

Operational Modal Analysis using Impulsive Input of a Flexible Wing Unmanned Aerial Vehicle

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Abstract: This paper presents the methodology employed to characterize the modal properties of an Unmanned Aerial Vehicle (UAV) with high aspect ratio and structural flexibility. A free-free configuration was chosen to conduct a Ground Vibration Test campaign. The data acquisition system is described. Operational Modal Analysis (OMA) was used to identify the modal characteristic of aircraft the only dynamic response data. In this study the OMA based on the Frequency Domain Decomposition (EFDD) method was applied to process the operational vibration data. In OMA the excitation chosen must be able to be represented by a white noise loading. It is very common to use random input to reproduce these characteristics. In this work, excitation of impulsive nature was used obtaining satisfactory results in comparison to preliminary information obtained from experimental modal analysis. Based on information from the OMA Ground Vibration Test (GVT) an aeroelastic flight test planning was conducted.

Keywords: Operational Modal Analysis, In-flight Testing, Aeroelasticity, Flexible UAV

INTRODUCTION

Commonly, modal characteristics of aircraft are experimentally obtained by means of a Ground Vibration Test (GVT), which in turn could be used to correlate and update numerical models and then to aeroelastically characterized the aircraft. Traditionally, the modal properties are estimated by standard Experimental Modal Analysis (EMA), which uses accelerometers and other displacement sensors (Ewins, 2000; Castillo-Zúñiga and Góes, 2012). The input-Output experimental modal analysis is not easily applied to aeroelastic tests in actual flight conditions because of the difficulties measuring the actual inputs due to aerodynamic loads. Therefore, only the response output level should be desirably used for the identification of aeroelastic systems. The Operational Modal Analysis (OMA) is a parameter identification methodology based in only-output dynamic system approach.

Mastrodi, Coppotelli and Cantella (2010) applied an aeroelastic identification methodology based only on output data for a fixed wing UAV. In the study they emphasized the utility of the technique in passive vibration control applications. Grapassoni (2013) evaluated different approaches of operational modal analysis. The techniques developed were applied in tests on operating conditions of technology to rotary wing systems. Follador, *et al* (2009) and Castillo-Zúñiga and Góes (2013) showed that the OMA approach is a suitable methodology for aeroelastic modal parameter identification.

The methods within this field are mainly classified between time domain and frequency having each of its advantages and limitations (Follador et al, 2009). The main disadvantages and limitations of time-domain OMA methods are associated with high computational effort and noisy modes. Algorithms that require non-linear iteration require the greatest computational effort. Noisy modes make it difficult to identify the order of the system and distinguish between real and spurious modes. Among the factors that contribute to having noisy modes are measurement noise, nonlinearities, leakage, and computational waste. In this work were used the Frequency Domain Decomposition – FDD (Brinker et al., 2000) and the Enhanced Frequency Domain Decomposition - FDD (Brinker et al., 2001) techniques.

Research Platform

The research platform is the EOLO, an Unmanned Aerial Vehicle (UAV) developed by Technological Institute of Aeronautics (ITA), in partnership with Flight Technologies Ltda and ACS Solutions Ltda. The aircraft is made of composite and was designed to study aeroelastic phenomena and to evaluate the interaction of flexible effects with the aircraft flight dynamics. Its wing span is 4 m and reaches a high aspect ratio, whose value is 18.9.

