Advanced systems and services for Ground Vibration Testing – Application for a research test on an Airbus A340-600 aircraft

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Abstract: Aerospace manufacturers are faced with the challenge of designing systems and components that have to be safer, more reliable, affordable, offer improved passenger comfort and have less environmental impact than their competitors. In addition, they have to systematically reduce development times in order to get new products to market earlier. In the usual case, only a few prototypes are available for testing and experimental verification, in most cases, only towards the end of the development cycle. To shorten development times while still assuring design critical issues like structural integrity and safety, aircraft development teams are faced with several Ground Vibration Testing (GVT) challenges: (i) ensure identification of all critical modes and assess their non-linear behavior; (ii) manage challenging logistical requirements linked to boundary conditions, structure configurations, the typical usage of high number of sensors with multiple shakers and multi-shift testing teams; (iii) reduce test campaign duration to match development schedule and costs; (iv) deliver accurate, validated and traceable reference data in support of the mathematical model updating and of the flutter certification process.

This paper will focus on some recent advances in systems and services that allow testing teams to realize an important testing and analysis time reduction without compromising the accuracy of the results. Emphasis will be put on system performance and openness of the selected industrial GVT platform that allows customization in terms of data acquisition and post-processing. Technical advances include efficient handling of very-high channel count (700) data, new capabilities in Normal Mode Testing, and the possibility to stream user-defined shaker excitation signals for dedicated experimental analysis of structures.

The new developments will be illustrated by means of a recently conducted Research Ground Vibration Test on an A340-600 aircraft with ONERA, DLR and Airbus as project partners.

1 INTRODUCTION

With important GVT campaigns on aircraft planned for the next decade, ONERA and DLR investigated various industrial players. Following successful GVT benchmarks, DLR and ONERA selected LMS and decided to base their new GVT systems on the LMS Test.Lab GVT solution. This solution already covers all common GVT requirements, and could easily be configured to fully manage DLR and ONERA's specific GVT methods and practices. In additional, the LMS Test.Lab GVT solution proved to have the necessary openness to integrate customized procedures to support DLR and ONERA's research initiatives.

2 PROJECT PARTNERS

DLR, the German Aerospace Center, is the German national research establishment for aeronautics and space. DLR's research portfolio ranges from fundamental research to innovative development of the applications and products of tomorrow. Among others, DLR operates large-scale research facilities for its own research projects and as a service provider for clients and partners. Approximately 6900 people work for DLR; the center has 33 institutes and facilities in 13 locations in Germany. The DLR Institute of Aeroelasticity is located in Göttingen. Ground Vibration Testing is one of the core competences of the Structural Dynamics Team of this Institute for more than 3 decades. Its mobile ground vibration testing facility comprises all the equipment needed for testing large aircraft structures.

ONERA (Office National d'Etudes et Recherches Aérospatiales) is the French national aerospace research centre, originally created by the French government in 1946. ONERA is a public research establishment, with eight major facilities in France and about 2,000 employees, including 1,500 scientists, engineers and technicians. Among numerous departments, including the large wind tunnel facilities department, the mission of the ONERA – DADS (Aeroelasticity and Structural Dynamics Department) is to develop, adapt, evaluate and apply theoretical, numerical and experimental methods for modelling, predicting, optimizing and identifying the static and dynamic behavior of structures in their environment (structure/fluid/thermal/control coupled systems). The activity is divided into a first half concerned with the development and validation of theoretical methods and a second half concerned with the developing and implementing methods and means for experimental identification and evaluation of new concepts. The ONERA ground vibration test team acts in its domain since the creation of ONERA.

From 1972, related to the 1st A300b Airbus, ONERA and DLR have separately tested all civil Airbus prototypes. Since 1999, ONERA and DLR have jointly performed the GVT's of all commercial Airbus aircrafts, as the A340-600, the A340-500, the A318 and the A380-800.

3 LMS GROUND VIBRATION TESTING SOLUTION

As a market leader of solution provider for structural dynamics, LMS is continuously improving their solution by listening to the needs of their customers and innovating new technologies. Thus, LMS has entered into an agreement with DLR, the German national research center for aeronautics and space, and ONERA, the French national aerospace research center, to deliver their next-generation GVT systems.

