Testing in Aerospace Research

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Aircraft Ground Vibration Testing at ONERA

During the development of a new aircraft, the Ground Vibration Test (GVT) is an important milestone because flutter computation relies on its results to determine the start of flight tests. Since the creation of ONERA after World War II, the GVT has always been the subject of fundamental research and application on industrial structures. On the occasion of the 70th anniversary of ONERA, an historical survey of the main methods and significant tests is proposed in this paper. After a brief introduction to the goals of a GVT, we highlight the continuous improvements made in this discipline in parallel with the progress in electronics, computers and algorithms, mainly focusing on internal studies at ONERA. Even though nowadays the GVT has reached maturity, aircraft dynamics is so challenging that several paths of research activities still remain. Keeping in mind the high quality standards expected by aircraft manufacturers, a vision of promising aspects for the future of GVT is finally proposed.

Introduction – A Brief History of Flutter

"*It is most probable that the first flutter accident of an aircraft occurred on December 8, 1903, when Professor Samuel Pierpont Langley, of the Smithsonian Institute, failed an attempted launch of his powered flying machine named "Aerodrome" from the Potomac River houseboat. That was only nine days before the Wright brothers' flight at Kitty Hawk*" [11]. Samuel P. Langley was nevertheless a renowned American astrophysicist and astronomer, who made airplane models powered by whirling arms and steam engines. In 1891, one of his unmanned models flew 3/4 of a mile before running out of fuel.

In this paper [11], one can read this description of flutter: "*From our present perspective, flutter is included in the broader term aeroelasticity, the study of the static and dynamic response of an elastic airplane. Since flutter involves the problems of interaction of aerodynamics and structural deformation, including inertial effects, at subcritical as well as critical speeds, it really involves all aspects of aeroelasticity (…). In man's handiwork, aeroelastic problems of windmills were solved empirically four centuries ago in Holland with the moving of the front spars of the blades from about the mid-chord to the quarter-chord position. We now recognize that some 19th century bridges were torsionally weak and collapsed from aeroelastic effects, as did the Tacoma Narrows Bridge in a spectacular fashion in 1940.*"

Why conduct a Ground Vibration Test on an aircraft?

Before going further, it is pertinent to recall the basic equation of flutter:

$$\begin{aligned}&[M]\ddot{Z}(t)+[C]\dot{Z}(t)+[K]Z(t)=\\&\left[C_{aero}\left(V^2\right)\right]\dot{Z}(t)+\left[K_{aero}\left(V^2\right)\right]Z(t)\end{aligned} \tag{1}$$

where $Z(t)$ is the structure displacement vector. $[M]$, $[K]$ and $[C]$ are the positive definite mass, stiffness and damping matrices, respectively. They are on the left-hand side of equation (1) and represent the structural behavior. On the right-hand side of equation (1), $[C_{aero}(V^2)]$ and $[K_{aero}(V^2)]$ are the aerodynamic damping and stiffness matrices describing the unsteady aerodynamic forces.

The GVT is part of an aircraft certification process and its purpose is to measure the aircraft dynamic characteristics (natural frequency, mode shape, structural damping coefficient and generalized mass of the most important vibration modes).These results make the computation of flutter prediction possible, as well as the updating of the FEM (Finite Element Model) of the structure.

The fundamental equation is derived based on the assumption of linear second-order differential systems:

$$[M]\ddot{Z}(t)+[C]\dot{Z}(t)+[K]Z(t)=F(t) \tag{2}$$

Where the right member $F(t)$ represents the forces applied by means of excitation devices (illustrated in Figure 1). Thus, identifying the dynamics comes down to estimating the matrices $[M]$, $[K]$ and $[C]$ in a modal basis.

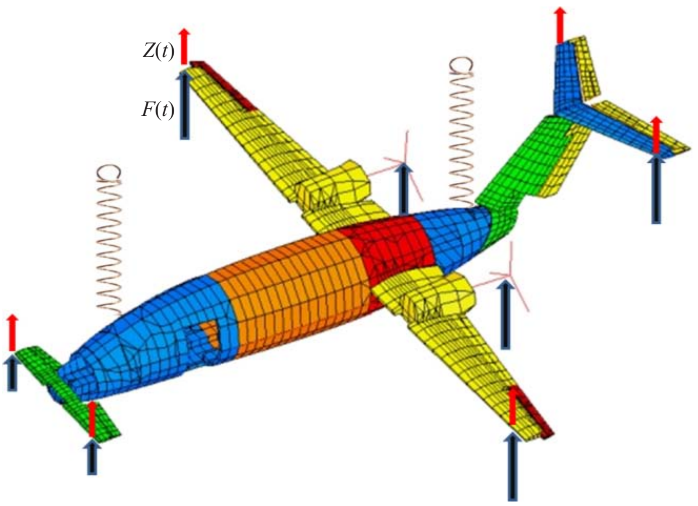


Figure 1 - Scheme of the Piaggio P180 Avanti FEM with forces, responses and soft suspensions

If real structures behaved as linear equation (2) predicts, it would be easy to characterize these matrices. Sensitive sensors and a few small forces well distributed over the structure would be enough to identify them. However, as the majority of vibratory modes are nonlinear, in practice these matrices depend on response amplitudes and therefore on excitation forces. In general, only the damping and stiffness matrices present these peculiarities:

$$[M]\ddot{Z}(t)+\left[C\left(Z,\dot{Z}\right)\right]\dot{Z}(t)+\left[K\left(Z,\dot{Z}\right)\right]Z(t)=F(t) \qquad (3)$$

Nevertheless, for almost all vibration modes observed on aircraft, these non-linear parameters are small compared to the inherent linear ones. Then equation (3) can be written in the following form:

$$[M]\ddot{Z}(t)+[C]\dot{Z}(t)+[K]Z(t)+\varepsilon f\left(Z,\dot{Z}\right)=F(t) \qquad (4)$$

Where ε is a small scaling coefficient and f is the nonlinear function, also called the Restoring Force in the specialized literature.

As a consequence, for flutter prediction and FEM updating, aircraft manufacturers need linear modal parameters, obtained from the highest possible level of excitation forces. Of course, as the aircraft is expected to perform its first flight a few weeks later, the GVT has to be a nondestructive test.

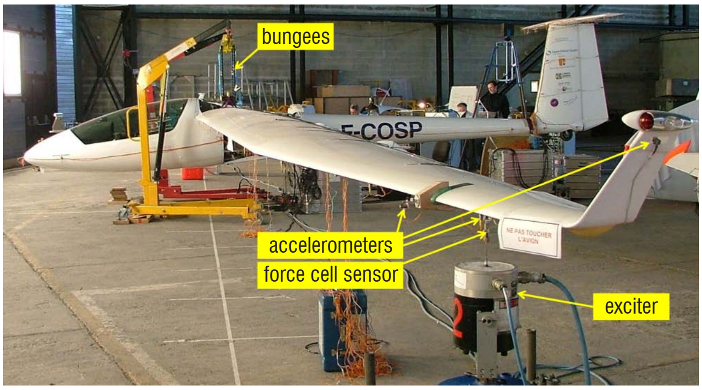


Figure 2 - GVT of a glider

Performing a GVT on an aircraft consists in applying external forces and measuring vibration responses. In addition, it should be noticed that, most generally, the aircraft will be uncoupled from the ground. To do that, the following devices are used nowadays (Figure 2).

The main difficulties come from nonlinear behavior, the high modal density and the possible lack of observability if the distribution of sensors is not optimal.

History of Ground Vibration Testing at ONERA: 1940s to 1970

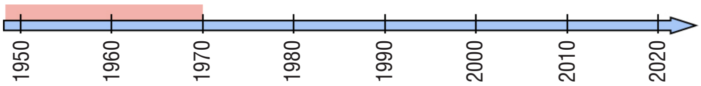


Figure 3 - GVT of the Do 17 R4 in 1939

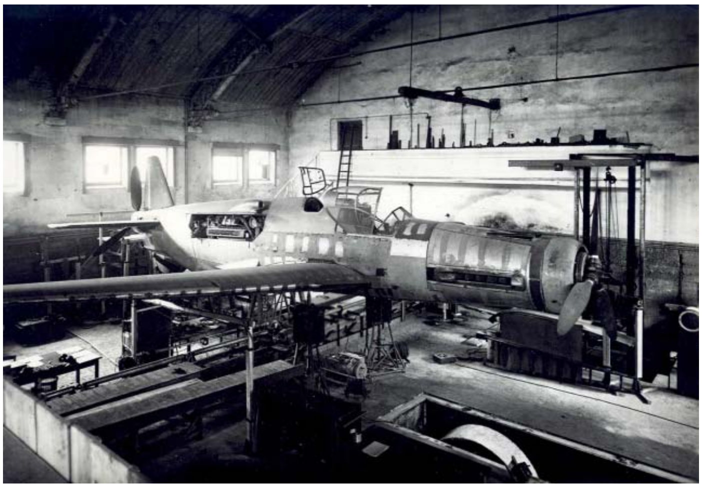


Figure 4 - GVT of the Do335 prototype at CTW

Just after the end of World War II, the French army based in the South of Germany created the "*Centre Technique de Wasserburg*" (CTW), particularly interested in aerodynamics and ground vibration testing. They performed an exhaustive analysis of the equipment, techniques and methods developed by the Dornier Company, based in

Friedrichshafen (Figure 3). One week after the official birth of ONERA, in May 1946, several top level civil and military personalities attended a demonstration of the GVT of an aircraft performed by Dornier (Figure 4). Some of those people, Mr. Mazet, Mr. Weber and Mr. Barrois, then became part of the management at ONERA.

At that time, excitation forces were delivered by unbalanced rotating systems and spring exciters controlled together with a sine signal, while measurements were performed with several fixed and mobile recorders, a tachymeter and a chronometer.

From Dornier technicians and engineers, most notably Mr. G. De Vries, and Wasserburg equipment, ONERA built its own team and applied the "Wasserburg" method for a GVT of the SNACASO SO-M1, Arsenal VG 70 and the SNCAN NC-271 aircraft in 1947. In parallel with the development and support on structural fatigue and structural static behavior, ONERA welcomed engineers of new French national aeronautic companies to train them in structural dynamics and flutter prediction.

Figure 5 - Mr. G. De Vries on the right hand side

Within the experimental and theoretical teams, French and German engineers developed new methods and techniques in a good atmosphere, as for instance the first developments and uses of electrodynamic shakers. Some of the Germans stayed in France, whereas some others went back and joined Mr. Dornier again at Friedrichshafen, working notably on the Dornier Do228 and the jet trainer Alphajet. Mr. G. De Vries [5] worked all along for the Structural department of ONERA until his retirement.

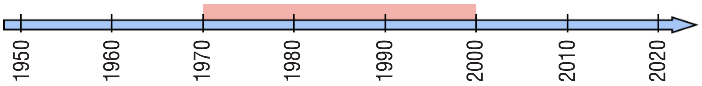
The demonstration of the GVT of a Wasserburg scale model in Meudon in December 1950 (Figure 5) gave national and international personalities in aeronautics and observers of many aircraft manufacturers an opportunity to focus on the benefit of flutter studies.

An example of test results is shown in Figure 6. It should be noticed that, although the Hertz (Hz) is nowadays the unit for frequencies, at that time the unit commonly used was cycles/minute (mn^{-1}).

