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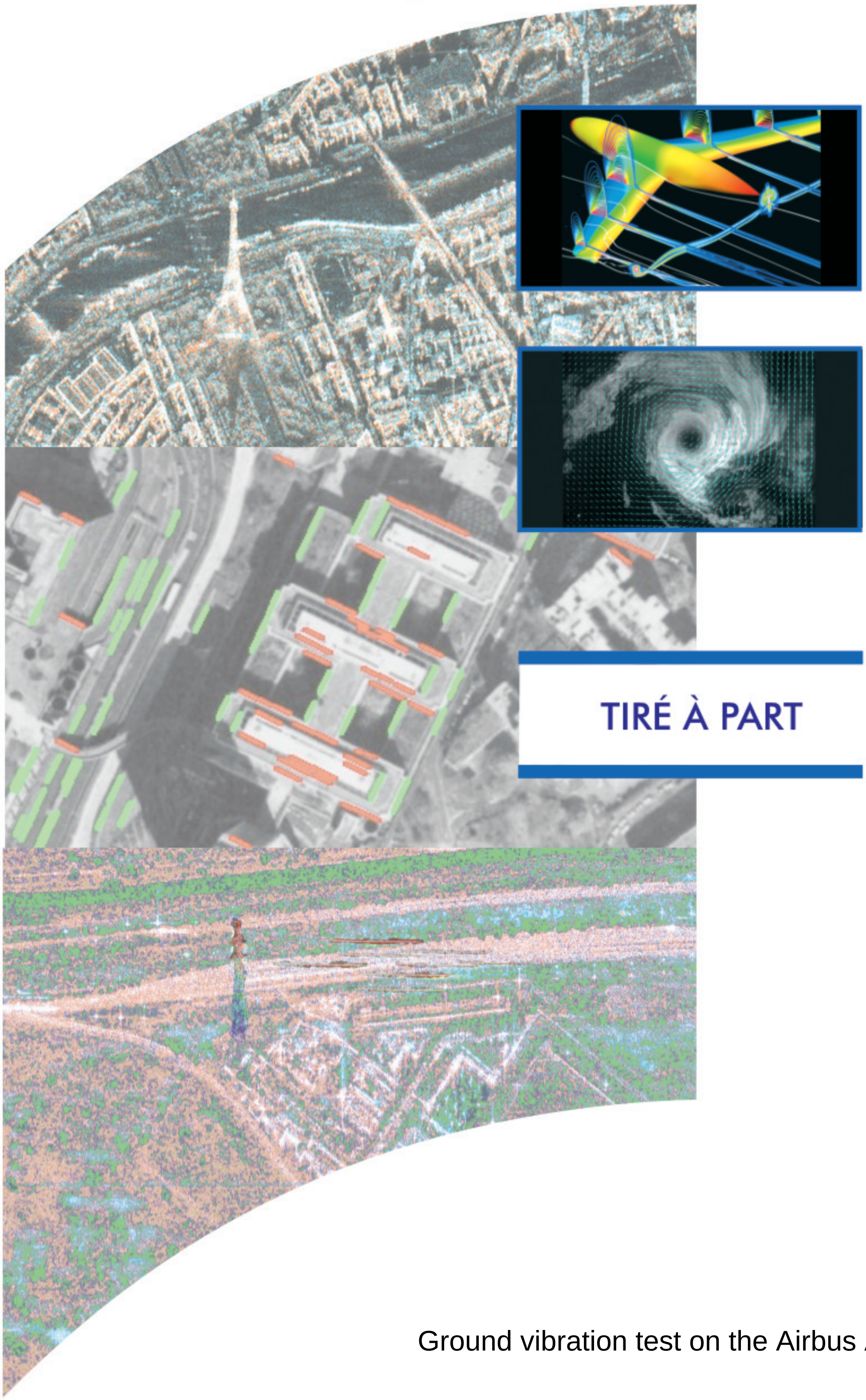

TIRÉ À PART

Ground vibration test on the Airbus A380-800

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Essais de vibrations au sol de l'Airbus A380-800

par

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Résumé Original :

This paper explains the keynotes of the ground vibration test of the Airbus A380, A380-800 version powered with Rolls Royce Trent 900 engines, test campaign carried out by ONERA and DLR on Airbus behalf.

