Smartphone-Based Digital Image Correlation for Vibrating Structures

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Serena Occhipinti[1], Tristan Chevreau[2], Paolo Neri[3], Christian M. Firrone[1], and Daniele Botto[1]

[1]Department of Mechanical and Aerospace Engineering
Politecnico di Torino, Torino, Corso Duca degli Abruzzi 24

[2]Ecole Centrale de Lyon,Lyon, 36 Av. Guy de Collongue

[3]Department of Civil and Industrial Engineering
Università di Pisa, Pisa, Largo L. Lazzarno 1

ABSTRACT
Digital Image Correlation (DIC) is a promising non-contact method for measuring the full-field dynamics of vibrating structures. This method needs one or two cameras to measure 2D or 3D dynamics. The frames of the recorded videos are then post-processed to correlate the structure points at different times and obtain displacement information. A plethora of cameras is available - in terms of frame rate, resolution, versatility, and overall quality - the choice of which depends on the specific application and spending constraints. The idea behind this work is to evaluate the feasibility of making DIC-ready videos using cameras built into a device that is part of everyday life: the smartphone. The proposed approach is an easy-to-handle procedure, suitable for teaching purposes or an early qualitative investigation. This paper discuss a simple experiment students or beginners can perform on simple vibrating structures. First, a simple 2D dynamics was investigated. The vibration of a clamped beam with moving constraints was recorded with a single smartphone. The beam had an L-type cross section to emphasize in-plane motion. The frames were post-processed with free software and the first modal shape was extracted. The goal of this assignment was to introduce students to the basics of DIC. Second, the 3D dynamics of a beam was studied with a single smartphone. The image of the beam was reflected by two mirrors and the reflected images were recorded by a single smartphone. A tool was developed to slip the recorded frame into two independent images. The images were post processed to obtain the full 3D dynamics of the beam. Third, the 3D dynamics of a beam was studied with two smartphones and an external clock to overcome smartphone synchronization difficulties.

Keywords: DIC, Smartphone, Dynamics, Pseudo 3D-DIC, Educational

INTRODUCTION

The request for accurate, non-contact, and cost-effective measurement techniques is driving ongoing research efforts. Among the available measurement techniques, Digital Image Correlation (DIC) has emerged as a powerful tool for capturing the full-field dynamics of vibrating structures. Traditional DIC systems rely on one specialized camera (2D-DIC for in plane measurements) or two specialized cameras (3D-DIC for three-dimensional measurements), along with lenses and specially designed setups. The high cost of dedicated cameras and lenses can be an obstacle to the wider adoption of DIC technology in various applications, such as in educational contexts.
In recent years, the ubiquitous presence of smartphones, equipped with increasingly advanced components, has opened up new possibilities for scientific applications. Smartphone-based measurements offers the advantage of portability, simplifying the acquisition process in non-laboratory environments. In [1] smartphones were used for determining natural frequencies of the structures for System Health Monitoring (SHM) purposes. This was possible by leveraging the built-in accelerometers, speak-

ers, and microphones of the smartphones. Also smartphone cameras has experienced exponential advancements in recent years, enabling users to capture high-quality images at high frame rate. The state-of-the-art devices can achieve 4K resolution and an extraordinarily high frame-rate of up to 960 fps. Thus, the adoption of these ready-available and user-friendly instruments, for images acquisition, coupled with the availability of open-source DIC software for both single and double cameras DIC applications, make smartphones well-suited for students, occasional DIC users, and those with limited resources who wanted to perform full-field 2D or 3D DIC-measurements. Xie et al. [2] demonstrated the feasibility of using smartphones and DIC to monitor the bi-dimensional displacement and strain field during compression tests. In the study by Mousa et al. [3], a single smartphone was employed to calculate the three-dimensional displacement field of a glass table. While this approach has been proved effective in generating 3D displacement maps, it cannot be properly classified as three dimensional measurement since it requires an high-fidelity numerical model of the specimen for accurately deriving out-of-plane motion from 2D-DIC measurements. In [4] 3D deformation measurements were performed through a portable smartphone-based pseudo 3D-DIC system. Stereo images were captured with a 3D-printed device consisting of four mirrors attached to a smartphone and subsequently exported to a computer for displacement analysis by dedicated DIC software. While numerous approaches have been explored for utilizing smartphones in surface displacement detection for structures, this paper introduces the first two-smartphone 3D-DIC system. The main reason behind the lack in the literature of DIC systems consisting of multiple smartphones is the fundamental requirement to achieve optimal video synchronization between them to enable accurate 3D-DIC measurements.
The objective of this work is to explore easy to handle single and double smartphone-based DIC approaches, suitable for teaching purposes or for preliminary investigation of the dynamic of a specimen. Thus, different DIC setups are examined with the aim of extracting the first modal shape of an L-Beam. Firstly, the mode of the beam was approximated with a pure flexural mode, and the in-plane displacement components of one side of the beam were extracted to characterize the modal shape. Secondly, a pseudo-3D system, utilizing two mirrors, was employed to analyze the three-dimensional displacement maps of the beam. Lastly, a stereo-vision setup with two smartphones was utilized to perform 3D-DIC analysis. According to this purpose, different synchronization methods are discussed.

