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Design of an Experimental Flutter Mount System

Aeroelastic instabilities may occur in aircraft surfaces, leading then to failure. Flutter is an aeroelastic instability that results in a self-sustained oscillatory behaviour of the structure. A two-degree-of-freedom flutter can occur with coupling of bending and torsion modes. A flexible mount system has been developed for flutter tests in wind tunnels. This apparatus must provide a well-defined 2DOF system on which rigid wings encounter flutter. Simulations and Experimental Tests are performed during the design period. The dimensions of the system are determined by Finite Element analysis and verified with an Aeroelastic Model. The system is modified until first bending and torsion modes become the first and second modes and other modes become higher than these. After this, a Modal Analysis is performed. An identification algorithm, ERA, is used to determine modes shape and frequencies from experimental data. Detailed results are presented for first bending and torsion modes, which are involved in flutter. The flutter mechanism is demonstrated by Frequency Response Functions obtained in several wind tunnel velocities until flutter achievement and by a V-g-f plot obtained from an identification process performed with an extended ERA. Mode coupling, damping behaviour and the self-sustained oscillatory behaviour are verified characterising flutter.
***Keywords**: aeroelasticity, flutter, flexible structures, wind tunnel tests*

Introduction

The study of aeroelastic phenomena, such as flutter, has been of great attention in aeronautical science. Flutter is a dynamic aeroelastic instability which involves the interaction, or coupling, of aerodynamic, elastic and inertial forces, yielding to an undesired self-sustained oscillatory behaviour that can lead to structure failure (Bisplinghoff et al, 1955). Nowadays, aircraft design emphasizes the maximization of performance by improving several items in aerodynamic, control systems, or structure, for example. Structural weight reduction can be applied to improve aircraft performance. The reduced structural weight often results in reduced stiffness, increasing the susceptibility to aeroelastic problems. The greater the knowledge on aeroelastic phenomena mechanism and modelling tools, the better and safer the aircraft design tends to be.

Wind tunnel tests are a safe and efficient way to study aeroelastic phenomena in aircraft structures. Flutter tests in wind tunnels may be conducted on flexible wing models like in Mukhopadhyay (1995), or on instrumented rigid wing models associated with flexible mounts like in Ko, Kurdilla and Strganac (1997) and in Waszak (1998). In this work, a flexible mount has been developed for flutter tests in wind tunnels. This mount system must provide a well-defined two-degrees-of-freedom dynamical system on which rigid wings can encounter flutter. A classical two-degrees-of-freedom flutter can be described as combination of bending and torsion vibration modes. So, the system (flexible mount plus rigid wing) first bending and first torsion will be the modes involved in flutter. The dynamical characteristics of these modes must be known and well defined. These characteristics must be coherent with the range of velocities of the wind tunnel in use; otherwise flutter will not be achieved during wind tunnel tests.

To assure the conditions above, the designer must determine some modal characteristics of the flexible mount system and wing before any wind tunnel test. A safe way to do that can be by simulations and experimental analysis. Finite Element Model (FEM) can be used as a design tool before the construction of the flexible mount system, after this, Experimental Modal Analysis (EMA) associated with an Identification Algorithm, can be used to certify the dynamical characteristics determined during the design period. Several Numerical Identification algorithms have been developed to calculate modal parameters from experimental data. The Eigensystem Realization Algorithm (ERA) is one of these algorithms. It is a time domain algorithm that can identify many modes simultaneously (Tsunaki, 1999; Juang, 1994).

This procedure is used in this work. Initially, vibration modes shapes and frequencies are determined by Finite Element analysis. During this design period, the system was modified until first bending and torsion modes became the first and second modes and the other modes became higher then these. This condition assures that higher modes will not be excited significantly by the same wind tunnel velocity range that will excite the modes involved in flutter (Dansberry et al., 1993). Some structural characteristics obtained with FEM analysis are used in simulations performed with an Aeroelastic Model developed to verify the dynamical behaviour of the experimental system. The critical flutter velocity of the experimental system can be determined with these simulations. The system is considered correctly designed if this critical velocity can be achieved with the available wind tunnel. Otherwise, the system must be modified, adjusting its aeroelastic behaviour to the characteristics of the available wind tunnel.

