ARTICLE IN PRESS

Mechanical Systems and Signal Processing ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Full-field linear and nonlinear measurements using Continuous-Scan Laser Doppler Vibrometry and high speed Three-Dimensional Digital Image Correlation

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ARTICLE INFO

Article history:
Received 9 May 2015
Received in revised form
10 November 2015
Accepted 8 December 2015

Keywords:
Full-field measurement
Continuous-Scan Laser Doppler Vibrometry
High speed three dimensional digital image correlation
Linear mode
Nonlinear deformation

ABSTRACT

Spatially detailed dynamic measurements of thin, lightweight structures can be difficult to obtain due to the structure's low mass and complicated deformations under certain loading conditions. If traditional contacting sensors, such as accelerometers, strain gauges, displacement transducers, etc., are used, the total number of measurement locations available is limited by the weight added and the effect each sensor has on the local stiffness of the contact area. Other non-contacting sensors, such as Laser Doppler Vibrometers (LDV), laser triangulation sensors, proximity sensors, etc., do not affect the dynamics of a structure, but are limited to single point measurements. In contrast, a few recently developed non-contacting measurement techniques have been shown to be capable of simultaneously measuring the response over a wide measurement field. Two techniques are considered here: Continuous-Scan Laser Doppler Vibrometry (CSLDV) and high speed Three-Dimensional Digital Image Correlation (3D DIC). With the use of these techniques, unprecedented measurement resolution can be achieved. In this work, the linear and nonlinear deformations of a clamped, nominally flat beam and plate under steady state sinusoidal loading will be measured using both techniques. In order to assess their relative merits, the linear natural frequencies, mode shapes, and nonlinear deformation shapes measured with each method are compared. Both measurement systems give comparable results in many cases, although 3D DIC is more accurate for spatially complex deformations at large amplitudes and CSLDV is more accurate at low amplitudes and when the spatial deformation pattern is simpler.

1. Introduction

The development of non-contact full-field measurement techniques has received increased attention as the design of high-performance structures has advanced. Due to complex geometries and the lightweight nature of these structures, there is an increasing need for experimental techniques capable of measuring the response at a large number of degrees of

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http://dx.doi.org/10.1016/j.ymssp.2015.12.003
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Please cite this article as: D.A. Ehrhardt, et al., Full-field linear and nonlinear measurements using Continuous-Scan Laser Doppler Vibrometry and high speed Three-Dimensional Digital Image Correlation, Mech. Syst. Signal Process. (2016), http://dx.doi.org/10.1016/j.ymssp.2015.12.003

Nomenclature

A_x	Amplitude of x laser position
A_y	Amplitude of y laser position
f	Frequency of input force
f_A	Scan frequency
f_x	x laser position frequency
f_y	y laser position frequency
N_x	Number of x laser position periods in Lissajous period
N_y	Number of y laser position periods in Lissajous period
T_A	Scan period
T_x	x laser position period
T_y	y laser position period
$x(t)$	x laser position
$y(t)$	y laser position
$\mathbf{z}(x,y,t)$	Stationary laser position in the time domain
$\mathbf{z}(x(t),y(t),t)$	Moving laser position in the time domain
$\mathbf{Z}(x,y,t)$	Stationary laser position in the frequency domain
$\mathbf{Z}(x(t),y(t),t)$	Moving laser position in the frequency domain

freedom without modifying the structural response significantly. Techniques such as Continuous-Scan Laser Doppler Vibrometry (CSLDV) and high-speed Three-dimensional Digital Image Correlation (high-speed 3D DIC) have been developed to meet this need. Both CSLDV and high-speed 3D DIC are non-contact, non-destructive, and capable of accurately measuring the dynamic response at thousands of points across the surface of a structure. Both techniques are also capable of providing "real-time" measurements, but this has seen limited to no implementation for several reasons. In the case of 3D DIC, significant computational power is needed to move and manipulate the thousands of image files sampled for each test. For CSLDV, real time measurement is theoretically feasible with the implementation of the harmonic power spectrum algorithm, but to the best of the author's knowledge this has never been done. For this work, these limitations are avoided by post-processing the data acquired with both methods.

CSLDV is an extension of traditional Laser Doppler Vibrometry (LDV), where the laser point, instead of dwelling at a fixed location, is continuously moving across a measurement surface. Therefore, obtaining vibration frequencies and deformation shapes from CSLDV signals is more challenging than from LDV signals since the moving measurement location requires the system to be treated as time-varying. Though this motion complicates the post-processing, the benefit provided by the continuously moving point is an increased measurement resolution with a drastically decreased measurement time when compared with traditional LDV. Several algorithms have been devised to determine a structure's deformation along the laser scan path. For example, Ewins et al. treated the operational deflection shape as a polynomial function of the moving laser position [1–6]. They showed that sideband harmonics appear in the measured spectrum, each separated by the scan frequency, and that the amplitudes of the sidebands can be used to determine the polynomial coefficients. Allen et al. later presented a lifting approach for impulse response measurements [7,8]. The lifting approach breaks the CSLDV signal into sets of measurements from each location along the laser path. Hence, the lifted responses appear to be from a set of pseudo sensors attached to the structure, allowing conventional modal analysis routines to extract modal parameters from the CSLDV measurements. However, this method works best when the laser scan frequency is high relative to the natural frequencies of interest, and for some structures this increase the measurement noise too much to be practical. Recently, algorithms based on Linear Time Periodic (LTP) system theory [9–14] were developed and used to derive input–output transfer function and power spectrum relationships from CSLDV measurements allowing the extraction of a structure's deformation from impulse, random, and sinusoidal excitations. When a structure is vibrating sinusoidally, many of the methods simplify significantly and in this paper the simplest method will be used based on Fourier analysis as was presented by Stanbridge, Martarelli, Ewins and Di Maio [1–6], and which is called the Fourier series expansion method in [7].

Displacements measured with 3D DIC are challenging to obtain since each individual measurement point has to be matched in each image from each camera for the duration of the experiment. For high sample rates, this requires an additional step of post-processing. Schmidt et al. [15] presented early work on the use of high-speed digital cameras to measure deformation and strain experienced by test articles under impact loadings. Tiwari et al. [16] used two high-speed CMOS cameras in a stereo-vision setup to measure the out of plane displacement of a plate subjected to a pulse input. Results compared favorably with work previously published and showed the capability of the 3D DIC system in a high-speed application, although over a short time history. Niezrecki et al. [17], Helfrick et al. [18], and Warren et al. [19] obtained mode shapes using 3D DIC with different test articles using discrete measuring points. Niezrecki et al. and Helfrick et al. also combined accelerometers, vibrometers, and dynamic photogrammetry to compare results obtained with DIC analyzed at discrete measurement locations. Each technique provided complimentary results between all measurement techniques showing the capability of 3D DIC, although 3D DIC was not processed along the entire surface. Abanto-Bueno et al. [20], Beberniss et al. [21], and Ehrhardt et al. [22] showed high speed 3D DIC's capability to measure full-field dynamic deformations under large amplitude loading. Although, handling the large amount of data in conjunction with the image files can prove to be difficult.

In this investigation, CSLDV and high-speed 3D DIC are used to measure the linear and nonlinear response of a clamped, nominally flat beam and plate. The linear response of each structure is measured when it is excited with a steady state sinusoid at selected natural frequencies using single-point mono-harmonic force appropriation. The nonlinear response of

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