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## DIGITAL HOLOGRAPHY USING A PHOTOGRAPHIC CAMERA

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### SYNOPSIS

In this work, an experimental device for measuring surface deformation of components and structures is presented. The proposed system is based on a digital holography setup, uses a commercial digital photographic camera as recording device of the holograms and presents all the advantages associated with holographic interferometry techniques. Some results already obtained with the experimental setup are also presented and discussed.

### INTRODUCTION

The structural analysis of components and structures has been benefited during the last years with the development of several techniques both numerical and experimental. In these last ones, the optical techniques, are nowadays well established and with proven results in different applications. When compared with conventional experimental methods they present several advantages, since they are full field, have high resolution and can perform measurements with no contact. However, optical techniques need expensive equipment like, lasers, special CCD cameras, frame grabbers with dedicated software and high quality optical elements.

The proposed approach is based on a digital holography (DH) setup using a commercial digital photographic camera and general application software. The original concept of digital holography was first introduced in 1980 (Yaroslavskii, 1980) and latter on a new concept was developed (Schnars, 1994). The set-up of DH is based in the same principle of holography or ESPI (Monteiro, 1996), but in this case no image formation system is used between the object and the video sensor. In digital holography, since holograms are digitally sampled, information about the interference between waves is stored in the form of digital matrices. Numerical processing can thus be performed to simulate the optical processes of interferometry and perform the hologram reconstruction. Both amplitude and phase distributions of the wave can be extracted numerically.

Compared to an ESPI system the proposed system has the advantage of being a less complex setup, since it uses less optical components and due to this fact doesn't needs the same laser power. Another advantage is that is not so dependent on a computer since all the process of grabbing and recording the holographic information is made in the digital camera and the post processing can be made afterwards in a computer using a general application programme like Matlab®.

## RESULTS

In the experimental setup a commercial digital camera, Nikon D200, with its lens removed was used to record the holograms. This camera has a sensor size of 23.6x15.8 mm with 3872x2592 pixels and a pixel size of 6x6  $\mu\text{m}$ . In figure 1 an image of the experimental setup is presented where is possible to see the camera without lens and all the optical setup needed to generate the illumination and reference beams. Some experiments were made in order to test the quality of the holograms obtained with this setup. In figure 1 is also shown an example of the phase map of an interferogram obtained for the rotation of a small bar of aluminium. The aluminium bar was clamped in one of its ends and loaded in the other one.

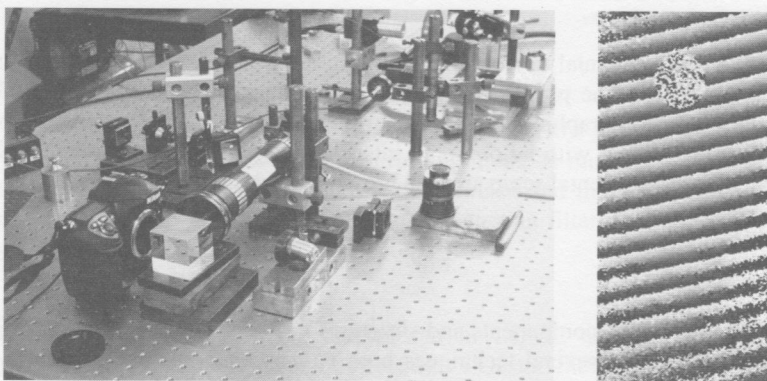


Fig.1 Image of the experimental setup and displacement field of an aluminium bar that was clamped in one of his ends and loaded in the other one.

## CONCLUSIONS

The proposed device, which is based on digital holography techniques, proved its potential to as a tool for structural analysis. With this system, it is possible to access information regarding structural behaviour of components and structures with high resolution and without contact. A compact and inexpensive system, when compared with other conventional ones like ESPI, can be obtained due to the less optical components and the reduced laser power needed. As DH recordings allow phase calculation by spatial phase shift only one hologram is involved in the phase calculation which means that this setup can be used with pulsed lasers in dynamic and transient measurements.

