Mechanical Systems and Signal Processing 94 (2017) 374–383

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Single-camera high-speed stereo-digital image correlation for full-field vibration measurement

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ARTICLE INFO

Article history:
Received 23 November 2016
Received in revised form 25 February 2017
Accepted 4 March 2017

Keywords:
Vibration measurement
Digital image correlation
Single high-speed camera

ABSTRACT

A low-cost, easy-to-implement single-camera high-speed stereo-digital image correlation (SCHS stereo-DIC) method using a four-mirror adapter is proposed for full-field 3D vibration measurement. With the aid of the four-mirror adapter, surface images of calibration target and test objects can be separately imaged onto two halves of the camera sensor through two different optical paths. These images can be further processed to retrieve the vibration responses on the specimen surface. To validate the effectiveness and accuracy of the proposed approach, dynamic parameters including natural frequencies, damping ratios and mode shapes of a rectangular cantilever plate were extracted from the directly measured vibration responses using the established system. The results reveal that the SCHS stereo-DIC is a simple, practical and effective technique for vibration measurements and dynamic parameters identification.

1. Introduction

Vibration measurements have been extensively implemented in many areas of engineering and industry, such as automotive, aerospace, shipping and railway, due to increasing concerns on the structural safety and durability [1–5]. These measurements not only provide necessary data for understanding the dynamic behavior of structures, but also contribute to the optimal design of the structures.

In order to collect accurate and adequate data for structural dynamics analyses, many measuring techniques including contact and non-contact approaches have been developed. Traditional contacting techniques for vibration testing (e.g., accelerometers and displacement transducers) can merely measure the response signals at the positions where they are attached. Even worse, the attachment of these additional sensors on the testing structure inevitably changes the natural frequencies and introduces extraneous damping, which could alter the response of the testing structure [6–8]. This alteration is particularly prominent when measuring the responses of light-weight, lightly damped structures (e.g., a thin metallic panel) [8]. Alternatively, laser Doppler vibrometers (LDVs) can realize non-contact and high spatial resolution measurements of mechanical vibrations with a wide frequency range, but LVDs are generally limited to a single measurement point at a time [9,10]. To overcome this significant drawback of LDVs and meet the strong demands for full-field vibration measurements at a time, continuous scanning laser Doppler vibrometers (CSLDVs) have been developed with the laser sweeping continuously over the surface of the structure [6,8]. However, these laser-based techniques are extremely vulnerable to small

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http://dx.doi.org/10.1016/j.ymssp.2017.03.008

shifts in experimental setup during tests. Moreover, selecting appropriate scanning parameters for CSLDVs when the tested structures are subjected to random loading is very tricky. Therefore, these disadvantages in the traditional measuring techniques have motivated the investigations on other non-contact, full-field optical techniques that can measure the response of a vibrating surface over a large area.

In the last few decades, full-field optical measuring techniques such as electronic speckle pattern interferometry (ESPI) [4,11], digital holographic interferometry (DHI) [12] and stereo-digital image correlation (stereo-DIC) [6,8,13–17] have been successfully applied to three-dimensional (3D) vibration measurements with the aid of high-speed cameras. Among these methods, the interferometric metrologies, i.e. ESPI and DHI, not only require a coherent light source and a vibration-isolated experimental condition, but also present particular sensitivity to environmental disturbances. Thus these high-sensitivity interferometric techniques are restricted to laboratory applications. By comparison, stereo-DIC using two synchronized high-speed cameras has been widely adopted to determine the 3D vibration responses of various structures, whether in laboratory or non-laboratory conditions, owing to its the distinct advantages of simple optical arrangement, easy specimen preparation and low requirement on experimental environment. For example, Helfrick et al. [6] successfully measured the modal vector/shape information of a dryer-cabinet panel using a high-speed stereo-DIC system and verified the accuracy of the measurement by comparing with the results of a scanning laser vibrometer. Ha et al. [13] used stereo-DIC to determine the modal parameters of an artificial wing that mimics a beetle's hind wing. Also, using the same technique, Berke et al. [14] measured the vibratory response of a rectangular alloy plate at elevated temperature up to 600 °C and assessed the influence of temperature on the thermomechanical vibratory response of the plate. Recently, Reu et al. [15] carefully compared LDV and stereo-DIC for their use in full-field vibration and modal testing. Their results confirmed that stereo-DIC is a competitive approach for vibration measurement compared with LDV, and may have significant advantages over the LDV method in certain tests.

