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MODAL SHAPE MEASUREMENT OF LARGE INDUSTRIAL COMPONENTS FRINGE PROJECTION WITH 2D-DIC

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This paper presents a novel application of a low-cost technique that allows the measurement of displacements maps in the three spatial directions of a dynamically deforming element, as is the case of a component subjected to sinusoidal vibration at its resonance frequency. The proposed technique is based on the integration of Fringe Projection (FP) and Digital Image Correlation 2D (2D-DIC). To perform a measurement, a single camera is used, which captures images of the specimen during deformation, and an additional projector that obliquely projects a blue fringe pattern. This fringe pattern allows the FP technique to be performed to the measure 3D shapes. Additionally, the studied component has a red speckle pattern to allow the 2D-DIC to be performed. Specifically in this study, the FP+2D-DIC technique was employed for first time to determine the first mode shape of a large industrial component. Namely, the liner for a car bonnet which was of 1.7 x 0.7m. The resonance frequencies of this component were found using a laser vibrometer when it was subjected to a free-free vibration test at its resonance frequency using a shaker. A high-speed camera recorded 500 images per second from which displacement maps in three spatial dimensions were calculated. The results demonstrate the capability to measure full field 3D displacements in large components subject to vibration using a single camera. Hence, this work presents an interesting alternative to stereoscopic DIC that has a lower cost and technical complexity but comparable accuracy and resolution.
Keywords: (e.g. Optical Techniques, Displacement measurement, Mode Shape)

1. Introduction

The study of structural elements subjected to vibration is a crucial task to undertake for increasing components life and for the reduction of vibrations and uncomfortable sensations to machine users. The traditional measurement by employing accelerometers [1] is standard practice, but only pointwise measurements are achieved. Additionally, the distribution of accelerometers are critical for the detection of vibration modes [2][3]. Furthermore, the use of accelerometer results in the addition of mass to the specimen which affects to the measurement.

Recently, optical techniques have been more applied since they allow non-contact full field measurements[4]. They include laser scanning Doppler Vibrometry (SLDV), laser interferometry (DSI and ESPI) and Digital Image Correlation (DIC). These techniques provide numerous advantages compared to traditional techniques such as measurement without contact (easing the measurement on rotating elements such as turbine blades [5]), study of strain gradients or detection of stress concentrators.

However SLDV laser scanning techniques have special vulnerability to rigid solid movements as well as to random vibrations [6]. On the other hand, techniques based on interferometry are limited in the measurement range of small displacements in one direction [7][8].

Besides, the wide availability of high-speed digital cameras together with the full-field optical technology such as 3D Digital Image Correlation (3D-DIC) [9] makes it possible to measure three dimensional displacement maps of elements subjected to vibration [10][11] [12]. However 3D-DIC needs a stereoscopic system of high-speed cameras for these transient studies. That means an increase in the cost and the complexity since the cameras are required to be perfectly synchronized and calibrated.

As an alternative, in this paper it is proposed the use of the novel integration of the techniques Fringe Projection (FP) [13] and Digital Image Correlation 2D (2D-DIC)[14].

2D-DIC and FP are two widely known techniques characterized by great versatility and sensitivity, but are limited to the measurement of in-plane displacements (x- and y-directions) and out of plane (z- direction) respectively. However, both have a very similar experimental setup (a single camera arranged perpendicular to a reference plane). Therefore, the integration of both techniques for simultaneously measure in and out of the plane displacements will decrease the cost and complexity of the set-up compared to 3D-DIC since a single camera and a fringe projector are required.

This integration of fringe projection with two-dimensional DIC has been previously proposed as a technical alternative for the measurement of displacement fields by several authors [15][16][17][18]. Nevertheless, no real alternative to 3D-DIC were achieved, especially for dynamic events.