The technical requests, means and methods used and specific developments for this test are treated.

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Ground Vibration Test of the Airbus A380-800

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Key words: Ground Vibration Test, Modal Analysis

Abstract. This paper explains the keynotes of the ground vibration test of the Airbus A380-800 version powered with Rolls Royce Trent 900 engines. The test campaign was carried out by ONERA assisted by DLR on behalf of Airbus. The technical requests, means, specific developments and methods used for this test are discussed.

Glossary:

ADC:	Analogue Digital Converter
Chan:	channel
FRF:	Frequency Response Function
GVT:	Ground Vibration Test
MIMO:	Multiple Inputs Multiple Outputs
MIF:	Modal Indicator Function
PRM:	Phase Resonance Method
PSM:	Phase Separation Method
SIMO:	Single Input Multiple Outputs

1 INTRODUCTION

On behalf of Airbus, the ONERA specialized team (Structural Dynamics and Coupled Systems Department, Experimental Aeroelasticity, and Modal Identification Unit) in cooperation with its German counterpart team from DLR Institute of Aeroelasticity in Göttingen carried out the first ground vibration test of the Airbus A380-800. This test campaign took place in the painting hall of the new Jean-Luc Lagardère (Aéroconstellation) production site in Blagnac (France) during January and February 2005 (View 1:).

The aim of such a test, non destructive one, is to deliver to Airbus, in addition to specific requests, the modal characteristics of the aircraft which are : resonance frequencies, mode shapes, structural damping values, and generalized masses. These data allow Airbus to update and validate the Finite Element Model of the aircraft in order to ensure the flight safety with respect to flutter (aerodynamic instability), the structural load predictions, the passenger comfort, and the prediction of the aircraft and systems behaviour facing a fan blade off event, source of windmilling excitations.

2 AIRCRAFT DESCRIPTION

Wing span:	80 m
Length:	63 m
Height:	24 m
Max Take Off Weight (MTOW):	560 t

Capacity : from 555 to 806 passengers
Landing gears: 5, one nose, two wing, and two body landing gears, 22 wheels in total.
Control surfaces all divided: 6 ailerons (3 per wing), 4 elevators, and 2 rudders.

Aircraft configuration during the GVT

The GVT was carried out on the A380-800 MSN#2 (Master Serial Number 2), the MSN#1 being preparing its first flight. While the outboard engines (Rolls Royce Trent 900) were real ones, the inboard ones were replaced, due to unavailability of the real items, by dummy masses replicating the actual mass and inertia of an engine. Metallic ballasts located at the front of the cargo deck and water tanks at the front of the main deck ensured the longitudinal balance compatible with the boundary conditions of the aircraft. For the previous tests carried out on Airbus A340 and A330 aircraft, the connection to the ground used 3 pneumatic suspension devices attached to the landing gear axles in place of wheels allowing low frequency quasi rigid-body modes (~ 0,8 Hz for the aircraft heave mode). Airbus selected, for the first A380 GVT, the aircraft to be installed on its 3-jack configuration, the landing gears being down and locked, fully extended but free off the ground. This configuration was selected among several other possibilities by means of short tests carried out during the previous GVT campaigns on A340 in the years 1999 and 2001. Consequently, taking into consideration the flexibilities of the jacks and measured data from accelerometers installed on the jacks themselves allowed Airbus to validate and update the Finite Element Model of the aircraft.

3 GVT OBJECTIVES

The GVT campaign in January/February 2005 in Toulouse included several tests devoted to specific objectives:

(a) Modal Identification of the aircraft:
- For the empty fuel configuration [0 – 30 Hz] frequency range
- For a partial fuel filling configuration [0 – 30 Hz] frequency range
- For some failure cases of control surface actuators

(b) Measurement of frequency response functions (FRFs) for windmilling purpose, separate single swept-sine excitations applied on the left hand side engines in both lateral and vertical directions (reference [3]) [0 – 45 Hz] frequency range

(c) Modal identification of the front cargo deck, the main deck and the upper deck, excitation by means of seismic exciters [2 – 25 Hz] frequency range

