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GROUND VIBRATION TEST OPTIMIZATION ON THE FALCON 6X

Elsa Bréus¹, Sylvain Huet¹, Isabelle Barber¹, Eric Garrigues¹, Pascal Lubrina², Cyrille Stéphan², Bernard Colomies³ and Arnaud Magnier³

¹ Dassault Aviation
78 quai Marcel Dassault, 92552 Saint-Cloud, France
elsa.breus@dassault-aviation.com

² ONERA
DAAA, ONERA, Université Paris Saclay F-92322 Châtillon - France
pascal.lubrina@onera.fr

³ SOPEMEA
5 rue Général Valérie André, 78140 Vélizy-Villacoublay, France
colomies@sopemea.fr

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Abstract: The Ground Vibration Test (GVT) of a new aircraft is a required certification test, on the critical path for the first flight authorization. For flutter certification, it is mandatory to have a validated numerical model hence the need of a GVT to characterize the structure and tune aircraft numerical model to conduct dynamic studies. Reducing the time needed to perform this test with increased precision and confidence in the results is of prime interest for an aircraft manufacturer. The GVT of Dassault Aviation latest aircraft Falcon 6X was performed in collaboration with ONERA and SOPEMEA. The test took 12 days and thanks to an adequate organization, results were derived very quickly allowing an update of the General Finite Element Model. Two reference methods used during GVT are the Phase Resonance Method and the Phase Separation Method. This paper describes how these two methods combined with SOPEMEA, ONERA and Dassault Aviation collaboration led to an optimized test campaign.

1 CONTEXT

On March 10th 2021, the new Dassault Aviation business jet Falcon 6X made its maiden flight. Latest aircraft of the Falcon family, the Falcon 6X presents the largest cabin (in terms of both width and height) in its category. It is also particularly remarkable for its acoustic comfort in the cabin. With a range of 5500 NM, it can fly from London to Hong Kong or Los Angeles nonstop. As with all Falcons, the Falcon F6X exhibits unparalleled performance on steep approaches to short runways.

To obtain first flight clearance, many ground tests have to be performed, among them the Ground Vibration Test (GVT) [1]. This test was performed on the first assembled Falcon 6X at Dassault Aviation facilities in Mérignac in collaboration with ONERA and SOPEMEA. The GVT is on the critical path for the first flight authorization. It provides information on the structure modal behavior necessary to update the General Finite Element Model. Therefore efforts have been made to reduce the time needed to perform the test while retaining the ability

to extract precise and trustworthy results. To do so testing equipment, methods and analysis procedures were carefully optimized.



Figure 1: Falcon 6X GVT set-up

2 FALCON 6X GVT TEST PLAN

During the previous Dassault Aviation GVT campaigns (Falcon 5X, 7X and 8X) the Phase Resonance Method (PRM) was mostly used. This experiment-proven method, also called appropriation or modal tuning, consists in exciting the structure at the resonance frequency of the target mode for various excitation levels [2]. This method directly provides the data needed to assess the dynamic behavior of the structure, with a high confidence. Nonetheless, it is particularly time-consuming.

For the Falcon 6X GVT campaign it was then decided to use the Phase Separation Method extensively. With the Phase Separation Method (PSM), swept sine signals are applied to the structure on a large frequency band. Several modes can be identified at the same time using the frequency response function between a large set of accelerometers and the excitation signal [3]. The PRM would then be used only to identify particularly challenging modes i.e. modes exhibiting nonlinear behavior or modes difficult to excite properly with generic excitations. Indeed with the PSM, shakers are installed at standard locations (wing tips, fin, front fuselage, horizontal tail plan tips), so that the introduced energy may excite the largest possible number of modes. Their configuration may then not be adapted to each mode. The PRM process leads to identifying and implementing the ideal shakers configuration for each mode. This is why PRM might be useful to identify modes not responding easily with the PSM runs.

Keeping in mind the updating of the General Finite Element Model (GFEM), the sequence of PSM runs (symmetric or antisymmetric excitations, shakers on the fuselage or the wings or the fin) is adapted depending on the need of information on the structure components.

The following strategy was then applied:

1. Perform PSM runs. Several shaker configurations are used and for each of them several levels of force are injected to build nonlinearity curves. Maximal acceleration values are set for the different parts of the structure.
2. Get a general overview of the dynamic behavior of the structure with a rapid post-processing and identify challenging modes for which the PRM would give useful insight.
3. Use PRM on the specified modes.
4. Improve PSM post-processing thanks to modal information provided by PRM.

5. Adapt PSM runs sequence depending on GFEM tuning needs and overall progress.

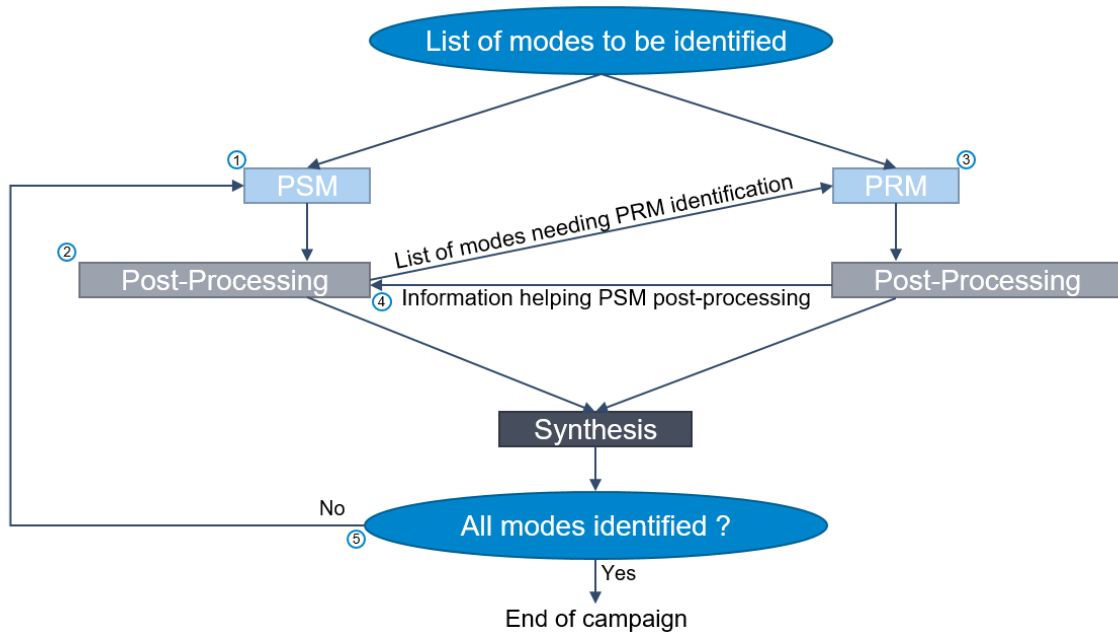


Figure 2: Planning updating

To conduct PSM excitations almost continuously, it is important to reduce the number of changes in shakers positions. Installing shakers, connecting them to the structure and adapting the acquisition chain, requires time. Depending on the accessibility at the excitation location, this time may vary from 10 minutes to 20 minutes. In order to maintain the number of position modifications as low as possible and due to the criticality of these positions for the accuracy of the results, optimal positions have been chosen ahead of the test campaign between SOPEMEA-ONERA and Dassault Aviation based on past teams know-how and predictive simulations.

