Modern solutions for Ground Vibration Testing of large aircraft

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ABSTRACT

Ground Vibration Testing (GVT) of aircraft is typically performed very late in the development process. Main purpose of the test is to obtain experimental vibration data of the whole aircraft structure for validating and improving its structural dynamic models. Among other things, these models are used to predict the flutter behaviour and carefully plan the safety-critical in-flight tests. Due to the limited availability of the aircraft for a GVT and the fact that multiple configurations need to be tested, an extreme time pressure exists to get the test results. The aim of the paper is to discuss recent hardware and software technology advancements for performing a GVT that are able to realize an important testing and analysis time reduction without compromising the accuracy of the results. The paper will also look at the connection between the GVT and the other components of the development process by indicating how the GVT can be planned using the virtual prototype of the aircraft and how the GVT data analysis results can be used to obtain a highly reliable model for flutter prediction. The presented modern GVT solutions will be illustrated using the recently performed demonstration test on the A310 and certification test on the A330 MRTT.

1 INTRODUCTION

1.1 EADS CASA Military Transport Aircraft Division

The Military Transport Aircraft Division (MTAD) of EADS CASA has experience in the design and manufacture of advanced aerostructures. This covers carbon fibre and metallic structures, as well as experience in automation processes (manufacture and assembly). At present it develops and/or produces aerostructures for a range of aeronautical programmes: horizontal stabilizers (A400M, Falcon 7X), flight control surfaces (B-777, B-737, Falcon 7X, A400M, Eurofighter), engine nacelles, fibre placement technology fan cowls (A340-500/600, A380, A318), metallic structures (A380 belly fairing, A318 fan cowls, A320 Section 18, A330/340 central box, and others), leading edges (Airbus), etc. MTAD is producing solutions designed to fit the differing needs of the world's air forces for tanker/transport aircraft. MTAD has recognised the wide range of mission requirements and offers customised solutions based on two Airbus platforms: the tried-and-tested A310-300 and the A330-200.

The MTAD division has the capability to project, build, certify and market complete aircraft. It has a successful line of light and medium military transport aircraft like the C-212 (more than 400 sold), CN-235 (more than 300 sold) and C-295 (more than 60 sold). These products complement the rest of EADS' portfolio and it has been the reason to establish the heavy military transport A400M Final Assembly Line in the EADS CASA facilities in Seville.

In view of its aircraft structural testing responsibility in the certification process of the A330 MRTT and the A400M, MTAD partnered with Álava Ingenieros and LMS International to renew their measurement hardware and software for Ground Vibration Testing (GVT). The new system was deployed and the test teams were trained at

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the occasion of a demonstration GVT on EADS CASA's A310 Boom Demonstrator Aircraft. Next to results from this test, the paper contains in addition results from the certification test on the A330 MRTT.

The EADS CASA's A310 Boom Demonstrator Aircraft has done, on January 30, 2007, its 12th test flight and the boom has been successfully deployed for the first time (Figure 1, Left). On March 30, 2006 the first phase of the ARBS (Air Refuelling Boom System) flight test programme was successfully completed after 3 years of development, where EADS CASA completed the design and manufacture of this new generation refuelling boom. The flight test programme is devoted to prove the performance of the new boom installed on an Airbus platform and it includes, for instance, opening the work envelope of the tanker or performing dry/wet contacts with an F-16. Preliminary results of these tests have shown that the aircraft platform and boom structure are free of any form of flutter vibration, the influence of the boom installation on the aircraft handling qualities has proved to be minimal and that there is no influence on the APU air intake.

The A330 MRTT (Multi Role Transport Tanker) is an aircraft with a maximum fuel capacity of 140 000 litres which also retains its full passenger capacity thereby retaining the dual use capability of the aircraft (Figure 1, Right). The in-flight transfer of fuel can either be carried out either by hose-and-drogue systems or by boom system. The entirely new ARBS (Air Refuelling Boom System) is a system with an advanced air refuelling boom main structure, fly-by-wire control with a larger refuelling envelope and controllability, including an automatic load alleviation system. The maximum nominal fuel flow is 1200 US gal/min.

Figure 1. (Left) A310 Boom Demonstrator Aircraft; (Right) A330 Multi Role Transport Tanker. © EADS CASA 2007.

1.2 History, challenges and trends in Ground Vibration Testing

Ground Vibration Testing of aircraft is typically performed very late in the development process (Figure 2). The main objective of a GVT is to experimentally determine the low-frequency modes of the whole aircraft structure for validating and improving its structural dynamic model as part of the flutter clearance process. Recently, more complex aircraft design raised additional testing requirements which are related to the increased use of composite materials, active systems and the need to quantify non-linear behaviour. At the same time, a high time pressure exists on the test schedule due to limited availability of the fully assembled physical prototype aircraft so late in the design cycle. The reconciliation of increased testing complexity and test results accuracy with cost and time reduction requirements for a GVT has motivated a lot of international research [1][2][3][4][5][6]. Next to research into more efficient test and analysis strategies, also the combined use and integration of Test and CAE (Figure 3) is definitely the path to follow [6][7][8][9].

For more than 3 decades, the use of the Phase Resonance Method or so-called Normal Mode Testing [10][11][12][13] has been almost exclusively required for GVT on *large aircraft* because this method is generally well suited for the separation of closely spaced modes. In Normal Modes Testing, essentially single sine excitation at the natural frequencies of the modes is used. By carefully selecting the shaker locations and the phase relation between the sine excitation signals, the aircraft is forced to act as a single degree of freedom system and the vibration response only contain a contribution from the mode of interest. Advantages of Normal Mode Testing are:

- The real (normal) modes of the corresponding undamped structure are directly measured;
- All eigenvectors are excited at a high energy level;
- Linearity tests can be easily performed.

The main disadvantage is that it is a very time-consuming testing procedure. Therefore, the phase resonance method is complemented and partially substituted by so-called phase separation techniques that find the aircraft modes by evaluating frequency response functions (FRF). The idea is that most modes are extracted from a fast phase separation technique (i.e. applying modal parameter estimation methods to broadband FRFs [14]), but that "critical" modes are identified based on Normal Mode Testing. According to [3], modes are considered to be critical in the following cases: they significantly differ from the predictions; they show non-linear behaviour; or they are important for flutter calculations. While phase separation techniques are only relatively recently applied to *large aircraft*, EADS CASA has been promoting the alternative approach of "random excitation" since the mid 80's for *small and medium size aircraft*. At that time, this new approach was successfully applied to the CASA trainer aircraft C-101 GVT. The same approach has been applied to the Eurofighter aircraft DA6 prototype GVT in the 90's [4].

A large variety of shaker excitation signals can be used to experimentally determine the aircraft broadband FRFs, which are required in phase separation testing. These excitation signals include harmonic signals like discrete stepped sines, periodic signals like multi-sines or a periodic chirp (i.e. very fast swept-sine), and transient signals like an impulse, a (burst) random, or a swept-sine signal. They differ largely in their spectral energy contents and test duration. Recently swept-sine excitation received a lot of attention, as it represents a good compromise between magnitude of excitation level needed for large aircraft and testing time [15]. An overview of shaker excitation techniques typically used in GVT context is given in Figure 4.