The Phase Resonance Method, also called "Modal Tuning" or "Modal Appropriation", whose reputation remains linked to ONERA, was derived from the Wasserburg method. It relies on the Basile hypothesis, also called "Proportional generalized structural damping matrix hypothesis". Described by Mr. Basile, an engineer at ONERA, and mostly verified on aircraft structures, it makes the identification of all modal parameters possible, including structural damping coefficients.

This PRM, still used today, consists in measuring each vibration mode individually. It requires adjusting the excitation locations, force amplitudes and signs, and the frequency of the sine excitation signal. Using Lissajous ellipses between velocity responses and this excitation signal and using current controlled exciter amplifiers, developed by ONERA, make the use of this method easier.

The 1970s to 2000: the path to the modern era and ONERA as a major actor in GVT



Initially, the aircraft displacements were recorded by means of paper-band manual sensors (Figure 7a). These devices were travelled by operators at each measurement location and the quantities were manually evaluated from the paper-bands. Later, velocimetry sensors (Figure 7b) were used for vibration measurements. Their mobile parts were permanently linked to the aircraft, while their fixed parts needed to be supported by a huge number of scaffoldings.

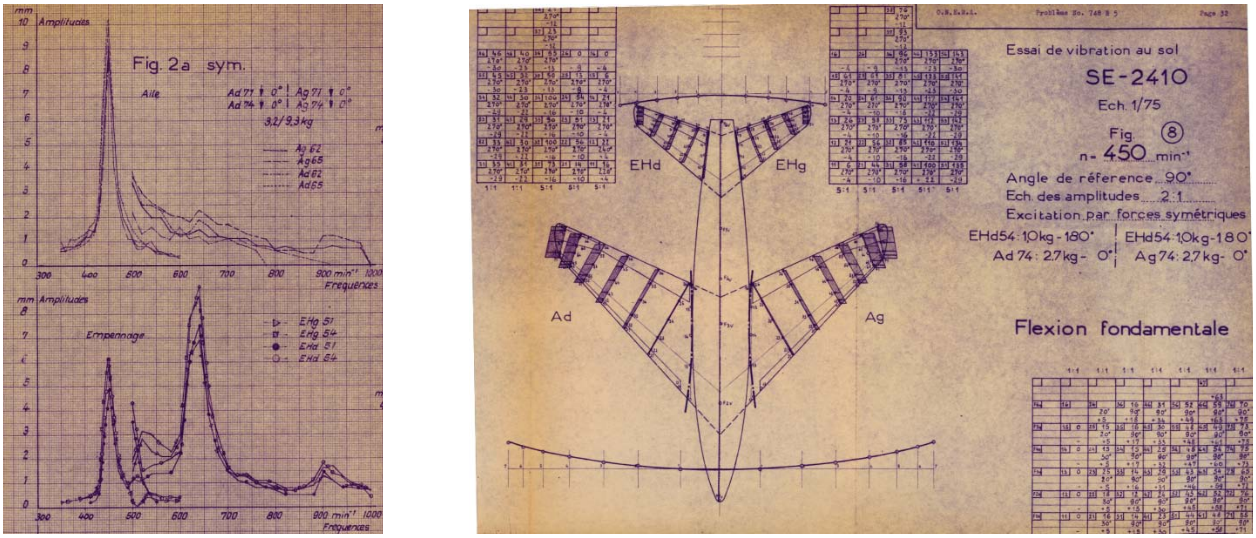


Figure 6 - Example of frequency responses and a mode shape plot (GVT of the SNCASE SE2410 in 1949)

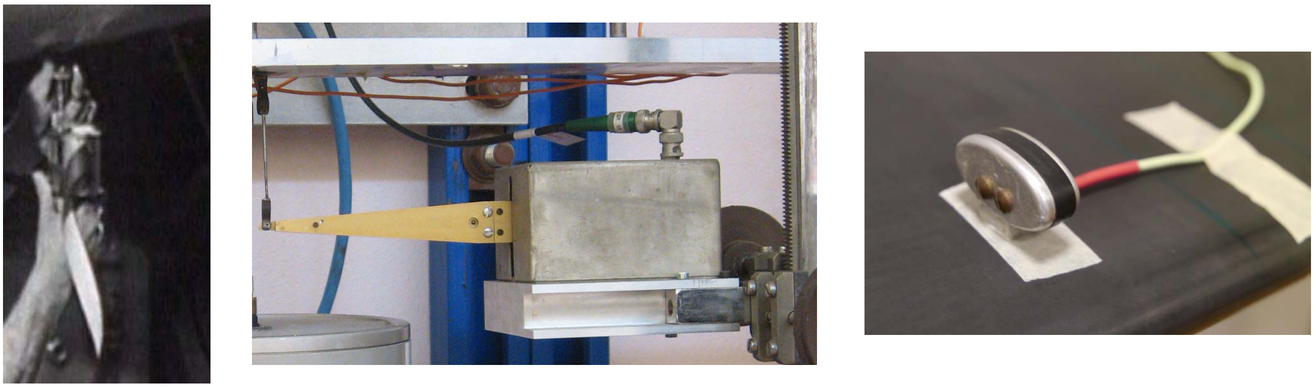


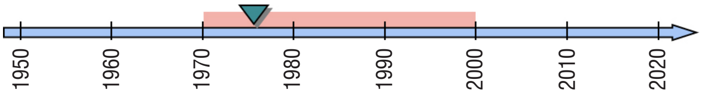
Figure 7 - ONERA displacement sensor, velocimetry sensor and accelerometer

They had the strong benefit of providing electrical signals recorded by an acquisition system. Thereafter, in the 1970s, ONERA developed small and affordable piezo-capacitive accelerometers (Figure 7c). Light and directly glued onto the aircraft, they did not need additional devices to support them. These were notably used for the first Airbus GVT in 1972 (see Figure 8).

With the first computers and FFT (Fast Fourier Transform) computation, one can say that the GVT entered the modern era.

The dissipation and generalized mass of a mode are now determined by the FQ (Force in Quadrature) method [5], which consists of superposing a dissipative force by means of an additional force in quadrature to the force making the aircraft vibrate at the resonance frequency. This method replaced the previous method consisting of adding local masses and deriving the generalized mass and the damping coefficient from the frequency deviations. Years later, to complement the FQ method, ONERA developed the CP (Complex Power) method [2].

Figure 8 - 1st Airbus (A300 B2) GVT in 1972



In 1977, for the GVT of the Ariane IV launcher components (see Figure 9), ONERA used the method called "Dat-Meurzec" for the first time. This was based on a curve-fitting process applied to the generalized coordinates and was, at ONERA, the first Phase Separation Method (PSM). Using frequency band responses measured, at that time, from stepped sine excitations, the method consists in applying a curve-fitting process from a first approximation of generalized coordinates in the near vicinity of each vibration mode.

Figure 9 - GVT of Ariane IV sections in 1977

Thanks to the continued increase in computer performance, this technique continued to improve and was

- tested in 1985 for a research GVT using a Dassault Aviation Falcon 20,
- used successfully in 1990 for a research GVT (Dassault Aviation, SOPEMEA, ONERA), dedicated to modal identification from excitation performed using control surface rotations on a Mirage 2000 [15],
- and finally used in 1999 during a research GVT (Airbus, DLR, SOPEMEA, ONERA) on an Airbus A340-300.

In parallel, other notable research activities were carried out on:

- the state of the art in EMA (Experimental Modal Analysis) in Europe, especially on damping estimation, coupled modes and nonlinearities
- GARTEUR (Group for Aeronautical Research and Technology in EURope) SM-AG19

  In the 1990s ONERA initiated a round robin survey of EMA in Europe, using a laboratory 2x2m model (see Figure 10), designed and manufactured by ONERA [1]. The model has been sent to several laboratories and comparisons of results were made among GARTEUR associated partners. This model is today still a reference.

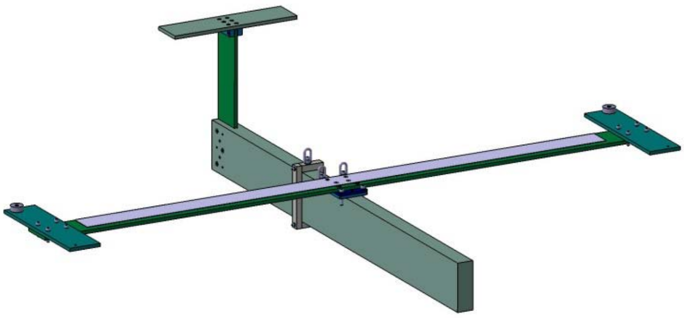
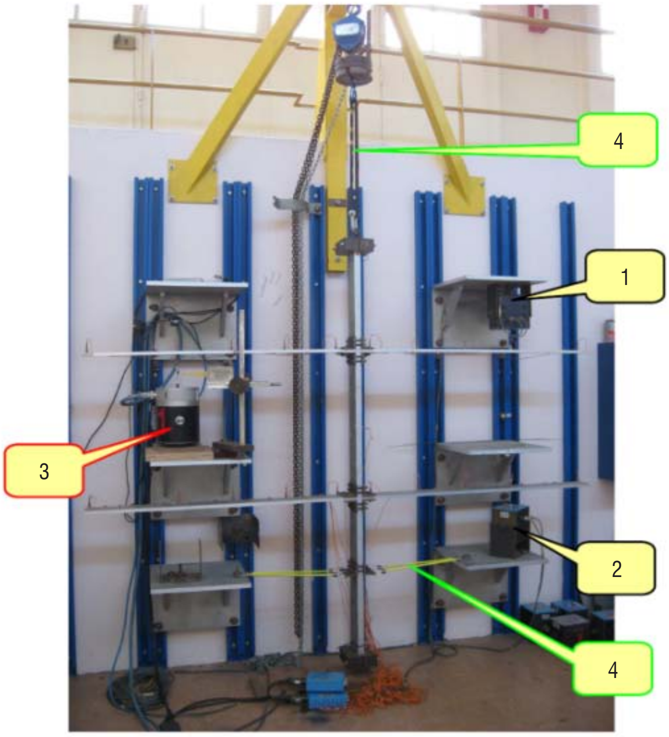


Figure 10 - GARTEUR SM-AG19 Computer-Aided Design

- New method for linear parameter estimation
  In the 1990s, Mr. C. Soize, ONERA Structural Department Director at that time, developed the Stochastic Linearization method with PhD students [10], [21], [22]. From time domain records of responses under random excitation, this method delivers the likeliest linear description of a structural behavior. Furthermore, the deviation between this linear model and the measurements provides information about nonlinearity contents. Applied to a real aircraft GVT, the method revealed its limits, mainly due to the low force levels delivered by random excitation with the 500 N max force exciters available at that time.

- Method for non-linear behavior estimation
  The idea of the POD (Proper Orthogonal Decomposition) method is to build an orthogonal basis dealing with the best energetic way for describing observed phenomena. PODs obtained from experimental measurements at a high force level are compared to PODs computed from analytical time-series, themselves obtained from measurements at a low force level (see the whole process in Figure 11). The best matching of PODs reveals the likeliest nonlinear model [4].



"Jagellios Blazon" Test Bed
(1) "external" force applied on beam #2
(2) "external" force applied on beam #4
(3) "internal" force applied on beam #1
(4) bungees for vertical and lateral suspensions

Figure 12 - Arm-tree lab model designed for method development and benchmarking

On the laboratory structure (Figure 12) excited by 2 shakers, the nonlinearity is well managed and measured by using a third shaker driven by the structure responses and considered as an internal component of the system. Without any use of the nonlinearity force measurements, the method is successfully applied when the nonlinearity location is known (Figure 13, Figure 14). The method suffers, for today, when multiple nonlinearity sites are involved and if their locations are not known [4].

