Digital Image Correlation Vibrometry

I. A. Jones[1a], G. Lu[2], J. Warburton[1] and H. Docx[1]

[1]University of Nottingham, University Park, Nottingham NG7 2RD, UK

[2]AVIC The First Aircraft Institute, P.O. Box 72, No.1 East Renmin Road, Yanliang District, Xi'an, Shaanxi, China

[a]arthur.jones@nottingham.ac.uk

Abstract. The present paper describes a low-cost approach to the capture of high-quality mode shape data using digital image correlation. Specifically, a method is presented which enables digital image correlation with conventional cameras (i.e. not high-speed) to be used for determination of vibration mode shapes. This can be used as a low-cost and full-field alternative to laser vibrometry. For each natural frequency of the structure under consideration, a sequence of images is captured asynchronously with the vibrations using the DIC system and the resulting displacement fields are correlated, using various alternative approaches, with the excitation signal driving the vibration. The resulting information is then used to reconstruct the amplitude and phase of the vibration at each point on the specimen, allowing a plot or a video animation of the mode shape to be constructed. This process is illustrated for the example of a vibrating steel plate. The resulting mode shape appears correct and is of higher quality than the displacement fields obtained using DIC alone.

Introduction

The experimental determination of vibration mode shapes has involved a range of techniques over many years, ranging from the generation of Chaldni figures (where powder granules congregate on nodal lines) via the use of impact modal analysis (for example, multiple-input single-output tests) to the use of scanning laser vibrometry. None of these normally gives a fine full-field measurement of vibration. Conversely, digital image correlation has become a popular method for experimental determination of stress and strain, with the technique being widely applied to quasi-static strain measurement including the use of 3D DIC techniques which can capture out-of-plane displacements and eliminate the effects of such displacement from the strain field. Recent years have seen the use of digital image correlation in conjunction with high speed cameras to capture the mode shapes of vibrating objects via a continuously-captured sequence of images. For example, Helfrick *et al*. [1] compare and contrast modal analysis via high speed DIC with with impact tests and laser vibrometry, while Wang *et al*. [2] use high speed DIC in conjunction with random excitation as the basis of establishing modal parameters.

Both laser vibrometry for modal analysis, and DIC in conjunction with high speed cameras, require capital-intensive equipment. Moreover, the displacements associated with vibration are often small, meaning that direct DIC measurements of vibration mode shapes will tend to be noisy, and high-speed cameras with low resolutions are likely be unable to resolve satisfactorily the small displacements encountered. The present approach aims to extend the capabilities of a DIC system to capture mode shape data with minimal outlay.

Outline of approach

The apparatus consists of a 3D DIC system with conventional cameras rather than high speed cameras. Images are captured asynchronously with the vibrations and used to determine 3D displacements in the usual manner. A variety of least-squares fitting techniques are used to exploit the relationship between the measured displacements and the excitation signal driving the vibrations. In the simplest case this involves performing linear regression of displacement *vs.* instantaneous excitation voltage, requiring the assumption that excitation signal and displacement response are in phase (or 180° out of phase). More sophisticated techniques are also being developed which take account of the phase of the instantaneous local displacement relative to the excitation signal and involve the fitting of Lissajous figures to relate displacement to excitation. These approaches build upon work carried out by Lu *et al*. [3] to determine elastic strain field distributions in composites, in which the elastic model was fitted to the strain results by performing a linear regression of strain against the load signal. The fitting of a linear elastic model has also been reported by other workers [4]. While Lu's work [3] involved static rather than dynamic strains or displacements, the underlying issue faced was the same as here: the measurements obtained from the DIC system are subject to significant noise as the values measured are approaching the strain or displacement resolution limit of the DIC system, but by fitting the measurements to an appropriate model such as linear elasticity or a sinusoidal response, the quality of the results can be significantly improved and useful results obtained where direct measurements might tend to be obscured by noise.