(d) Modal identification of the left hand flaps in their fully extended configuration (view 5) [0 – 20 Hz] frequency range

4 TEST EQUIPMENT AND STAFF

	Numbers	Marks
Drive signals	16 chan. 4 chan.	ONERA for PRM VXI Technologies for frequency range excitation (for PSM)
Exciters	13 2 2	PRODERA 550N long coil stroke, RMS 2200N, RMS 700 N
Force measurements	16 5	Current pick-up at amplifiers of exciters (*) PCB (3) et Kistler (2) Force cells (*)
Accelerometers	500 350	PCB Entran
conditioners	896 chan.	PCB (496 chan.), DLR (384 chan.) and Hewlett Packard (20 chan.)
ADC	896 chan.	VXI Technologies
Computers		Dell PC, HP PC, Carri Systems PC, Sun and HP Unix Workstations

(*) Remark : in order to compensate for the low frequency phase shifts of the accelerometers and their associated conditioners, an analogue electronic filter was used for the force measurement channels.

Accelerometer distribution:

- For aircraft modal identification : 450 accelerometers
- On systems, for windmilling purpose : 260 accelerometers
- For modal identification of decks: 80 accelerometers
- Additional accelerometers (driving points etc.) : 60 accelerometers

In order to reduce both the installation phase duration and the length of cables, the accelerometers devoted to the fuselage were glued inside the aircraft. Scaffoldings were installed under wings, horizontal stabilizer, and engines for the accelerometer installation, the work on the aircraft and the handling of the exciters. A 4-axis mobile plate-form (3 translations, 1 vertical axis rotation), attached to the crane of the hall, was used for working on vertical fin and for supporting the related exciter (View 3:).
A specific shelter (View 2:) was installed by Airbus to be used by ONERA – DLR as measuring and post-processing laboratory. Digitalisation equipment were installed close by this shelter (View 4:), whereas the amplifiers of exciters were distributed near the excitation locations.

ONERA/DLR people on test site:

- 25 people during installation and refurbishing phases
- 6 engineers and 7 technicians for measuring-analysing phases, in 2 shifts, typically working from 7h00 A.M. to 9h30 P.M.

Test campaign schedule:

- 2 days for pre-installation, shelter equipment, off aircraft presence ;
- 5 days for accelerometer and exciter installation, cabling, and set-up validation ;
- 23 days for measurement and preliminary analysis ;
- 1 day for refurbishing ;
- 2 days for test equipment storage, off aircraft presence.

5 METHODS

5.1 Test strategy

According to the technical request placed by Airbus, the test strategy promoted by ONERA and DLR since 1999 was used (references [1] and [2]). This strategy consisted of (Figure 1:):

1) modal identification method (PSM) based on mathematical curve fitting of FRFs stemming from time domain data for the majority of modes, and
2) classical modal tuning method (PRM) based on the experimental adjustment of sine excitation frequency and force pattern fulfilling the single structural mode excitation ("all" accelerometer responses orthogonal to the sine generator function). This accurate but time-consuming method was applied only for modes of special importance.

5.2 Data processing

The data from swept-sine excitations were analysed instantly after one run, during the follow-on measurement. Two means of spectral analysis were applied to the time domain data :

1) the spectra were directly computed via Fourier transform without any averaging using the Fast Fourier Transform (FFT), and
2) the time series were partitioned into blocks with a large overlap weighted by a Hanning window, Fourier transformed, and the resulting spectra were averaged by means of the peak reference hold (PRH) technique.