All the above-mentioned investigations have convincingly suggested that stereo-DIC technique using two synchronized high-speed cameras is a practical and powerful experimental technique for full-field 3D vibration measurement. However, in using regular stereo-DIC for the determination of full-field vibratory responses, the requirement of two precisely synchronized high-speed cameras brings several limitations. This is because: (1) the use of two high-speed cameras and the corresponding device to precisely synchronize them greatly increase the cost on the hardware investment, especially when using two ultra-high speed cameras; (2) precise synchronization of the two high-speed cameras is generally considered to be complicate; (3) the intensity variations and nonlinear geometric distortion between the image pairs may unavoidably bring difficulty in achieving precise stereo matching between the two images and thus decrease measurement accuracy [18]. Therefore, it is desirable to develop a pseudo stereo-DIC technique using a single high-speed camera for full-field 3D vibration measurements during a single shot.

Recently, a single-camera stereo-DIC technique was introduced by Pankow et al. into the experimental mechanics community for displacement measurement at high framing rates [19]. The technique was later optimized and carefully investigated by the present authors [20,21], and shown to be effective and accurate in performing both static and dynamic deformation measurements by combining with a single conventional or high-speed camera [22]. However, adoption of the single-camera high-speed stereo-DIC (SCHS stereo-DIC) for vibration measurements has not been investigated so far. Based on the recent refinements [20–23] we made to the SCHS-stereo DIC technique, this paper aims to investigate the feasibility and practicality of this technique for vibration measurements. In this paper, the single-camera high-speed stereo-DIC system is used to record the surface images of a rectangular cantilever plate excited by an impulse hammer. By processing the captured images using the regular stereo-DIC algorithm, full-field vibration responses of the cantilever plate are retrieved and further used to extract the natural frequencies and damping ratios. Also, with the established system, the first three mode shapes of cantilever plate are measured by exciting this plate using a shaker at its natural frequencies. Experimental results show a good agreement with those obtained from the finite element analysis (FEA) and/or accelerometers, and validated the effectiveness and accuracy of the proposed technique for vibration measurements.

2. Experimental set-up and measuring principles

2.1. Experimental set-up

Fig. 1 schematically shows the experimental set-up of the established SCHS stereo-DIC system for full-field 3D vibration measurement. The system consists of a high-speed camera placed before the test object, a zoom lens mounted on the high-speed camera, a four-mirror adapter located between the test object and the high-speed camera. Note that the four-mirror adapter is composed of a perpendicular aluminum block, two mirror mounts, four planar mirrors (denoted as M_1, M_2, M_3 and M_4) and some fixed rods. The inside two mirrors are fixed on the two sides of the perpendicular aluminum block and form a 90° angle with each other, while the outside two mirrors are glued tightly to mirror mounts and then mounted on rotating stages, thus allowing the outside two mirrors to rotate around their axes. Before the tests, the test sample is tightly clamped onto a fixed support. Then, as shown in Fig. 1, by adjusting the posing angles of the two outside mirrors and the lens of the camera, two views of the test sample surface via two different optical reflection paths can be projected onto two halves of the camera sensor target. Also, the locations and orientations of these two views on the recorded image can be finely tuned by adjusting the mirror mounts. In summary, the established SCHS stereo-DIC system can achieve stereo imaging with the help of the four-mirror adapter, but at the expense of losing half of the spatial resolution of the high-speed camera.