After this design period the physical system is mounted and an EMA is realized to verify experimentally the results determined preliminary by the FEM analysis. Then, the ERA modified by Tsunaki (1999) is used to identify the modes shape and frequencies involved in the classical flutter mechanism.

After this design and construction period, wind tunnel tests are performed to confirm experimentally the achievement of flutter and to characterize the phenomenon. Frequency Response Functions are measured at several wind tunnel flow velocities. The system is tested since low wind tunnel velocities until velocities as near as possible of the flutter one. These frequency responses show the evolution of the first bending and torsion modes with increasing velocity, showing the modes coupling at flutter velocity. The signals measured during these experiments are also used in an identification process performed with an extension of the Eignsystem Realization Algorithm (Rebolho, 2006), known as EERA, resulting in a *V-g-f* plot of the system.

The main objective of the development of this flutter mount system is the design and tests of controllers for active flutter suppression. Other applications like the development of real time

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Identification Algorithms can be developed using data generated and applied in wind tunnel tests.

Nomenclature

B_o = control matrix
$\bar{c}$ = mean aerodynamic chord
D_a = aerodynamic damping matrix
D_s = structural damping matrix
K_a = aerodynamic stiffness matrix
K_s = structural stiffness matrix
M_a = aerodynamic coupling matrix
M_s = structural coupling matrix
$\bar{q}$ = dynamic pressure
S = planform area
Uo = free stream air velocity

Greek Symbols

ψ = vector of generalised coordinates
δ = vector of control surface deflections

Flutter Mount System

The flexible mount system provides a well-defined two-degrees-of-freedom dynamic system on which rigid wing will encounter the bending-torsion flutter. A side and perspective view of the flutter mount system are presented in Fig 1. The flutter mount system consists of a moving plate supported by a system of four circular rods and a centred flat-plate strut. These rods and the flat-plate provide the elastic constraints to the system and the rigid wing model fixed in the moving plate will oscillate in a two-degrees-of-freedom mode, pitch and plunge, when flutter is encountered. The rods, flat-plate and moving plate are made of steel and all connections are fixed-fixed end. Their dimensions are: rods 0.0055m in diameter; moving plate is 0.6 × 0.3 m; flat-plate is 0.7 × 0.1 × 0.002 m and the wing model has a NACA0012 airfoil section with 0.8 × 0.45 m.

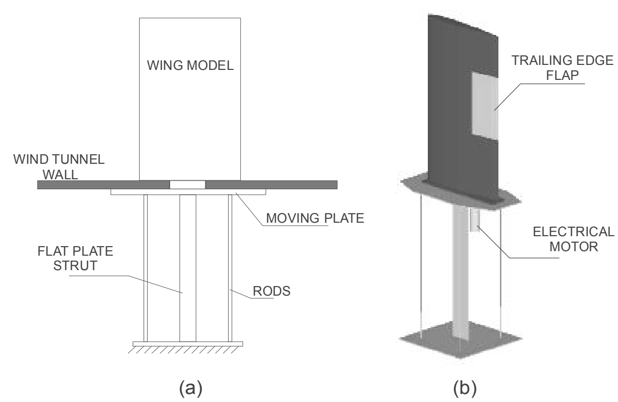

Figure 1. Side and perspective views of the flutter mount system.

The wind-off characteristics of the flutter mount system are strongly determined by the dimensions of the flat-plate strut, the rods and the mass of the moving plate and wing model. Modifications in the length and cross section of the flat plate strut and rods modify the frequencies and mode shapes of the flexible mount system. However, different wing models could be tested with the same flexible mount system by adding weights to the aft and fore inboard position in the moving plate, modifying the mass and inertia of the system. These weights can also be used to decouple the pitch and plunge modes by moving the centre of gravity of the flexible mount and wing model to the system elastic axis, altering the critical velocity. The system elastic axis is located in the vertical centreline of the flat plate strut and centre of the moving plate. The four rods assure a parallel pitch and plunge displacement relative to the wind tunnel wall.

