Airbus Beluga XL State-of-the-art Techniques to Perform a Ground Vibration Test Campaign of a Large Aircraft

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AIRBUS BELUGA XL STATE-OF-THE-ART TECHNIQUES TO PERFORM A GROUND VIBRATION TEST CAMPAIGN OF A LARGE AIRCRAFT

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Abstract: After the completion of the Airbus A350 XWB 900 Ground Vibration Test (GVT) in 2013 and the A320 NEO GVT in July 2014, the ONERA-DLR joined team performed the GVT of the new BelugaXL aircraft in May-June 2018. The test was completed in 8 measurement days for 2 mass configurations, thanks to efficient methods and tools. The originality of this structure comes from its very large fuselage and its rear section with two large additional vertical planes, which made the modal identification particularly challenging. This paper describes the process followed, the methods used, and the interactions with engineers in charge of aeroelastic computations during the test, and how they allowed the success of this campaign.

1 INTRODUCTION

The joint team from the French aerospace laboratory ONERA and the German Aerospace Center (DLR) performed the Ground Vibration Test of the new Airbus Beluga XL large transport aircraft in May-June 2018. As for previous tests like on the Airbus A350 XWB 900 in 2013 and the Airbus A320 NEO with Pratt & Whitney engines in 2014 [1][2], the specifications of these tests were particularly oriented to the FEM (Finite Element Model) updating for aeroelastic computations. A main challenge of this BelugaXL aircraft GVT (Figure 1) was the excitation and the modal identification of the very large fuselage and the rear section with the two large additional vertical planes, called Auxiliary Fins, on both sides of the horizontal tail plane.

Figure 1 : Airbus BelugaXL during Ground Vibration Test

Figure 2 : Right auxiliary fin

To succeed in the completion of the ambitious technical demands, new modal exciters with very large coil strokes and seismic exciters were used. Recent improvements on developed excitation methods and post-processing tools were applied. This paper describes the test equipment, the processes followed and the methods used in this particularly hard context and how those contributed to the successful achievement of this challenging test campaign.

2 BELUGA XL DESCRIPTION

The BelugaXL program was launched in November 2014 to address Airbus' transport capacity requirements in view of the A350 XWB ramp-up and Single-Aisle production rate increases. Six aircraft will be built between 2019 and 2023 to gradually replace the five BelugaST. The aircraft will operate from 11 destinations as Airbus' method of transporting large aircraft components.

Based on an A330-200 Freighter, the BelugaXL is highly modified with the lowered cockpit, the cargo bay structure and the rear-end and tail, giving the aircraft its distinctive look (Figure 3). This new Airbus oversize transport aircraft is tailored to carry large airframe components such as twin wings of A350 or simultaneous fuselage sections of A350 with sections of Single-Aisle family. The BelugaXL cross section (more than 8m) is much bigger than those of all existing cargo aircraft. The BelugaXL is powered by Rolls Royce Trent 700 engines.

The first aircraft specimen performed its maiden mission from Toulouse (France) on the 19th of July, 2018.

Figure 3: BelugaXL aircraft

3 GENERAL OVERVIEW OF TEST REQUIREMENTS

3.1 Planning, structural configurations and specifications

The Ground Vibration Test was performed on the first manufactured BelugaXL in Airbus facilities in Toulouse (France) six weeks before its first flight. With respect to the high level of technical demands specified and the industrial planning, only 8 measurement days for 2 mass configurations were scheduled. In this late phase of aircraft development, the time slot for such a test is very short. For this reason it required a very efficient GVT organization.

The aircraft was placed on the Airbus pneumatic soft suspension devices typically dedicated to long range aircraft, to decouple rigid body modes from flexible ones (Figure 4). Due to the particularity of the font part of the fuselage and the use of standard landing gears for this aircraft, adaptations (elevations) of the main landing gear suspension device were designed and made by Airbus.

Figure 4 : Main landing gear air spring suspension devices

Figure 5: HPJ (orange structure) put in the fuselage

During the time frame, the GVT had to address two mass configurations:

- Structural configuration 1 (C1) - light aircraft, empty fuselage
- Structural configuration 2 (C2) - High Platform Jig (HPJ) in the fuselage

Both configurations were empty of fuel. The control surfaces were set in neutral position (direct law with no feedback).