The main challenge before changing aircraft configuration is to confirm that all important modes of the configuration were sufficiently excited and were then correctly identified. That is why it is essential to derive quickly modal properties from the time signals obtained during PSM runs. To do so two people from ONERA-SOPEMEA used TestLab commercial software with additional in-house tools. In parallel five people from Dassault Aviation were post-processing time signals acquired using their own in-house tools. Runs were analyzed by both teams to treat the largest dataset possible with increased confidence in the results before aircraft configuration change.

The ONERA Work-Progress software enables all people involved in the GVT to be informed about the status of the test, the runs already performed, the post-processing already performed, the modal identification already performed, and the future runs in preparation. All those pieces of information are available in a single database accessible for each contributor.

Following sections will read testing equipment in more details as well as tools for modal identification used by ONERA, SOPEMEA and Dassault Aviation. Both topics combined with the special care put on the planning as described led to an optimized GVT campaign.

3 TESTING EQUIPMENT

3.1 General GVT Area Arrangement

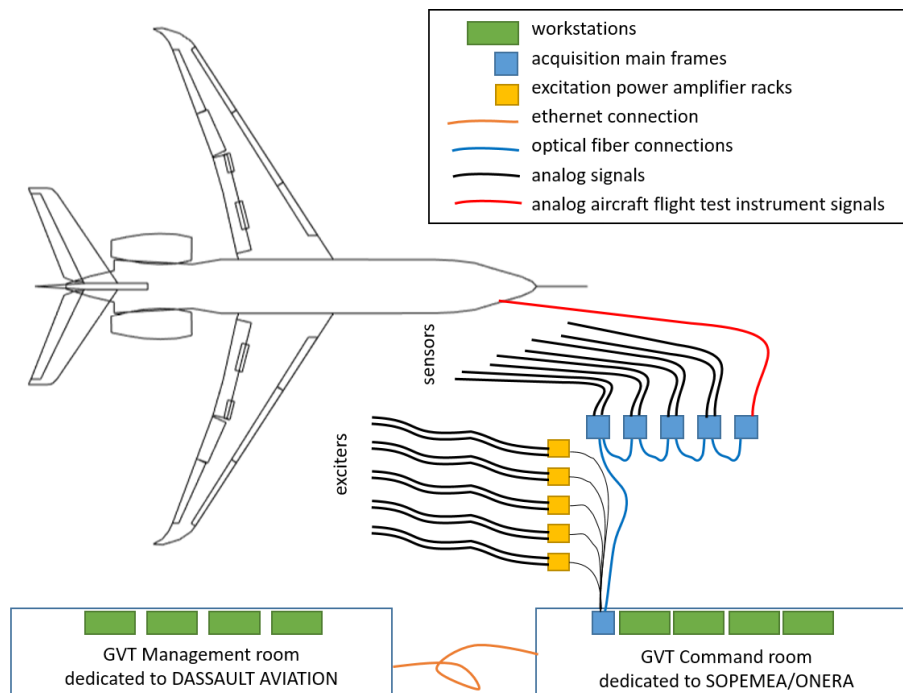


Figure 3: General GVT area arrangement

3.2 Excitation Devices

The ONERA-SOPEMEA team deployed on the aircraft a total of 15 PRODERA electrodynamic shakers with different forces (200 N, 500 N, 1000 N) and displacement (10 mm pp or 25 mm pp) depending on the excitation localization (Figure 4).

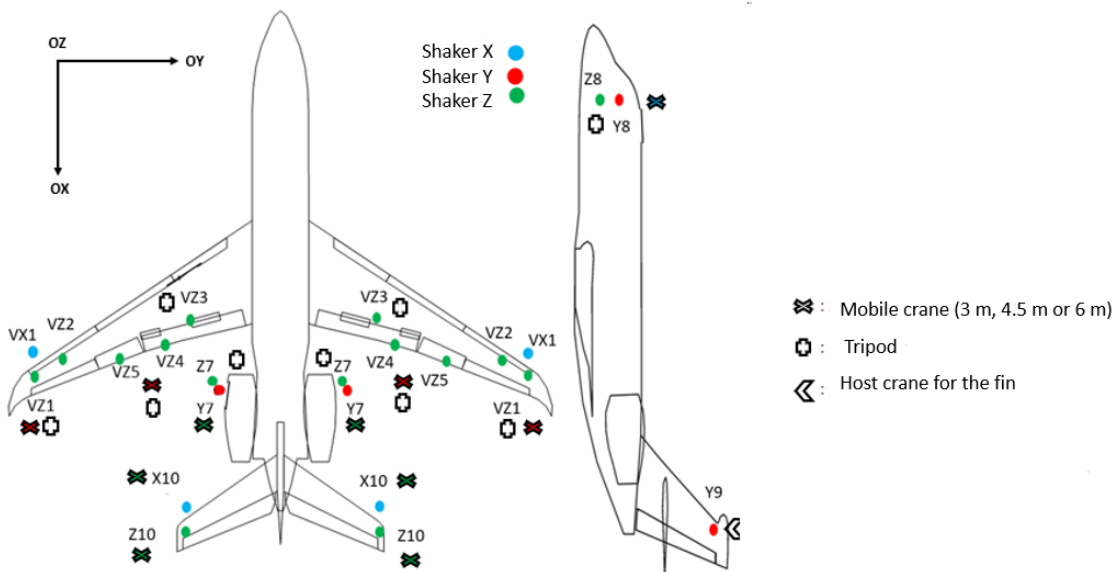


Figure 4: Excitation sites

During the Falcon 6X GVT, three types of devices were used for the shakers depending on space hindrance:

- Mobile cranes for excitation sites on upper surfaces notably (Figure 5)
- Tripods for excitation sites on lower surfaces notably (Figure 6)
- Hoist crane for fin

These devices enabled to decouple the shakers from the ground by using different technologies. For the mobile cranes and hoist crane, the suspension frequency (around 1 Hz) is defined by the length of the cable and the mass of the shaker. Two configurations are available for the tripods depending on the frequency band to excite. Exciter can whether be blocked on the device for excitation below 5Hz or suspended on the device (above 5Hz). Specific excitation interfaces were glued or screwed on the aircraft for each excitation site to transmit the effort from the shakers, without damaging the aircraft.



