Chapter 5
Operational Modal Analysis of Satellites using Direct-field Acoustic Test Data

Bart Peeters, Alberto Garcia de Miguel, Umberto Musella, and Ivan Ngan

Abstract During acoustic qualification testing of satellites, the structural responses are being monitored and measured. The main objective of this paper is to explore the application of Operational Modal Analysis (OMA) to this structural response data. Acoustic qualification testing happens either in a reverberation chamber or by using so-called direct field testing where the test object is surrounded by many loudspeakers. This paper reports on a study involving the Structural and Thermal Model (STM) of the PROBA-V satellite. Several impact, compact shaker and direct field acoustic noise (DFAN) tests have been executed on this structure to study the influence of different test conditions on the control quality of a direct field acoustic environmental test and to identify the dynamic properties of the structure.

The purpose of the paper is to track and compare the modal parameters of the specimen during various testing phases for an enhanced understanding of the structural behaviour under acoustic loading. Classical Experimental Modal Analysis (EMA) will be applied to data from preliminary tap and compact shaker tests and Operational Modal Analysis will be applied to data from DFAN tests. During these DFAN tests, the structure is excited by a well-controlled acoustic field, but the forces acting on the satellite are not measurable and therefore structural Frequency Response Functions are not available which means that output-only OMA needs to be applied instead of input-output EMA.

Finally, the modal test results are compared with the modal parameters from a Finite Element Model of the satellite.

Keywords Operational modal analysis · satellite testing · direct-field acoustic test

Introduction

During a recently organized DFAN Master Class which had as objective to gather and disseminate know-how and experience related to spacecraft direct field acoustic testing, ESA made available the Structural and Thermal Model (STM) of the PROBA-V satellite. Several acoustic and tap tests have been executed on this structure to study the influence of different test conditions on the control quality of a direct field acoustic environmental test and to identify the dynamic properties of the structure.

Environmental testing is a necessity to ensure the survivability of hardware during launch of space vehicles. Particularly during the ignition and liftoff launch stages the main source of dynamic loading is characterized by a non-deterministic acoustic environment. Hence, the environmental acoustic test becomes a fundamental qualification test to evaluate if an aerospace structure (e.g. payload), system or component can withstand the vibratory load it will encounter during its operational life. DFAN testing is a well-established technology to perform acoustic qualification of satellites and large components such as antennas or solar panels [1]. The background, motivation and advanced possibilities of DFAN testing can be found in [2, 3].

This paper is not related to DFAN testing methodologies as such, but to the exploitation of the structural vibration data acquired during these types of tests by means of Operational Modal Analysis. Together with the pressure responses measured

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for acoustic control purposes, the structural responses, typically accelerations and strains, are also acquired to ensure the safety of the structure and validate its performance against the acoustic excitation. Often, the spacecraft is instrumented with a large number of sensors, requiring large efforts in terms of test preparation. The application of OMA creates an additional use case for this data by gaining more insights in the structural behaviour of the spacecraft. Recently, OMA was successfully applied to an antenna reflector during a DFAN test [4]. The objective of the present paper is to explore in how far this technology can be expanded towards a full satellite.

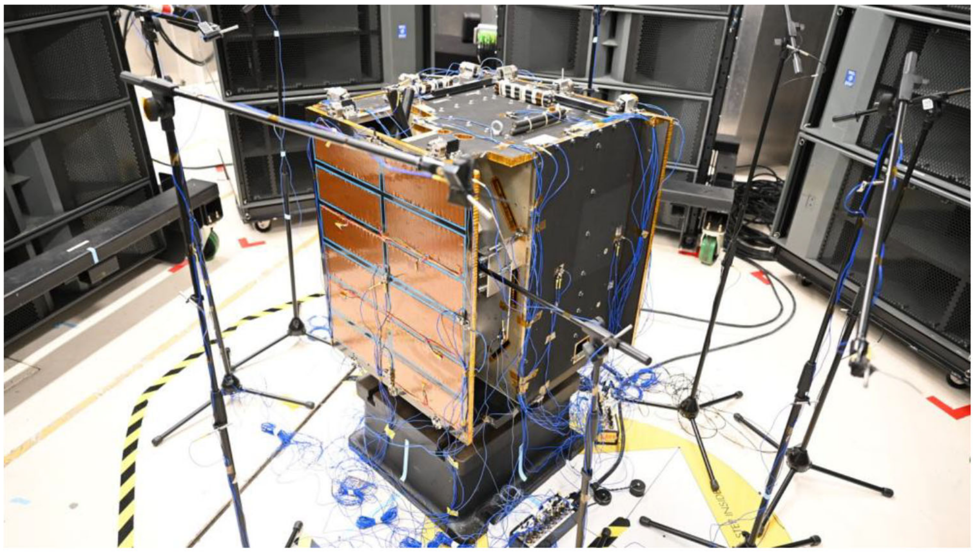

Fig. 1 PROBA-V STM instrumented with sensors and surrounded by microphones for capturing and controlling the sound field at the test facilities of Siemens Industry Software NV, Leuven, Belgium. Courtesy of ESA and Redwire Space NV

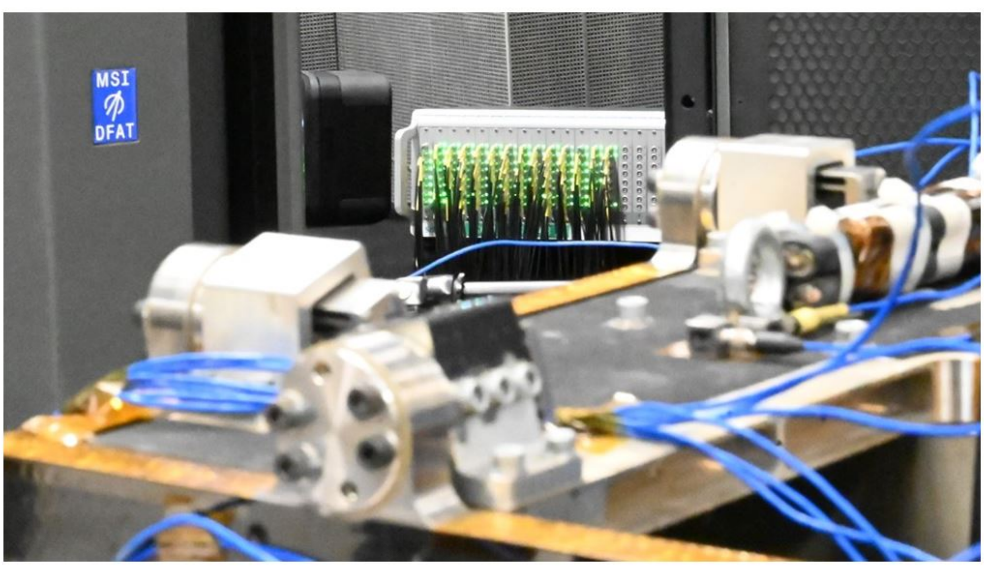

Fig. 2 In Background: Simcenter SCADAS Lab controller and data acquisition system; and MSI-DFAT loudspeakers. Courtesy of ESA and Redwire Space NV

Test Set-up

The DFAN test campaign was conducted in March 2024 in the Siemens facilities in Leuven, Belgium (Fig. 1). The loudspeaker equipment, or Noise Generation System (NGS), was provided by MSI-DFAT (Fig. 2) and installed inside a large semi-anechoic chamber. It consisted of 4 stacks of 3 subwoofers and 4 stacks of six 3-way cabinets distributed in a circle of 4.5 m diameter. Two Simcenter SCADAS Lab systems have been used, one providing DFAN MIMO acoustic control as implemented in Simcenter Testlab software, and the other acquiring structural response data (Fig. 2).