For this campaign, the objectives were to obtain the modal characteristics of the complete aircraft and its control surfaces, in detail:

- Resonance frequencies,
- Generalized masses and damping ratios,
- FRFs (Frequency Response Functions),
- Structural nonlinear behavior.

Experimental modal data are necessary for FEM updating, aeroelastic computations and finally certification. As tests were on the critical path of the program, the impact on planning was minimized thanks to an optimized workflow.

The frequency band was defined to be able to identify all modes of interest, from all rigid body modes to the first torsional modes of each lifting and control surface. The 6 rigid body modes of the aircraft were identified, to update the stiffness and the damping coefficient values of the soft pneumatic suspensions.

As the control surfaces and their associated actuators come from the well-known A330 Airbus aircraft, no measurement dedicated to actuator failure configurations was performed.

3.2 Equipment

More than 600 ICP accelerometers have been installed over the entire structure of the aircraft in order to be able to identify the global structural behavior together with local modes from control surfaces, the heavy dummy payload structures (HPJ), and also to the dimensions of the fuselage related breathing modes.

The sensors were connected with approximately 7000m cables and combined via special patch panels, then bundled in a multi-wire cable and routed to the measuring system. Roughly 300 accelerometers from a new development [3] have been used during this test. These accelerometers can be rotated by 360° in their electrically isolated housings. This type of sensor was used at positions where surface normals differ significantly from global coordinate directions. In order to install and connect such a large number of sensors without mistakes in a short time, it requires a very good installation plan and a well-trained team.

33 exciter locations were used during the test campaign to properly excite all modes of interest. Furthermore, a well-structured measurement plan was needed to quickly switch from one point of excitation to the next, so that only short breaks between the individual measurement runs arise and the short test phase was used as efficiently as possible. In total 19 shakers were used during the test, of 5 different types (Figure 6).

For excitation on the engines, 1000N Prodera exciters were used; on most other structural parts (such as wings, control surfaces, etc.) 500N Prodera exciters were used. Besides, seismic exciters were used to excite the HPJs inside the fuselage.

A particular challenge of this GVT was the excitation on the top of the two big auxiliary-fins of the BelugaXL, which had to be simultaneously excited from two cranes in parallel. For this purpose, special shakers (modified APS 420) with a very large coil stroke of up to 15cm peak-peak were used for the first time during a GVT for Airbus. These shakers were mounted in two so called pendulum devices, which were brought into position with the cranes.

With the use of these shakers, significantly larger vibration amplitudes could be introduced into the structure and there were, despite the higher amplitudes, fewer aborts because of exceeding the maximum stroke.

The excitation forces were permanently measured by 2 means:
- force cells installed on each active driving point,
- the coil currents at the active power amplifiers.

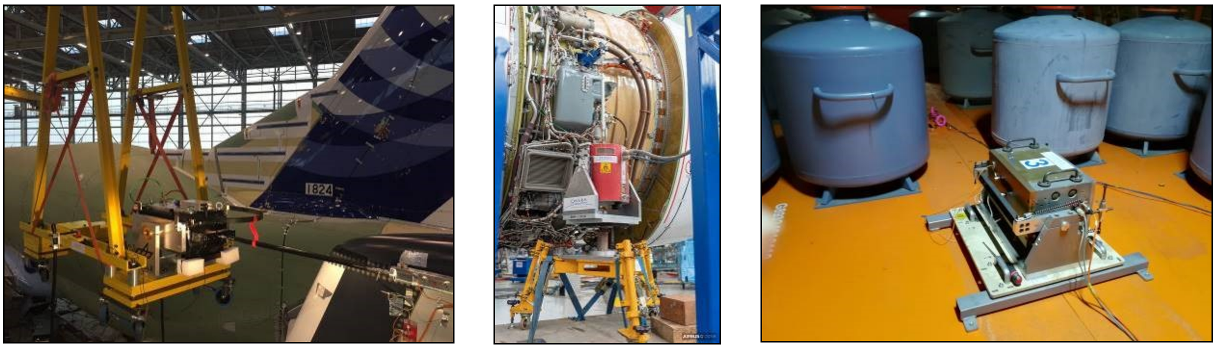

Figure 6 : View of typical exciters used

Left : APS exciter on top of LHS auxiliary fin, middle : Prodera exciter on right engine, right : ONERA seismic exciter for the HPJ

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. The frontends were optimally distributed under the aircraft so that the analogue signal routing was kept as short as possible in order to achieve a better signal to noise ratio. These frontends were connected by optical fiber cables to allow for data flow in a ring-shaped data bus. The V12-L acquisition modules inside the LMS Scadas III frontends were used due to their very low cut-off frequency of 0.05 Hz of the analogic high-pass filters. This very low high pass filter makes it possible to identify even the low rigid body modes of an aircraft on pneumatic suspensions, so that the boundary conditions can be accurately determined.