Figure 5: Example of crane



Figure 6: Example of tripod

Excitation forces introduced in the structure were measured simultaneously by two different ways:

- with the measurement of the responses of force cell sensors installed on each shaker rod,
- with the measurement of the current in the active power amplifiers and then in the shaker coils.

Specific “Driving Point” accelerometers were glued at each excitation site to allow modal mass computation.

Furthermore, some shakers were equipped with displacement sensors measuring the coil strokes as well as accelerometers placed on their bodies. These sensors were used to monitor shakers to avoid damage during experiment.

3.3 Acquisition System

The Siemens Scadas III hardware available around the GVT period was used. This system was composed by V12 and V12L modules for a total number of 648 channels, spare included, dedicated to acquisition and 12 analog channels dedicated to provide excitation signals, all installed in 6 frontends and linked together by optical fiber. This system was mainly installed in between the aircraft and the GVT command room, where were installed the computers and the people in charge of the measurement and post-processing.

3.4 Sensors

For this GVT, 519 accelerometers were used. This number and each sensor location were chosen according to modes computed by the GFEM. They allow to uniquely identify each mode. The IEPE (Integrated Electronics Piezo-Electric) sensors were specially developed for GVT applications, they have a high sensitivity for low acceleration amplitudes and low frequencies range (0.1 – 500 Hz). The TEDS (Transducer Electronic Data Sheet) functionality integrated in these sensors enables reading the internal data of these sensors to improve writing of the test set-up and avoid mistakes.

All the accelerometers had to be glued to attachment parts. Tests were performed to check that these units have a unitary transfer function in the measurement frequency range of interest and could be glued as interface between the structure and the sensors (Figure 7).

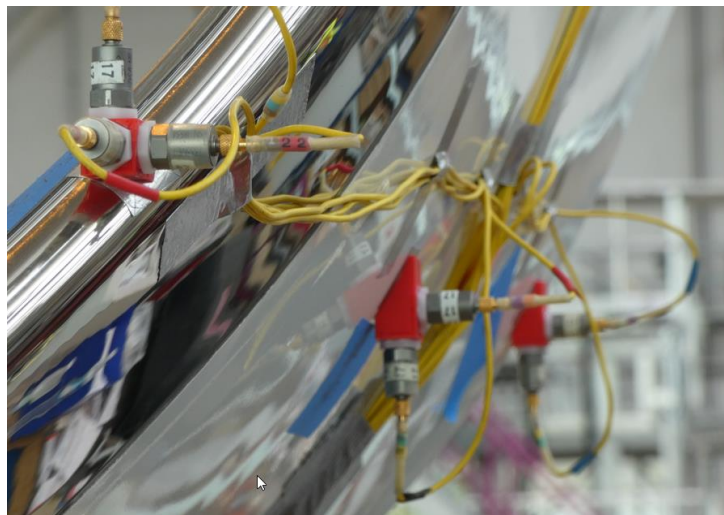


Figure 7: Accelerometer attachments (red parts) on a winglet

4 METHODS AND TOOLS FOR MODAL IDENTIFICATION

Both PRM and PSM methods have been applied: PSM for all structural modes, PRM for some of them. The use of both PSM and PRM reduces possible uncertainties on extracted modal parameters for complicated modes, which are particularly difficult to identify with a satisfying degree of confidence.

4.1 Phase Resonance Method

The Phase Resonance Method is the classical and historical method used for aircraft GVTs. This method proceeds mode by mode independently. It requires the tuning of the excitation sine frequency with the undamped resonance frequency of the target mode, the selection of the excitation sites, direction and the tuning of the amplitudes (phases being 0 or π). This tuning operation is realized manually by experimented operator using adapted instruments (dedicated excitation force keyboard), specific response signal visualizations such as Lissajous ellipses, and quality criteria. The quality criteria used to validate appropriation are as follows:

- Closed Lissajous between the reference excitation signal (1 V amplitude) and the velocity responses distributed over the structure (control on screens),
- On line separated real parts and imaginary parts mode shapes,
- Appropriation coefficient close to 1. Appropriation coefficient also called Modal Indicator Function (MIF) is defined in equation (1) with φ being the modal shape vector

$$MIF = 1 - \frac{\sum(|\text{Imaginary}(\varphi)| * |\varphi|)}{\sum|\varphi|} \quad (1)$$

This method requires the structure to comply with the Basile hypothesis (orthogonality of the generalized damping matrix with the mass and stiffness matrices). The excitation signal being a mono frequency sine, the PRM enables to maximize the use of the force available in each exciter and then, guaranty high excitation force levels.

Once modal tuning criteria are satisfied:

- The mode shape measurement consists in the cosine approximation of the time samples of the responses of all sensors collected during some periods. With this result, a specific software (2D Mode Shape Plots) permits to draw the mode shape in a 2D representation (Figure 8). In addition, this software allows to recalculate the generalized mass values when the operator changes the normalization point.
- The damping coefficient and generalized mass values derived from the specific Force in quadrature method and/or the Complex Power method. A dedicated ONERA software ("NMT Modal Parameter") is used for the treatment of those specific measurements.
- A specific measurement is then carried out to provide the specialists with a view of the structural nonlinear behavior of the measured mode by gradually increasing or decreasing the level of excitation strength and re-appropriating the mode by modifying the excitation frequency. The plot of the mode frequency as a function of the level of excitation makes it possible to verify that the measurement of the mode is carried out at the highest excitation level. The new MNLP (Manual Non Linear Pursuit) Testlab software, developed for this GVT by Siemens out of SOPEMEA and ONERA specifications, embedded in the NMT Testlab workbook has been used for this purpose.

