Mechanical Systems and Signal Processing 118 (2019) 259–276

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Evaluation of noise in measurements with speckle shearography

H. Lopes [a,*], J.V. Araújo dos Santos [b], P. Moreno-García [c]

[a] DEM-ISEP, Instituto Politécnico do Porto, Portugal
[b] IDMEC, Instituto Superior Técnico, Universidade de Lisboa, Portugal
[c] Departamento de Ingeniería Mecánica y Diseño Industrial, Escuela Superior de Ingeniería, Universidad de Cádiz, Spain

ARTICLE INFO

Article history:
Received 11 September 2017
Received in revised form 23 July 2018
Accepted 15 August 2018

Keywords:
Speckle shearography
Speckle interferometry
Numerical simulation
Measurement noise

ABSTRACT

Speckle shearography has the advantage of allowing non-contact, full-field and high resolution measurements. Nevertheless, due to its nature and to its sensitivity to ambient perturbations, the measurements may present high levels of noise. The evaluation of the experimental noise is needed in order to assess the degree of accuracy of the measurements. This assessment is not straightforward since the measurements will involve resolving simultaneously the phase discontinuities and the phase fluctuations produced by the noise which are 2π wrapped. The phase discontinuities can be easily removed if the phase map is smooth and the phase jumps are not greater than 2π rad. However, this procedure cannot be directly applied for resolving the random phase fluctuations produced by the noise. In this work, a method is proposed to efficiently evaluate the noise in measurements with speckle shearography whenever it is in the range $[-\pi, \pi]$. The limits of the proposed method are assessed by applying it to phase maps with added noise, which are obtained through the numerical simulation of speckle shearography. The results show a very good evaluation of noise with low and moderate amplitudes. Finally, the proposed method is used to evaluate the experimental noise in rotation fields of a free-free aluminum beam measured with speckle shearography.

1. Introduction

Since the early 1970s, when laser speckle interferometry began to be fully understood and the first speckle pattern interferometry and speckle shearography systems were developed [1–5], a large amount of improvements have been reported. Besides the obvious enhancements coming from the use of more efficient lasers, data acquisition and control systems, as well as high resolution video cameras, among others improvements, the development of image processing algorithms used to extract quantitative information of accurate displacements and their derivatives is also very important. Nevertheless, a complete understanding, quantification and correction of the measurement noise and errors is still lacking in the literature.

A difficulty in the study of noise and errors in the measurements with speckle interferometric techniques is linked to their many sources and the complexity of their description. For instance, according to Zastavnik et al. [6] there are several errors in shearography that are discussed in the literature, namely errors due to (1) linearization of the equations describing shearography, (2) environmental disturbances, (3) application of phase reconstruction algorithms, (4) assumption of constant

* Corresponding author.
E-mail address: hml@isep.ipp.pt (H. Lopes).

https://doi.org/10.1016/j.ymssp.2018.08.042
0888-3270/

sensitivity vectors, (5) measurement errors of the shearing distance and assumption that this distance is constant, (6) lack of stability of the measurement components setup, and (7) rigid body translation and rotation. Picart [7] lists several potential error sources related to the laser source, the Pockels cell, the polarizing beam splitter, the interferometrical cavity optical setup and the detection, when one uses a Mach-Zehnder interferometer. This author also classifies the different errors as random or systematic. Kreis [8] discusses several difficulties and problems one faces in the quantitative evaluation of the interference phase. These difficulties and problems are categorized as follows: (1) sign ambiguity, (2) absolute phase problem, (3) varying background illumination, (4) electronic noise, (5) speckle decorrelation, (6) digitization and quantification, and (7) environmental distortions.

The measurement noise and errors are also difficult to quantify because we need results from an updated model of the specimen to compare with the shearography measurements. A possible and limited way is to use directly a finite element analysis as a tool to define reference results. It was with this approach that Rosso et al. [9] reported a difference of up to 12% in the displacement gradients of a centrally loaded steel plate measured with shearography and the results of a finite element model. A similar comparison between simulations of a complete shearography system and finite element results was carried out by Goto and Groves [10]. The tested samples were a flat plate loaded axially and a cylinder loaded by internal pressure. The material properties uncertainty, loading inaccuracy and manufacturing tolerances caused an error of 4π (two fringes) on the central area of the phase maps. The time dependent creep behavior of the PZT shear actuator is, according to Zastavnik et al. [11], a major source of measurement errors. The influence of external vibrations on the noise is also studied, showing that environmental isolation is crucial. Practical suggestions are given to quantify the influence of the PZT creep as well as how to estimate the time dependent noise due to the environmental influences.