3.3 Teams

The work was organized in 2 shifts with 7 people per shift. A single team consisted of several positions:
- team manager
- technicians for shaker handling
- technicians and engineers for excitation control, data acquisition and checks
- engineers for modal identification and model correlation

The work rate was 6 days a week, from 7 a.m. to 12 p.m. during 8 days of measurement.

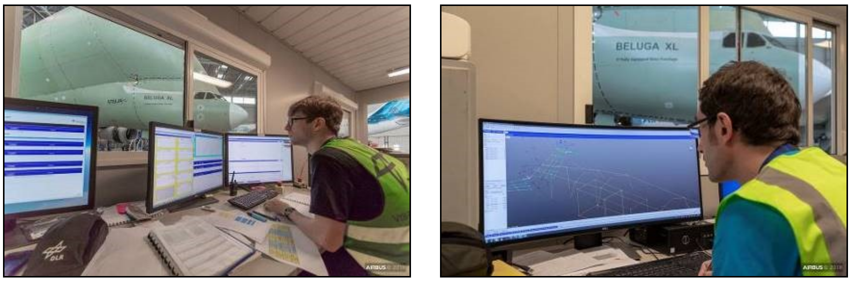

Figure 7 : Inside the GVT command room

4 METHODS

For modal identification of aircraft structures during a GVT, there are two available methods, (a) the Phase Resonance Method (PRM) and (b) the Phase Separation Method (PSM). Since the test time of GVT has been reduced significantly in the past, the time consuming PRM has been skipped completely from GVT. To achieve similar quality from PSM where a large number of modes are excited in a single excitation run that are separated mathematically afterwards, extended PSM methods have been developed by DLR/ONERA. These methods include user-defined excitation signals based on swept-sine excitation, different levels of excitation to detect nonlinear behavior [1][2], dedicated signal processing algorithms [4][5] and a database for modal model determination [2].

4.1 Phase Separation Method

The excitation of the structure is performed for different exciter configurations at different locations and directions of the structure. The exciter signal can be varied (1) in type, which means to modify the type of signal itself, typically random or swept-sine excitation and (2) force level, which means to raise the amplification factor. Generally random signals are used to get a quick overview about the structural dynamic characteristics of the structure. The energy level at each frequency line for random excitation is very low and therefore the displacement amplitude levels of the responding structure are not realistic for operating conditions. Based on the information from the quick overview, optimized excitation signals for swept-sine runs are determined to achieve much higher displacement levels depending on the force amplitude. Additionally limitations are respected in terms of response or force levels. To identify nonlinear behavior the input force level is increased to analyze the modal parameters over force and displacement level.

A typical data workflow is presented in Figure 8 from time domain data to frequency response function calculation, and then to modal analysis and modal model correlation. These steps are conducted with commercial software Test.Lab and in-house tools to address specific aspects in experimental modal analysis that are related to GVT.

