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Multiple-aperture one-shot shearography for simultaneous measurements in three shearing directions

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ABSTRACT

A new shearography configuration was developed to simultaneously acquire images of a specimen in three different shearing directions, the proposed configuration is capable of performing measurements of shearography with multiple shearing directions using just one single interferogram. The device uses a three aperture mask and a single imaging lens to produce interference speckles with carrier fringes in three different directions. A set of three wedge prisms are used in combination with the three apertures to produce simultaneous shearing interferograms for three different orientations. A single high-resolution image of the specimen is captured for each loading level and the phase maps are computed by FTM (Fourier Transform Method). Additionally, as the device has no movable parts and just a single shot image is acquired, it is very compact, robust and can be successfully used outside the optical bench. The paper presents the optical setup and a practical application for the new technique.

1. Introduction

Composite materials are very good options for construction and repair of pipes, tanks and pressure vessels used in the oil and gas industry due to their high resistance to corrosion and the ability to be cold-applied without a welding arc being opened. Composites are non-homogeneous materials usually formed by combinations of fibers and a polymeric matrix. Repairs and protective coating of composite materials area frequently applied over steel parts locally in Oil & Gas plants. In this non-ideal environment there is a high incidence of internal defects that can reduce their mechanical performances. Nondestructive Techniques (NDT) are frequently required to verify the integrity of critical parts and ensure a high level of reliability [1], since they allow quick monitoring of the structure's integrity.

Shearography is an optical Nondestructive Technique (NDT) capable of measuring displacement gradient fields on the surface of materials [2]. Since it is a quasi-common-path interferometric technique [3], shearography is less sensitive to environmental disturbances when compared with other interferometric techniques [4], making it suitable for inspections in the field [5].

A typical shearography setup requires some basic elements, as shown in Fig. 1: an illumination module, an interferometer and a specialized software to drive the measurement procedure. Image acquisition and processing usually involves temporal phase-measurement (TPM) techniques, which requires a sequence of, at least, three interferometric images with known relative phase shifts [6]. This approach requires high stability during image acquisition to minimize measurement errors.

As alternatives for enabling measurement in hostile environments, different techniques have been proposed in the literature. The most promising are the so named one-shot techniques. The measurement is done from a single image for each loading state [7]. These include simultaneous acquisition of images with multiple sensors [8] and simultaneous acquisition of multiple images in a single sensor for instance using diffractive optical elements [9–13]. High-quality results can also be obtained from a single image for each loading state using carrier fringes and Spatial Phase Measurement (SPM) [14]. SPM are very effective to reduce disturbances coming from environmental factors, and thus allowing dynamic measurements [15].

By adding carrier fringes, it allows the phase signal to be determined unambiguously from a single interference image [16]. Several works have proposed solutions for the generation of carrier fringes and their processing [15,17] . In the double exposure method [17], the carrier fringe addition occurs by the difference between the interferogram acquired before and after a movement of the light source. Another possibility is to generate the fringes directly in the speckle by tilting one of the arms of the Mach-Zender interferometer [18]. In this case the carrier fringes are directly generated on the speckle of a single interferogram. The main disadvantage is that the Mach-Zender interferometer requires a greater number of optical elements than the traditional Michelson interferometer, which make the shearography system bulky and more sensitive to disturbances for applications in industrial environments.

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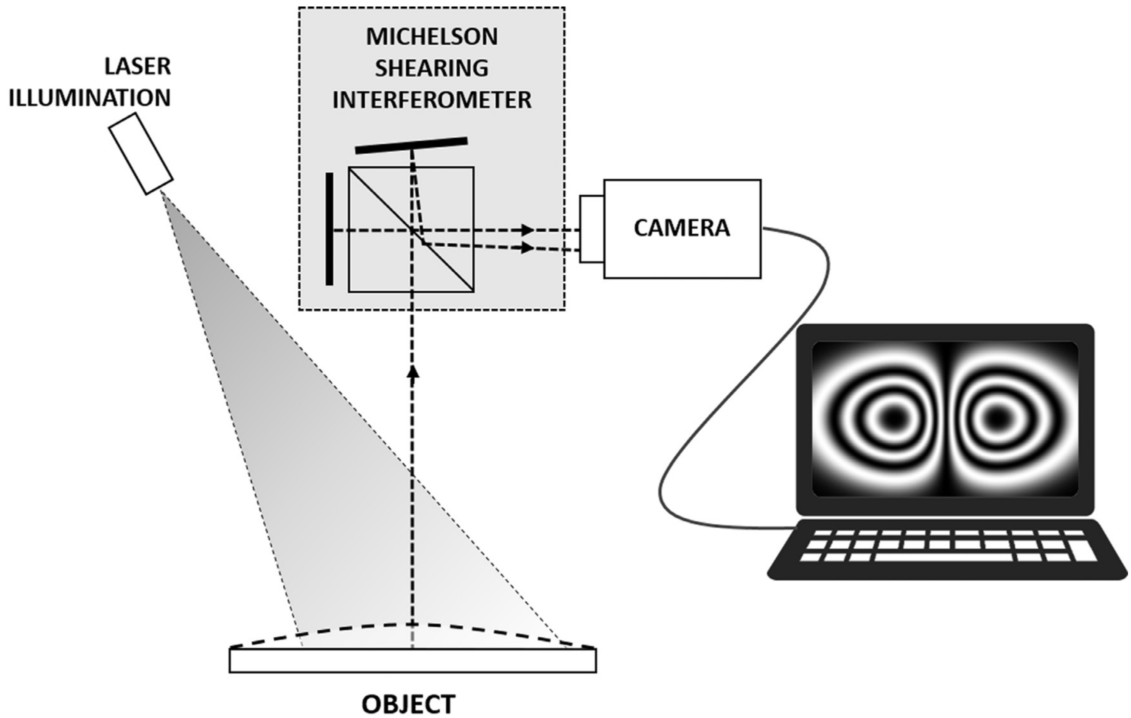

