AIRBUS A350 XWB GVT - State of the art techniques to perform a faster and better GVT Campaign.

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T I R É À P A R T

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AIRBUS A350 XWB GVT: Etat de l'art des techniques pour réaliser une campagne plus rapide et meilleure.

par

P. Lubrina, S. Giclais, C. Stéphan, M. Boeswald *, Y. Govers *, N. Botargues **

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Résumé traduit :

En avril et mai 2013, les spécialistes de l'équipe conjointe de l'ONERA et du DLR ont réalisé les campagnes d'essais de vibration au sol du nouvel AIRBUS A350 XWB conçu en composite. La première campagne fut réalisée sur le premier prototype d'avion pendant 9 jours de mesures. La seconde campagne quant à elle fut réalisée durant 2 jours de mesures sur le troisième prototype, avec pour objectif unique la mesure de la dynamique structurale de l'atterrisseur avant.

La très courte période dévolue à ces campagnes d'essais, imposée par un emploi du temps strict et chargé de la FAL (Final Assembly Line) d'Airbus, a conduit à adapter les techniques de test et à mettre en place un flux de travail optimisé pour respecter le cahier des charges du test.

La forte coopération entre les équipes d'AIRBUS, de l'ONERA and du DLR a permis de réaliser la plus courte campagne d'essai de vibration jamais faite sur un avion long-courrier. Le programme de test impliqua la mise en oeuvre des méthodes d'extraction modale et d'appropriation modale, propices à l'évaluation des comportements structuraux non-linéaires. Grâce notamment à un nouveau système de gestion de base de données, la base modale la plus riche de ces trente dernières années fut obtenue et livrée.

Cet article décrit les processus mis en œuvre et les méthodes appliquées dans ce contexte particulièrement difficile et comment ceux-ci ont contribué à la réussite de ces campagnes d'essais.

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AIRBUS A350 XWB GVT: State-of-the-art Techniques to Perform a Faster and Better GVT Campaign

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ABSTRACT

In April and May 2013, the ONERA-DLR specialized team has performed the GVT (Ground Vibration Testing) campaigns of the new composite design AIRBUS A350 XWB. The first GVT was performed on the first aircraft prototype with duration of 9 measurement days. Another GVT was performed within 2 measurement days on the third prototype with focus on the nose landing gear dynamics.

The very short time devoted to those test campaigns, imposed by a strict and busy planning from AIRBUS A350 XWB FAL (Final Assembly Line), required to adapt test techniques and methods and an optimized workflow to meet the challenging test requirements.

A strong synergy between AIRBUS, ONERA and DLR teams allowed performing the shortest GVT campaign on a long range aircraft never before realized. The test program involved mixing PSM (Phase Separation Methods) and PRM (Phase Resonance Methods), addressing nonlinear behaviours. Due to novel database systems, the most complete modal model database ever delivered was obtained.

This paper is devoted to describe the processes followed and the methods used in this particularly hard context and how those contributed to the successful achievement of this demanding test campaign.

Keywords : Ground Vibration Testing, structural nonlinearities, modal identification, Phase Separation Method, Phase Resonance Method

1. Introduction

In April and May 2013, the ONERA-DLR specialized team has performed the GVT (Ground Vibration Testing) campaigns of the new composite design AIRBUS A350 XWB. The first GVT was performed on the first aircraft prototype with duration of 9 measurement days. Another GVT was performed within 2 measurement days on the third prototype with focus on the nose landing gear dynamics.

The very short time devoted to those test campaigns, imposed by a strict and busy planning from AIRBUS A350 XWB FAL (Final Assembly Line), required to adapt test techniques and methods (ref [1], [2], [6] notably) and an optimized workflow to meet the challenging test requirements. If the PSM (Phase Separation Method) was the main method used, some modes were measured thanks to the PRM (Phase Resonance Method).

Fig. 1 : Artist view of the A350-XWB-900

2. Airbus A350-XWB-900 description

The A350 XWB is an all new family of mid-sized wide-body twin-engine airliners to shape the efficiency of medium-to-long haul airline operations, overcoming the challenges of volatile fuel prices, matching rising passenger expectations and addressing increasing environmental concerns.
The A350 XWB Family consists of three passenger versions with true long-range capability of flying up to 8,500nm/15,580km. The current paper deals the first Ground Vibration Test of the family done on the intermediate version (-900: 314 seats in a typical three-class configuration).

