INFLUENCE AND SUPPRESSION OF HARMONIC COMPONENTS IN OPERATIONAL MODAL ANALYSIS OF AN UNMANNED AIRCRAFT VEHICLE

David Fernando Castillo Zúñiga, davidfer@ita.br[1]
Clécio Fischer, fischer@ita.br[1]
Luiz Carlos Sandoval Góes, goes@ita.br[1]

[1]Technological Institute of Aeronautics (ITA), Comando-Geral de Tecnologia Aeroespacial (CTA), 12228-904 - São Jose dos Campos-SP-Brazil.

Abstract. *Modal Operational Analysis (OMA) is a methodology to estimate the modal parameters of a structure using only dynamic response data, without assuming the knowledge of the excitation forces. The excitation chosen must be able to be represented by a white noise loading. However, an important aspect in the case of OMA is the presence of harmonics added to the random excitations load, mainly due to the associated rotary systems. Due to the presence of harmonic excitation, the process of identification of the modal parameters can lose its robustness and can provide an unsatisfactory parameters identification. In this work is evaluated a presence de harmonic components in the OMA of the Vector-P Unmanned Aerial Vehicle due to a 2-stroke reverse rotation gasoline engine. The OMA technique used is the Frequency Domain Decomposition method (FDD). The Vector-P is instrumented with a set of accelerometers on the wing and the horizontal stabilizer. The harmonics associated with motor operation are high frequency; the engine operates in a range of 1000 - 2500 rpm. In this work OMA methodology is applied treating the harmonics as operating or artificial modes.*

Keywords*:* *Operational Modal Analysis, Harmonic Component, Harmonic Suppression, Unmanned Aerial Vehicle, Aeroelasticity*

1. INTRODUTION

Traditional Input/Output identification techniques are not easily carried out for aeroelastic systems in operative flight conditions because of the intrinsic difficulty on measuring actual input loads. Therefore, only the response output level should be desirably used for the identification of aeroelastic systems. This Ouput-Only approach is known as Operational Modal Analysis (OMA). Follador, *et al* (2009) showed that the OMA approach is a suitable methodology for aeroelastic modal parameter identification. In their work were applied the EFDD (Enhanced Frequency Domain Decomposition) identification method to identified the aircraft aeroelastic parameters from in-flight data.

Mastroddi, *et al* (2010) applied an Output-Only, O-O approach to fixed wing UAV. The authors show how the use of the Output-Only, O-O approach allowed to passively reduce the operative aeroelastic vibrations, via piezoelectric-patch devices (PZTs,) mounted aboard the UAV.

The algorithms used in OMA assume that the input forces are stochastic in nature. As the input forces to the structure are not measured in OMA, special attention must be paid to identify and separate harmonic components from true structural modes and eliminate the influence of the harmonic components in the modal parameter extraction process (Jacobsen et al, 2007).

A flight test campaign was carried out on the Vector-P UAV. The aircraft is made mainly of composite material and it presents a relatively common configuration for vehicles of the same size, with an almost square fuselage, wing flaps with no dihedral, two vertical stabilizers, horizontal tail and a tail boom (Santos et al, 2011). The total configuration for the test had a weight of 27 kg. Other important characteristics of the aircraft are shown in Tab.1.

Table 1. Unmanned Aerial Vehicle Vector P Specifications (adapted from http://www.vectorp.com/vectorp_specifications.html)

Wingspan	2.6 m
Fuselage Length	1.525 m
Max Speed	185 Km/h
Engine	3 W 2-stroke reverse rotation gasoline engine.
Max Range	775 Km, depending on fuel on board
Cruise Speed	129 Km/h
Max Altitude	3 Km
Max Endurance	6 hours depending on fuel and payload on board
Max Takeoff Weight	34 Kg
Empty Weight	23 Kg
Max Fuel	12.3 liters
Fuel Per Hour	2.3 liters
Landing Speed	74 Km/h
Max Payload Weight	11.3 Kg, with fuel for one hour
Payload Vol. (Internal)	(225 x 225 x 685) mm

2. Theoretical Background

The Operational Modal Analysis (OMA) is a parameter identification methodology based in only-output dynamic system approach. The techniques for OMA methodology can be formulated in time domain and frequency domain both (Follador et al, 2009). In this work was used the Frequency Domain Decomposition (FDD) technique described in (Gade et al, 2006).