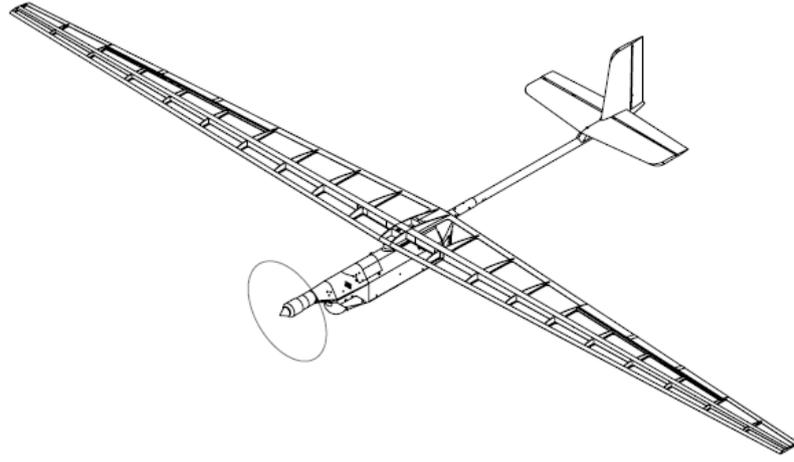


Figure 1 – EOLO: Flexible UAV.

THEORETICAL BACKGROUND

Frequency Domain Decomposition - FDD

The estimating of the modes using the FDD technique has as principal feature the Singular Value Decomposition (SVD) of each of the spectral density matrices (Gade et al, 2006). The first stage in this technique is to get the frequency content of the output responses forming the output Power Spectral Density (PSD) matrix.

The Frequency Response Function (FRF) matrix $\mathbf{H}(\omega)$, relating the inputs $x(t)$ and the measured responses $y(t)$ can be expressed in terms of poles λ_k and residues, R_k :

$$\mathbf{H}(\omega) = \sum_{k=1}^m \left(\frac{\mathbf{R}_k}{j\omega - \lambda_k} + \frac{\mathbf{R}_k^*}{j\omega - \lambda_k^*} \right) \quad (1)$$

with

$$\lambda_k = -\sigma_k + j\omega_{dk} \quad (2)$$

where m is the total number of modes of interest, λ_k being the pole of the k^{th} mode, σ_k the modal damping (decay constant) and ω_{dk} the damped natural frequency of the k^{th} mode.

The output PSD matrix can be expressed relating the FRF matrix of the system and the input PSD matrix $\mathbf{G}_{xx}(\omega)$:

$$\mathbf{G}_{yy}(\omega) = \mathbf{H}(\omega)^* \mathbf{G}_{xx}(\omega) \mathbf{H}(\omega)^T \quad (3)$$

where $*$ and the superscript T denotes complex conjugate and transpose, respectively.

Assuming that the excitation inputs have flat spectrums over the frequency of interest, the corresponding PSD matrix can be taken as a constant real diagonal matrix, $\mathbf{G}_{xx}(\omega) = \mathbf{C}$. Substituting Eq. (1) in Eq. (3) the output PSD matrix $\mathbf{G}_{yy}(\omega)$ can be expressed as:

$$\mathbf{G}_{yy}(\omega) = \sum_{k=1}^m \left(\frac{\mathbf{A}_k}{j\omega - \lambda_k} + \frac{\mathbf{A}_k^*}{j\omega - \lambda_k^*} + \frac{\mathbf{B}_k}{-j\omega - \lambda_k} + \frac{\mathbf{B}_k^*}{-j\omega - \lambda_k^*} \right) \quad (4)$$

If lightly damped model is considered, the contribution of the modes at a certain frequency is limited to a finite number, typically one or two modes. Indicating these modes by $Sub(\omega)$ the response PSD matrix can then be written as:

$$\mathbf{G}_{yy}(\omega) = \sum_{k \in Sub(\omega)} \left(\frac{d_k \boldsymbol{\psi}_k \boldsymbol{\psi}_k^T}{j\omega - \lambda_k} + \frac{d_k^* \boldsymbol{\psi}_k^* \boldsymbol{\psi}_k^{*T}}{j\omega - \lambda_k^*} \right) \mathbf{s} = \boldsymbol{\psi}_k \text{diag} \left(2 \text{real} \left(\frac{d_k}{j\omega - \lambda_k} \right) \right) \boldsymbol{\psi}_k^T \quad (5)$$

where $\boldsymbol{\psi}_k$ and d_k are modal shape and the scale factor of the k^{th} mode respectively.

