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Evaluation of a novel compact shearography system with DOE configuration

Fabio Aparecido Alves da Silva[a], Daniel Pedro Willemann[b], Analucia Vieira Fantin[a,*], Mauro Eduardo Benedet[a], Armando Albertazzi Gonçalves Jr.[a]

[a] *Laboratory of Metrology and Automatization, Federal University of Santa Catarina, UFSC, CEP 88040-970, Florianópolis, Santa Catarina, Brazil*
[b] *State University of Santa Catarina, UDESC, CEP 88790-000, Laguna, Santa Catarina, Brazil*

A R T I C L E I N F O

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A B S T R A C T

The most common optical configuration used to produce the lateral shifted images, in a Shearography system, is the Modified Michelson interferometer, because of its simple configuration. Tests carried out in recent years have shown that the modified interferometer of Michelson is a device that presents good results in a laboratory environment, but still presents difficulties in the field. These difficulties were the main motivation for the development of a more robust system, able to operate in unstable environments. This paper presents a new shearography configuration based on Diffractive Optical Element (DOE). Different from the diffractive common-path setups found in literature, in the proposed configuration, the DOE is positioned between the image sensor and the objective lens and mounted on a flexible holder, which has an important function to promote the system's robustness. Another advantage of the proposed system is in respect to phase shifting, since it is insensitive to wavelength variations. The lateral movement of the DOE produces a phase shifting in the shearography system. Since the pitch of the diffractive grating used is about 60 times greater than the wavelength of a green laser, the DOE configuration becomes much more robust to external influences compared to the Michelson Interferometer configuration. This work also presents an evaluation of the proposed shearography system designed, and some comparative results regarding a classical shearography system.

1. Introduction

Shearography [1–3] is a special case of the DSPI (Digital Speckle Pattern Interferometry) techniques [4–6] where the speckled interfering wave fronts come from the sample, which are the reference and the object simultaneously. Shearography has the advantage of allowing short coherent length illumination and are less sensitive to environmental disturbances than other holographic techniques [3]. However, tests carried out in recent years have shown that the Shearography system based on quasi-common path interferometers, like modified Michelson interferometer, presents good results in a laboratory environment, but still presents difficulties in the field due to higher vibration levels induced by industrial equipment in operation . These difficulties were the main motivation for the development of a more robust system able to operate in unstable environments. The proposed configuration presents a common-path interferometer based on Diffractive Optical Element (DOE). The idea of using a DOE as shearing device in shearography applications is not new [7–9]. Different from the DOE common-path setups found in literature, in the proposed configuration, this optical element is placed between the image sensor and the objective lens, and assembled on a flexible holder, which has an important function to promote the system's robustness. The design using a DOE to generate the lateral shifted images is an effective alternative regarding classical interferometers, and becomes much more compact and robust to external influences. This work describes the development and the evaluation of a shearography system based on DOE configuration and presents comparative results to another Shearography system based on Michelson interferometer.

2. Shearography

A traditional shearography setup requires some basic elements: an illumination module, an optical device to generate the double image, an excitation module and a specific software that drives the image acquisition procedure. Fig. 1 shows the basic setup for shearography measurements.

An expanded laser beam illuminates the specimen under investigation, which generates speckle patterns on the surface [5]. The head sensor is designed to form the laterally sheared image of the surface. After the acquisition and processing of the images, shearography mea-

* Corresponding author.
E-mail address: analucia.fantin@labmetro.ufsc.br (A.V. Fantin).

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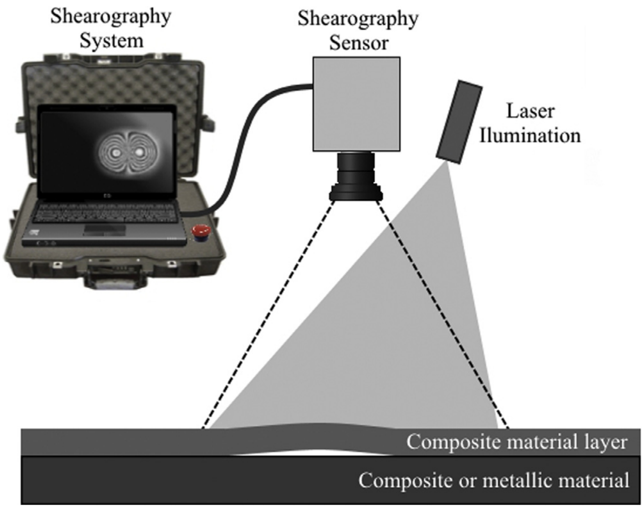

Fig. 1. Basic setup for shearography measurements.

surement reveals changes in the deformation field of the surface of the structure under investigation, in response to an applied load. In spite of shearography inspections occurring only on the external surface of the material, this technique is highly sensitive to subsurface flaws as disbonds, delaminations, core damages, core splices, joint separations as well as surface damages [10–13]. The defects located below the surface, after application of the load, causes non-uniform deformation on the surface. For this reason, shearography has been used as a non-destructive method for inspection of composite materials.

