Chapter 5
Enhancing Standard GVT Measurements with Digital Image Correlation

S. Manzato, E. Di Lorenzo, and P. Mäckel

Abstract In recent years, high-speed cameras permit to record high-resolution images at several thousand frames-per-second. In addition to this, Digital Image Correlation (DIC) measures full-field displacements and strains in 3D from stereo camera images and perform Operational Deflection Shape and Modal Analysis on the data. Several papers have demonstrated the validity of the approach on laboratory cases, comparing and validating the results with those obtained using more standard measurement techniques (accelerometers, strain gauges, lasers). Very limited cases have been however investigated on the possibility to combine high-speed DIC and standard accelerometer-based measurement to fully exploit the advantages of both techniques. In this paper, the possibility to combine global acceleration measurements on an F16 during a classical Ground Vibration Test with local full-field camera measurement is investigated. The advantages of the combined approach are clear, as the standard measurement will provide the global mode shapes of the aircraft, which can be used for certification and modal validation, while the local high-speed camera measurement system can provide displacement and strain field data with an unmatchable spatial resolution. In particular, the paper will focus on the possibility of using the local displacement measurements to better characterize the non-linear behavior of the connection between the wing and the payload.

Keywords Ground Vibration Testing · Digital Image Correlation · Modal Analysis · non-linearities

5.1 Introduction

Over the last two decades, there has been a growing research and industrial interest in contactless measurement technologies. This has mostly been driven by the increasing usage of lightweight materials and topologically optimized structures (thanks to Additive Manufacturing and 3D printing), but also by scenarios were standard sensor cannot deliver high quality results. While Laser Doppler Vibrometry is a quite establish solution to achieve contactless measurement with high spatial resolution, image-based techniques are now attracting more and more attention, as they can achieve an incredibly high spatial resolution. Without the need or repeating the measurement multiple time. While in the past this technology was mostly used in static and quasi static testing, it was also proven that it was similarly possible to apply it to dynamic problems as well. In parallel, the quality of high-speed cameras has also drastically improved, not only in terms of frame rates, but also Signal to Noise Ratio, linearity and resolution, which are essential requirements for DC. Also size and weight have been significantly reduced, so that stereo high speed camera systems are easier to handle. Furthermore the computational power and memory available on modern Laptop and Desktop PCs is able to handle the high amount of space and time domain data generated by the stereo high speed system for FFT processing.

A thorough overview of photogrammetry and optical methods, with application to structural dynamics, is available in [1]. In [2], a detailed comparison between Digital Image Correlation (DIC), Laser Doppler Vibrometry (LDV), Electronic Speckle Pattern Interferometry (ESPI) and accelerometer-based measurement is performed, with a specific focus on the identification of the dynamic response. Many other similar publications have been published and presented in recent years, but most of the time on dedicated test cases, often in lab conditions. Some examples of operational measurements on rotors are reported in [1, 3].

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In this paper, the objective is to use a stereo high-speed camera systems to measure the displacement field of the wing end of an F16 during a GVT campaign. The measurement where performed under a limited time window of 2 days by two experienced users, who however had never had the chance to perform such a measurement in a comparable combined scenario, with the goal of integrating the DIC measurements and results with those from a standard GVT system (which uses accelerometers). A theoretical overview of DIC measurement and analysis is outside the scope of the paper, but a detailed and thorough description can be found in [4], which also describes the software VIC3D of Correlated Solutions applied here.

5.2 F16 Ground Vibration Test

Every 2 years, Siemens Industry Software organizes for its customers, as well as anybody interested, a Master Class to share best practices on how to perform successfully a GVT, covering all topics from instrumentation, to test setup, data analysis, validation and verification of numerical models and finally covering also the fundamentals of flutter testing [5]. The theory is of course applied on the fly on a real F16 aircraft, shown in Fig. 5.1.

The standard instrumentation used on the aircraft includes:

- A combination of single axis and triaxial ICP accelerometers, measuring a total of 109 Degrees-of-Freedom (see Fig. 5.2)
- Two electro-dynamic shakers exciting each wing tip in the vertical direction;
- Two load cells or impedance heads at the interface between the shaker stinger and the structure to measure the applied forces.

In order to facilitate interpreting the results and visualize the mode shapes, it is highly recommended to build a geometry with the location of the transducer (Fig. 5.2). This process can be quite time consuming and prone to errors, which are particularly important when the results are used to validate a numerical model.

Figure 5.3 show the results obtained by applying modal analysis on the 109 $\times$ 2 FRF matrix measured using a Pseudo Random excitation profile. On the left, the measured FRFs at 1 DOF are compared with those synthesized using the identified modal model. On the right, the AutoMAC allows to verify that the modeshapes are orthogonal and there is no spatial aliasing.

In the occasion of the Master Class, we generally have the opportunity to keep the aircraft instrumented for some extra time for research purposes. In the past, for example, we tested the applicability of photogrammetry to generate a geometry of the text object that could be used for mode shapes expansion when a CAD or FE model is not available [5] (Fig. 5.4), or to collect data on a representative structure to develop/validate engineering approaches to deal with non-linearities in structural dynamics [6] (Fig. 5.5).