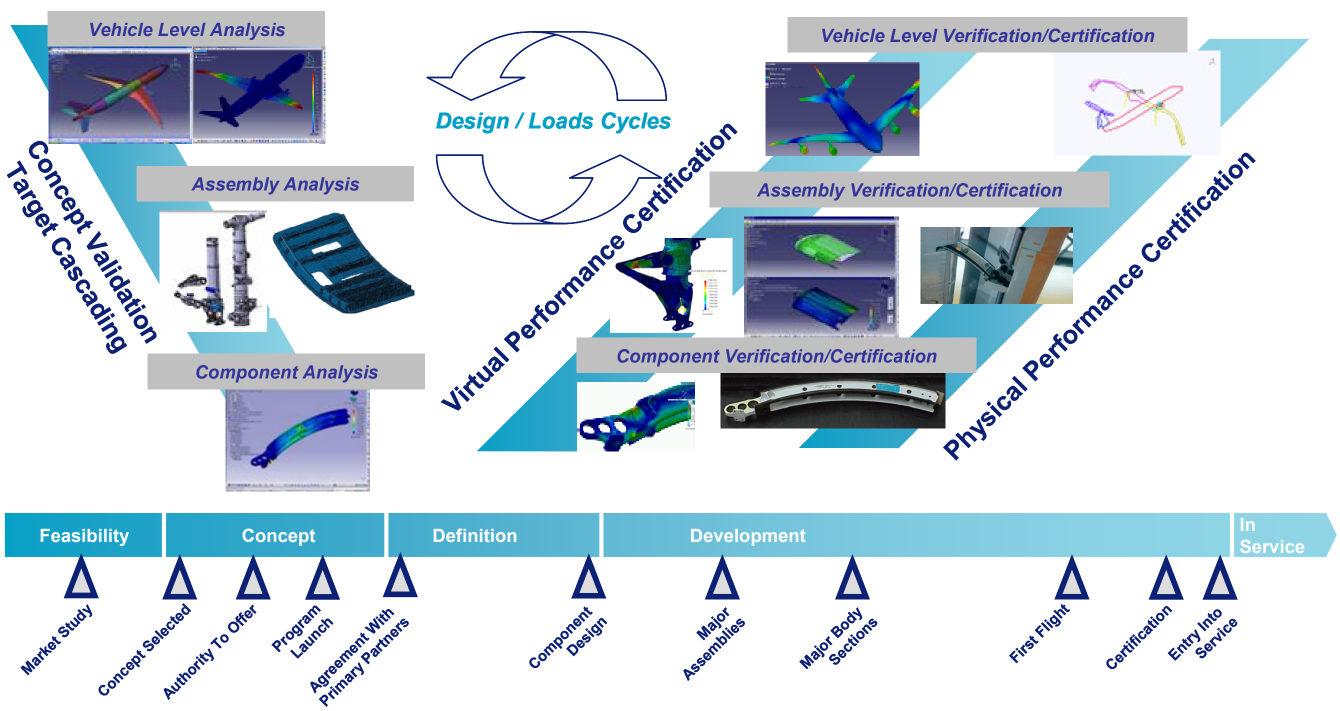

Figure 2: Aircraft development process. The Ground Vibration Test takes place shortly before the first flight.

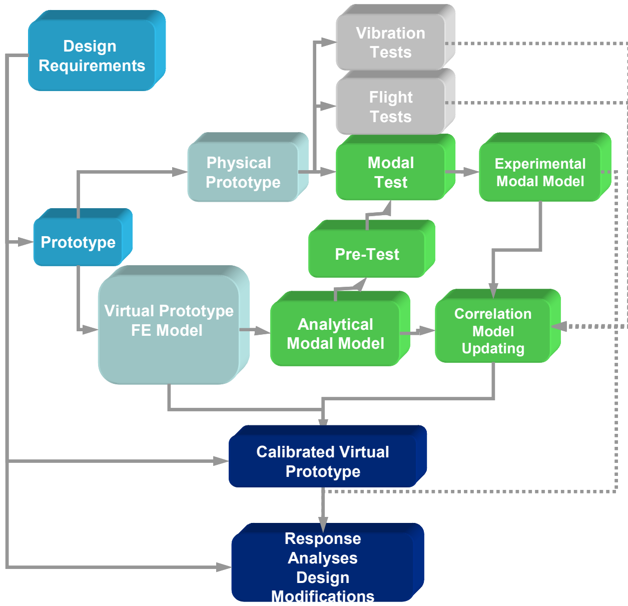

Figure 3: The integrated structural dynamics process. The combination of Test and CAE leads to an increased testing efficiency.

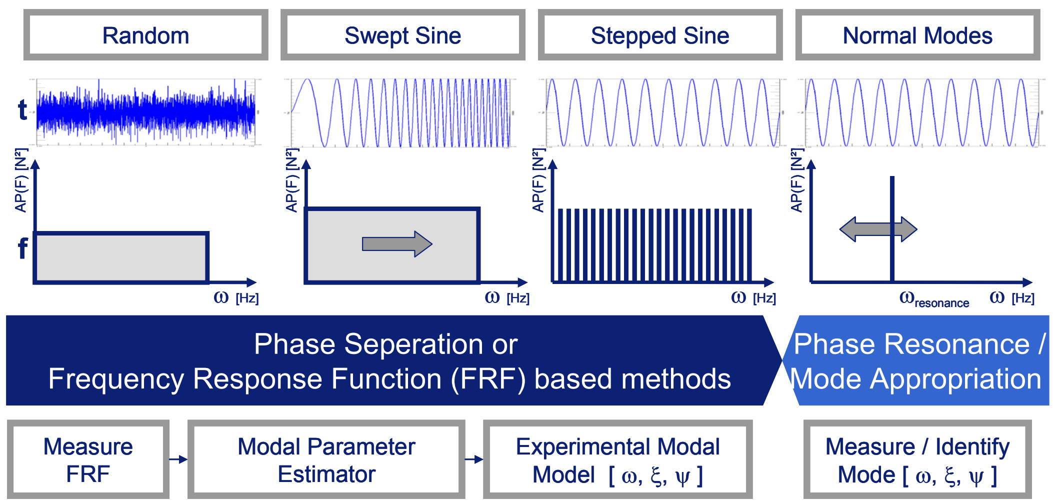

Figure 4. Dynamic excitation signals and modal parameter estimation strategies in Ground Vibration Testing.

2 GROUND VIBRATION TESTING AT EADS CASA

2.1 Test equipment

A GVT campaign typically requires the involvement of different teams from different divisions or companies. In the present case, teams from EADS CASA, Álava Ingenieros and the Engineering Services division of LMS International cooperated. In this section, an overview is given of the recently installed GVT solution at EADS CASA that avoids making compromises on the level of data management and engineering collaboration.