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### SYNOPSIS

In this work an experimental device for surface deformation assessment on components and structures is presented. The system is based in a holographic interferometric technique and benefits from all the advantages associated with these techniques such as: high resolution, full field, non contact and the possibility of post processing the obtained numerical data. To perform measurements the proposed device uses digital holograms recorded with a standard digital photographic camera. In order to test and validate the system proposed some experimental results are presented and discussed.

### INTRODUCTION

Optical techniques are nowadays well established with proven results in different areas. They present several advantages when compared with conventional ones, since they are full field, high resolution and non contact techniques. The structural analysis of components and structures has been benefited during the last years with the development of several techniques both numerical and experimental. In what concerns experimental techniques the association of data electronic recording to holographic interferometry give an important contribution for its development and diffusion. However, these experimental techniques are time consuming due to the enormous quantity of data available in each measurement and on one hand need expensive equipment such as special CCD cameras, lasers, and high quality optical elements. The setup here purposed allows the measurement of the surface deformation in a simple, fast, and inexpensive way, yet provides full-field and non-contact measurements.

The measuring system is based on a conventional digital holography setup using a standard digital photographic camera. This is basically an off axis holographic setup with the holographic plate replaced by a CCD and numerical reconstruction of the recordings. The hologram reconstruction is performed by computer according to a procedure that was first reported, some 20 years after Gabor's landmark paper (Gabor, 1948), by Goodman and Lawrence (Goodman, 1967) and Yaroslavskii and coworkers (Kronrod, 1972), (Yaroslavskii, 1980). The milestones in the evolution of the technique and algorithms have been; the use of a CCD camera to acquire the hologram (Schnars, 1994), the reconstruction of the phase in addition to the amplitude (Cucho, 1999) and the measurement of polarization states (Colomb, 2002). Nowadays the pair of Fresnel holograms, which represent the undeformed and the deformed states of the object, are generated on a CCD target and stored electronically. This technique uses the same principle of speckle interferometry techniques (Monteiro, 1996), but in contrast to this one no lens or other imaging device is used between the object and the video sensor. In digital holography, since holograms are digitally sampled, information of optically interfering waves is stored in the form of matrices. Numerical

processing can thus be performed to simulate the optical interferometry, spatial filtering, etc. This way it is possible to calculate the interference phase, which is the phase difference between the two object waves, directly from the holograms, without generation of an interference pattern. The angle between reference and object beams generates a spatial carrier which allow phase calculation of each hologram. This characteristic is very useful when pulsed illumination is used to study vibration o transient phenomena.

## DIGITAL HOLOGRAPHY

Digital holography (Yarovslavskii, 1980) is a lensless imaging method in which a hologram is recorded with a CCD-camera and reconstructed numerically. The hologram results from the interference between two wave fronts, one reflected or transmitted by the object and the other is the reference. The digital reconstruction of the complex wave (amplitude and phase) near the object is based on the Fresnel transform, which can be performed with an approximation of the diffraction integral (Goodman, 1996).

The conventional holographic setup for recording off-axis holograms is schematically shown in Fig.1. A plane reference wave front and the diffusely reflected object wave front are interfering at the surface of the hologram plane. In this study the CCD target of a standard digital camera (Nikon D200) is used.

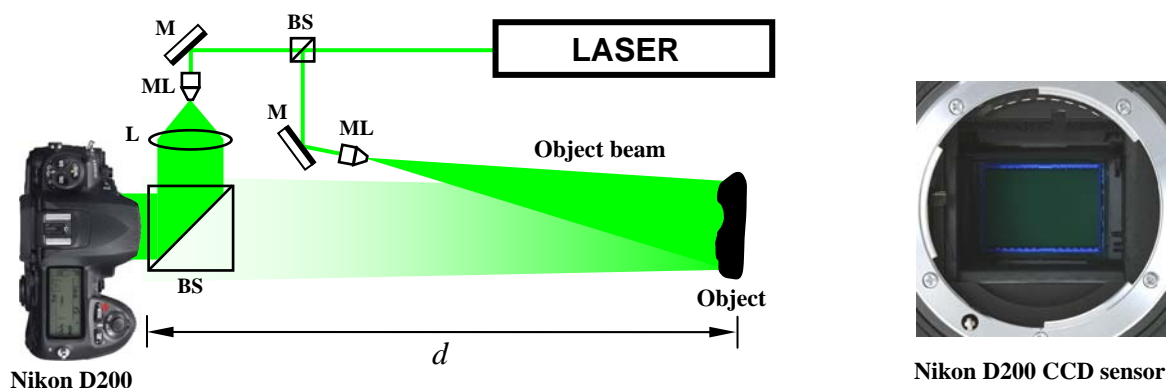


Fig.1 Experimental setup: BS - Beam Splitter; M - Mirror; ML - Microscopic lens; L - Lens.