Fig. 5.1 The tested F16 aircraft

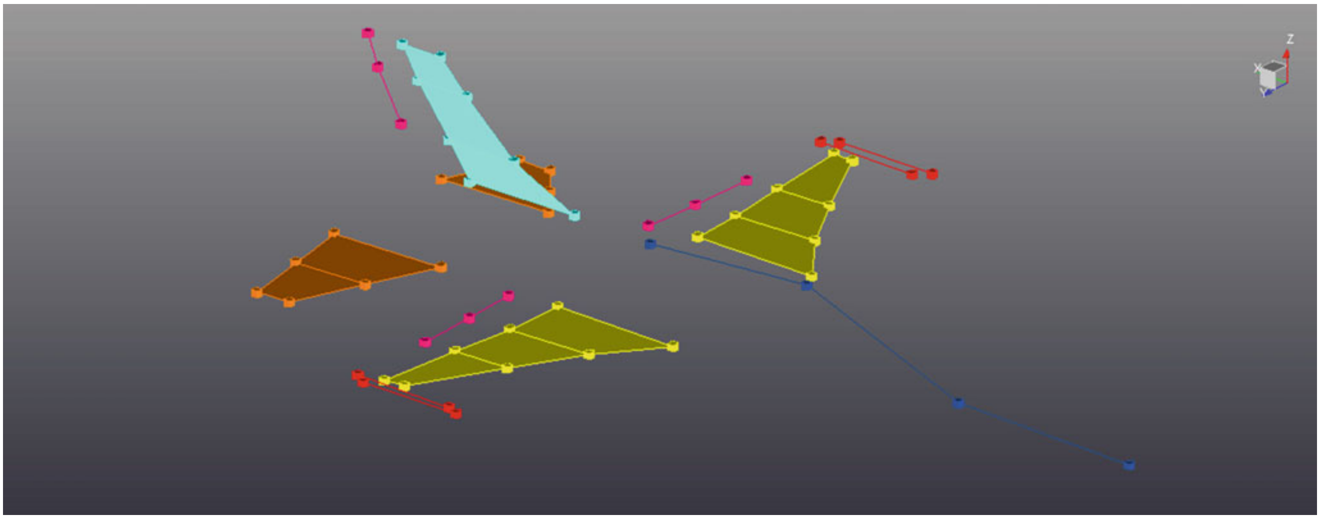

Fig. 5.2 Standard GVT test geometry with measurement points

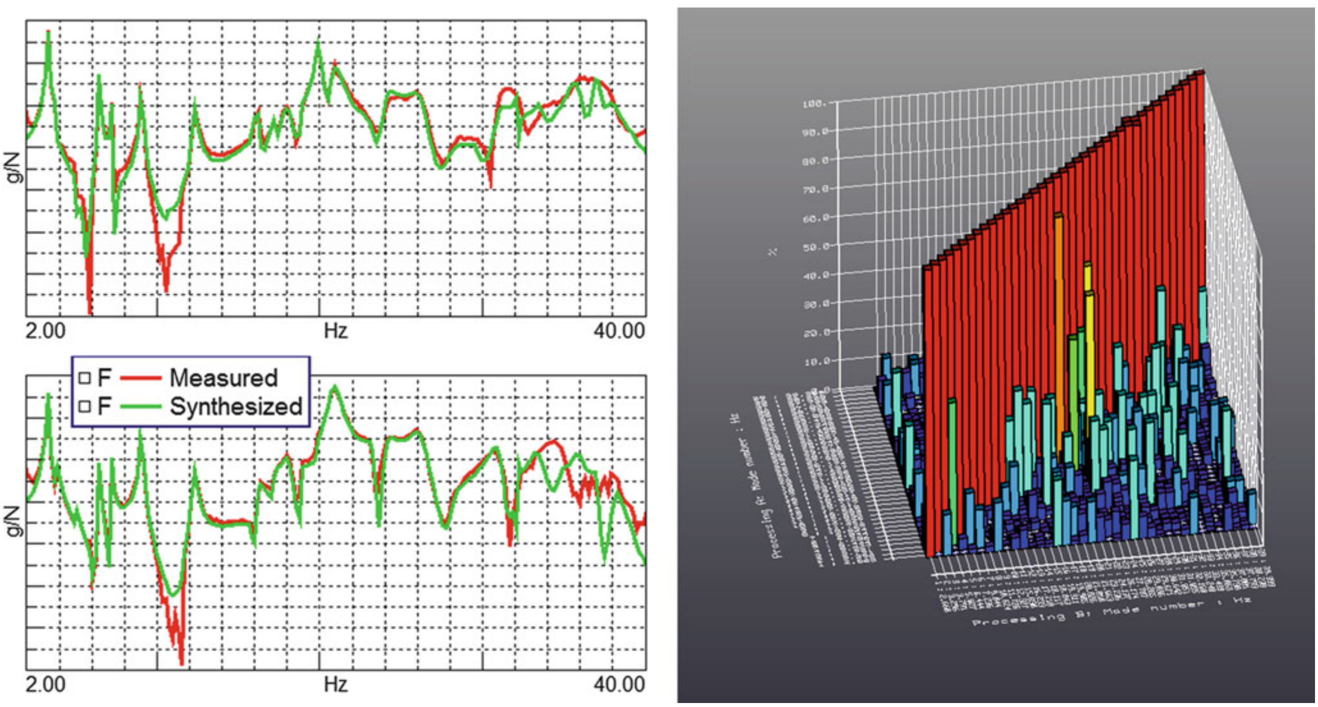

Fig. 5.3 Modal analysis results. Left: measured vs. synthesized FRFs. Right: autoMAC matrix for the identified mode set

For the more recent master class, organized in September 2016, it was decided to further focus on optical techniques, and in particular on full-field dynamic DIC. The test campaign was planned and designed to get a clear answer to the following questions:

- Can High-Speed Camera with Digital Image Correlation be used in a GVT context?
- Can it be used in combination with a standard GVT measurement setup and what is the added value of combining the two systems?
- What is the best way to combine the results from the two systems together?

