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Optical measurement on dynamic buckling behavior of stiffened composite panels under in-plane shear

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ABSTRACT

The buckling behavior and failure mode of a composite panel stiffened by I-shaped stringers under in-plane shear is studied using digital fringe projection profilometry. The basic principles of the dynamic phase-shifting technique, multi-frequency phase-unwrapping technique and inverse-phase technique for nonlinear error compensation are introduced. Multi-frequency fringe projection profilometry was used to monitor and measure the change in the morphology of a discontinuous surface of the stiffened composite panel during in-plane shearing. Meanwhile, the strain history of multiple points on the skin was obtained using strain rosettes. The buckling mode and deflection of the panel at different moments were analyzed and compared with those obtained using the finite element method. The experimental results validated the FEM analysis.

1. Introduction

High-performance, lightweight, multifunctional, and low-cost structures are becoming essential in the construction of modern aircraft. Typical components that are widely used for composite aircraft structures include M-shaped, I-shaped, L-shaped, and multi-wall structures. The laminate panel can be made of a multilayer fiber reinforced composite laminate or sandwich. These light-weight grid structures of composite panels are usually used in important parts of a modern plane (fuselage and wing), which should have the capacity to remain in operation well beyond the buckling load. The aircraft composite structures are subject to air compression, shear and thermal load in service and are prone to different buckling modes in different loading stages [1,2].

In particular, these components will inevitably appear fatigue and damage over time, so the composite panels will undergo more complex buckling and post-buckling in the grid structures with local damages or defects [3,4]. Local large deformation during post-buckling will cause complex damages in layers and between layers, including fiber breakage, matrix cracking, delamination, debonding, and plate-rib separation. The final sudden collapse of the structure becomes inevitable.

The development of buckling mode is a basic feature of the structural deformation of stiffened panels. There are a lot of research on the buckling and post-buckling behavior under compression [5–7], shear [8], and other complex compression-shear loading conditions [9]. Optimizing the composite structure to improve the ultimate bearing capacity and establishing numerical model to predict the post-buckling behavior of composite structures are essential. It is very also important to verify such models using well-documented experimental results. Zhu et al. [5] used the shadow Moiré technique to directly monitor the buckling wave evolution of a specimen during the entire compressive loading process.

Optical measurement techniques method has advantages of non-contact, full-field, high accuracy and real-time [10]. Phase shifting method can accurately measure phase change with three fringe patterns at least, which is suitable for phase measurement on quasi-static load condition. For dynamic phase measurement, Li et al. [11,12] employed time sequence speckle pattern interferometry to measure large deformations of pure Ni thin films subjected to bending without phase shifting method or carrier fringe. Qian [13] reviewed the applications of windowed Fourier fringe analysis, which is able to extract phase from only one fringe pattern and is naturally a good choice for dynamic measurement. However, the above measurement methods are difficult to ensure both the sub-millimeter accuracy and the square-meter-level measurement area.

In recent years, non-contact and full-field optical surface profilometry has become increasingly important in both industrial applications and scientific research [14–16]. Fringe projection profilometry (FPP) was developed to measure the full-field height topography of a stiffened composite panel under compression

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[6,7]. For discontinuous surface objects, Wang et al. [17] considered a multi-frequency fringe method without phase-unwrapping. Xu et al. [18] proposed a multi-frequency projected fringe profilometry for measuring objects with large-depth discontinuities. The nonlinear phase error in the measurement system is caused by the nonlinear electronic noise in a projector and CCD, and the non-sinusoidal wave from external environment. Ma et al. [19] investigated some effective and practical phase-error correction methods, such as look-up-table (LUT) compensation, intensity correction, gamma correction, and a LUT-based hybrid method, for determining the most suitable method for different test environments. Lei et al. [20] proposed a unique method of multi-frequency inverse-phase fringe projection, which can not only measure the topography of a discontinuous object, but also can eliminate the influence of nonlinear errors.

In this context, the FPP method has been developed as a reliable means to detect the dynamic buckling of a composite panel with I-shaped stringers under in-plane shear. The basic principles of the dynamic phase-shifting technique, multi-frequency phase-unwrapping, and nonlinear phase error compensation are briefly described. Then, the test setup for the optical and electrical measurements is introduced and used for real-time monitoring of the deformation process of the composite specimen under an in-plane shear load. The full-field buckling deflection obtained from the nondestructive optical measurement is compared with that obtained through the numerical prediction.

