Optics Communications 355 (2015) 33–43

Contents lists available at ScienceDirect

Optics Communications

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

Vibration measurement based on electronic speckle pattern interferometry and radial basis function

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ARTICLE INFO

Article history:
Received 30 April 2015
Received in revised form
12 June 2015
Accepted 14 June 2015
Available online 19 June 2015

Keywords:
Vibration
Amplitude fluctuation electronic speckle pattern interferometry (AF-ESPI)
Radial basis function (RBF)

ABSTRACT

A method incorporating amplitude-fluctuation electronic speckle pattern interferometry (AF-ESPI) with radial basis function (RBF) was proposed to investigate vibration characteristics of structures. The vibration patterns were obtained by AF-ESPI. A novel pre-filtering RBF method was presented to improve the quality of patterns. The out-of-plane vibration amplitude was rebuilt after fringe analysis. Ideal pre-filtering widow sizes for the presented RBF were given based on numerical experiments. For validation, an aluminum circular plate with fixed boundary was determined and compared with FEM, confirming the effectiveness of the proposed method. Finally, vibration characteristics of sandwich panels with honeycomb core were measured. The influence of presence of a pre-notch at different location was also investigated.

1. Introduction

Vibration is the motion of a body or system of connected bodies displaced from a position of equilibrium. Resonant frequencies, mode shapes and amplitudes are the usual parameters chosen for structural vibration investigation. In many cases, the amplitude excited at the resonant frequency can cause a disastrous failure, especially when the flaws are existed in the structures. Therefore, to prevent fatigue failures and get the information for optimization of manufacturing process, accurate measurement on vibration characteristics of structures is crucial.

There are a host of techniques used for vibration measurement, such as accelerometer transducer method, laser Doppler vibrometers (LDVs), holography, digital image correlation (DIC) and electronic speckle pattern interferometry (ESPI). Accelerometer transducer method is a traditional method used to detect and monitor vibration [1,2]. Unfortunately, the transducers adhered on the surface would change the mass of the structure. Besides, only the discrete data can be obtained, and the measured locations must be decided before testing. LDVs are commonly used for vibration measurement. However, complex and high requested works should be prepared before testing [3]. Holography is also well known [4]. Although this method is suitable for high frequency measurement, it is possible to apply mainly in laboratories—to ensure the stability of the holographic equipment. As for DIC, it is a practical and effective optical technique for surface deformation measurement [5,6]. However, the accuracy and computational efficiency of DIC rely on the algorithm. Moreover, the high speed camera must be used during the vibration testing [7]. And large numbers of images would be analyzed after image capturing. Fringe projection can also be applied in vibration analysis [8,9]. One of the outstanding features of this technique is its ability to provide high-resolution, whole-field 3D surface profiling of objects in a non-contact manner. Nevertheless, a high-speed camera is the essential recording device for vibrating objects. Besides, to obtain absolute amplitude map in real-world coordinates, the sequence of deformed fringe images should be processed after fringe analysis, phase unwrapping and system calibration.

Among all optical methods, ESPI is a popular full-field, nondestructive testing tool for dynamic displacement measurement [10,11]. It is more insensitive to environment than holography. The most widely used technique to study dynamic response by ESPI is the time-averaged method, which measurement system is low in cost and easy to set up [12]. And there are three different image-processing methods based on the time-averaged technique: the video-signal-addition method, the video-signal-subtraction

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http://dx.doi.org/10.1016/j.optcom.2015.06.035
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method, and the amplitude-fluctuation method. Amplitude-fluctuation ESPI (AF-ESPI) which was proposed by Wang et al. produces the better visibility and higher resolution of fringe pattern than other two methods [13]. Because both resonant frequencies and the corresponding mode shapes can be determined experimentally, AF-ESPI has been applied on the vibration measurement of many materials [14,15].

Although stable vibration fringe patterns can be obtained by AF-ESPI, the resulting images are unavoidably contaminated by the optical noise, electronic fluctuation and air disturbance. A multitude of methods have been used to remove the noise, such as mean filter, median filter, low-pass Fourier filter, partial differential equation (PDE) based method [16], spin filters [17] and Fourier transform based method [18]. Radial basis function (RBF) method, which is a powerful mathematical tool for scatter data approximation [19], can also be applied to filter the image. It has been used extensively in the context of multivariate interpolation including image interpolation from scattered data because of its advantage of involving a single independent variable regardless of the dimension of the problem [20–22].