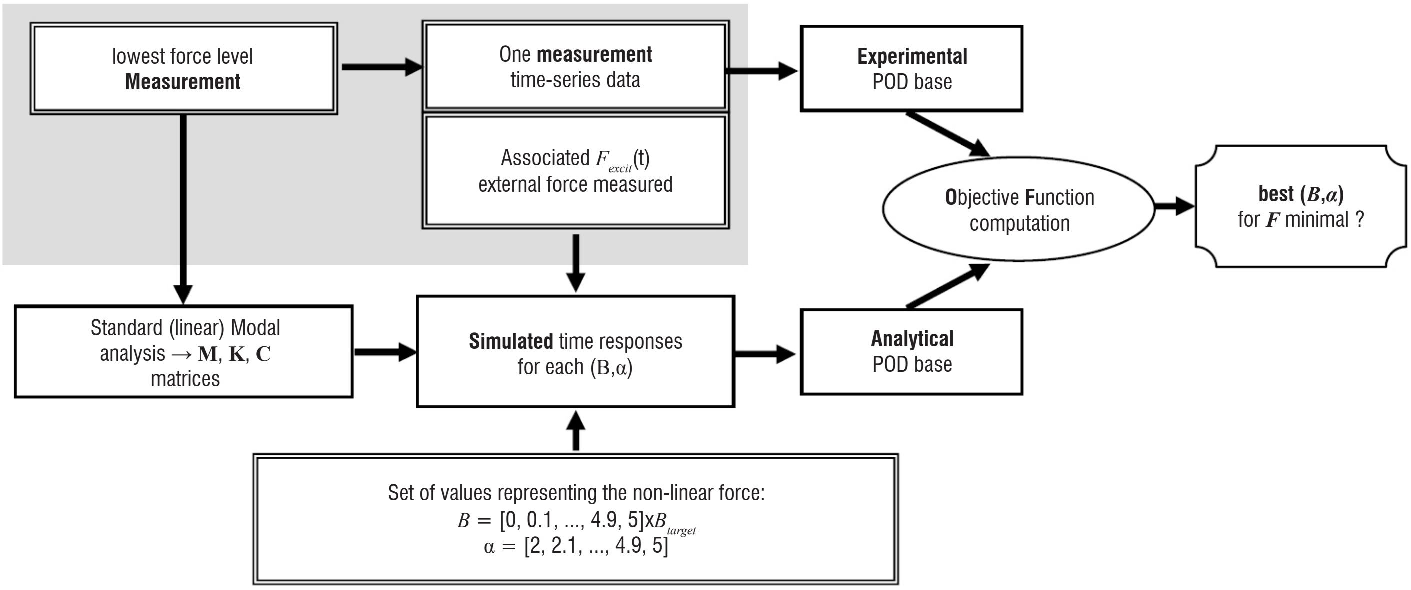


Figure 11 - Process for the identification of nonlinear parameters

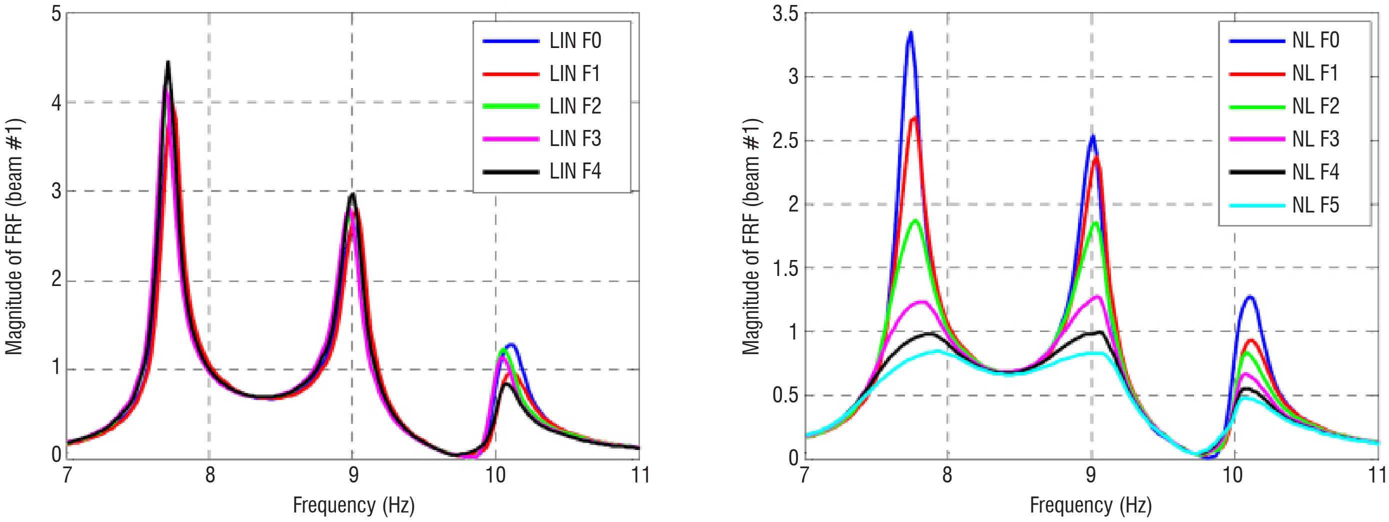


Figure 13 - FRFs (Frequency Response Function) of 1 sensor when a nonlinearity internal force is applied (right side) or not (left side)

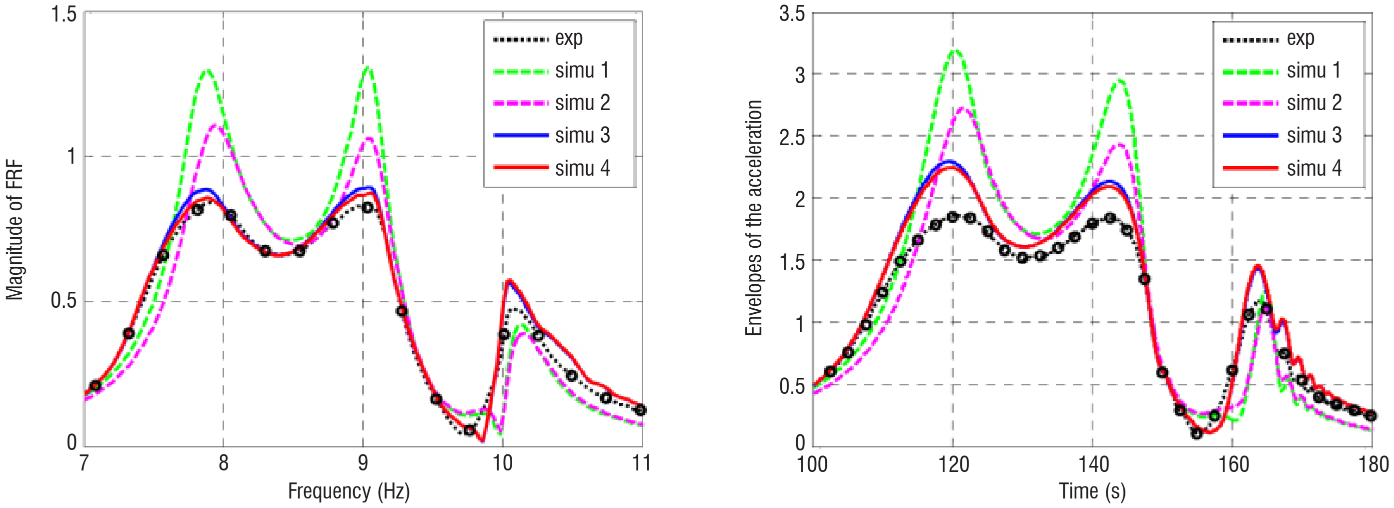
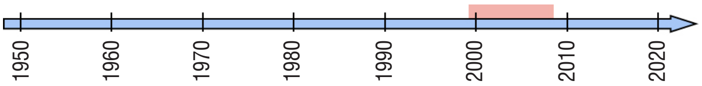


Figure 14 - Predictability: comparison between measured and computed FRFs from nonlinearity POD identification used lower force levels

1999 - 2008: The biggest GVT system in the World, the largest civil aircraft and a new test strategy emerges



1999 was an important milestone in GVT history at ONERA. It corresponds to the complete renewal of the ONERA GVT system, in coordination with SOPEMEA. The main motivations were new industrial requirements (test duration reduction, rapid transmission of final results, maintaining the result quality) and increasing dimensions of modern aircraft. A complete new acquisition system, based on HP VXI 16 bit resolution hardware was selected, able to go up to 1024 synchronous channels, running with SDRC I-DEAS Test software. New ICP TEDS PCB accelerometers and long-stroke 500N PRODERA exciters were specified and purchased to complete the system.

During the last four decades, numerous methods were created to process data coming from Phase Separation (PSM) [7], for instance:

- Time domain methods like LSCE (Least Squares Complex Exponential), Ibrahim Time Domain, etc.
- Frequency domain methods like Polyreference and Direct Parameter.

In practice, frequency domain methods gained attention because they allow the user to focus on a particular frequency band. ONERA started to use market standard EMA methods, like Polyreference (SDRC) and LSCE (LMS). Both algorithms rely on the decomposition of FRFs as a series of rational fractions

$$\left[H(s)\right]=\sum_{j=1}^{N}\left(\frac{\left[R_j\right]}{s-\lambda_j}+\frac{\left[R_j\right]^*}{s-\lambda_j^*}\right)+\frac{\left[U\right]}{s^2}+\left[L\right]$$

where the $[R_j]$ are the residues and the λ_j are the poles. Matrices $[U],[L]$ denote the upper and lower parts taking into account the influence of out-of-frequency band modes. These parameters are estimated by curve-fitting of experimental FRFs. The quality criterion of this step is to match analytical and experimental FRFs as closely as possible. Finally modal parameters are obtained in a second step. Frequency and damping values are easily computed with poles, while mode shapes estimation is based on the $[R_j]$.

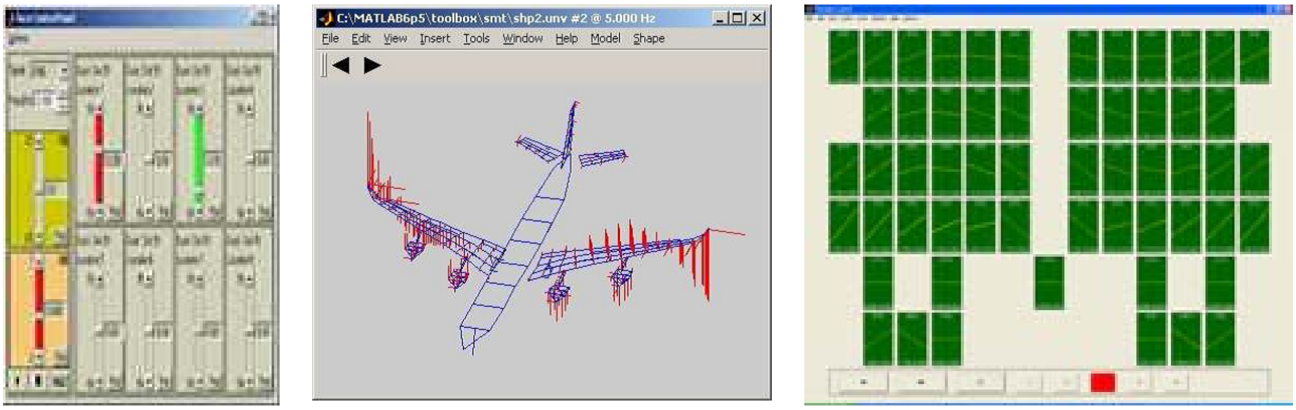


Figure 15 - Force setting interface, 3D mode shape representation and Lissajous displays of the ONERA modal appropriation software

Compared with PRM, these techniques permitted a strong increase in productivity, but without reaching the same levels of excitation. Anyway, throughout this period, they became more and more used in GVTs.

