23rd ABCM International Congress of Mechanical Engineering
December 6-11, 2015, Rio de Janeiro, RJ, Brazil

GROUND VIBRATION TEST USING ACOUSTIC EXCITATION: APPLICATION ON A COMPOSITE WING

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Abstract. *Ground vibration testing is essential for the accurate determination of the dynamic behavior of structural components, especially in aerospace industry. The information obtained from these tests helps the validation and improvement of dynamic models used in various stages of design. Among other functions, these models predict the natural frequencies and mode shapes of the structure. The most common methods for vibration test make use of an electromechanical shaker. This type of driver may cause problems both for the test as to the structure. This paper presents the application of a vibration test methodology using acoustic excitation. It aims at reducing the number of equipment needed to perform the test as well to obtain a form of excitation less intrusive to the structure. The test was performed in a composite wing with known numerical frequencies. Its fundamental frequencies and mode shapes obtained from analytical and numerical way were compared with experimental results and showed good results.*

Keywords: *Ground vibration test, acoustic excitation, modal analysis*

1. INTRODUCTION

An aircraft wing is an elastic structure and in presence of aerodynamic loads, it starts to vibrate. Because of self-excitation, the natural frequencies change during flight. If the changes of natural frequencies occur in a direction in which the magnitude of the bending and torsional frequencies of the wing are the same, the aircraft will experience a catastrophic phenomenon called flutter (Scanian and Rosenbaum, 1996). The design of an aircraft must avoid it. One way to predict the occurrence of it is the use of dynamic models of the aircraft. These models use, among others information, the aircraft vibrational behavior. The natural frequencies and modal shapes can be obtained by several ways, including finite elements analysis and modal experiments, known as Ground Vibration Testing (GVT).

GVT of aircraft is typically performed very late in the development test. The main objective of a GVT is to determine experimentally the low-frequencies modes of the aircraft for validating and improving its dynamic model (Peters et al, 2009). More complex aircraft design and the usage of composite materials raised additional testing requirements. At the same time, there is only a short period in which the fully assembled aircraft is available for testing, due to limited schedule and high cost of down time (Allen et al, 2010). This scenario has motivated a lot of international research (Peters et al, 2009).

A typical laboratory vibration test often involves a single force applied in one direction by a high impedance electrodynamic shaker (Daborn et al, 2014). In contrast, when in flight, an aerial vehicle is excited over its external surface by normal and tangential fluid forces in all directions. It should be noted that attach the structure to the shaker significantly alters its dynamics response. Moreover, some structures are very fragile and can be damaged during the experimental testing.

One solution for the excitation problem is use a pressure wave to excite the aircraft. It would avoid problems with contact and can excite the whole structure (Ferreira, 2015). Acoustic excitation is used for many purposes, including damage detection (Collini et al, 2011), load simulation (Assmus et al, 2011), fluid flow (Zhang et al, 2010) and many others.

Several configurations are possible, but the simplest is an amplifier and a speaker sending known waves to the structure. Moreover, the test can be faster than the traditional ones, since the initial setup is easier. The operator just need to select the wave, turn on the speaker and move a sensor through the structure, e.g., an accelerometer or a piezo electric sensor (PZT). Recently, Ferreira et al. (2015) validated the technique using a plate with known vibrational behavior and proposed improvements, as the usage of a microphone to get better coherence between the results.

In this work, the wing of the Anequim, which is a prototype airplane developed by the CEA (Centro de Estudos Aeronauticos) of the UFMG, was submitted to the modal analysis testing using acoustic excitation. The experimental modal parameters, natural frequencies and mode shapes, were compared with the theoretical modal parameters calculated using Finite Element Method.

2. THEORY

2.1 Modal Analysis

For extracting modal parameters such as natural frequency, damping factor and vibration modes, we can use the Theoretical Modal Analysis and Experimental Modal Analysis (Souza, 2008). The first procedure is the formulation of a mathematical model of the structure under study through a discretization technique, as the Finite Element Method (FEM). The second procedure uses the experimental data obtained from the system response, which are usually given by Frequency Response Function (FRF). In modal analysis technique, the FRF of the structure can be measured at a single point, with the impulsive excitation applied elsewhere in the structure, or by the principle of reciprocity, the structure can be excited at a single point, using random broadband signals, with the frequency response function measured at various points of the structure.