Fig. 1. Typical shearography setup.

Another more promising option is the use of a double aperture and a wedge prism [19] to produce a couple of sheared images and carrier fringes simultaneously. This setup requires fewer optical elements, since the wedges are responsible for the lateral shear. Also, the carrier fringes resulting from the double aperture allows phase measurement without any movable elements, which makes the optical configuration simpler and robust.

Generally, in an inspection, two perpendicular shear measurements are made. This, because the quality of the result of the shearography depends of the shear direction, then a defect or a deformation will be more visible depending of that shear [15]. However, guarantee the same load for each measurement is difficult in some cases. By that, previous works explored the simultaneous capture of multiple shearing directions. With the use of a pair of modified Michelson interferometers, SPM and polarization, it is possible to capture two perpendicular shear direction in a single image [20]. Also, it is possible to separate the shearing directions by the use of different wavelength and a camera color [21]. Other application use multiple-image shearography to get the second derivatives components as a method to determine curvatures [22].

In this paper, a novel configuration to perform shearography measurements with multiple shearing directions and just one single interferogram for every load level is proposed. This paper also describes the optical setup and presents a real evaluation using a specimen with mechanical loading.

2. Carrier fringe analysis

The fringe pattern analysis by the Fourier Transform Method (FTM) was developed by Takeda et al. [16] in 1982. All information needed to phase retrieval can be encoded simultaneously in a single image, allowing analysis of transient events. The method requires the presence of carrier fringes usually formed by a set of high frequency parallel fringes [16]. The carrier fringe frequency can be later removed by different ways [16].

The intensity distribution of an interferogram can be expressed by:

$$I_0(x,y) = I_b(x,y) + I_m(x,y)\cos\big(\phi_i(x,y)\big) \tag{1}$$

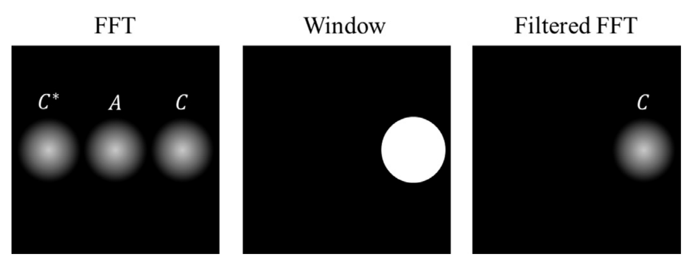

Fig. 2. Carrier fringe analysis in the Fourier spectrum. On the left, the FFT image with the expected three halos is shown. In the middle, a mask representing the band-pass filter applied in the frequency domain. On the right, the resulting FFT image after filtering.

Where $I_b(x, y)$ is the background intensity, $I_m(x, y)$ is the signal amplitude and $\phi_i(x, y)$ is the unknown phase value as functions of the image coordinates (x, y).

After adding the carrier frequency $2\pi f_0 x$ to the expression, it can be re-written as:

$$I_0(x,y) = I_b(x,y) + I_m(x,y)\cos\big(\phi_i(x,y) + 2\pi f_0(x)\big) \tag{2}$$

Applying the 2D spatial Fourier transform to the interferogram, the result is:

$$\mathcal{F}\{I_0(x,y)\} = G\big(f_x,f_y\big) = A\big(f_x,f_y\big) + C\big(f_x - f_0,f_y\big) + C^*\big(f_x + f_0,f_y\big) \tag{3}$$

The result performed, in the frequency spectrum contains three halos, as shown in the Fig. 2. The zero frequency located at the central halo of the spectrum A is the DC term. The desired information is present on the right and left halos $C(f_x - f_0, f_y)$ and $C^*(f_x + f_0, f_y)$, where f_x, f_y are the fringe frequencies concerning to the phase map $\phi_i(x, y)$. Since the terms C and C^* are symmetric, a window filter around the carrier frequency is used to keep only the frequencies contained in the C halo.

A key-step in analyzing carrier fringes is to generate non-overlapping halos in Fourier spectrum. Therefore, it is important to produce a high enough carrier frequency in order to isolate the main frequencies from