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Evaluation of the Digital Image Correlation method for the measurement of vibration mode shapes

M.F. Mat Tahir [1, 2 a)]
Stephen J. Walsh [1 b)]
Daniel J. O'Boy [1 c)]
[1]Department of Aeronautical and Automotive Engineering,
Loughborough University, Leicestershire, LE11 3TU, UK.

[2]Department of Mechanical and Materials, Faculty of Engineering and Built Environment,
Universiti Kebangsaan Malaysia, Selangor, Malaysia.

Digital Image Correlation (DIC) is a modern non-contact, full-field optical technique that is being used for the measurement of static and dynamic displacement problems, material testing and fracture mechanics. In particular, three dimensional DIC is able to measure the out-of-plane vibration mode shapes and deformation of a vibrating structure. Thus, this technique can potentially provide an important validation tool between measured and predicted results. This paper presents some preliminary evaluation results from using the DIC measurement approach. The DIC method was implemented using two low-speed charge-couple device cameras and a phase-locked measurement technique synchronised to the excitation. A 1.2mm thick steel plate with clamped boundary conditions was chosen as the test sample. Resonant frequencies and mode shapes were compared to predictions made using a Finite Element analysis and the experimental Chladni method of visualizing vibrating mode patterns. This comparison reveals some of the advantages and limitations of the DIC method for vibration mode shape analysis

1   INTRODUCTION

Every material or structure tends to vibrate naturally at certain frequencies which are known as natural frequencies or resonance. It will vibrate with a certain standing wave pattern when it's being forced into resonance vibration. There will be nodal conditions at specific points and antinodes at other points resulting from flexural waves reflecting from boundaries (standing

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[a)] email: m.f.mat-tahir@lboro.ac.uk
[b)] email: s.j.walsh@lboro.ac.uk
[c)] email: d.j.oboy@lboro.ac.uk

wave patterns). If the amplitude of the vibration is large enough and the natural frequency in the range of human audible range, the vibrating object will amplify and produce an audible sound wave. Thus, knowing the natural frequencies for any structure or object is important in understanding structural vibration and sound behaviour. However, despite knowing the natural frequency, it is still a challenging task to know and visualise exactly the mode shape except for objects with simple shapes and boundary conditions.

Ernst Chaladni, a German physicist describes a technique that shows the mode shapes of vibration of a solid surface in 1787[1]. The Chaladni's technique involved drawing a bow over a piece of metal whose surface was lightly covered with sand, which when it reached resonance caused the sand to move and concentrate along the nodal line. His technique is one of the classic ways on how to visualize the shape of sound and vibration. Today, optical full-field measuring systems are progressively being utilized as a part of the examination for the enhanced portrayal of materials and parts. One of the techniques is the Digital Image Correlation method which is widely used for full-field and three dimensional displacement measurements. 3D Surface geometry and displacement can be determined by the images taken from a stereo pair of charge coupled device (CCD) cameras. In a sole snapshot, this non-contact full-field method can take measurements at numerous of points on the surface of an entity. Even with the occurrence of huge deformation amplitudes or macroscopic rigid body movements, deformation measurements with very high resolution are still possible since the system determines the absolute position and displacement of the object in space[2].

DIC works by digitizing light intensity values through a rectangular arrangement of pixels fixed in the CCD cameras. Each cell of the arrangement possesses a numerical grayscale value related to the intensity of the light reflected from the object. Through a correlation process, a computer is able to distinguish and track an exact point defined by its adjacent light intensity value in a series of images. A speckle pattern is applied to the object prior to imaging and by tracking discrete points in images taken by a stereo pair of cameras and applying photogrammetric principles, shape, strain, and displacement can be measured[3].