Both methods have advantages and shortcomings. The first method tends to deliver noisy data in the high-frequency range, a fact that may spoil the further analysis. This problem is overcome by the averaging procedure of the second method. However, the windowing technique may result in leakage effects in the low-frequency range, especially in case of lightly damped modes.
The noise effect on the resulting FRFs, computed using spectra from pure FFT, is illustrated in figure 9. In this high-frequency domain, the PRH averaging technique delivers accurate data. Figure 10 demonstrates the leakage effect of the averaging procedure in the low-frequency range. The height of the peaks is underestimated leading to an overestimation of the damping. During the GVT, the FFT method was applied as the standard procedure leading to accurate estimation of modal parameters in the low-frequency range. In case of problems with the modal analysis in the high-frequency range, the second method was then applied specifically for this domain.
The FRFs were analysed in three steps :

(1) The multivariate mode indicator function (MMIF) is computed. It exhibits minima in case of resonances.
(2) The absolute values of the real parts and the absolute values of the imaginary parts of all FRFs are averaged. This function exhibits local maxima in case of resonance of the modes which contribute significantly to the structural response of the test run being analysed.
(3) The FRFs are modally analysed by the Frequency Domain Direct Parameter Identification (FDPI) method to extract the modal parameters (resonance frequency, damping ratio, generalized mass, residues). FDPI is a phase separation technique implemented in the LMS Cada-X software package.

The best possible modal model must be derived from the results of the different test runs. In-house software tools, so-called *correlation tools* or *mode filtering tools*, were developed to collect all relevant information from the FRF data, to easily display them, and to compare and correlate the modal parameters from different test runs. Quality criteria from modal identification like the MIF value and the modal participation factor are stored together with the modal parameters and mode shapes in the same data set in order to facilitate the selection process.
The following information is stored for each identified mode:

- resonance frequency ;
- viscous damping ;

- identified generalized mass ;
- normalisation point for the generalized mass ;
- mode indicator function (MIF) value indicating the phase purity of the identified modes ;
- participation factor P measuring the relative importance of the mode for the FRF ;
- the excitation level of the mode in the particular FRF (see section 6.4).

The selection process for the modal model is supported by the correlation tools. All above mentioned information can be calculated or extracted from the database using these interfaces. Additionally, correlation functions like the MAC value or the cross-orthogonality check can be used to identify multiple-extracted modes or to detect modes which are not yet included in the modal model.

5.3 Used Software

Excitation driving	**ONERA** + **IDEAS Test** for frequency range excitations **ONERA** for PRM
Acquisition – visualisation	**IDEAS Test** for frequency range excitations **ONERA** for PRM
Data Treatment	**ONERA** for frequency range excitations **ONERA** for PRM
Modal Identification	**LMS** for frequency range excitations (PSM)
Modal data filtering	**DLR** for PSM modes
Data delivery	**ONERA** and **DLR** for data and plots delivery

6 A380 GVT SPECIFIC DEVELOPMENT

Among the developments carried out by ONERA and DLR for this test campaign, we can note :

- the improvement of the vibration modes filtering and modes correlation tools ;
- the modification of modal exciters on tilting seismic devices ;
- the development of the Jack Safety Device (section 6.1), which gives indications to the measurement operator about specific aircraft-jack connection response levels and stops authoritatively the excitation forces if the response levels exceed pre-determined thresholds.

Regarding to the methods, we can quote:

- the development of an excitation force notching process (section 6.2) ;
- the improvement of the virtual single excitation input process (section 6.3) ;
- the Modal Characterisation Functions from PSM modal identifications, exhibiting the non-linear structural behaviour (section 6.4).

6.1 Jack Safety Device

Vibrating an aircraft installed on jacks entails the risk of instable states. Figure 6 shows the configuration. More precisely, an aircraft pitch motion might be induced when vertically exciting the horizontal stabilizer with large forces. A safety device, the so-called *Jack Safety Device*, was developed in order to avoid any critical states and, hence, to ensure the safety of the aircraft during the excitation phases of the GVT. Figure 5 explains its philosophy. For each channel, a limit value is defined well below a value which is considered to be critical for this specific signal. An example for a critical value would be an acceleration of the aircraft in the vertical direction of one g close to the jack.

The measured values for each channel are used twofold: firstly, a violation of the limit value is checked by analogue comparators which have the ability to instantly cut the excitation and, secondly, the signals are recorded by a data acquisition system which allows the evaluation of the responses of the structure by means of a software which provides an online display of the present values and which delivers a warning when a certain adjustable threshold is exceeded. It is important to note that the analogue path represents the actual “safety device” with an automatic shutdown of the excitation whereas the digital path is for information only. The latter allows to reduce the excitation level well before the automatic shutdown steps in. The 12 monitored channels included 3 signals streaming from weighting units mounted atop the jacks and 9 acceleration signals on the jacks (the 3 translations for each jack).