3.1 Identification of all modes

One of the most important challenges in aircraft Ground Vibration Testing is to ensure identification of all critical modes and assess their non-linearity. The usage of experimental modal data for subsequent flutter analysis comes along with the requirement for the identification of the full set of modal parameters. The accuracy of modal damping is especially important for flutter analysis and it is numerically linked to the generalized mass in the evaluation procedure. Therefore, it's important to identify accurately the generalized mass during Ground vibration Testing.. Today, the identification of modal parameters is largely based on analysis of frequency response functions, while the modal tuning method is still available if necessary. Various Multiple Inputs Multiple Outputs excitation methods, like random, swept sine, stepped sine, are the starting point to obtain reliable frequency response functions for a wide frequency range. All these excitations have their own benefits and weaknesses in terms of measurement time, data accuracy and achievable energy level. In order to obtain the best compromise between accuracy and efficiency, the test team defines the test schedule with the appropriate LMS Test.Lab acquisition modules. It should be mentioned here that the determination of suitable sensor and excitation points as well as the definition of a minimum number of independent excitation configurations is of high importance for the success of a ground vibration test. Typically, this information is a result of pre-test analysis methods performed by the test teams in preparation of the test. Another aspect to ensure high quality test results is the assessment of reasonable excitation force levels to be used for FRF measurements. The definition of excitation force profiles, e.g. as a function of frequency, is decided by the test team on the spot based on evaluation of preliminary excitation runs. The resulted FRFs can easily be analyzed by LMS Test.Lab modal analysis with LMS PolyMAX modal parameter estimator.

For non-linearity assessment (but also for the consolidation of modal parameters obtained from FRF analysis), stepped sine excitation and normal mode testing are 2 excitation methods suitable for structural identification within a small or local frequency range. Such detailed investigations are performed only on critical modes. Stepped sine testing can easily be set up to measure different excitation levels. The resulted FRFs of different excitation levels are then overlaid for frequency shift check. Normal mode testing is a direct modal acquisition module which excites at one frequency at a time, maintaining a well-controlled amplitude and phase difference between shakers. The frequency precision provided by LMS SCADAS III QDAC is down to 0.0001 Hz. The dynamic response is then measured directly with all the sensors and online animated in the software for visualization. Once the resonance frequency is tuned, various methods for damping estimation can be applied in order to obtain modal data like eigenfrequency, damping, mode shape, and generalized mass.

3.2 Size of the object

With increasing size of a structure, its structural dynamics properties are typically shifted towards the lower frequency range. As a consequence, and due to very low damping factors, long measurement times are required to achieve sufficient frequency resolution in the FRFs. The very low frequency range with eigenfrequencies of elastic mode shapes between 1,5 Hz and 2 Hz and the relatively high modal density (i.e. 16 elastic modes in 2 Hz for some large civil aircrafts) can cause difficulties in ground vibration testing in many different ways. The most obvious problem is high-pass filtering of dynamic response signals. Very low cut-off frequencies are required to permit accurate modal identification. Next to this, very low acceleration signal levels have to be measured while at the same time displacement response levels can be immense. The low acceleration response levels may require dedicated sensors. In order to identify as good as possible the dynamic structural behaviour, but still respecting the aircraft structural limitations, the large displacement response levels require vibration exciters with very long stroke. Another challenge related to the size of an aircraft is the logistic part. Bigger plane means longer cables between sensors and acquisition system. Longer cables are more prone to noise contamination. Pre-gain of sensor signals close to the pick-up locations might be required. Depending to the aircraft manufacturer's intended use of the GVT results, observing the dynamic deformations of large aircraft could require more and more sensors. Consequently, very huge amount of data is being produced and must be processed in the experimental modal analysis. Examples of such extended use of GVT results include SEI or windmilling studies, SMI investigations, vibro-acoustic comfort optimization and transfer path analysis.

