Full-field modal analysis using high-speed 3D digital image correlation

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Abstract. Digital Image Correlation (DIC) is a non-contact full-field image analysis technique which allows to retrieve strains and displacements in three dimensions at the surface of any type of material and under arbitrary loading. In recent years, high-speed and high-resolution cameras have been developed for static as well as for dynamic applications. As consequence, the application fields for DIC have broadened and it has proven to be a flexible and very accurate measurement solution for deformation analysis and material characterization. Nevertheless, nowadays DIC is often used in a qualitative manner rather than as a metrological tool. This is especially due to the time-consuming task related to the post-processing of the images. When compared to other vibration testing techniques, full-field approaches (such as DIC) allow a greater flexibility by providing a very dense number of experimental data over a single measurement. Another advantage is related to the fact that the geometry is automatically extracted from the images. In this paper, the possibility to combine global acceleration measurements on a small component with local full-field standard machine vision quasi-static camera measurements is investigated. In particular, the regularization properties of DIC and their impact on modal analysis will be studied in detail. Strains and displacements could be used in a second stage for modal analysis purpose in order to characterize the dynamic behaviour of the specimen in a certain frequency range. Different approaches could be used for combining the data obtained during the tests. The most obvious approach would be the alignment of the time histories based on reference signals for Frequency Response Functions (FRFs) calculation prior to perform any further processing. Unfortunately this is not always possible because of synchronization issues. An alternative possibility, in case broadband random excitation is used, requires to process time data into auto and crospsowers and identify the modal parameters by using Operational Modal Analysis (OMA).

1. Introduction
Nowadays the typical setup when testing and validating numerical models of a mechanical structure comprises a certain number of transducers (e.g. accelerometers, strain gauges, etc.). By only using a limited number of transducers it is not easy to comprehensively and quickly measure the dynamic response, especially when dealing with large-size structures such as utility-scale wind turbines or helicopter blades.

Furthermore, placing transducers is a labor intensive and time consuming task and it could introduce electrical noise to the measured signals due to the extensive and unavoidable wiring. This is one of the reasons behind the development of image processing techniques to perform modal analysis of
mechanical structures without contact and without having to instrument the specimen. Another reason for advancing in the research in this field is connected to the damage detection and evaluation in lightweight structures. In fact, for this type of systems such as composite materials and 3D printed structures it is mandatory to avoid adding weight by placing sensors on their surface. This allowed the development of embedded fiber optics within the material layers and the development of noncontact measurement techniques. Among the others, a scanning Laser Doppler vibrometer (SLDV) has seen an impressive increase of use in the last years, but it is limited to sequential measurements (i.e. one point at a time) and in order to measure at several locations it needs to scan the entire surface while the excitation signal is repeated over time. This could lead to an inconsistency in the measurements since the physical excitation or the system itself can change over time during a single measurement. An alternative technique which is further discussed in this paper is the Digital Image Correlation (DIC) which allows to measure the full-field response of a structure. These approaches allow to measure the dynamic behavior in a very accurate manner since they are able to measure at many more points if compared to conventional testing techniques using strain gauges, accelerometers or displacement sensors. Various applications in the field of experimental mechanics require a full-field data set for the analysis of a system, e.g. VFM and FEMU for material identification ([1], [2], [3]), the detection of structural damage on components, etc. Digital image correlation (DIC, [4]) is one of the many available methods on the market (besides Moiré interferometry, speckle pattern interferometry, the grid method [5], etc.) that provides the ability of producing those full-field datasets and especially DIC has gained more interest over the last years due to its simpler setup and lower hardware cost. DIC only requires a set of cameras and a specimen which has been speckled (i.e. a gradient must be present in the photographed specimen, which can be created with spray paint, a marker, stickers, etc.), which allows tracking of points on a sub-pixel level if one assumes the conservation of optical flow. Images are thus compared between cameras and over time in order to find correspondences, which leads to a set of displacement data.

2. Digital Image Correlation: working principle

Figure 1 shows the DIC working principle: the first image of camera 1 is used as a reference image to which the image of the second camera (taken at the same time) is compared. The corresponding points can be triangulated into a three-dimensional point in space (denoted as [X,Y,Z]) if the orientation of the cameras is known (by performing a pre-test calibration). The same matching of points can be done over time so each measurement point can be tracked over time, leading to a total deformation tracking of the surface area of a specimen (in which the deformation is indicated as [U,V,W]).