In this paper it is employed a recently developed methodology [19][20] for the integration of these techniques (FP + 2D-DIC) for the measurement of large 3D deformations. Contrary to previous approaches, this methodology avoids using telecentric lenses, which are expensive and limit the size of the specimen. Moreover, since a single camera is employed, a correction process for in-plane displacement is required due to they are distorted by shape or out-of-plane displacement.

Specifically, in the present work, this new methodology has been firstly applied to vibration analysis. In particular, it is applied to determine the first modal shape of the first resonance frequency of a large industrial element such as the inner part of the bonnet of a vehicle. The purpose is to demonstrate that this technique can be employed by employing a high speed camera and a LCD projector to vibration analysis of large industrial components.

2. Experimental Methodology

2.1 FP + 2D-DIC technique using RGB pattern encoding

The methodology employed to integrate FP and 2D-DIC requires the acquiring of an image where only fringe pattern is present and another different image showing only a pattern of randomly distributed spots called speckle. Those images are suitable to process FP and 2D-DIC respectively. Additionally, both images must be captured at the same instant to be able to represent the same deformation state. To simultaneously acquire both patterns, RGB colour encoding [17] was employed. Therefore, using a RGB camera, a blue fringe pattern and a red speckle pattern, it is possible to obtain a colour image where both patterns are superimposed and can be extracted and processed independently as the fringes appear in the red channel image and speckle pattern on blue channel as presented in Figure 1.

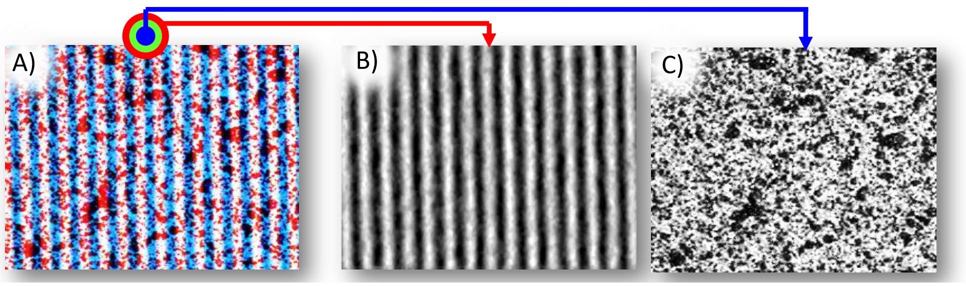

Figure 1: RGB image decomposition process A) Original image. B) Image of stripes C) Image of speckle.

Intensity of light across the projected blue fringe pattern observed in the red channel presents a sinusoidal intensity profile and the out-of-plane displacement will be measured as function of its phase [21]. This displacement is measured respect to a flat reference surface, where the projected fringes are parallel and equally spaced by a *P* pitch. Therefore, the out-of-plane displacements Δz are proportional to the lateral displacement of the fringes

$$\Delta z = K\Delta\varphi \, . \tag{1}$$

Where *K* is the fringe constant in mm/radians [20] and $\Delta\varphi$ is the phase difference in each pixel that is obtained between the reference image and the image studied. In this work, the phase difference of fringes have been processed using the Phase-Stepping method [21]. However, this method measures the phase difference of the projected fringes, but this phase is wrapped between -π and π, requiring a process called unwrapping to obtain a continuous phase map [22]. For this purpose an unwrapping process guided by quality map was employed.

Moreover, speckle pattern images observed on the blue channel of RGB images have been processed using commercial software VIC 2D (Correlated Solutions Inc.).

However, as discussed previously, in-plane displacements measured by 2D-DIC are distorted when the element is not flat or undergoes out-of-plane displacements. This distortion is illustrated in the pin-hole model presented in Figure 2 where a point on the surface is shifted from $\mathbf{Q_1} = (x1, y1, 0)$ to $\mathbf{Q_2} = (x1 + \Delta x, y1 + \Delta y, \Delta z)$.