We can also find in the literature several models for the analysis of noise and errors. For example, Abdullah et al. [12] developed a theory to describe the error contribution of non-collimated object illumination in an out-of-plane shearography system. It is demonstrated that the non-collimated illumination wavefronts contribute to errors of the order of 5–10% in the quantification of out-of-plane surface derivatives. Abdullah and Petzing [13] optimized and updated the theory presented in [12], by including phase error terms, which are dependent on the object distance. Thus, the phase error contribution takes values of 0.15% at a 1000 mm distance and 1.48% at a 200 mm distance.

The quality and confidence of measurements of large-scale structurally loaded aircraft wheels, obtained with a speckle shearing interferometer, was considered by Ibrahim et al. [14]. They rely on the repeatability and reproducibility of the data to define the quality of the measurements. The surface displacements components in the range 0–15 μm were measured and correlate well with pointwise data collected using a linear variable-displacement transducer (LVDT). Creath and Schmit [15] presented the analysis of the error magnitude in spatial phase-measurement produced by the three, four and five points numerical algorithms for the computation of the intensity (irradiance) recorded by a detector. They found that all the algorithms produce a similar result if the modulation intensity in the edges of the interferogram is kept greater than 50% of that at the centre. Huntley [16] considered the noise in the production of phase maps by digital phase stepping speckle interferometry. The study includes quantitative descriptions of speckle decorrelation and electronic noise, which are, according to this author, the two main noise sources. The optimum ratio of object beam to reference beam intensities, the effect of speckle diameter and the methods for noise reduction are also discussed. Huntley [17] also reviewed the main interferometric techniques and numerical algorithms used to measure displacement and strain fields in solid mechanics. The systematic and random errors associated with several procedures are also studied in this work and it was found out that this last type of errors in the measurement of strain fields vary inversely with the square of the gauge length (spatial resolution). Systematic errors of phase-shifting speckle interferometry were also investigated theoretically and numerically by Picart et al. [18]. The proposed algorithms, describing the influence of the modulation parameter and the systematic errors, were validated by numerical simulation and show a good agreement with the theoretical analysis. It was also found that the accuracy obtained is limited by the contribution of the modulation parameter. The contribution of this parameter appears to be quite larger than the contribution of the systematic error.

Once the measurement noise and errors are defined and described, one may try to minimize their influence, by calibrating the devices used in the shearography system by improving the numerical techniques used in the post-processing of captured images. A noise immune phase unwrapping method was proposed by Kadono et al. [19]. The method was verified with computer simulations and actual experiments with a speckle shearing interferometer. The authors concluded that the best filtering is obtained when the size of the spatial window takes multiples of the average speckle size. In a method proposed by Molimard et al. [20], the decorrelation effects are counteracted by evaluating translations at local level. The procedure of signal-to-noise ratio optimization is applied to simulated speckle patterns and to captured images from a plate specimen, subjected to mechanical deformation. More recently, Zastavnik [6] proposed a procedure to calibrate and correct shearography measurements. The procedure is illustrated by two test cases, which are based on the minimization of the discrepancy between experimental and finite element analysis results.

The present work aims at defining a method for the evaluation of the noise present in experimental measurements obtained with speckle shearography. We consider here that noise is a source of random uncertainties in experiments and therefore can be treated statistically [21]. Thus, in the present work we do not take into account systematic errors, which cannot be treated statistically [21,22] and are linked to the calibration of the instruments and the experimental procedures [21]. The accuracy and limits of the method are assessed by applying it to numerical phase maps with added noise, thus simulating measurements on a free-free beam. The results show a very good evaluation of the levels for small and moderate noise. The proposed method is also used to evaluate the experimental noise in rotation fields of a free-free aluminum beam,