In order to keep the complexity of the setup to a minimum and to fit the measurements in the limited time frame available, the DIC analysis was focused on a local area of the aircraft, namely the wing tip, the payload support and the payload itself. In particular, this area was chosen as the connections between these three components showed a non-linear response when

Fig. 5.4 Left: left wing with markers for photogrammetry. Right: Measured point cloud used for mode shape expansion

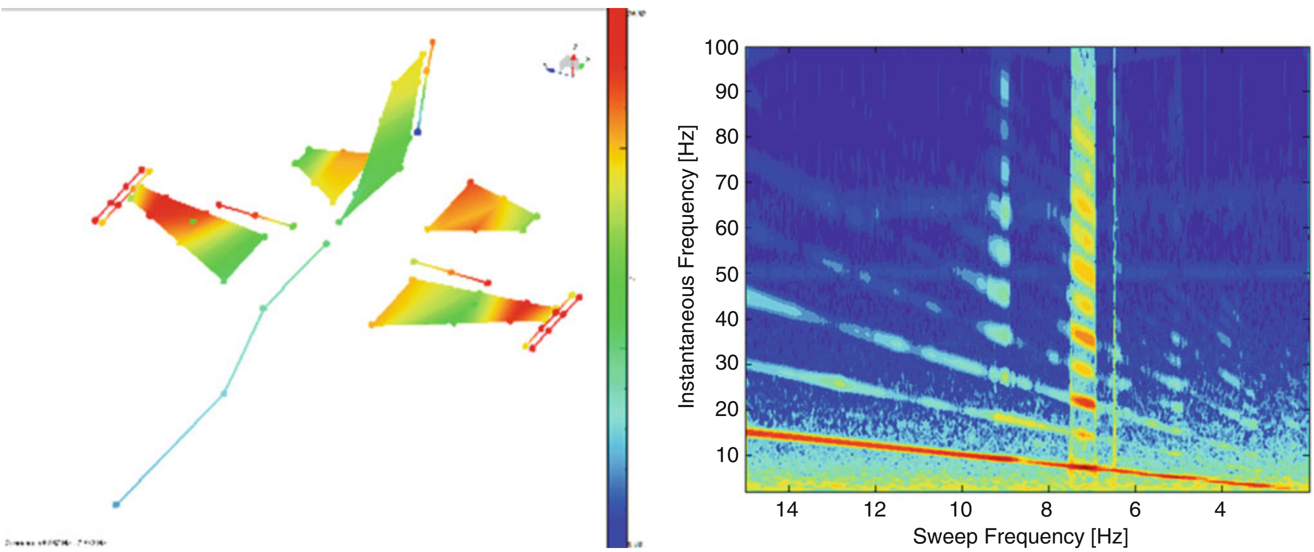

Fig. 5.5 Nonlinear dynamics assessment: Left: linearity map. Right: time frequency analysis

exciting one of the low frequency modes. The availability of the full field displacement field can provide more accurate information on the non-linearity than the use of few accelerometers.

In Fig. 5.6 the system used for measurement is shown. Two Photron FASTCAM AX100 cameras with were used in a stereo system arrangement of isi-sys GmbH. Lenses with a comparable short focal length of 20 mm have been selected in order to allow 3D measurements from below the wing. To simplify the setup, the speckle pattern was obtained by attaching printed stickers to the lower side of the wing, Finally, artificial lighting was used to allow sufficiently short exposure times to reduce motion blurring. An example of the two frames captured by the stereo camera pair of the system is shown in Fig. 5.7.

To calibrate the 3D stereo camera system and record and process the images, the VIC-3D software, with the special FFT-Module, was used. The FFT-Module of VIC-3D was developed by Correlated Solutions INC, USA in 2009/2010 for vibration and running mode analysis using the phase separation method. Due to the instantaneous full field recording principle in combination with High Speed Cameras this principle is one of the only method which can be applied for full field operation mode analysis. In parallel, to drive the shakers and measure accelerometers, LMS SCADAS with LMS Test.Lab software were used.

However, streaming data synchronously on a PC from the two setups is not possible, as pictures are collected on an internal storage device and then need to be transferred to a PC after the measurement is finished. Also, synchronization between the

Fig. 5.6 Camera Instrumentation overview with the stereo system on the left and the whole setup with the extra lights on the right

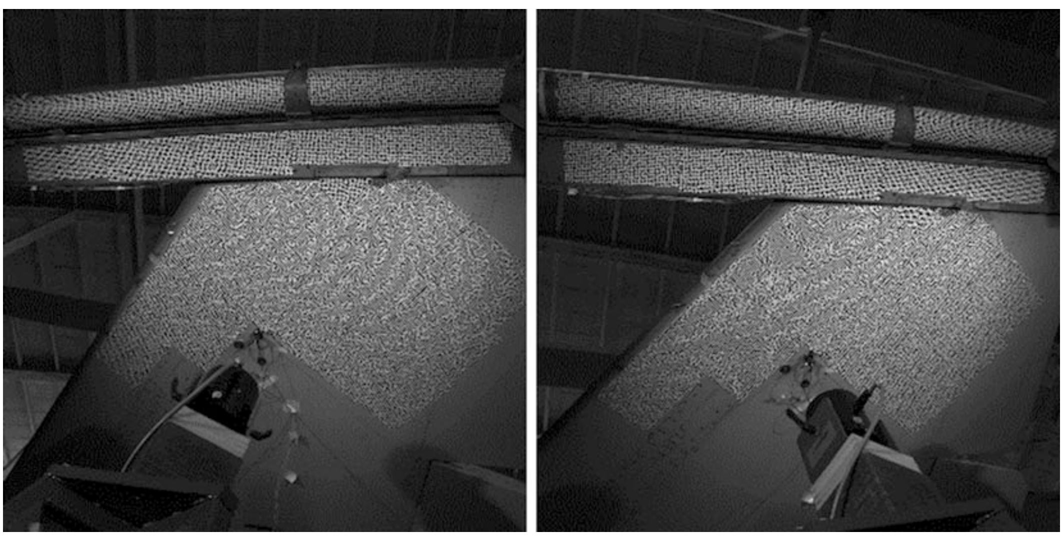

Fig. 5.7 Example of a stereo image pair of the F16 wing tips from below. The payload support and the payload itself. On the center of the lower part the electrodynamic shaker and the connection to the wind is seen

two systems can be an issue if data are to be processed simultaneously, as the internal clocks might be slightly different. Thus other means of combining the data from the two systems were investigated, and will be discussed in next section.