Ferreira et al. (2015) used acoustic excitation to measure the natural frequencies and mode shapes of a carbon plate. They obtained results with less than 10% of difference when compared to the numerical model, and less than 5% compared to a modal analysis with impact excitation. In addition, they pointed some limitations of the technique, as the difficulty to excite the system below 10 Hz, low data coherence below 15 Hz and coherence drops at the FRF peaks.

There are several ways to treat the data obtained from the system FRF. For the experimental analysis, the method of Chebyshev Orthogonal Polynomials (Mason and Handscomb, 2003) was implemented in a Matlab® code. Further explanations of the method can be obtained from Arruda et al. (1996).

2.2 Anequim project

Anequim is a racer airplane 100% build with carbon fiber materials using computerized machine systems. It was designed and built at Center for Aeronautical Studies of Federal University of Minas Gerais (CEA –UFMG), using 3D design tools and supported by computational codes for aerodynamic design, structural and aero-elastic analysis. The Anequim uses an aeronautical four-cylinder engine with displacement of 360 in3 , and achieves the top-level speed of 575 km/h (310 kts). With this velocity, the Anequim will become the world's fastest four-cylinder airplane ever built and will be able to set new records in the FAI C1a category (maximum take-off weight under 300 kg). This velocity range brings the need of a detailed flutter analysis. Fig. 1 shows the Anequim project.

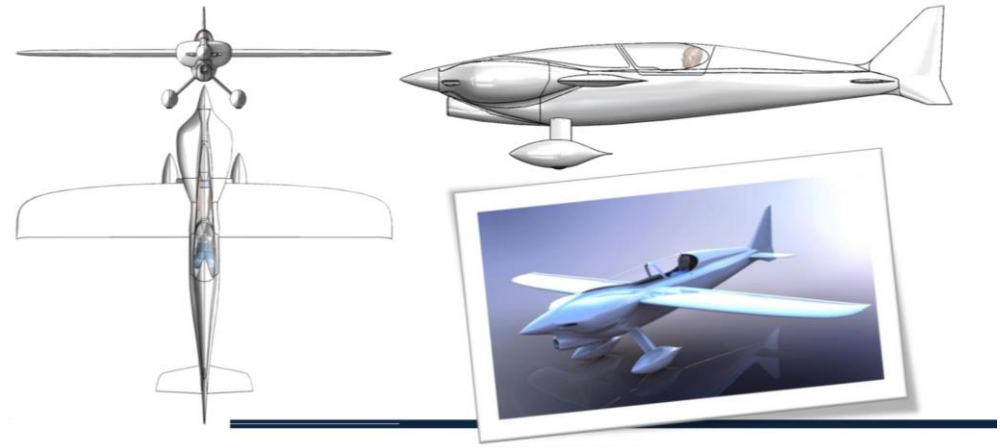


Figure 1. Anequim project

To perform flutter analysis, Silva (2014) developed a Finite Element Model (FEM) of Anequim wing, using the software FEMAP®/NX NASTRAN®. The model used a mixed mesh, and it is composed of CQUAD4 elements, with LAMINATE formulation, to model the principal structural components (spar, ribs and panels). RBE2 rigid elements were used to model the aileron articulation line. MASS elements were used to model the fuel mass and properties of the airplane`s gravity center. RBE3 elements were used to transfer the mass weight to the structure. SPRING elements were used to model the aileron`s command stiffness. Figure 2 shows the model constructed by Silva (2014). The frequencies obtained from this model (Tab. 1) were compared to the results of the GVT.

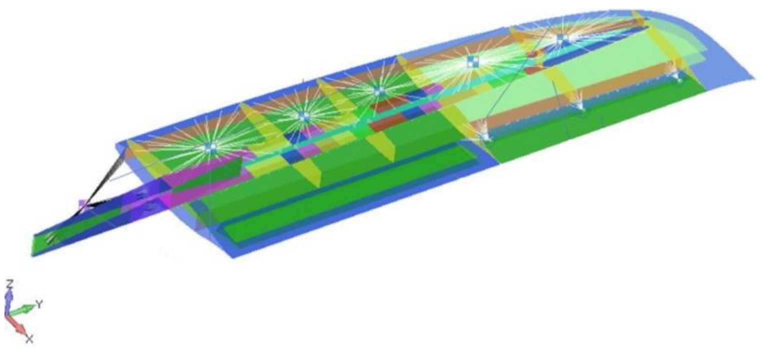


Figure 2. Detail of the wing used into FEM. (Silva, 2014)