In parallel, based on VXI hardware, ONERA has developed a new PRM software suite and a new force control device, improving the ergonomics of the method. It became a new "standard" for PRM for the next 10 years (Figure 15).

An improved test strategy has also been developed, combining classical PRM with PSM. This strategy, investigated during a research GVT on an Airbus A340-300 in 1999 was applied during the GVT of the Airbus A340-600 prototype in 2001, both performed by ONERA/DLR/SOPEMEA GVT experts [9]. It was the first time that PRM and PSM were combined, reaping the benefit of their individual advantages, to obtain the best and most complete modal model of a tested aircraft in the shortest time (see the detailed test strategy in Figure 16). The use of a FEM in pre-testing, in order to help to define the right number of accelerometers and exciters and their locations, was also an additional way to improve the test efficiency.

Still in 2001, the Airbus A340-500 GVT (ONERA/DLR GVT team) was performed. For the first time, it had to be certified to address the post Fan Blade Off wind-milling event. In order to achieve the certification goals with respect to Airbus requirements, ONERA developed excitation stimuli and specific push-pull rods connecting the exciters to the engines [17].

In order to simulate the rotating excitation due to an unbalance, ONERA proposed the use of 2 electrodynamic exciters acting

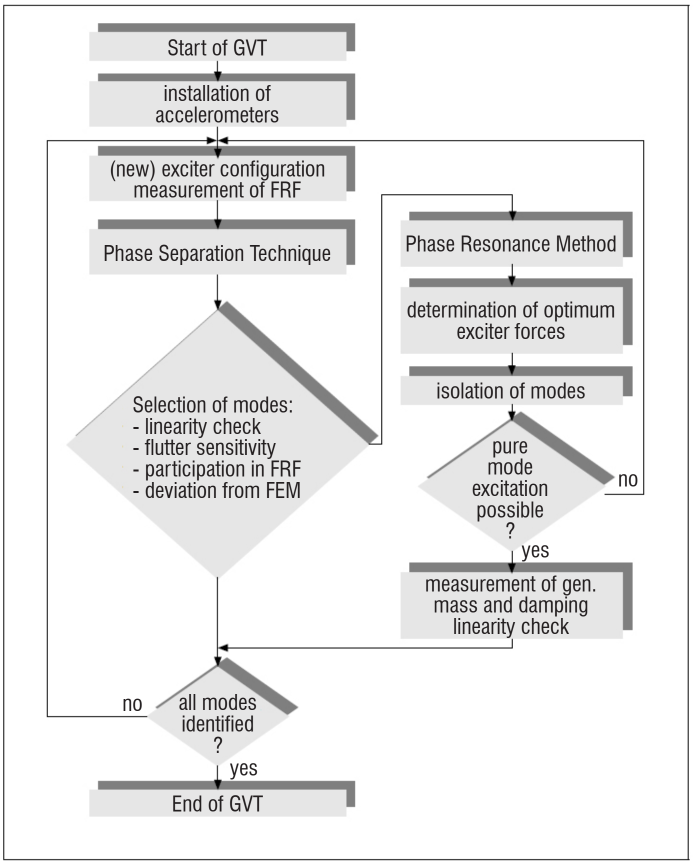


Figure 16 - Optimized test strategy applied during A340-600 GVT in 2001

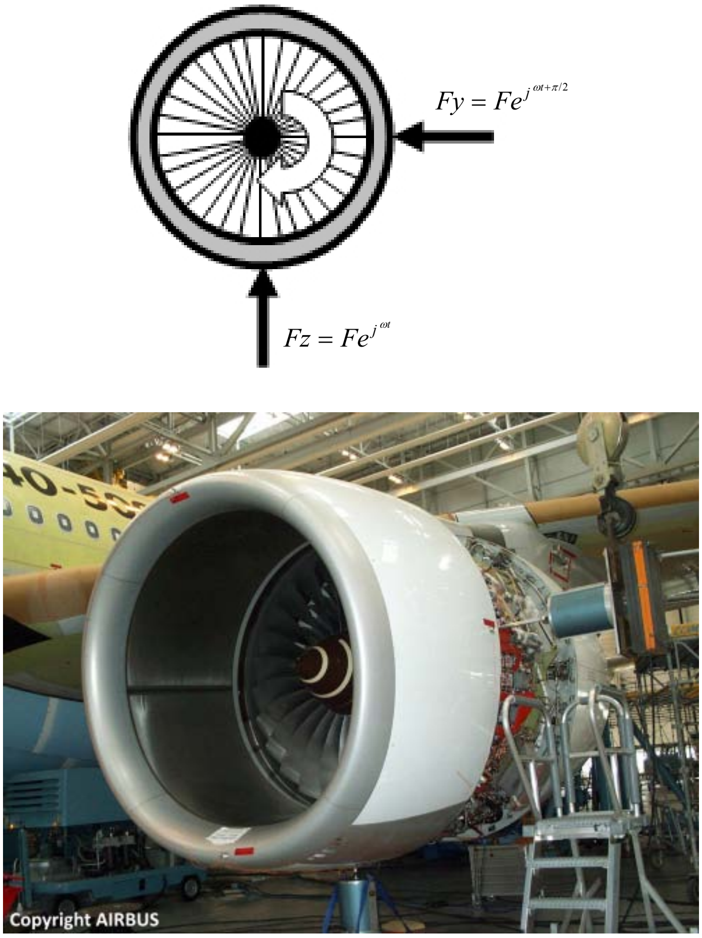


Figure 17 - Circular excitation by means of 2 orthogonal exciters

simultaneously in quadrature with exciters placed with a 90° geometrical deviation (Figure 17).

Excitation signals used for PSM became, most of the time, swept-sines. These swept-sine excitations are either symmetric or antisymmetric force patterns applied with two shakers, generally installed in a symmetric setup. Given that in this case the forces are by definition correlated, it is not possible to use the H_1 estimator directly on the frequency data:

$$\left[H_1(\omega)\right]=\left[P_{ZF}(\omega)\right]^{-1}\left[P_{ZZ}(\omega)\right] \qquad (6)$$

Where $[P_{ZZ}(\omega)]$ and $[P_{ZF}(\omega)]$ are respectively the output and input-output power spectral densities.

One solution is to build augmented matrices from the combination of all runs, for instance two runs in the case of symmetric and anti-symmetric excitations. This solution had been adopted until this moment for classical PSM runs with swept-sines, but it could not be used for wind-milling excitations, where Y and Z excitations were correlated, and had to be applied, by principle, simultaneously.

This is why the SVDP (Single Virtual Driving Point) processing method was developed. The SVDP process defines a virtual driving point, which would give rise to vibratory responses strictly similar to those obtained with correlated forces. SVDP relies on the equivalent complex power:

$$CP(\omega)=\sum_{shakers}F_s(\omega)\dot{Z}_s(\omega)=F_V(\omega)\dot{Z}_V(\omega) \qquad (7)$$

Where $F_s(\omega)$ is an excitation force acting on a driving point s, $\dot{Z}_s(\omega)$ is the velocity at driving point s, $F_V(\omega)$ is the virtual force and $\dot{Z}_V(\omega)$ is the velocity response of the virtual driving point. The virtual driving point does not exist physically. It is just an imaginary driving point of the virtual force, which has the same excitation energy as the multi-shaker setup and produces the same response.

Once the SVDP process has been applied, SIMO (Single Input Multiple Output) FRFs with regard to the virtual driving point are obtained and classical curve-fitting can be directly used on them. As no hypothesis is necessary about the purity of symmetry of the mode shapes, as from that time the SVDP method has been standardized for swept-sines runs for all subsequent GVTs.

Figure 18 - General view of the A380 in the painting hall during the GVT

In 2005, the GVT of the Airbus A380-800, the largest civil aircraft ever built, was performed (ONERA/DLR GVT team) [13]. To illustrate the size of this test campaign (Figure 18), we can mention:

- 850 accelerometers
- 50 different excitation locations
- 25 km of cables

Pursuant to the technical requests made by Airbus, the test strategy promoted by ONERA and DLR since 1999 was applied:

- Modal identification method (PSM) based on mathematical curve fitting on measured FRFs for the majority of modes
- Classical modal tuning method (PRM) for modes of special importance only.

The development of specific devices and processing methods contributed to the success of this test campaign. One can recall the improvement of the mode filtering and correlation tools, with various criteria, such as the generalized modal mass, MIF (Mode Indicator Function), participation factor, and MAC (Modal Assurance Criterion) to help us to discriminate and to sort modes. The use of home-made

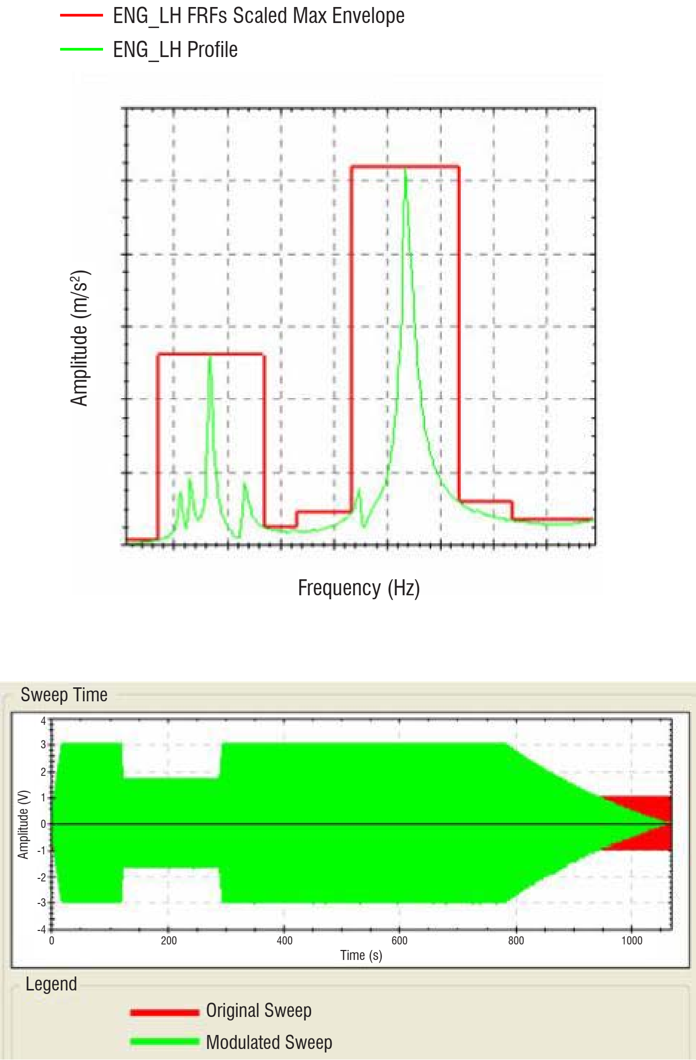


Figure 19 - Maximizing the force level over frequencies and example of a modulated excitation time signal

seismic exciters to excite the two decks in the fuselage can also be recalled. SVDP processing was enhanced and generalized for all PSM runs.

