COMPOSITE MATERIALS AND STRUCTURES TESTING BY ELECTRONIC HOLOGRAPHY

Dan N. Borza [1]

[1] *Laboratoire de Mécanique de Rouen, Institut National des Sciences Appliquées de Rouen Place Blondel, BP 08, Mont-Saint-Aignan, France*

SUMMARY: The paper presents the use of phase-stepped electronic holography as an NDT tool, in particular using vibration stressing for detecting structural and material damage, and using thermal stressing for detecting defects in composites. After a short introductory description of this technique and of the most frequently used stressing methods used in testing, some of the criteria used for localization and identification of defects are presented and illustrated with experimental results. Both material damage and assembling faults are detected by applying these criteria and by an adequate choice of the frequency range of excitation and of the optical setup parameters.

KEYWORDS: interferometry, electronic holography, non-destructive testing, stressing techniques, wrapped phase, fringe visibility, vibrations, thermal.

INTRODUCTION

Emerged in the nineties as the natural development of electronic speckle pattern interferometry (ESPI), electronic holography is becoming a powerful technique for non-destructive testing of composite materials and structures. Electronic holography is based on the phase-stepped recording and displaying of speckled images. The use of a dedicated processor allows for real-time visualisation of fringe patterns related to the time-dependent surface deformation of the tested object. Compared to classical holographic interferometry NDT, two major and opposite characteristics are evident. On one side, electronic holography is more effective in testing because of its intrinseque real-time character and phase imaging possibilities. On the other side, image resolution is far behind that of silver halide emulsions used in holography. A significant consequence of these characteristics consists of somewhat different stressing techniques possible to apply in order to reveal the defects of the components under test. Vibration stressing is made easier, especially at low frequencies, because slowly varying displacements don't obstruct the real-time time averaged observation. The same applies for thermal stressing, with repetitive cycles applied while successively renewing the reference image. On the contrary, some specific stressing techniques, such as the continuous displacement time-averaged holography is generally prohibited, unless some provisions are made for several frames image integration, generally not available.

Phase shifted electronic holography

Phase shifted electronic holography [1] is an interferometric whole-field displacement measuring technique based, like the ESPI (Electronic Speckle Pattern Interferometry), on recording with a CCD camera the primary interference fringes in an on-axis interferometric setup. The general setup is illustrated in Fig. 1. It consists of three main blocks: the beam-splitting and object illumination module, the interferometer, and the computer control and acquisition module.