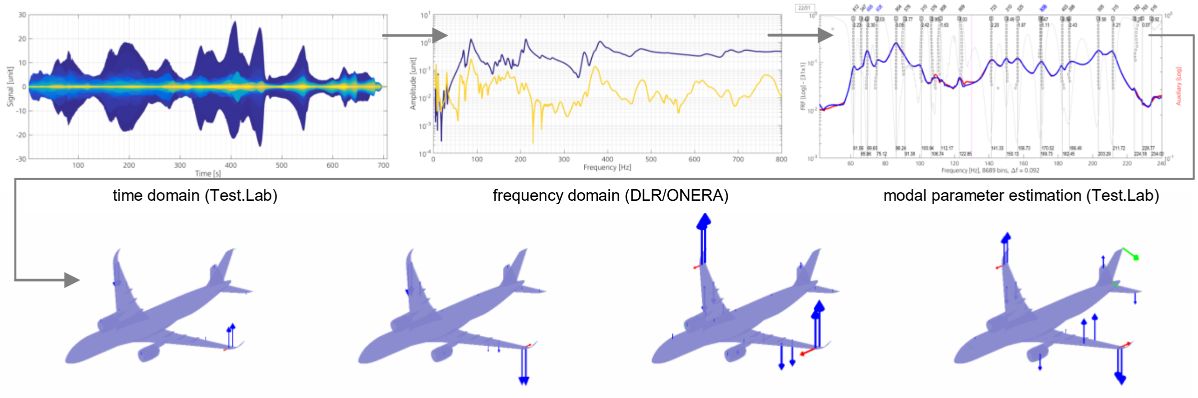

Figure 8 : Schematic data flow between TestLab and DLR/ONERA software

A specialty of aircraft structures is the symmetry. If swept-sine signals are used on a symmetric structure, symmetric and antisymmetric modes can be excited separately. Therefore the modal density can be reduced in the output spectra and the excitation force levels can be increased in every symmetrical and antisymmetrical mode. To realize such excitation configurations, often two or even more shakers are used. In the following you have to deal with correlated input signals (symmetric or antisymmetric swept sine signals). Correlated input signals do not allow a direct estimation of the frequency response functions. The method called Single Virtual Driving Point (SVDP) described in [4] and [5] allows for direct transformation referencing on a "virtual" driving point. This estimation method is commercially not available, but implemented in ONERA and DLR in-house tools. It was used to determine the FRFs from all multi-shaker swept-sine excitation runs.

4.2 Modal correlation

After modal analysis has been performed on a specific dataset obtained from an excitation run, the corresponding modal data and the corresponding FRFs are transferred into a dedicated SQL database. Due to the fact that specific modes can be identified multiple times from different excitation runs with slightly different properties, a need of systematic correlation among individual test data sets arises together with a need of the assessment of the accuracy of modal analysis results e.g. based on evaluation of specific quality criteria. Currently there is no software on the market to collect, filter, classify and post-process modal parameters. The DLR correlation tool has been developed to cope with this type of problem; see Figure 9 and Figure 10 from an example test case.