For this test, a force notching process was also developed, in order to maximize the level of the force excitation provided over the frequency band of interest. The classical broadband excitation signals for electrodynamic shakers are random and swept-sine signals. While random signals can be used to achieve a quick insight into the structural dynamic behavior at a very low level of input energy, as the total energy is distributed over the entire frequency range of excitation, swept-sine excitation signals are more appropriate to achieve higher response levels.

In practice, the frequency band is automatically split into several subbands, ensuring a constant excitation force amplitude around vibration modes (Figure 19). From this force pattern computation, an excitation template is generated for the sweep-sine, which maximizes the force level, with respect to limitations (maximum acceleration levels, maximum exciter strokes, and maximum voltage of amplifiers). The resulting excitation signal is a swept-sine whose amplitude is modulated over time (Figure 19).

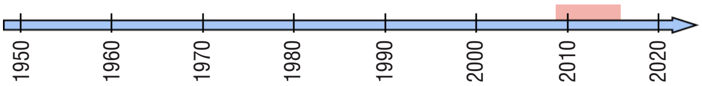
In the context of PSM modal identification, linearity plots, also called impedance plots, have been standardized (Figure 20) to obtain the eigenfrequency and damping coefficient of a mode as a function of the excitation level. This excitation level is given in terms of either a displacement, or the excitation complex power, or a generalized force:

$$P_{Gen} = \sum_{i=1}^{n} p_i u_i / u_{max} \qquad (8)$$

where p_i are the individual forces, u_i are the driving point amplitudes, and u_{max} is the maximum displacement for the target mode.

Figure 20 shows an example of a linearity plot for a control surface mode. Typically, a drop in the eigenfrequency is observed while the excitation level increases and a saturation effect appears at high force and amplitude levels. It is expected to reach this saturation range during the test.

2009 - 2016: A new GVT system, a 21st Century design aircraft and a mature test strategy optimizing productivity



A new GVT system was acquired in 2009, in partnership with the DLR. It occurred with the arrival of new people at ONERA and the DLR to renew and to complete both GVT teams. This new system, able to go up to 768 synchronous channels, is based on LMS SCADAS III 24 bit resolution hardware. The input and output modules are plug and play, the transducer conditioners are embedded in the input modules and, thanks to optical fiber connections between frontends, the architecture can be distributed all around an aircraft. This system runs with LMS Test.Lab and the PolyMAX method is used for PSM modal identification. ONERA and the DLR worked in collaboration with LMS to significantly improve their Normal Modes Testing solution dedicated to PRM.

A research GVT on the first Airbus A340-600 was undertaken in 2011, within a framework founded by the DGAC and LUFO. In this context, new methods and means were developed and new techniques were proposed. One can speak about the use of long-stroke 1000N exciters (dedicated to engine excitation), control surface rotation excitation, taxi vibration testing, fuel sloshing sensor, and new rigid Airbus platforms for exciter support.

On the subject of methods, ONERA developed a new method to optimize sensor placement named ARISPO (Anti-Redundancy Information Sensor Placement Optimization). In the latter, the selection of sensor positions is performed using an algorithm based on the Fisher information matrix, I. This matrix I gathers the weights of possible positions by a sum of modal vector products:

$$I = \sum_{k=1}^{N_s} \Phi_k^T \Phi_k \qquad (9)$$

with Φ_k denoting the kth row of the modal matrix, Φ. Removing or adding a sensor directly yields its contribution to the identification process. It is quantified by a matrix norm of I, generally the determinant.

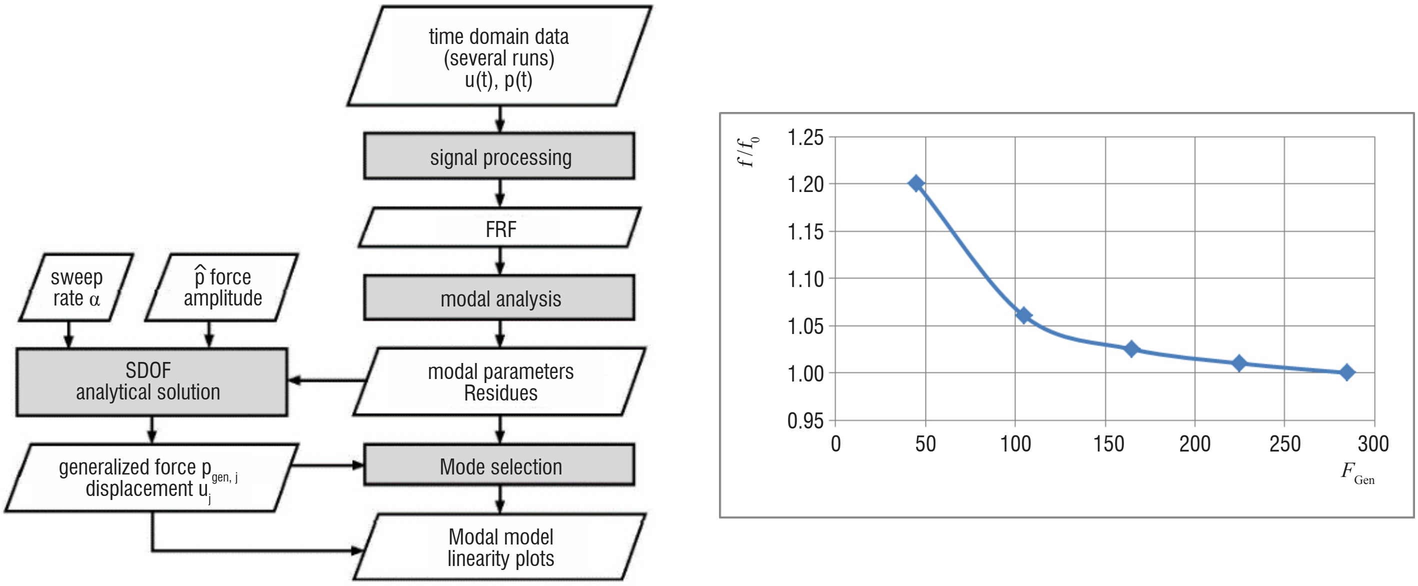


Figure 20 - Computing linearity plots from swept-sine excitations and result example of a control surface rotation mode

In practice, a set of sensors implies about 400-600 accelerometers. In addition, the planning of sensor placement is made through modal vectors computed by the FEM, which can have several thousands of degrees of freedom (each DOF is a candidate for a sensor). Hence, the number of possible combinations is huge, and it would not be possible to test the Fisher information matrix for all of them.

Furthermore, the Fisher information matrix I does not quantify the amount of information shared by two sensors. We proposed in [23] to quantify the redundancy between two potential DOFs by the following formula:

$$R_{kl} = 1 - \frac{\left\| I_k - I_l \right\|}{\left\| I_k + I_l \right\|} \quad (10)$$

If two potential DOFs k and l have a redundancy R_{kl} close to 1, then they are redundant and only one should be kept. If R_{kl} is close to 0, then each of them contributes its own information. This measure is used as a second criterion to select the most relevant placement for sensors.

Finally, we proposed to use an expansion algorithm in two steps:

- Place the next sensor where it maximizes the Fisher information matrix
- Delete those sensors that are redundant with this sensor

This algorithm is stopped when all sensors have been placed on the structure. An example of sensor placement performed with this algorithm is shown for an A340-600 in Figure 21.

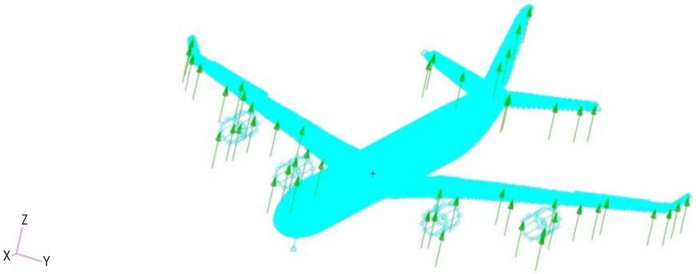


Figure 21 - Example of sensor placement optimization (only Z sensors represented)

In parallel, ONERA also worked on controllability. Two criteria were selected for the optimization of exciter positions. They are aimed at meeting the ONERA quality standards for modal identification:

- A good MIF,
- A significant amplitude.

First, let us define the MIF (Mode Indicator Function). The structural response, Z, for a purely real force vector, F, is given by:

$$Z(\omega) = H(\omega) F(\omega) \quad (11)$$

Where $H(\omega)$ is the frequency response function matrix. Expanding into real and imaginary components and dropping the frequency notation for the sake of clarity, the equation becomes:

$$Z_r + iZ_i = H_r F + iH_i F \quad (12)$$

If a normal mode can be excited at a particular frequency, a force vector F must be found such that the real part Z_r of the response vector is as small as possible compared to the total response. Then, the MIF is computed by:

$$MIF = 1 - Z_r Z^T / \left\| Z \right\|^2 \quad (13)$$

The basic idea is to compute the MIF for different exciter set and different force patterns. The force excitation system that yields the best MIF will be considered as the best one. A force excitation is defined by three characteristics:

- The number of exciters
- The force pattern
- The instrumented degrees of freedom (DOF)

For example, the force pattern is a unit force in the case of an exciter, and can be [1 1] or [1 -1] in the case of two exciters.

If two exciter sets can give similar or very close MIFs, it might not be relevant to choose the one among them that gives the most significant value. As our goal is not to fine tune the mode, but rather to excite it under reasonably good conditions, both of them could be suitable. The highest amplitude criterion should enable us to retain the most robust solution between them. It is expected too that it will help to confirm the exciter sets from previous experiences and from mechanical nous.

An example of such an application is presented in Figure 22 for three exciters. The goal was to reveal the fuselage modes of the A340-600. The algorithm proposed two vertical exciters on the HTP (Horizontal Tail Plane) and a lateral one on the nose landing gear.

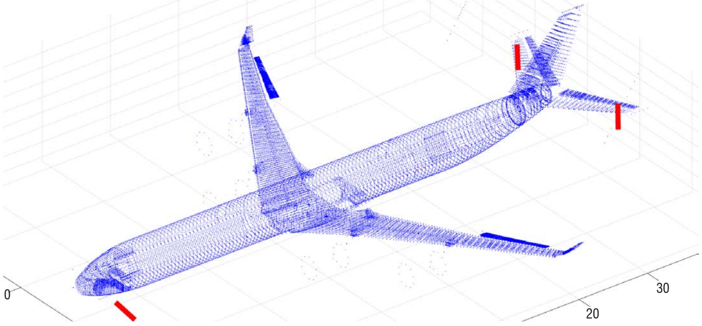


Figure 22 - Exciter placement (red lines) optimized to reveal fuselage modes

Developments were carried out on new excitation stimuli, such as multi-sine sweeps [12], tested during the research GVT on the A340-600. Their benefits have been evaluated in terms of nonlinearity detection, data quality and test productivity. The following combinations were tested:

- Decomposition of the frequency range of a single sweep sine in a combination of two sweep-sine signals running simultaneously in sub-frequency ranges (the complete frequency range covered remains unchanged). The principal objective was to reduce the duration of the acquisition run.

- Cover the same frequency range with two different levels of force (Figure 23). The principal objective was to detect nonlinearities and to have, in the same run, at least two different sets of information (frequency, damping and energy applied) for different modes to build their corresponding impedance curves quicker. Figure 24 shows the results obtained with the SVDP processing for a symmetric excitation. It clearly displays nonlinear behaviors.

