# HIGH SPEED DIGITAL IMAGE CORRELATION FOR MODE SHAPE MEASUREMENTS ON A CARBON FIBER CURVED PANEL

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**Abstract**

Traditionally, vibration measurements have been done by pointwise transducers such as accelerometers or Scanning Laser Doppler Vibrometers, what implies a limited characterization due to a low number of sensors over surfaces as well as the difficulty of an accurate spatial distribution of the transducers on complex surfaces. Furthermore, some of them may add a supplementary mass to the object, modifying its response under dynamic loading events [1].

Full-field optics techniques are widely used on experimental mechanics in order to perform different characterizations, both in static and dynamic tests. In this paper, Digital Image Correlation, DIC, and High Speed Cameras, are applied to determine the mode shapes [2] of a carbon fiber aeronautical panel. It was carried out in Forced Normal Mode tests, FNM. The results show full-field displacements corresponding to each mode shape over the whole surface in a non-invasive way. Simultaneously, a digitalization of the curved panel is obtained.

## 1. Introduction

Experimental modal analysis is used for identifying modal parameters such as natural frequencies, mode shapes and damping ratios of a structure under vibration loads. In this way, different methodologies have been developed in order to define the Frequency Response Functions (FRF) or Impulse Response Functions (IRF) which provide modal identification [1]. This characterization is useful in structural integrity studies and predictive maintenance of a component and also to improve finite element models.

Piezoelectric transducers and laser vibrometry are common measurement systems in experimental modal analysis. However, for full-field analysis it is necessary to use a large number of measurement points or even a large number of accelerometers, what is expensive and may not be operative. Furthermore, some transducers are invasive when sticking on the element surface, adding mass to the element. This mass increment implies a natural frequency modification which is known as mass-loading effect [3]. Another problem that must be faced when using pointwise transducers is to exactly determine the spatial position of the measurement points, especially when the element is complex.

Digital Image Correlation, DIC, is an optical technique that offers a non-invasive full-field displacement measuring. DIC, in its 3D version (using a stereoscopic system compound by cameras), allows to measure on curved elements and simultaneously obtain a 3D digitalization of the surface. These advantages lead 3D-DIC to be considered in vibration analysis [5]. One of the most interesting applications of 3D-DIC is to determine mode shapes on forced normal mode tests, FNMT [6][8]. In these tests, the element is excited at one of its resonance frequencies with a sinusoidal signal, thus the corresponding mode shape might be measured. Considering this, high speed cameras make 3D-DIC

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can be used to get mode shapes whose natural frequency may reach high frequencies rates over thousand hertz.

Consequently, 3D-DIC in its high speed version using high speed cameras is considered for modal characterization at different scenarios of new materials, particularly, with orthotropic or anisotropic behavior. In this study, different mode shapes of a carbon fiber aeronautic panel were determined using 3D-DIC in FNM tests exciting with a shaker and under free-free boundary conditions. Previously, natural frequencies were obtained performing a random signal test.

## 2. Fundamentals of Digital Image Correlation

Digital Image Correlation (DIC) is an optical technique used for measuring deformations and displacements of mechanical elements. DIC works correlating a sequence of digital images captured during the test from an initial state (non loaded) to a loaded final state, where deformation are taking place. The surface must present a random speckle pattern Figure 1. The surface is virtually divided in some regions known as facets. Facet is the smallest unit and on which the algorithm performs a tracking, analyzing the initial and final position of each facet to construct displacement experienced and the strain field, Figure 2.