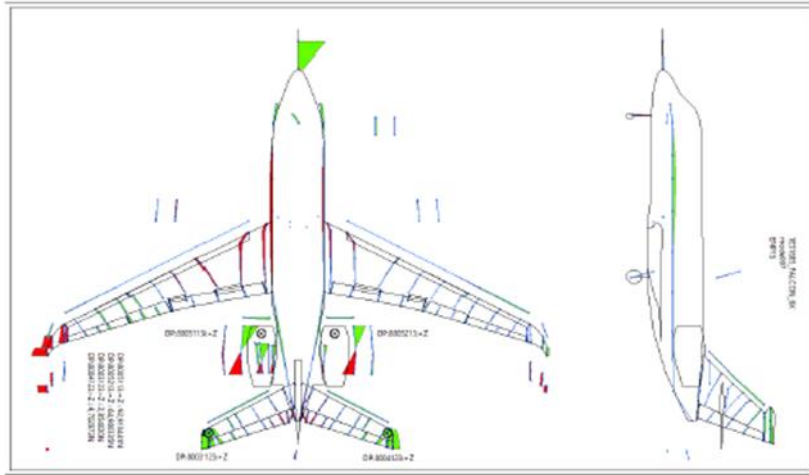


Figure 8: 2D folded down lines mode shape representation example

This method provides a precise identification of the modes and has proven its robustness facing structure nonlinear behavior. It gives modal parameters in real time but requires a good experience for tuning modes. It has been used for some modes which require the use of a lot of excitation sites (>2) for having all the nodes of the aircraft tuned at the same time.

4.2 Phase Separation Method

This technique proceeds with large frequency band excitation, collecting time responses, processing FRFs and using modal identification software, generally based on the hypothesis of linear structural behavior [3].

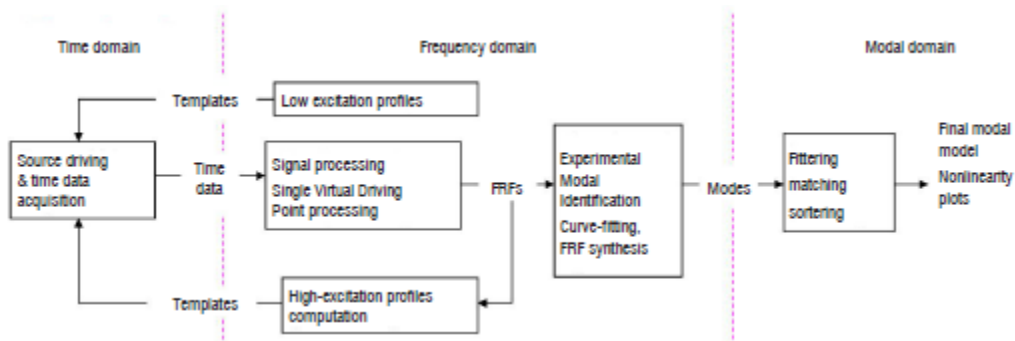


Figure 9: Typical process used in PSM

In order to prevent the aircraft from severe responses and to preserve the exciters and their associated connection to the aircraft, the Force Notching technique is used [2]. From preliminary runs acquired under low excitation force levels, the highest and intermediate excitation force level signals are computed. The resulting swept sine signals, composed of several constant excitation levels around modes, are played for the next measurements.

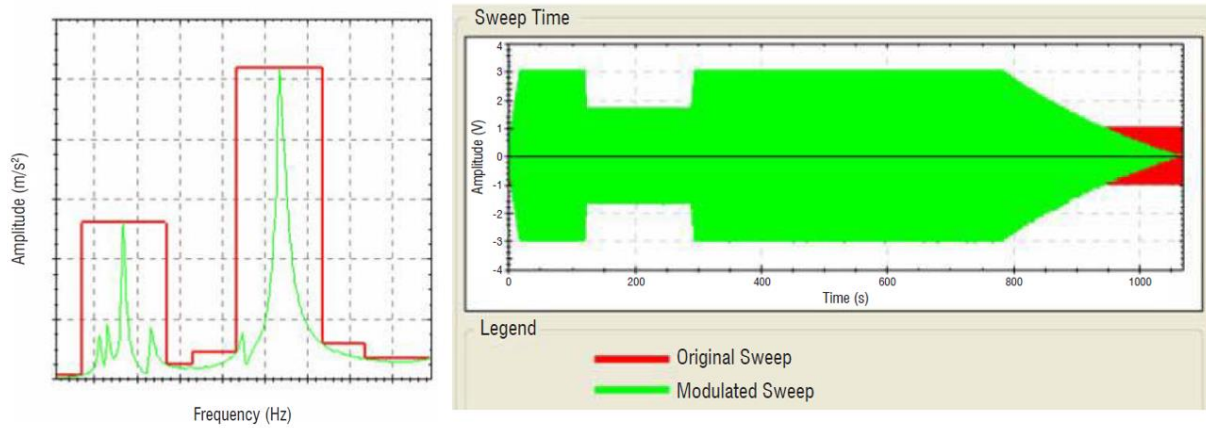


Figure 10: Force notching process

Over the years ONERA, SOPEMEA and Dassault Aviation each developed their own analysis tools. To gain in robustness, post-processing time and confidence in the results, both teams were performing modal analysis in parallel. Following sections present methods and tools used by both SOPEMEA-ONERA and Dassault Aviation.

4.2.1 ONERA-SOPEMEA Post-Processing

In 2005, ONERA introduced the technique of Single Virtual Driving Point (SVDP [4]) for correlated excitation signals sent to several exciters. Typically 2 exciters placed symmetrically to the aircraft are active during each measurement, with strictly equal signals, favorable to enter energies in the symmetrical modes, or with a phase shift of 180° favorable to enter energies in the anti-symmetrical modes. Single force and single driving point acceleration, called virtual, are computed and used for FRF (Frequency Response Function) computations. Then, the modal identification consist in a SIMO (Single Input Multiple Output) process. Others quantities such as coherences are computed in the ONERA SVDP software. This method relies on equation (2) where:

- CP is the complex power
- F_s is the force introduced by each exciter
- D_s is the displacement at each driving point
- F_v is the single virtual force
- D_v is the single driving point displacement
- ω is the frequency

$$CP(\omega) = \sum_{shakers} F_s(\omega) \dot{D}_s(\omega) = F_v(\omega) \dot{D}_v(\omega) \quad (2)$$

The Siemens Testlab Polymax software was used for modal identification. Thanks to the ONERA FRF – Synthesis software, the poles computed by Polymax were systematically verified and if necessary manually adjusted or added if missing. This software is designed to ease the comparison between the measured FRFs and the synthesized ones. It permits a real time correction of the synthesized FRFs following the pole adjustments. In addition local quality criteria (one per sensor and per mode) and global quality criteria are computed in order to assist the specialist in this task.