In this research, AF-ESPI was applied to investigate the vibration characteristic of panels. Moreover, a novel pre-filtering RBF method was presented to improve the quality of patterns obtained by AF-ESPI. Proper size of pre-filtering window was given based on numerical experiments. Then central lines of dark and bright fringes can be extracted by thinning algorithm easily. Furthermore, traditional RBF method was used to reconstruct the continuous amplitudes. Compared with simple fringe methods, the method proposed in this paper does not increase the measurement sensitivity, but it offers following advantages: (1) both the resonant frequency and the corresponding mode shape can be obtained simultaneously, (2) a regular CCD camera is used, (3) the quality of fringe pattern can be improved, and (4) the vibration amplitude can be rebuilt directly from the fringe pattern without calibration or coordinate system transformation. For evaluating its real performance, the pre-filtering method was tested on the AF-ESPI patterns and compared with traditional mean filtering (MF) and low-pass Fourier filtering (LFF) methods, confirming the good noise reduction capacity of the presented method. To verify the feasibility and effectiveness of the proposed method, an aluminum circular plate with fixed boundary was measured and compared with FEM. The comparison of the results demonstrates close agreement. Finally, sandwich panel with carbon-fiber honeycomb cores, which has been received much attention in recent years, was determined by the proposed method. Such kind of structure is widely used in a host of fields, such as aerospace, automotive, marine and light weight structures, because of their excellent capacities of heat resistance, energy absorption and high ratios of strength to weight and stiffness to weight [23–25]. To understand the influence of crack on dynamic behaviors, a pre-notch was introduced at different locations. Results clearly indicate that interference patterns obtained by AF-ESPI and RBF can provide fringes with high quality and quantitative values related to vibrating amplitudes.

2. AF-ESPI

Fig. 1a illustrates the optical system of AF-ESPI for out-of-plane vibrating measurement. When the out-of-plane vibrations of an object are to be measured ESPI, the system is operated in time average. At any time t, the light intensity is given by

$$I(t) = I_0 + I_R + 2\sqrt{I_0 I_R}\ \cos\left(\Delta\varphi + \frac{4\pi}{\lambda}A\ \cos\ \omega t\right) \tag{1}$$

where I_0 is the object light intensity, I_R is the reference light intensity, $\Delta\varphi$ is the phase difference between object and reference light, λ is the wavelength of laser, A is the vibration amplitude and ω is the angular frequency. The intensity is averaged over a time τ, obtaining

$$I_{\tau 1} = I_0 + I_R + \frac{2}{\tau}\sqrt{I_0 I_R}\int_0^{\tau} \cos\left(\Delta\varphi + \frac{4\pi}{\lambda}A\ \cos\ \omega t\right)d\tau \tag{2}$$

Take the time average for m times cycles, we can get $\tau = 2m\pi/\omega$. Then, Eq. (2) can be worked out as

$$I_{\tau 1} = I_0 + I_R + 2\sqrt{I_0 I_R}\ \cos(\Delta\varphi) J_0\left(\frac{4\pi}{\lambda}A\right) \tag{3}$$

where J_0 is a zero-order Bessel function of the first kind.

Assume that the amplitude has changed from A to $A + \Delta A$, then the second intensity can be expressed as

$$I_{\tau 2} = I_0 + I_R + \frac{2}{\tau}\sqrt{I_0 I_R}\int_0^{\tau} \cos\left[\Delta\varphi + \frac{4\pi}{\lambda}(A + \Delta A)\cos\ \omega t\right]d\tau \tag{4}$$

Expand Eq. (4) using Taylor series expansion and neglecting the higher-order terms, Eq. (4) can be represented as

$$I_{\tau 2} = I_0 + I_R + 2\sqrt{I_0 I_R}\ \cos(\Delta\varphi)\left[1 - \frac{1}{4}\left(\frac{4\pi}{\lambda}\Delta A\right)^2\right] J_0\left(\frac{4\pi}{\lambda}A\right) \tag{5}$$

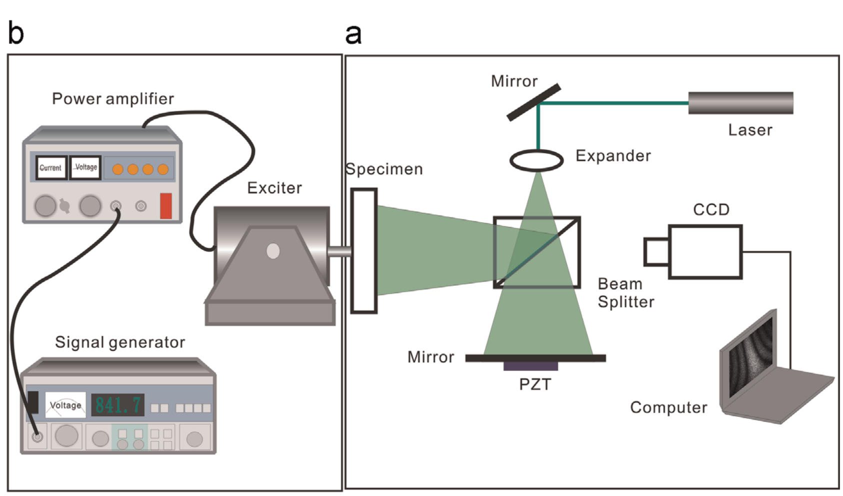

Fig. 1. Schematic of vibration measurement system: (a) AF-ESPI setup for out-of-plane displacement; and (b) modal testing arrangement.