Table 1. Wing numerical frequencies - Adapted from Silva (2014)

Mode	1	2	3	4	5
Frequency [Hz](1)	15.98/17.57	37.81/36.48	0, 20 and 40$^{(2)}$	56.21/56.83	85.43/85.41
Mode shape	First bending	Local Modes	Aileron rotation	Second Bending	First Torsion

(1) Modes with two frequencies correspond to Symmetric and Antisymmetric cases, respectively;
(2) Values of command stiffness were adjusted to obtain these results, according to aeronautical standards;

3. EXPERIMENTAL SETUP FOR THE MODAL ANALYS

All the experiments were made at the airplane's left wing. The wing was removed from the airplane and fixed by two points to simulate cantilevered. The choice of the quantity and location of the measurement points was made considering the tradeoff between refinement of the results and experimental time. The mesh consists of 62 points, with refinement close to the aileron and wing tip, as shown in Fig. 3.

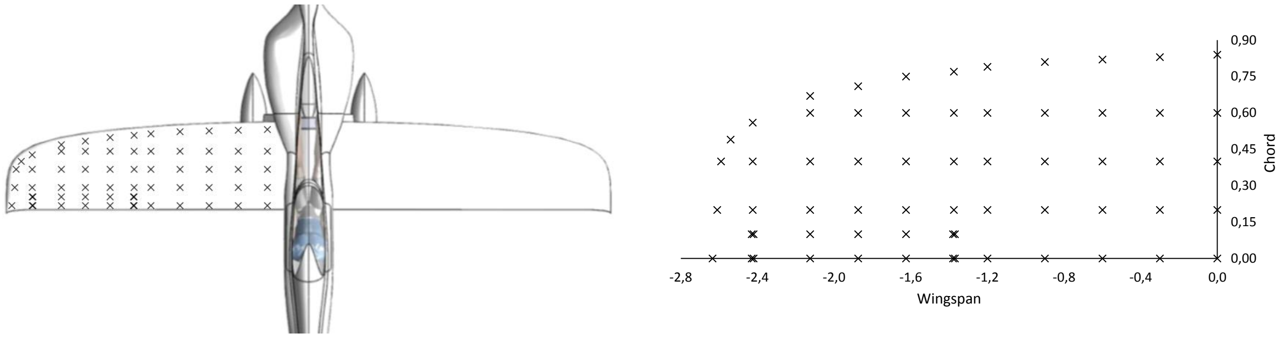


Figure 3. Schematic diagram of the measurement points

The wing was excited using a Crate Speaker model BX-25 and the response measured with a PCB 333A3 accelerometer in each one of the 62 points (Fig. 3). The vibration data-logger/analyzer used to record the signals was LDS PHOTON II. The data were analyzed using a Matlab® code with Chebycheff Orthogonal Polynomials method to extract the experimental natural frequencies and the mode shapes. The LDS PHOTON II was used to generate the excitation signal and send to the speaker. A PCB microphone was placed between the speaker and the wing to be used as the refence for the Frequency Response Functions (FRFs). The speaker was located under the wing around 200 mm. It is important to mention that the experiments showed that the best excitation was obtained with the speaker at the wing tip. The experimental setup is shown in Fig. 4.