In figure 2 it is observed that the displacements measured in the CCD of the camera do not correspond to the real ones and a virtual in-plane displacement exists due to out-of-plane displacement ($\mathbf{\Delta x_{\Delta z}}$, $\mathbf{\Delta y_{\Delta z}}$). Therefore, ($\mathbf{\Delta x_{\Delta z}}$, $\mathbf{\Delta y_{\Delta z}}$) must be subtracted from the displacements measured in the CCD by 2D-DIC [19], leading to next mathematical expresions:

$$\Delta x = L\Delta x_{CCD} - \Delta x_{\Delta z} \tag{2}$$

$$\Delta y = L\Delta y_{CCD} - \Delta y_{\Delta z} \tag{3}$$

Where *L* is the lateral magnification (in mm/px) at z_0 distance between reference and optical centre the lens.

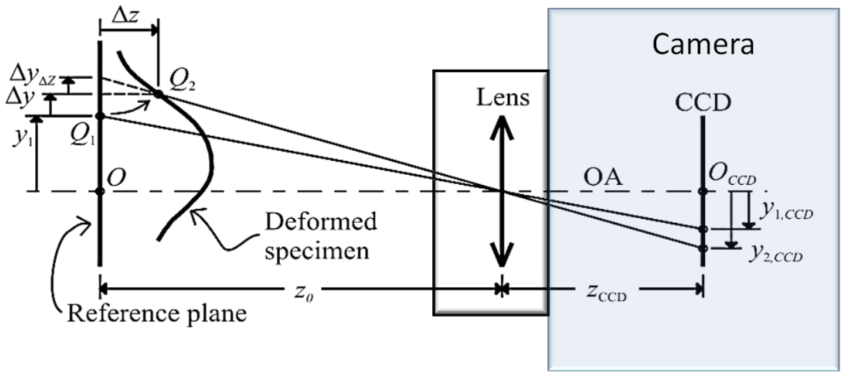

Figure 2: Schematic illustration showing the error in the processing of 2D-DIC when the studied element experiences out-of-plane displacement during the deformation.

From equations 5 and 6, it is observed that, in order to perform the correction of the virtual displacements, it is necessary to know the distance z_0 between the optical center of the lens and the reference surface, the value of lateral magnification L in mm / pixel and the position of the optical center on the CCD (O_{CCD}) from which the position of the pixel is measured. Furthermore, optical axis of the camera (OA) must be aligned perpendicular to the reference.

To perpendicularly align the system respect the reference surface a laser emitter is placed parallel to the optical axis of the camera. Additionally, a mirror is also placed on the reference surface. Thus, the camera will be perpendicular to this surface when the laser is reflected on itself as described in Felipe-Sesé et al [20].

Once the system is aligned, the value of z_0 is obtained by processing 2D-DIC between two images of the reference surface. In one of the images the optical center is in position z_0 and in the other image the camera is shifted Δz along the optical axis using a micrometric platform. In this case, the displacements in *x*- and *y*- directions must be zero, however, 2D-DIC measures a virtual radial displacement ($\Delta r=\mathrm{sqrt}(\Delta x^2+\Delta y^2)$) known as radial displacement cone shown in Figure 3 (CRD), which may be related to the value z_0 according to equation 7:

$$z_0 = \Delta z\left(\frac{1}{m}+1\right) \quad (4)$$

Being m the slope of the cone ($m= \Delta z/z_0$)

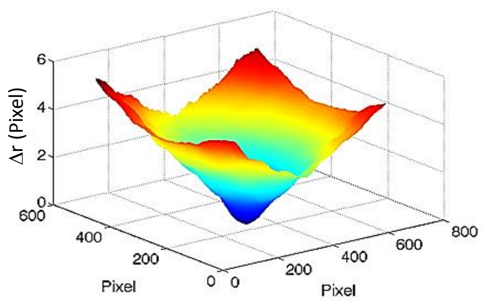

Figure 3: Radial Displacement Cone.

In consequence, the vertex of the cone of radial displacements offers the position of the centre O_{CCD} in the CCD of the camera. Hence, if the camera is arranged perpendicular to the reference plane and there are no optical aberrations, must be located in the centre of the CCD.