A350-XWB-900 characteristics

Dimensions		**Capacity**		**Performance**	
Overall length	66.89 m	Pax typical seating	314 (3 classes)	Range	15 000 km 8 000 nm
Fuselage width	5.96 m	Freight :		Mmo	Mach 0.89
Max cabin width	5.61 m	LD3 capacity underfloor	36	Max Take Off Weight	268.0 t
Wing span (geometric)	64.91 m	Max pallet number underfloor	11	Max Landing Weight	205.0 t
Height	17.05 m	Bulk hold volume	11.3 m^3	Max zero fuel weight	192.0 t
Track	10.60 m	Total volume	172.3 m^3 (LD3+bulk)	Max fuel capacity	138 000 l

The A350-XWB-900 is powered with 2 Engines RR Trent XWB (374 kN each one, 84 000 lbs each one).

The A350 XWB brings together the very latest in aerodynamics, design and advanced technologies. Over 70 percent of the A350 XWB weight efficient airframe is made from advanced materials combining composites (53 percent), titanium and advanced aluminium alloys. The aircraft innovative all new Carbon Fibre Reinforced Plastic (CFRP) fuselage results in lower fuel burn as well as easier maintenance.

From structural dynamics point of view, the vast number of innovations raised a big challenge by moving away from known structures.

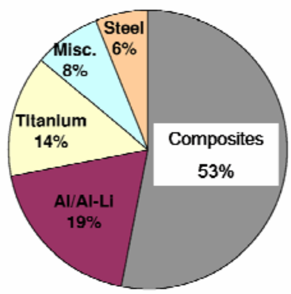

Fig. 2 : A350 XWB Material breakdown

The A350 XWB final assembly has been thought out with efficiency in mind, in order to reduce the assembly time compared to current programmes and to enable a more effective test programme. Elements of the aircraft arrive at the A350 XWB assembly facility – located in Toulouse, France – already equipped and tested. Like a well-planned, high-technology puzzle, the jetliner then comes together through an optimised workflow that moves in steps through several stations within the integration building.
As a full part of this streamlined process, GVT coming just before painting, it had to guarantee an optimised workflow fully integrated to the assembly line.

3. GVT general specifications

GVTs have been performed on first A350XWB prototypes. Tests were on the critical path of the programme. Impact on planning has been reduced to the very minimum thanks to an optimised workflow and to enhanced integration with Final Assembly Line (FAL). At the end:

- First aircraft MSN was exclusively dedicated to main vibration testing during 9 days from 7am to12pm 7/7.
- Nose Landing Gear testing has been performed over a week-end.
- FAL working parties were resumed during remaining night shifts.

During this reduced and fixed timeframe, the GVTs had to address two fuel mass configurations, several hydraulic configurations for control surfaces and several Nose Landing Gear configurations (steering system, shock absorber lengths).

For each configuration, key dynamic structural properties had to be identified:

- eigen-frequencies,
- mode shapes,
- generalized mass & damping,
- transfer function,
- structural non-linear behaviour.

Measurement and Excitation strategies had both:

- to be optimised to fit with the strong time constraint,
- to be adjusted live taking into account encountered structural specificities:
    - to remain in acceptable levels versus structural/hardware limitations,
    - to provide the best measurement quality.

Modal data were directly post-processed and were analysed on site to allow live trouble shooting and early model calibration.

4. GVT equipments

For conducting such a GVT, it is mandatory to have enough equipment for vibration excitation and for measurement of vibration response. Due to the size and weight of an aircraft, the frequency range considered is typically low. Except for special purpose measurements, the upper frequency limit of excitation has been in this case not higher than 50 Hz. The lower limit of the frequency range depends on the suspension characteristics. Except for dedicated measurements for the identification of eigenfrequencies of rigid body motion, the lower frequency limit of the measurements was around 1 Hz. Consequently, the shakers used have a long coil stroke to excite at such low eigenfrequencies with sufficient excitation force.
For FRF measurements, swept-sine excitation with multiple shakers has been used. The excitation forces are typically selected for symmetric or anti-symmetric excitation.
For this purpose, the power amplifiers driving the shakers should have "Zero-Phase" characteristic, i.e. no phase shift between drive signal input to the amplifier and the excitation force output generated by the shaker. Without zero-phase characteristic, it would be difficult to realize symmetric or anti-symmetric excitation, especially in excitation configurations where shakers/amplifiers of different type are mixed.
Tripods are required to locate shakers at specific positions on the aircraft. These tripods must be stable enough to carry the shakers and to compensate the excitation force. In addition, they must be capable of fine tuning the relative position of shakers with respect to the aircraft. On the other hand, the tripods must include an elastic degree of freedom propitious to avoid the parasite motion of the shaker due to the possible flexibilities of the tripods, platforms and scaffoldings on which they are installed.