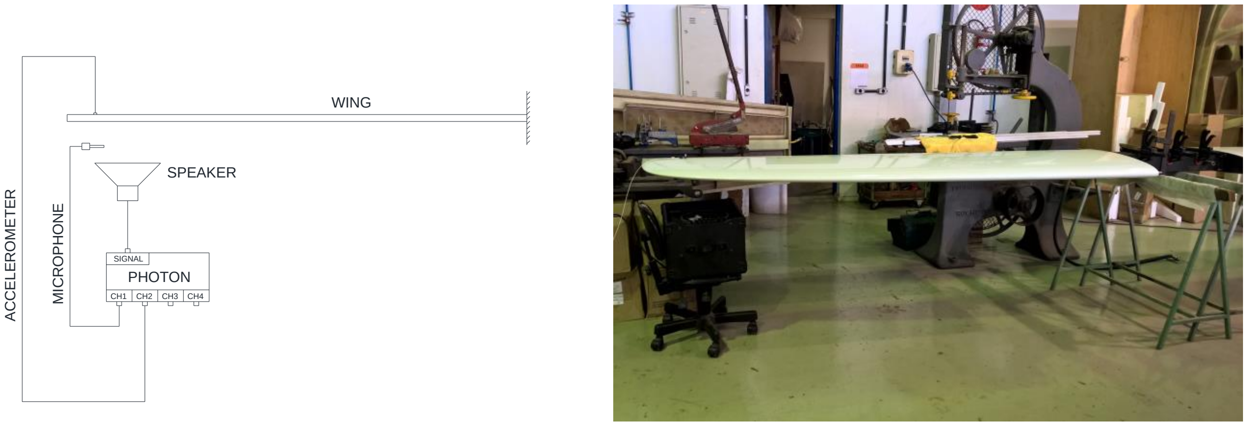


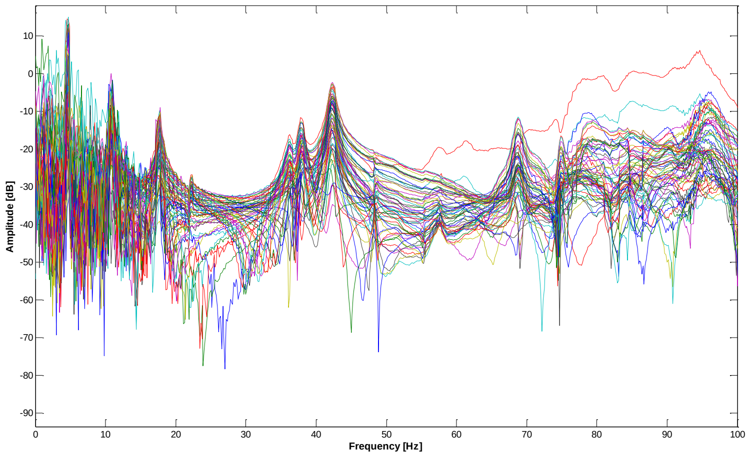
Figure 4. Acoustic excitation experimental assembly

According to Silva (2014), the first five fundamental frequencies occurs below 90 Hz. Therefore, the excitation frequencies were generated using a Sweep Sine with constant amplitude and frequency from 5 Hz to 90 Hz in three seconds. The measurements were performed using a 240 Hz of sampling frequency with 0.16 Hz of discretization frequency using Hanning window. The system made 10 measurements and took the results average.

4. RESULTS AND DISCUSSIONS

Figure 5 shows the Frequency Response curves and coherence for the 62 measurement points. The region below 15 Hz presented problems similar to those reported by Ferreira et al. (2015). In this range, the data showed noise and coherence was below 1. The noise can be attributed to the speaker inability to excite the wing at low frequencies. Tests with the speaker and microphone are able to generate and measure below 5 Hz, but the power transmitted in this frequency band is not sufficient to excite such a large object as the wing. Problems with coherence can also be attributed to the presence of ambient noise during the test. The usage of a microphone as reference eliminated the problem of coherence drops at FRF peaks.

In the frequency range between 15Hz and 90Hz, the data presented low noise with some dispersion after 80 Hz. Figure 5 shows the FRF and coherence data and in Tab. 2 are presented the identified modes compared with the results of numerical model developed by Silva (2014).



