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Original

Contouring reflective plates along a curved strip using the intensity integration technique: Experimentation and simulation

A. Vijaya*, G. Subramanian, V.S. Lakshmipriya

School of Mechanical Engineering, SRM University, India

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Abstract

The intensity integration technique (IIT) is one of the simplest intensity-based image processing techniques used to determine the deformation field of a reflective specimen (1D or 2D) under loaded conditions. It works on the energy conservation principle. The total quantity of light that falls on the specimen, before and after loading it, is assumed to be the same, and hence, the integrated (cumulative) intensity is used as a correlation parameter to find the change in position of any point from one state to the other. Because the cumulative intensity is unidirectional, it is simple to apply IIT on the one-dimensional object. This work aims to apply IIT on the curved strip to find the deformation field of centrally loaded clamped plates along that stripe. The experimental results are compared with the numerical solution. Simulation is done to mimic the behavior of the several types of curved strips (grid pattern) at various positions for different loading conditions based on one-to-one mapping of finite element (FE) models with experimental images.

Keywords: Intensity integration technique; Centrally loaded clamped circular plate; FE modeling; MATLAB simulation; Partial slope and curvature

1. Introduction

Various optical measurement techniques and methods have been developed over the last five decades in the field of optical metrology and structural mechanics (De la Torre, Hernández Montes, Flores-Moreno, & Santoyo, 2016). Optical measurement techniques mainly make use of reflected light rays from the specimen to obtain its deformation field applying either interferometric or non-interferometric principles (Kulkarni & Rastogi, 2016). Moiré methods, electronic speckle shearing interferometry and holographic interferometry are techniques which work on interferometric principles. The Moiré shearing interferometers (Subramanian & Subramanian, 1996; Wang & Yim, 1992) use shearing grid procedures for obtaining the curvature and slope contours of the loaded reflective specimens. Electronic speckle shearing interferometry (Aebischer & Waldner, 1997; Groves, James, & Tatam, 2004) records the intensity of fringe patterns obtained because of the interference between the speckle shear waves scattered from the object in the loaded state.

Electronic speckle pattern interferometry (ESPI) (Muravski & Fit'o, 2005; Tendela, Galizzi, Federico, & Kaufmann, 2011) records the intensity images of speckle patterns produced on rough surfaces in load and unloaded state. The fringe pattern is obtained by subtracting the intensity images and applying phase shifting procedure to determine the displacement. Digital image correlation (DIC), a well-known technique, aims to correlate the images of physical speckle patterns generated on the object surface in the loaded and unloaded states (Chu, Ranson, & Sutton, 1985; Hild & Roux, 2006; Schreier, Orteu, & Sutton, 2009). The references listed are representative and not exhaustive. Thus, the literature related to correlation techniques like ESPI and DIC requires two intensity images captured in loaded and unloaded states. The correlation between the images is achieved through numerous phase-shifting techniques in ESPI, and by maximizing the correlation coefficient between the subsets through various scanning procedures in DIC.

The intensity integration technique (IIT) is also an intensity-based image correlation technique based on the energy

* Corresponding author.
E-mail address: avijaya.ravikumar@gmail.com (A. Vijaya).
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conservation principle. It has similarities with the other techniques like ESPI and DIC in capturing two digital images in different states of the object but it differs in the experimental set up and correlating algorithms. This technique does not project any speckle pattern on the specimen surfaces (DIC), nor does it use a more complicated experimental setup (ESPI). The experimental setup for IIT has an optical bench where the specular reflecting cantilever specimen is illuminated with a diverging laser beam (Subramanian & Jagannath, 2001). The reflected light from the specimen is made to fall on the screen. The reflected images in two states of the specimen are captured using a CCD camera and used for finding the deformation field. The cumulative sum of image intensities reflected off any specular reflecting specimen across two states (load and unload) is assumed to be same. The difference in the pixel positions where the cumulative sum of reflected intensity arrays is equal in the two states of the specimen gives the shift along the length of the cantilever. This shift in the reference point (pixel location) is used to determine the slope of a tip-loaded cantilever.

