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Simultaneous 3D digital holographic interferometry for strain measurements validated with FEM

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ABSTRACT

This work introduces a digital holographic interferometer in a simultaneous 3D configuration to detect superficial strains. The system uses a single monochrome sensor and three different lasers in a two exposure method, which can successfully measure the superficial deformation during a controlled deformation. An aluminum plate with a well-known geometry is used as a proof of principle. The deformation and all physical variables are simulated with a finite element algorithm. The comparison between the experimental and the simulated results helps to validate the system's measurements with very good agreement. A description of the technique is presented.

1. Introduction

Nowadays, there are a wide range of optical metrology techniques that offer high sensitivity and high resolution results. They usually involve a light source, a beam-handling optics, a detector and a data handling system. Recent advances in electronics result in smaller and more powerful optical metrology systems, but a constant among them is the illumination source used to modulate and to obtain the measurements. A laser is widely used in these fast whole field nondestructive tests [1,2].The optical nondestructive testing (NDT) techniques, or also called non-contact non-invasive techniques, are used in science and industry to evaluate the mechanical properties of a sample with no damage on the sample. Many of the non-contact optical techniques such as fringe projection, electronic speckle pattern interferometry (ESPI), shearography, digital holographic interferometry (DHI), etc. [3–6], are in continuous development. During the last couple of decades NDT are increasingly replacing their mechanical counter-parts due to their remote sensing and non-invasive features. DHI is a predominant technique because it does not need any moving part within the interferometer's path, as compared to for instance ESPI that requires additional moving hardware for phase acquisition. The optical phase when using DHI can be easily acquired and transformed into a displacement [7–9]. The mechanical study of a sample with DHI is achieved using one, two or three illumination positions. The sample illumination can be done sequentially [10] or simultaneously [11]. The last case gives the three orthogonal displacement components u, v and w with just two images taken at two different sample states [12]. An extension of this technique was presented when three different lasers are used with a single high resolution monochrome sensor [13]. This new configuration gives the opportunity to use long coherence length lasers that can be applied to measure large object areas.

In what follows a further analysis is carried out such that not only the displacement information is obtained but also the strain data is calculated from it. Strain gradient maps over an object's surface helps to evaluate structural features such as in homogeneities and cracks which are directly related to material's failures, a typical issue present in industrial environments [14,15]. Strain measurements using other techniques besides DHI have been widely reported [16–21]. However, in temporal phase shifting techniques the use of piezoelectric translators introduces long acquisition times considering the required number of images. This makes impossible to record fast events even when a pulsed laser is used and most of them are limited to smooth surfaces. The processing advantages of DHI, which needs just two image holograms for a measurement, made it possible to report fast strain measurements even in a non-repeatable experiment [22,23]. Therefore, a much more robust system is required to inspect different objects under diverse type of deformations.

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A system like this needs to be validated under controlled conditions in order to compare its measurements with a more conventional measuring technique.

An aluminum plaque is used to gather the strain information to be validated for the DHI system: this type of plaque's strain data can be easily obtained using a finite element method (FEM), instead of using another available optical technique. As is well known, a FEM algorithm can simulate the material, the forces and other parameters present in a real experiment [24]. The application of FEM in mechanical studies helps to solve systems which have complex strain and stress responses subject to even simple deformation [25–27]. It is also used in studies which involve heat transfer [28], flow [29], fluorescence tomography [30], and biomechanics [31], among many more.

As proof of principle of the proposed DHI setup, the smooth surface aluminum sample is deformed to create strain maps during a mechanical compression, where all its physical parameters are introduced into the FEM algorithm. The experimental results obtained with the DHI system will be described in Section 3, where details on how the sample is fixed and deformed and all the optical parameters of the interferometer will be introduced. A description of the recording and processing of the holograms will be presented, considering the use of a single monochrome sensor that captures three sample images simultaneously in one image. Finally, the orthogonal displacement components along the x, y and z axes are presented and compared with the FEM model. An algorithm creates the experimental strain maps which are compared with the strain numerical simulation, showing that the results obtained with DHI are in quite good agreement with those calculated with the FEM method.