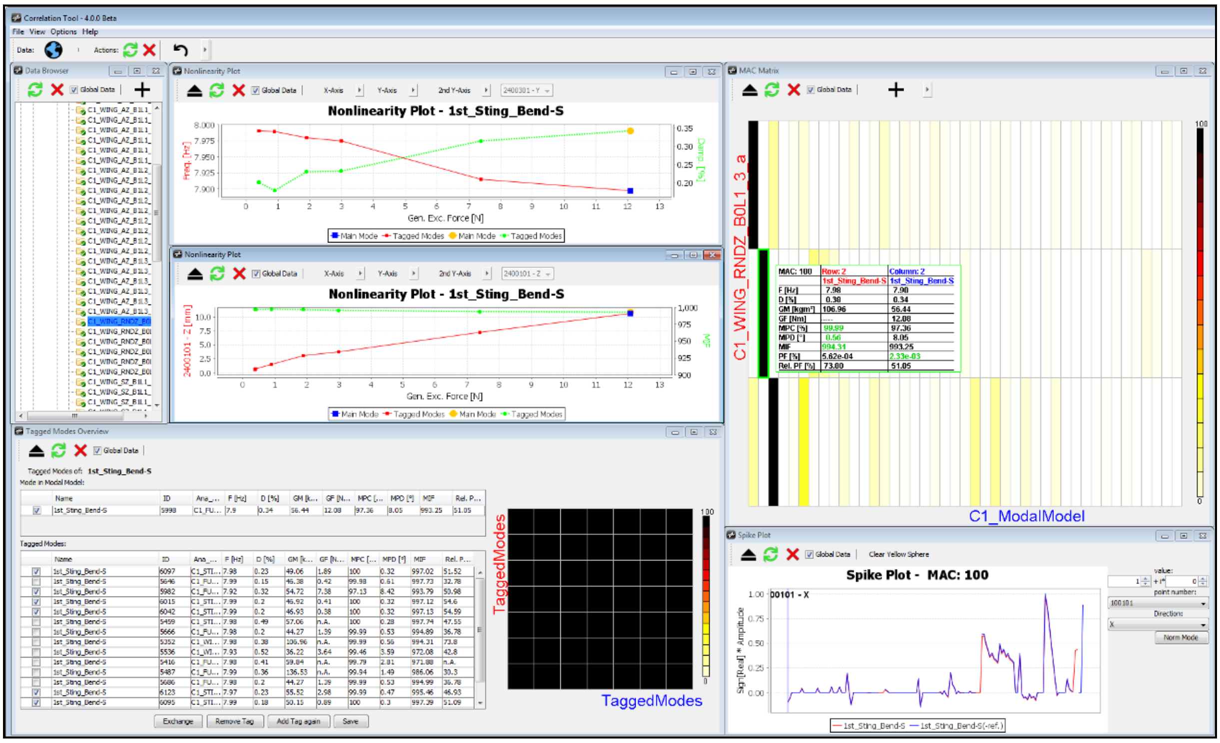

Figure 9: DLR Correlation Tool : view on left monitor

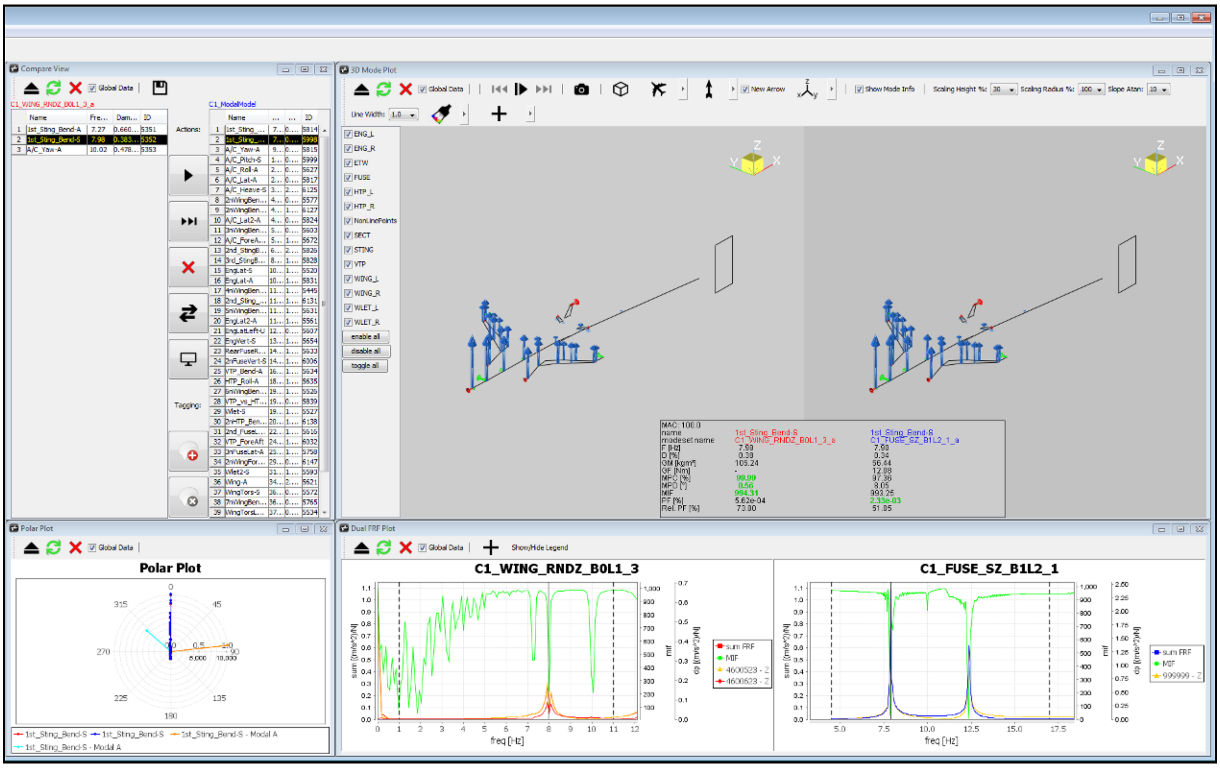

Figure 10: DLR Correlation Tool : view on right monitor

The tool has a user based access to the SQL database. At first the modes are given a name. If the mode is "new", it is added into the modal model. If the mode is already contained in the modal model, the user checks with quality criteria like modal phase collinearity (MPC), mean phase deviation (MPD), mode indicator function (MIF) or generalized force (GF), if the identification accuracy of a mode is "better" than the current mode in the modal model. If yes, the mode in the final modal model is exchanged, if no, the mode is simply tagged. This means, it has been labelled to be a member of a family of modes that belong to a single mode in the modal model. There are several means to check if modes from a new dataset are already represented in the final modal model or if modes of a new type are contained in the current dataset. The Modal Assurance Criterion (MAC) gives a fast indication if two modes are linearly independent or collinear. In addition, a spike plot and an animated 3d plot are available to support the operator in the interpretation and verification of modal analysis results. This process has to be repeated for each modal dataset from each excitation run and for each mode contained in these datasets to ensure highest quality of the final modal model that is an equivalent mathematical model of the tested object.