To excite the aircraft, standard random and burst random excitation profiles were used first. In the VIC-3D FFT module, time data can be converted to the frequency domain and Operational Deflection Shapes (or Running Mode analysis) performed. However, no averaging process is foreseen and consequently broad band random spectra will be quite noisy and the shapes might not be extremely clear (also considering displacements are calculated from the measurements). Consequently, sine sweep excitation was used, which yielded a much higher signal to noise ratio. To keep the sweep speed low enough and comply with the storage space available in the cameras, the frequency range had however to be limited between 5 Hz and max 30 Hz. To analyze the non-linear response, excitation was applied at two different levels. Finally, in order to limit the amount of data to be stored and the processing time, the displacement outputs are calculated on a reduced grid than the one on which the DIC is performed. Example of the calculated Operational Deflection Shapes from the image processinareis shown in Fig. 5.8.

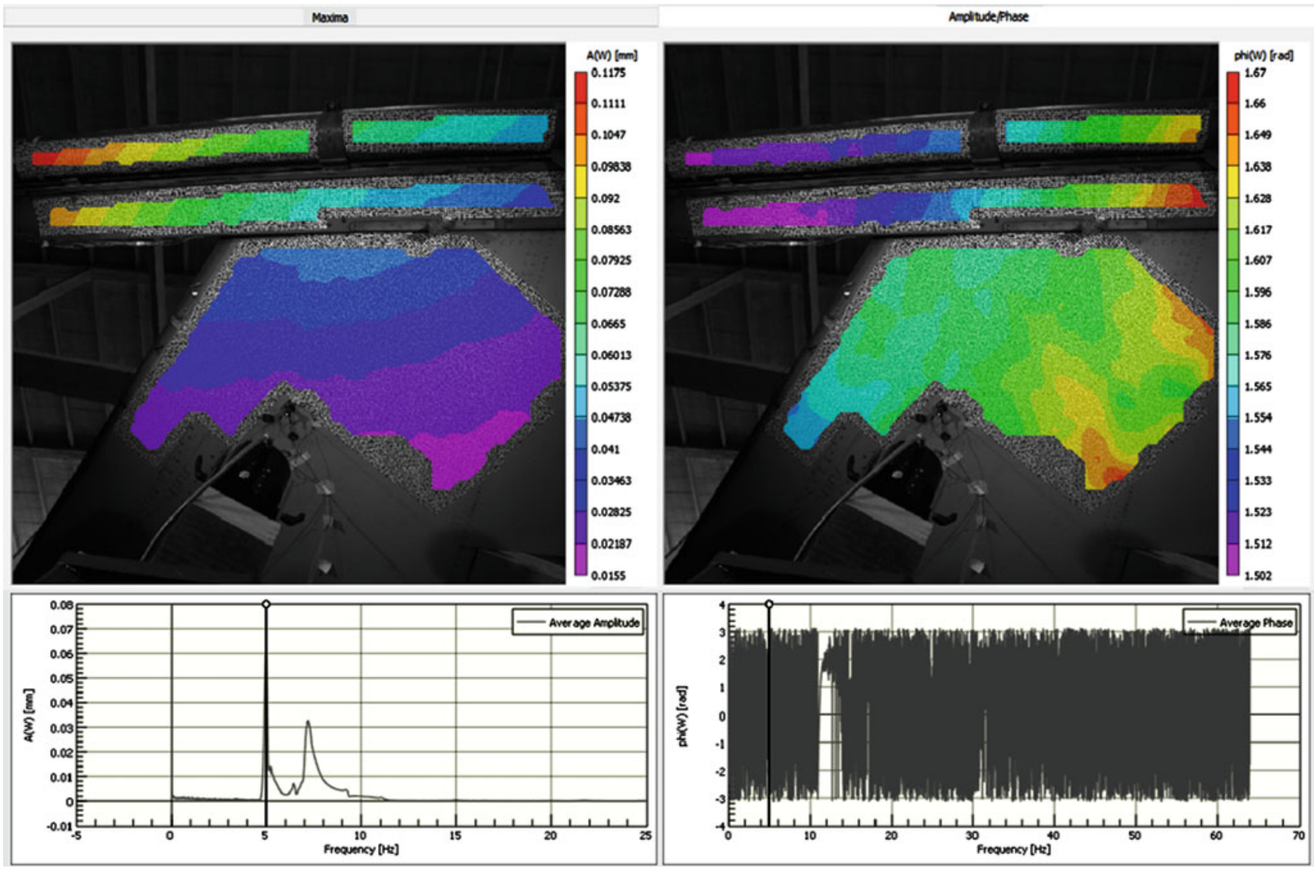

Fig. 5.8 DIC processing in the CIV3D software. Example of an Operational Deflection Shape

5.3 Combining Standard and Full-Field Measurements

As mentioned above, one of the objectives of the work was the identification of the most practical ways to combine the data and results from the two systems.

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 calculating the Frequency Response Functions (FRFs) from the DIC displacements, but it would also require a perfect synchronization. As it was not possible to use a reference clock (i.e. GPS based) for both systems, this accurate alignment cannot be achieved.

