of Fig. 11(a) is referred to as a Fresnel hologram. The interference pattern is recorded by a CCD camera. The maximum spatial frequency that can be recorded using a CCD camera is limited by the resolution, i.e., pixel size. (In our experiments we used a CCD camera with a pixel size $\Delta x = 11\ \mu m$.) To record a hologram of the entire object, the resolution of the camera must be sufficient to record the fringes formed by the reference wave and the wave from the object point farthest from the reference point. For the recording of a hologram it is necessary to have at least two sampled points for each fringe; therefore, the maximum spatial frequency that can be recorded is $f_{max} = 1/(2\Delta x)$. This means that the interference fringes obtained between the light coming from the object and the reference should have a period greater than $2\Delta x$. This can be obtained in two ways. The first is by reducing the angle θ_{max} between the light coming from the object and the reference (this can be achieved by increasing the distance d between the object and the camera). The object dimension is D; for $d \gg D$ we have $\theta_{max} = D_r/d$. The second method is by a magnification of the interference pattern using an optical system [see Fig. 11(b)]. The magnification is $M = a'/a$. In other words, the lens forms a reduced image of the object in the plane (x_1, y_1). If the reference is a point source located close to the object (this is not necessary but is convenient), the lens will image it as a point source in the plane (x_1, y_1) close to the image of the object. In fact this lens reduces the angle Θ_{max} on the CCD chip. In practice using the arrangement of Fig. 11(b), the hologram of the demagnified image of the object is recorded.

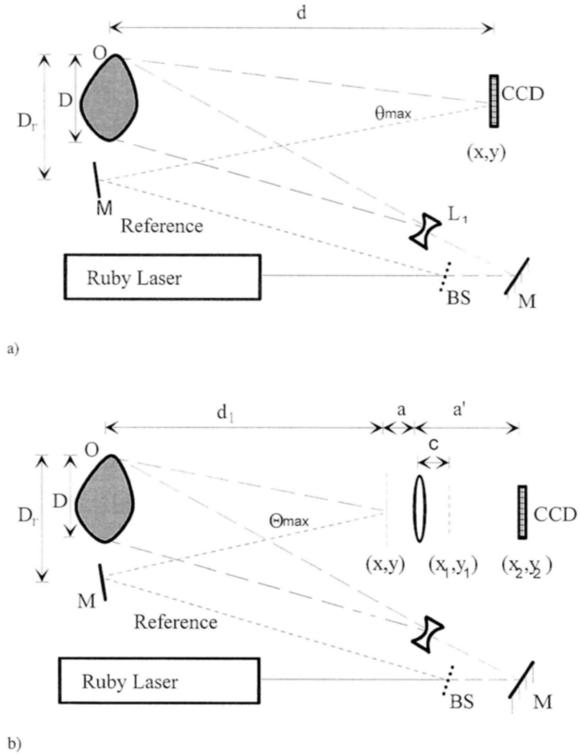


FIGURE 11 Experimental setup for double-pulsed ruby laser digital holographic interferometry: (a) without magnification of the interference pattern and (b) with magnification of the interference pattern.

Digital Reconstruction of Hologram. The reconstruction of the hologram is carried out by simulation of the reference wave that illuminates the hologram. By Fresnel diffraction the complex amplitude in a given plane at a distance z from the hologram can be calculated. This calculation can be carried out using a fast Fourier transform (FFT) algorithm.

Experimental Results

In our experiment the object used was a circular metal plate (diameter 20 cm) fixed at its center. The plate was excited by a loudspeaker (behind the plate) vibrating at a frequency of 1297 Hz. The distance between the object and the camera was 120 cm; the minimal period of the interference between the light coming from the object and the reference was thus $\lambda/\theta_{max} \cong 4.2\ \mu$m. For the recording we used the arrangement shown in