6.2 Excitation Force Notching

In order to use at their best capabilities and performance of the various exciters regarding to each structural excitation location impedance, and also to preserve the structural integrity of the exciters, their interface with the structure and the structure itself, an Excitation Force Notching process, equivalent to the one known for satellite qualification tests, was developed (Figure 2:).

<u>Process Steps:</u>

Phase 1:

- preparation of time domain data input blocks (parameters : constant amplitude, starting and final frequencies, sweep rate, sample frequency) ;
- Global tuning of ADC input range levels preserving from overload risks ;
- 1st excitation with low excitation-force level (20% of the maximum force available) during which time domain data blocks are played as excitation signals and time domain responses of sensors are collected ;
- Computing FRFs from the time domain data.

Phase 2:

- From the FRFs of Phase 1, time domain data input blocks preparation : determination of the frequency steps and their related constant input signal amplitudes with respect to :
  - the parameters used for the Phase 1 ;
  - the constraints established by the customer ;
  - the maximum force expected for the new measurement.

  All this, of course, is performed according to the linear structural behaviour hypothesis ;
- ADC input range level determination for each channel preserving from overload risks ;
- 2nd excitation with high excitation force level during which the new time domain data blocks are played as excitation signals and time domain responses of the sensors are collected ;
- Computing FRFs from the time domain data.

6.3 Virtual Single Driving Point Process

Some previous GVTs and studies demonstrated that the best adapted excitation waves for the present test and structure context would be the exponential rate swept-sine. Except specific request or specific situation, the symmetry of the aircraft was used to apply symmetric and antisymmetric excitations, which allowed, firstly to distinguish the symmetrical and antisymmetrical structural modes which is a welcome benefit in case of high modal density (16 modes within 2 Hz at low frequency) as long as the modes are not asymmetric, and secondly to double the excitation energy.

Using correlated excitation, instead of computing the FRFs as MIMO from the combination of the measurements issued from symmetrical and antisymmetrical excitations, is not compatible with the force notching process and could be risky in case of asymmetrical non-linear modes. Consequently, the concept of the virtual single excitation driving point, which allows the use of the existing SIMO process, was used (reference [3]).

$$P(\omega) = F_V \times \dot{X}_V = \sum_{exciters} F_e \times \dot{X}_e$$

$P(\omega)$: *Complex Power*

F_V : *Virtual single constant force*

$\dot{X}_V$: *Velocity response of the virtual driving point*

F_e : *Actual excitation force acting at the driving point e*

$\dot{X}_e$: *Velocity response of the actual driving point e*

6.4 Modal Characterisation Functions from Swept-sine Testing

It is well-known that the dynamic behaviour of real structures deviates from linearity to a certain extend. In case of aircraft structures, sources of non-linearity are, e.g., the bearings of the engines, the landing gears, if extended, and control surfaces like rudders, elevators and ailerons. In most cases, the corresponding dynamics can be described as *weakly non-linear*, i.e. it is possible to describe them in terms of linear modal parameters like eigenfrequencies, modal damping, generalized masses, and mode shapes, but these parameters might depend on the excitation level of the structure. Strongly non-linear effects which involve, e.g., very asymmetric resonance peaks including jump phenomena, should be excluded.
The linearity of modes is traditionally checked by appropriating the modes at various excitation levels in order to produce so-called linearity plots in which, e.g., the eigenfrequency of a mode is plotted as a function of the excitation level. The corresponding functions are called "modal characterization functions", linearity plots or impedance plots. In case of a linear mode, the corresponding curve should be a horizontal line. Any deviation, thus, indicates a non-linearity. The excitation level is given in terms of a maximum (or modal) displacement or a generalized force:

$$p_{Gen} = \sum_{i=1}^{n} p_i u_i / u_{\max}$$

where p_i are the individual forces, u_i are the driving point amplitudes, and u_{max} is the maximum displacement for the appropriated mode.
In swept-sine testing, the necessary quantities (modal amplitudes, effective input forces, eigenfrequencies) are not directly measured like in the case of modal appropriation, but they can be derived from the measured frequency response functions using additional information about the swept-sine run like excitation force amplitude and sweep rate. Figure 7 depicts the necessary steps to accomplish this calculation. The time domain data of several swept-sine runs are processed and, from the resulting frequency response functions (FRFs), modes are identified via modal analysis. The resulting modal parameters and residues are used together with the force amplitude and sweep rate to compute the generalized force and the modal displacement for each identified mode. From this information, it is possible to generate linearity plots for selected modes. The applied method is documented in detail in reference [4].

