Investigation of Non-Resonant Vibration Behaviour by a Newly Developed Time-Averaged ESPI Method

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Summary This paper introduces a newly developed time-averaged electronic speckle pattern interferometry (ESPI) method to investigate non-resonant vibration behavior of structural components. Different from traditional ESPI method, fringe patterns including both at resonant and non-resonant frequencies are used in the newly developed method. Experimentally speaking, fringe patterns are continuously recorded from time to time. Fringe patterns of reliable quality can be obtained by subtracting two images captured at different time intervals. Based on the fringe formula derived in this paper, the whole-field displacement data can be accurately evaluated. A non-resonant vibration case was adopted for demonstration of the newly developed method. The obtained results are well matched with the FEM results.

INTRODUCTION

Utilizing optical methodologies on vibration measurements can be divided into two categories. The first category is the “whole-filed” measurement method, including holography, electronic speckle pattern interferometry (ESPI), moiré method, digital image correlation (DIC) method, and others. The second category is the “point-wise” measurement method, e. g. laser Doppler vibrometer. Most of the research activities are focused on the dynamic behaviour of a structure at resonant frequencies. The requirement of miniaturization of modern engineering systems makes the interface gaps become much smaller, the interfacial interferences may be occurred even though the system components are away from the resonance frequencies while the externally applied force is above certain level. To attempt to solve the problem, the ESPI, with the use of different detectors and signal/image processors, also known as the TV-holography or the digital speckle pattern interferometry (DSPI), was used in this paper. When ESPI is employed on vibration measurement, time-averaged (TA) method, stroboscopic method, pulsed laser [1] and the reference wave modulation method [2] are the most commonly used methods. The TA ESPI is the most popular method for vibration measurement because of the lower cost and higher system reliability. Achieving accurate quantitative measurement of vibration displacement heavily depends on “stable” fringe patterns. Unfortunately, measuring vibration behaviour of the weak structures or vibration at low frequency resonant modes or the lack of good vibration isolator or outside well controlled laboratories, the challenge is the TA ESPI fringe patterns are always contaminated with environmental noise.

To investigate the environmental disturbance problem, in this paper, the environmental disturbances are considered as initial phase difference between the reference and objective images. The effects of environmental noise on the object in vibration and the optical system of ESPI were formulated as a function of zero order Bessel function modulated by the noise induced equivalent phase terms. In real applications, the vibration images are continuously recorded with a self-assembled TA ESPI system, and then subtracting two arbitrarily selected recorded TA ESPI images with the use of the same initial reference image to obtain “stable” vibration fringes.

DEVELOPING NEW METHODOLOGY

As shown in Fig. 1, a self-assembled ESPI system was used to perform the experiments. A structure was vibrated with amplitude “*A*” and measured with a typical out-of-plane TA ESPI system; the obtained TA ESPI fringes are bright and dark when $1-J_o(kA)$ respectively reaches local maximums and local minimums. The associated displacement can then be determined by fringe order, wavelength of light source and measurement sensitivity *k*. As mentioned in previous paragraph, the fringe patterns are distributed by the environmental noises and the typical fringe patterns are shown in Fig. 2. Clearly, determining the displacement field at a resonant frequency with the ambiguous fringe patterns shown in Fig. 2 is difficult. Assuming the environmental noise acts on the optical setup and introduces an additional phase; the frequency spectrum is broad, however, filtering or damping high frequency environmental noise can be easily achieved only low frequency environmental noise has to be considered. Then the environmental noise additional phase can be simplified as a linear function of time with new introduced parameters initial phase difference and time-averaged phase change. The fringe formula of a TA ESPI image is [3]

$$\begin{aligned} f(kA,\delta\Phi) &= \left|\cos(\varphi+\Phi)[1-J_o(kA)\cos\delta\Phi]+J_o(kA)\sin(\varphi+\Phi)\sin\delta\Phi\right| \\ &= \left|C_1\left(1-J_o(kA)\cos\delta\Phi\right)+C_2 J_o(kA)\sin\delta\Phi\right| \end{aligned} \tag{1}$$

As indicated in Eqn. (1), the fringe patterns are determined by the vibration amplitude, the optical setup and $\delta\Phi$; where $\delta\Phi$ can be treated as the environmental noise introduced equivalent initial phase difference between the reference image and the vibration images; C_1 and C_2 are determined by the environmental noise introduced initial phase when the reference speckle image was grabbed. As two different TA ESPI fringe patterns were captured by using the same

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reference speckle image but different $\delta\Phi$, say $\delta\Phi_1$ and $\delta\Phi_2$. These two images are subtracted from each other and the resulting image can be described by the absolute zero-order Bessel function, $|J_0(kA)|$ modulated with a trigonometric function as

$$\begin{aligned} f(kA;\delta\Phi_1,\delta\Phi_2) &= \left|J_o(kA)\left[C_1(\cos\delta\Phi_2-\cos\delta\Phi_1)+C_2(\sin\delta\Phi_2-\sin\delta\Phi_1)\right]\right| \\ &= \Delta f(kA;\delta\Phi_1-\delta\Phi_2)\cdot\left|F(C_1,C_2,\delta\Phi_1,\delta\Phi_2)\right| \end{aligned}$$