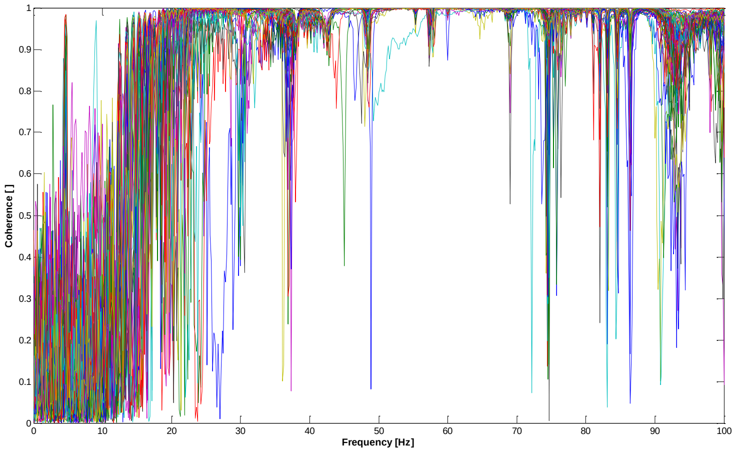


Figure 5. Frequency Response and Coherence from 15 Hz to 90 Hz

Table 2. Comparison between experimental and numerical frequencies from 15 Hz to 90 Hz

Mode	Numerical Frequency [Hz]	Experimental Frequency [Hz]	Mode	Observations
1	-	17.7	Rigid Body	Rigid body caused by the support
2	**15,98/17,57***	**22.1**	**First bendig**	-
3	**-**	36.4	Bending	Similar to the first bending mode.
4	-	37.9	Rigid Body	Similar to the fist rigid mode
5	-	42.3	Bending	Bending outside the spar line
6	-	48.3	Rigid Body	Similar to the fist rigid mode
7	**56.21**	**68.5**	**Second bending**	**-**
8	-	74.8	Bending	Similar to the second bending

It can be noted that the two found bending modes occurred at frequencies greater than those predicted by the numerical model. This is due to the differences between the model stiffness and the actual stiffness of the wing and the interference of the fixation used to simulate the cantilever.

Other modes have been found besides the ones predicted by the model. Among these modes, three are rigid body, caused by the interaction between the support and the wing. The other three modes are similar to the first and second modes. These similar modes could be related to asymmetric and antisymmetric configurations, but it could not be concluded because the right wing was not instrumented. Figures 6, 7, 8 and 9 show the modes described in Tab. 2