Finally the DLR Correlation Tool provides a modal model containing a linear independent set of modes. Each mode in the modal model is the best candidate mode of a family of modes identified from multiple excitation runs and found to be similar in terms of the MAC criterion. The family or a subset of the family can be used to analyze nonlinearity of modes or to determine the test uncertainty in terms of the scatter among the mode family members.

In the previous paragraph it is mentioned that the correlation tool provides the best mode of each mode family. This mode is the main mode in the final modal model and therefore delivered to the customer. The DLR/ONERA philosophy of establishing modal models in the Correlation Tool is to deliver modes preferably on high excitation levels which are indicated by high values of the parameter generalized force. Proceeding in this way, the delivered results are more realistic since operating conditions of the tested structures usually cause high amplitudes of deformation [1][2].

Nevertheless, it may occur that sometimes modes that have been excited on a much lower level of energy show a better phase purity and reliability. The reason can be found in the linear modal analysis process to which the assumption of linearity and time-invariance of the test object apply. If these assumptions are not fulfilled e.g. with increasing excitation force level or increasing response amplitude level, the accuracy of the corresponding modal parameters will degrade and in such cases the selection of modes from lower excitation force levels can be meaningful.

4.3 Test data access and progress overview

In the present Airbus context, a GVT can only be efficient if test data are analyzed on site as fast as possible. In case of BelugaXL GVT, 3 people have been working on data processing described in Figure 8. Final modal data have been stored in a multi-user access database which is accessible for Airbus from DLR correlation tool to view and to compare modes with each other and with modes from the finite element model.

Figure 11 : Airbus on-site access to database and correlation tool

Data can be exported in different formats e.g. universal file format (UFF) or Excel tables. Nonlinear modes can be discussed and actions can be taken to place additional excitations if necessary. For example, as the excitation of Auxiliary Fins was particularly important for the model updating, the decision from Airbus of adding runs with increased level of excitation was made by a constant monitoring of vibratory accelerations, in near-live time after each run performed.

The online access to the final data is as important as the information about the current and next excitation run which is performed. Since more than 300 excitation runs have been acquired, such information is shown via a tool called the ONERA test progress manager. Test progress transparency is a key enabler for interactive test management.

5 RESULTS

5.1 Modal model

A total number of 314 runs were made for modal identification of structural configurations C1 and C2. For both mass configurations, in total 2245 modes were identified. From this set of modes, 1017 were selected as reliable and were combined for providing the non-linearity plots. The final modal model consists of 100 master modes (one per family mode) for the 1st structural configuration and 107 master modes for the 2nd structural configuration.

During the BelugaXL test, all rigid body modes have been identified below 1 Hz for both configurations, and excited by random excitation.

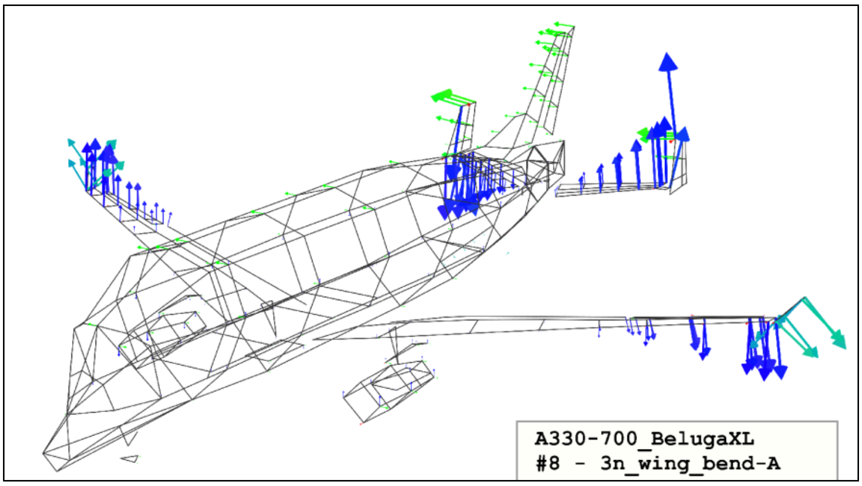

Figure 12 : Shape of the 3 nodes wing bending of structural configuration 2

For each mode of a modal model, the following data are provided:

- the mode shape (see Figure 12)
- the eigenfrequency, damping ratio and modal mass at the highest level of excitation,
- the nonlinearity plot (evolution of eigenfrequency and damping over generalized force).