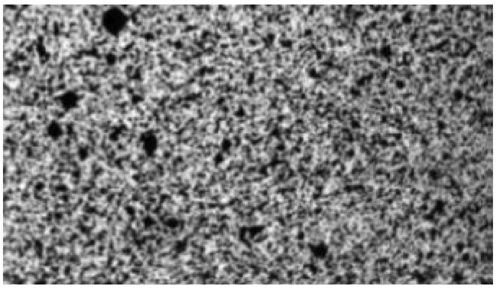

**Figure 1.** An example of a random speckle pattern.

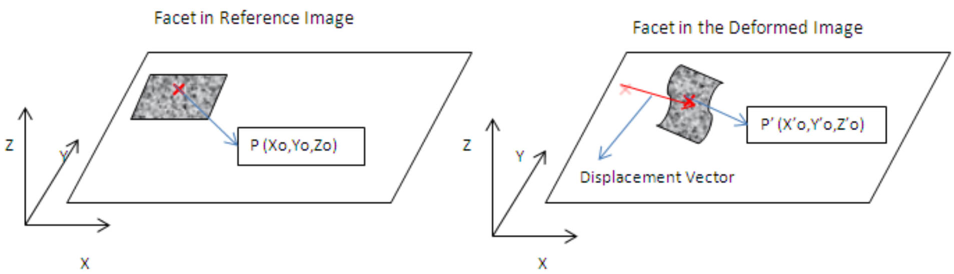


**Figure 2.** Displacement of a facet from a reference image to a strained image using DIC.

In 3D-DIC, an accurate calibration must be performed to define the relative position between cameras theirselves and between the cameras and the object.

## 3. Experimental Setup

In order to measure with 3D-DIC, firstly the panel's surface was treated to generate the random speckle pattern (Figure 3). This treatment consisted in applying a first layer of white paint and,

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afterwards, the speckle using black paint. The generated speckle was carefully sized to be well-defined in the test images [9]. Thus, DIC algorithm is able to identify in a better way the facets it will track.

In the same figure, it can be observed, the panel hung from two of its corners to simulate free-free condition on a frame built with aluminium bars and screwed on an optical table. Additional bars were attached to the frame so that the structure was considered rigid.

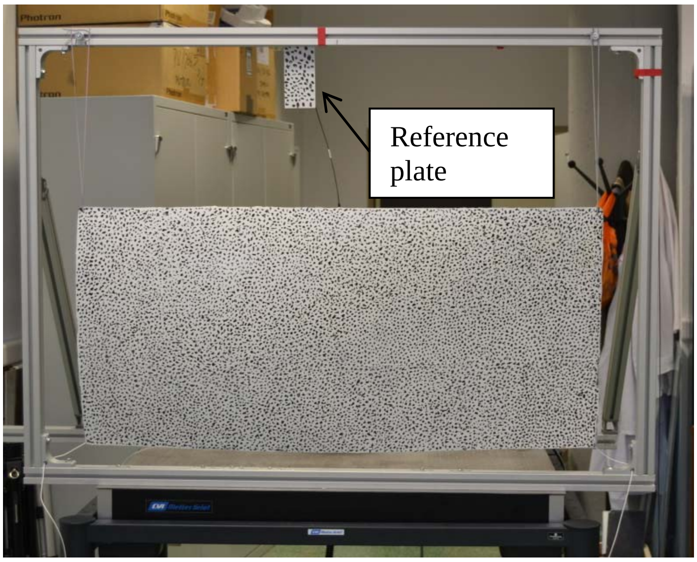


**Figure 3.** Carbon fiber panel hanging from the upper corner to a frame structure.

In all tests, the panel was excited using an electrodynamic shaker, shown in Figure 4, which provides excitation to the panel on its rear face attaching a stinger. The shaker amplifier was supplied with the corresponding excitation signal from the digital analyzer Photon+ of Brüel&Kjaer. This analyzer was also used to register the accelerometer signals.

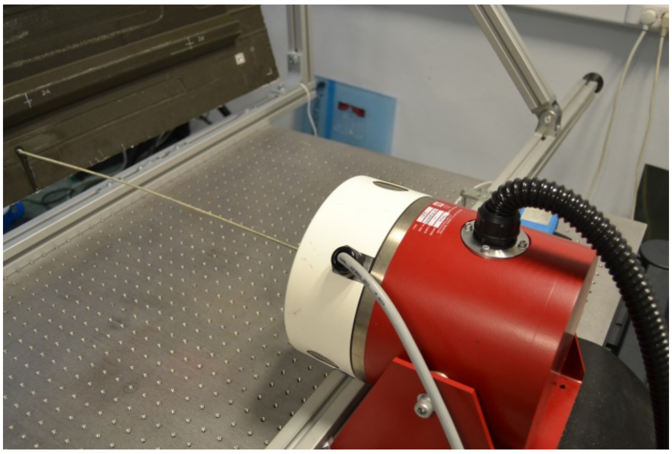

**Figure 4.** Electrodynamic shaker attached to the panel using a stinger.

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### 2.1. Natural Frequencies Identification