Fig. 3 : View of the aileron exciter (1st GVT)

Fig. 4 : View of the nose landing gear exciters (2nd GVT)

For risk mitigation purposes, the excitation forces are measured twice with different measurement principles. Primarily, the excitation forces are measured using piezo-electric force sensors installed at the excitation points of the structure. In addition, the excitation forces are measured using the coil current provided by the shaker power amplifiers. Displacement sensors are used to measure the relative displacement of the shaker armature in the shaker housing, e.g. for optimization of excitation

force signals in the very low frequency range, where the limitation is not the peak force of the shaker, but the driving point displacement response.
The vibration response is mainly measured in terms of acceleration response using acceleration sensors qualified for the very low frequency range. More than 500 acceleration sensors have been installed for the GVT on A350 and have been measured simultaneously.
The whole data acquisition system was based on ONERA's and DLR's combined LMS Scadas III frontends controlled by the Test.Lab software. Distributed data acquisition has been realized by placing 8 LMS Scadas III frontends around the aircraft. These frontends were connected by fibre-optical cables to allow for data flow in a ring-shaped data bus. The V12-L acquisition modules inside the LMS Scadas III frontends have been used due to their very low cut-off frequency of 0.05 Hz of the analogue high-pass filters. As these modules provide 24-bits accuracy of data acquisition, the time consuming process of acquisition channels range setting is useless.

5. GVT teams

The aircraft access was organized in three shifts. While two shifts were dedicated to vibration testing, the 3rd shift was for the aircraft manufacturer. Therefore the ONERA-DLR GVT team was split into two teams, one for each shift.
A single team consists of several positions.

1. team manager
2. technicians for shaker handling
3. electronics specialists
4. engineers for data acquisition and data checks
5. engineers for modal identification
6. engineers for model correlation

This kind of team setup guarantees a highly efficient GVT performance which is especially relevant since the time slot offered by aircraft manufacturers to conduct such a GVT.

In addition to the excitation equipment necessary to perform the PRM in a good way (number of exciters to be controlled simultaneously) compared to the PSM, it may be noticed another difference between these methods. While the PRM does not require extensive post-treatment and then human resources, the PSM involves a lot of investigations by several specialists in modal analysis to assemble a final modal model in "real time" (see section 7.3).

Fig. 5 : Inside the GVT command room container

6. GVT methods applied

Two complementary kinds of excitation methods were applied during the tests:

- Phase Separation Method (PSM)
- Phase Resonance Method (PRM)

The PSM was used most of the time since it has the best compromise between time-consuming and modes providing (ref [4]). It is basically a curve-fitting of Frequency Response Functions (FRFs) with a linear modal model. FRFs are obtained from applying random or swept-sine excitations, with two shakers in general. Preliminary swept sine excitations at low force or random excitations give a first series of FRFs. Then the Force Notching process, introduced for the Airbus A380-800 GVT in 2005, is applied by knowing these FRFs. Frequency dependent excitation forces are automatically designed by maximizing the force levels over the frequency band, without exceeding maximum levels of acceleration required by Airbus.

For very few excitation force patterns, during the 2nd GVT dedicated to the modal identification of the nose landing gear modes, the multisine simultaneous sweep technique introduced successfully by ONERA and DLR on previous GVT (ref [3]) has been applied.

PRM, the standard method used by ONERA and DLR for aircraft GVTs before 2000, is sometimes considered as an outdated method. Nevertheless PRM is up to now the most accurate and robust method for modal analysis, especially when nonlinear structural behaviours are encountered. Contrary to PSM, PRM aims to make a structure vibrate as a purely real mode by finding the best excitation force pattern; then it gives a snapshot of a mode and does not need any complex mathematical algorithms for post-processing. Accompanied methods such as Force in quadrature and/or Complex Power are applied to evaluate both structural damping coefficients and generalized mass values.