DIGITAL IMAGE CORRELATION

Digital Image Correlation (DIC) is a well-established non-contact technique for measuring displacement and deformation of structure by analyzing images of those objects captured before and after deformation. In subset-based DIC algorithms, such as the one implemented into the open-source software Ncorr [5], the process involves segmenting a reference image into smaller regions, called subsets. These subsets are then tracked within the deformed images. After tracking the position of each subset from the reference image within the deformed image, a two-dimensional displacement map can be generated for the entire measurement field.
For three-dimensional digital image correlation (3D-DIC) measurements, which involve examining motion with out-of-plane components, it is essential to acquire at least one stereo image pair at each measurement time. This can be achieved by placing two cameras at the appropriate relative angles or by using a pseudo 3D-DIC configuration, which offers a cost-effective alternative to the traditional two-camera configuration. Pseudo 3D-DIC systems are characterized by the use of a single camera, instead of the traditional two-camera configuration, and optical devices of negligible cost. Carefully designed configurations have the ability to split incoming light beams to create two sub-images on the camera sensor, thus generating a dual perspective of the sample.In both traditional and pseudo 3D-DIC measurements, a calibration process is essential. This involves capturing a series of images of a calibration target to precisely align the cameras with each other and with the specimen under investigation. Given a dual perspective of the scene, it becomes possible to triangulate the two-dimensional point maps computed by 2D-DIC, thus enabling the generation of a 3D displacement map.

METHODOLOGY AND EXPERIMENTAL SETUP

Figure 1 shows the experimental setup, which consists of a beam with one end attached to the moving coil of a shaker and the other end free to move. The beam section has an L-shaped geometry, with a constant thickness of 2 mm. It features an edge of 20 mm connected to the shaker and the other edge of 10 mm. The total length of the beam is 280 mm, while the length of the clamped beam portion is 4 mm. The white surface of the beam was sprayed with black paint and then a black speckle pattern was applied. This operation is essential to correctly perform the DIC analysis. To investigate the first modal shape of the beam, a sinusoidal signal at 33 Hz, which corresponds to its first resonant frequency, was sent to the shaker. The excited modal shape is mainly flexural, but because of the geometry of the beam section it also has a torsional component. The beam motion was studied by DIC performed with three different setups. The first approach utilizes only a smartphone, allowing us to study the in-plane motion. Consequently, during this analysis, we neglected the out-of-plane beam motion, which arises

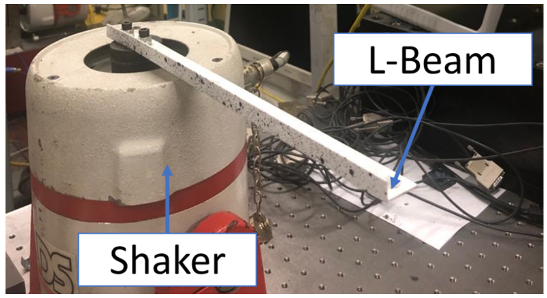
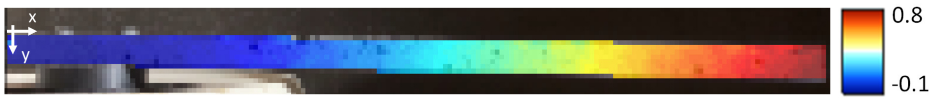
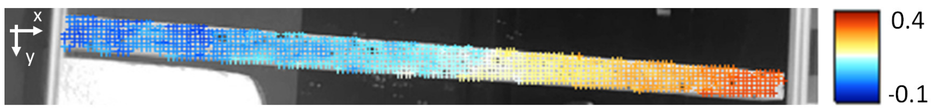


Figure 1: Experimental setup: beam clamped to a shaker exciting its first mode shape.