2. Basic principles

2.1. Fringe projection profilometry

A 2D periodic sine fringe pattern is projected onto an object surface and then modulated by the 3D object height into the distortion fringe pattern, which can be reconstructed into a real 3D shape. As shown in Fig. 1, a periodic sine fringe pattern generated by computer displays on the computer's extended screen are projected from the projector to the object surface, while the CCD is simultaneously triggered to grab the distortion fringe, which displays on the computer's monitor.

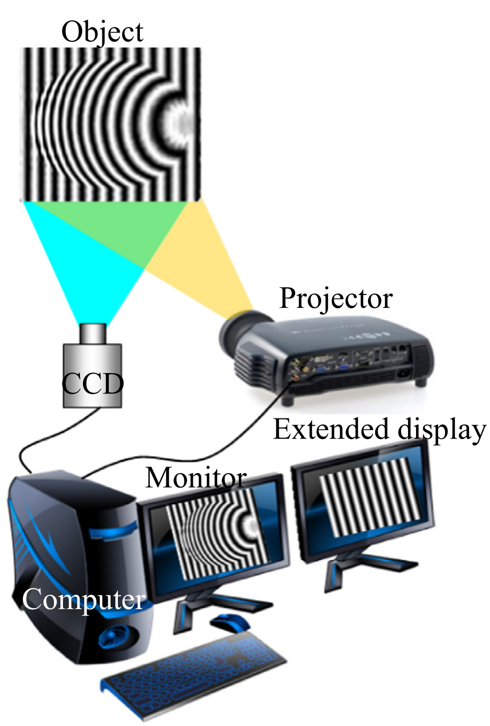

Fig. 1. Fringe projection profilometry using two displays.

In an ideal case, the response function between the camera and projector is linear. A parallel sinusoidal fringe modulated by the measured object changes to a distortion fringe, which can be expressed as

$$I = a + b\ \cos[2\pi f + \varphi], \tag{1}$$

where a and b are the background light and surface reflectivity, respectively, and f is the fringe spatial frequency. The phase φ corresponds to the object height h. If the object is removed, the sinusoidal fringe projected onto the reference plane as a parallel fringe is expressed as

$$I_r = a + b\ \cos\left[2\pi f + \varphi_r\right], \tag{2}$$

where the phase φ_r is the initial phase of the reference plane.

As seen in Fig. 1, the phase difference between the object and the reference plane is written as

$$\Delta\varphi = \varphi - \varphi_r. \tag{3}$$

Generally, the relationship between the height and phase difference can be written as

$$h = \sum_{i=0}^{\infty} A_i \Delta\varphi^i. \tag{4}$$

In this way, a set of experimental height data can be used to determine $i+1$ unknowns, A_0, A_1, A_2,… and A_i. The unknown parameters can be obtained by a linear least-squares method.

2.2. Dynamic phase shifting method

For a fixed optical measurement setup, the calibration coefficients A_i between the phase difference and the object height are known invariants. The measured object height h can be calculated from the phase difference $\Delta\varphi$. After the different initial phases δ_i are introduced into Eq. (1), the phase-shifted light intensity is rewritten as

$$I_i = a + b\ \cos\left[2\pi f + \varphi + \delta_i\right]. \tag{5}$$

For the four-step phase-shifting algorithm, four sinusoidal fringes with initial phases δ_i=0, $\pi/2$, π and $3\pi/2$ (i=1, 2, 3, 4) are projected continuously onto the object surface. Accordingly, the distortion fringes are captured simultaneously by camera. As shown in Fig. 2, the adjacent four images in the image sequence are used for the four-step phase-shifting calculation (PS). The wrapped phase φ_i^w for moment i is obtained as

$$\varphi_i^w = wrap(\varphi_i) = \tan^{-1}\left(\frac{I_{i+3} - I_{i+1}}{I_i - I_{i+2}}\right). \tag{6}$$

The intensities of I_i, I_{i+1}, I_{i+2}, and I_{i+3} correspond to the initial phases of 0, $\pi/2$, π, and $3\pi/2$, respectively. In practice, an *atan2*() function is used to obtain a wrapped phase φ_1^w, which then unwraps to the full-field phase φ. The function *wrap*() indicates a phase wrapping operation.

2.3. Multi-frequency phase-unwrapping method

For a discontinuous object, a spatial phase-unwrapping algorithm for the dynamic phase-shifting method is dependent on adjacent pixels, and error propagation occurs easily owing to the discontinuous area of measured object. A multi-frequency phase-unwrapping algorithm (MPU) is independent of the adjacent pixels and can avoid the abovementioned disadvantage [17,18].

Several sets of phase-shifted sinusoidal fringe images are