In order to calibrate the software, panels which have a specific series of dots on a rigid flat surface with a known distance are included with the DIC packages. Pictures of the calibration panel are evaluated by the DIC software to know the position of the cameras relative to each other, which then becomes the reference to which all subsequent stages are compared. A surface observed by the camera is divided into smaller sub-areas called subset or facet where each of the subset contains specific characteristic speckles and represent material points of an object. A series of measurement is taken to evaluate the surface displacement and strain on the object surface. The correlation algorithm then tracks the speckle and gray value patterns for each subset and transforms the corresponding subset position in each camera[4]. As the surface deformation is measured, displacements of individual surface points and subsequently surface strain can be evaluated.

Vibrations often involve the measurement of tiny displacements. Therefore, understanding the sensitivity of DIC measurements is needed, especially for measurements in the out-of-plane direction and where low speed cameras are employed (through phase tracking). Most of the time, in order to know the distance per pixel to sample size relation, the width of the field-of-view is divided by the number of active pixels across the width of the pixel array. The sensitivity will decrease as this number gets larger but are also influenced by a number of factors, including lighting, camera sensitivity and speckle pattern uniformity.

The 3D-DIC method has seen remarkable growth in recent years, with applications in aerospace, micro-scale measurements, bio-materials, and fracture mechanics[5]. High speed cameras are normally used for the DIC purpose when dealing with the higher frequency of

movement including researchers who are using high speed cameras for dynamic testing of materials and structure[6]. Thorsten[7] on his paper presents examples of the analysis of harmonic vibration and transient events from material research and industrial applications by using high-speed cameras (Nanosense MK III) with 1280 x 1024 pixels resolution. The maximum frame rate at full resolution of these cameras is 1000 Hz. Then, Thorseten et al[8] also measure the mode shapes of a car bonnet frame structure made out of fibre-reinforced thermoplastic composite material by single frequency excitation using a shaker. The results are compared with modal analysis based on the accelerometer and simulations based on the CAD model using FE analysis techniques. Helfrick[3] presents some preliminary results for the analysis and correlation of data measured using the DIC approach along with traditional accelerometers and a scanning laser vibrometer for comparison to a finite element model.

2 METHODOLOGY

The aim of this experiment was to determine and capture the mode shape of a clamped steel panel by using the low speed camera and the 3D DIC system produced by LaVision, in order to obtain guidance on frequency limits and best operational practice. The panel measured was a rectangular steel plate with dimension of 307 x 208 mm with 1.2mm thickness clamped between two sub frames. The plate was excited at a single frequency by an electrodynamic shaker positioned beneath it.

Nastran NX was used as the Finite Element Model to be compared with. The natural frequencies of the plate were determined by running an experimental modal analysis prior to DIC setup with traditional accelerometers. With these resonance frequencies, the mode shape image for the panel was captured by both DIC experiment and Chaladni method.

2.1 Determination Of Natural Frequencies Of The Plate

Theoretically

The natural frequencies for different boundary condition of the rectangular plate can be calculated by using the following equation:

$$f_{ij} = \frac{\pi}{2}\left[\frac{G_x{}^4}{a^4} + \frac{G_y{}^4}{b^4} + \frac{2J_xJ_y + 2v\left(H_xH_y - J_xJ_y\right)}{a^2b^2}\right]^{1/2}\left[\frac{Eh^3}{12\gamma(1-v^2)}\right]^{1/2}$$

(1)

Where γ is the mass per unit area of the plate and the coeffcients G_x, H_x, and J_x can be determined from the Table 1 with their boundary conditions. Likewise, the remaining G_y, H_y and J_y can be determined by replacing x with y and m replacing by n.

Table 1- Coefficients described in Eq. 1.

Boundary Condition	Mode, m	G_x	H_x	J_x
Clamped-Clamped (CC)	1	1.506	1.248	1.248
	2	2.5	4.658	4.658
	m (m>2)	$m+\frac{1}{2}$	$\left(m+\frac{1}{2}\right)^2\left[1-\frac{2}{\left(m+\frac{1}{2}\right)\pi}\right]$	H=J

Reference : Leissa[9], Blevins[10]

Experimentally

A thin flat panel is used to represent an automotive-type panel. In order to achieve a highly uniform clamped boundary condition; the panel was placed inside a metal frame. The test panel was placed between the two sub frames and clamped using 28 bolts. The lower sub-frame has grooves around its periphery so that the clamping load is distributed evenly over a small plate area around the circumference.