This process holds some intrinsic requirements towards the images: a gradient, as well as contrast, must be present so features can be tracked. The size of those features lead to the minimal size of the so-called subset (also called interrogation window – indicated in yellow in figure 1), which encompasses several features and which is tracked throughout the set of images. This is needed since a single pixel is not a unique item due to the limited amount of grey-scales which are stored in an image (usually 8 bit cameras are used, so a maximum of 256 grey scales are available). A cluster of pixels is however a unique set of data which can be tracked, while it will also reduce the measurement noise at the same time. This subset is restricted in the way it can deform by assigning a so-called “shape function” to it, leading to an even higher amount of robustness against noise (more information on the shape function can be found in [5] and [6]). This, together with image interpolation for sub-pixel accuracy [7], leads to high-quality and precise measurements of shape and displacements. From here on other metrics can be derived; strains can be identified by looking at the relative displacement between neighboring points [8], velocities, accelerations and strain rates can be derived if the timestamp of each image is known, stresses can be calculated if the correct material model is known [9], etc., which leads to the versatility of this optical-numerical technique [10].
3. Case study: helicopter blade

The possibilities of DIC as a measuring tool are further explored by using it as a data-source for performing a full-field modal analysis by measuring a tail blade of a helicopter, which is dynamically excited by a shaker. The high data-density of DIC lends itself as a proper tool for this since there is little surface preparation needed, while also having the benefit that the specimen is not locally loaded with accelerometers, which could alter the behavior of the structure in the case of fragile or small structures.

Figure 2 indicates the specimen on which a white base coat has been applied, which is needed to create enough contrast after applying the speckles (i.e. features). It also indicates the clamping on the right hand side, as well as the free end of the structure. Figure 3 indicates the setup after attaching all accelerometers (indicated as a red star), while the shaker is indicated in a blue dashed square. This state, as imaged by the camera, can eventually be seen in figure 4 (as imaged from the top).

Throughout the vibration test the specimen was imaged from the top with two AVT Mako U-130B cameras, of which the specifications can be seen in table 1. Each camera was equipped with a 12mm lens, leading to a standoff distance of about 2500mm. The applied speckle pattern was optimized for this specific setup with a pattern generator in order to achieve the maximum available spatial resolution, leading to a sampling of 6 pixels per speckle, a black/white ratio of 99.98% and a usage of the dynamic range of 55%. After performing a calibration the intrinsic and extrinsic parameters are determined (indicated in respectively in table 2 and table 3).
Figure 2. Blade with white base coat.

Figure 3. Speckled specimen with attached accelerometers indicates as a red star.

Figure 4. Specimen as imaged by the left camera.
Table 1. Mako U-130B specifications.

| Parameter                              | Value                                      |
|----------------------------------------|--------------------------------------------|
| Resolution [pixels]                    | 1280 (H) x 1024 (V)                       |
| Pixel size [μm]                        | 4.8 x 4.8                                  |
| Theoretical max. frame rate at full resolution [fps] | 168                                        |
| Mass [g]                               | 60                                         |
| Dimensions [mm]                        | 49.5 x 29 x 29                             |

Table 2. Camera intrinsic parameters.

| Parameter | Camera 0 | Camera 1 |
|-----------|----------|----------|
| Fx, Fy [pixels] | [2649.28 ; 2649.35] | [2606.88 ; 2606.88] |
| Cx, Cy [pixels] | [665.40 ; 271.68] | [625.72 ; 292.30] |
| κ          | [-0.375 ; 0.256 ; -0.375] | [-0.124 ; -0.003 ; 1.209] |
| P          | [0.0033 ; 0.0019] | [0.0033 ; 0.0019] |

Table 3. Camera extrinsic parameters.

| Parameter | Translation camera 0 - 1 | Parameter | Rotation camera 0 – 1 |
|-----------|--------------------------|-----------|------------------------|
| Tx [mm]   | 415.03                   | Θ [°]     | 2.73                   |
| Ty [mm]   | -2.92                    | Φ [°]     | -10.34                 |
| Tz [mm]   | 61.87                    | Ψ [°]     | -0.06                  |

4. Results: conventional modal analysis
The helicopter blade has been instrumented by means of ten accelerometers, as shown in Figure 3. One of the main objectives of this paper concerns the comparison between conventional modal analysis and full-field DIC-based modal analysis. On one hand the blade has been fixed to a rigid structure; on the other hand the blade is free to move. Several typical excitation signals have been sent to the shaker in order to dynamically excite the blade (random and sine testing). Hammer testing has also been performed and results of all tests are very similar in terms of modal parameters. Figure 5 shows the shaker signal during a sine sweep and two of the measured acceleration signals. Frequency Response Functions (FRFs) can then be calculated and a modal parameters estimator, such as Polymax [11], can be used in order to determine the natural frequencies, damping ratios and mode shapes of the helicopter blade.
Table 4 shows the list of natural frequencies obtained with the conventional modal analysis in the frequency range up to 400Hz. The first four mode shapes are shown in figure 6.

**Table 4.** Helicopter blade natural frequencies and damping ratios in the range [0 - 400] Hz.

| # mode | Natural frequency [Hz] | Description      |
|--------|------------------------|------------------|
| 1      | 20.1                   | 1st bending mode |
| 2      | 104.7                  | 2nd bending mode |
| 3      | 152.1                  | 1st torsion mode |
| 4      | 252.5                  | 3rd bending mode |

**Figure 5.** Shaker force signal during sine sweep (left); Accelerometers signals during the same sweep (right).

**Figure 6.** Helicopter blade mode shapes obtained by using conventional modal analysis based on ten 3D acceleration signals (marked points).
A discrete number of sensors is enough to characterize the global modes of a structure. On the other hand a full-field measurement technique allows to better identify local modes and to obtain enriched information which could be used for damage identification. The Modal Assurance Criterion (MAC) is used to validate the estimated modal model.