Wind-off Dynamic Characteristics

A Finite Element Model is generated during the design period of the experimental system in order to establish its basic dimensions. This model is employed as a tool in the flexible flutter mount system design. The cantilever boundary condition was adopted for the flexible mount system in the rods and flat plate strut basis. The first three natural frequencies are documented in Table 1. Modes shapes in chordwise direction were not investigated, however the natural frequency of the first chordwise bending is also demonstrated in Table 1.

Table 1. Natural frequencies of the flexible mount system and wing model determined by FEM.

Mode	Frequency (Hz)	Description
1	1.3	First bending
2	2.1	First torsion
3	13.6	Second bending
4	15.5	First chordwise bending

First bending (pitch) and first torsion (plunge) are the modes involved in the flutter mechanism. The Finite Element results show these modes well defined and the other modes higher than these. This condition assures that the wind tunnel flow velocity that will excite the first bending and first torsion modes will not excite significantly higher frequencies, resulting in a phenomenon as near as possible of a two-degrees-of-freedom one.

Another important characteristic determined using FEM analysis is the stiffness of the modes involved in flutter. They are shown in Table 2.

Table 2. Pitch and plunge stiffness.

K_{plunge} (N/m)	K_{pitch} (Nm/rad)
1290	44

The structural data of Tables 1 and 2 are used in an aeroelastic model developed to simulate the aeroelastic behaviour of the system (De Marqui et al., 2005). The equations of motion are developed using the Lagrange's equations and the principle of virtual work, as it is described in the aeroelastic literature (Bisplinghoff et al., 1955 and Fung, 1955).

Expressions for the kinetic and potential energy are determined and the Lagrange's equations are then applied. After this, the generalized forces acting on the system are determined by using the Principle of Virtual Work and the generalized equations of motion are assembled. These equations are then used to determine the equilibrium solution and perturbation equations and the state space equations of motion are obtained (Eq. 1).

$$\begin{bmatrix} \ddot{\tilde{\Psi}} \\ \dot{\tilde{\Psi}} \end{bmatrix} = \begin{bmatrix} -\left(M_S - \frac{\bar{q}S\bar{c}}{2U_0^2}M_S\right)^{-1}\left(K_S - \bar{q}SK_a\right) & -\left(M_S - \frac{\bar{q}S\bar{c}}{2U_0^2}M_a\right)^{-1}\left(D_S - \frac{\bar{q}S}{2U_0}D_a\right) \\ I & 0 \end{bmatrix} \begin{bmatrix} \dot{\tilde{\Psi}} \\ \tilde{\Psi} \end{bmatrix} + \begin{bmatrix} -\left(M_S - \frac{\bar{q}S\bar{c}}{2U_0^2}M_a\right)^{-1}\bar{q}SB_0 \\ 0 \end{bmatrix} \tilde{\delta} \tag{1}$$

In Eq. (1) can be observed that the effect of the aerodynamic forces is to modify the mass, damping, and stiffness properties of the system. It is this aerodynamic coupling that is the essential feature of aeroelastic systems and leads to the flutter instability.

The flutter velocity determined during simulations is about 24 m/s, as can be seen in Fig. 2. This figure shows the evolution of the eigenvalues of the system with the increasing velocity and the instability is verified when any of the eigenvalues are in the right half or on the imaginary axis of the s-plane. The maximum flow velocity of the existing wind tunnel in the Aerodynamics Laboratory in the EESC-USP is 50 m/s. So, the structural characteristics determined above and the stability analysis performed show that flutter can occur in this wind tunnel.

After the design period, the system is constructed. Then, an Experimental Modal Analysis (EMA) is performed to verify the natural frequencies and modes shape prior to any wind tunnel flutter test. In this test, frequencies below 25 hertz are investigated. The measurement points are located at the flat-plate strut because it provides the elastic constraints to the system and the wing model is considered rigid. Thirty measurement points are located on the flat plate strut as shown in Fig. 3. Point 21 is also the excitation point.