The panel was excited over the frequency range (white noise) of 0 to 1250 Hz using an electrodynamics shaker and an accelerometer placed on the upper side of it to capture the flexural response (PCB Piezotronics 352c44). The in-line connection between plate and shaker incorporated a force transducer (B&K ICP 8230), positioned at 110mm in the x-direction and 80mm in the y-direction, measured from the left bottom corner of the panel. The block diagram of the experiment setup is shown in Fig. 1 to illustrate the apparatus while Fig. 2 illustrates the measured mobility of the flat panel (also shown is the reference infinite plate mobility value).
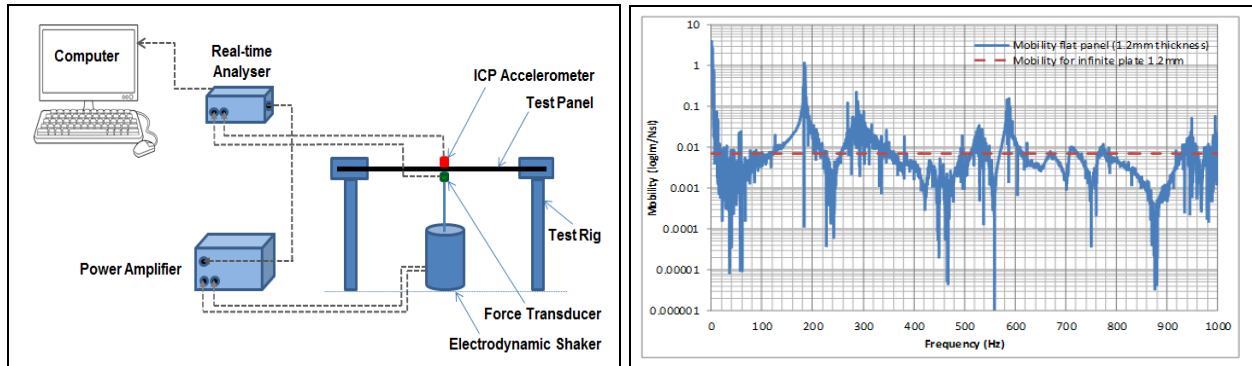

Fig. 1 – Schematic representation of the experimental setup. Fig.2 – Measured mobility of the flat panel with the reference of infinite plate mobility values.

2.2 Sample Preparation

The sample surface has to exhibit gray contrasts for the correlation technique to be accurate. The ideal surface texture should therefore be isotropic and not have specific orientation, where the speckle pattern is non-periodic with no repeating textures. The plate was sprayed completely with matt black paint before white sparkle paint was added. Figure 3(a)

represents examples of the panel with white sparkle that being used for measurement while Fig. 3(b) shows the plate condition with the test rig clamped.
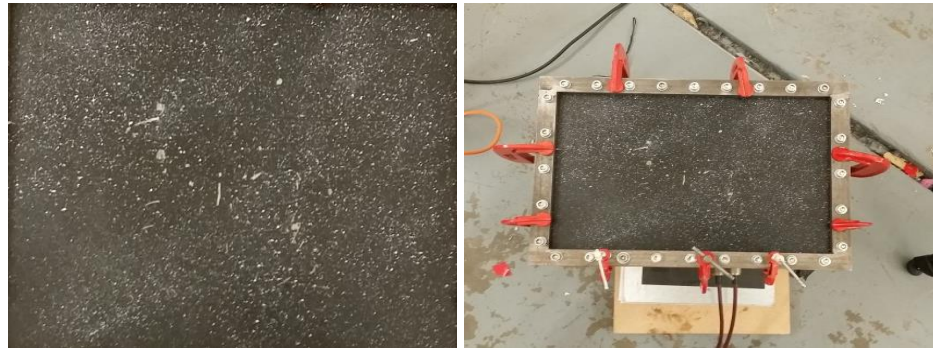

Fig. 3 – Experimental apparatus: (a) Sample steel plate with the white speckle applied ;(b) Photograph of test rig used to achieve clamped boundary conditions with 28 bolts and additional 9 G-clamps, view from above.