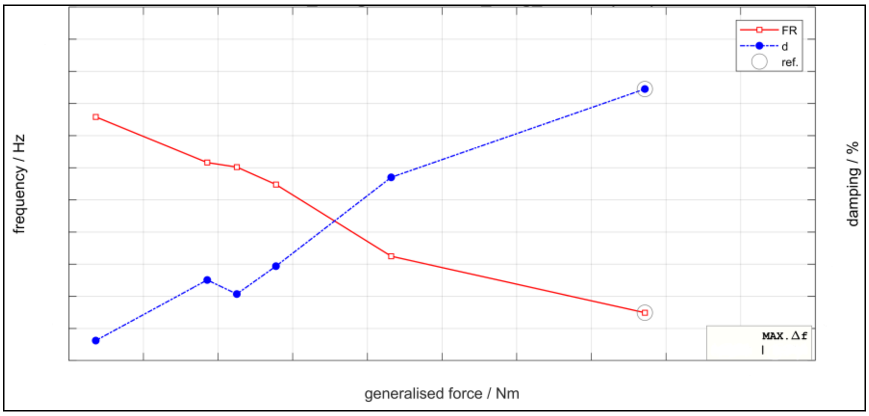

Figure 13 : Example of nonlinearity plot

In general, frequency decreases as a function of force, while damping increases, like the example on Figure 13. Observing this kind of asymptotic trend is auspicious for the manufacturer, because it means that a sufficient level of force was applied during the test. But of course, each mode can show a pattern of its own, because these evolutions are very case-dependent. Obtaining these trends is still a main challenge of GVT, and absolutely impossible to compute with an FE model at the present time. This explains why GVT is and will remain essential for certification.

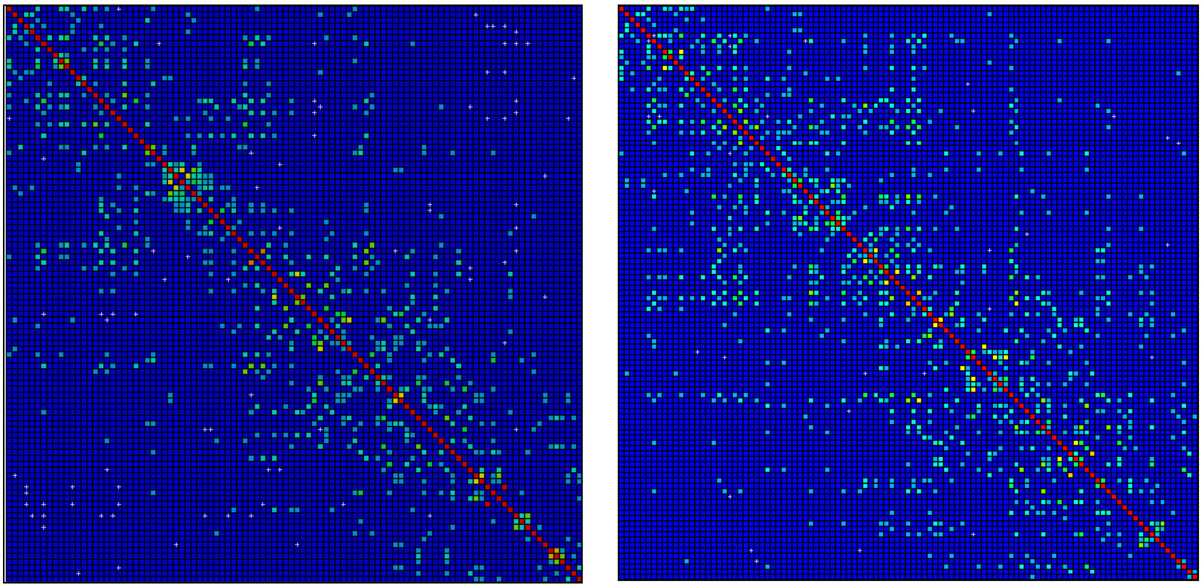
Figure 14 : Auto-MAC of structural configurations C1 (left part) and C2 (right part)

The auto-MACs of structural configurations C1 and C2 are depicted on Figure 14. The matrices are mainly diagonal, with few noticeable extra-diagonal terms. They are due to modes whose shapes are very similar; in general the movement of a sub-component enables the analyst to distinguish them.