A total of 25 free-field microphones were installed around the test specimen, 22 of them used as control candidates (Fig. 3). The latter were placed at random positions between the loudspeakers and the satellite surfaces following the recommendations of [1]. The DFAN tests considered in this paper were executed using 18 control microphones and the 4 remaining ones served as additional monitoring microphones. The final selection of control microphones was done based on a pre-test analysis aiming at maximizing the uniformity of the acoustic field [5].

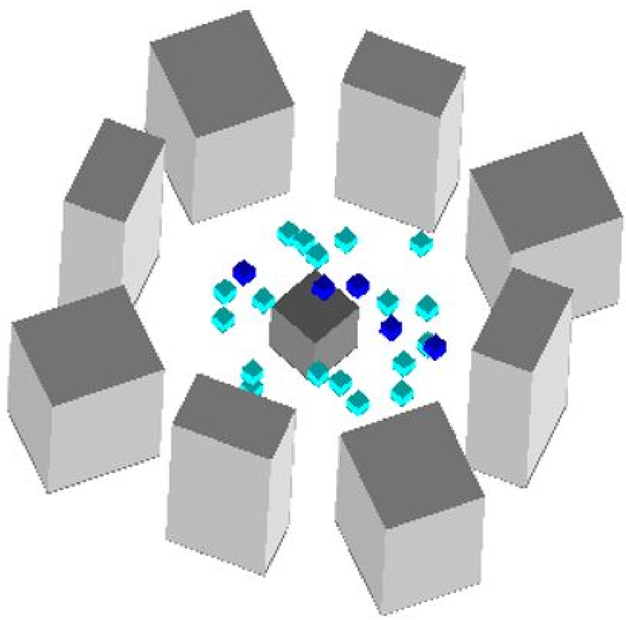

Fig. 3 DFAN test configuration. The blue markers indicate the microphone positions

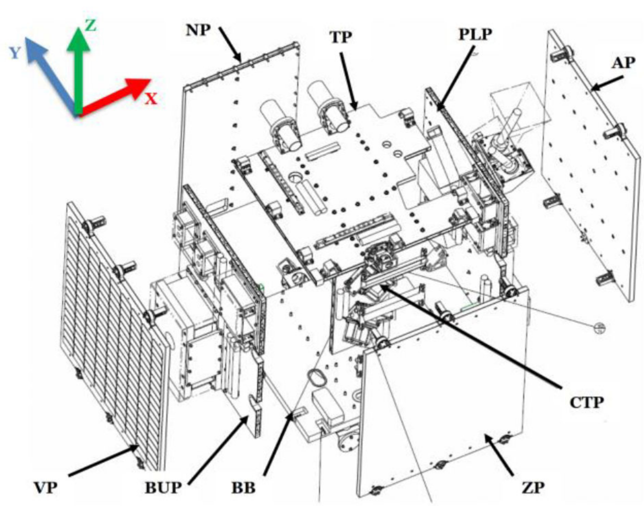

Fig. 4 Exploded view of the PROBA-V STM [6]. Courtesy of ESA and Redwire Space NV

The satellite was instrumented with more than 100 accelerometer channels, which will be heavily exploited in this paper. An exploded view of the PROBA-V with the naming of the different panels is provided in Fig. 4, reproduced from [6]. More details on the DFAN test set-up can be found in [2].

Impact (tap) Testing, Compact Shaker Testing and Experimental Modal Analysis

After the satellite instrumentation was completed and before the DFAN tests were run, preliminary impact testing (sometimes also called tap testing) was performed. In this study, the objective of these tests is to obtain a baseline set of satellite modal parameters for comparison with the results obtained during the DFAN tests. In addition, also shaker testing was performed, not with a large shock & vibration shaker, but a compact Simcenter Qsources Integral shaker attached to the satellite.

A (gentle) impact was applied at a “robust” location, i.e. at the intersection of 3 panels (Fig. 4): TP, NP, PLP, of the satellite in both the X- and Y-direction (Fig. 5, Left). For each direction, the impact was repeated 15 times, allowing for data averaging and coherence calculations. The Simcenter Qsources Integral shaker was attached at approximately the same location as the impact location (Fig. 5, Right). The shaker has a miniature size, ideal for hard-to-reach locations. It is self-supporting and self-aligning; has an integrated force cell and accelerometer; and covers a wide excitation frequency range: 20-2000Hz. The highly controllable shaker forces are attractive in cases where one may not be comfortable applying impact excitation to a satellite.

The driving point FRFs (in X-direction) and corresponding coherences are represented in Fig. 6. For the case of shaker excitation (Fig. 6, Right), also the shaker force PSD is shown. A band-limited (20-300 Hz) pseudo-random excitation signal

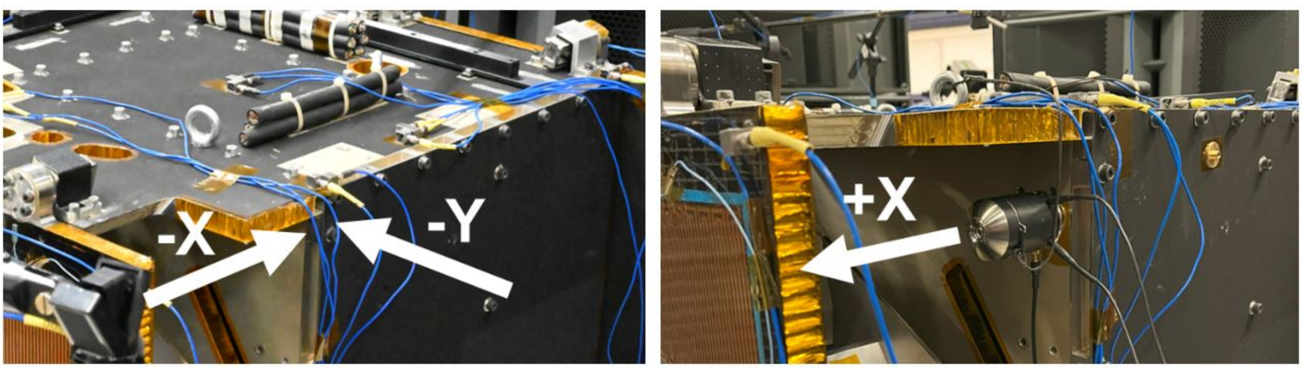

Fig. 5 (Left) Location and direction of the impacts; (Right) Location and direction of the Simcenter Qsources Integral shaker. Courtesy of ESA and Redwire Space NV