Figure 1 A340/600 aircraft during the GVT

DLR and ONERA each has selected a LMS SCADAS III 384-channels data acquisition system which can be combined to form a 768-channels test system with optical cables for master/slave configuration. These optical cables, range from 0,5m to 100m, allow to distribute LMS SCADAS III master or slave frames around or inside the test object. The channels are distributed over a total of 8 frames, offering the right balance between the number of transducer patch locations and the number of master/slave cables. Compared to their previous acquisition systems, the LMS SCADAS III have been proved to be extremely robust and stable for industrial usage. The Plug-and-Play way to interchange signal conditioning modules allows also fast modifications of the hardware configuration.

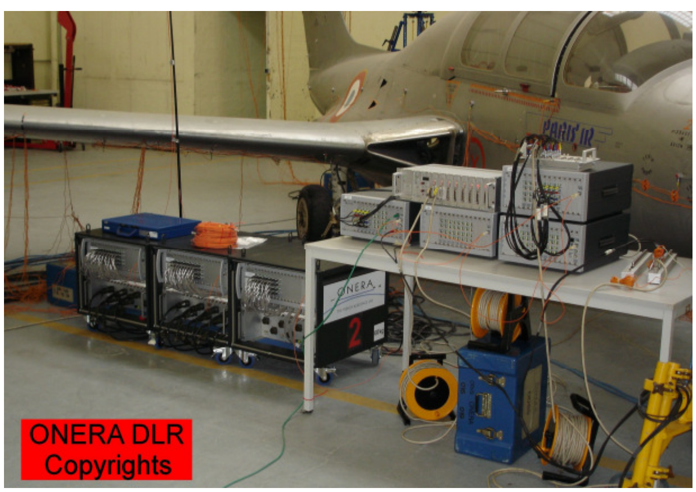

Figure 2 LMS Scadas III frontends during the ONERA + DLR approval tests in ONERA facilities

Size and weight of the aircraft leads to dynamic behavior at very low frequency. To support this, LMS has a special signal conditioning module for ICP sensors. The cut-off frequency of the analogue high-pass filters of this data acquisition module is at 0,05 Hz which allows for measurements at very low frequencies using ICP sensors. Besides, this module can also directly read TEDS information stored in ICP sensors such as calibration values. For example, the sensitivity of all the sensors is read in a few seconds for all the sensors and transferred to the software in order to accelerate the setup time for measurement channel definition. This capability brings advantage, especially for a Ground Vibration Test.

More sensors also mean more data. With the multiple screen technology available in most of the graphical card in PC, users would like to investigate a huge amount of data on several screens. One of the standard features of LMS Test.Lab is to allow users to put multiple displays in separate windows. It simply extends the One-screen application to multiple-screen application and provide more ergonomic graphical user interface for data visualization during and after the measurement. With the .lms optimized project data structure, users can deal with huge amounts of data organized in a hierarchical way without compromising stability and performance of the database. Furthermore, all analysis results are managed in the same database, with an unambiguous link to the test data. The complete set is 100% traceable, documented with aircraft configuration, test and analysis parameters.

3.3 Reduce time and cost

Time is money. LMS Test.Lab, as an engineering platform, is developed with the objective to reduce test time. LMS Test.Lab modules are optimized for the most popular test & analysis sequence. In most of the cases, Ground Vibration Test teams operate a number of PCs with specific objectives from preparation of test, test execution, validation of test data, analyze data to data reporting. These different tasks can be done in parallel in order to reduce waiting time. LMS Test.Lab allows user to share, copy data simply by network devices. As a fact, during execution of a test run, another test run can easily prepared by another engineer, and at the same time, data are validated and analyzed by another engineer without losing any time.