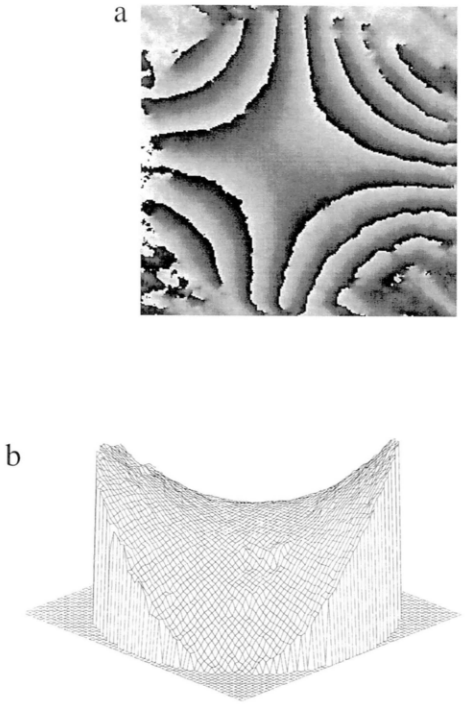


FIGURE 12 Plate vibrating with a frequency of 1297 Hz, pulse separation 150 μs: (a) phase map and (b) pseudo-3-D representation of the deformation.

Fig. 11(b), with a lens located in front of the camera that magnifies the interference pattern 6 times. Two holograms were recorded with a pulse separation of 150 μs. Figure 12(a) shows the filtered phase map obtained by subtracting the reconstructed phases of the two holograms. Fig. 12(b) shows a pseudo-3-D representation of the deformation.

COMPARISON BETWEEN DIGITAL HOLOGRAPHIC INTERFEROMETRY AND ESPI

Speed Consideration

The most important difference between the digital holographic interferometry and the speckle interferometry (or image plane digital holographic interferometry) is that in the first one we need a reconstruction to determine the phase; in the second it is possible to obtain the phase without any reconstruction. For the reconstruction of the hologram we used an FFT algorithm, which is time consuming. The number of required operations in this case is given by $2N\log_2N$, where N is the number of digitalized points. For our experiments we used an array with $N = 512 \times 512 = 2^{18}$ points; thus the number of operations were $2 \times 2^{18} \times 18 = 9.4 \times 10^6$. Our PC (486 DX 33) can carry out this calculation in about 20 s. However, we have to compare two phases; this time, therefore, has to be doubled. In addition, other operations need to be performed: calculation of the phase by using the arcustangens function, subtraction between the two phases, and representation of the result on a monitor. The time for one analysis with our computer takes about 1 min, but it could be speeded up 10 times by a faster PC.

The method without the reconstruction is faster because we calculate the phase from three adjacent pixels; the number of operation inside the parentheses is thus only $4N$. In our experiment with 512×512 pixels this operation was carried out in about 1 s.

Spatial Resolution Consideration

In the image plane hologram (speckle interferometry) we have a reconstruction which fills more pixels but with reduced resolution. In the Fresnel hologram we have less image points but the resolution is better. Experimentally it was possible to verify it by analyzing fringes obtained using the two methods.

CONCLUSION

The digital double-pulsed holographic interferometry methods are powerful tools for the analysis of vibrations. In particular the pulse separation in the range of 0.01–1 ms will allow the study of transient events. The methods allow a quick analysis of the interferograms without the development of films and hologram reconstructions. At present the quantitative analysis is not as accurate as in the case of holographic interferometry using films. In our experiment we reconstructed the hologram with 512×256 points only. If the deformation of the object between the two pulses is too large, there will be too many fringes, which cannot be analyzed. It was demonstrated that a good result can be obtained using a standard CCD sensor if the number of fringes does not exceed 20. The accuracy can be improved by using cameras with more pixels and of smaller pixel size that will be available in the near future.

Two recording methods (Fresnel and image-plane holograms) were presented. The Fresnel hologram needed a digital reconstruction of the wave front using FFT transforms. When the hologram is recorded in the image plane, we have two possibilities: digital reconstruction of the wave front or direct phase calculation using the spatial-carrier phase-shift (or sinusoid-fitting) method. The advantage of the sinusoid fitting is that it is much faster because it does not need any FFT calculation. The advantage of digital reconstruction with respect to the direct phase calculation, is the simulation of the reconstruction of the wave fronts (amplitude and phase) in space. We can simulate the propagation of the wave front through lenses and apertures and reconstruct focused (or defocused) images of the recorded object. It is thus a more general method than speckle interferometry where we can determine the interference phase only in the plane of the camera sensor.

The system can certainly be extended to determine the three components of the deformation by illuminating the object from three directions and by observing with three cameras. Three-dimensional measurements are necessary for the modal analysis where the results have to be correlated with the numerical calculations. A system measuring two components of the deformation was tested in our laboratory.

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