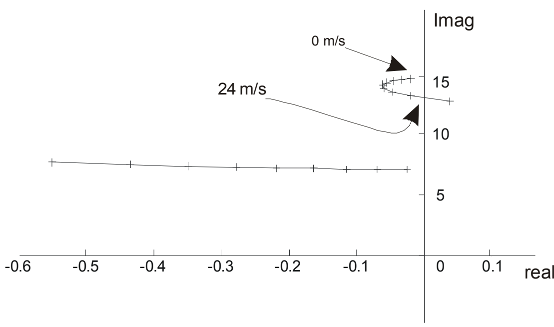

Figure 2. Instability achieved at a velocity of 24 m/s.

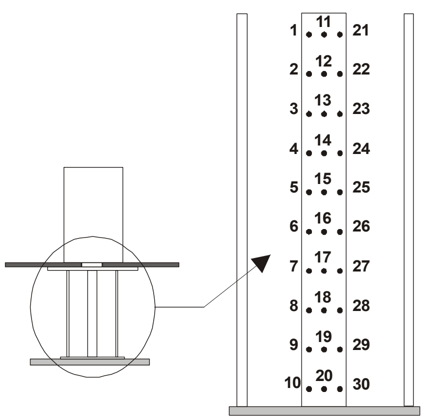

Figure 3. Flat plate strut discretization.

The exciter employed during the tests is an impact hammer Kistler type 9724A2000 with a Kistler Power Amplifier 5134A. The outputs are measured by a Kistler accelerometer 8303A10M4 with a Power Suply type Kistler 5210. This accelerometer is a capacitive one and it has a frequency range including low values, being able to measure the low frequencies of the system. A dual-channel B&K Dynamic Signal Analyzer type 2032 measures the frequency responses.

The EMA is performed to obtain frequency responses of the system. From these frequency responses modal characteristics are determined. Figure 4 shows some frequency responses obtained. The frequency responses are named as $H_{out,in}$ according to the measurement points in Fig. 3.

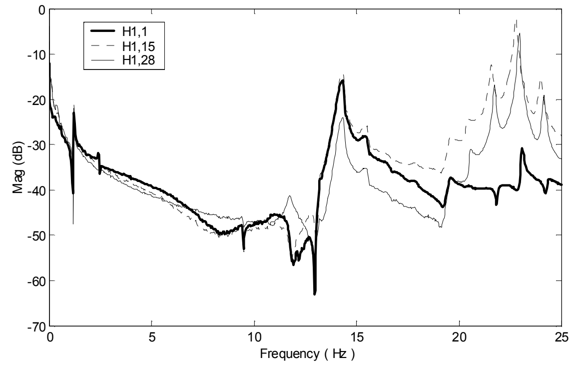

Figure 4. Some Frequency Response Functions of the mount system and wing model.

The Eigensystem Realization Algorithm (ERA) (Tsunaki, 1999) is employed to determine the modes shapes and frequencies from the experimental data. Natural frequencies are documented in Table 3 and modes shapes are presented in Figs. 5, 6 and 7. Rods and chordwise modes are not investigated in the EMA.

As can be verified in Figs. 5 and 7, the shape of the first and second bending modes are quite different from the expected ones. The second bending mode assumes a shape similar to the first bending mode and vice versa. These changes are caused by the parallel displacement in pitch and plunge caused by the arrangements of the rods of the flexible system and by the influence of the inertia of the wing in the results obtained during the Experimental Modal Analysis.

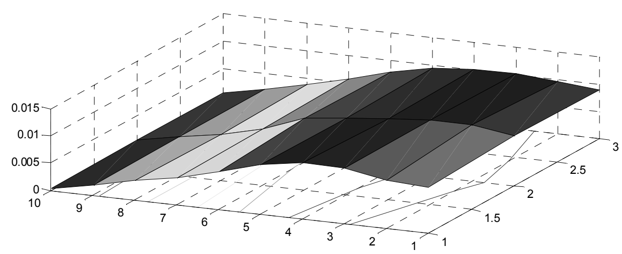

Figure 5. First bending mode identified by the ERA.