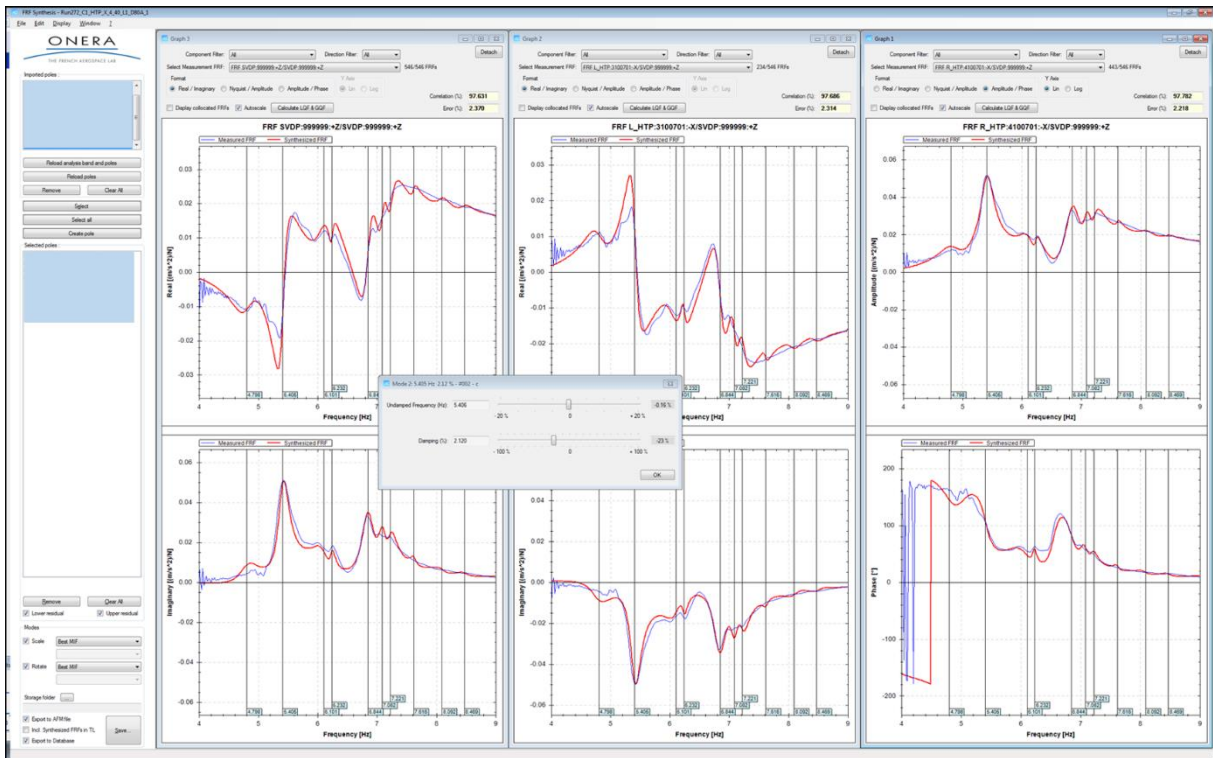


Figure 11: FRF synthesis layout example

The data (poles, mode shapes) are stored in a SQL database called “OMNI”. The ONERA software Modal Model Builder (MMB) is designed to correlate the modes together, to filter them and to assemble them in different families, each family being representative of one single mode. Then, for each family, non-linearity curves can be delivered using the most reliable modes, and the master modes of each family are the ones delivered to Dassault Aviation. The GVT of this new Dassault Aviation aircraft gave the opportunity to use for the very 1st time in an industrial context, those OMNI data base and MMB software.

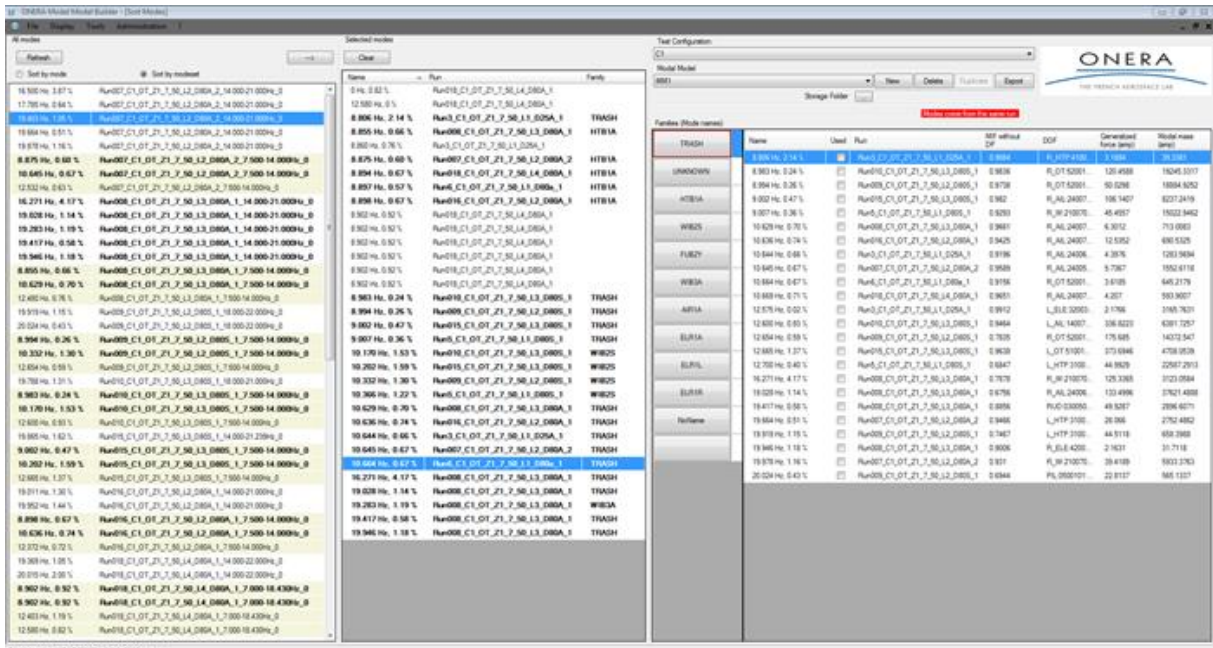


Figure 12: MMB layout

The MMB offers the possibility to visualize the mode shapes whether in a 3D animation (with multiple view options) or in the historical folded down lines 2D view. The 2D representation eases the visualization of both the node line positions and the torsion / bending relative contributions on the lifting surfaces.