A similar expression to Eq. (5) is obtained by taking the singular value decomposition of the output PSD matrix as shown in Eq. (6) and Eq. (7). This decomposition is performed to identify the parameters of the system. It is obtained a set of singular values in a diagonal matrix Σ and a singular vectors matrix Φ , that contain approximations of the modal shapes. The damped natural frequency occurs at the position where the singular value has the maximum magnitude.

$$G_{yy}(\omega) = \Phi \Sigma \Phi^T \quad (6)$$

$$\Phi \Phi^T = I \quad (7)$$

The SVD technique is able to identify closely coupled modes or even repeated modes (GADE et al, 2006).

Enhanced Frequency Domain Decomposition - EFDD

In the approach introduced by Brinker et al. (2001) the modal frequencies and damping are more accurately estimated. A spectral density function of a degree of freedom associated with a specific mode is formed. For this, it is important the premise that in the frequency region in which this mode is the system response will be dominated by it. Once the spectral density function is created for the one-degree-of-freedom system, the correlation function of this system is determined by applying the inverse Fourier transform to the spectral density function. After obtaining the correlation function for the system of a degree of freedom a linear regression is applied and the logarithmic decrement of the function is obtained. The damping factor can be obtained as a function of the logarithmic decrement and the damped natural frequency is calculated from the period associated to the free decay of the correlation function.

MATERIALS AND METHODS

GVT Setup

The suspension of the structure in an experimental modal test (GVT) has a fundamental role for the correct identification of the modal properties of the structure. A GVT campaign for the complete configuration was executed reproducing a free-free supporting condition as shown in Fig. 2. For this aircraft configuration tested, the wing had already been integrated with the fuselage and tail. The aircraft assembly with instrumentation has a mass of approximately 8.6 kg.



Figure 2 – OMA GVT Setup.

Data Acquisition System

A data acquisition system was developed for the aircraft and its architecture is shown in Fig. 3. The heart of that architecture is an on-board data acquisition and control system (NI/MyRio) retrieving information of all sensors installed in the aircraft, a board computer (FlightTech SNC-200), a pressure sensor (SpaceAge Subminiature Air Data Boom 101100), an inertial unit, accelerometers, strain gauges (CEA-06-125UW-350), strain rosettes (CEA-06-250UR-350), actuators and angular positions sensors.

The accelerometers placement in wing UAV is shown in Fig. 4. A total of 19 different positions for acceleration sensors are determined for the present configuration. The accelerometers used for in-flight data acquisition are the ADLX345 with 16 g range, a bandwidth of 1600 Hz and high resolution of 13 bits. Preliminarily, some EMA GVT campaigns were done for the non-framed wing of the EOLO aiming to define a preliminary position for the acceleration and strain sensors for the aircraft (Castillo-Zúñiga et al, 2017).