2.2 Experimental set-up

The previously described methodology was employed to analyse the displacements undergoing on an industrial element when it was subjected to sinusoidal excitation at its first resonance frequency. The specimen was a car bonnet of approximately 1,8x0.8m provided by Centro Ricerche Fiat, Italy. The test was performed as a free-free test and, hence, the element experienced relatively large displacements. Therefore, the element was suspended by two cables of reduced stiffness (Figure 4B) and was excited by its lower part by means of a shaker (Figure 4C). The connection was made by a threaded rod attached to the element in order to provide minimum stiffness. The camera used was a Photron SA-3 high speed camera equipped with Vivitar lens with a focal length 28mm acquiring 500 images per second.The projector employed was an Epson X11 projecting a blue grid of 20mm pitch.

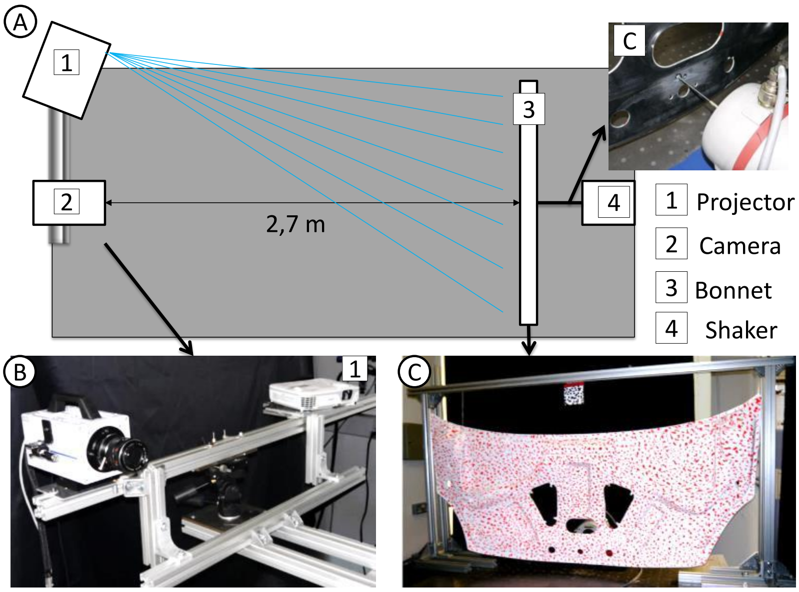

Figure 4: A) Schematic illustration of the set-up employee seen from the top. B) Camera and projector system. C) Car bonnet suspended by cables. D) Shaker and connection.

2.3 Identification of the modal frequency

The resonance frequency of the bonnet under study was found using a laser vibrometer (Polytec OFV-2500). This vibrometer recorded the response of the element studied when it was impacted by a hammer and allows determining the frequencies to which the bonnets tends to vibrate. As shown in Figure 5, the first resonance mode is at 10.25Hz which was the frequency at which the bonnet was excited.

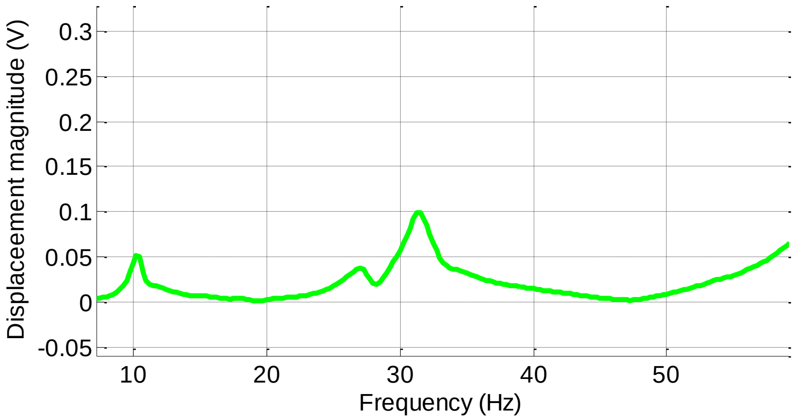

Figure 5: Bonnet response as a function of frequency.