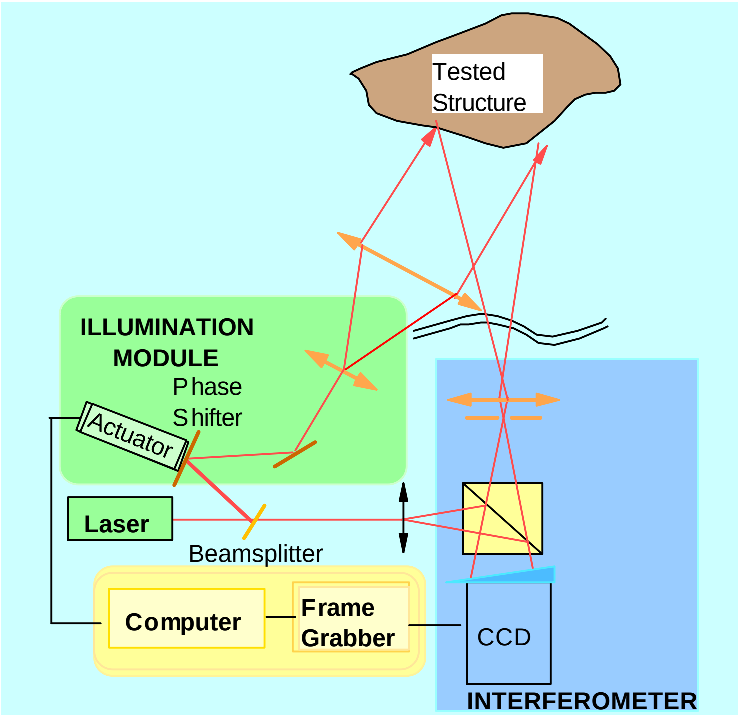


Fig 1: Electronic holography setup

The system has two basic operating modes: real-time / time-average mode as used in vibration based NDT, and double-exposure / phase image mode, as used in NDT with quasi-static thermal, pressure or mechanical stressing.
A part of a laser output beam is illuminating the object under test. The CCD camera simultaneously receives the wavefront diffused by the object and a second, reference beam coming directly from the beamsplitter following the laser.
In the real-time / time-average mode, assuming that the object undergoes a steady-state harmonic vibration at a frequency either great enough with respect to the frame acquisition frequency (25 Hz) or an integral multiple of this, the current image $I_i(x,y)$ is described by the relation:

$$I_i(x,y) = I_{OBJ}(x,y)\{1 + C(x,y)\cos[\varphi(x,y)+\alpha]J_0[\varphi_d(x,y)]\} \qquad \alpha = i\frac{\pi}{2},\ i = 0, 1, 2, 3 \qquad (1)$$

where:
$I_{OBJ}(x,y)$ is the object image;
C(x,y) is the local contrast;
φ(x,y) is the local phase;
α is an arbitrary phase shift;
$J_0(z)$ is the zero-order, zeroth kind Bessel function of argument z.

In electronic holography with nearly normal object illumination and observation, the phase φ_d is direcly related to the out-of-plane vibrational amplitude d(x,y) at any visible point of the object surface by the approximate relation:

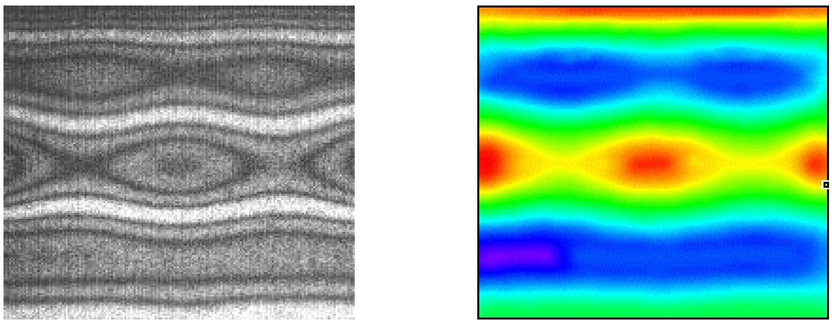
$$\varphi_d(x,y) = \frac{4\pi}{\lambda} d(x,y) \tag{2}$$

In phase-shifted electronic holography [1], several (usually four) successive images I_0, I_1, I_2, I_3 are acquired, while the phase of the object beam is modified in equal steps by a piezo-electric actuator. The image processor calculates and displays at the video frame rate the resulting image I_R, based on the formula: $I_R = (I_0 - I_2)^2 + (I_1 - I_3)^2$. It may be easily seen that this expression leads to:

$$I_R = AI_{OBJ} J_0^2 [\varphi_d(x,y)] \tag{3}$$

with A being a constant. The displayed image is continuously updated as a function of the last four acquired images, while the voltage waveform applied to the piezo-actuator has a staircase waveform.

One can see, Figure 2a, that the real-time images displayed on the monitor represent the image of the object, covered by interference fringes having the same expression as the reconstruction of a time-averaged holographic interferogram, that is related through the Bessel function of zeroth kind and first order to the local amplitude of vibration d(x,y). The whole-field displacement measurement sensibility is very high, each supplementary fringe occurring, in the first approximation, every half of the laser light wavelength, that is, for a frequency-doubled YAG laser, every 0.25 μm. The Figure 2b depicts the the amplitudes map as calculated from the electronic hologram.



a b

Fig. 2: electronic hologram of vibrating plate (a); calculated amplitude map (b)

NDT by low-frequency vibration stressing of structures

Low-frequency vibration stressing may reveal, by using real-time electronic holography, local variations of rigidity in structures when exciting steady-state vibrations of the structure. Some of these local anomalies represent material defects and some other are structural defects.