The excitation was provided by LDS permanent magnet shakers model V450, having a sine force peak using forced air cooling of 311 N and a peak-to-peak stroke of 19 mm (Figure 5, Left). Labworks Model PA-138 shaker amplifiers provided the power. The forces injected into the aircraft are measured by PCB 208C03 force cells and the aircraft vibration response is measured by PCB 333B32 and PCB 393B04 accelerometers.

The shakers were controlled and the transducer signals recorded by a 700-channel LMS data acquisition system consisting of 4 SCADAS III front-end frames [16] connected in master/slave mode with 8 sources and 700 measurement channels (V12 modules). The LMS Scadas III is a completely digital front-end with 1 sigma-delta ADC per channel, 24-bit data transfer and ultra-low noise floor. The V12 modules provide Voltage, ICP and TEDS signal conditioning. The sensor connectivity was facilitated by embedding the front-ends in 2 racks with patch panels (Figure 5, Right). Next to a data acquisition PC that processes and stores the data, also two analysis stations are available that allow to perform an on-site modal analysis, ensuring an optimal use of testing time and engineering resources. The PCs are equipped with LMS Test.Lab data acquisition and analysis software [17]. Test.Lab covers all GVT test modes in one user environment: MIMO random, swept sine, stepped sine and normal modes (phase resonance) are all available, working with the exact setup database, allowing a very fast transition from one test mode to another. Furthermore, a seamless integration between test and analysis is realized by offering the analysis capabilities as add-on functions in the acquisition workbooks allowing almost real-time modal parameter estimation which can be considered as an advanced check of measurement quality and data validity during the measurement process.

Figure 5. (Left) Engine shaker excitation. (Right) 700-channel LMS data acquisition system.

2.2 Test conditions

The new GVT system was deployed and the test teams were trained at the occasion of a demonstration GVT on EADS CASA's A310 Boom Demonstrator Aircraft. During the test, the aircraft must be in a condition “ready for flight” and in a configuration as close as possible to the configuration of flight test. The flight control systems (control surfaces, spoilers and airbrakes) are serviceable and kept in 0° position. The flap and slat systems are serviceable retracted and locked. The control systems of the trimmable horizontal tail serviceable and horizontal tail kept in 0° position. The hydraulic systems were switched on (elevator hydraulics, ailerons, rudder). The refuelling boom system was empty and stowed and, finally, the landing gear was extended and the tyres were flattened in an attempt to reproduce ideal free-free boundary conditions.

2.3 Phase separation testing with random excitation

The first test carried out was a random excitation test involving 6 shakers at the wings and the horizontal tail plane (Figure 6, Left). The test duration was around 410 s, representing 40 averages of data blocks of 10.24 s for computing the power and cross spectra, coherences and FRFs. The random test gives a good first indication of the presence of the resonances. Unfortunately, this test suffered from low energy input at low frequency. This is observed in the low force levels at the lowest frequencies (Figure 6, Right) and as a consequence a not correct driving point behaviour (Figure 7) and a poor reciprocity (Figure 8, Left) at these frequencies. A possible solution to this problem is to add masses to the shakers so that the force level becomes the limiting factor of excitation rather than the stroke. The PolyMAX modal parameter estimation method [18] was applied to the random excitation FRFs. The related stabilization diagram is shown in Figure 8 (Right). The PolyMAX method allows analysing a large frequency band containing a high number of modes in a single analysis run.

A quality indicator for the measurements is the (multiple) coherence function that combines the effects of leakage, noise and non-linearity on the FRFs measured at a certain degree of freedom (DOF). Due to the high channel counts typical for GVTs, browsing through all coherence functions is rather cumbersome. An idea is to average the coherences over certain frequency ranges and plot the average values at each sensor location in a geometry display. For instance, the coherences of close and structurally related locations should not differ too much. In Figure 9 (Left) the averaged coherences in a very low frequency band are plotted. It is obvious that the FRF quality at the wings is relatively good, whereas the fuselage and horizontal tail plane locations have lower coherences. Figure 9 (Right) shows a high-frequency band. It appears that the left wing and especially the left engine suffer from low coherences in this frequency band. Most probably the reason for this is that the left wing has only 1 shaker attached whereas the right wing is excited by 2 shakers (Figure 6, Left).

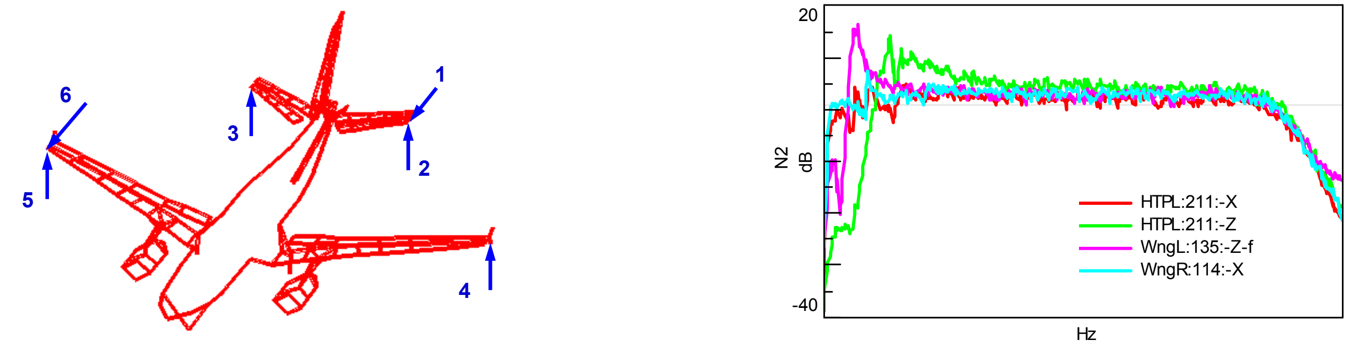

Figure 6. (Left) Shaker locations during random tests. (Right) Power spectra of some input forces.

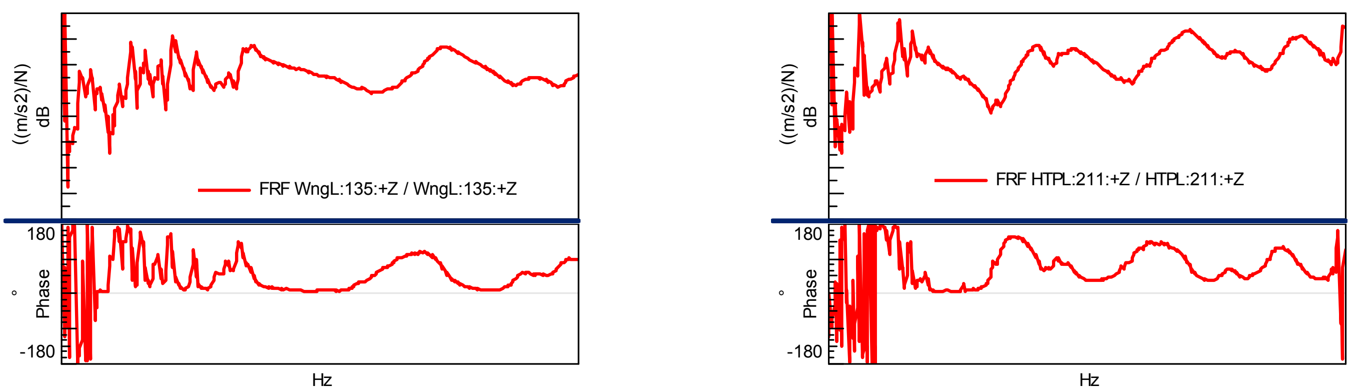

Figure 7. Driving point FRFs.