As it was mentioned before, natural frequencies must be identified to the later mode shape measurement. In this test, the panel was excited at a wide range of frequency with a white noise random signal from 20 Hz to 600 Hz. The response of the panel was monitor with the information acquired from three accelerometers. These accelerometers were placed at points of the panel where high response was expected and also to avoid nodal points in which some mode could not appear. In Figure 5 is shown one of them placed in the middle of the upper part (no. 1) whereas the other two were placed on the two lower corners (no. 2 and 3), keeping distance from rigidizers. A forth accelerometer was positioned on the shaker armature to register the signal excitation (Figure 6).

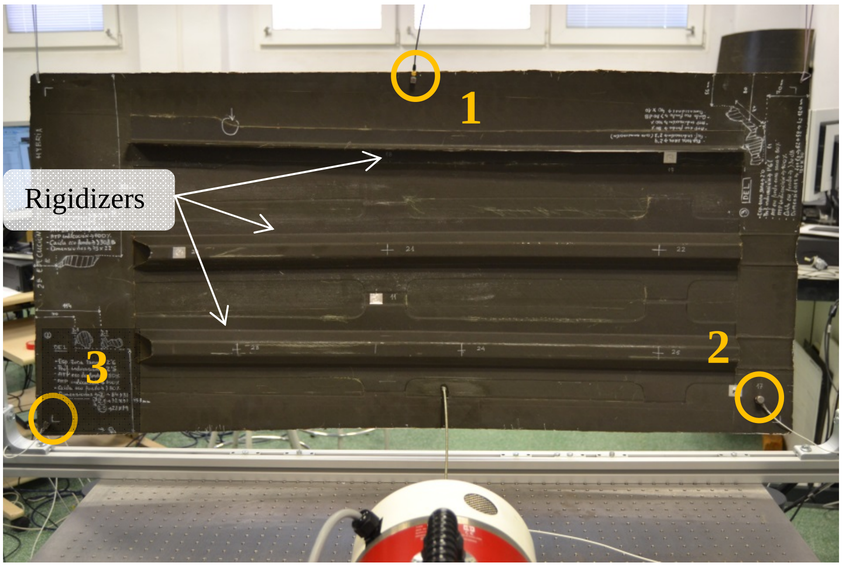


**Figure 5.** Accelerometers positioning on the panel's rear surface.

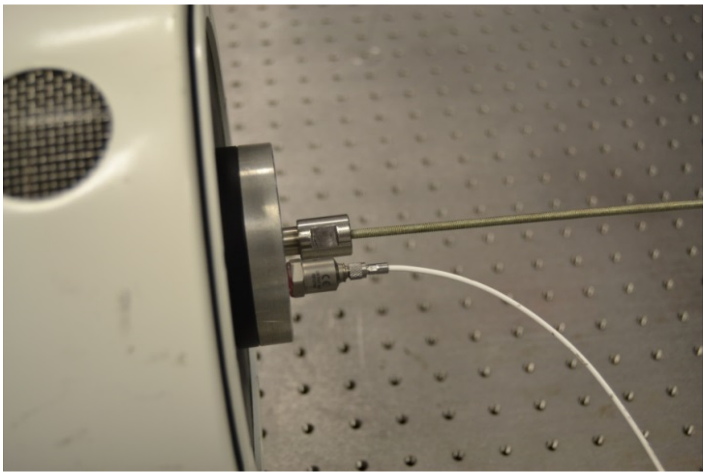

**Figure 6.** Accelerometer monitoring the excitation on the shaker armature.

The signals from each accelerometer were registered by the digital analyzer Photon+ and simultaneously processed by the controller software RT Pro Photon. The accelerometer on the shaker armature was set as excitation. Thus, three frequency response functions were obtained from each

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panel accelerometer. Frequency analysis consisted in a frequency span of 600 Hz and 1600 frequency lines, yielding a resolution of 0,37 Hz. Hanning window was also applied to avoid leakage and several averaged windows were taken to reduce noise influence. Finally, natural frequencies were identified as peaks in the FRFs plot.