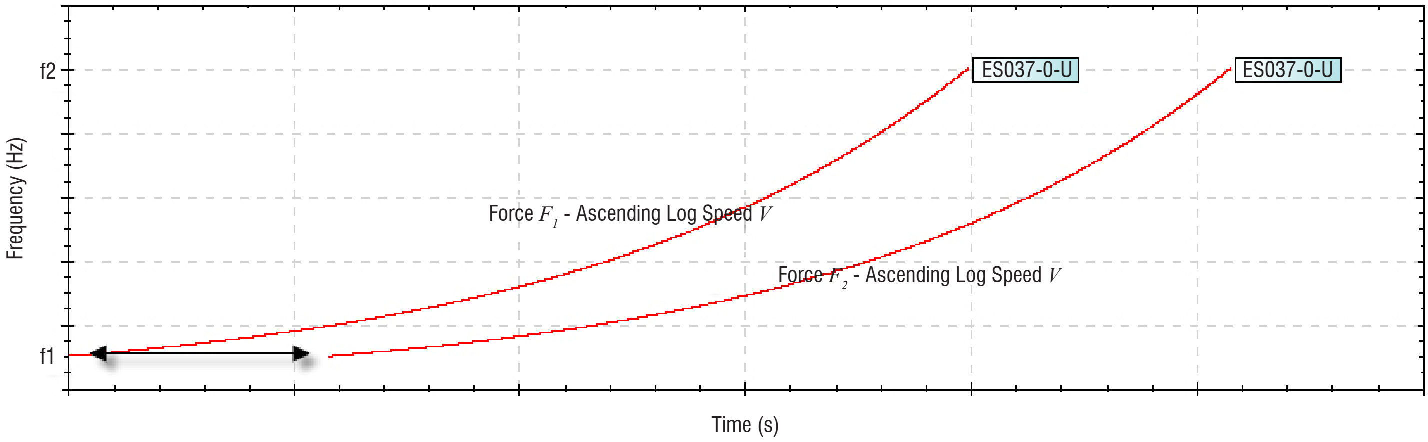


Figure 23 - Sweep sine combination to cover frequency range f_1-f_2 with two different levels of force

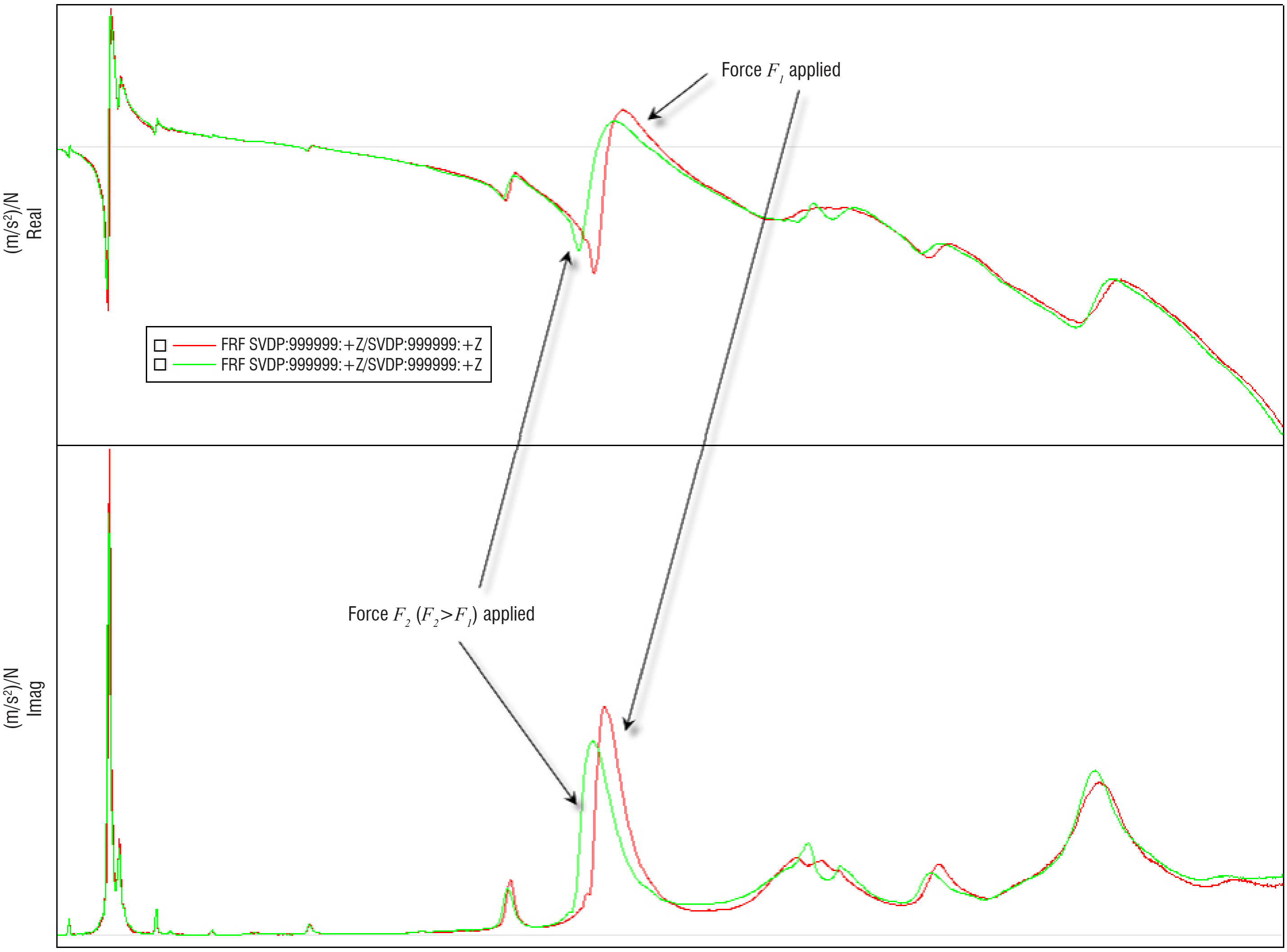


Figure 24 - FRFs of the virtual driving point for each sweep sine of the combination for the symmetric excitation

All of these tools, integrated into the ONERA GVT Tools software suite, are a real benefit to meet the expectations of a modern GVT. The modal model has also been improved, by completing the modal parameter delivery, especially by adding nonlinearity plots for damping.

In 2013, ONERA and DLR performed GVT campaigns for the new Airbus A350 XWB-900 [18] (Figure 25). A first GVT was performed on the first aircraft prototype and a second one on the third prototype exclusively dedicated to the nose landing gear dynamics. The very short time devoted to those test campaigns (9 measurement days for the complete aircraft GVT and 2 measurement days for the nose landing gear GVT) was imposed by a challenging specification from the Airbus A350 XWB FAL (Final Assembly Line), making it necessary to optimize our test strategy.

Figure 25 - GVT campaign of the A350 XWB-900 in Airbus facilities (Toulouse, France)

PSM was used most of the time during the first GVT campaign, since it was the best compromise between time-consumption and mode providing. PRM, known as the most accurate method when non-linear structural behaviors are encountered, was applied for engine modes and for all of the nose landing gear modes of the second GVT campaign.

For speeding up the PSM use, we set up a specific workflow (Figure 26), from excitation signal definition and time data acquisition, to EMA, passing by SVDP and force notching processing. The DLR Correlation Tool was used for data delivery (modal model and non-linearity plots).

In the end, schedules were respected, with 180 modes placed in the final modal model propitious to be used for the FEM updating and flutter computation. Productivity, without any negative impact on quality, was improved (Figure 27 and Figure 28), demonstrating the maturity of our test strategy for GVT campaigns.

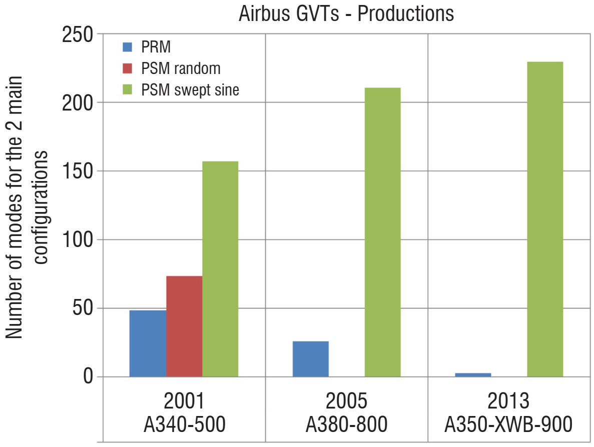


Figure 27 - Diagram of the mode numbers from the different methods for the last major Airbus GVTs

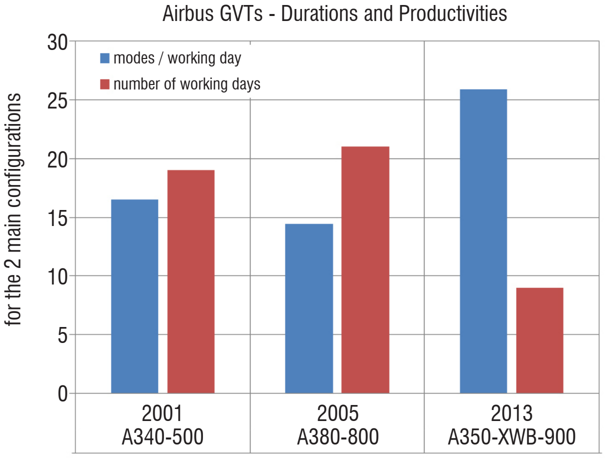


Figure 28 - Diagram of the GVT duration and productivities for the last major Airbus GVTs

In 2014, it was the time for the A320 NEO GVT [25] (Figure 29). The new A320 NEO family incorporates two new engines and sharklets. Here again, schedule constraints (only 7 days dedicated to measurements) and the need for data delivery (mode shapes) quickly after a

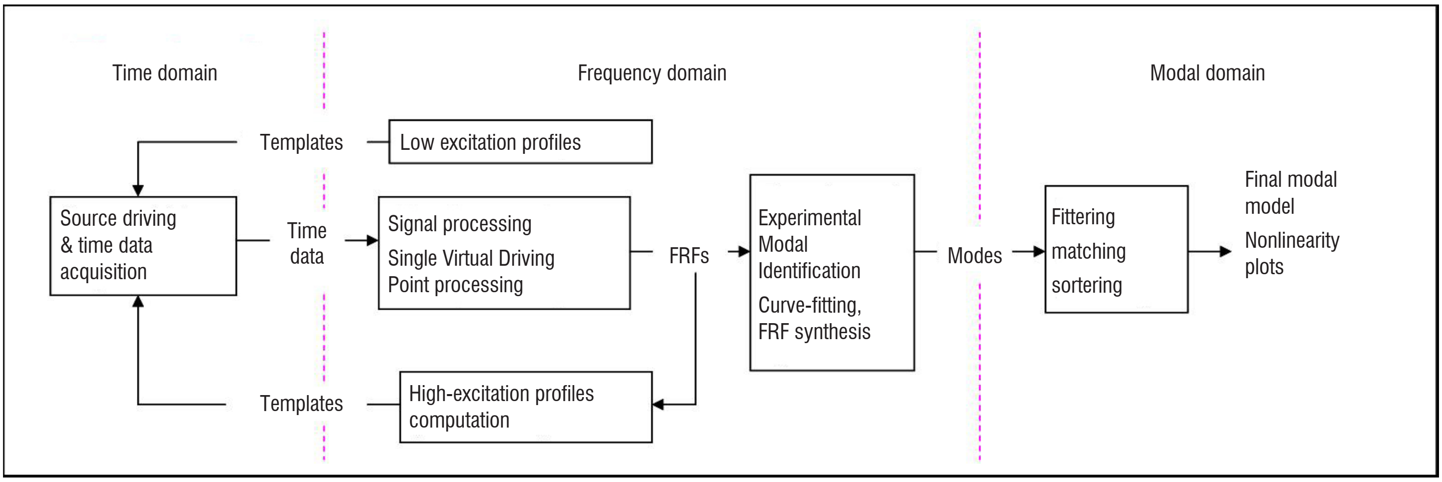


Figure 26 - Data workflow for PSM

measurement (within the following hour) required the improvement of our test techniques and methods.