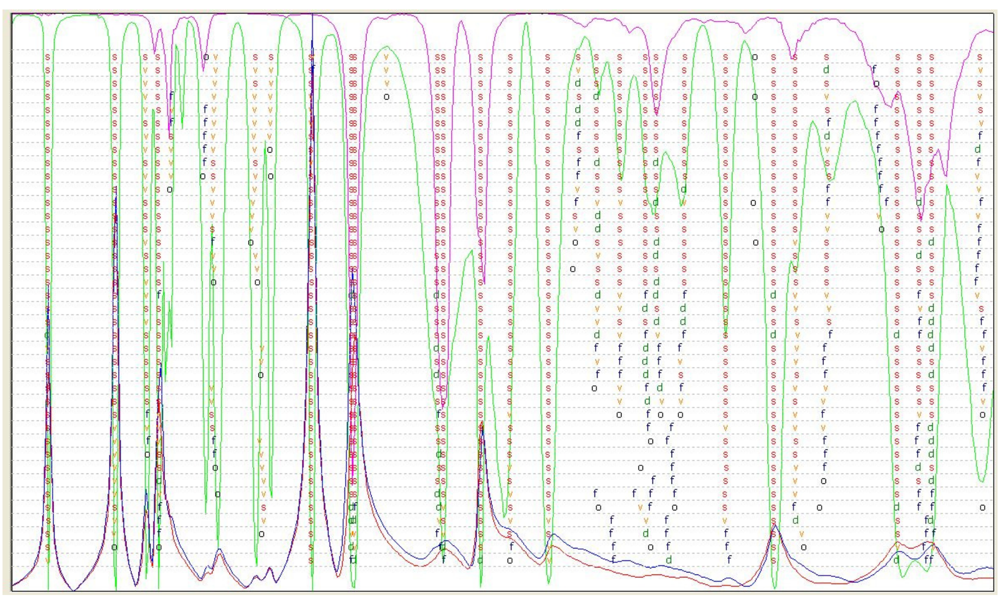

Figure 3 Polymax Stabilisation diagram

One of the most popular modal parameter estimators, LMS PolyMAX, also plays a very important role for reduction of analysis time. The solver can treat a huge amount of data, with either equally or not-equally spaced frequency axis, measured in displacement, velocity or acceleration thus right after measurement, modal analysis can be performed without any interpolation or conversion of data. In addition, data volume will not be increased due to post treatment. The PolyMAX analysis procedure is very fast, also on large data sets.

3.4 Accurate and validated result

Accuracy and reliability of the GVT results are key for program success. Amongst other use cases, the resulting experimental modal models are used for correlation and updating of finite element models. Those models are subsequently used for certification-relevant flutter prediction. To obtain a good modal model, accurate measured data is primordial. The high dynamic range of the LMS SCADAS hardware avoids the need to apply tedious and time-consuming input range selection procedures. High quality data is available, even when the input range is simply set the maximum and signal levels are relatively low. As an added bonus, overloads are avoided, saving re-test time.

During random excitation, online principal component analysis is used to check whether the excitations are correlated or not, such that the frequency response function can be calculated correctly. During and after the measurement is done, data can be validated by coherence checks. Due to the huge number of measured degree of freedom, it's not so obvious to go through individual curves. One of the visualization tool called coherence plot can be used to identify, for example, weakly excited point at a selected frequency band on a geometry display. On the same geometry display, not measured or overloaded point can also easily be identified.