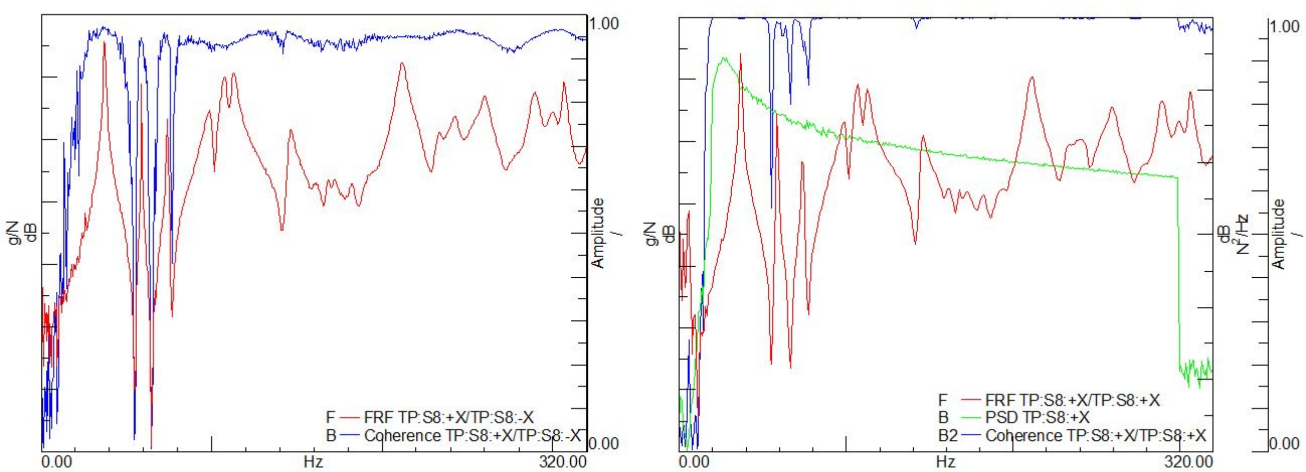

Fig. 6 PROBA-V modal testing. (Left) Impact testing: driving point FRF (red) and corresponding coherence (blue); (Right) Qsources testing: driving point FRF (red), corresponding coherence (blue), and shaker force input PSD (green)

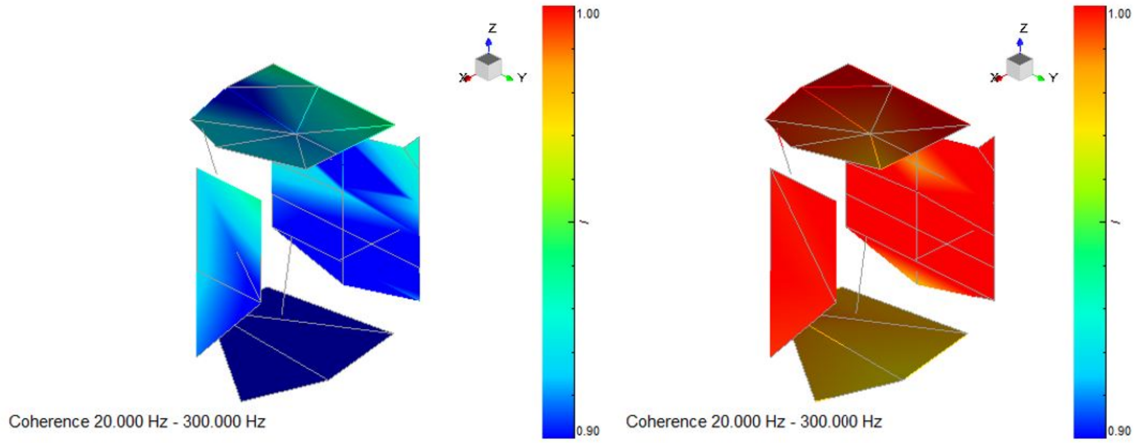

Fig. 7 PROBA-V modal testing – averaged coherences 20-300Hz plotted on the geometry (color scale is between 0.9 and 1). (Left) Impact testing; (Right) Qsources testing