A second asset of PRM is its applicability on highly nonlinear structure. In the case of landing gear dynamics, PSM could not provide any useful results, as FRFs based curve-fitting rely on linear behaviour and cannot take into account strong nonlinear phenomena like multi-harmonic responses or jumps. Even if a kind of linearization could be obtained by applying random excitation, this solution has not been selected during this test as it does not allow significant level of response. Only PRM can be applied because it guarantees that, even if responses show a nonlinear structural behaviour (such as multi-harmonic), identified modes are the best linearizations for a constant level of excitation. Applying PRM for different levels of forces makes an access to the dependencies of eigenfrequency, structural damping and generalized mass with those forces and the amplitudes of structural responses.

Even if PRM could be very time-consuming, it was mandatory to keep the ability to apply it during a test since its precision is worth the effort. During the primary test on full aircraft, three modes were identified by PRM since they involve engines-wings joints which are particularly important for aircraft design. Furthermore, all the nose landing gear modes delivered during the 2nd GVT were obtained by this modal tuning method.

6.1. Data work flow

As a rule; the data workflow is organized according to the nature of data used as inputs. For the PRM, the workflow is simple since only 2 works stations are involved : the first one for the excitation control and measurement, the second one for the post-treatment when necessary.
For the PSM (see following figure), three successive kinds of data are handled: time data such as accelerometers and force cells signals, frequency data (FRFs, auto and cross spectral powers) and finally modes.

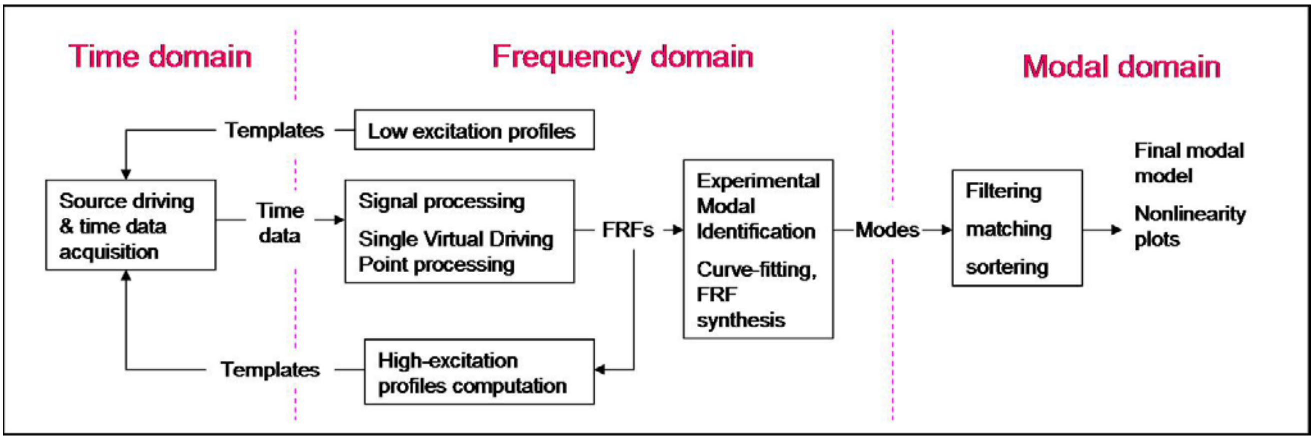

Fig. 6 : Data workflow for PSM

After signals have been acquired, Frequency Response Functions (FRFs) are computed thanks to the Single Virtual Driving Point algorithm. Then a linear modal is obtained by curve-fitting FRFs for each run. All modes coming from these different runs are finally stored into a database and used for forming the final modal model.

In order to be sure that the maximum level of force is applied to the structure, a feedback step in frequency domain aims to compute the best excitation profiles according to FRFs at low excitation.

6.2. Modal identification

Since PSM became the dominant method in GVT, modal identification appeared to be the bottleneck of post-processing. Here modal identification only refers to the curve-fitting process of FRFs by a linear modal model. Even with using mature commercial tools, it is still a challenge to find a satisfying model on experimental data. In fact, there are two effects that explain this situation.

Contrary to PRM, PSM method enables analysts to identify several modes for the same run. As curve-fitting algorithms have become more robust, it is now possible to find “high-frequency” modes, i.e. modes above main structural modes. Hence a balance is achieved between the time saved during curve-fitting, and the time devoted to these modes which were not analysed in previous GVTs.

As a consequence, there was the counterintuitive need to increase human resources significantly for curve-fitting process, as more and more modes were identified during GVT.