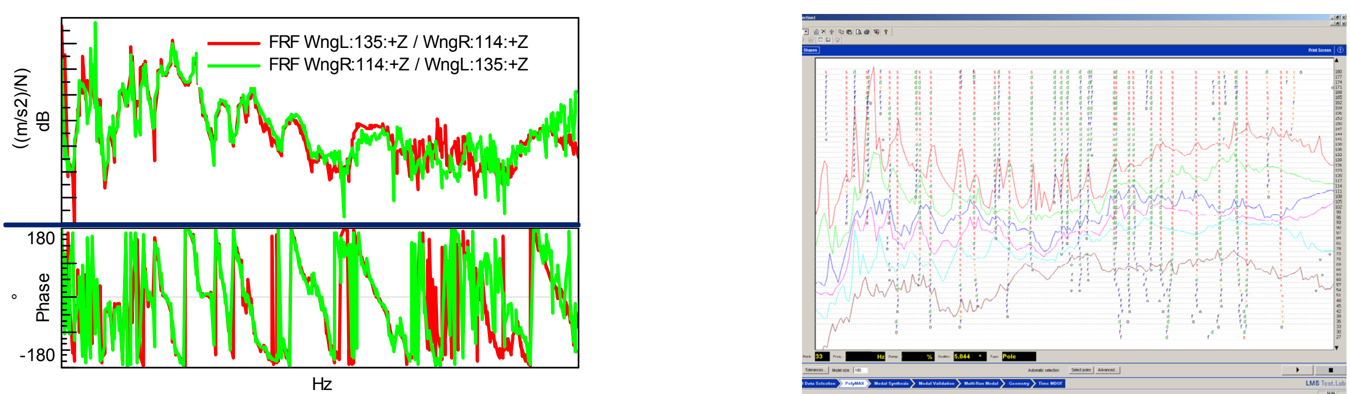

Figure 8. (Left) Reciprocal FRF: Left wing vertical – right wing vertical. (Right) PolyMAX stabilization diagram.

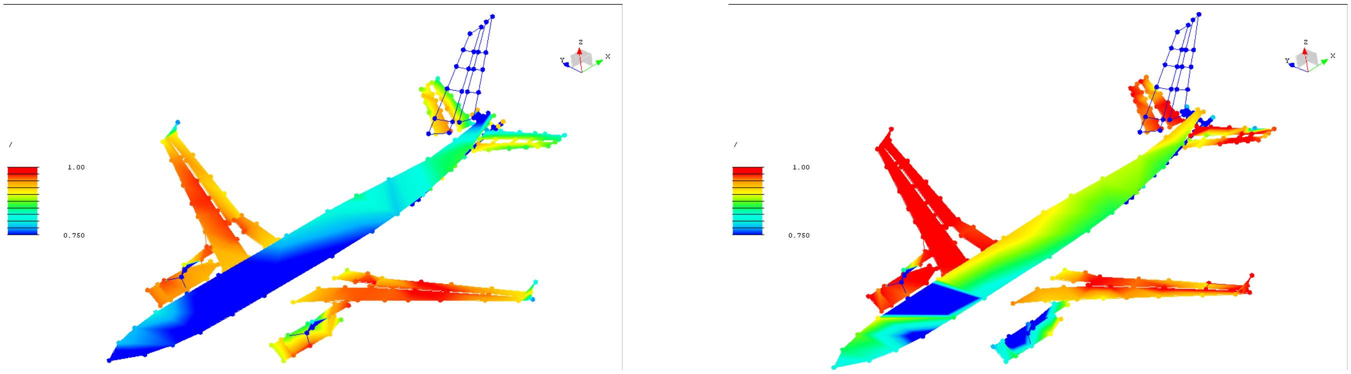

Figure 9. Averaged coherences in a geometry display. (Left) very low frequency band; (Right) high frequency band. The color scale corresponds to averaged coherences between 0.75 and 1.

2.4 Phase separation testing with sine sweep excitation

After the random test, MIMO sine sweep excitation [19] was applied using a pair of 2 shakers attached at different locations (Figure 10). Sine sweep excitation is attractive because it is a good compromise between magnitude of excitation level needed for large aircraft (aircraft is possibly non-linear and broadband excitation levels may be too far away from operational vibration levels) and testing time (testing faster than when using stepped sine) [15]. The FRFs obtained by sine sweep testing (Figure 11) are of better quality than when exciting by random noise. Again, the PolyMAX method was used to estimate the modal parameters from the FRFs (Figure 12).

It is interesting to take a look at the so-called “system FRFs” [17]. These are the transfer functions [N/V] between the Voltages [V] of the source signals and the actual forces [N] measured by force cells between the shaker stingers and the aircraft. As shown in Figure 13, these system FRFs are not flat in the lower frequencies. It is also clear that a Voltage send to a certain shaker has a significant influence on the force measured at the other shaker due to the large shaker-structure interaction that exists in the lower frequency band.

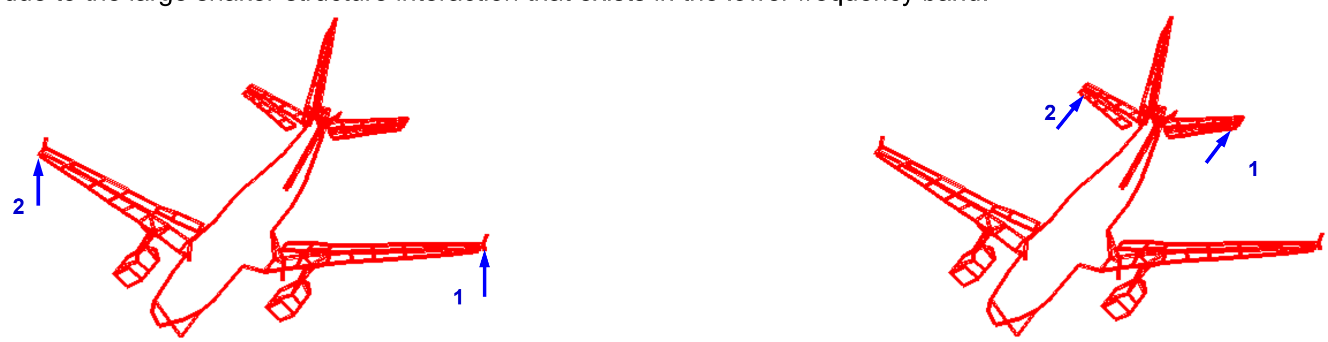

Figure 10. Shaker locations during vertical wing testing and longitudinal horizontal tail plane testing.