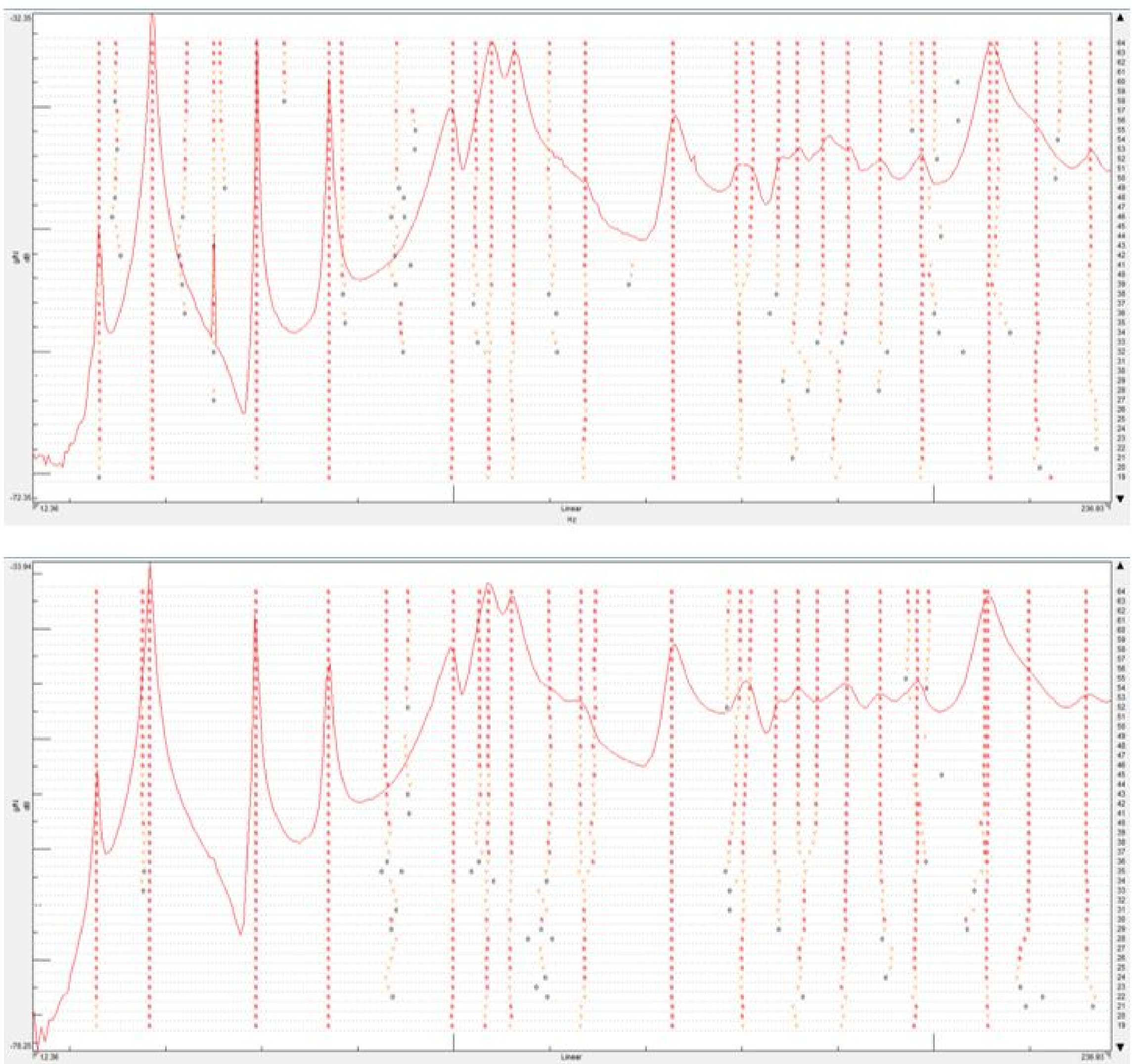

Fig. 8 PROBA-V modal testing – Polymax stabilization diagrams. (Top) Impact testing; (Bottom) Qsources testing

was used. Resonances are clearly visible in the FRFs and the coherences are good in the frequency range of interest, although there is a clear difference between impact and shaker excitation as can be seen in Fig. 7: for all measurement locations, the shaker coherences are superior. Polymax [7] was applied in a frequency range from 12 to 237 Hz. Fig. 8 shows the stabilization diagrams that are used to select the modes. Afterwards, the MLMM method [8] was run for 30 iterations to further improve the initial modal parameter estimates. MLMM is an optimization method in which the difference between measured and synthesized FRFs is minimized. Both Polymax and MLMM are implemented in Simcenter Testlab. The shaker tests took place 15 days after the impact tests. Overall, the resonance frequencies slightly decreased (on average with 0.5%).

A typical result is presented in Fig. 9 where a very good fit between measured and synthesized driving point FRFs can be observed; both for the impact and the shaker data. The conclusion of this section is that Experimental Modal Analysis (EMA) applied to the impact and shaker FRFs yields a high-quality baseline set of modal parameters. The modes themselves will be presented in next section together with the Operational Modal Analysis (OMA) results (Fig. 20, Table 1).

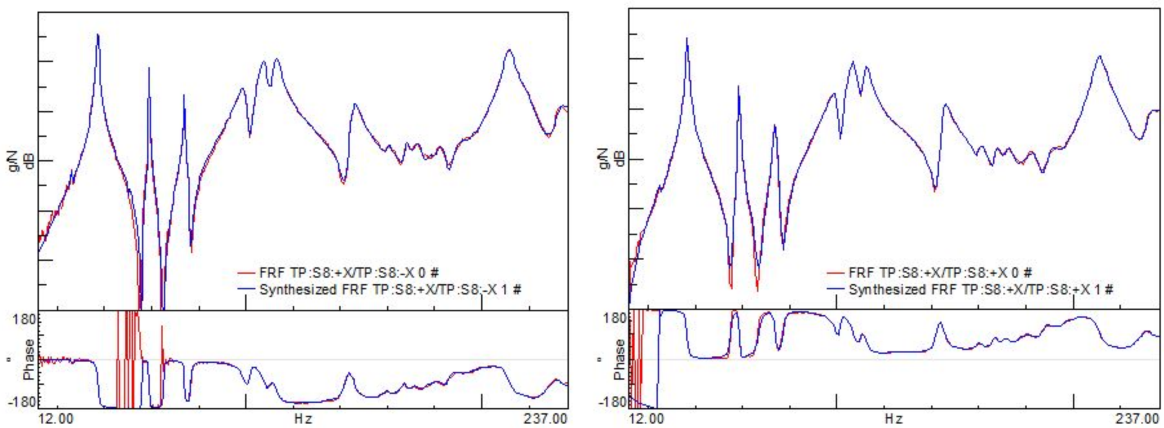

Fig. 9 PROBA-V modal testing – measured (red) and synthesized (blue) driving point FRF. (Left) Impact testing; (Right) Qsources testing

Direct Field Acoustic testing and Operational Modal Analysis

DFAN Tests with Different Number of Drives

DFAN tests have been conducted with different number of drive signals: 1, 2, 4 and 8. In this manner, different acoustic fields are generated to excite the structure, i.e. from a fully correlated field (1 drive) to a highly diffuse field (8 drives). The acoustic field can be assessed using established metrics for DFAN testing [9]. Whereas all 4 tests were able to maintain a stable OASPL of 125 dB over time and achieved a 1/3^{rd} octave spatially averaged SPL close to the reference profile and within the set tolerances (+-3 dB) in all bands, the acoustic field is quite different as indicated in Figure 10 and Fig. 11. The dispersion plot (Fig. 10) includes the responses of all the 22 microphones selected as control candidates, i.e. the 18 finally selected via pre-test analysis plus 4 remaining ones left as monitor sensors to check the acoustic fields in uncontrolled locations. The “dispersion” is the difference in dB between the individual microphones and the spatial average of the control microphones. It can be observed that the uniformity of the acoustic field improves when increasing the number of drives from 1 to 8. Figure 11 shows the “Sinc Indicator Function” (SIF) introduced in [10] as a diffusivity metric. The SIF has a value between 0 (bad) and 1 (good) and is based on the deviation of the measured pairwise microphone coherences from the theoretically expected coherences in a perfectly diffuse field. When increasing the number of drives from 1 to 8, the SIF, averaged over the frequency range, significantly improved from 0.15 to 0.84.

Also, the structural responses are quite different in the 4 different tests (Fig. 12). Following observations can be made:

- Results from tests with 1 and 2 drives are relatively similar to each other, as well as results from tests with 4 and 8 drives, but both groups differ considerably from each other.
- There is for instance a 6 dB difference in level at the frequency of the 1^{st} bending mode of the AP panel.
- Despite the amplitude level differences, the frequency content is quite similar across the 4 tests. This qualitative observation is confirmed by the OMA analysis of the 4 tests: the same structural modes are found back for all cases. In the following, we will then only focus on the 8-drives case.