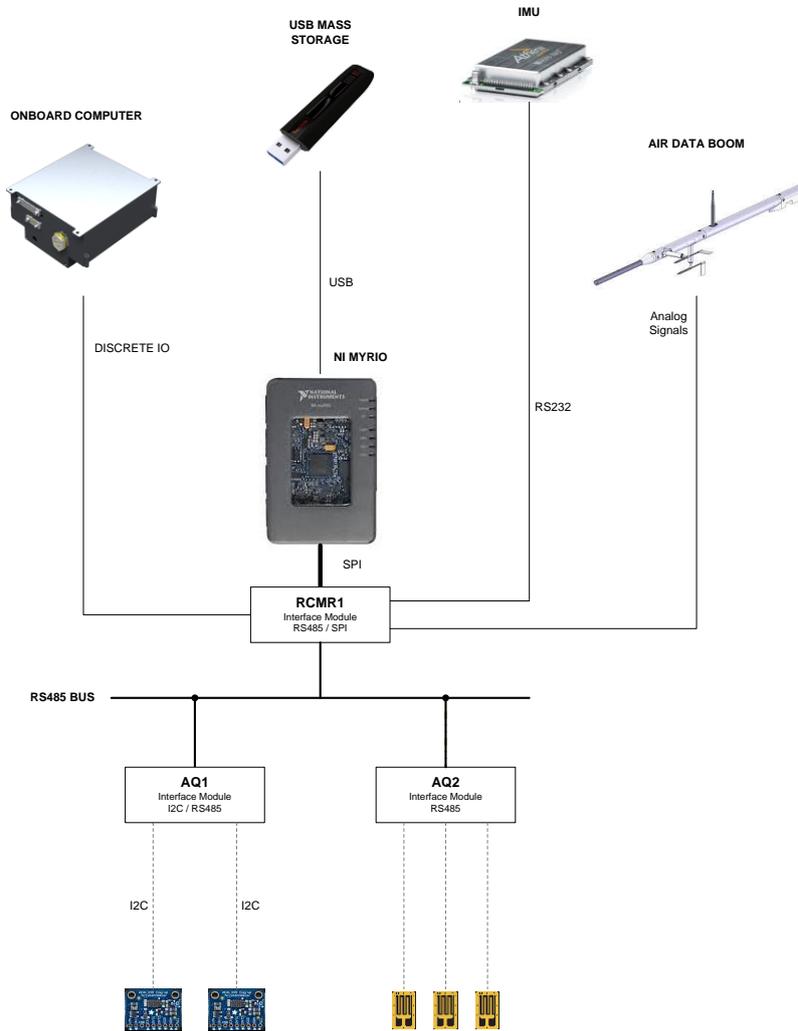


Figure 3 – Data Acquisition System Arquiteure.

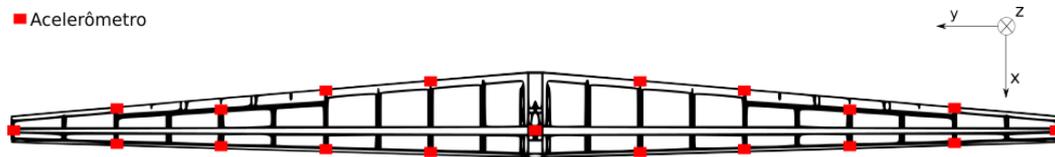


Figure 4 – Accelerometers placement in EOLO wing.

Figure 5 shows the responses of the accelerometers, from a test in which a series of manual pulses are applied to the wing tips, taking as a time interval between the two the time required for the system to rest. The sampling frequency was 50 Hz. PSD matrices were calculated using the responses of accelerometers by means of the Welch methodology. A hanning window was used, having an overlap of 50%, resulting in a spectral resolution of 0.24 Hz.