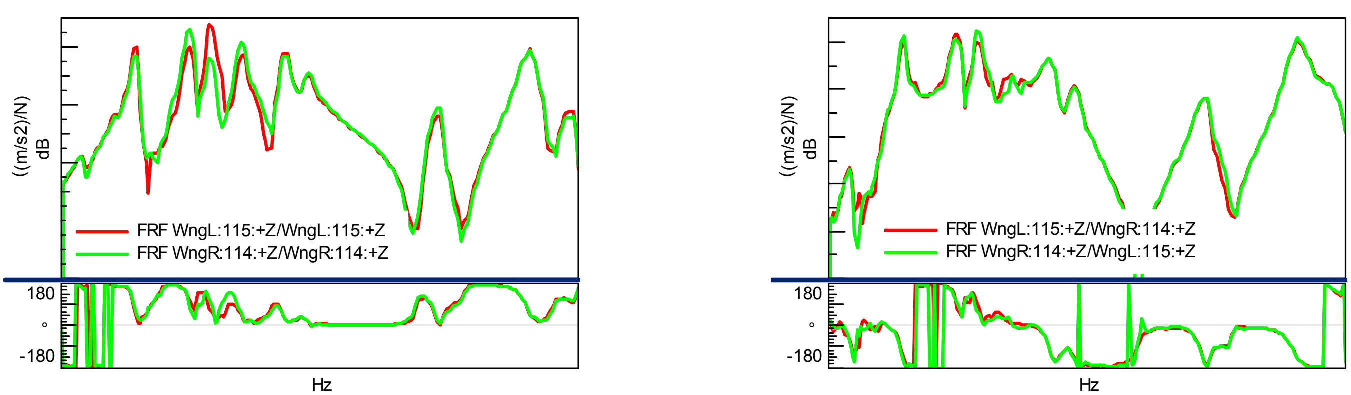

Figure 11. Vertical wing sine-sweep tests. (Left) driving point FRFs; (Right) reciprocal FRFs.

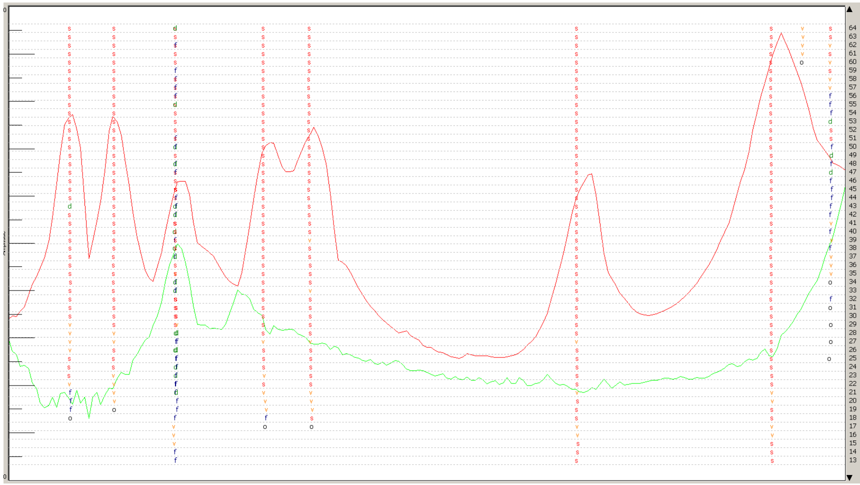

Figure 12. PolyMAX stabilization diagram: lowest frequency band from wing vertical sine sweep tests.

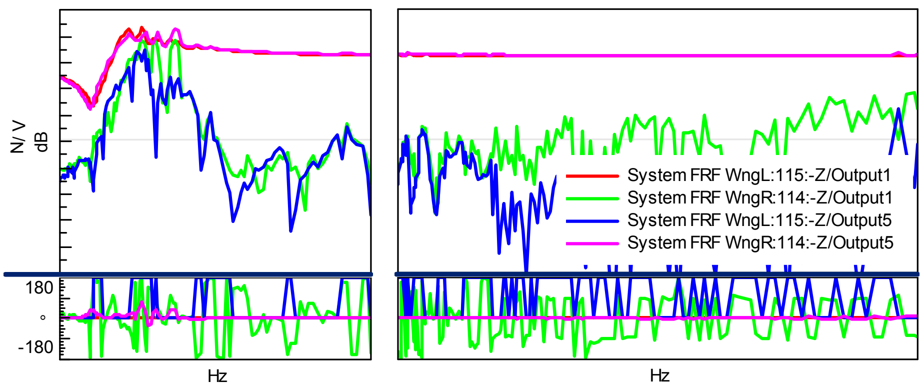

Figure 13. System FRFs [N/V]. (Left) Low-frequency band with large shaker-structure interaction. (Right) High-frequency: flat "system" FRFs / low shaker-structure interaction.

2.5 Phase resonance testing

With a selection of 2-shaker excitation combinations that were used for MIMO sine sweep testing (Section 2.4), the phase resonance (or Normal Modes) testing capabilities of the new GVT solution were verified. The following modes were subjected to phase resonance testing: all engine modes, horizontal tail plane (HTP) roll mode, HTP yaw mode, as well as elevator rotation and twist modes. In general, the automatic tuning algorithm [17] immediately detects the modes under investigation. In cases where the automatic tuning does not converge, a manual tuning is required. Figure 14 shows a mode shape visualisation which is typically used in Normal Modes testing. Respectively the real part (or "coincident", i.e. acceleration response in-phase with force) and the imaginary part (or "quadrature", i.e. phase difference of 90° between acceleration response and force) of the mode shape are shown. When the mode is perfectly tuned, the real part should be zero. Also a non-linearity check was performed at the mode represented in Figure 14, i.e. the HTP 1st bending + wings 2nd bending (S) mode. The tuning procedure was repeated at 5 different shaker force levels. Figure 15 shows the relation between eigenfrequency of the normal mode and force level. In case of a perfectly linear system, this curve should be a horizontal flat line.

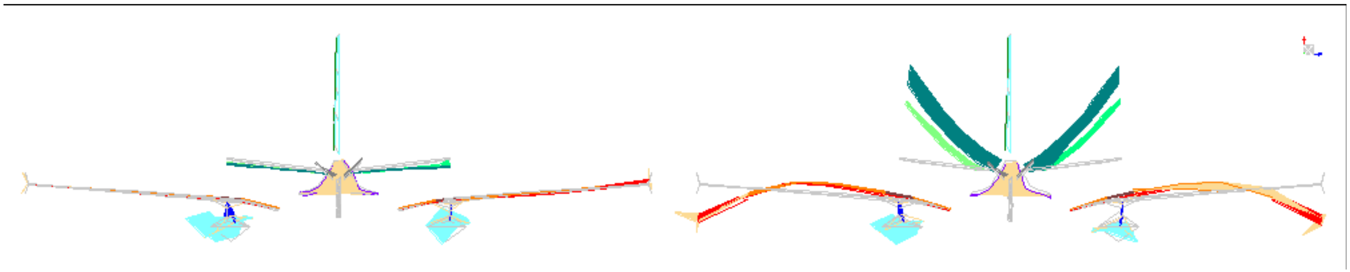

Figure 14. Mode shape visualisation typically used in Normal Modes testing: coincident and quadrature part [17].