An alternative possibility is to process time data into half auto and crosspowers, identify the modal parameters using operational modal analysis and then combine the mode sets using a common reference. Although sine tests were performed, the excitation profiles in the frequency range of interest is equivalent to a white noise (Fig. 5.9) and Operational Modal Analysis can then be reliably applied.

One of the big advantages of DIC is that geometry is automatically calculated by the system. The point coordinates can then be added in Test.Lab to the original F16 geometry and the two geometries be aligned (Fig. 5.10). As a consequence of the alignment, a common reference point can be determined, which will be useful to merge the mode shapes. Figure 5.11 shows first a comparison of the displacements obtained from DIC on the same point for the two levels. In the 30 N test, the excitation spanned from 5 to 30 Hz, with a sweep speed of 0.25 Hz/s. In the 75 N test, it was decided to decrease the sweep speed to 0.1 Hz/s to better characterize the non-linear response of the mode at 7.4 Hz. This however required to limit the max frequency to 12 Hz.

For the selected reference point, the spectra from the acceleration signal (integrated to displacement) are compared with those directly obtained from the DIC. The dominant peaks match very well, with the main difference, as expected, being the better Signal-to-Noise Ratio achieved with accelerometers. This could be caused by the fact that raw time data were processed, without using any of the available filters in VIC3D.

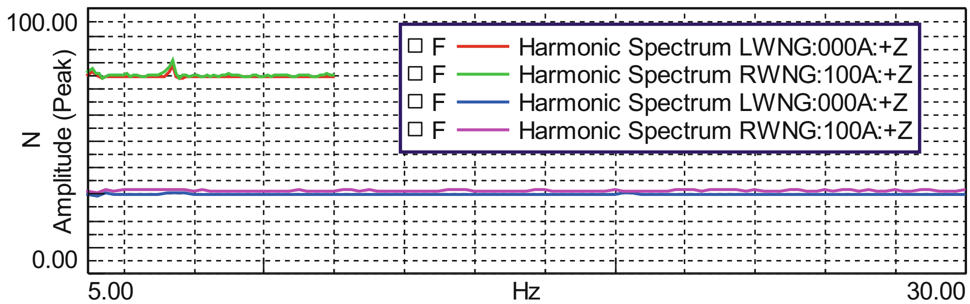

Fig. 5.9 Reference input force spectra for the two excitation levels

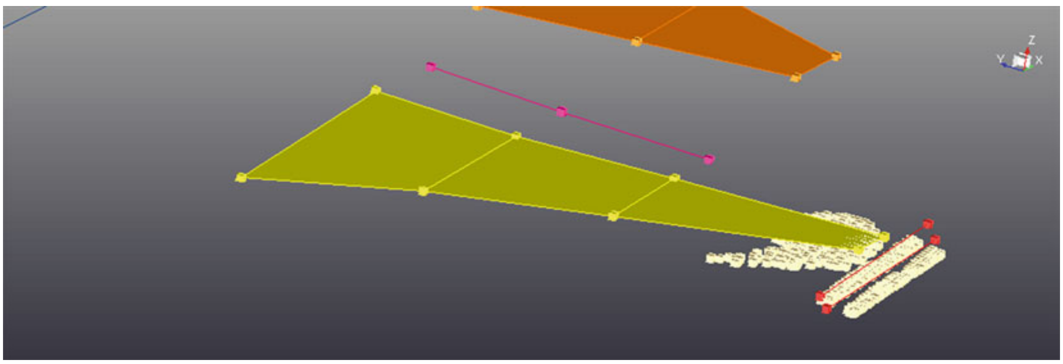

Fig. 5.10 DIC geometry overlaid to the standard one

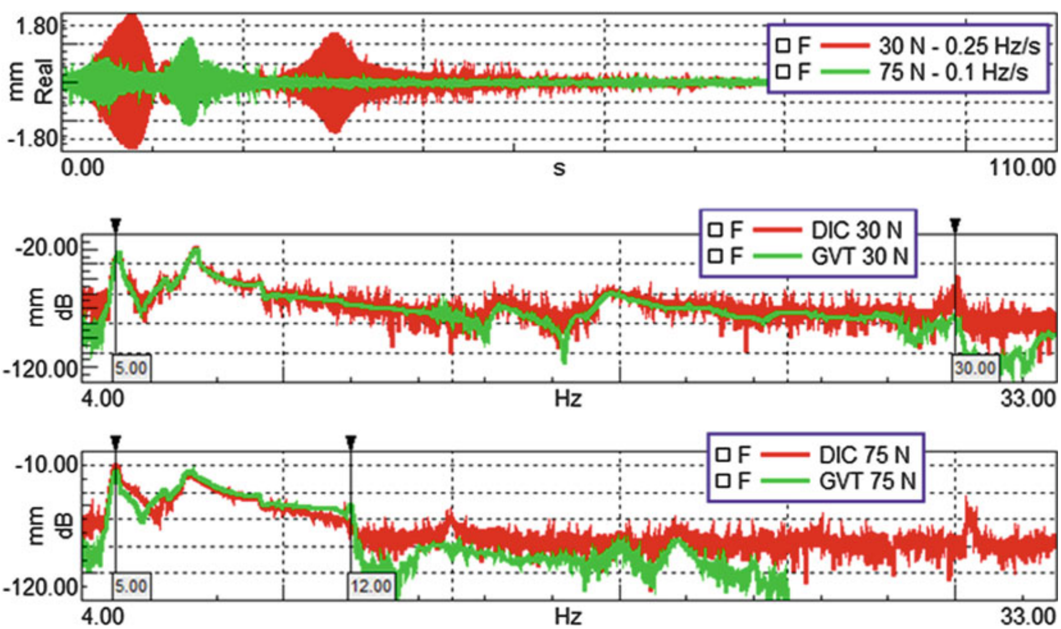

Fig. 5.11 Comparison between DIC and standard measured data on the same reference point

First, the data from the standard GVT system will be measured. As two shakers are used, FRFs need to be calculated using two sweeps with different phases between the shakers to have uncorrelated forces. To compute the Operational Modal Analysis (OMA) modes, the complete time histories are considered. However, the second sweep is not available in the DIC system, as the internal memory didn't allow to store all data. Only the symmetric modes are then expected to be found in that case. Also, as the DIC focused on the left wing tip area, only dominant wing modes will be considered and up to 12 Hz to allow a comparison between all runs.