Results

The present work is illustrated with experimental measurements captured using the technique. A steel plate was sprayed with a stochastic pattern, supported on foam pads and excited using a loudspeaker driven from a signal generator approximately at various resonant frequencies of the plate. Each resonant frequency was identified manually by observing the “dancing” of a plastic bead on the plate. The plate was viewed using a Dantec Q400 3D DIC system with two 5MP monochrome cameras, illuminated with a conventional photographic flash unit, and a sequence of (typically) 59 images was captured at regular intervals. The instantaneous excitation voltage was also captured for each image. After performing correlation on the images using Dantec’s standard ISTRA4D software, the resulting displacement fields were post-processed by performing linear regression, and least squares fitting of a phase-shifted sinusoidal response, against the excitation voltage signal. A video animating the displacements with time was also produced, which takes account of the phase angles of the local displacements. The results are promising: while a typical directly-captured displacement field captured at maximum displacement (for 357 Hz) is of acceptable but somewhat noisy quality (Fig. 1), the gradient field (i.e. the linearised local displacement per volt of excitation) shows significantly cleaner results (Fig. 2). Note that no spatial smoothing has been used although this would have given less noisy results at the expense of reduced spatial resolution. In this case the measured displacements are in the order of 0.08 mm though acceptable results have so far been obtained for displacements down to around 0.015 mm. A typical screenshot from the animation, obtained without assuming the excitation and displacement are in phase or 180° out of phase, is shown in Fig. 3.

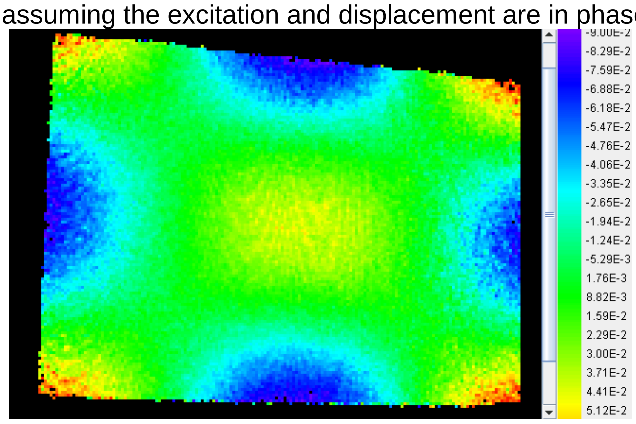

Fig. 1: Displacements at maximum amplitude.

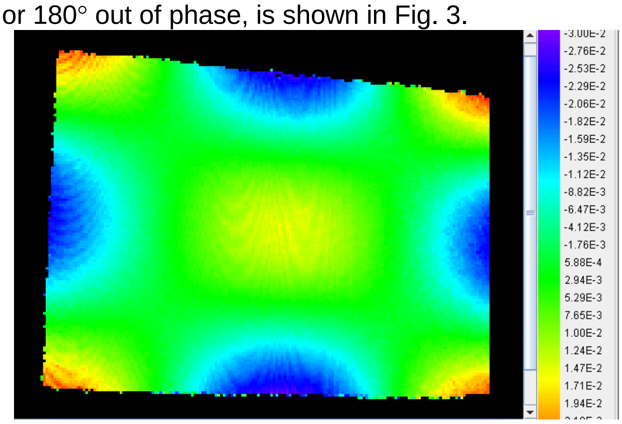

Fig. 2: Mode shape assuming linear response to excitation

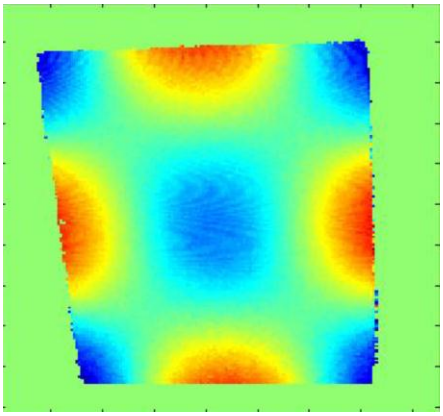

Fig. 3: Screenshot of displacement field taken from animation of mode shapes

Conclusions

The use of least-squares fitting of a proportional or phase-shifted relationship between instantaneous displacement and amplitude provides a promising basis for full-field estimation of mode shapes from digital image correlation data captured without the use of high-speed cameras. Further work will be required to refine the algorithms for handling arbitrary phase relationships between displacement and excitation voltage, and to assess the accuracy of the method especially for situations involving low vibration amplitudes.

Acknowledgements

The authors are very grateful to Mr Tom Buss for his assistance in undertaking the experiments.

References

[1] M. N.Helfrick, C. Niezrecki, P. Avitabile, T. Schmidt: *Mech. Systems and Signal Processing*, 25 (2011) 917–927.

[2] W. Wang, J. E.Mottershead, T. Siebert, A. Pipino: *Mech. Systems and Signal Processing*, 28 (2012)333–347.

[3] G. Lu, M. Y. Matveev, I. A. Jones and A.C. Long: Improving strain field measurements for textile composites. *Proc. International Conference on Engineering Mechanics (ICEM16)*, Cambridge, July 2014.

[4] G. Nicoletto, G. Anzelotti, E. Riva, Opt Laser Eng. 2009;47(3-4):352-359.