### 2.2. Mode Shapes Measurement

Based on natural frequencies identification, a setup of 3D-DIC using two high speed cameras was managed to capture mode shapes of the panel in a full-field way when forced normal mode tests were performed. The two cameras were placed at a certain distance of the panel which allowed to have a view and capture the whole area of the panel. In Figure 7, it can be seen the cameras setup that ensures a suitable stereoscopic vision. Before performing the tests, a proper calibration of the stereoscopic system was carried out.

In these tests, excitation consisted in a sinusoidal signal whose frequency was a natural frequency of the panel. The same controller software RT Pro Photon was used to generate the signal from the digital analyzer.

Regarding to the cameras setting, it was needed a perfect synchronization capturing pairs of images simultaneously and performing the correlation between images using 3D-DIC algorithm. Furthermore, the frame ratio was chosen with the objective of measuring a well-defined vibration cycle. Hence the frame ratio was set at least ten times greater than the excitation natural frequency, thus more than ten points were taken per cycle.

Additionally, at the top of the aluminium frame, a plate was fixed (Figure 3). This plate was used for detecting whether vibration transmission from the panel to the structure appeared, and therefore could modify the panel behavior.

**Figure 7.** Optical setup for 3D-DIC full-field measurement.

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## 3. Results

Figure 8 shows the FRFs as result of the three accelerometers measurement. It is observed how the three accelerometers registered a wide variety of modes throughout the proposed spectrum, identified as peaks, so it is highlighted the complexity of the panel tested. Some of the modes are common to all accelerometer whereas others cannot be clearly identified each one, what proves the importance and influence of the positioning of a limited number of transducers.