Table 5.1 Reference GVT modes for random excitation and comparison to OMA results on Sine Sweep data

	Freq. Rand	Freq. 30 N	Freq. 75 N	Damp Rand	Damp. 30 N	Damp. 75 N
Mode 1	5.121	5.076	5.003	0.66	0.79	0.81
Mode 2	6.503	6.537	6.401	0.41	1.08	1.536
Mode 3	7.417	7.369	7.205	0.41	0.809	2.665
Mode 4	9.334	9.314	9.221	0.8	0.729	1.144
Mode 5	11.919	11.756	11.618	0.65	1.067	1.161

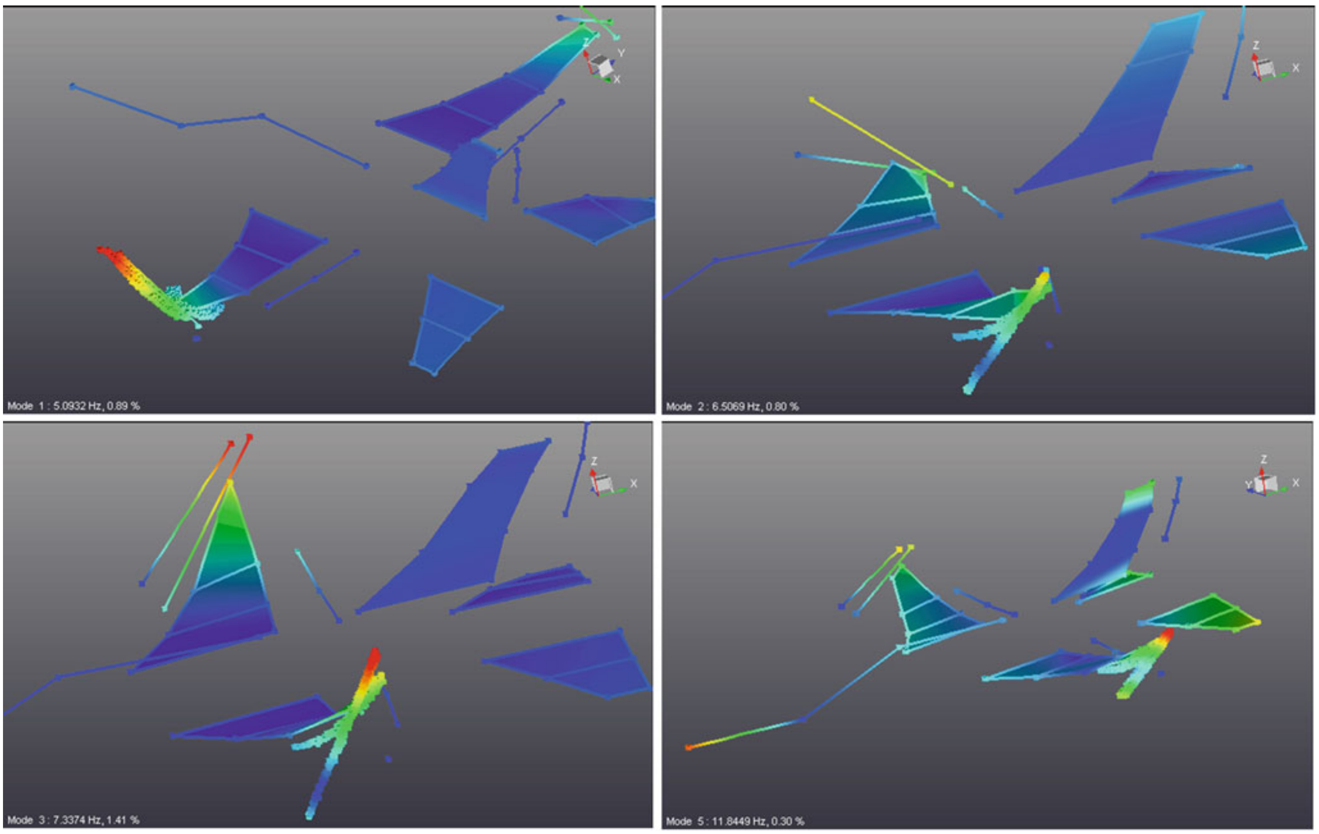

Fig. 5.12 Examples of identified mode shapes with GVT and DIC modes combined

The same processing is repeated also for the data collected at the higher excitation level. In Table 5.1, the results obtained with OMA are compared to those from standard random excitation and FRF modal analysis. It can be observed that, as the excitation level increases, the frequencies decrease while damping increase. This will be further investigated in the next section.

Modes will be now calculated applying OMA on the DIC time histories. Similar settings are used to compute the cross-powers and calculate the modal parameters. To merge the modes, the standard procedure available in the LMS Test.Lab software is used:

- The same DOF Id is used for the common points between the two datasets
- The point is selected as reference for the Crosspowers calculation.
- The two modesets are loaded in the Multi Run Modal worksheet;
- The software looks for pairs of modes to merge based on the natural frequency.
- The two modesets are rescaled and merged assuming the modal component on the reference DOF need to be the same.
- As modal components are always computed as displacements, there is no need to integrate acceleration before merging.