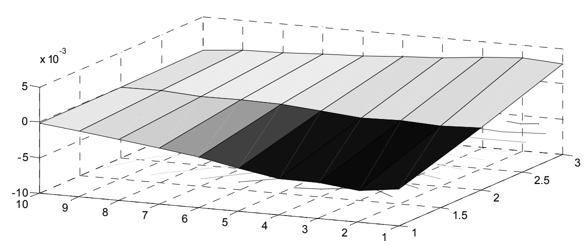

Figure 6. First torsion mode identified by the ERA.

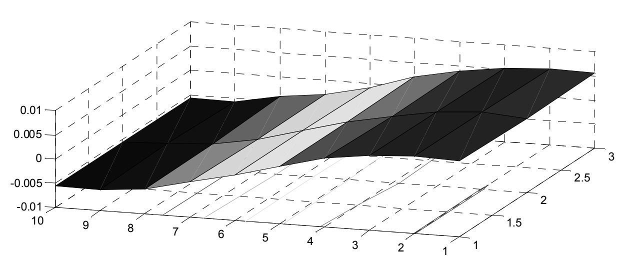

Figure 7. Second bending mode identified by the ERA.

The data presented in Table 3 show first bending and first torsion modes well defined and show the third mode higher than these, as was expected from the conceptual design and from the finite element analysis. The shape of the modes obtained by the ERA, Fig. 4 and 5, show the decoupling between first bending and first torsion modes and prove the correct relation between the position of the centre of mass of the wing and the system elastic axis previously described. A balancing was done before these tests and a mass of 0.3 kg was added to the flat plate in the leading edge region. These results associated with the stiffness characteristics previously determined assure that flutter will be obtained during tests performed in the existing wind tunnel.

The above analysis takes into account only the structural aspects of the flutter problem. Obviously the interaction of these characteristics with the aerodynamic ones has to be considered in the flutter analysis. Aerodynamic forces and moments, lift and pitch moment in the case of this study, will be exciting the modes involved in the classical bending-torsion flutter. As consequence, the elastic characteristics of the structure and the resulting aerodynamic restoring loads (responsible for aerodynamic damping when no mechanical friction is assumed and caused by the upwash induced by the wake vortices) will be reacting and dissipating energy to the airstream. When the critical speed is achieved, the aerodynamic damping vanishes because the aerodynamic restoring forces lose their dissipative characteristics and the self-sustained oscillatory behaviour is verified. This procedure is given in standard text Fung (1993).

Table 3. Natural frequencies of the flexible mount system and wing model identified with ERA.

Mode	Frequency (Hz)	Description
1	1.2	First bending
2	2.4	First torsion
3	11.7	Second bending

Wind Tunnel Tests

The system is also tested in wind tunnel. These tests were performed in the wind tunnel of Aerodynamic Laboratory of EESC-USP. This wind tunnel has a section test of approximately 2 m^2 and maximum velocity of 50 m/s. Figure 8 shows the system mounted in the section test.

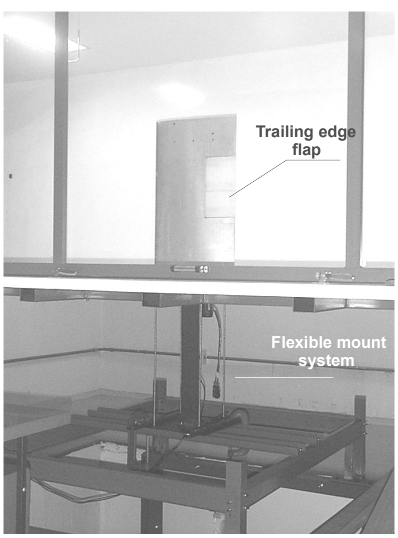

Figure 8. Flutter mount system and wing in the wind tunnel.