The above concept is introduced for two-dimensional surfaces, like plates, for determining the surface topology (Subramanian & Ramana kumar, 2006). In order to obtain the deformation field over the whole domain, it is segregated into several unidirectional strips optically and IIT is applied along these strips. These horizontal strips in the unloaded specimen change their shapes while loading the plate. The change in position of the pixel is clearly visible in the vertical direction and not along the horizontal direction. Since IIT is unidirectional, the shift Δx experienced by the pixels from their original position in the guidelines is determined by using cumulative intensity as the correlation parameter. Thus the slope values at each point in the guideline are obtained with the help of the following equations:

$$\frac{\partial w}{\partial x} = \frac{\Delta x}{2D} \tag{1}$$

$$\frac{\partial w}{\partial y} = \frac{\Delta y}{2D} \tag{2}$$

In the above D denotes the distance between the object and screen.

The objective of this study is to apply unidirectional IIT on a curved strip instead of straight line strips as in earlier work (Subramanian & Ramana kumar, 2006) while contouring a centrally-loaded clamped circular plate. The shape of the curved strip is carefully chosen in such a way that it is non-overlapping. The deformation is computed along the curved strip. Many such strips may be used to cover the whole field.

In the present study, firstly, an optical experiment is conducted on a centrally loaded clamped circular plate with the curved strip (S-shaped grid) projected on it. The images with the curved strip in load and unload conditions are captured. IIT is applied along the curved strip to find the deformation field of a centrally loaded clamped plate along its length. The results are compared with the finite element (FE) analysis.

Secondly, a centrally loaded clamped circular plate is modeled and analyzed for known central deflection in ANSYS (Lawrence, 2002). The nodal coordinates and nodal partial slope values are exported to MATLAB to create a mathematical model of it. The mathematical model and the experimental images are mapped and compared one-to-one in a simple manner, taking into account the magnification factor. This is in contrast to more complex procedure where the comparison of FE modeling with experimental data is done by considering the displacement and strain field as images and their decomposition (Lampeas, Pasialis, Lin, & Patterson, 2015). The slope values along the curved strip are extracted, and a simulation is presented to mimic the behavior of the loaded specimen and change in position of the curved strip under different loading condition as well as for different spatial positions within the field.

2. Intensity integration technique (IIT) and experimental verification

2.1. Intensity integration technique

When the specular reflecting specimen is illuminated with a laser, the reflected intensity from it is made to fall on the screen, captured as the image before and after loading. The intensity integration technique, which builds on the principle of energy conservation, considers the total quantity of light reflected off the specimen to be equal in both states. This is applicable for small loading conditions. The cumulative sum of intensities, from the reference point (generally on the edge of the work piece where the slope is zero) on both images, used as correlation parameter, to find the shift Δx or Δy in terms of the change in indices of a point along the intensity array, utilized for determining the slope using Eq. (1) or (2) (Subramanian & Jagannath, 2001).

A circular reflecting plate made of Perspex sheet of diameter 40 mm is clamped tightly around the edges using a fixture, and a collimated beam of laser light is made to fall on it. The laser and other optical elements along with the specimen are placed on the optical bench for better alignment. The experimental setup is the same as in (Subramanian & Ramana kumar, 2006), except for the shape of the grid. The S-shaped curved strip, printed on a transparent sheet, acts as grid. It allows light through the transparent region in it and thus, a curved strip is projected on the plate by placing the grid on the path of the laser. The screen receiving the reflected light from the specimen is kept by the side of the bench at a distance D from the specimen in a near-normal position. The angle the reflecting light path makes with the illuminating light path is about 7°. Accordingly, the specimen is tilted slightly with respect to the illumination direction. The images, captured using a camera with half an inch CCD sensor from the matte white screen, get digitized and transferred to the computer. The central deflection 'w' is given on the plate through the thread mechanism which, in turn, is attached to the dial gauge. Once the experimental setup is aligned properly, the specimen is loaded with a pin for central deflection of 0.07 mm. The loaded image is captured first, and the deflection is released to capture the unloaded image.

The experimental setup is shown in Figure 1.