7. ONERA DLR Specific tools

7.1. Force Notching

The force notching is used for maximizing the level of force excitation provided over frequency band (ref [3]). It relies on previous knowledge of structure dynamics, such as FRFs obtained at a low level of force excitation. By using the relation between input and outputs given by FRFs, it is possible to compute a maximum level of force for each frequency. In practice, the frequency band is automatically split into several sub-bands (see following figure on the left), according to amplitude evolution of FRFs. With 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, maximum voltage of amplifiers). The resulting excitation signal is a swept-sine whose amplitude is modulated over time (see following figure on the right).
The new version of the LMS Test.Lab software makes easy the use of computed excitation stimuli files.

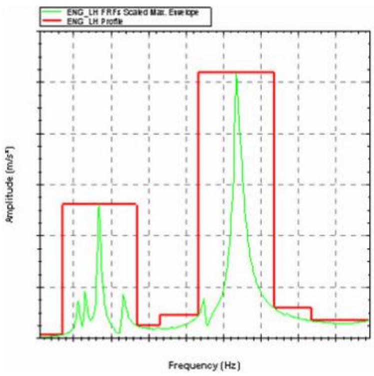

Fig. 7 : Maximizing level of force excitation over frequency range

Fig. 8 : Example of amplitude-modulated excitation signal

7.2. SVDP: Single Virtual Driving Point

In general, for an aircraft, swept-sine excitations are either symmetric or antisymmetric forces applied with two shakers. As forces are in this case by definition correlated, it is not possible to use the H1 estimator on data directly

$$H_1(\omega) = P_{XX}(\omega) P_{XF}^{-1}(\omega)$$

where $P_{XX}(\omega)$ and $P_{XF}(\omega)$ are respectively the output and input-output densities of spectral powers.

One solution consists to build augmented matrices from the combination of all runs, for instance two runs in the case of symmetric and anti-symmetric excitations. Although it is mathematically correct, here the Single Virtual Driving Point (SVDP) process is preferred since it allows the use of existing Single Input Multiple Outputs (SIMO) processing on each run (ref, [3], [5], [7]). The SVDP defines a mathematical construction of a virtual driving point, which would have given rise to vibratory responses strictly similar to those obtained with correlated forces. SVDP relies on the equivalent complex power

$$P(\omega) = \sum_{shakers} F_s(\omega)\dot{X}_s(\omega)$$
$$P(\omega) = F_V(\omega)\dot{X}_V(\omega)$$

where $F_s(\omega)$ is a excitation force acting on a driving point s, $\dot{X}_s(\omega)$ the velocity at driving point s, $F_V(\omega)$ the virtual force and $\dot{X}_v(\omega)$ the velocity response of the virtual driving point. Once the SVDP process has been applied, SIMO FRFs are obtained and classical curve-fitting can be directly used on them.

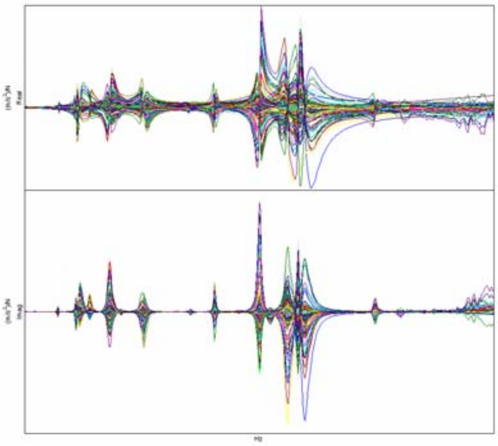

Fig. 9 : Example of FRFs for all accelerometers (imaginary and real parts)

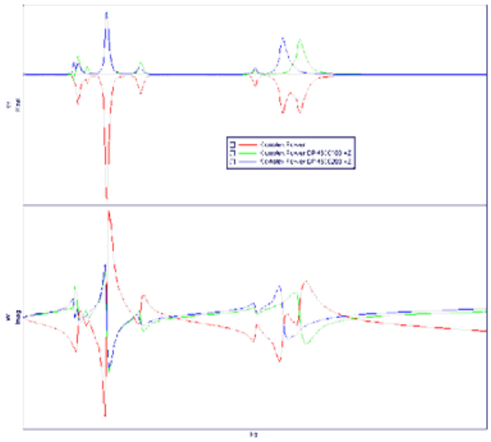

Fig. 10 : Example of FRFs : the real driving points (blue and green curves) and the SVDP (red curve)