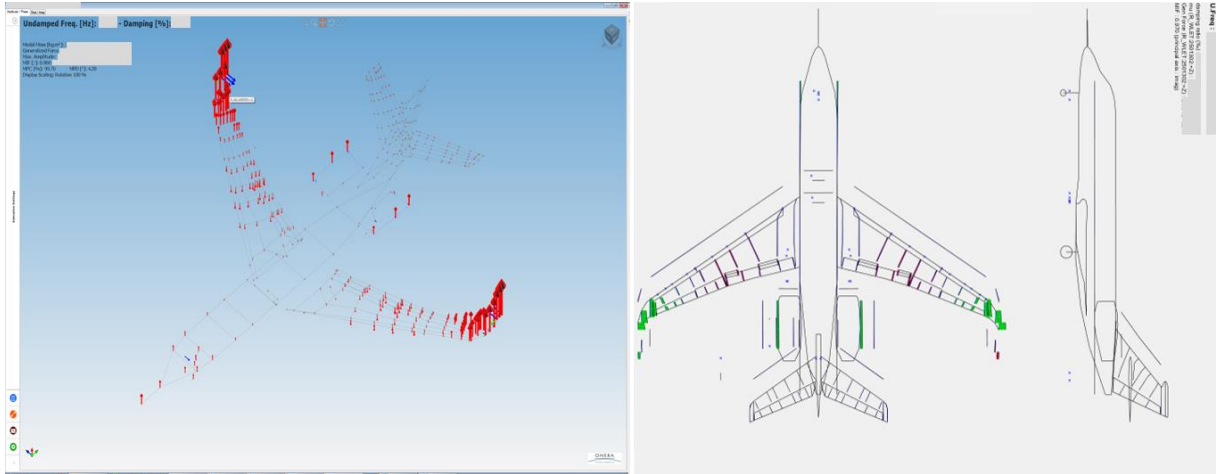


Figure 13: 3D animated mode shape and 2D folded down lines mode shape representation examples

Based on the AFM (ASCII File Mode) format available in the Siemens Testlab suite, the AFM+ file format has been designed by ONERA+SOPEMEA+Dassault Aviation. In addition to the modal data, this format makes it possible to exchange information such as forces introduced in the structure for the mode considered or the normalized generalized forces for example.

4.2.2 Dassault Aviation Post-Processing

Starting from time signals acquired by ONERA-SOPEMEA equipment, Dassault Aviation modal analysis team used its own in-house software ALAMO (ALgorithm for Aircraft MODal analysis). ALAMO was evaluated on several tests (simulations, ground and flight tests of civil and military aircrafts, equipment tap-tests) and gave very good results in agreement with other reference software. It is based on the curve-fitting of the all frequency response functions between each accelerometer and the excitation, by a rational fraction polynomial model using two methods successively LSCF (Least Square Complex Frequency domain [3]) and MLE (Maximum Likelihood Estimation [5]). These methods are widely used and their performances were compared to others well-known methods such as LSCE (Least-Square Complex Exponential) or FDPI (Frequency Domain Direct Parameter Identification) [3].

LSCF aims to fit the transfer function of a sensor s with a function as follows:

$$\hat{H}_s(\omega_k) = \frac{\sum_{h=0}^n \beta_{s,n-h} z^{-h}}{\sum_{h=0}^n \alpha_{n-h} z^{-h}} = \frac{B_s(z)}{A(z)} \quad (3)$$

Where

- n is the order of $B_s(z)$ and $A(z)$ polynomials
- z the Z-transform such as $z^{-h} = \Omega_h(\omega_k) = e^{-hj\omega_k dt}$ with dt sampling rate

Transfer function is thus estimated on a discrete frequency domain ω_k . The modal properties are derived from the roots of $A(z)$ polynomial. The LSCF minimizes the following cost function:

$$\varepsilon_s^{NLS}(\omega_k) = W_s(\omega_k) \left(\hat{H}_s(\omega_k) - {}^m H_s(\omega_k) \right) \quad (4)$$

Where ${}^m H_s(\omega_k)$ is the measured transfer function for sensor s and $W_s(\omega_k)$ a weighting function giving more importance to some sensors or frequency points.

To improve curve-fitting, a second algorithm is applied using the first LSCF estimation: the Maximum Likelihood Estimation. The cost function is defined as:

$$\varepsilon_s^{NLS}(\omega_k) = W_s(\omega_k) \ln \left(\frac{\hat{H}_s(\omega_k)}{{}^m H_s(\omega_k)} \right) = W_s(\omega_k) \ln \left[\frac{\sum_{i=0}^n \beta_{s,n-i} \Omega_i(\omega_k)}{\sum_{i=0}^n \alpha_{n-i} \Omega_i(\omega_k)} \times \frac{1}{{}^m H_s(\omega_k)} \right] \quad (5)$$

Minimizing this cost function leads to the maximum likelihood estimation with the hypothesis of ε_s^{NLS} being uncorrelated from one output to the other [3]. Maximum likelihood estimation consists in minimizing the cost function:

$$\ell = \sum_s \sum_k |\varepsilon_s^{NLS}(\omega_k)|^2 \quad (6)$$

As it can be seen, comparing blue and green curves on Figure 14, the estimate of the measured transfer function is better when using MLE after LSCF (blue curve is closer to experimental data in black).

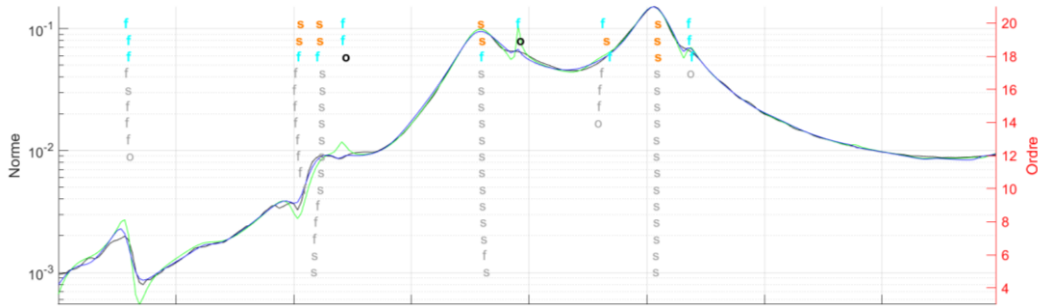


Figure 14: Experimental FRF (black) with LSCF (green) and MLE (blue) estimates

Once the denominator of the transfer function is derived (i.e. mode natural frequencies and damping ratios are known), mode shapes are obtained using a linear least squares fitting to derive numerator of each transfer function.