Figure 29 - GVT campaign on the A320 NEO PW MSN 6101 in Airbus facilities (Toulouse, France)

In order to meet these requirements, the DLR Correlation Tool was improved, giving Airbus the capability to access the current modal model online. During the A320 NEO GVT, the task of modal correlation was a specific challenge, and online access enabled the user to do it on-site. Finally, the huge amount of data was condensed down from about 3321 poles identified from all FRF datasets to only 78 master modes in the final modal model for the main configuration.

In addition, ONERA and the DLR shared the work progress table of all individual work stations (exciter preparation, data acquisition, modal identification and modal correlation) in an online multi-user access worksheet.

The data acquisition and processing status could be tracked easily by everybody involved in the GVT, including the customer. This visibility allows instantaneous decisions from the customer to orientate the test.

Finally with regard to this test, we can also add that a MIF per component was provided for each mode and that synergy between PRM and PSM results was enhanced to complete our test process (Figure 30). The A320 NEO GVT was completed in time, despite very challenging specifications and with all expected results delivered with the required quality.

Figure 31 - Photogrammetry on the "Paris" aircraft at ONERA (S1Ch, Meudon)

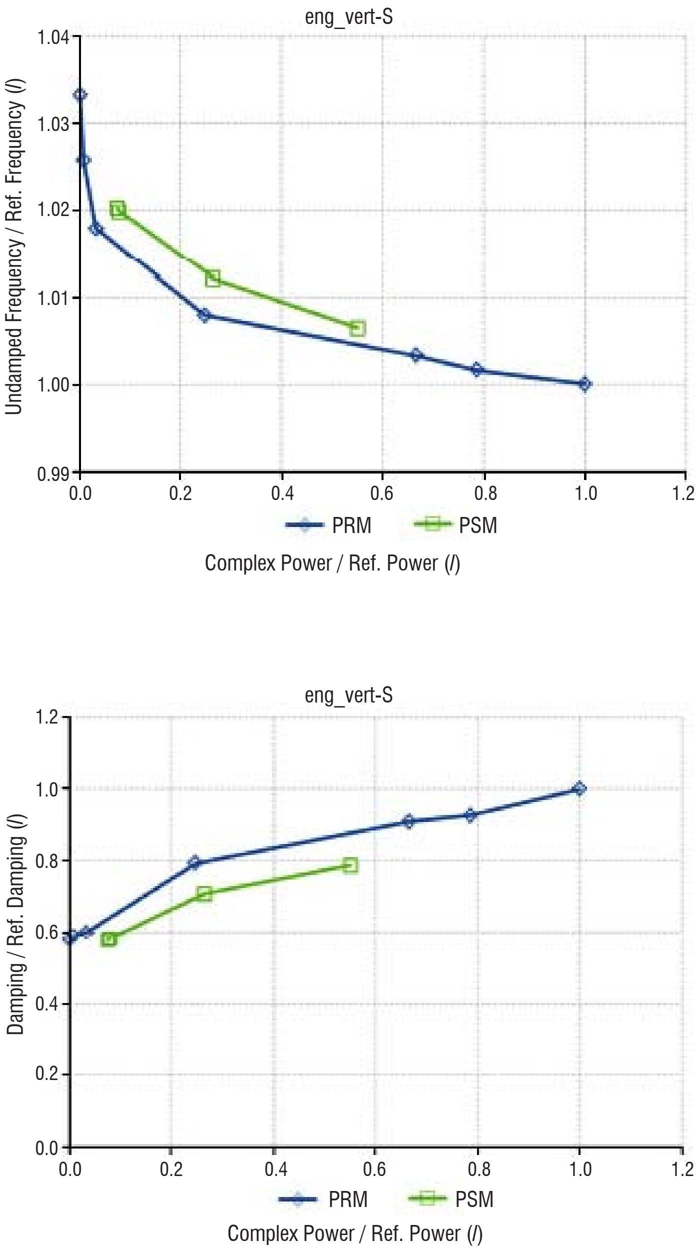
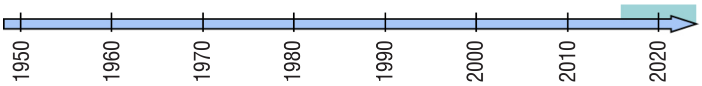


Figure 30 - Example of a comparison between linearity plots for the symmetrical vertical engine mode: PSM and PRM

…and in the future



The ONERA research strategy is closely linked to the current challenges in structural dynamics. This results in:

- A constant enhancement of our tools and means, both software and hardware
  As a matter of technological survey on measurement, we can mention new technologies such as photogrammetry (Figure 31). Recent studies on our Paris aircraft showed promising results but, up to now, far short of the accuracy required at ONERA.

- Data processing: FRF Minimum Variance Method

  In modal analysis, the FRF estimation is generally made through a two-step process: first densities of spectral power (PSDs) are computed using the Welch method (averaged series of periodograms), then these are combined in a least-squares inverse to obtain FRFs. Although this signal processing is now well-mastered, it does not take advantage of the large number of sensors used during a GVT, like spectral methods developed in radar literature. Here we studied the advantages of the Capon spectral method compared to the Welch method [19], [24].

  Contrary to the Welch method, the Capon method estimates all spectra at the same time, not one after the other. In fact, it assumes that, in a set of sensors, noise is uncorrelated among channels. Thus, the more channels there are, the less influenced by noise the FRFs are. Although the difference is not obvious for a set of 5-10 sensors, FRFs are significantly improved for more than 50 sensors. Finally, it is even possible to directly obtain FRFs from signals, skipping the spectra step for computation efficiency, if they are not required for modal analysis.

  An example is presented in the following pictures (Figure 32 and Figure 33) from the GVT of an UAV (Unmanned Aerial Vehicle) named EOLE. 145 sensors and two shakers (one on each rudder) were installed. It can be observed that FRFs are significantly less noisy using the Capon method.

Figure 32 - EOLE UAV GVT (CNES, ONERA, Aviation Design, PERSEUS Student Project www.onera.fr\focus\eole)

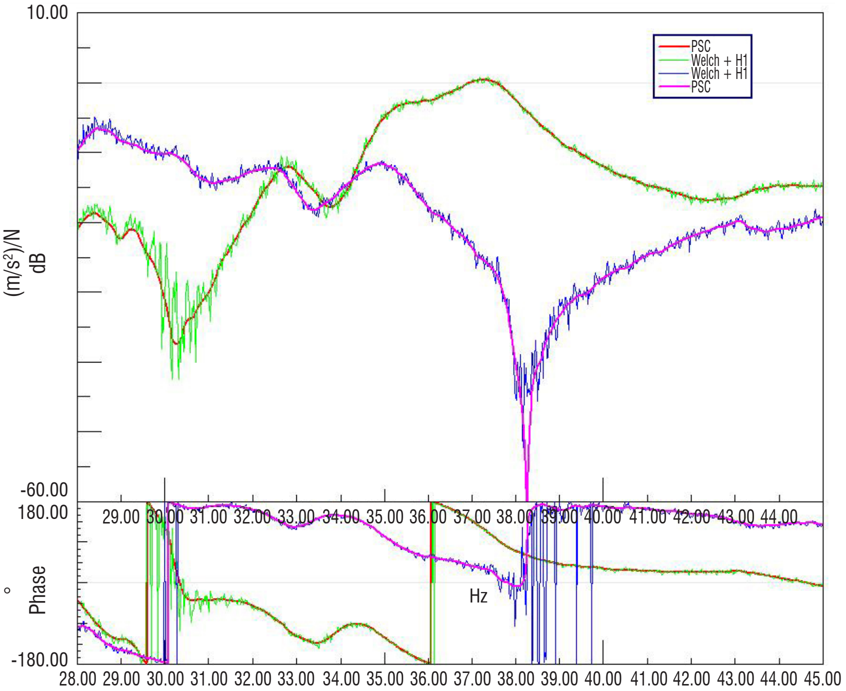


Figure 33 - FRFs computed through Welch signal processing (green and blue curves) and Capon method (red and magenta curves)