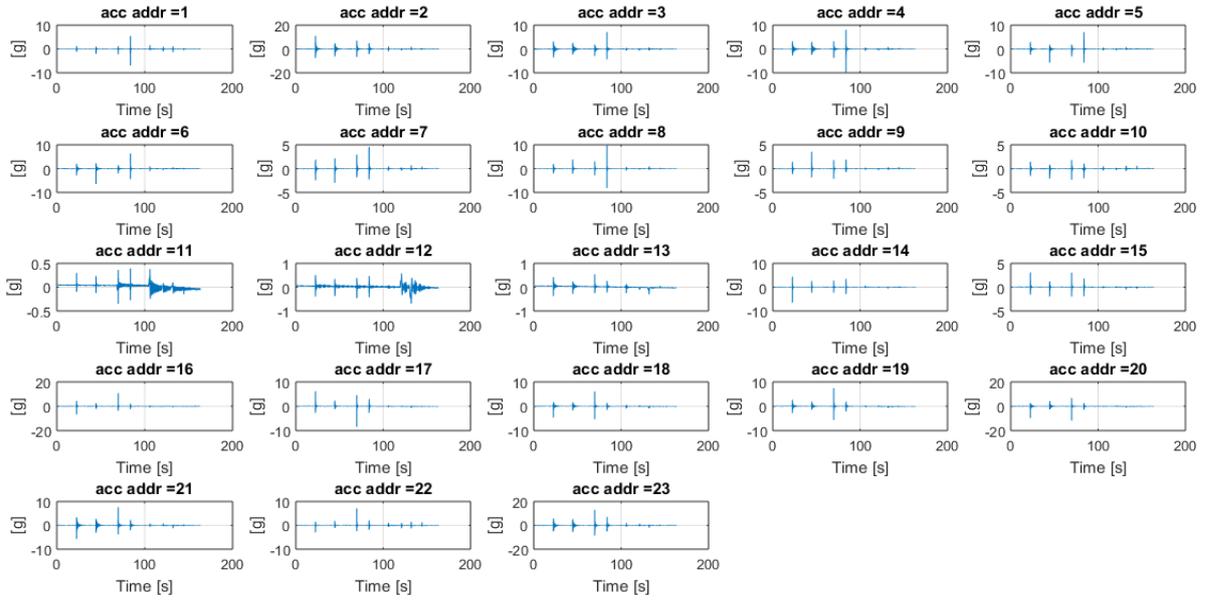


Figure 5 – Frequency Domain Decomposition of acceleration response from OMA GVT data.

OPERATIONAL MODAL ANALYSIS

The Frequency Domain Decomposition was applied for PSD matrix. Figure 6 shows the evolution of the first two singular values of the PSD matrix for the acceleration responses, in which the peaks indicate the presence of the modes. It is observed that for this campaign the second singular value did not indicate the presence of coupled modes. However, this finding is conditioned to this type of excitation and cannot extend conclusively to other forms of loading.

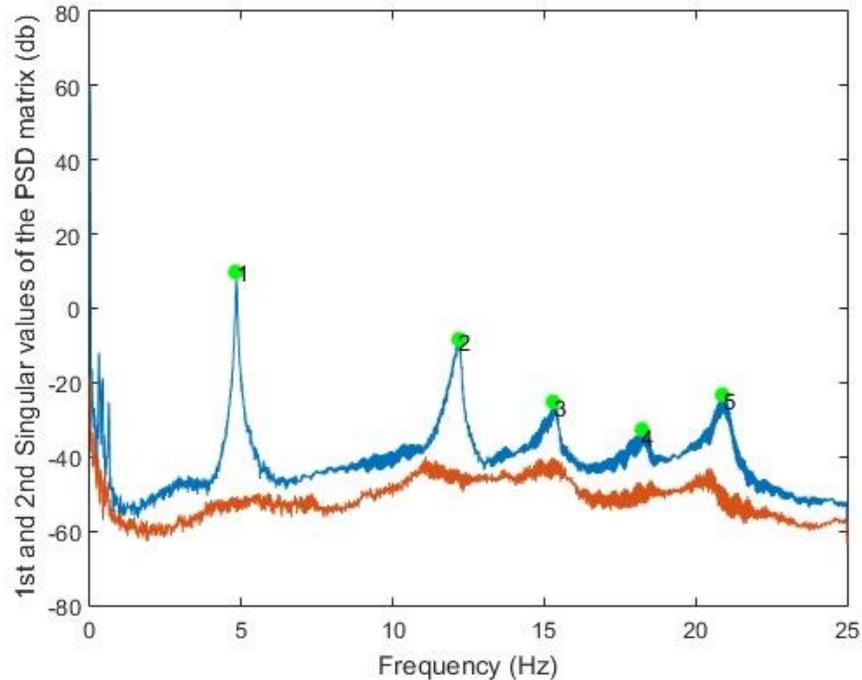


Figure 6 – Frequency Domain Decomposition of acceleration response from OMA GVT data.

From the application of the EFDD methodology, five modes were identified in the frequency range from 0 to 25 Hz. These modes are bending and torsional modes. The first mode is a symmetric bending mode, followed by an antisymmetric bending mode and then the first symmetric torsional mode. The next two identified modes correspond to the first antisymmetric torsional mode and the second symmetric bending mode. Table 1 shows the descriptions of the modes identified and the modal frequencies and damping ratios associated with them. The damping factors identified by the OMA approach were of the same order as those of the EMA approach (Castillo-Zúñiga et al, 2017), with the main difference for the first mode, where there was lower damping for the first mode. The identified modal forms are shown in Figure 7.