ALAMO generates AFM files which can be sent to ONERA-SOPEMEA but also to Dassault Aviation modal synthesis tool: ANATOOLS (ANALYSIS TOOLS).

4.3 Modal Synthesis

Modes are identified several times with the different runs from the PSM. Some modes are also identified using the PRM. All modes occurrences are gathered in ANATOOLS. They can come from Dassault Aviation modal analysis team, ONERA-SOPEMEA team or PRM identifications. ANATOOLS allows visualization of all parameters stored in the AFM file i.e. modal parameters and shapes as well as information on the modal analysis (frequency band and order chosen in LSCF and MLE algorithms) and confidence criteria (Modal Indicator Function, Dassault Aviation in-house curve-fitting criteria).

Once grouped in families, modes occurrences are plotted on non-linearity curves. Non-linearity plots show the evolution of frequency, damping ratio, modal mass with generalized force. Those curves are particularly useful to make sure that a sufficient level of force was applied to identify a mode. Indeed modal properties tend towards an asymptotic value with the excitation level. The level of force injected has to be high enough to counteract aircraft nonlinearities such as small plays or frictions in aircraft structure. Using the generalized force as abscissa permits to compare PSM and PRM identification on the same graph. PRM information (modal properties, shapes, nonlinearity curves) can be automatically read in ANATOOLS thanks to interoperability between ONERA-SOPEMEA and Dassault Aviation tools.

ANATOOLS allows also a direct comparison between experimental results and the FE numerical model. MAC can be computed between both model and experimental modes, charts comparing modal properties are available as well as mode shapes superposition helping the General FE model updating.

5 RESULTS

In a 12 days test campaign, 5 aircraft configurations were tested, PSM and PRM were both used to identify the first 35 modes as well as other modes involved in flutter mechanisms. This use of both methods combined with adequate test planning helped to reduce the time needed for aircraft immobilization.

267 PSM runs were performed while PRM was used for only 16 modes. Thanks to improved modal identification software suites and the use of large coil stoke exciters, good correlations were observed between both PSM and PRM as depicted in Figure 15.

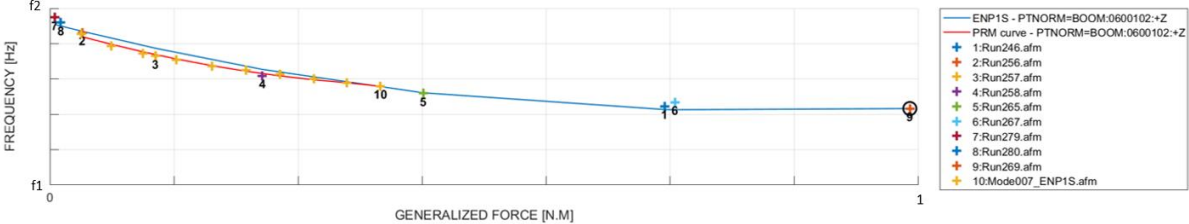


Figure 15: Non-linearity curve with PSM (blue) and PRM (red) on the engine symmetric pitch mode

Using non linearity curves helps to better understand variations in modal properties. One example on the Falcon 6X was particularly remarkable the anti-symmetric engine pitch mode (denoted ENP1A in following figures). Computing a MAC matrix between all occurrences found of this mode in one configuration yields a figure exhibiting two shapes in the same family. When looking at the MAC matrix in Figure 16, one could think that 2 different modes are tagged with the same name. On Figure 16, a value of 100 means than the two shapes compared are identical. However when looking at the nonlinearity curves in Figure 17, it can be noticed that the naming is correct. Indeed this change in shape corresponds to the crossing between the anti-symmetric engine pitch mode and the 5 nodes wing bending mode (denoted WIB5A).