3. Diffractive optical element - DOE

Diffractive Optical Element [14–16] is an optical element containing a series of repeated elements on a plate surface, which can be thin grooves or lines. This periodic structure changes, in a controlled manner, the phase or the amplitude of a light wave. There are two types of DOEs: reflection and transmission. In the transmission type, the regular depth variations of the thin grooves are responsible for the light phase modulation. The superposition of the emerging waves results in a symmetric angular distribution of the maximums of intensity, called diffraction orders. The diffraction angle of the light θ_m, in a given diffracted order m, can be calculated by

$$\theta_m = \sin^{-1}\left(\frac{m\lambda}{\Lambda} - \sin\theta_i\right) \quad (1)$$

where λ is the wavelength, Λ the groove spacing and θ_i the incident angle of the light.

The groove spacing (Λ) determines the angle of separation of the diffractive orders where small values of Λ give large angles and vice-versa. When the grating duty cycle is 50%, the element is a binary phase grating. The phase difference ϕ_d between the output emerging waves is produced by the depth variations and can be evaluated through:

$$\phi_d = \frac{2\pi(n-1)d}{\lambda} \quad (2)$$

where n is the refraction index of the grating material and d is the depth of the slit. If the slit depth is adjusted in order to reach a phase difference ϕ_d equal to π, it results in the cancellation of the light propagation in the order 0 and in the subsequent even orders. Then, the efficiency of diffraction (η_m) of each positive or negative odd order can be reached by:

$$\eta_m = \left(\frac{2}{m\pi}\right)^2 \quad (3)$$

Small variations in the periodic geometry of the grids vary the angle and the grating efficiency. Unfortunately, the designed DOE tolerances are difficult to achieve due to faults in the diffractive grating manufacturing processes. However, some calculations allow the evaluation of the effects of these faults in the performance of the diffractive elements [16] and, for this reason, the geometry of the periodic grid pattern must be known. A Scanning Electron Microscope (SEM) was utilized to evaluate the geometries of diffractive optical elements. Nevertheless, as the DOE material is not conductive, an ultrafine layer of conductive material should be deposited on the DOE surface to be analyzed in the SEM, making it use impossible in the shearography system after the analysis. Therefore, an alternative method was used to evaluate the performance of two different diffractive gratings: the first one was a blazed grating with higher intensities in the 0 and +1 orders (0+1 DOE), and the second one was a binary grating with higher intensities in the −1 and +1 orders (−1+1 DOE). Fig. 2 shows a test bench containing a laser power meter to measure the grating efficiencies.

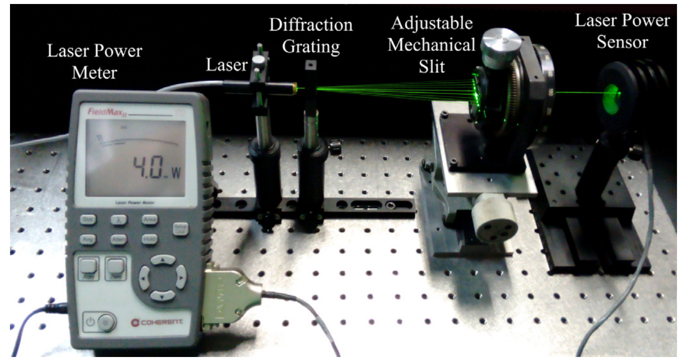

Fig. 2. Test bench to evaluate DOE efficiency.

Table 1
Order efficiencies of the two evaluated grids compare to the ideal values.

Diffraction order	Order efficiencies (% I_{laser})			
	DOE 0+1		DOE −1+1	
	Manufacturer data	Measured	Ideal	Measured
−4	–	<1	0	<1
−3	–	<2	4.5	3
−2	–	<1	0	<1
−1	–	<2	40.5	39
0	41	29	0	<1
+1	32	40	40.5	39
+2	–	9	0	<1
+3	–	<1	4.5	3
+4	–	<1	0	<1

Initially, only the light intensity of the laser was evaluated, which was used as a reference for calculating the efficiency of each DOE order. Then, by using an adjustable mechanical slit positioned between the diffractive grating and the sensor of the laser power meter, it was possible to select the diffracted beam, whose intensity would be evaluated. For an ideal binary phase grating, the strongest light propagation happens in the first positive order where 40.5% of the incident light is directed. By symmetry, an equal amount of 40.5% of the incident light propagates to the negative first order [16]. Table 1 shows the diffraction order efficiencies for an ideal binary phase grating when the incident light is perpendicular to the back or front surface of transmission gratings $(\theta_i = 0)$.

The −1+1 DOE presented a small variation when compared to the theoretical values. However, interference remains predominant in orders −1 and +1. The contribution of the other odd orders is irrelevant, since these have very low intensities. On the other hand, the 0+1 DOE presented an intensity difference of 11% between its main orders. In addition, +2 order had a higher efficiency than expected and, in this case, the application of this grid in the shearography system produces a triple interference, which degrades the interferogram quality. Therefore, as