Table 1 – OMA identified modal properties

Mode	Frequency [Hz]	Damping [%]
1 st Symmetrical bending mode	4.83	0.7
1 st Anti-symmetrical bending mde	12.2	1.9
1 st Symmetrical torsional mode	15.3	2.9
1 st Anti-symmetrical torsional mode	18.2	3.6
2 nd Symmetrical bending mode	20.9	3.5

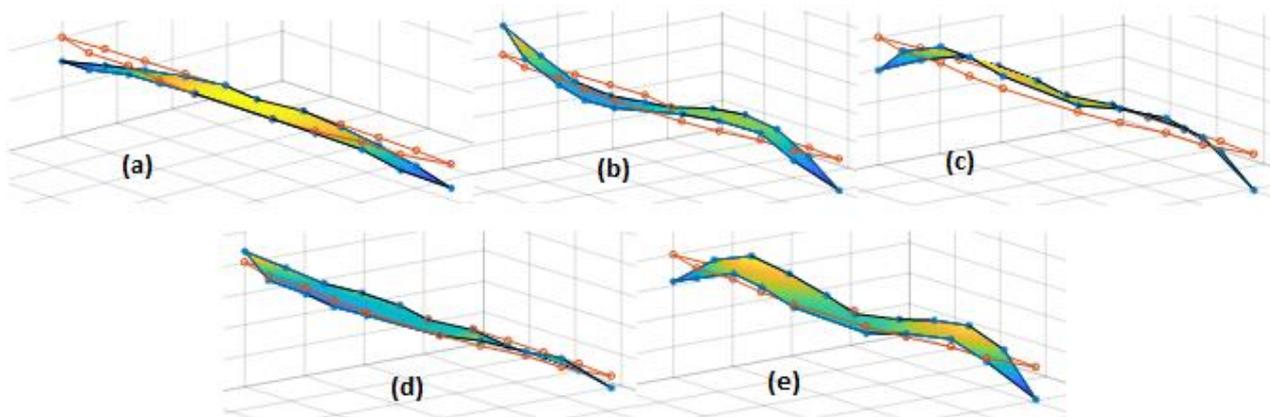


Figure 7 – OMA identified modal shapes and damped natural frequencies.

Flight Test Maneuvers

For the planning of the flight test maneuvers required for operational modal analysis were taken into account the following features of the flight envelope of EOLO: maximum operating speed (32 m/s) and cruising speed (15 m/s). The following range of speeds chosen in order to cover the entire flight envelope of the EOLO: 12, 16, 20, 24, 30,. The goal of each maneuver is to keep fixed flight condition, leaving the aircraft under atmospheric disturbance. The duration of each operation for a certain speed was set at 120 s.

CONCLUSIONS

The use of frequency-based methodologies was defined for operational modal analysis. From the application of the FDD and EFDD methodologies in GVT campaigns of the configuration of the unshaded integrated aircraft, it was possible to verify the feasibility of the modal characterization of VANTs without knowledge of the entrance. For these types of techniques it is generally assumed that the input has white noise characteristics, and in the tests performed so far it was possible to have a good result with the application of impulsive inputs. This is a fact that is consistent with the expected frequency content of an impulsive signal, where it is ideally expected to be constant across the frequency band. This good behavior of the methods against manual impulsive inputs opens the front of opportunities for the creation of simplified models of modal characterization of VANTs of the type, at least in a preliminary way, obtaining reduction of time and costs associated to the tests. Limitations of this type of strategy have yet to be outlined.

The next step is to perform a flight test camping and then applying the OMA approach to determining the modal properties in function of each operation condition. The modal frequency and damping trends will be extrapolated in order to identify aeroelastic flutter instabilities.

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