The generalized force can be varied by different means:

1. Variation of force amplitude ;
2. Variation of force introduction point ;
3. Variation of sweep rate.

Global modes of the structure can be excited using very different load introduction points. The efficiency of the excitation, i.e. the load level, depends on the amplitude of the mode shape at these points. Thus, for global modes, method 2 is widely applied. The efficient excitation of control surface modes is only possible by exciting the control surface itself. In order to obtain different load levels it is thus necessary to apply method 1, i.e. using swept-sine runs with different force amplitudes. Method 3 is not practically applied, because its effect on the load level is, in general, smaller than the effect of the other methods.

In the preparatory stage of the A380-800 test, this method was implemented into an existing modal analysis environment by the following procedure:

1. For all modes from all runs used for further treatment the eigenfrequency, modal amplitude, and the generalized force were computed and stored ;
2. During the selection (filtering) process to obtain the best modal model, all non-selected modes, which can be associated to a selected mode in the reference data set, were unambiguously labelled ;
3. A separate graphical user interface (GUI) collected all identified modes of a certain type and either produced on-line linearity plots for a selected mode or exported the necessary information in an ASCII-format for further off-line treatment.

Figure 8 shows an example of a linearity plot for a control surface mode. Typically, a drop of the eigenfrequency is observed while the excitation level increases, and a saturation effect becomes apparent at high levels. During the test, it was expected to reach this saturation range.

7 FIRST TEST STATEMENTS AND CONCLUSION

To illustrate the size of the A380-800 GVT campaign, we can mention:

- 25 km cables ;
- 50 excitation locations ;
- 65 GB of collected binary data ;
- 112 vibration modes coming from PSM for the empty aircraft configuration (Figure 3:) ;
- 8 modes per Hz in low-frequency range for the empty aircraft configuration (Figure 4:) ;
- 38 test runs and approximately 30000 FRFs for windmilling purpose.

Developments carried out by ONERA and DLR, as a matter of test strategy, equipment and methods, have demonstrated their pertinence in such industrial context of an ambitious technical goal regarding to the size of such an aircraft.

The motivation and the perfect cooperation of AIRBUS, DLR and ONERA teams allowed to solve the foreseen and unforeseen difficulties and fulfil the technical request within the allowed test duration.

ONERA and DLR are continuing their cooperation in order to reinforce the progress made as a matter of data quality and accuracy and of test productivity.

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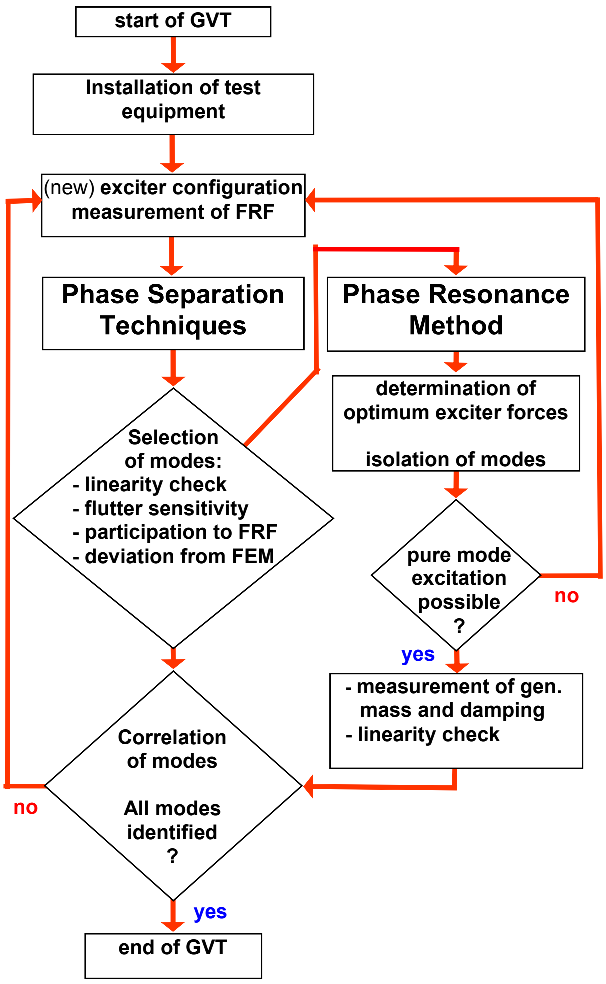