5. Results: full-field modal analysis

Various tests were performed (including hammer testing, shaker random testing and shaker sine testing), however only the results of one shaker sine test will be indicated further here for the sake of simplicity. During this test the shaker amplitude was fixed at 0.1V and the frequency spectrum ranged from 6 to 50Hz during a 30 seconds test. Throughout this test the blade was imaged by both cameras at their maximum synchronized recording speed and these images were post-processed with the settings mentioned in table 5 so a full-field displacement and strain map was obtained, with the respective noise levels indicated in table 6.

| Parameter                  | Value |
|----------------------------|-------|
| Subset [pixels]            | 25    |
| Step [pixels]              | 5     |
| Interpolation              | B-spline |
| Shape function             | Affine |
| Strain window [pixels]     | 7     |
| Strain interpolation       | Q8    |

Table 5. DIC processing parameters.

| Parameter                  | Value       | Parameter                  | Value       |
|----------------------------|-------------|----------------------------|-------------|
| Horizontal in-plane displacement U [µm] | 4.5         | Exx []                    | 2.98×10^{-4} |
| Vertical in-plane displacement V [µm]    | 4.5         | Eyy []                    | 3.58×10^{-4} |
| Out-of-plane displacement W [µm]         | 26.6        | Exy []                    | 2.04×10^{-4} |

Table 6. Noise level displacements & strains.

Figure 7 indicates the full-field displacement map of the blade during loading, while figure 8 indicates an extraction of the blade tip during the first resonance frequency (indicating a peak displacement at image 300, which is around 20Hz). An enlarged side view of the blade can indicate the mode shape during this loading stage (as seen in figure 9). After deriving the time-displacement correspondence the full-field velocity and acceleration maps can be identified by a derivation of the identified displacement function (e.g. the velocity map in figure 10).

Figure 7. Out-of-plane displacement during loading [mm].
Figure 8. Blade tip displacement [mm].

Figure 9. Blade deflection shape [mm].

Figure 10. Velocity [mm/s].
One of the objectives of the work was the identification of the most practical ways to combine the data and results from the cameras and from the accelerometers. The most obvious approach would be to align the time histories based on reference signals prior to perform any further processing. This would have the advantage of allowing to calculate the Frequency Response Functions (FRFs) from the DIC displacements, but it would also require a perfect synchronization [12].

An alternative possibility is to process time data into half auto and crosspowers, identify the modal parameters using Operational Modal Analysis (OMA) and then combine the mode sets using a common reference [13]. During the performed sine tests the excitation profile in the frequency range of interest is equivalent to a white noise and OMA can then be reliably applied.

The steps going from the data acquisition to the modal analysis results for the DIC data are listed here:

1. Export displacement field of all images from MatchID software;
2. Manipulation and data reduction in Matlab to build the displacement time histories of all points measured during the entire measurements;
3. Import time histories in Simcenter Testlab for each measured Degree-Of-Freedom (DOF);
4. Import the geometry from MatchID software;
5. Calculate auto- and crosspowers and perform OMA

One of the main difficulties is related to the huge amount of data to be post-processed. In this case more than 10000 points were exported from the camera measurements and the geometry is presented in figure 11. Figure 12 shows the displacement time history measured by the cameras of a point randomly selected on the blade surface during the sine sweep test. The amplification of the oscillation around the resonance frequency is quite evident.

![Figure 11. DIC measurement points and accelerometers (red points).](image)

Finally, the mode shapes can be calculated. Unfortunately the cameras frame rate did not allow to go higher than 50Hz, which only allows the 1st mode identification (around 20Hz). This is explicitly shown in figure 13, where the 1st mode shape obtained by using the DIC modal analysis is compared to the one already shown in figure 6.
**Figure 12.** Displacement time history of a point on the helicopter blade surface measured by using the cameras.

**Figure 13.** 1st bending mode shape: Digital Image Correlation modal analysis (left) vs conventional accelerometers based modal analysis (right).

**Conclusions**

In this paper, an application which combines conventional modal analysis with standard machine vision quasi-static cameras and DIC analysis is presented. The quality of the measured DIC data is very good and its application in the modal analysis field in order to enrich the conventional modal analysis results with high density data is very promising. However some limitations need to be taken into account:

- Data reduction techniques should be implemented to allow faster and accurate processing with current processors capabilities
- Higher performance cameras need to be used for having a higher frame rate which allows to increase the maximum frequency to be analyzed.

A very interesting field of application is the combination of Digital Image Correlation and conventional modal analysis to perform a very accurate validation of Finite Element (FE) models due to the very high spatial resolution. This is one of the main advantages of DIC which shows also potential for identifying defects in lightweight strictures where the weight of sensors could be an issue when instrumenting the specimen for testing.
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