The merged modes are displayed in Fig. 5.12. The displacement output of VIC measurements are superposed on the left wing tip (in flight direction). In the left top image the bending of the wing tip, the payload support and the payload itself can be seen, as well as in the above Fig. 5.8.

The results show that the modes obtained with the two systems and then merged are compatible and the processing applied can be considered correct. These results allow then to give a clear reply to some of the initial questions:

- High-Speed Cameras measurements and DIC processing can be used in a GVT context and can be very useful and practical if limited to a specific area in this application, although e. g. gas and steam turbine blade up to wind turbines can be monitored in full scale (although full scale is possible, but technically more challenging).
- Measuring wider areas at equivalent pixel resolution comes with lower displacement measurement sensitivity and spatial resolutions, thus a compromise is needed.
- Combining standard measurement with local DIC can then be considered as an optimal solution.
- Using OMA to combine the modal results can be considered as a viable and more practical alternative than recombining time data, in particular when an accurate synchronization signal is not available.
- However, synchronizing the measurement systems remains the only solution if FRF calculation is required.
- In general, it is suggested, if possible, to use sine excitation as is the one that will compensate for the lower signal to noise ratio (related to the measurement of displacements) for spectral analysis using camera-based systems. In other cases (lighter structures), broadband random excitation might still suffice.

5.4 Preliminary Analysis of Non-linear Response

As mentioned and already reported in [6], non-linear response was identified at the connection between the wing and the payload. From the results summarized in Table 5.1, it can be already observed that in general the wing modes have a softening effect, with natural frequencies decreasing with increasing load, while damping increase (normally because of friction). This can be also observed in the Autopowers in Fig. 5.13. For a linear system, the FRFs scale the response to the input. However, if we try to scale the measured Autopowers either from acceleration measurement or the DIC to the force levels in Fig. 5.13, we can observed they don't really match and we can observe s general shift of the peaks to lower frequencies and a decrease of amplitude response at resonance because of damping. This is mostly evident in the 7.4 Hz resonance corresponding to the symmetric wing torsion.

Similarly, if we perform a time-frequency analysis using a Short-Time Fourier Transform on the DIC data, we see in the response not only the excitation frequency, but also its higher harmonics excited. However, the low signal-to-noise ratio of the camera based measurements in this scenario makes the detection of higher order harmonics more difficult than when