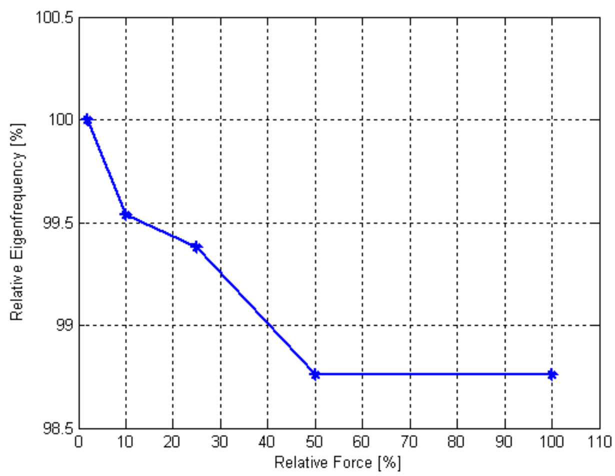

Figure 15. Linearity check for HTP 1st bending + wings 2nd bending (S) mode excited using the phase resonance method at 5 different force levels with 2 vertical HTP shakers.

2.6 Mode shapes

In this section, some mode shapes are shown which have been estimated using the 3 above-described excitation methods (random, sine sweep or phase resonance). Mode shapes from both the A310 (Figure 16 – Figure 18) and the A330 MRTT (Figure 19) are represented. For practical reasons, the vertical tail plane was not measured during the demonstration GVT on the A310.

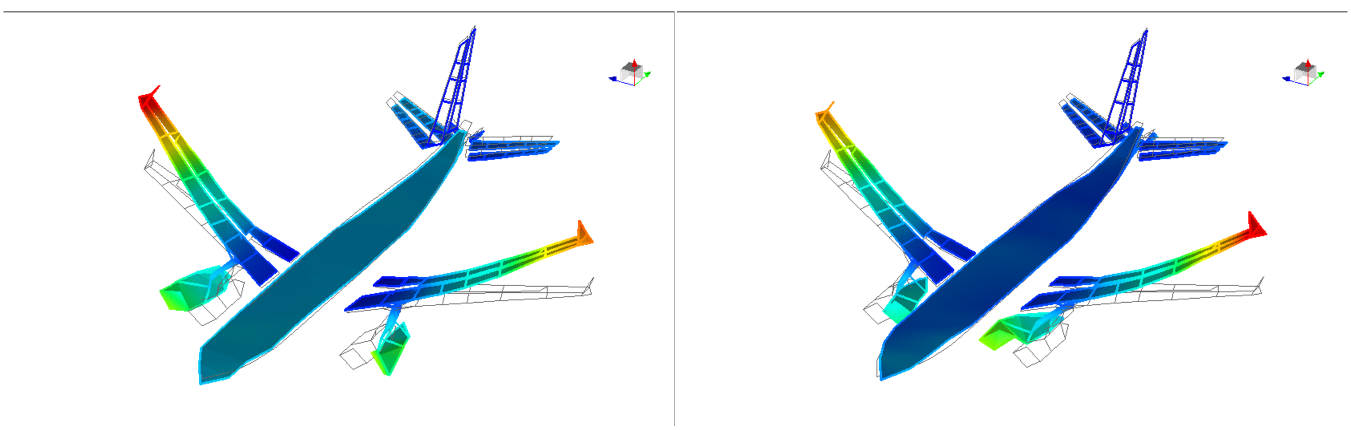

Figure 16. A310 mode shapes. (Left) Wings 1st bending + engine lateral in phase with wings (S); (Right) Wings 1st bending + engine lateral in counter-phase with wings (S).

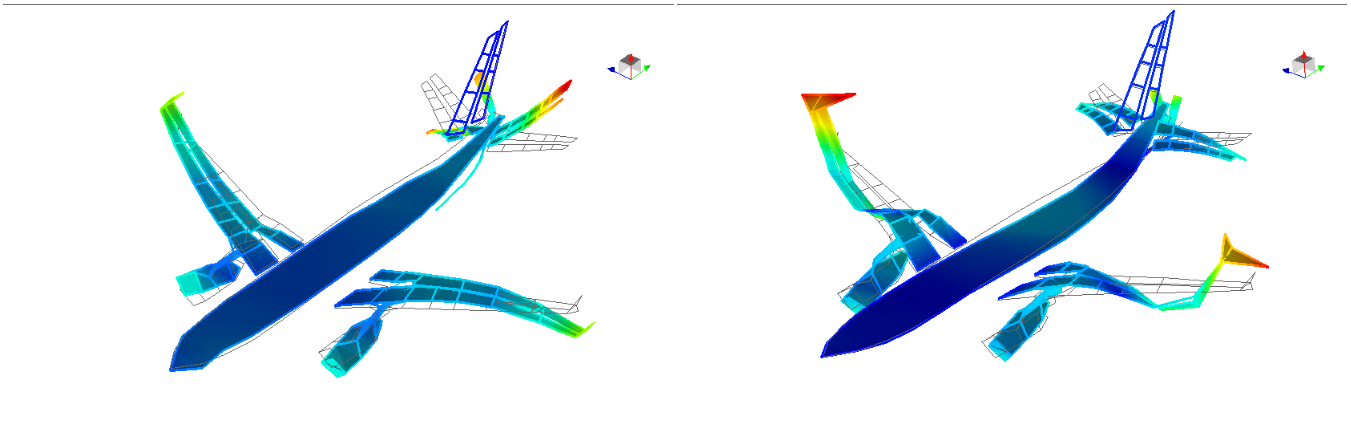

Figure 17. A310 mode shapes. (Left) HTP 1st bending (A) + wings 2nd bending (A - in counter-phase with HTP) + wings for-aft (A) + boom 1st lateral bending; (Right) Wings 3rd bending + HTP 1st vertical bending (in counter-phase with wings) + wings for-aft + ruddervator bending.