2.3 Phase Locked Measurement

Ideally, for vibration measurements of a higher frequency, a high speed camera should be used to capture the movement of the plate, which can add significant cost. A practical alternative uses a low speed camera, where it is assumes that at resonance, subsequent standing waves are similar in both amplitude and nodal position. Since the camera's frame rate may not fast enough to capture several images in a single cycle, it is possible to skip several cycles before advancing to the next phase, but the signal is accurately tracked by the phase locking. Figure 4 below represents how knowing and controlling the camera frame rate, it is possible to replicate a single wave cycle.
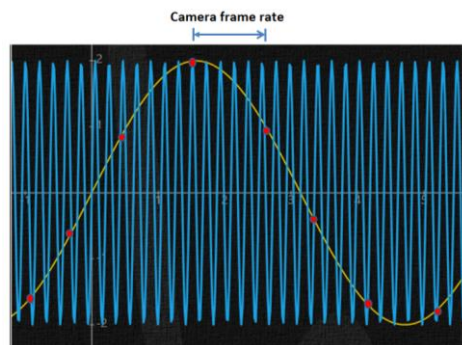

*Fig. 4 – Reconstruction of a single wave signal from purely cyclical motion.*

The red line represents the actual displacement experienced by a point on the panel and the dot where the position of the wave for each image is taken. By knowing the time the image was taken, the replication of single wave signal images can be created. The practical limitation is generally dependent on the camera sensitivity and the scene lighting, which both affect the system's ability to freeze motion[11].

2.4 Digital Image Correlation Method

The digital image recording is done via a CCD (charge coupled device) camera which converts photons to electric charge based on the photoelectric effect. Two sets of camera Imager E-lite5M with 5 mega pixel and 12 bit colour resolution were used for the DIC experiment. The frame rate can go up to 14 frames per seconds depending on system configuration. The distance between the camera system and the specimen was determined by available lenses and is set so that the specimen roughly fills the field of view. If the specimen is larger than the field of view, data is lost at the edges; if the specimen is much smaller, the spatial resolution suffers. Two LED light with one additional halogen light was used to provide an intense light source since the images need to be captured in short period of time (fast shutter speed).

DaVis 8.2.1 software from LaVision was used as a tool to capture and post process the entire sized image. In DaVis software there are 256 colours, indexed from 0 to 255, which are arranged in the order of the active palette, containing intensity values from 0 to 65535 counts, which have to be displayed with 256 colours. The user selected colour resolution by mapping from pixel intensity to the colour in which the pixel is displaed in screen[12].