The FDD technique is an extension of the Basic Frequency Domain (BFD), usually known as peak-picking technique. 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. 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 $\boldsymbol{H}(\omega)$, relating the inputs x(t) and the measured responses y(t) can be expressed in terms of poles λ_k and residues, $\boldsymbol{R}_k$:

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

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 kth mode, σ_k the modal damping (decay constant) and ω_{dk} the damped natural frequency of the kth mode.

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

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

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, $\boldsymbol{G}_{xx}(\omega) = \boldsymbol{C}$. Substituting Eq. (1) in Eq. (3) the output PSD matrix $\boldsymbol{G}_{yy}(\omega)$ can be expressed as:

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

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:

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

where ψ_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 $\boldsymbol{\Sigma}$ and a singular vectors matrix $\boldsymbol{\Phi}$, that contain approximations of the modal shapes. The damped natural frequency occurs at the position where the singular value has the maximum magnitude.

$$\boldsymbol{G}_{yy}(\omega) = \boldsymbol{\Phi \Sigma \Phi}^T \quad (6)$$

$$\boldsymbol{\Phi \Phi}^T = \boldsymbol{I} \quad (7)$$

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

3. FLIGHT TEST METHODOLOGY

3.1. Data acquisition system and accelerometers placement

The data acquisition system for flight test of the Vector-P consists of an embedded control system (CompactRIO), accelerometers, GPS, inertial unit, pressure sensor and actuators. CompactRIO is a reconfigurable embedded control and acquisition system. The CompactRIO system's rugged hardware architecture includes I/O modules, a reconfigurable FPGA chassis, and an embedded controller. The accelerometers used for data acquisition were of DC type (PCB) with low frequency band response (0-100 Hz) with ±10 m/s^2 amplitude range and high sensitivity 200 mv/g. The choice of positioning for the accelerometers in flight test was based on two objectives: to have a point of comparison with the results of experimental modal analysis (GVT) and to identify the modes that would have predominance in any aeroelastic instability, according to the results of numerical aeroelastic analysis. A total of 6 accelerometers was used, and their placement is presented in Fig. 2.

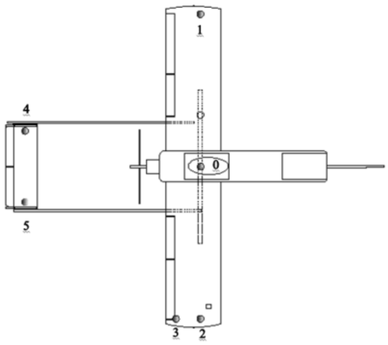

Figure 2. Accelerometers positioning in the airframe.

3.2. Flight test manouvers and spectral parameters

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 Vector-P: maximum operating speed (51.4 m / s) and cruising speed (35.8 m/s). The following range of speeds chosen in order to cover the entire flight envelope of the Vector-P: 25, 30, 35, 40, 45, 50 m/s. The goal of each maneuver was 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.

PSD matrices were calculated using the responses of the six accelerometers for each flight condition by means of Welch methodology. With a sample frequency of 1000 Hz, a hanning window was used having a overlap de 50% resulting in a spectral resolution of 0.24 Hz. The FDD was applied for each PSD matrix correspondent to the each flight condition.