5.2 Special case of HTP behavior

One of the main originalities of this aircraft comes from the presence of two large auxiliary fins on the HTP (Figure 15). Due to their sizes and masses, they have a deep influence on the dynamic behavior of the HTP, and hence on the whole aircraft dynamics. Furthermore, strong structural nonlinearities were expected for dedicated modes with dominant motion at the horizontal tail plane and the auxiliary fins.

Figure 15 : HTP view with the two auxiliary fins

Therefore the structure was excited with extra-long coil stroke shakers at the auxiliary fins in order to highlight them as much as possible, with restrictions in acceleration and force limits. The shakers were positioned with pendulum devices from two cranes (Figure 16).

Figure 16 : Auxiliary fins excitation

This excitation was the most challenging one, because the symmetric and antisymmetric excitations from two shakers supported by pendulum devices were never performed before. It turned out that the whole system was very stable and all excitation runs could be performed without any problems. The maximum force at the excitation was about 500N at each shaker while the maximum coil stroke was at 80mm peak to peak.

Especially the HTP yaw mode shows strong nonlinear behavior. While crossing the eigenfrequency of the 1st in-plane bending of the HTP, the mode shape changes. In fact the fin amplitudes change direction. This special behavior is clearly visible in Figure 17 where modes 1 to 3 are above the eigenfrequency of the 1st in-plane bending mode, mode 4 is at the border and modes 5-7 are below that eigenfrequency.

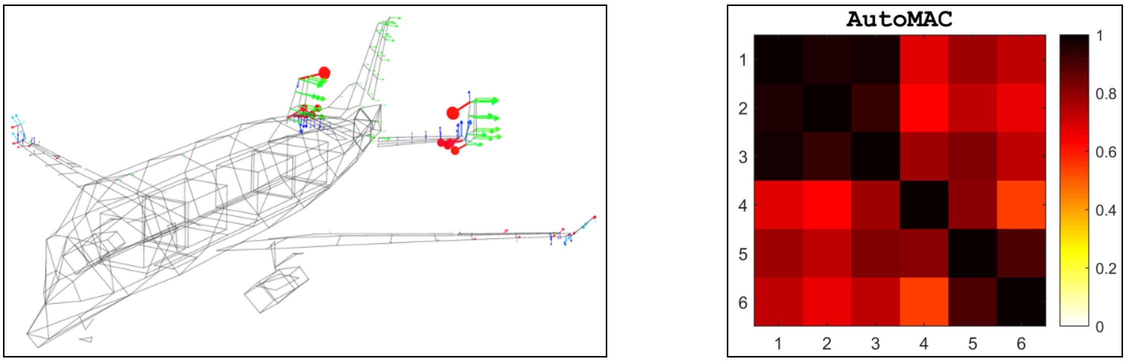

Figure 17: HTP yaw mode (left) with Auto-MAC matrix (right)

6 CONCLUSION

A Ground Vibration Test is done with 3 goals in mind:

- Delivering the modal model for FE model updating and flutter predictions
- Supporting first flight safety and allowing a fast flight domain opening
- Serving as means of compliance in front of Airworthiness Authorities

Since GVT is performed just before the first flight of an aircraft, it is placed on the critical path of development process.

The BelugaXL GVT was fulfilled with respect to all specifications and with all expected results delivered in required quality. Performing such a test relies on the maturity of methods, optimized workflow, and last but not the least, on the high experience of involved teams. Besides, for this GVT the collaboration between ONERA-DLR test providers and Airbus engineers was particularly fruitful; this explains much of the success of this campaign.

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8 ACRONYMS

A/C	Aircraft	MAC	Modal Assurance Criterion
FEM	Finite Element Model	MIF	Mode Indicator Function
FRF	Frequency Response Function	MPC	Modal Phase Collinearity
GF	Generalized Force	MPD	Mean Phase Deviation
GVT	Ground Vibration Test	PRM	Phase Resonance Method
HPJ	High Platform Jig	PSM	Phase Separation Method
HTP	Horizontal Tail Plane	SVDP	Single Virtual Driving Point