When exciting steady-state vibrations in order to discover such damage or defects, there are several criteria allowing to find them. One has to carefully inspect the real-time fringe pattern in order to find one or several of the next distorsions of the fringe patterns:

1. separate, local vibration of a small or particular region of the tested structure (Fig. 3a - non-uniform mass distribution in a carbon fiber composite plate, Fig. 3e - damage of the lower panel of a car door);
2. vibration modes of a particular component of the structure, indicating incorect boundary conditions (Fig. 3b - incorrect fixation at left side of a car door handle, marked **A**);

3. coupling between the vibrations of two or several distinct components of a structure (Fig. 3 c - vibration coupling between lower panel and the window, through the window joint of a car door, Fig. 3 e - coupling through the frame);
4. abrupt changes in the direction of nodal lines (Fig. 3 c, e, f - local panel damages);
5. local anomalies in the iso-amplitude fringe pattern pattern outside the nodal lines of a mode (Fig. 3 d, f).

Often, several such situations occur simultaneously. The distinction between the last two cases corresponds to the particular appearance of time-averaged fringe patterns, with nodal lines of much brighter intensity.

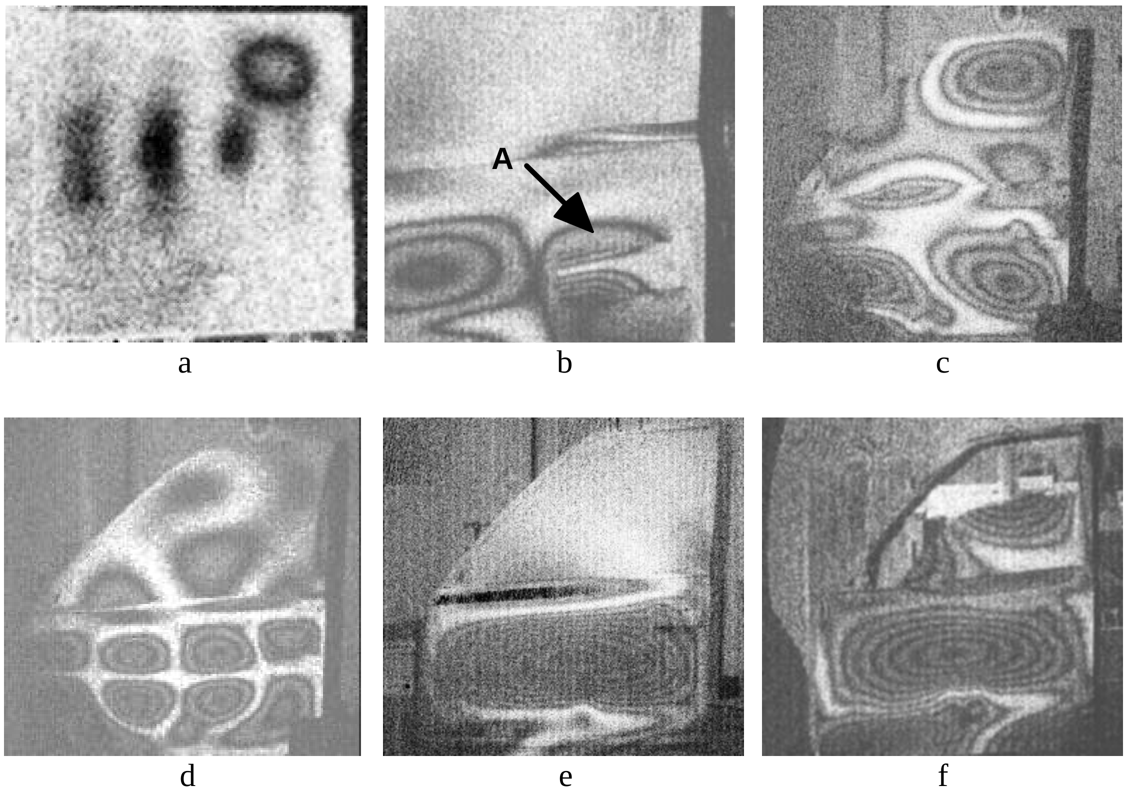


Fig. 3: Different defect visualization criteria for electronic holography NDT by vibration

The excitation of the object under test may usually be done through a loadspeaker or, in case of larger structures, by a shaker. If higher frequency control is necessary, piezo-electric excitation may be considered. As seen in these examples, the vibration stressing method may reveal both structural and material defects.