4. INFLUENCE AND SUPRESSION OF HARMONIC EFFECTS

The consequences of having harmonic components present in the responses depend on both the nature of the harmonic components (number, frequency, and level) and the modal parameter extraction method used. For FDD technique, the main consequences are that: harmonic components are potentially mistaken for being structural modes, harmonic components might potentially bias the estimation of the structural modes (natural frequency, modal damping, mode shape), a high dynamic range might be required to extract “weak” modes, the picked FFT line might be biased by the harmonic component(s) and the harmonics must be away from the structural modes (Jacobsen et al, 2007. It is important that harmonic components inside the desired SDOF function are identified and their influence eliminated before processing with the modal parameter extraction process.

The harmonics associated with motor operation are high frequency (the engine operates between 100 and 2500 rpm). In order to evaluate and suppress the harmonic influence is applied a low-pass filter of fourth order of 100 Hz. Then the PSD are calculated from the unfiltered and filtered signals. Figure 3 compares the filtered and unfiltered PSD. In this case harmonic components and the associated peaks are treated as artificial structural modes and while they are not close to the structural modes object of study (below 60 hz) can be treated as artificial structural modes (Cruz, 2006).

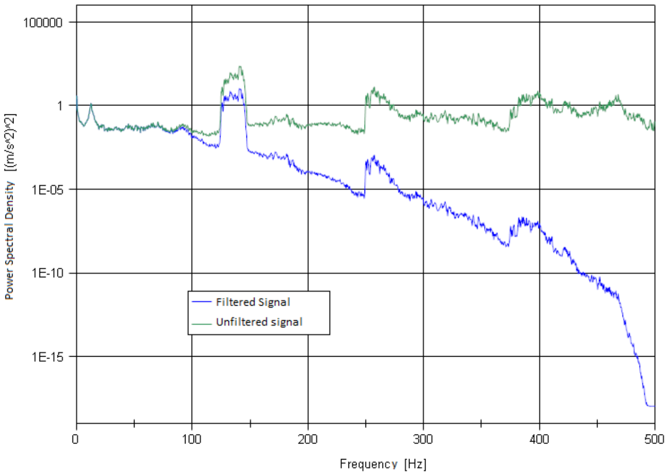

Figure 3. Comparison between filtered and unfiltered power spectral densities.

5. OMA RESULTS

The data were analysed using the MATLAB® software for identifying modal parameters through FDA/OMA techique. Figure 4 shows the variation of the main and second singular values with respect to the airspeed. The main singular value points two relevant peaks. It is observe that in their respective frequency these modes are the only dominant . There are small variations in frequency that are the result of the modal frequencies dependence of the mass configuration of the aircraft, the limitations of the spectral resolution, and the influence of noise.