2. Method

The conventional technique in Digital Holographic Interferometry is the two-exposure method where an image hologram is recorded at a particular object state (known or otherwise unknown) and a second image hologram is acquired for an object state different from the first. Each recorded hologram includes the optical overlapping of a reference and an object beam on the camera sensor [32], which registers a total intensity (I) in each case, expressed by:

$$I(x,y) = |R(x,y) + O(x,y)|^2 \tag{1}$$

where R is the reference and O is the object beam, viz.,

$$O(x,y) = o(x,y)\exp[i\varphi(x,y)] \tag{2}$$

$$R(x,y) = r(x,y)\exp[-2\pi i(f_x x + f_y y)] \tag{3}$$

where, o and r represents the amplitude of the object and reference beam respectively. The variable f is the reference wave spatial frequency in the x and y direction, while φ is an optical phase term representing the light scattered from the object surface. Eq. (1) can be rewritten by substituting Eqs. (2) and (3) as:

$$\begin{aligned} I(x,y) &= a(x,y) + c(x,y)\exp[2\pi i(f_x x + f_y y)] \\ &\quad + c^*(x,y)\exp[-2\pi i(f_x x + f_y y)] \end{aligned} \tag{4}$$

where $*$ denotes the complex conjugate and a and c are:

$$a(x,y) = o^2(x,y) + r^2(x,y) \tag{5}$$

$$c(x,y) = o(x,y)r(x,y)\exp[i\varphi(x,y)] \tag{6}$$

In order to find the relative optical phase change due to the undergone object deformation, the procedure is as follows. Eq. (4) is Fourier transformed by means of a fast-Fourier-transform (*fft*) algorithm, see for instance [33], which results in:

$$FT\{I\} = A(f_x + f_y) + C(f - f_x, f - f_y) + C^*(f - f_x, f - f_y) \tag{7}$$

Eq. (7) relates to the case when a single reference-object illumination beam pair is used, but this can be easily rewritten for the 3D-HI system [13] as follows,

$$FT\{I_k\} = \sum_{k=1}^{3}[A_k(f_x + f_y) + C_k(f - f_{kx}, f - f_{ky}) + C_k^*(f - f_{kx}, f - f_{ky})] \tag{8}$$

where k represents each of the three different lasers used and the term A_k depicts the incoherent and/or the DC term present in the system. The terms C_k and $C_k{}^*$ denote the lateral spectral lobes for each illumination wavelength. Considering 3 illuminations, C_1, C_2 and C_3, each one will have a complex conjugate term which is then filtered in, to leave the complex conjugate one out. Next, the remaining one is inverse Fourier transformed in order to obtain its corresponding optical phase distribution by performing the calculation:

$$\varphi_k(x,y) = \arctan\frac{Im[c_k(x,y)]}{Re[c_k(x,y)]} \tag{9}$$

This procedure is repeated for the object in its deformed state and the optical phase distribution is obtained for each illumination as $\varphi'_k(x,y)$, and finally the relative phase difference for each illumination is calculated as:

$$\Delta\varphi_k(x,y) = \varphi'_k - \varphi_k \tag{10}$$

This relative optical phase difference can be associated to a physical displacement through the sensitivity vector found in the experimental set up [12], which can be expressed as,

$$\Delta\varphi_k = \left(\frac{2\pi}{\lambda}\right)\vec{d}\cdot\vec{s}_k \tag{11}$$

that in turn may be rewritten as a matrix,

$$\begin{pmatrix}\Delta\varphi_1\\ \Delta\varphi_2\\ \Delta\varphi_3\end{pmatrix} = \frac{2\pi}{\lambda}\begin{pmatrix}\vec{s}_{1x} & \vec{s}_{1y} & \vec{s}_{1z}\\ \vec{s}_{2x} & \vec{s}_{2y} & \vec{s}_{2z}\\ \vec{s}_{3x} & \vec{s}_{3y} & \vec{s}_{3z}\end{pmatrix}\begin{pmatrix}u\\ v\\ w\end{pmatrix} \tag{12}$$

where u, v and w are the orthogonal displacement components along the x, y and z axes respectively. With this information and considering small deformations applied to the object, it is possible to find the surface strain data. This strain is defined as the length variation in a line segment of two points in the sample divided by the length of the original line segment [34,35]. The in-plane strain terms to be calculated may be expressed in their engineering reduced form as:

$$\varepsilon_x = \frac{\delta u}{\delta x} \tag{13a}$$

$$\varepsilon_y = \frac{\delta v}{\delta y} \tag{13b}$$

$$\gamma_{xy} = \frac{\delta u}{\delta y} + \frac{\delta v}{\delta x} \tag{13c}$$

where ε_x and ε_y are the normal strain maps along the x and y directions respectively, and γ_{xy} is the xy shear strain term. The latter can be solved considering that 3D-DHI obtains the three components of deformation u, v and w as function of x and y, i.e. $u(x,y)$. Certainly, this does not give enough data to evaluate all the derivatives required for all the strain equations in a direct form [36] without an approximation algorithm [37]. However, for the validation process only three strain maps are presented as proof of principle of 3D-DHI used in a simultaneous manner.