The holograms are recorded electronically and stored in the camera memory. Then they are transferred to a computer for post processing using dedicated image processing software. This allows the recording of holograms without computer.

The real image can be reconstructed from the digitally sampled hologram. For that, the diffraction of the reconstructing wave at the microstructure of the hologram is computed by numerical methods. The diffraction of a plane wave at the hologram is described by the Fresnel-Kirchhoff integral. This study is based on the initial assumption that the distance  $d$  between the hologram and the real image is much greater than the maximum dimension of the CCD chip. With this restriction on the separation between the hologram and the real image, for the near-field region where Fresnel diffraction phenomena can be observed, the distance  $d$  satisfies the condition (Schnars, 1994):

$$d^3 \gg \frac{\pi}{4\lambda} \left[ (x - \xi)^2 + (y - \eta)^2 \right]_{\max}^2 \quad (1)$$

Therefore, the Fresnel approximation can be used to calculate the complex amplitude of the diffracted wave in the plane of the real image (Schnars, 1994)

$$\Gamma(\xi, \eta) = \frac{ia}{\lambda d} \exp\left[-i \frac{\pi}{\lambda d} (\xi^2 + \eta^2)\right] \times \iint_{-\infty}^{\infty} t(x, y) \exp\left[-i \frac{\pi}{\lambda d} (x^2 + y^2)\right] \times \exp\left[i \frac{2\pi}{\lambda d} (x\xi + y\eta)\right] dx dy \quad (2)$$

Where  $(x, y)$  and  $(\xi, \eta)$  are the coordinates in the hologram plane and in the plane of the real image,  $t(x, y)$  is the amplitude transmittance of the hologram, and  $a$  is the amplitude of the incident wave. The function  $\Gamma(\xi, \eta)$  can be digitized if the hologram transmission  $t(x, y)$  is sampled on a rectangular raster of  $N \times N$  matrix points, with steps  $\Delta x$  and  $\Delta y$  along the coordinates. The terms  $\xi$  and  $\eta$  are replaced by  $m\Delta\xi$  and  $n\Delta\eta$ , where  $m$  and  $n$  are integers. The discrete representation of Eq.(2) is given by (Yarovslavskii, 1980):

$$\Gamma(m, n) = \exp\left[i\pi\lambda d \left(\frac{m^2}{N^2\Delta x^2} + \frac{n^2}{N^2\Delta y^2}\right)\right] \times \sum_{k=0}^{N-1} \sum_{l=0}^{N-1} t(k, l) \exp\left[-i \frac{\pi}{\lambda d} (k^2\Delta x^2 + l^2\Delta y^2)\right] \times \exp\left[i2\pi \left(\frac{km}{N} + \frac{ln}{N}\right)\right] \quad (3)$$

$\Gamma(\xi, \eta)$  is a matrix of  $N \times N$  points, which describes the wave field in the plane of the real image. In this transformation  $\Delta\xi$  and  $\Delta\eta$  are the pixel sizes in the reconstructed image and the relations between  $\Delta x$ ,  $\Delta y$  and  $\Delta\xi$ ,  $\Delta\eta$  are as follows (Yarovslavskii, 1989):

$$\Delta\xi = \lambda d / N\Delta x, \quad \Delta\eta = \lambda d / N\Delta y \quad (4)$$

From the numerical standpoint, Eq.(3) is a representation of the Fresnel approximation in terms of an inverse discrete Fourier transformation. Because the reconstructed wave field  $\Gamma(\xi, \eta)$  or  $\Gamma(m, n)$  is a complex function, both the intensity and phase can be calculated. The phase can be obtained by taking the modulus and squaring Eq.(2):

$$I(\xi, \eta) = \left| \Gamma(\xi, \eta) \right|^2 = \text{Re}^2[\Gamma(\xi, \eta)] + \text{Im}^2[\Gamma(\xi, \eta)] \quad (5)$$