7.3. Modal model assembly

Considering a linear structural behaviour, it would be sufficient to use only very few excitation points to excite all modes of an aircraft. However the practical application shows that several excitation configurations are needed during GVT: vertical and lateral engine excitations, vertical and axial wing excitations, HTP excitation, VTP excitation… The general goal is to put as much energy as possible per mode, i.e. to increase the level of generalized force until maximum per mode. These numerous tests are mandatory for optimising the reliability of experimental modal model and taking into account nonlinear structural behaviour. In practice, for each excitation configuration, several runs are performed at different levels of excitations. From all these runs, each structural mode can be identified a significant number of times. During the modes sorting and filtering process, the whole set of modes identified by curve-fitting is carefully analysed by structural engineers and sorted by nature.

All identified modes are stored into a database system with multi user access. Each mode is stored not only with its modal properties but also with numerous fields containing meta information. A specially designed software tool called "Correlation Tool" was developed to review the modes in the database. The Correlation Tool can be installed on different computers, even on the customer computer to give online access (read only) to the current modal data.
One feature of this database software is that modes which have been identified from different FRF datasets with almost identical properties can be grouped in a mode family based on MAC correlation. For each family, the most representative mode is selected as a member of the final modal model delivered to Airbus. To support the process of correlation of modal datasets and finally the generation of the final modal model different quality indicators and other criteria are applied, for example, level of excitation, generalized force and value of Mode Indicator Function (MIF) are used here. The concept of mode families can also be applied to evaluate scatter on test results or even to analyse the results in terms of non-linear behaviour. If the members of a mode family are considered to be reliable enough (i.e. confidence in the results assessed by quality indicators), they can become affiliated to a "master mode" and their damping ratios and eigenfrequencies can be plotted as a function of force level or other parameter of the database. In this GVT, the work of modal correlation was a specific challenge. Finally, the huge amount of data was condensed down from about 2600 poles identified from all FRF datasets to only 180 master modes in the final modal model for the main configuration. For sure, this correlation work had to be performed in a short period of time leading to specific requirements of the graphical user interface ergonomics.