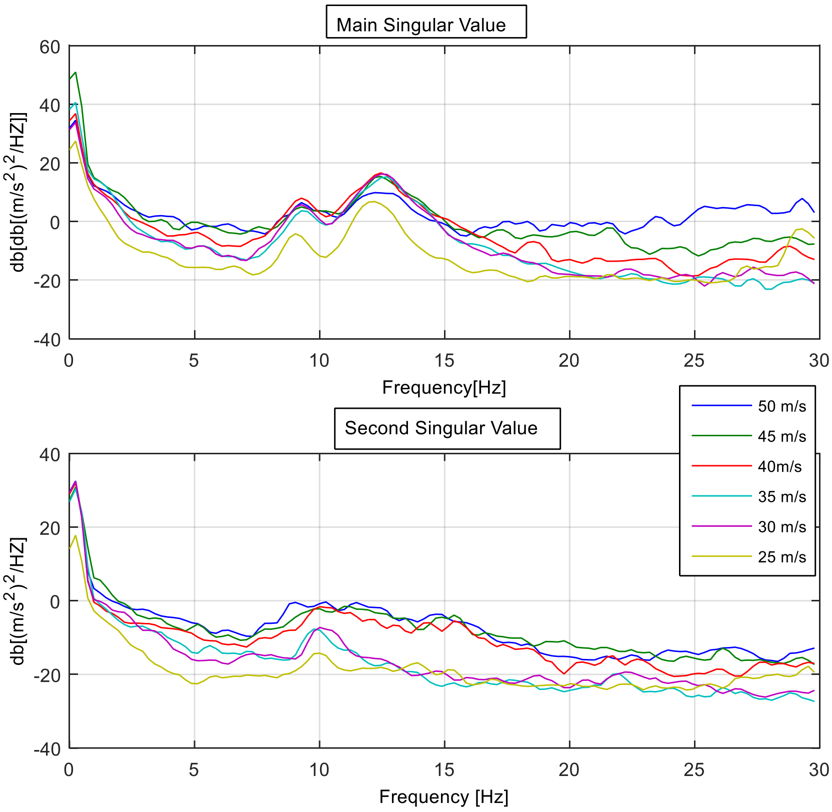

Figure 4. First and second singular values for each velocity.

The identified modes of vibration including frequency and damping factors for each airspeed are shown in Table 2. For most airspeeds the first frequency peak appears around 9.28 Hz and the second frequency peak around 12. 45 Hz. The damping calculation procedure assumes the singular value peak being proportional to the main peaks of the equivalent FRFs. The noise and low spectral definition at some low speeds do not allow estimating modal damping.

Table 2. OMA/ In-flight test identified modal charateristics.

	1st Symetric Tail-Booms Bending		1st Wing Bending	
Velocity (m/s)	**Frequency [Hz]**	**Damping (%)**	**Frequency[Hz]**	**Damping (%)**
50	9.28	-	12.21	-
45	9.28	-	12.45	4.47
40	9.28	5.05	12.45	4.02
35	9.28	5.39	12.69	4.34
30	9.28	5.05	12.45	4.77
25	9.03	4.58	12.21	4.93

Figure 5 shows the modes shapes corresponding to the tail-booms 1st bending mode and the 1s bending mode wing. For the tail-booms 1st bending mode is observed a vertical displacement of the empennage while the movement of the wing is less significant. The modes shapes have a good relationship with the analogous modes identified in GVT by Castillo-Zúñiga et al (2012, 2013).

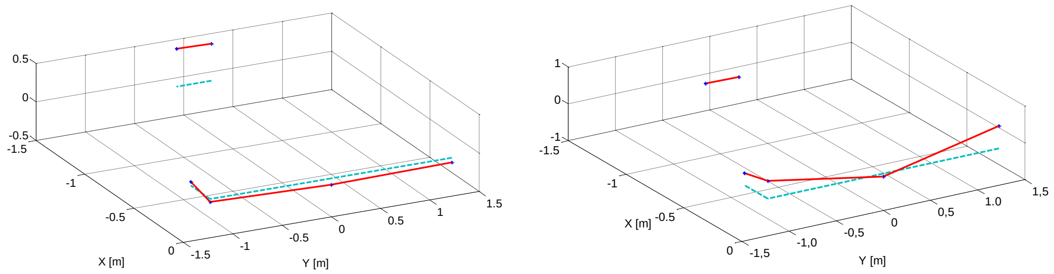

Figure 5. OMA Identified natural modes:tail-booms bending and wing bending.

6. CONCLUSIONS

By the implementation of the OMA methodology to Vector-P it was possible to obtain satisfactory modal identification results having the presence of harmonics if the associated peaks these are treated as artificial structural modes and while they are not close to the structural modes object of study.

The operational modal analysis FDD methodology used proved to be very useful for the identification of the resonant frequencies given to the facility that has the technique of decomposition in singular values to point to the modes that dominate a given frequency. Limitations were observed in the modal damping estimation and therefore it is advisable to estimate this parameter with other types of techniques such as EFDD.

Future work will include examination of mechanical suppression systems like implementing a set of dampers in the aircraft engine support structure.

7. ACKNOWELEDGMENTS

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