Re denotes the real part and Im the imaginary part and finally the phase is calculated by:

$$\Phi(\xi, \eta) = \arctan \frac{\text{Im}[\Gamma(\xi, \eta)]}{\text{Re}[\Gamma(\xi, \eta)]} \quad (6)$$

Since the holograms are digitally stored they can be reconstructed separately, and the phase calculated by Eq.(6) for each state of the object. The interference phase, which is the phase difference between the undeformed and deformed objects, is then calculated by:

$$\Delta\Phi(\xi, \eta) = \begin{cases} \Phi_1 - \Phi_2 & \text{if } \Phi_1 \geq \Phi_2 \\ \Phi_1 - \Phi_2 + 2\pi & \text{if } \Phi_1 < \Phi_2 \end{cases} \quad (7)$$

$\Phi_1$  and  $\Phi_2$  are the phases of undeformed and deformed objects, respectively. Equation (7) permits the calculation of the interference phase directly from the digitally sampled holograms. In Fig.2 all the process is presented in a schematically way. Fig.2(a) and 2(b) present respectively the digital holograms of the undeformed and deformed object. Fig.2(c) presents the image of the object that was numerically reconstructed from one of the

holograms and Fig.2(d) the interference phase distribution calculated directly from the two holograms.

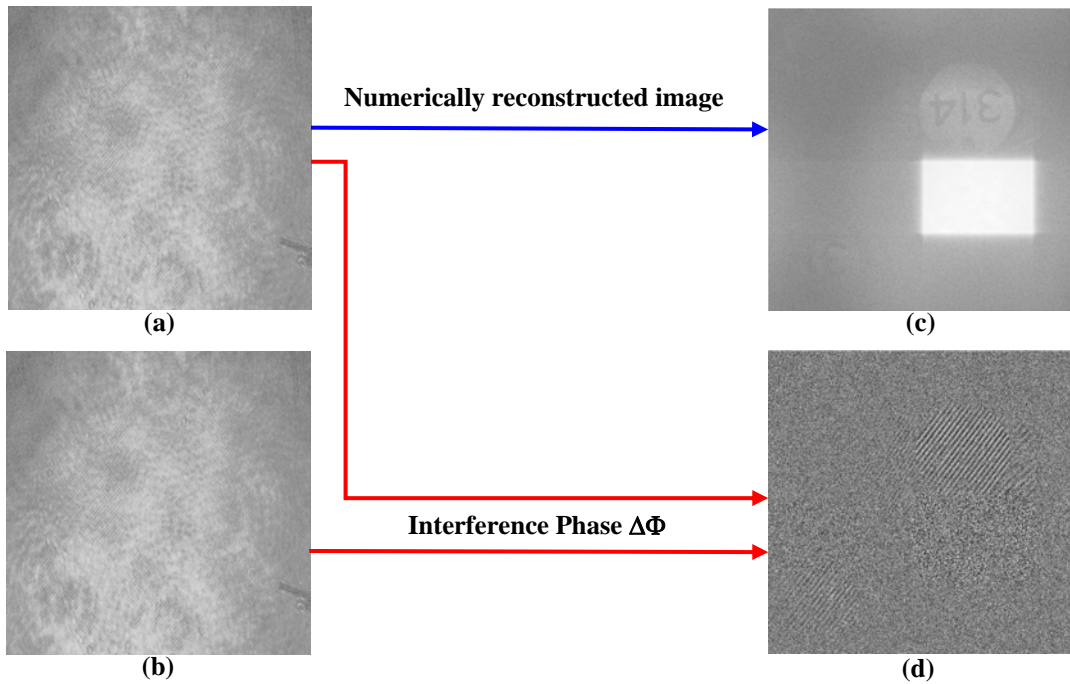


Fig. 2 (a) - Digital hologram of the undeformed object; (b) - Digital hologram of the deformed object; (c) - Numerically reconstructed image of the object; (d) - Interference phase distribution for an object rotation.