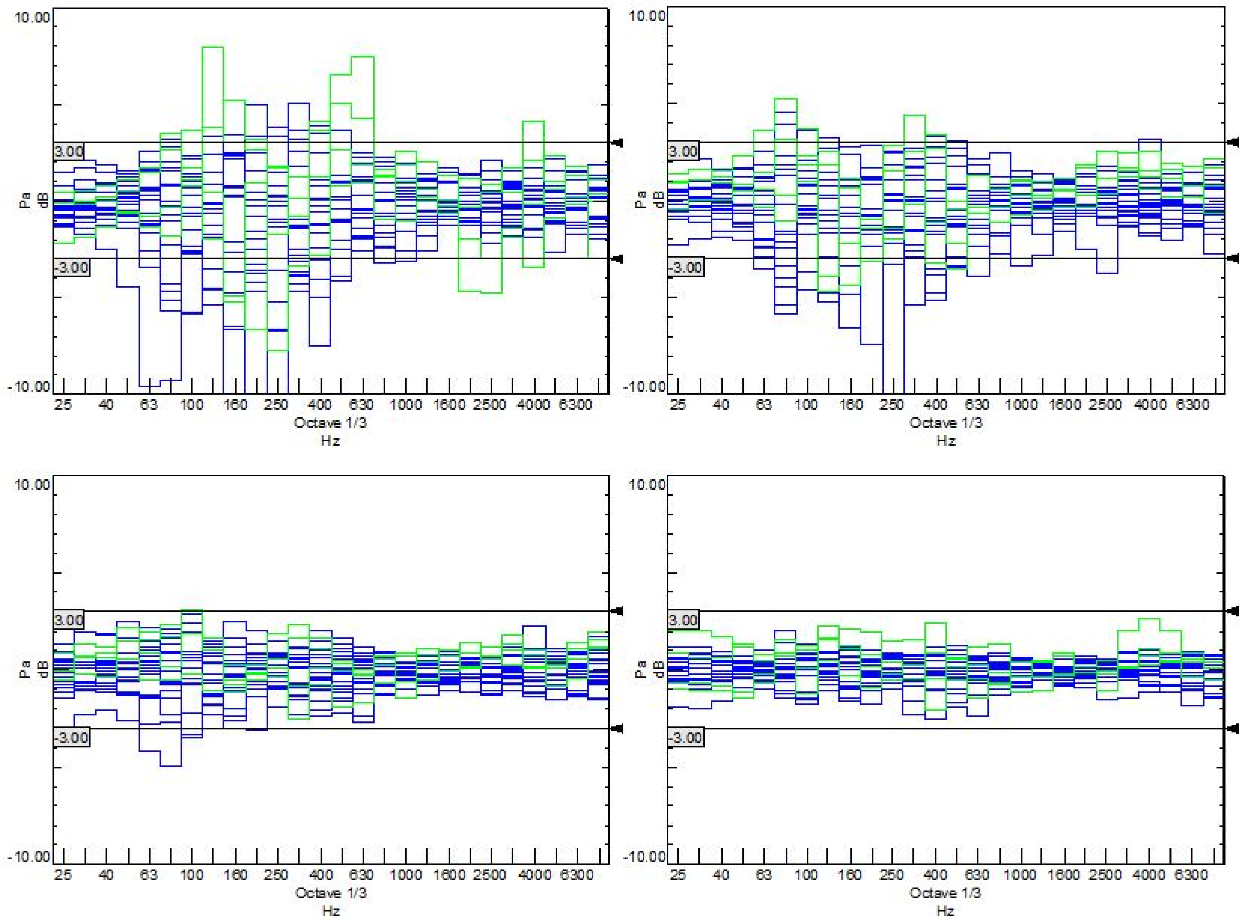

Fig. 10 Dispersion at control (blue) and measurement (green) microphones. (Top) 1 and 2 drives; (Bottom) 4 and 8 drives

Some more observations on the influence of the number of drives on the PROBA-V structural responses can be found in [2].

Operational Modal Analysis

The Operational Modal Analysis (OMA) variant of Polymax [11] as implemented in Simcenter Testlab will be used to estimate the modes from the DFAN data. A detailed discussion on data pre-processing for Operational Modal Analysis can be found in [11] and references therein.

First auto- and cross correlations are computed from the time domain data. In an OMA setting, the response correlations behave like impulse responses. So, just like in impact testing, an exponential window can be applied to the correlations before computing the Fourier transform. The exponential window reduces the effect of leakage and the influence of the higher time lags, which have a larger variance. Moreover, the application of an exponential window to impulse responses or correlations is compatible with the modal model and the pole estimates can be corrected.

As part of the pre-processing, a selection needs to be made on a subset of the sensors that will serve as so-called "reference sensors" for the cross-correlation and cross-spectra calculations. For a successful OMA, it is not needed that the full cross spectrum matrix between all available sensors is calculated. It suffices to calculate a subset of columns of this matrix: the cross-spectra between all sensors and the selected reference sensors. It is important that the ensemble of reference sensors can observe all modes of interest. For the PROBA-V, the X-, Y-, and Z- channel of a triaxial sensor at the TP panel were selected as reference channels (Fig. 13).

Figures 14 and 15 illustrate the pre-processing for OMA. 120 s of full-level DFAN data (Fig. 14, Top) is reduced to a correlation function that decays in less than a second (Fig. 14, Bottom). A single-block Fourier transform is then applied to these correlations to obtain the so-called "half spectra" represented in Fig. 15.

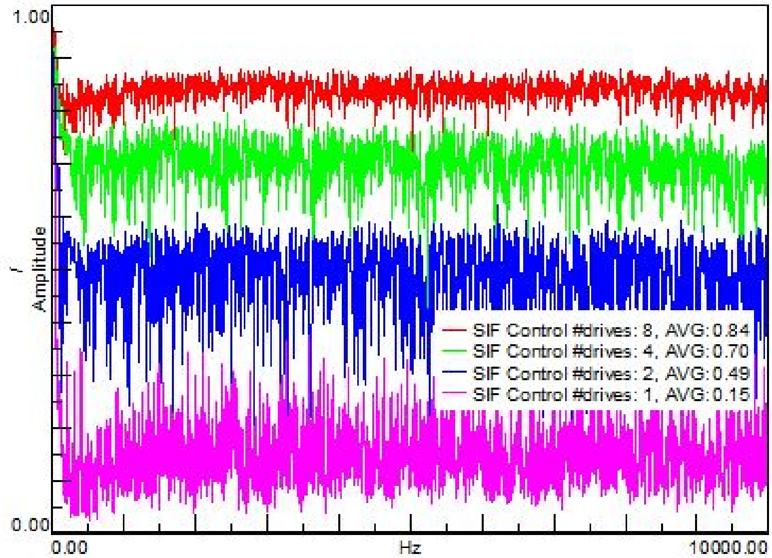

Fig. 11 SIF for the DFAN tests with different number of drives: 8, 4, 2 and 1

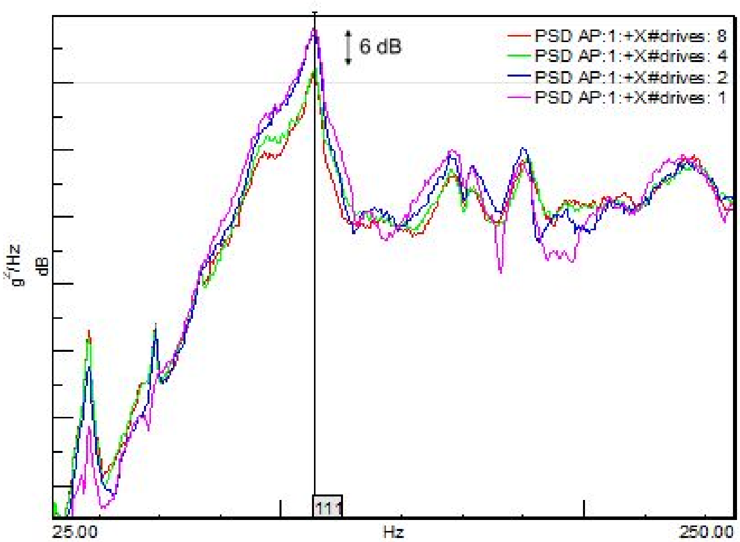

Fig. 12 Acceleration PSD at centre location of the AP panel for different number of drives: 8, 4, 2 and 1. The cursor indicates the frequency of the 1^{st} bending mode of the AP panel