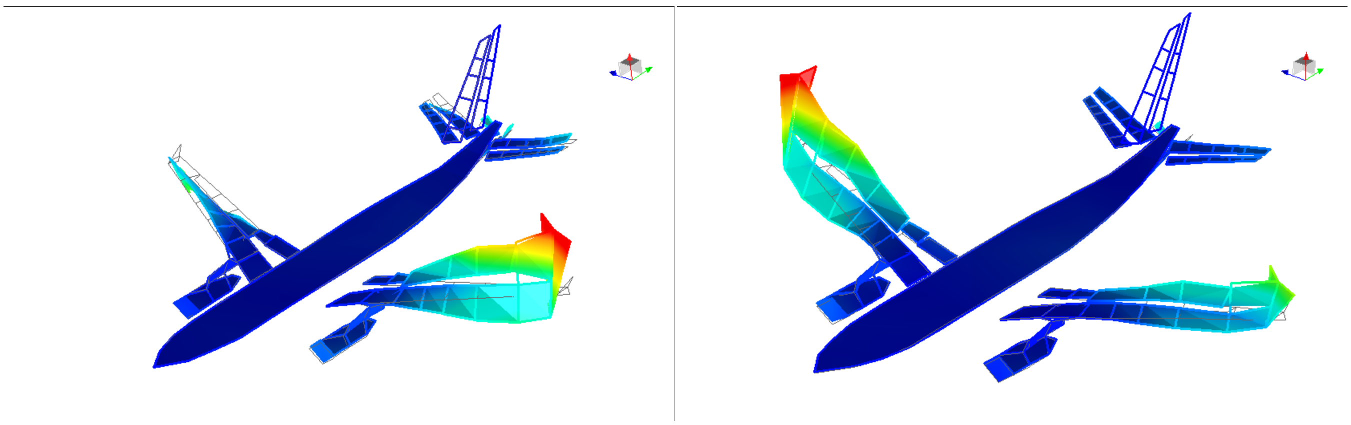

Figure 18. A310 mode shapes. (Left) Left wing torsion; (Right) right wing torsion.

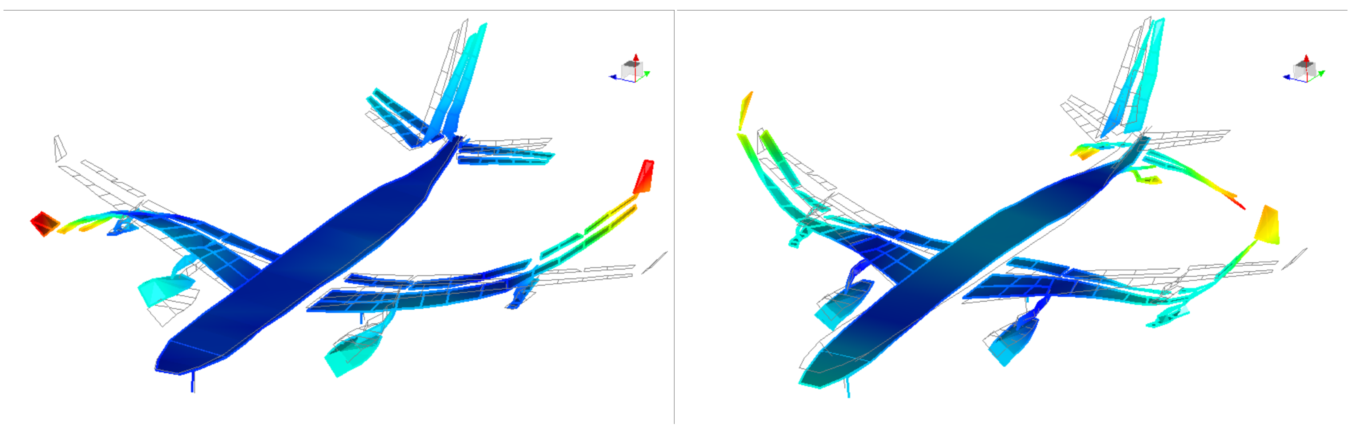

Figure 19. A330 MRTT mode shapes.

3 INTEGRATED USE OF FINITE ELEMENT MODELS

This section discusses the integrated use Finite Element (FE) models during the GVT. The FE technique is the standard tool for structural analysis. The FE model available before the GVT can be used to make predictions on the aircraft dynamic behaviour and to optimize the test arrangement and duration. As an example, the FE model of the A330 MRTT is represented in Figure 20.

Pre-test simulations make use of:

- Preliminary FE-model
- Estimated aircraft GVT masses
- Estimated GVT (close to free-free) boundary conditions.

The normal modes obtained from the FE model before the test represent an accurate enough estimation of the aircraft eigenfrequencies and mode shapes. This information is used to plan the test, i.e. to determine excitation conditions, shaker locations and accelerometer locations.

During the first days of the GVT, the aircraft is weighted and the rigid body eigenfrequencies are measured. With these results, a second loop of normal modes calculations is performed. Figure 21 shows an example of the mass corrections to the "nominal" FE model which are needed to match the masses of the actual aircraft configuration which is being tested during the GVT. Typically this correction is a reduction to account for missing elements like passenger seats, galleys, etc. Figure 22 shows how tuning the FE model to accurately reflect the aircraft mass distribution and test boundary conditions leads to an improved prediction of the rigid body modes. Blue dots show the position of the estimated rigid body eigenfrequencies before the GVT while the green dots show the final rigid body eigenfrequencies right in the 45 degrees line when comparing numerical values (FE) with measured values (GVT).

Once the model has the correct test-measured masses and test-measured boundary conditions, the right comparison between all flexible modes can be made to know whether the FE model needs to be updated or not. In case that the frequencies of all modes lie inside a reduced margin (lower than 5%) the model needs not to be updated. On the contrary, for larger differences the model needs to be corrected. The correction needs to account for local effects [20] or absent components [21]. A good approach for model updating is the "delta stick" approach in which the missing stiffness is introduced via external stick models running thru each component elastic axis.

Figure 23 represents the comparison of measured and computed normal modes for the A330-MRTT showing that all frequencies are located very close to the 45 degrees line thus indicating a very good matching. More details on the discussed results can be found in [22].

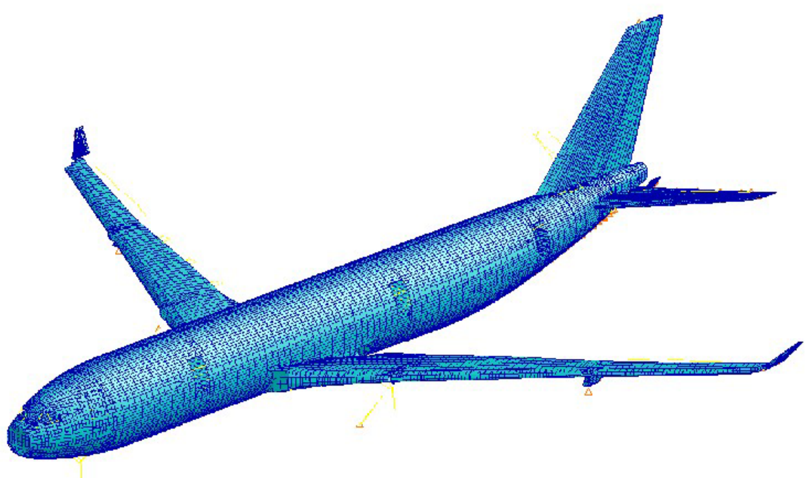

Figure 20. A330 MRTT FE model [22].