From the obtained interference phase distribution, calculated directly from the two holograms, is possible to apply image process algorithms in order to extract all the needed information. Some examples are presented in Fig.3, which includes selection of the area of interest, filtering, unwrapping and three-dimensional representation of the displacement field.

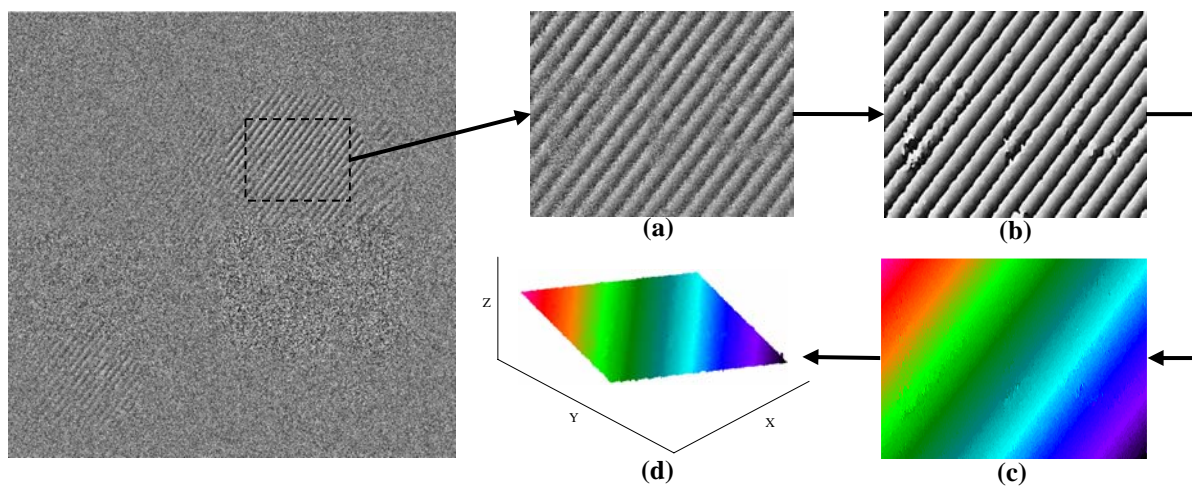


Fig. 3 (a) - Selected area of the object phase distribution; (b) - Phase filtering; (c) Representation in pseudo color of the unwrapped phase distribution; (d) - Three-dimensional representation.

So far, most methods that aimed to retrieve the complex wave from the hologram were directly inspired by the optical reconstruction process: In the classical configuration the chemically processed photographic plate – the hologram – is illuminated, and the image

(respectively the virtual image) is generated by the diffracted wave. The translation of this physical process into a numerical algorithm is nearly literal. Simulating the diffraction process boils down to computing the propagation of a complex wave and this can be done using several approximations (Kreis 1997). The most evident disadvantage of the approaches that imitate the physical process is that the reconstructed image is severely corrupted by interference terms like: the zero order term and the out-of-focus twin-image. The presence of these terms still remains a determining factor that limits the quality of the reconstructed image, or at least the field of view.

## EXPERIMENTAL RESULTS

To apply digital holography successfully, some precautions need to be taken. The replacement of the photographic film by the CCD, conventional optical recording techniques have to be modified to meet the requirements placed by the use of this photo detector. As long as the sampling theory is fulfilled, digitally sampled holograms can be reliably reconstructed without any loss. However, the spatial resolution of CCD sensors is generally about an order of magnitude lower than that of photographic emulsions. For this reason, the maximum allowable angle between the object and reference wave fronts (interference angle), is limited to a few degrees.