Figure 1: Test strategy

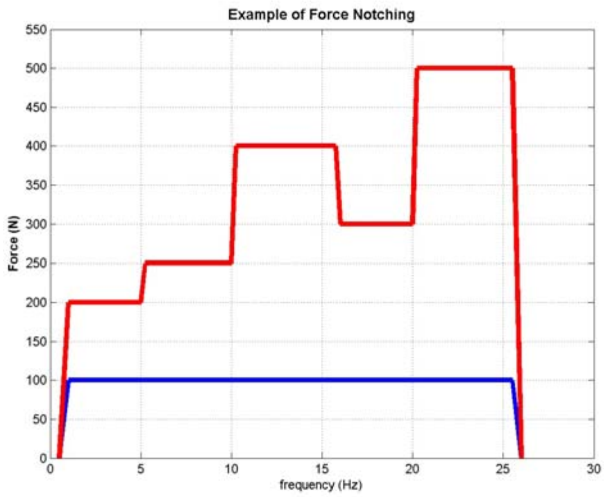


Figure 2: Excitation force notching example

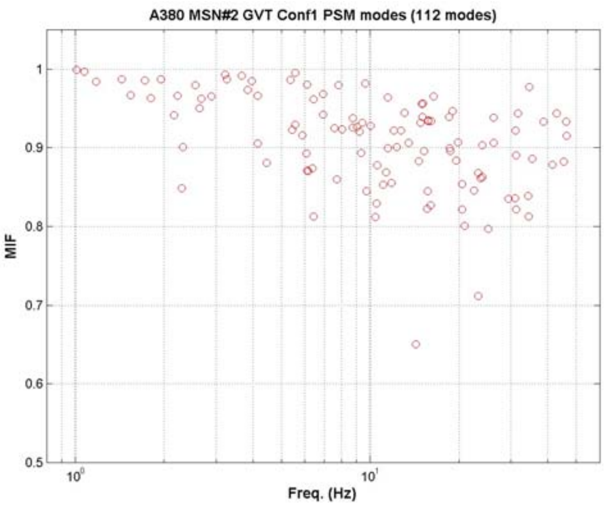


Figure 3: Test strategy MIF values of PSM modes of one structural configuration

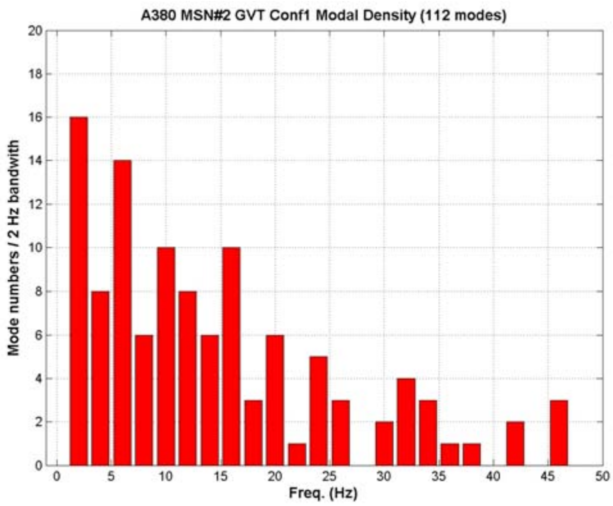
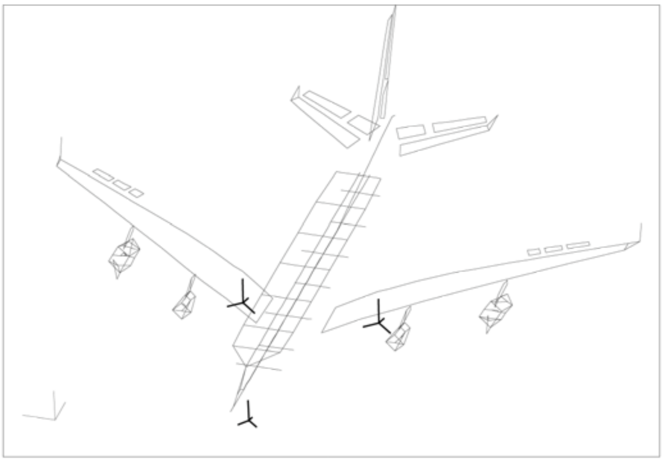