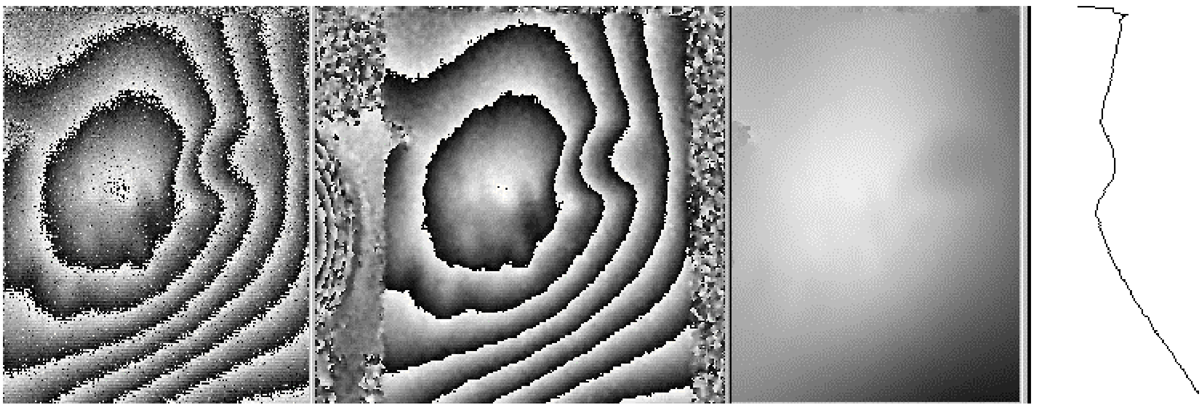
Double-exposure phase image display mode

In the double-exposure / phase image mode, the current image I(x,y) displyed on the electronic holography monitor is described by the relation:

$$I_i(x,y) = I_{OBJ}(x,y)\left[1 + C(x,y)\cos(\varphi(x,y)+\alpha)\right] \qquad \alpha = i\frac{\pi}{2},\ i = 0, 1, 2, 3 \qquad (4)$$

Four successive images I_1, I_2, I_3 and I_4 are recorded with the object in the reference state, while the phase of the object beam is modified in equal steps by a piezo-electric actuator. Then during the quasi-static stressing of the object, successive series consisting each of four phase-stepped impages of the deformed object J_1, J_2, J_3, J_4 are acquired. The image displayed on the monitor is obtained by a pixel-by-pixel operation between the eight frames [2] giving directly the modulo 2π phase (Fig. 4a) related to the deformation by a relation similar to (2).

Filtering (Fig. 4b) and phase unwrapping (Fig. 4c) this image (Fig. 4) produces diretly the deformation map at the surface. Fig. 4d shows a vertical profile obtained from the deformation map shown in Fig. 4c.



a b c d

Fig. 4: Measuring static deformations by electronic golography

The interest of the real-time phase display is the possibility to acquire directly phase images, and letting the phase unwrapping procedure to be the only one which is done, at today's state-of-the-art, in post processing. In NDT, there is another interest - the high contrast of the real-time fringes, allowing the observer to localize defects more easily.
Several stressing methods may be used for CND purposes when using electronic holography. The most general ones are thermal stressing and pressure stressing, mostly used with composites. One of the main problems is identifying on the fringe pattern, generally irregular and complexe, a certain type of defect. In order to do this, several approaches and solutions have been proposed.
One solution is making a catalog of different defects and of their appearance in a fringe pattern. This solution implies that in routine testing of a specific composite, stressing conditions should be made identical or similar in all tests. Another emerging approach is making use of inverse methods in order to predict by calculus which could possible be the defect leading to a certain deformation map holographically measured. This approach could eventually lead to some benefits like constructing maps related to material properties distribution across the object surface. Finally, one more pragmatical approach is to find stressing and recording specialized methods which allow only some specific types of defects to be seen on the fringe patterns [3].
Such a specialized NDT method may be the recording of time-average holograms or electronic holograms while the object is continuously deforming, a method used for visualizing the trajects of metallic fiber insertions inside a tire. Another specialized stressing method useful in studying the fiber trajects inside a hygroscopic composite is the self-stressing by water absorbtion.