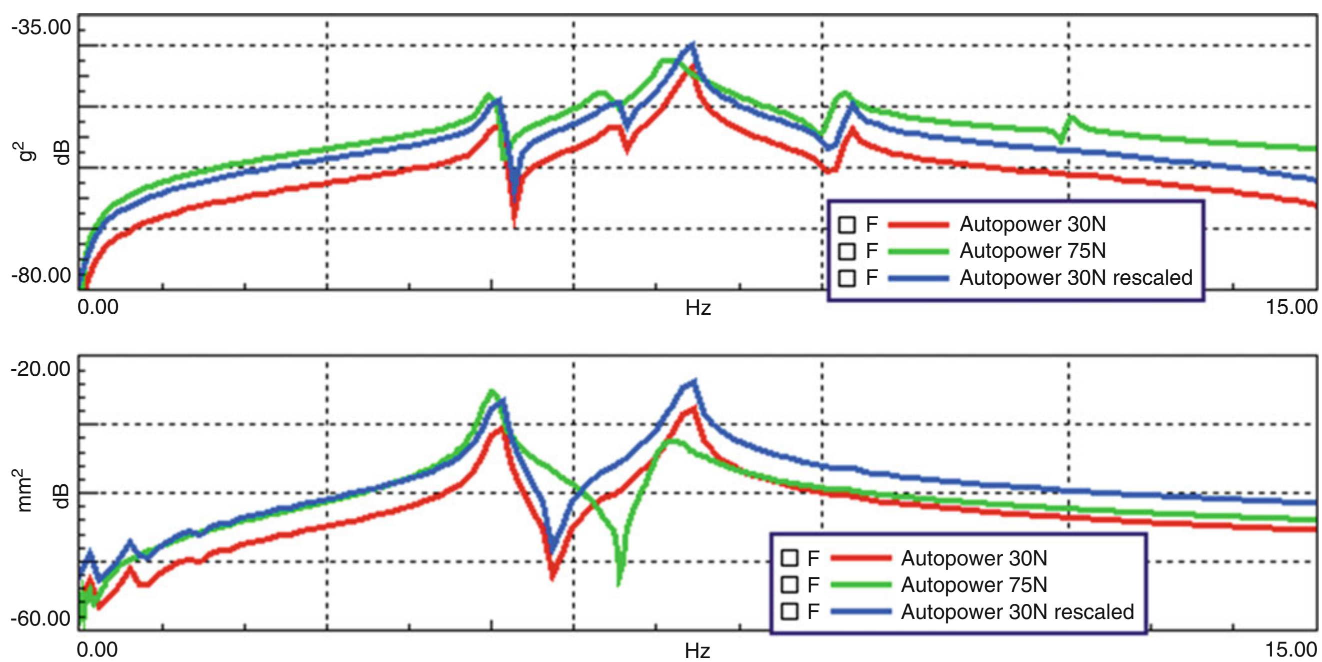

Fig. 5.13 Response linearity plots: autopower comparison

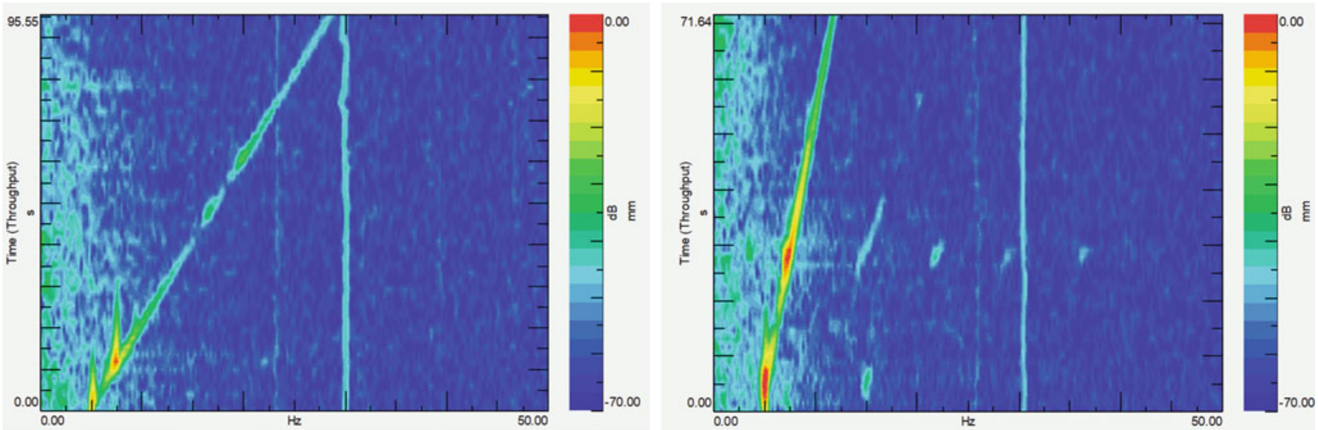

Fig. 5.14 Low (left) vs high (right) time-frequency analysis plot for DIC data

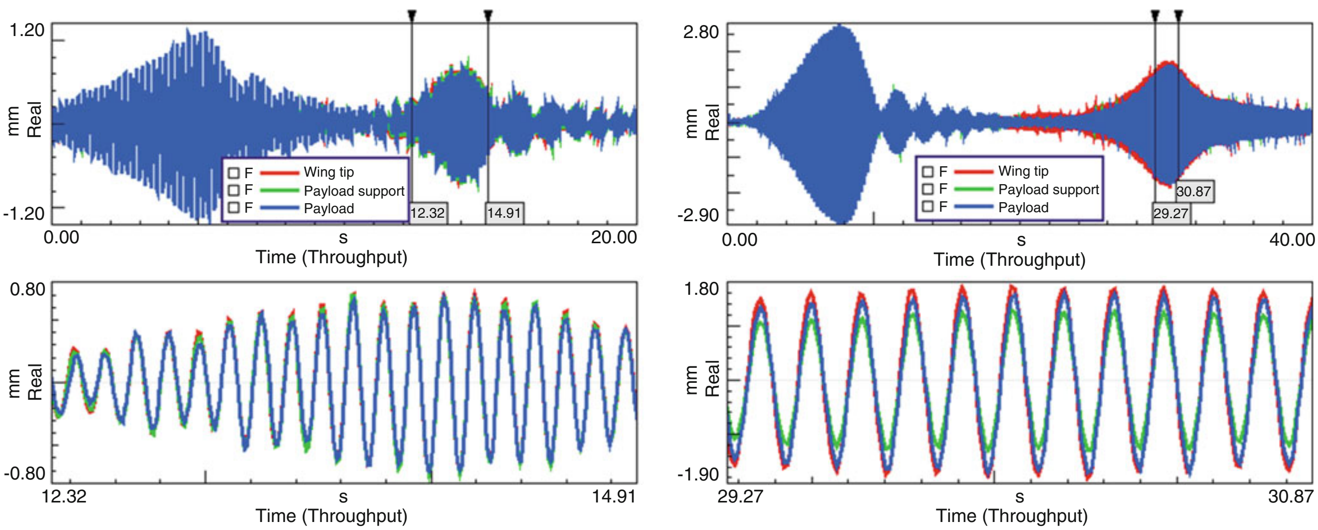

Fig. 5.15 Linearity analysis on time histories. Left: 30 N. Right: 75 N

using accelerometers (Fig. 5.14). The same limitations can also be observed in the time histories. Normally, for increasing load, higher harmonic distortion is observed using accelerometers. Here, however, the limited acquisition bandwidth and the low SNR make these distortions difficult to visualize (Fig. 5.15).

5.5 Conclusions

In this paper, an application combining standard acceleration measurement with high-speed camera and DIC analysis is presented. The test object is a full F16, fully instrumented for a GVT, with the DIC focusing on a limited area at the left wing tip, including the payload and its connection to the wing. The test was performed using industrial solution (LMS Test.Lab with LMS SCADAS and a DIC system of isi-sys based on FASTCAM AX100 cameras of Photron in combination with 3D software of Correlated Solutions.

The activity was considered successful, as it could be proven data:

- DIC can be used for dynamic analysis on a full scale structure, although the limited sensitivity relate to the measurement of displacements can become an issue at higher frequencies
- Even though the systems might be difficult to synchronize at the moment of the measurement, modal analysis, and in this case operational modal analysis, provides a simple mean of combining the modal results.

- The great advantage over other measurement techniques is that DIC provides a very high spatial resolution without the need of repeating the measurement multiple times.

On the other hand, some limitations were also identified. First of all, the internal memory of the camera limited the total amount of data that can be acquired. The OMA results on DIC are then biased by fact that only one sweep was considered and thus input are uncorrelated. It was decided to measure a relatively wide area of approx.. 2 m × 1 m, which obviously causes the sensitivity at higher frequency to decrease. This makes non-linear investigations a bit difficult, since higher harmonics are difficult to distinguish. This can be dangerous since DIC results improve when the force is higher and non-linear response can be activated.

It should be also taken into account that this is maybe not the optimal scenario for using DIC, but it anyhow proves the validity of the method and the possibility to combine it with more traditional techniques to further enrich the information we can derive from our data.

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