3. Results

In this section I will be presented the results of the displacements in the x-, y- and z-directions obtained with the proposed FP + 2D-DIC methodology.

Figure 6 shows the out-of-plane displacement maps measured in the different phases of the excitation.

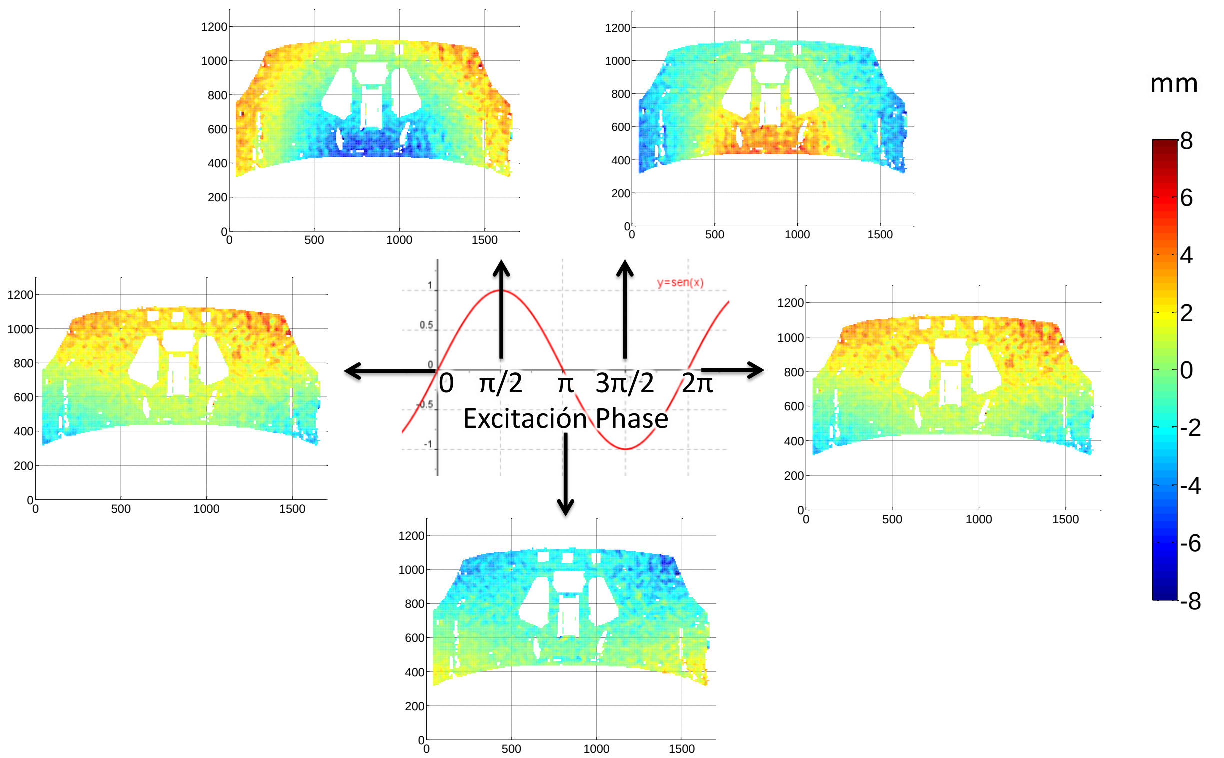

Figure 6: Out-of-plane displacement maps experienced by the car bonnet as function of excitation phase.

The displacements measured in x- and y- direction are significantly smaller than those measured in the Z direction as seen in the maximum displacement results in Figure 7.