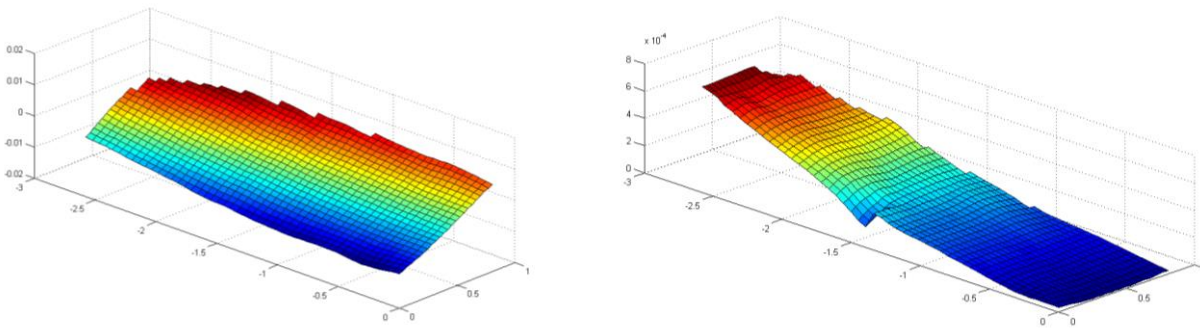


Figure 6. First and second experimental modes

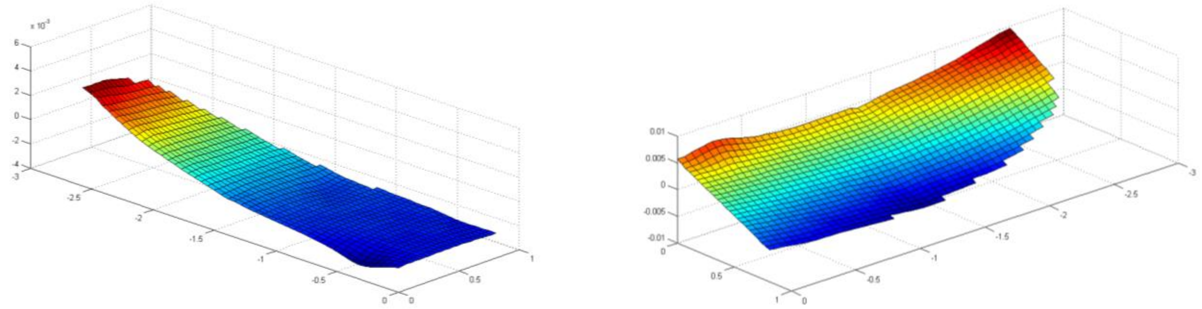


Figure 7. Third and fourth experimental modes

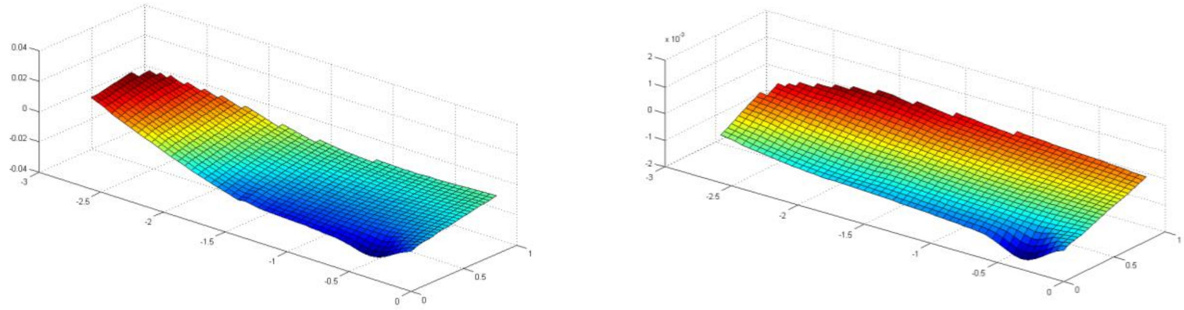


Figure 8. Fifth and sixth experimental modes

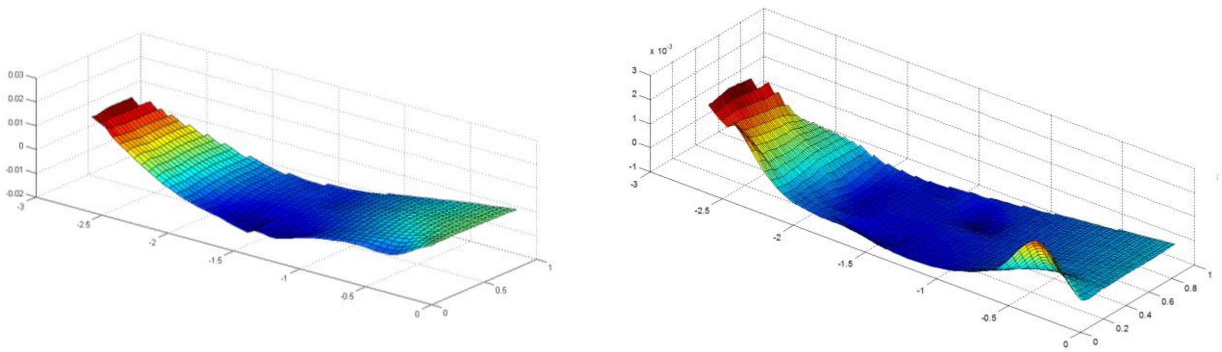


Figure 9. Seventh and eighth experimental modes

Silva (2014) predicted local modes at 37.8 Hz and aileron modes at 0 Hz (Rigid body), 20 Hz and 40 Hz. Both modes were not observed in the present analysis. Local modes are hard to detect in a global analysis as the one performed Because they require local analysis or a refined mesh. The aileron modes were obtained according to aeronautical standards and are only theoretical. The aileron command stiffness was not changed during the experiment, so these modes could not be observed.

5. CONCLUSIONS

The feasibility of a modal analysis with acoustic excitation was studied. The experimental results were compared to numerical simulations available in the literature. The experimental frequencies were greater than the numerical, indicating differences between the model stiffness and reality. The mode shapes obtained were consistent with the expected and matched with the simulation.

The experiment showed that acoustic excitation is a feasible technique in the studied frequency range. However, more studies are needed to determine the source of the problem with the coherence below 15 Hz. As a suggestion for future works would be to use a focused excitation in this frequency with a bigger speaker or a different type of signal. Another suggestion is to measure the acceleration of both wings to determine asymmetric and antisymmetric configurations.

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7. RESPONSIBILITY NOTICE

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