(a)



(b)

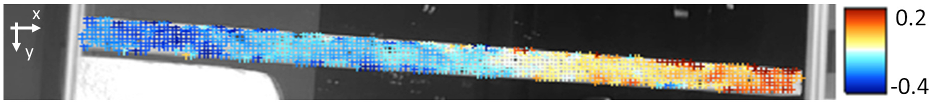
(c)

Figure 2: Maximum displacement in the y-direction of a clamped L-beam excited at its first resonance frequency. The results were obtained using smartphone-based DIC approaches: a) Single smartphone 2D-DIC analysis; b) Pseudo-3D DIC system with mirrors and a smartphone; c) Dual-smartphone 3D-DIC equipped with an external clock for synchronizing displacement data.

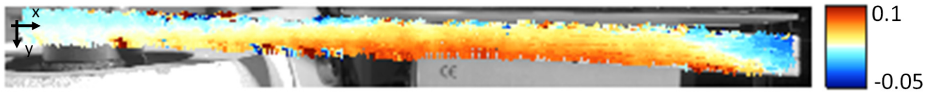
from its torsional component and potential misalignment between the smartphone's camera and the beam. Secondly, a pseudo 3D-DIC setup was used. It consists of two mirrors and a smartphone. The two mirrors are positioned with a relative angle and allow us to simultaneously record the motion of the beam from two different perspectives. Thus, this setup allows 3D-DIC analysis by dividing each frame in two images to be analyzed using open-source 3D-DIC software. Lastly, the same 3D-DIC software was employed to analyze images captured by two smartphones placed with a relative angle. The main challenge in using two smartphones is to obtain camera synchronization. Attempts to synchronize cell phone cameras, included methods using strobe lights, have shown difficulties and require dedicated external hardware, making them unsuitable for the purposes of this research. In this study, we bypassed this challenge by employing a post-processing algorithm that allowed us to extract synchronous displacement information from asynchronous image pairs. This method involves interpolating 2D-displacement data obtained from one camera using a sine wave at the same frequency as the excitation frequency. To do it, the Smoothed Harmonics Method presented in [6] was used. This interpolation allows us to compute the in-plane displacement of each point at each time step, aligning it specifically with the timestamps of the other camera. Hence, this approach requires the acquisition of only one synchronized image pair within the videos. To enable this synchronization, a millisecond resolution clock was strategically placed in the common field of view of the cameras and a text recognition algorithm was used to find the synchronous frames.

RESULTS

Figure 2 illustrates the obtained vertical displacement maps (in y direction) acquired using the three DIC setups. The results show that all configurations effectively captured the flexural component of the mode shape. For the out-of-plane displacement



(a)



(b)

Figure 3: Maximum out-of-plane displacement map of a clamped L-beam excited at its first resonance frequency. The results were obtained using smartphone-based DIC approaches: a) Single smartphone 2D-DIC analysis; b) Pseudo-3D DIC system with mirrors and a smartphone; c) Dual-smartphone 3D-DIC equipped with an external clock for synchronizing displacement data.

maps, depicted in Fig. 3, a distinction is observed between the results of the pseudo 3D-DIC system and the two-smartphone 3D-DIC system. The pseudo 3D-DIC system, due to lower image resolution, struggles to accurately analyze out-of-plane motion characterized by small amplitudes. In contrast, the two-smartphone system reliably recorded the torsional component of the mode shape.

CONCLUSION

This study presents three distinct setups for performing Digital Image Correlation (DIC) analysis, utilizing either one or two smartphones. To show the advantages and limitations of each setup, they were employed to capture the first mode shape of a plastic beam with an L-section geometry. Two-dimensional DIC analysis (2D-DIC) is an easier-to-use option than 3D-DIC. It requires the use of a single smartphone and eliminates the need for a calibration process. However, it's important to note that 2D-DIC typically exhibits lower accuracy when compared under equal image scales to 3D-DIC. This arises from out-of-plane motions due to actual motion of the specimen or to the misalignment between the camera and the specimen, which introduce errors in-plane measurements. Therefore, in cases involving non-planar motion or requiring higher accuracy, the use of 3D-DIC is necessary.

The adoption of a single smartphone for 3D-DIC analysis (referred to as pseudo 3D-DIC) simplifies the implementation of the technology by eliminating the need for synchronization between multiple cameras, which is challenging. On the other hand, measurements from pseudo-3D systems generally show lower accuracy than those performed with systems employing multiple cameras. This can be attributed to the division of sensor resolution and the introduction of image distortions due to the complexity of additional optical devices. The last approach involves the use of two smartphones. In contrast to the previous methods, this approach was capable of capturing the torsional behavior of the L-beam. In this study, we successfully addressed the synchronization challenge between two smartphone cameras by implementing an approach that involves the placement of a clock within the field of view of the cameras. This approach facilitates the use of 3D smartphones-based DIC, making it more accessible and user-friendly.

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