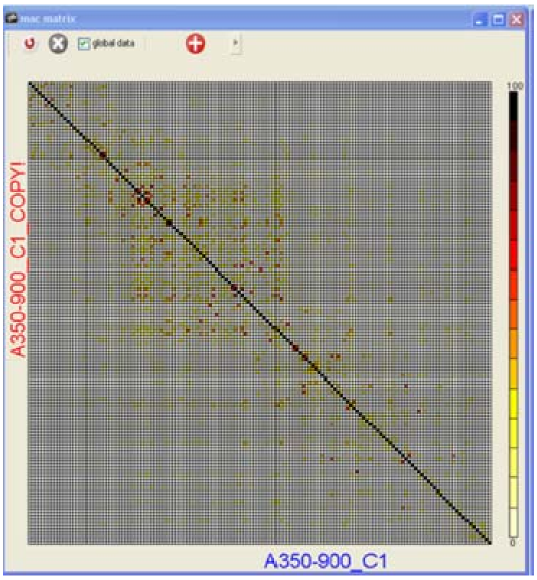

Fig. 11 : Auto-MAC matrix

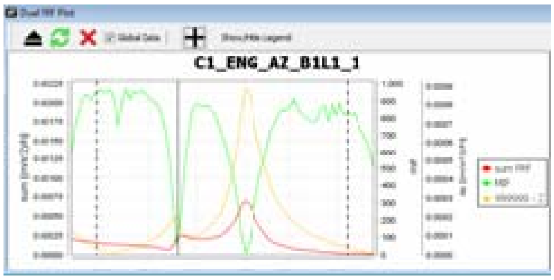

Fig. 12 : MIF and SVDP FRFs of the run analysed

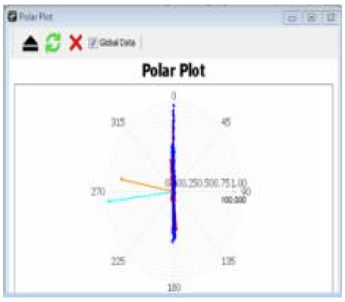

Fig. 13 : Polar diagram of one selected mode shape

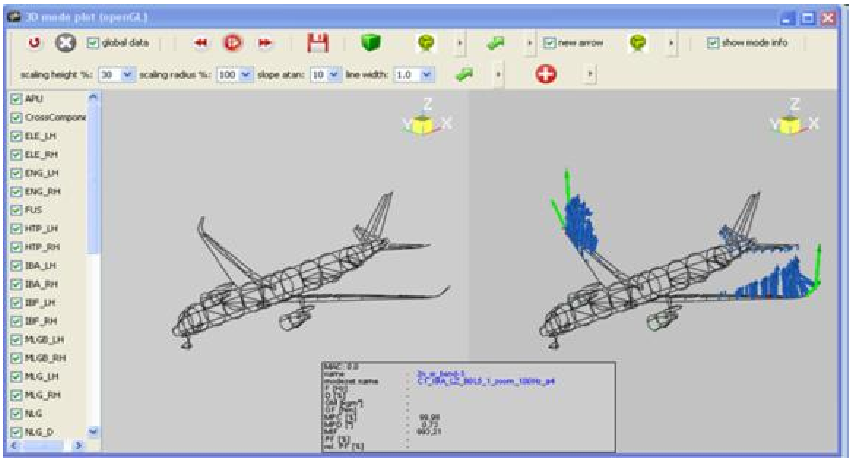

Fig. 14 : Dual mode shapes plot

Fig. 15 : Linearity plot (resonance frequency and structural damping ratio / Generalized excitation Force)

7.4. PRM environment

Even if this method is test time consuming and needs many exciters to be installed and controlled simultaneously, the faculty of this traditional modal tuning method to deliver reliable "local" modal parameters in case of significant non linear structural behaviour (here "local" means for a certain excitation force level introduced in the structure) has motivated its use for only three engines modes during the 1st GVT but for all the nose landing gear modes identified during the 2nd GVT.
In addition to the know – how transferred by ONERA and DLR to LMS for a better performance of the Test.Lab NMT (Normal Mode Testing) workbook, other developments, such as multi-Lissajous ellipses preparation, complex power and force in quadrature corrections, were carried out to make the pre-test and post-test works easier in using the PRM technique.

8. Results

For the main configuration tested (empty fuel) performed in 7 working days, we consider as modal identification inputs the 143 excitations runs performed from 23 excitation force patterns. These ones are mainly symmetrical and anti-symmetrical forces. The frequency band [1:50 Hz] was divided in 2 sub-bands, and for each sub-band at least 2 force levels were applied. Furthermore, very low frequency excitations were dedicated to rigid body modes and higher frequency bands up to 80Hz were applied on engines for sustained engine imbalance purpose.
For the main mass configuration, those modal identifications provided approximately 2600 poles. From this set of poles, 975 modes were reliable enough to be kept and to contribute to linearity plots. Finally 180 of them, including rigid body modes, were considered as master modes and constitute the modal model propitious to be used for the FEM updating and flutter computation. It may be noticed that excitation runs performed from engines Y and Z and wings X and Z provided the majority of modes.
For the second mass configuration, wing tanks were partially filled. Although only one working day was dedicated to it, there were enough runs to identify 50 master modes in the modal model of this mass configuration.

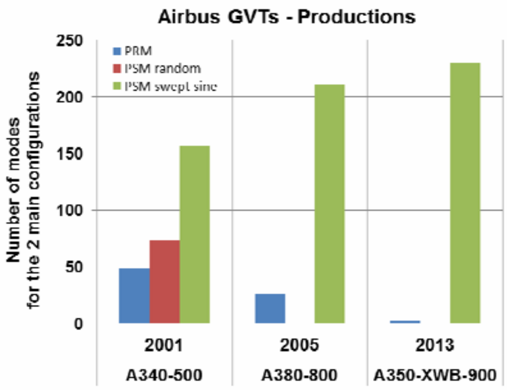

Fig. 16 : Diagram of the modes numbers from the different methods for the last major Airbus GVTs

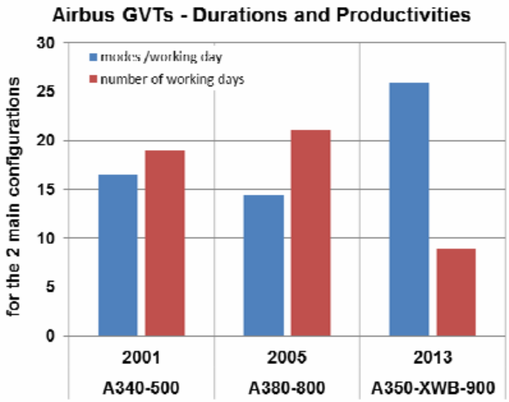

Fig. 17 : Diagram of the GVT duration and productivities for the last major Airbus GVTs