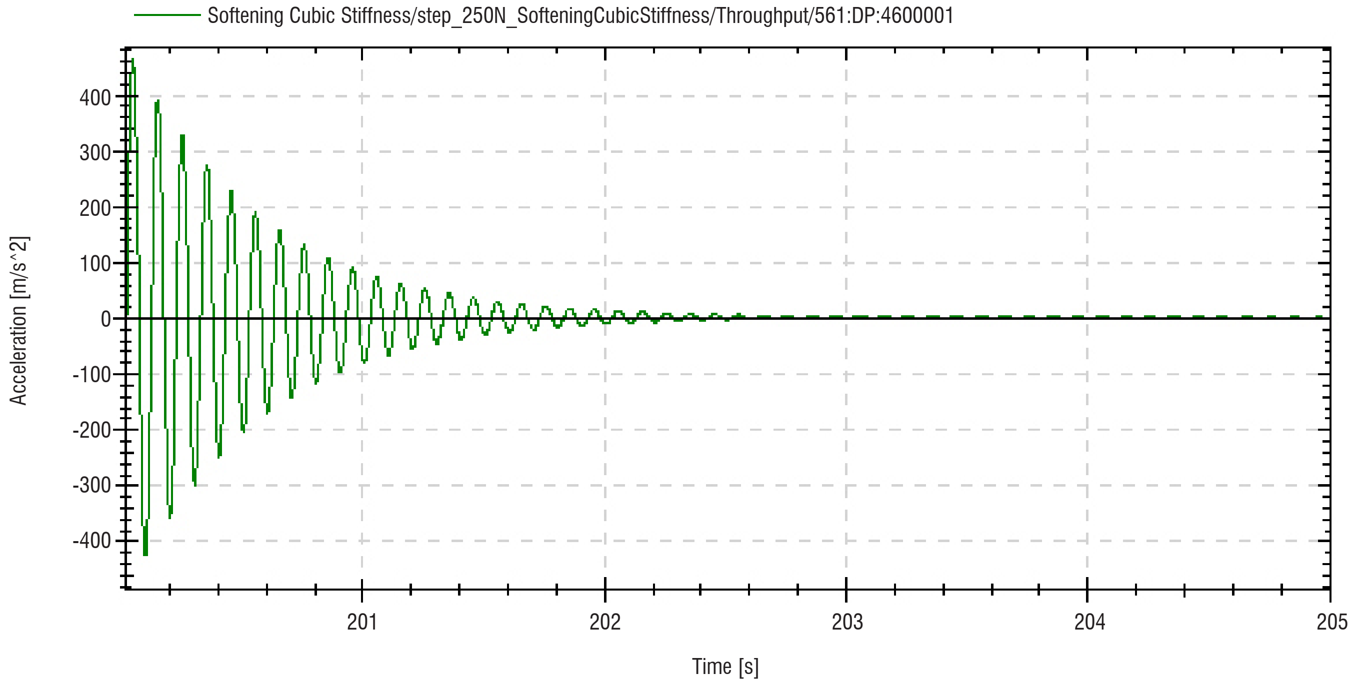


Figure 34 - Time response of a static relaxation

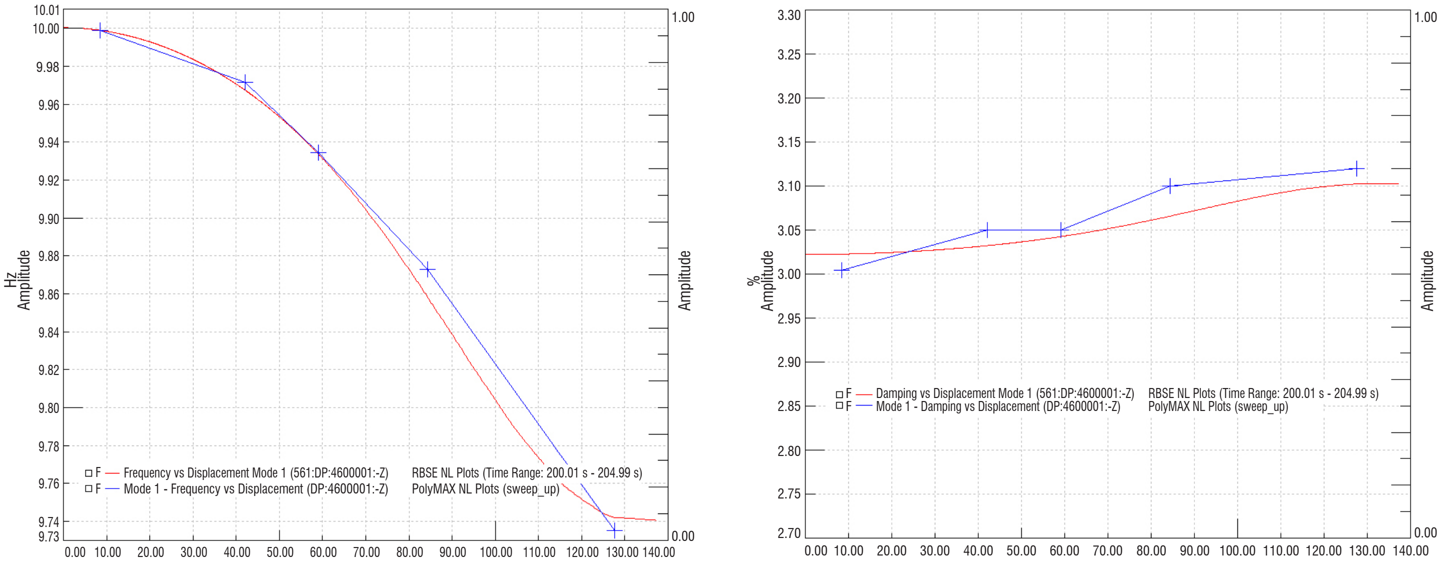


Figure 35 - Nonlinearity plots (frequency and damping) with PSM (cross in blue) and RBSE (line in red)

- Data analysis: Recursive Bayesian-Stephan Estimation
  ONERA is also working on the RBSE (Recursive Bayesian-Stephan Estimation) method. An original method was proposed in [26] for the identification and the tracking of poles of a weakly nonlinear structure from its free responses. Let us consider a structure harmonically excited close to a resonance frequency. Suddenly the excitation is shut down. We suppose that its free response will reveal the whole dependency of its modal parameters (frequency and damping) during its decrease. Then, the idea is to process the measured signals and to extract this dependency from them.

This signal processing method is based on a model of multi-channel damped sines whose parameters evolve over time. Their variations are approximated in discrete time by a nonlinear state space model. States are recursively estimated by a signal process that couples a two-pass Bayesian estimator with an EM (Expectation-Maximization) algorithm. An iterative procedure between them allows an accurate and robust tracking of poles. As a result, equivalent modal parameters such as frequency and damping are obtained as functions of amplitudes.

An application of this method to a nonlinear (cubic stiffness) 1 DOF system is shown below (Figure 34 and Figure 35). We can see that the evolution of modal parameters given by this technique is close to the values obtained by classical curve-fitting of FRFs.

This method has been also applied to a real fan blade specimen. Comparison with results obtained more classically with closed loop control step sine is really satisfying (Figure 36).

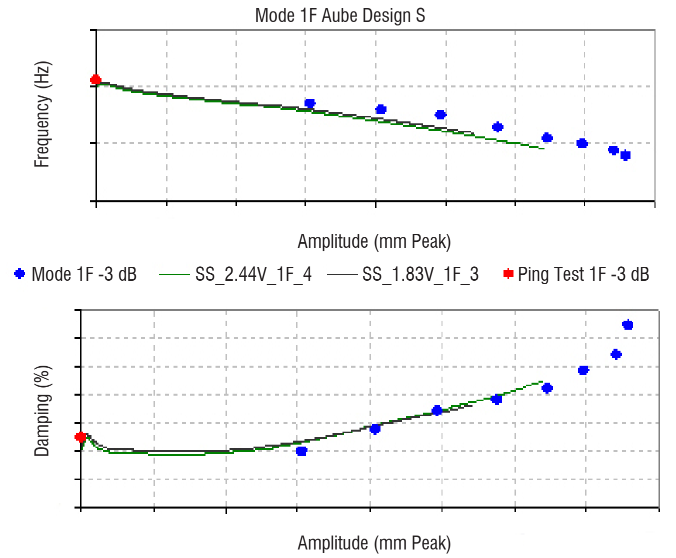


Figure 36 - Linearity plots of a fan blade mode: RBSE (in green), PSM (blue points)

- Nonlinear mode identification
  From the concept of nonlinear modes, new techniques have been proposed by the UL (University of Liège) to compute and to identify invariant manifolds that can gather all of the necessary information for describing the dependency of structures on force levels. Within this framework, ONERA shared the FEM and data tests made on the Paris aircraft with the UL, in order to assess the benefits of nonlinear modes compared to linear ones [16]. Promising results were obtained and work is still in progress to apply them during a GVT.

- Result quality
  Recent developments have been achieved to provide uncertainties on modal parameters from PSM, exhibited between modal synthesis and real measurements. This new piece of information may complement the existing criteria for the selection of the most accurate identification.

Some other research topics should be investigated to apply them in a real industrial context:

- automatic PRM [20],
- combination of external (shakers) and internal (control surfaces) excitation forces,
- productivity and dynamic test program follow up (Real Time Modal Analysis),
- GVT by sub-structuration [3], [14].

With regard to industrial applications, in addition to the long standing and strong cooperation between ONERA and the DLR in performing GVTs for Airbus, in November 2016 ONERA and SOPEMEA signed a partnership to perform GVTs for other aircraft manufacturers, as well as for other sectors outside the aeronautical field.

Conclusion

Throughout its history, Ground Vibration Testing at ONERA has always been strongly related to modal testing and modal analysis, hardware improvements and aircraft innovations. In parallel to the progress made in numerical predictions, several aspects still need to be addressed to render the tests easier, more accurate and more productive. Bearing this in mind, the Morane-Saulnier MS-760 "Paris" aircraft owned by ONERA is a strong advantage for testing new methods and means on an industrial scale.

Quality for identified modes is always linked to the expense of time for testing and data processing. Within the high pressure context of GVT, future studies will be increasingly driven by test purposes, i.e., FEM updating and flutter calculation, in order to balance the involvement of effort and the required accuracy on results. By developing research studies on the one hand, and by enriching the interactions between test suppliers and manufacturers on the other hand, it is the authors' opinion that future GVTs will not only be performed within a still challenging period of time, but will also provide information more focused on the purposes ■

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The authors thank Mr. Marc Rapin, former engineer at ONERA, for his inputs about the history of GVT at ONERA.

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Acronyms

ARISPO	(Anti-Redundancy Information Sensors Placement Optimization)
CTW	(Wasserburg Technical Center (*Centre Technique de Wasserburg*))
DGA	(French Armament Procurement Directorate (*Délégation Générale à l'Armement*))
DGAC	(French Civil Aviation Authority (*Délégation Générale de l'Aviation Civile*))
DLR	(German Aerospace Center (*Deutsches Zentrum für Luft- und Raumfahrt*))
EM	(Expectation-Maximization)
EMA	(Experimental Modal Analysis)
FAL	(Final Assembly Line)
FEM	(Finite Element Model)
FFT	(Fast Fourier Transform)
FRF	(Frequency Response Function)
FQ	(Force in quadrature)
FRF	(Frequency Response Function)
GARTEUR	(Group for Aeronautical Research and Technology in EURope)
GVT	(Ground Vibration Testing)
HP	(Hewlett-Packard)
HTP	(Horizontal Tail Plane)
ICP	(Integrated Circuit Piezoelectric)
LMA	(Applied Mechanics Laboratory (*Laboratoire de Mécanique Appliquée*))
LMS	(Leuven Measurement Systems)
LSCE	(Least-squares Complex Exponential)
LUFO	(German Federal Research in Aeronautics (*Luftfahrtforschung*))
MAC	(Modal Assurance Criteria)
MIF	(Mode Indicator Function)

NEO	(New Engine Option)
ONERA	(The French Aerospace Lab (*Office National d'Etudes et de Recherches Aérospatiales*))
POD	(Proper Orthogonal Decomposition)
PRM	(Phase Resonance Method (also called Modal Appropriation, Modal Tuning, Normal Mode Testing))
PSM	(Phase Separation Method (also called Global Method))
RBSE	(Recursive Bayesian-Stephan Estimation)
SIMO	(Single Input Multiple Output)
SDRC	(Structural Dynamics Research Corporation)
SDRL	(Structural Dynamics Research Lab)
SVDP	(Single Virtual Driving Point)
TEDS	(Transducer Electronic Data Sheet)
UAV	(Unmanned Aerial Vehicle)
XWB	(eXtra Wide Body)

Nomenclature

Z	Displacement at one location of a structure
$\dot{Z}$	Velocity at one location of a structure
$\ddot{Z}$	Acceleration at one location of a structure
$[M]$	Structural mass matrix
$[C]$	Structural damping matrix
$[K]$	Structural stiffness matrix
$[C_{aero}]$	Aerodynamic damping matrix
$[K_{aero}]$	Aerodynamic stiffness matrix
V	Velocity of a structure in a fluid
F	Excitation force
$f\left(Z,\dot{Z}\right)$	Restoring force
$[H_1(\omega)]$	H_1 estimator FRF matrix
$[P_{ZZ}(\omega)]$	Output power spectral density matrix
$[P_{ZF}(\omega)]$	Input-output power spectral density matrix
CP	Complex power
P_{Gen}	Generalized force
p_i	Individual force at excitation point i
u_i	Individual amplitude at excitation point i
u_{max}	Maximum displacement amplitude
I	Fisher information matrix
Φ_k	kth row of the modal matrix
R_{kl}	Redundancy between DOFs k and l
PRM	Phase Resonance Method (also called Modal Appropriation, Modal Tuning, Normal Mode Testing)
PSM	Phase Separation Method (also called Global Method)

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