NDT by repetitive thermal stressing of composite materials

Thermal stressing in holographic interferometry is limited by the rapidly increasing number of fringes, owing to the general dilatation. This is hiding the defects and may finally produce a loss of contrast by speckle decorrelation. With electronic holography, we tested with good results the repetitive thermal stressing according to a cycling temporal law. The convenient choice of the reference frames, along with the sawtooth fringe profile in the wrapped phase image displayed allow detection, in a metal-plastic composite plate assembled by gluing, of inclusions and voids (as in Fig. 5) otherwise hidden in a too dense fringe pattern.

Often enough, one can obtain higher-contrast and a better localization of fringes by realizing the second part of the double-exposed hologram after having initially heated the object.

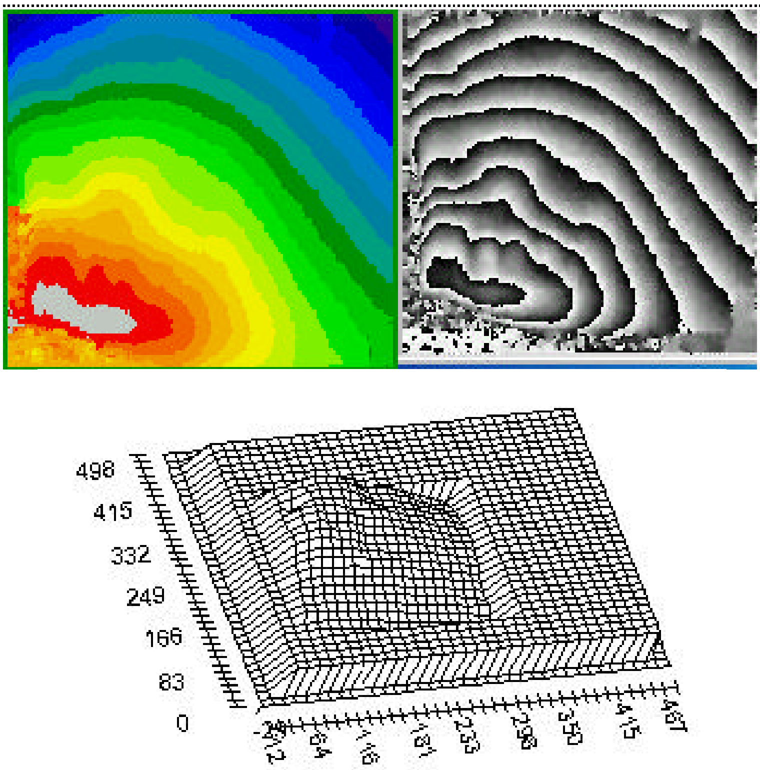


Fig. 5: Wrapped phase (upper image, right), unwrapped phase (upper image, right) and object deformation by electronic holography with thermal stressing

CONCLUSIONS

Phase stepped electronic holography is an effective technique for testing composite structures and materials. The results are directly related to the stressing technique used. New stressing methods may be implemented, adapted to the specific material or structure under test. Vibration testing may contribute to detecting structural and (composite) material defects, while quasi-static stressing techniques are mainly intended for composite NDT.

REFERENCES

1 Stetson, K. A., Wahid, J., "Real-Time Phase Imaging for Nondestructive Testing", *Experimental Techniques*, Vol. 22, No. 3, Society foe Experimental Mechanics, May/June 1998.

2 Stetson, K. A., Brohinsky, W. R., Appl. Opt. Vol. 25, 2643 - 2644 (1986)

3 Borza, D. N., "Specialized stressing techniques for holographic testing of composites", *Journal of Composites part B: Engineering*, 984, Vol 29, Iss. 4, Elsevier Science, 1998.