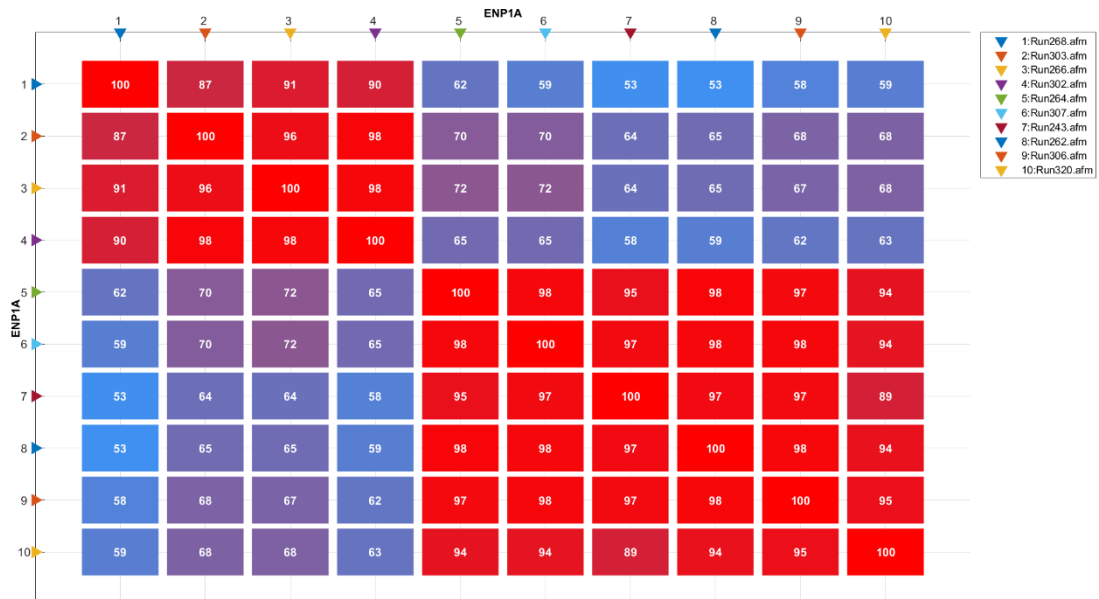


Figure 16: ENP1A MAC Matrix

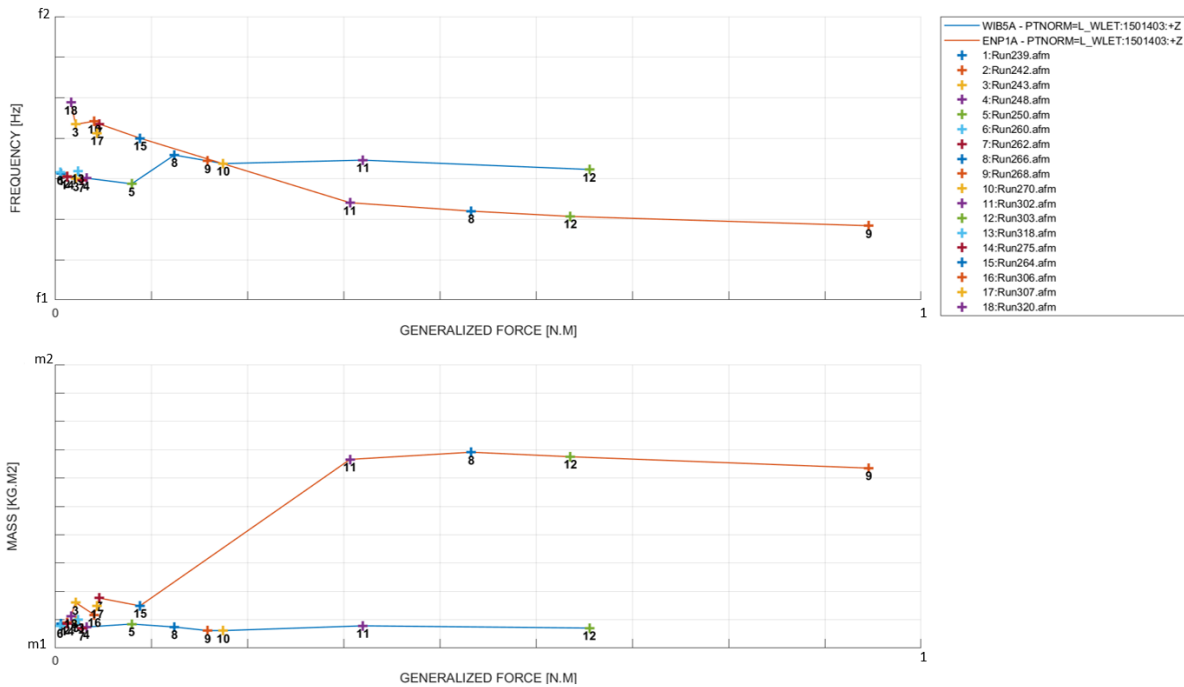


Figure 17: ENP1A and WIB5A non-linearity curves in frequency and generalized mass

Thanks to ONERA-SOPEMEA and Dassault Aviation tools interoperability, the modal synthesis was easily converged with both teams. The experimental results were immediately used for the GFEM tuning.

General FE model updating was done in synergy with post-processing and GVT test planning. Two strategies were performed in parallel for the GFEM tuning. The first one was mostly based on engineering judgement and experience to define aircraft parts to be tuned and with which order of magnitude. The iterative process was completed with a second updating strategy based on semi-automated optimization. Engineering judgement is still needed for this method to define aircraft properties to be modified. Dassault Aviation in-house FE solver ELFINI is then used to find the optimal values for the chosen variables. At the end of the GVT campaign,

Falcon 6X GFE model was tuned as shown in Figure 18. With an updated numerical model, flutter clearance can be obtained for the first flight.

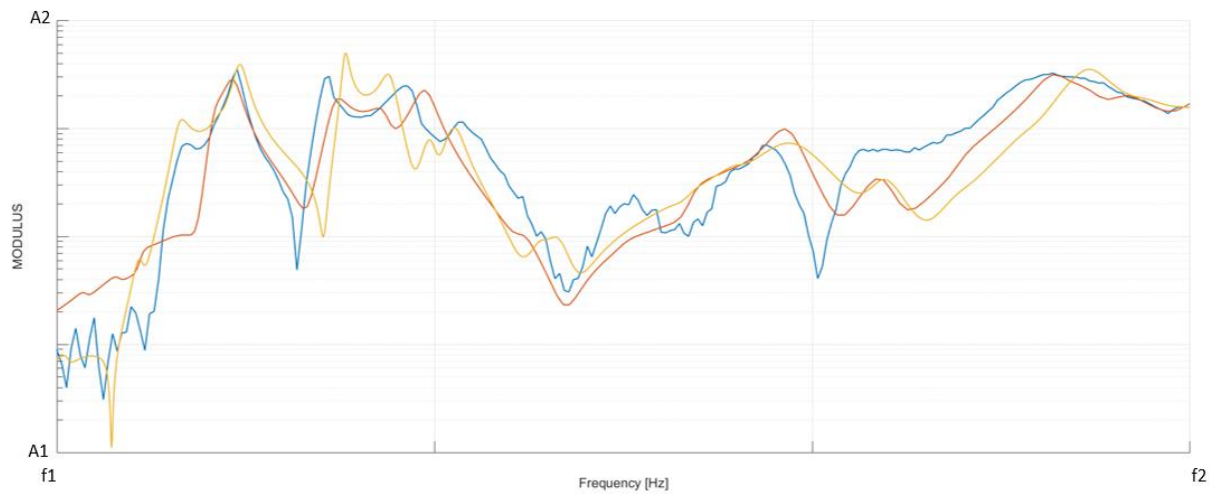


Figure 18: Frequency Response Functions: experimental (blue), numeric before (red) / after (yellow) tuning

6 CONCLUSION

The Falcon 6X GVT campaign was completed within the number of days initially planned with confidence in the results. To respect the time schedule appropriate testing equipment was selected. The use of both Phase Resonance Method and Phase Separation Method helped to reduce the time needed to identify precisely all structural modes involved in flutter mechanisms. Confidence in the results was obtained by the parallel data processing of both Dassault Aviation and SOPEMEA-ONERA teams. The experimental results were immediately used for the GFEM tuning which is necessary for the first flight authorization. The flutter clearance was obtained thanks to the GFE model updated at the end of the GVT. With the complete success of this GVT test campaign, this type of organization will be reproduced on future Falcon aircraft.

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