Since the function $F(C_1,C_2,\delta\Phi_1,\delta\Phi_2)$ with parameters C_1 and C_2 is speckle contained function, the computed fringe patterns should be determined by the function $\Delta f(kA;\delta\Phi_1-\delta\Phi_2)$ and can be described as

$$\Delta f(kA;\delta\Phi_1-\delta\Phi_2)=\left|J_o(kA)\sin\left(\frac{\delta\Phi_2-\delta\Phi_1}{2}\right)\right|$$

RESULTS AND DISCUSSIONS

Based on the above discussions, subtraction of two TA ESPI fringe patterns contaminated with environmental noise is proposed to extract “stable” fringes. Figure 3 shows typical fringe patterns obtained by subtracting two images in Fig. 2. For a special case, while $\delta\Phi_1$ and $\delta\Phi_2$ are of the same value, the output fringe patterns will be vanished, however, in real case this special phenomenon is difficult to be observed unless two images are identical. Fig. 3 shows the proposed method can be used to obtain the “stable” fringe pattern of resonant mode case. This new developed ESPI method can also be used for exploring non-resonant vibration behavior. As shown in Fig. 4, three TA ESPI fringe patterns were captured when the specimen was excited at the non-resonant frequency 110 Hz. Fringe patterns T12, T23 and T31 shown in Figs. 5 were obtained by subtracting two random selected TA ESPI images shown in Fig. 4. Figures 5(a) and 5(c) show that fringe patterns T12 and T31 are in good agreement with the finite element analysis result shown in Fig. 5(d).

CONCLUSIONS AND ACKNOWLEDGEMENTS

By continuously recoding the TA ESPI images and then subtracting two arbitrarily selected TA ESPI images, reliable images can be extracted and used to investigate the vibration behaviour of the aluminium plate at non-resonant frequencies. It was found that the resultant vibration images match well with the finite element results. This research was supported in part by the National Science Council (grant nos. NSC 95-2221-E007-150 and NSC 95-2221-E007-011-MY3).

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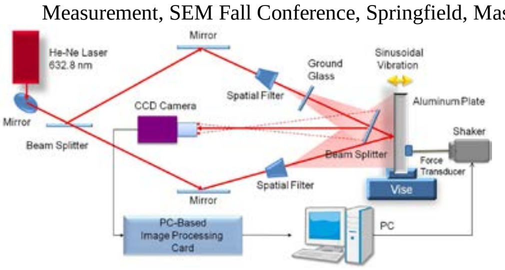


Fig.1 Typical out-of-plane ESPI optical setup for vibration measurement

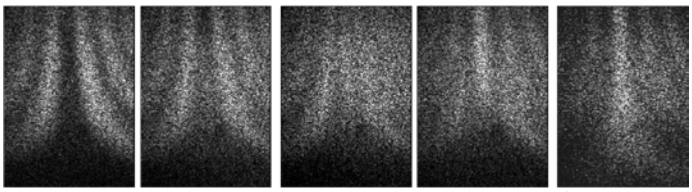


Fig. 2 An aluminum plate was excited by a constant driving force at the 2nd resonant frequency. Images were arbitrarily captured from continuously recorded TA ESPI images. The gray level distribution is not clear.

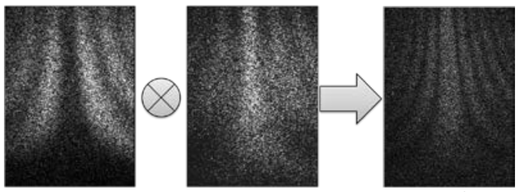
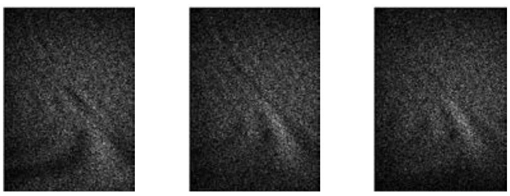
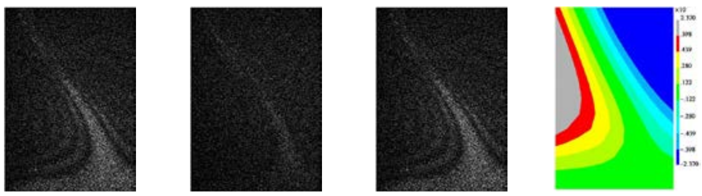


Fig 3. Fine and stable images can be obtained from two arbitrarily selected TA ESPI images by subtraction.



(a) T1 (b) T2 (c) T3

Fig. 4 TA ESPI images computed from the TA ESPI images obtained at a non-resonant frequency (110Hz)



(a) T_{12} (b) T_{23} (c) T_{31} (d) FEM result

Fig. 5 Three images obtained by the newly developed ESPI method from three images captured from an aluminum plate vibrated at 110Hz matched well with the finite element results.