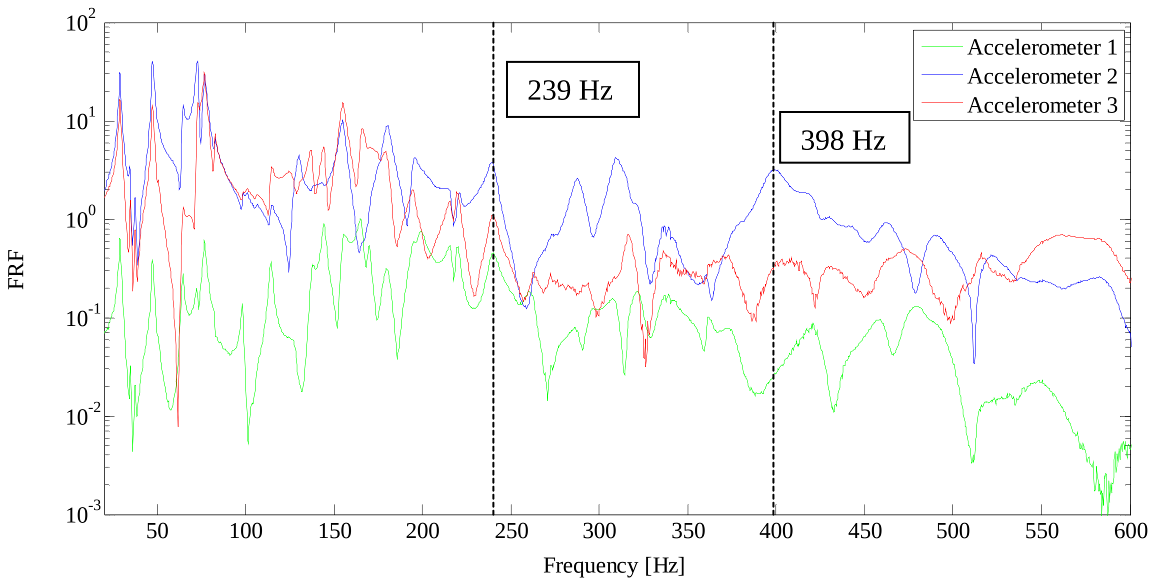


**Figure 8.** Frequency response functions from the three accelerometer positioned on the panel.

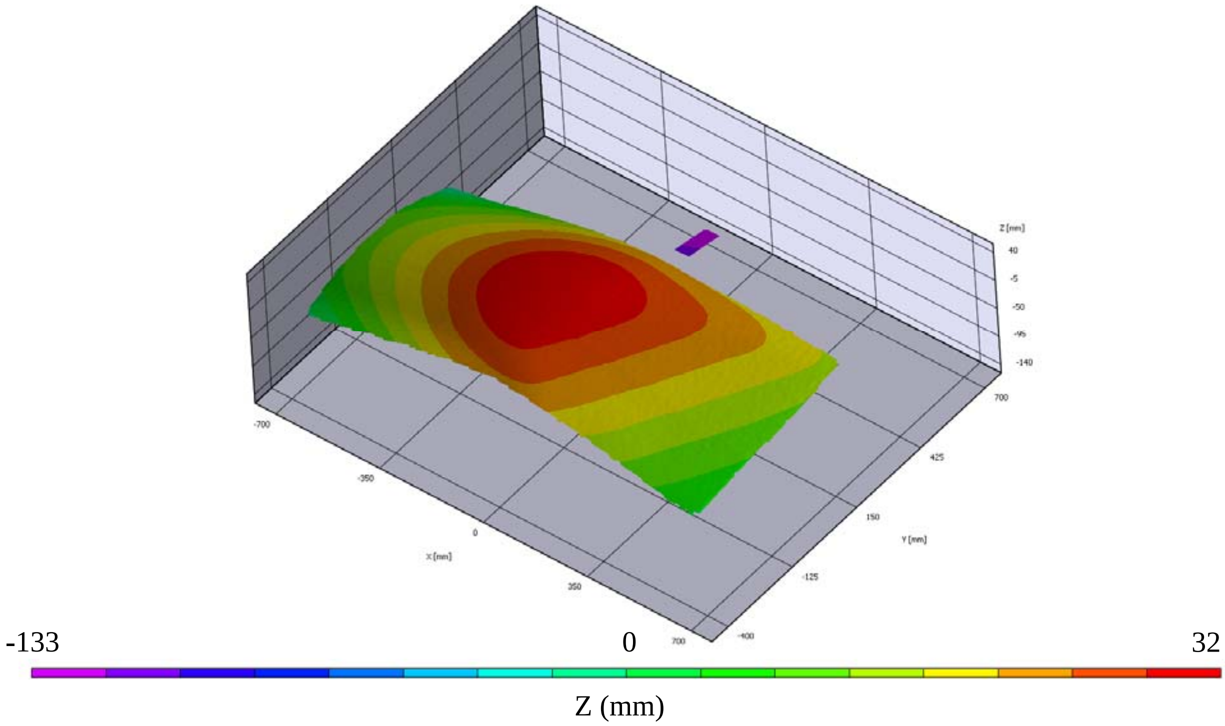


**Figure 9.** Three-dimensional digitalization of the panel and the reference plate

Due to the wide number of modes involved during the excitation, only two modes were selected to perform the FNM tests. Considering that displacements are greater at lower frequencies than at higher frequencies (where acceleration increases), the modes were selected, one in middle of the spectrum and other at the higher spectrum. Thus, it is possible to prove the accuracy of DIC at high rates of frequencies. Figure 8 shows the two modes at 239 Hz and 398 Hz.

In Figure 9, it is observed a three-dimensional digitalization of the panel at the reference state, in which its curved shape is perfectly defined. Figure 10 shows the full-field mode shapes of the panel, normalizing Z-displacement, i.e., perpendicular to the plane of the frame structure. The first mode, which appears at 239 Hz, produces a wavy shape along the contour of the panel. About the second one, at 398 Hz, has a more concentrated displacement. In this case, the wavy shape appears again but only along the bottom of the panel. Moreover, the number of waves in this side increases. The behavior of this mode is due to its higher stiffness. In both cases, the full-field measurements lead to conclude that the inner region remains undeformed due to the effect of the presence of rigidizers in this area and hence the affected area was just the contours.