The practical limitation on the oscillation frequency is dependent on camera sensitivity and lighting. The software has the ability of 64K intensity for 256 colours. However, because of light source limitation and the needed to capture the lowest exposure time to "freeze" the motion, the intensity count was reduced to 1K. This means it will register a new colour after an interval of four counts. Thus, the exposure time of 100μs can be achieved. By reducing the pixel intensity, the transition between each colour result becomes less smooth, but it is reasonable since the result expected is not focusing too small area or spatial resolution but at the size of plate on overall.
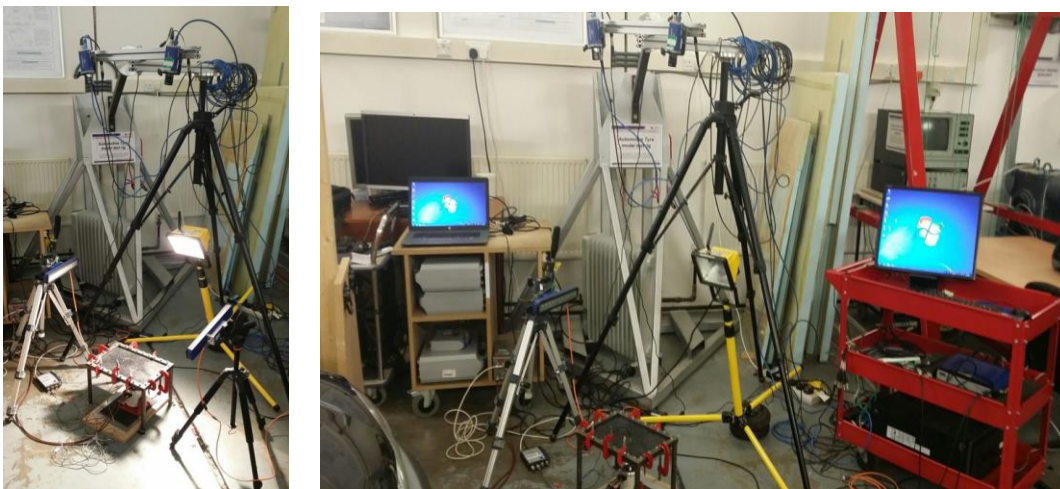
Fig. 5 – Photograph of the DIC setup between the camera and plate with the additional lamp. Fig. 6 – Photograph of the complete setup between the DIC equipment and Photon setup.

Figure 5 shows the DIC setup for between the camera and the test panel with the additional lighting while Fig. 6 demonstrates the setup for the complete DIC testing and the panel vibration with shaker underneath the plate as vibration source. The DaVis 8.2.1 systems were being controlled separately with the Bruel and Kjaer Photon Plus signal analyser (with integrated signal generator). Photon Plus software was used to excite the shaker at designated frequency

which was determined earlier. However, the voltage reading from the shaker was captured by the analogue to digital converter to represent the voltage of shaker movement for each picture taken.

The experiment started by doing the calibration test, capturing an image of the calibration plate which controls the camera lens for the required focusing distance and reasonable aperture size. The image must be set to have a good focus and sharp image and the exposure time are not over or under-exposed. Next, after the calibration image is captured correctly, at least one static image of the plate was taken as the base to be compared with the dynamic images that will be taken during test later on. Then, the dynamic test began by providing a sinusoidal vibration source underneath the plate at a chosen natural frequency. A set of 40 sequential images representing two complete cycles of the plate were captured according to the calculated frame rate. The number of the image can be determined according to the user preference, as a high number of images can represent a good replication of the single wave signal, but it also will take a lot of memory space for storage. Finally, the series of images was processed began by combining the static image with the series of dynamic image. This static image will become the base comparison of the plate's displacement before and after the load is given.

3   RESULTS

3.1 First Mode (1, 1) At 185 Hz

The first mode expected to be seen was at the frequency of 185 Hz (experimentally), shown in Fig. 7(a) as 40 sequential images taken respectively, with the voltage provided to the shaker from the power amplifier plus one static image at the beginning. Every point/image captured by low speed camera represents the location of the shaker movement (higher frequency) which then can replicate the single wave signal image.
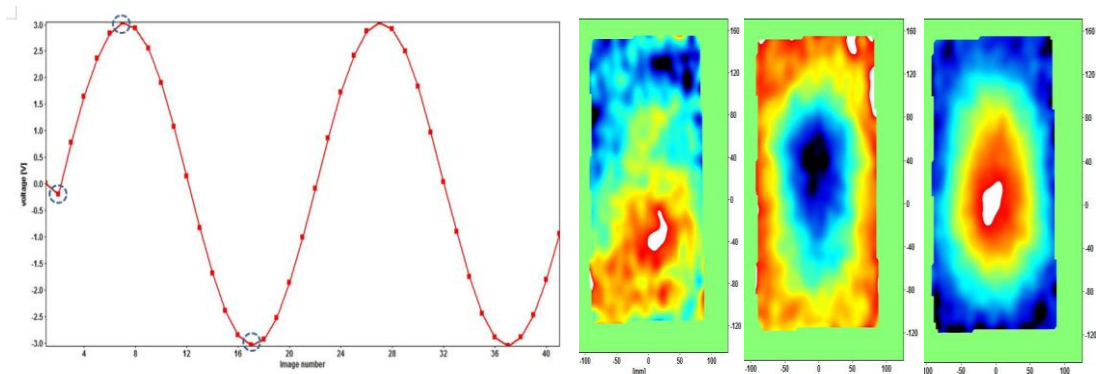