Theoretically, OMA relies on the assumption that the excitation is white noise. In such cases, it is not needed to measure the excitation sources, and the response measurements are sufficient to characterize the system (up to the input-output scaling). In practice, the white noise assumption can be relaxed a bit and OMA still provides good results when the (unknown) excitation spectrum is relatively "smooth". A closed-loop test like DFAN typically does not satisfy the white-noise assumption, but nevertheless, by comparing a DFAN OMA half spectrum with an FRF obtained from impact testing (Fig. 16), it seems that roughly the same resonance peaks can be observed, which is a promising starting point for applying OMA.

The half spectra are fed into the (Operational) Polymax method to yield estimates for eigenfrequencies, damping ratios and mode shapes. As part of this process a so-called stabilization diagram (Fig. 17) is computed that allows to discriminate between physical and computational modes. As a quality measure for the modal analysis process, the measured spectra are compared with the synthesized spectra computed using the estimated modal parameters (Fig. 18). The correspondence is very good in this case, indicating that the measured data is well explained by the identified modal parameters. Some of the identified mode shapes are shown in Fig. 19. Please note that in this paper, we mainly focus on the OMA modes that are included in the impact testing baseline set of modal parameters.

Modal Correlation

Impact Test (EMA) versus DFAN Test (OMA)

The modes retrieved from the DFAN test using OMA are compared to the baseline modes found by applying EMA to the impact test data:

- The eigenfrequencies and damping ratios agree very well (Table 1).
- Also, the mode shape estimates are in good agreement as indicated by the MAC values (Fig. 20). A MAC value expresses the correlation between 2 modal vectors.

Test versus Finite Element Model (FEM)

It is also interesting to compare how well the modes identified from Tests correspond to the Finite Element Model (FEM) modes. Hereto, Simcenter Testlab Modal Correlation was used. Figure 21 shows the Test – FE comparison for 6 modes of which the mode shapes agree very nicely. This indicates that a rather quick and easy impact test and / or a more detailed analysis of available DFAN data could be used for validating and improving the FEM of a satellite.

Conclusions

This paper showed the successful experimental identification of the modal parameters of the PROBA-V satellite by applying Operational Modal Analysis to DFAN data. The OMA results agreed very well with the EMA modal parameters obtained

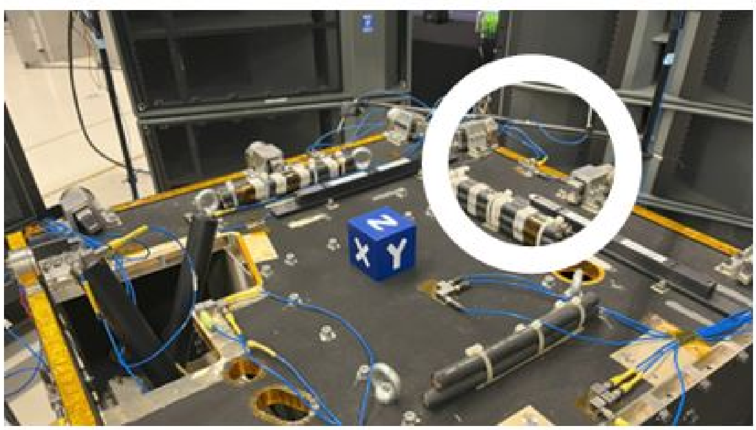

Fig. 13 Location of triaxial reference sensor for OMA. Courtesy of ESA and Redwire Space NV

Table 1 Comparison of eigenfrequencies and damping ratios estimated using EMA (Impact data) and OMA (DFAN data)

	EMA – Impact		**OMA – DFAN**			**EMA – Impact**		**OMA – DFAN**	
Mode #	f [Hz]	ξ [%]	f [Hz]	ξ [%]	*Mode #*	f [Hz]	ξ [%]	f [Hz]	ξ [%]
1	26.2	1.1	25.5	1.3	*8*	162.4	1.8	161.9	2.4
2	37.2	1.1	36.6	1.4	*9*	167.6	1.0	166.7	1.2
3	59.0	0.2	58.8	0.3	*10*	171.6	1.2	171.5	1.2
4	74.1	0.4	73.7	0.8	*11*	176.9	1.3	177.3	1.6
5	112.7	1.5	111.7	1.2	*12*	182.5	1.4	181.8	1.2
6	128.2	2.6	126.4	2.1	*13*	188.7	2.2	185.5	1.0
7	158.7	1.1	158.9	1.3	*14*	232.7	1.0	231.0	0.8

from impact testing and shaker testing. Such modal tests are not significantly adding to the environmental test schedule. Simcenter Qsources shaker testing is very repeatable and benefits from highly controllable force levels, leading to superior coherences compared to impact testing. Nevertheless, both impact and shaker testing yield reliable modal parameters after applying Polymax combined with MLMM.

There are several advantages associated to the use of OMA in a DFAN context:

- OMA allows an enhanced exploitation of test data that was measured for another purpose (acoustic qualification).
- The modal parameters are obtained under realistic loading and with realistic boundary conditions.
- The interaction between the structure and the acoustic environment can be investigated.

Acknowledgments The authors would like to acknowledge the contribution of MSI-DFAT (Baltimore, USA) and DV2 (Metz, France) in the preparation and execution of the DFAN test campaign. Also, the authors would like to thank ESA and Redwire Space NV (Kruibeke, Belgium) for facilitating the use of the PROBA-V STM and FEM.