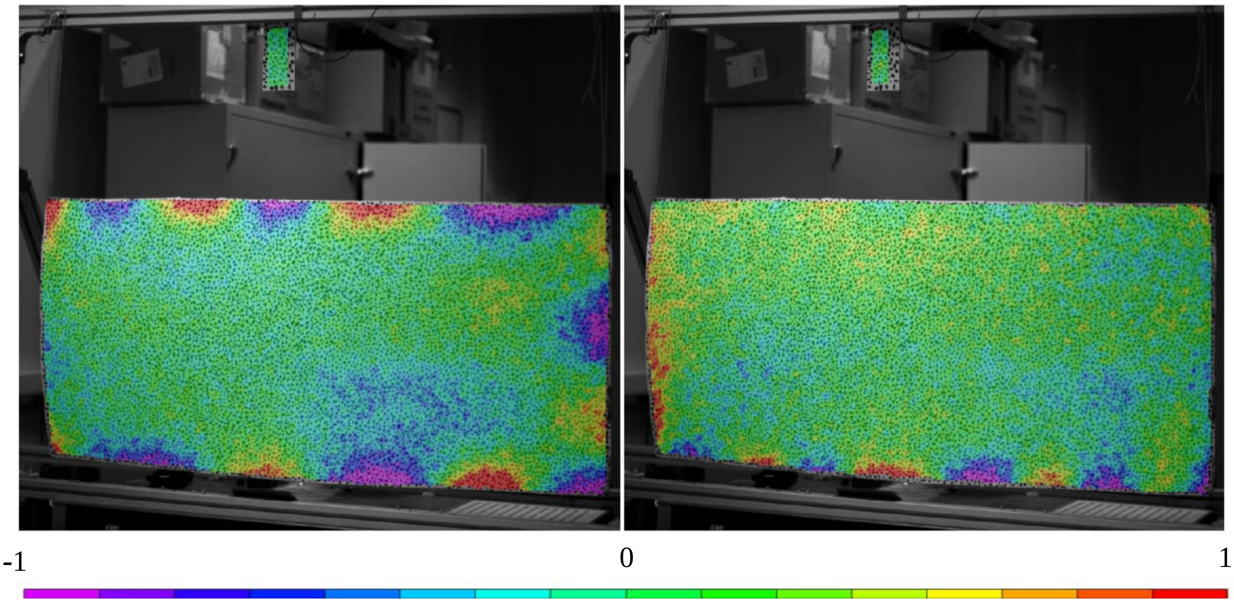


**Figure 10.** Normalized mode shapes measured by 3D-DIC in Z direction. On the left, 239 Hz mode. On the right, 398 Hz mode.

Comparing FRFs with mode shapes, it can be seen that, likewise no peak was found at 398 Hz in the FRF of the first accelerometer (Figure 8), there is no displacement at this point in the corresponding mode shape (Figure 10). See location of accelerometers in Figure 5. However, significant displacements were measured in the mode at 239 Hz where the accelerometers were positioned, as observed in FRF plots.

Finally, it is also necessary to highlight that, in all the tests, there was no transmission detected in the plate used to measure displacement of the structure.

## 4. Conclusions

In this paper, full-field mode shape measurements were performed on a big carbon fiber panel. An analogous test using accelerometers, for instance, would have implied a large number of

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accelerometers to properly define mode shapes. Furthermore, the panel is equipped with transversal rigidizers, as it is seen in Figure 5, resulting complex mode shapes. In fact, the measured mode shapes would involve gathering a lot of accelerometers on each wavy area in order to register the high displacement gradient. Consequently, 3D-DIC and high speed cameras have a great advantage in this sense. In addition, due to its non-invasive feature, no modification of the modal behavior has been produced as a result of the mass-loading effect. Another advantage is the acquisition of 3D digitalization before to excite the panel, so spatial positioning of each measuring point is accurately defined, unlike the accelerometers positioning. Another remarkable fact is the coherence between mode shapes and FRFs, measured by 3D-DIC and accelerometers respectively.

Therefore, 3D-DIC has been shown as a particularly interesting technique for modal characterization of composite materials components and, also, finite element models could be updated.

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