Fig. 7 – Illustration of mode shape reconstructure from left (a) Graph number of image vs voltage values from shaker for mode (1, 1) at 185 Hz; (b) Images at numbers 2nd , 7th and 17th positions in the graph.

Figure 7(b) shows a series of selected images that represent the behaviour of the mode during the given frequency. Image number 2 shows displacements near zero, which are the specific times in the cycle when the deformation is almost distributed evenly on the panel. Next, the voltages start increasing and reach the highest value, the bottom of the plate can be seen at the centre of the plate as shown in image 7. Then when the voltage was decreasing and reach the lowest value, the peak deflection of the panel can be seen near the centre of the plate as shown in image 17.

The mode behaviour captured by the DIC camera represents the same predicted mode shape from the FEM simulation for the first mode and also the image captured from the Chaladni method as shown in figure 8 below.
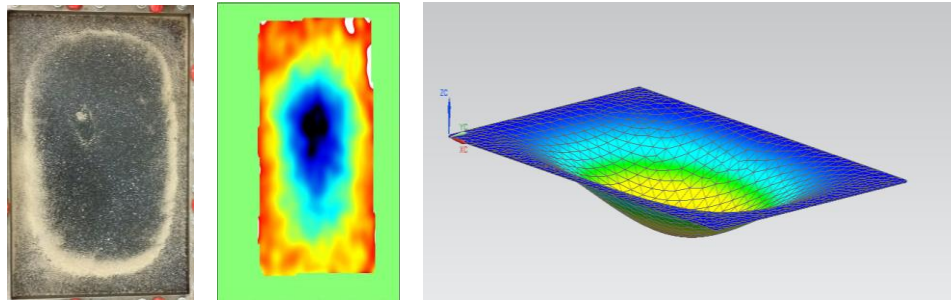

Fig. 8 – Mode shape (1,1) visualisation from left: (a) Chaladni method; (b) DIC method; (c) FEM analysis.

3.2 Selected Mode Patterns Of The Plate

The mode (2,1) captured was at the frequency of 290 Hz and mode (2,2) taken at the frequency of 585 Hz (determined experimentally). Figures 9 and 10 below show the images of the mode shape captured using the Chaladni method, DIC method and FEM analysis.
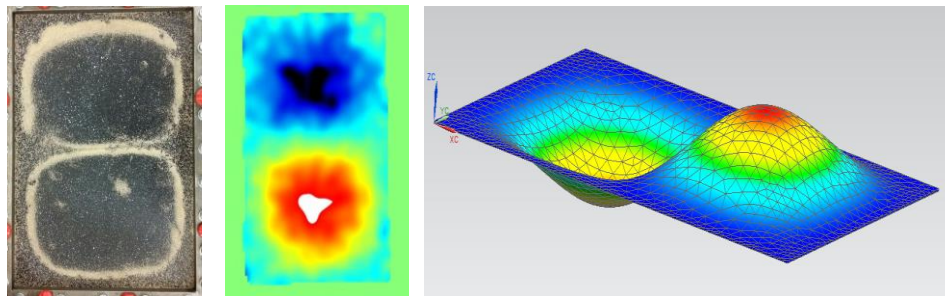