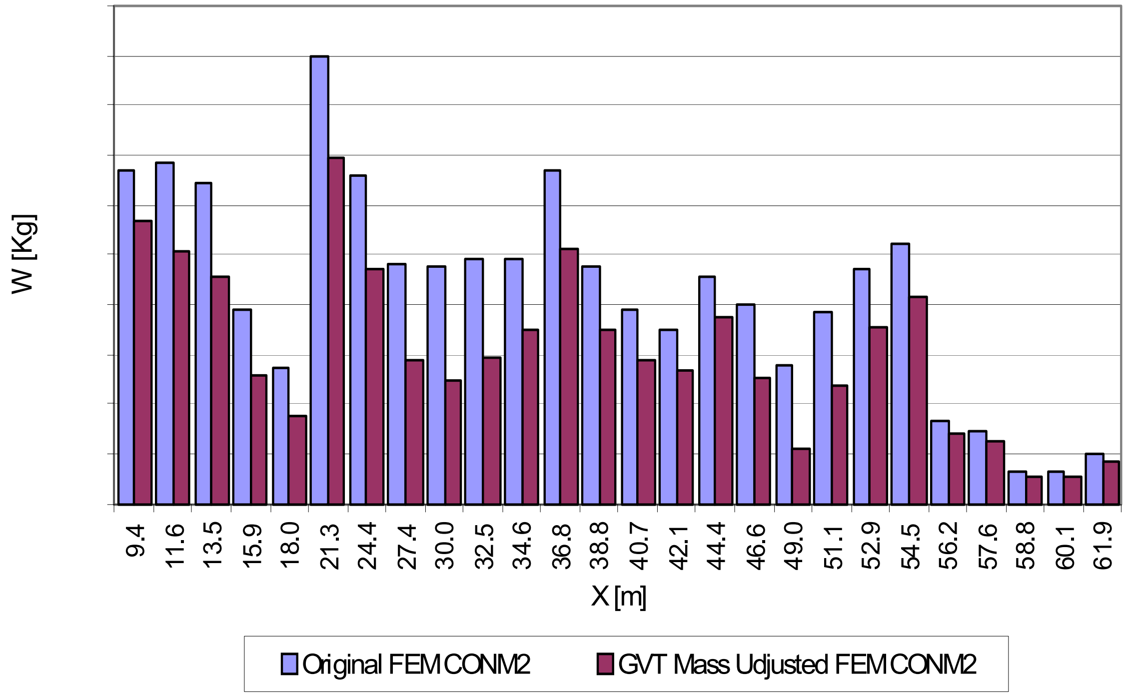

Figure 21. Comparison OWE (operational weight empty) and GVT-adjusted fuselage mass distribution [22].

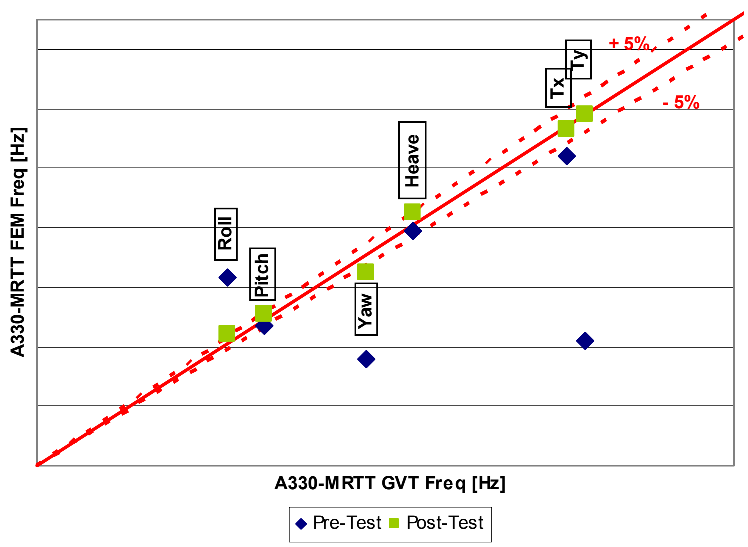

Figure 22. A330 MRTT FEM-GVT comparison of the eigenfrequencies of the rigid body modes [22].

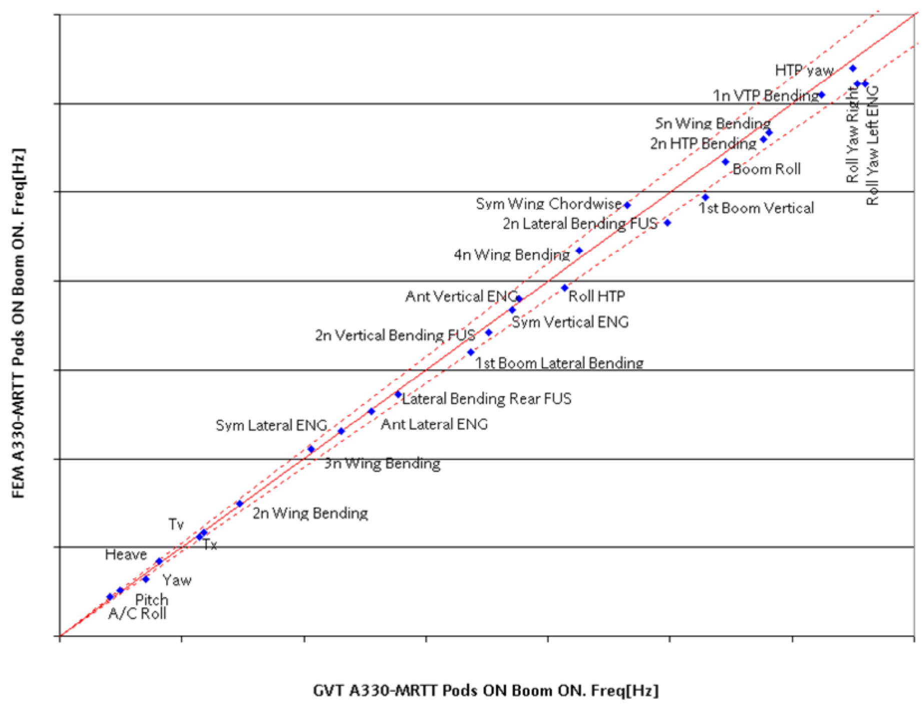

Figure 23. A330 MRTT FEM-GVT Normal Modes frequency comparison [22].

4 CONCLUSIONS

This paper showed how a new 700-channel Ground Vibration Testing system was successfully deployed during a demonstration test on the A310 and later also successfully used during a certification test on the A330 MRTT. The new hardware and software solution is designed to cope with the main challenge of today's GVT campaigns i.e. reduction of the testing and analysis time without compromising the accuracy of the results. Highly efficient testing is made possible by the integration of complementary excitation techniques in a single software environment. Built-in modal analysis capabilities ensure that the test data are validated and the aircraft modal parameters are available almost in real-time during the test. The paper also demonstrated that the integrated use of Test and FE models allows an optimal planning of the GVT and has the advantage that an updated FE model is available shortly after the test.

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