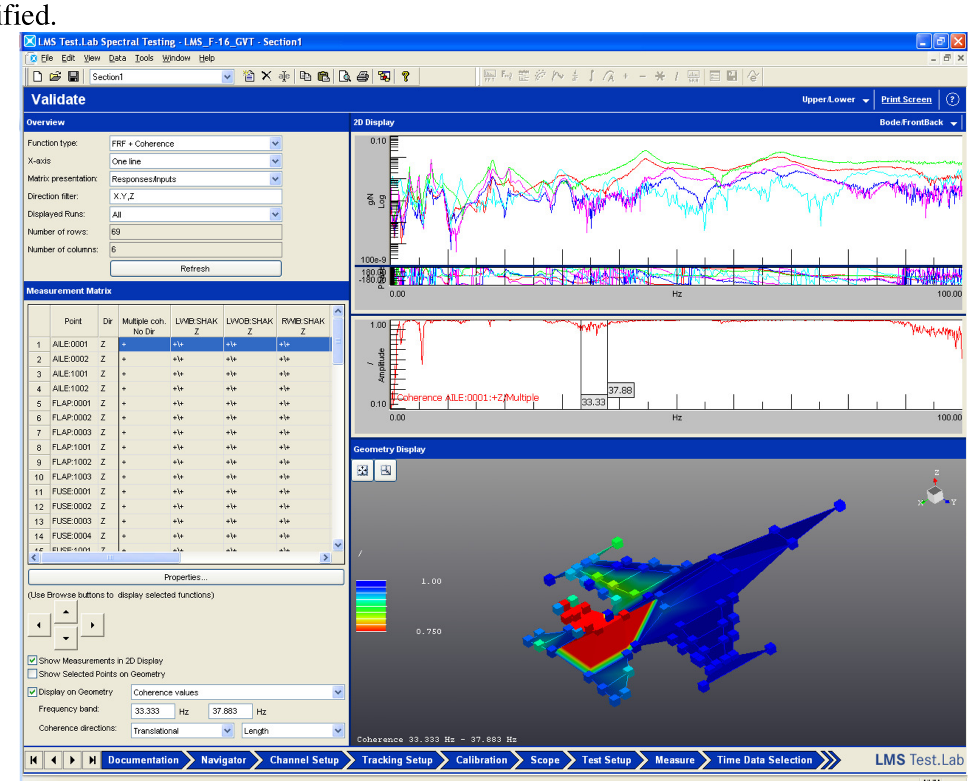

Figure 4 Example of FRF and coherence shown in 2D display together with coherence plot indicate weak coherence point in the geometry

When the measured data is validated, one can use this data to perform modal analysis. There are various tools like MAC, MPC, MPD, synthesis FRF can be used to validate the identified modal model. Besides, MAC can also use to compare the test modal model and the simulated modal model.

3.5 Openness of software

Despite the standard features of the LMS Test.Lab Ground Vibration Testing solution which allows standardization of the most common tasks during test campaign, in the other hand, the openness of software allows engineers to create their own procedures.

One of the examples is in normal mode testing. ONERA have designed a manual tuning device which allows quickly changing the amplitude, phase and frequency of different shakers globally or individually. In order to adapt the test procedure of ONERA, LMS implemented interfacing between the device and normal mode testing module. In parallel, another (commercially available) device, specified by DLR, has been integrated as a standard, so other users can benefit from the same ergonomic graphical user interface and ease of manipulation.

Figure 5 Excitation Force Control devices used by ONERA and by DLR

Interfacing with other programming platform is one of the strong needs of DLR and ONERA. The openness of LMS Test.Lab allows them to easily export data in batch way and in their internal format for proprietary processing procedure. The processed results are re-imported in the GVT database, so they are managed in sync with all other test campaign results, and can be reported in the exact same way as the native test and analysis results.

3.6 Collaboration for improvement

With DLR and ONERA’s extensive 60 years of Ground Vibration Testing experience, a few improvements are integrated in LMS Test.Lab solution. This win-win situation benefit DLR and ONERA, as service suppliers, to take GVT testing practices to the next level and meet ever more stringent deadlines of their customers. In addition, the LMS Test.Lab Ground Vibration Testing solution is now improved with expert’s know-how. The continuous collaboration between these 3 entities will contribute to the advancement of the overall GVT methodology and practices.

Most of the time, Ground Vibration Testing is performed with random, swept sine, or tuned fixed sine excitation. Though, an aircraft is a lightly damped structure and thus these techniques might translate to higher measurement time. A new method is implemented in LMS Test.Lab platform which allows user to design their own excitation patterns for excitations either in frequency or time format, these patterns are then replayed during the measurement. This important capability helps ONERA and DLR on researching the best suited excitation signal and thus increases their efficiency.

Another important extension in the TestLab is force quadrature methodology. This method calculates in a reliable manner the damping estimate in the normal mode testing procedure. When the excitation force levels are well measured, the method delivers reliable generalized mass values. ONERA has transferred their know-how to LMS making possible the application of this method in the Normal Mode Testing workbook

In addition to real time 3D animated mode shape plots, Lissajous display is one of the indicators to recognize resonance during normal mode testing. The common practice is to examine all degrees of freedom; nevertheless, for a huge amount of sensors, it became difficult to easily identify the problem area by simply look into the name of the measured point. ONERA thus suggested building displays based on the geometrical distribution of sensors. These displays are fit into different windows and allow global view of all the sensors at the same time.