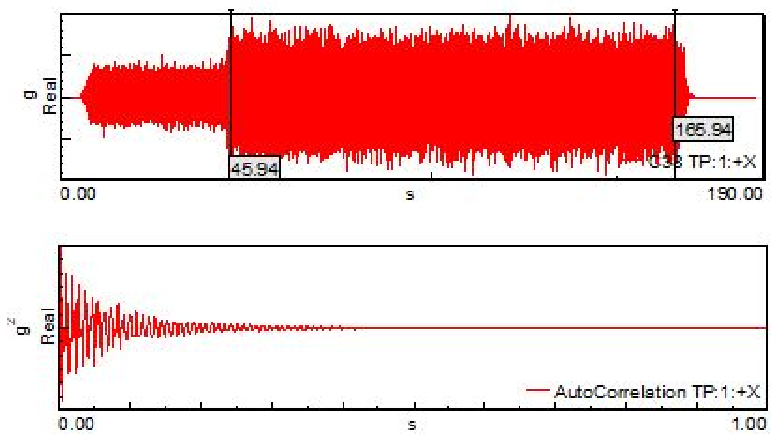

Fig. 14 (Top) Acceleration time recording during DFAN testing. A 2-minute segment at full level is selected for further processing. (Bottom) Acceleration auto-correlation computed from the time data

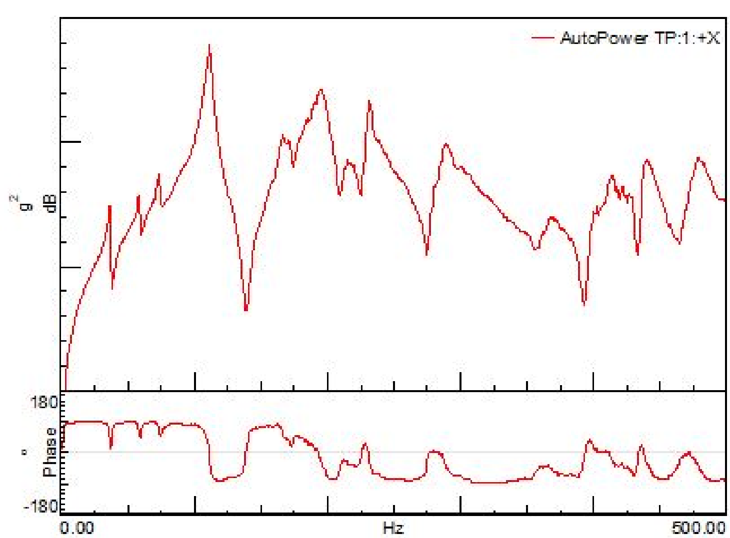

Fig. 15 "Half" power spectrum computed as the DFT of the (windowed) autocorrelation window of Figure 14 (Bottom)

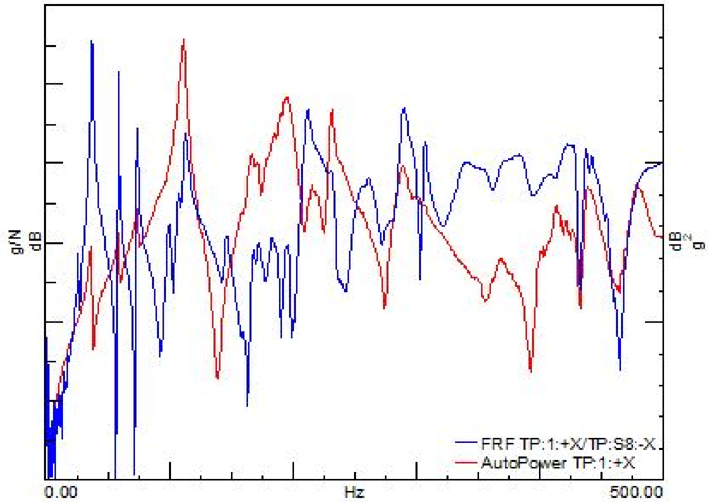

Fig. 16 Comparison of impact testing FRF (Left axis / blue) and DFAN half spectrum (right axis / red)

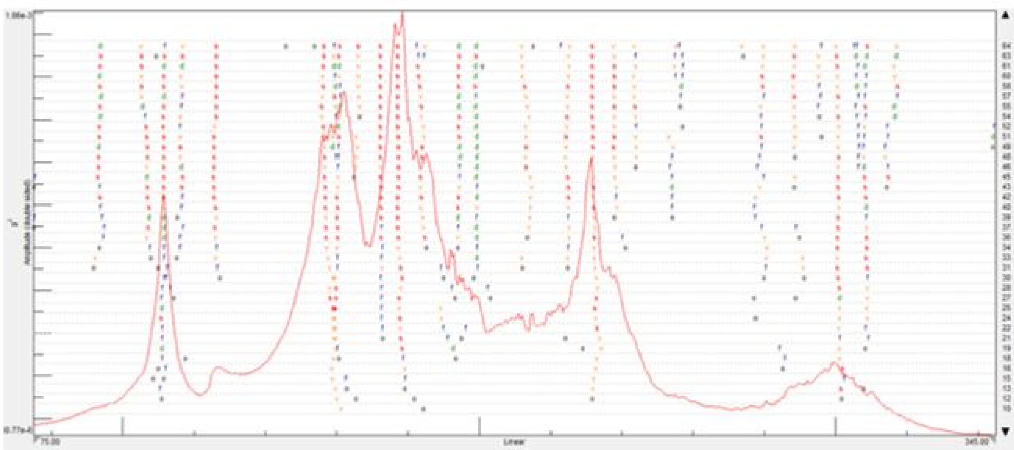

Fig. 17 PROBA-V DFAN testing – Operational Polymax stabilization diagram

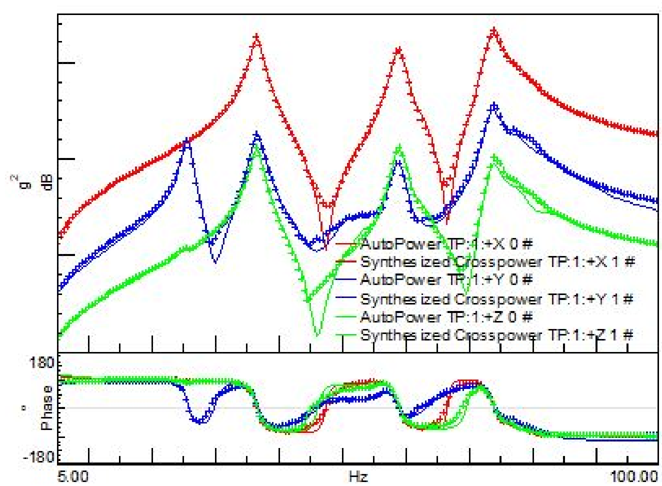

Fig. 18 PROBA-V DFAN testing – Measured (crosses) and synthesized (line) power spectra of the 3 reference sensors