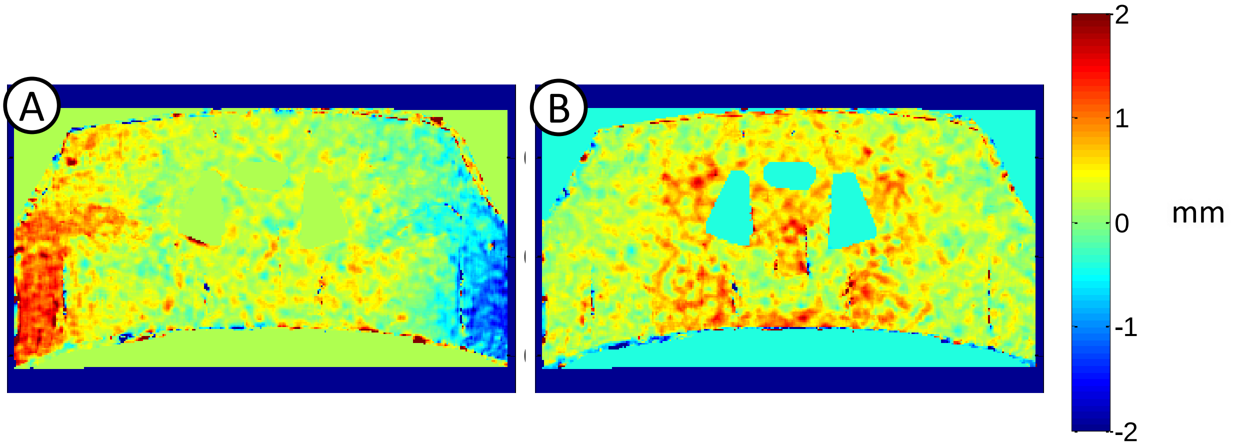

Figure 7: Maximum displacement maps in x- A) and in y- direction of the bonnet during the free-free test.

4. Discussion

From the displacement maps of Figure 6, it can be observed that FP + 2D-DIC allows obtaining a map of precise displacements when a large element is subjected to a vibration test. In this case a range of + -5mm out-of-plane displacement is measured which would imply 0.37% of the distance between object and the camera and 0.6% of the field of view of the camera which demonstrates the sensitivity of the system. Displacements in z- direction when this same element is studied to its first modal shape have been previously studied by other authors employing 3D-DIC and finite element method [12] [23] and the clear similarity of the results reinforce the potential of the FP+2D-DIC technique as a low-cost alternative for 3D-DIC for vibration analysis and its ability to validate numerical results. Additionally, it is observed that the registered mode shape is a complex mode and the phase varies along the surface of the specimen.

On the other hand, in view of the results of the in-plane displacements shown in Figure 7, it is observed that the technique not only allows measuring out-of-plane displacements, but also it is possible to measure in-plane displacements. However, it is observed that, since this first modal shape presents mainly a bending along a vertical axis, the deformation in y- direction is negligible and only a slight deformation in x- direction is observed in a total range of 3mm. That represents less than 0.2% of the total width of the piece, which again demonstrates the high sensitivity obtained.

5. Conclusion

In the present work a new industrial application of the integration of the out- and in-plane displacement measures obtained employing Fringe Projection and Digital Image Correlation 2D respectively has been presented. This recent integrating approach allows analysing displacements in the three spatial dimensions using only a camera and a projector.

Additionally, the good results obtained in the vibration test of a panel of approximately $1.2m^2$ demonstrates that it is possible to perform such analysis of 3D displacements even in large industrial components subjected to dynamic conditions as vibration. For that purpose, it has been only required the use of a single high-speed camera and a conventional projector, reducing considerably the cost regarding the use of 3D-DIC technique which requires two cameras.

The results of displacements obtained are comparable to those observed in the bibliography obtained by numerical techniques or with 3D-DIC.

Therefore, it is concluded that the presented technique represents a real alternative of low cost to 3D-DIC for the dynamic measurement of displacement maps in the three spatial dimensions.

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