Figure 4: Modal density of one structural configuration

MIF = 1 when all accelerometer responses are orthogonal to the excitation forces (PRM) or when all mode shape vector components are real (PSM).



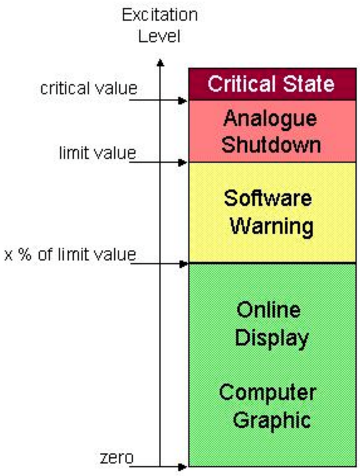


Figure 5: Jack Safety Device – principle

Figure 6: Suspension of the aircraft on jacks

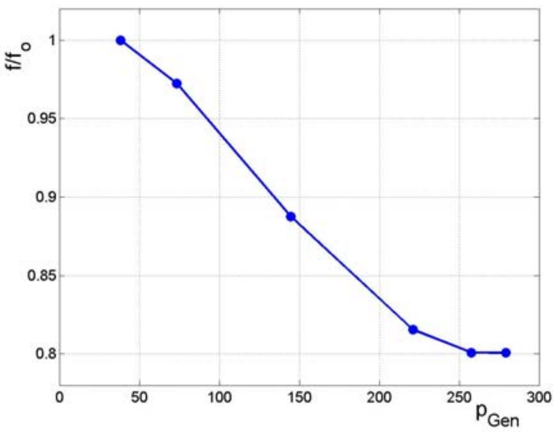


Figure 7: Computing linearity plots from swept-sine excitation runs

Figure 8: Example of a linearity plot for a control surface mode

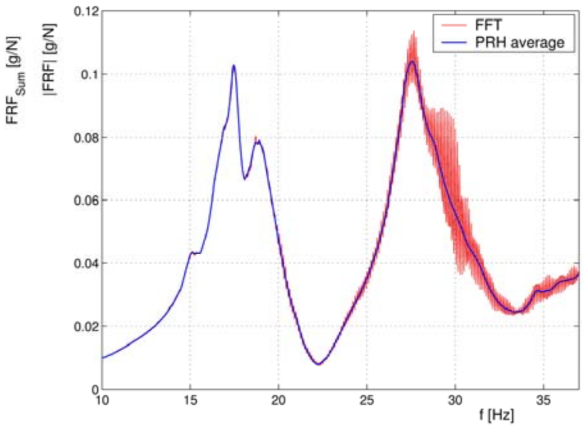


Figure 9: Comparing FRFs from spectra computed from FFT and PRH averaging; high-frequency range

Figure 10: Comparing FRFs from spectra computed from FFT and PRH averaging; low-frequency range

View 1: General view of the A380 in the painting hall during the GVT **© AIRBUS 2005**

View 2: Test laboratory **© AIRBUS 2005**

View 3: Vertical stabilizer and platform © **AIRBUS 2005**

View 4: Test laboratory and ADC equipment © **AIRBUS 2005**

View 5: Flap test preparation © **AIRBUS 2005**

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