Fig. 9 – Mode shape (2,1) visualisation from left: (a) Chaladni method; (b) DIC method; (c) FEM analysis.
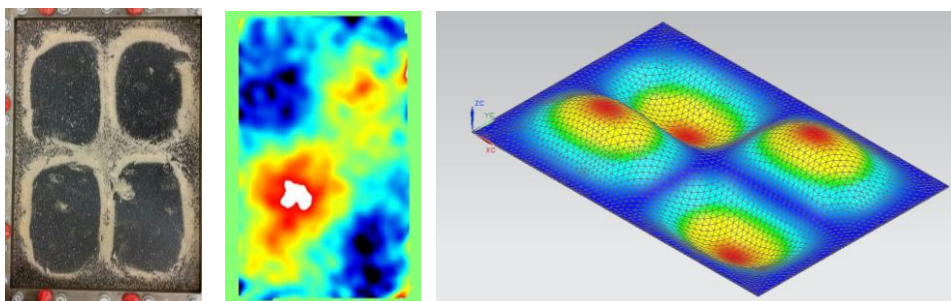

Fig. 10 – Mode shape (2,2) visualisation from left: (a) Chaladni method; (b) DIC method; (c) FEM analysis.

3.3 Selected Mode Patterns For Free-Free Boundary Condition Plate

The Chaladni method and DIC method also been run on additional free-free boundary condition steel plates in order to validate that it can work with other setup and boundary condition cases. The shaker was excited on the centre of the plate at a specific resonance frequency. Figure 11 shows the result between Chaladni and DIC method for two selected frequencies.
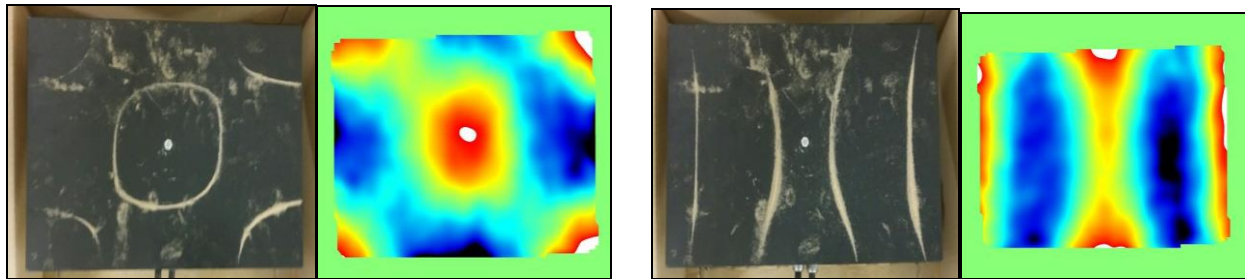

Fig. 11 – Comparison free-free plate Mode shape between Chaladni method and DIC method from left, at (a) 290 Hz (b) 380 Hz respectively.

4   DISCUSSION AND CONCLUSIONS

This paper presents comparison results using a digital image correlation method and validation of the images with the Chladni plate method. The results from the DIC method are very promising and give a good correlation with finite element model results. The accuracy of the measurements depends on several factors. The most important is the accurate knowledge of the natural frequencies. By knowing the exact resonance frequency, the plate can be vibrated at the precise and correct mode shape. Second is the excitation factor, as the amplitude of vibration is directly proportional to the image intensity recorded. If the intensity is too low, some modes will not be sufficiently excited and if the intensity is too high, there is a possibility of the base of the rig moving and giving an incorrect data interpretation.

The DIC method for determining the mode shape using the low speed camera provides a good result when comparing with finite elements and Chaladni method. Although it is relatively costly for the setup which involves cutting edge equipment such as lenses and cameras, it is still much cheaper compared with the setup using high speed cameras and can still provide a promising result. However, there are limitations on low speed cameras when compared with high speed cameras especially at high frequency cases. The setup only works on a known repetitive sinusoidal vibration or noise source. Therefore, the low speed camera can't run on any experiment that involves impact or transient causes. Other than that, the low speed camera itself has higher limitations on the exposure time value, which will restrict the maximum frequency that can be captured. Finally, it will require a longer time to capture more images to represent a complete vibration cycle. If the number of images needed to be taken as a complete cycle is higher, longer period of sampling time is needed to be completed.

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