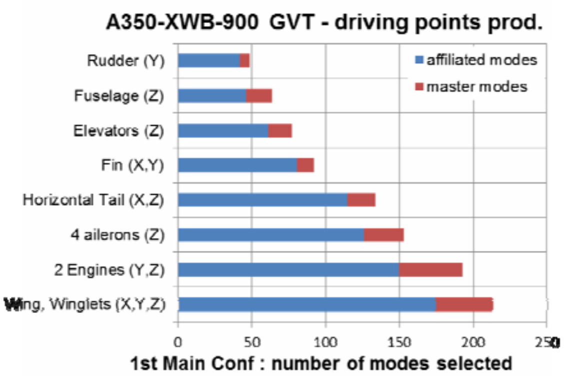

Fig. 18 : Diagram of the mode productivities of the different driving points

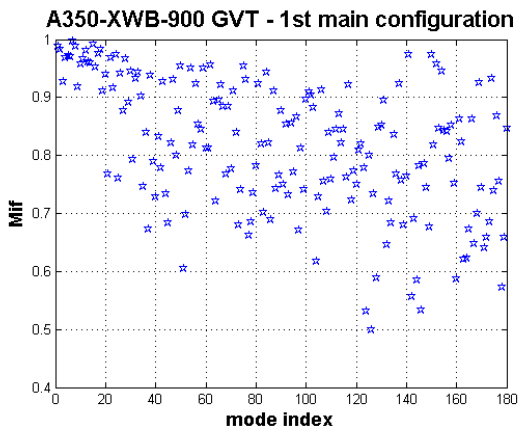

Fig. 19 : MIF values of the 180 modes delivered

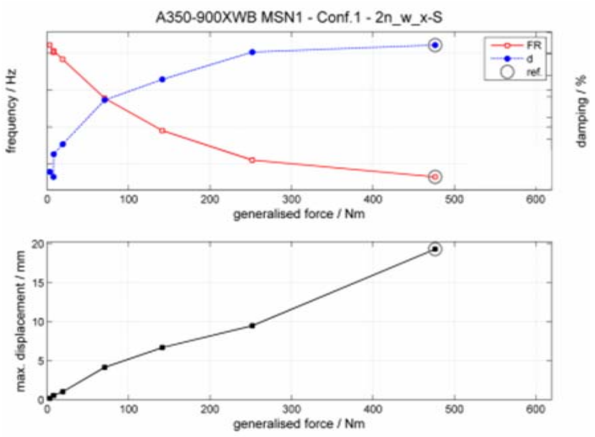

Fig. 20 : Example of linearity plot

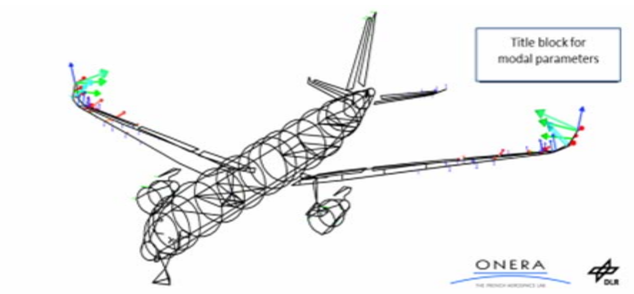

Fig. 21 : Example of mode shape plot

9. Conclusions

Ground Vibration Test is a major milestone on the critical path of aircraft development process. It is performed for several goals. First of all, it delivers the modal model which can be used for flutter predictions and model updating. The results of computation are then a support for first flight safety and allow a fast flight domain opening. And finally, they serve as means of compliance in front of Airworthiness Authorities.

The success of such a test relies on several complementary aspects. High-end test hardware and best in class customized software were developed, implemented and used for productivity and quality. Innovative methods and optimized data-flow inspired from production line enables a time reduction without decreasing the amount of data. And, of course, the human factor is also a strong feature during a test. A highly skilled, integrated and flexible team was particularly involved during this test, and their work is directly linked to the quality of delivered results. Thanks to all these elements, the A350XWB GVT has been fulfilled in a record time, with respect to very challenging specifications and with all expected results delivered in required quality.

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