To achieve good quality reconstruction, digital recording of holograms has to satisfy the Nyquist sampling theorem. For exact recovery of the image of an object in digital holography, sampling theorem implies that the interference fringe spacing must be larger than two pixels. So, the interference angle between the object and reference wave fronts have to be limited within a few degrees, given by the formula:

$$\alpha_{\max} = \frac{\lambda}{2\Delta N}, \quad (8)$$

being  $\Delta N$  the pixel size. For efficient use of the CCD area, it is important that the sampling theorem should be fulfilled across the entire CCD sensor. For an object with a lateral size  $L_{ox}$ , the distance  $D$  between the object and the CCD target has to be greater than  $D_{min}$ . This is needed to allow spherical wavelets from each point on the object to interfere with the reference wave in the recording plane at an angle no greater than  $\alpha_{max}$ . If the centers of the object and CCD target are both on the optical axis of the system, then the minimum allowable distance is given by the following equation:

$$D_{\min\text{-in-line}} = \frac{\Delta N}{\lambda} (N \cdot \Delta N + L_{OX}) \quad (9)$$

For the experimental setup used the holograms were recorded with a standard digital camera. A Nikon D200, with objective lens removed was selected for this application. This camera has a sensor size of 23.6x15.8 mm with 3872x2592 pixels and a pixel size of 6x6  $\mu\text{m}$ . In Fig.4 an image of the experimental setup is presented where it is possible to see the camera without lens and all the optical setup. An image of the sensor of D200 was also shown in fig.1. Some experiments were made in order to test the setup and some results are presented in Fig.2. In Fig.4 is also shown the phase map of a small aluminium bar and its displacement field due to a rigid body rotation. The aluminium bar was clamped in one of its ends and loaded in the other one. In fig. 4 is represented a three-dimensional presentation of the displacement field in pseudo colour. In this graphical presentation the dimensions in the plane are in millimetres and the measured displacements in micrometers.

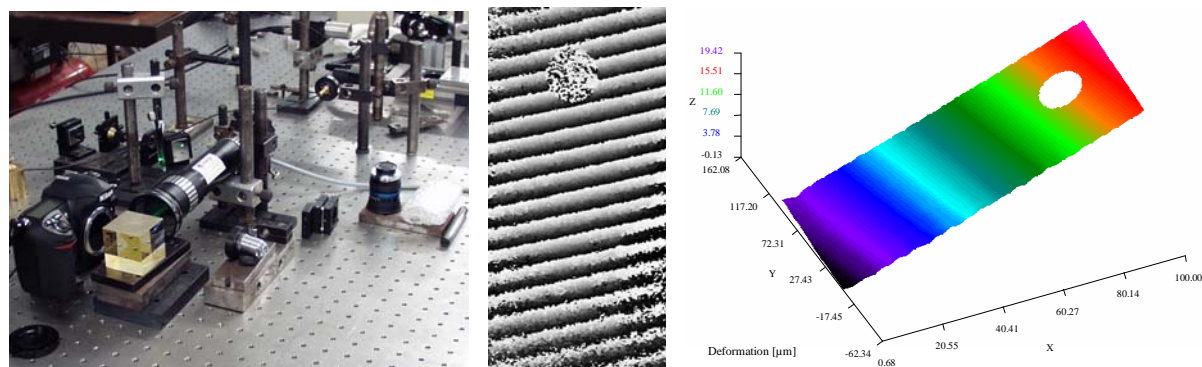


Fig.4 Image of the experimental setup. Displacement field and three-dimensional representation of an aluminium bar that was clamped in one of his ends and loaded in the other one.

## CONCLUSIONS

Compared to an ESPI system the proposed one has the advantage of using a less complex setup. This leads to a compact solution since less optical components are involved. Due to this fact the optical efficiency increases and less laser power is needed. Being a technique without an image system all the aberrations inherent to it are avoided. Another advantage is that it does not depend on a special hardware image recording, since all the process to obtain the holographic information is made with a digital camera. The data post processing can be made afterwards in a computer. All this together leads to a final system that costs much less than a conventional ESPI or a digital holography with a conventional CCD video camera.

Digital holography has a wide range of applications which gets broader as new image recording detectors became available. Noise suppression, higher resolution, precise parameter adjustment and faster recordings are the main characteristics needed for new detectors. However, robust algorithms are the essential issues which will be the focus in the future development of this technique.

The proposed device is based on the digital holography technique and proved its potential to be used in structural analysis. With this technique is possible to access information regarding the structural behaviour of components and evaluate its integrity with high resolution and without contact. Due to the reduced number of optical components less laser power is needed and more compact and less expensive systems can be obtained. This way a reliable tool for inspection and control can be easily constructed as far as a laser source is available.

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