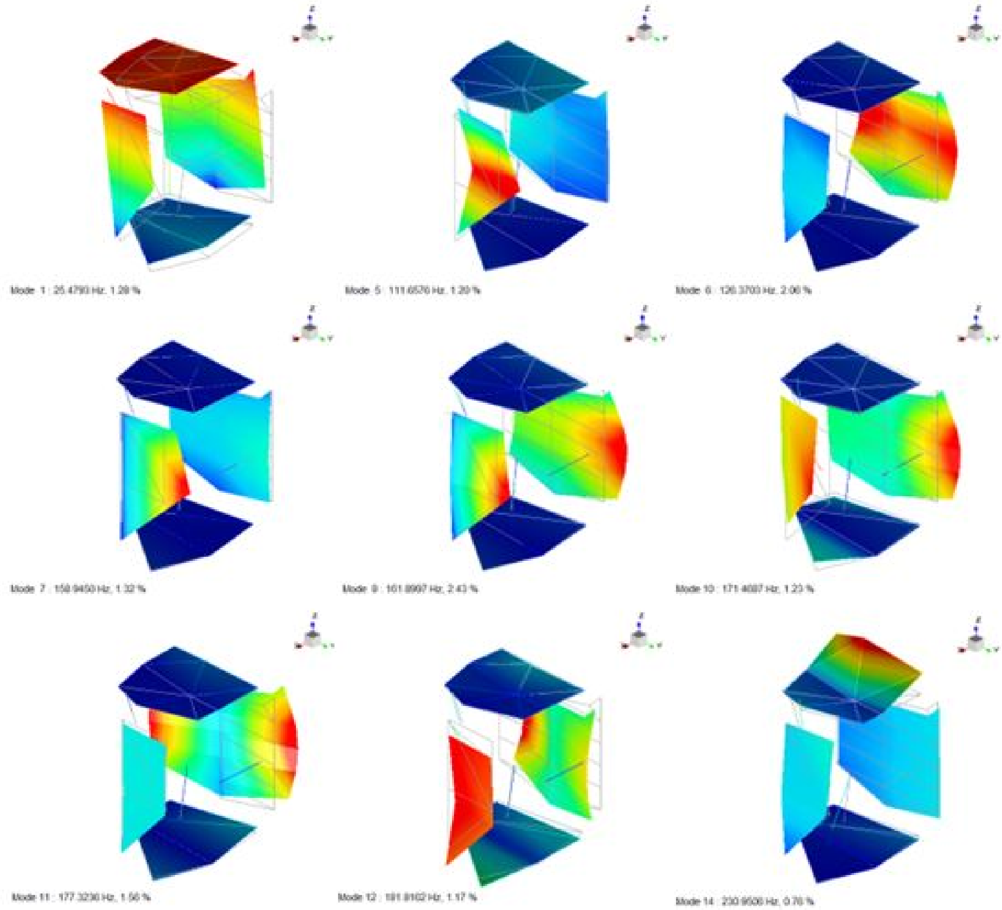

Fig. 19 PROBA-V DFAN testing – mode shapes obtained by OMA (Mode # 1, 5-8, 10-12, 14 of Table 1)

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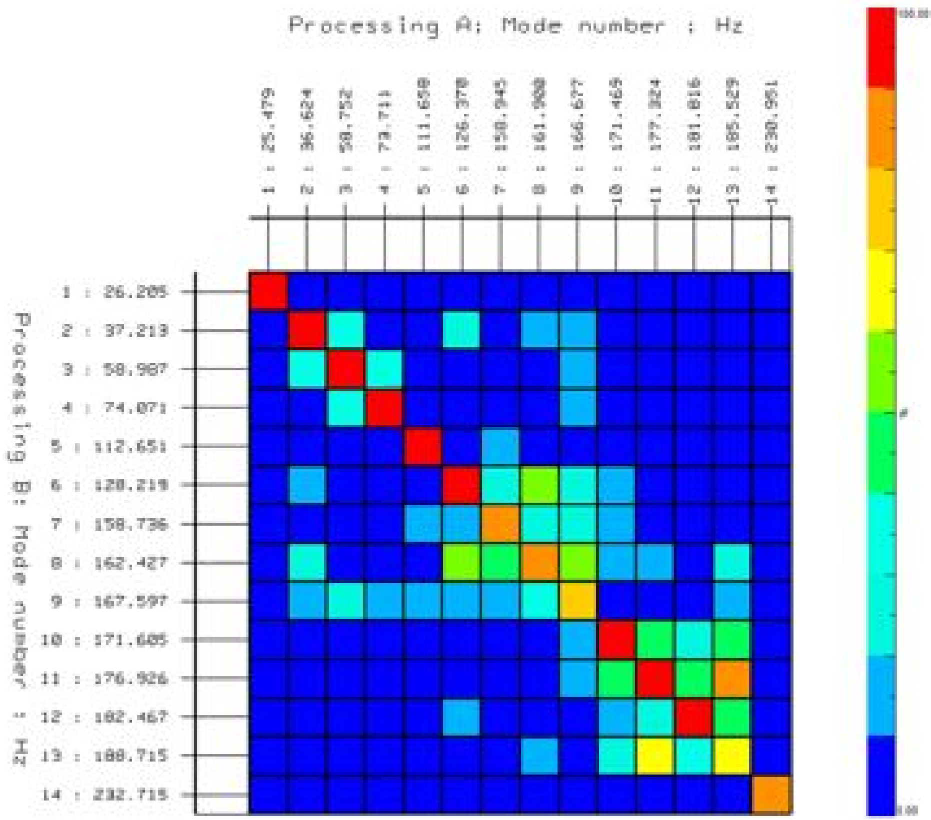

Fig. 20 MAC between DFAN – OMA (columns) and Impact – EMA (rows) mode shapes

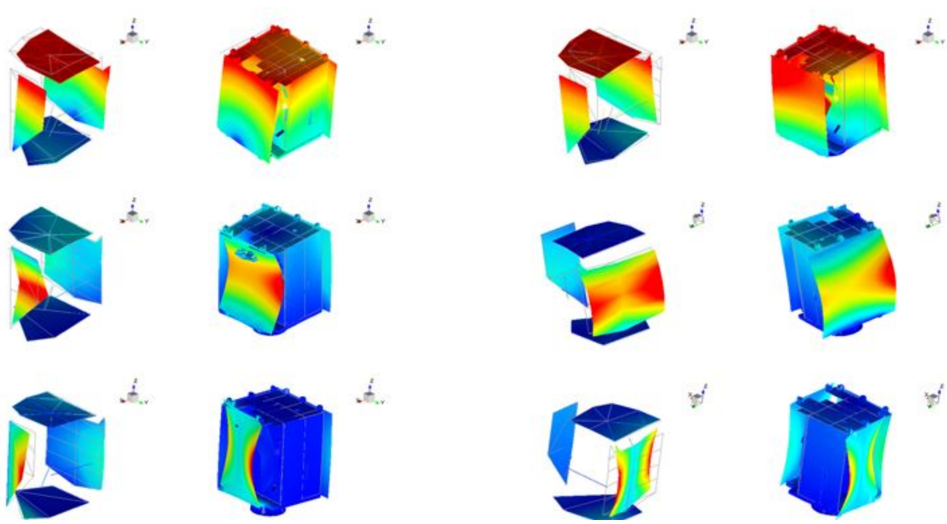

Fig. 21 Side-by-side comparison of Test (left) and FEM (right) mode shapes. 6 mode pairs are shown (Mode # 1-2, 5-7, 11 of Table 1)