4 A340-600 RESEARCH GVT

In March 2011, DLR and ONERA conducted a research campaign on A340-600 at Airbus. The objective of this campaign is to validate newly developed GVT strategies and to optimize the team work between DLR and ONERA. During the Ground Vibration Testing campaign, more than 650 channels are used for dynamics measurement. Eight LMS SCADAS III frames are linked together in master/slave configuration and distributed around and inside the aircraft. More than 16 shakers, for example, a very long stroke (50 mm) shaker with sine excitation force up to 1000 N specified by ONERA for better excitation capable to exhibit non-linear structural behaviors, are ready to connect to the aircraft in order to address the defined shaker configuration.

Figure 6 ONERA and DLR racks with LMS Scadas III inside the fuselage, linked with optical fibers

Various novelties are tested during the research GVT. First of all, a French-German team mixed with senior and junior engineers and technicians is trained to collaborate in the most efficient way. Secondly, the sensors for the measurement of the fuselage are installed inside the fuselage which helps to easily identify location of the sensors based on the frame number. This reduced tremendously the sensors setup time. Depending to the objective of the GVT deliveries, the aircraft is placed on air-spring devices allowing very low frequency boundary conditions, or the aircraft is landed on the ground with its landing gears and tires, near normal usage conditions. The optimization of sensors location and exciters location are derived from analysis of ONERA and DLR based on the observability and controllability analysis using the finite element model. It results sometimes into a non-symmetric, yet highly optimized set of sensor locations.

Figure 7 AIRBUS ONERA DLR team members

From test preparation to reporting data, the chain of engineers and PCs are located in the "commander container". Six PCs are connected in network, the PCs chain starts from preparation of excitation profile, test setup, data processing, modal analysis, collecting data from aircraft FTI (Flight Test Instrumentation) systems to assembling various modal model and model validation. All these tasks are executed simultaneous to avoid downtime.

Figure 8 GVT command room

The hardware was reliable even with high environmental constraints like up to 35-40°C inside the fuselage or outside environment for Taxi test with frontend operation in vibratory conditions. The amount of data reached 9 to 10 GB for individual project and LMS Test.Lab remained stable and the software was reliable during the whole period of the test campaign. As results, some modes identified during the campaign.

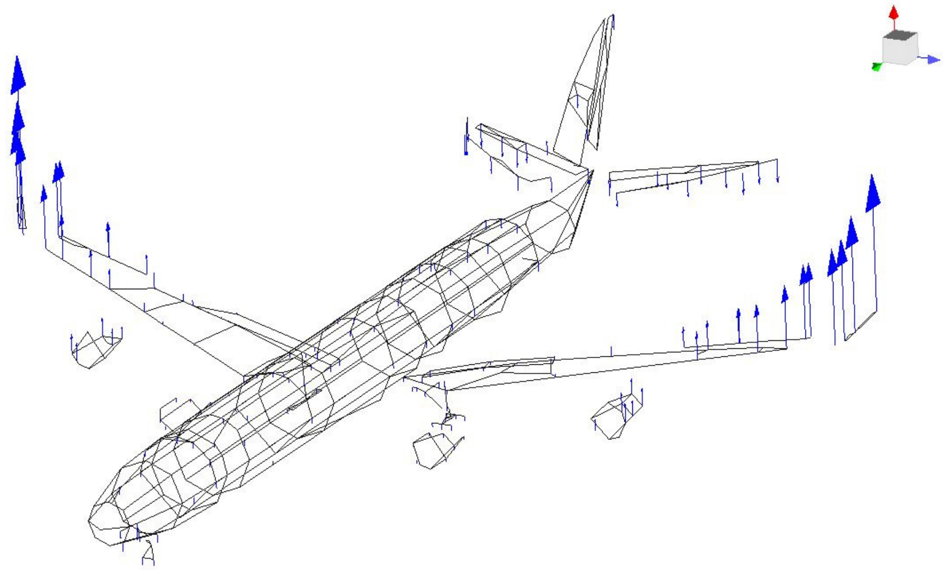

Figure 9 Mode shape example

5 CONCLUSION

The research A340-600 Ground Vibration Testing campaign is successful both in hardware and software logistic and human collaboration. Various technologies are introduced and tested in a real size object in the ground vibration testing context.

6 ACKNOWLEDGEMENT

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