Basically the wind tunnel tests are realized to verify experimentally the flutter achievement with the dynamical characteristics previously determined. Initially, the wind tunnel tests are preformed to determine the critical flutter velocity. After this, some experiments are performed to characterize the achieved phenomenon. Frequency responses are obtained with few wind tunnel velocities to verify the evolution of pitch and plunge modes with increasing velocity. Flutter will be achieved with the coupling of these modes. Data obtained in these experiments are also used in an off-line identification process using the EERA. This procedure results in the quantification of frequencies and damping of the modes involved in flutter, resulting in a *Vgf* plot of the system.

The experimental system instrumentation for wind tunnel tests includes accelerometers, strain gauge bridges and an encoder. The position of the sensors in the experimental setup is observed in Fig. 9.

One accelerometer (Kistler KBeam 8303A10M4) is located in the centre line of the flat plate strut measuring the plunge acceleration during the experiments. Other two accelerometers (Kistler KBeam 8304B10) are installed in the moving plate; the signals measured with these accelerometers are used to calculate the pitch acceleration.

Strain gauges are located in the centreline of the flat plate strut in a maximum strain position determined from the finite element analyses. One strain gauge (Kiowa KFG-5120C123) is used to measure plunge displacements and the other (Kiowa KFC-2D211) is used to measure pitch angles.

A brushless electrical motor (Thompson BLD–2315B10200) installed in the lower surface of the moving plate, as can be verified in Fig. 1, is used to drive the trailing edge flap. The flap is connected to the motor by a rod. The electrical motor has an encoder used to measure the actual angular position of the flap. A PID controller was tuned to assure the correct control of the trailing edge flap position by the motor.

A dSPACE® DS 1103 processor board is used to develop the real time control of the flap and for data acquisition. This board has a 400 MHz Power PC 604e processor, I/O interfaces with 16 A/D and 8 D/A channels and incremental encoder interface. The signals of the accelerometers, strain gauge bridges and flap position can be acquired simultaneously. The computational codes for data acquisition and signal processing are developed in Matlab/Simulink®. The Simulink® code is compiled in Matlab® using Real-Time Workshop® compiler resulting in a C code. This C code is downloaded to the dSPACE® board to perform signal processing and I/O control.

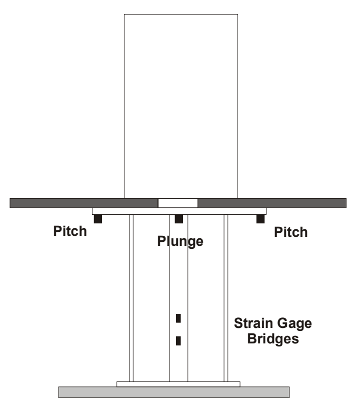

Figure 9. Position of the sensors for measurements during wind tunnel tests.

In the first experimental test, the verification of the critical flutter velocity is performed. The wind tunnel velocity is gradually increased and the pitch and plunge signals measured using the dSPACE® system. The wind tunnel velocity is obtained from the pressure measurements performed with a static pitot tube associated with a Betz manometer, a barometer and a temperature sensor installed on the test chamber. Flutter characteristics are observed at velocity of 24 m/s when the self-sustained oscillatory behaviour is measured. Figures 10 and 11 presents, respectively, the pitch and plunge signals measured during the experiments.

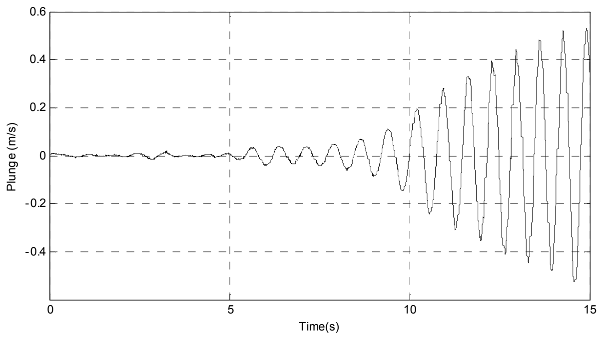

Figure 10. Plunge response measured during wind tunnel tests at velocity of 24 m/s.

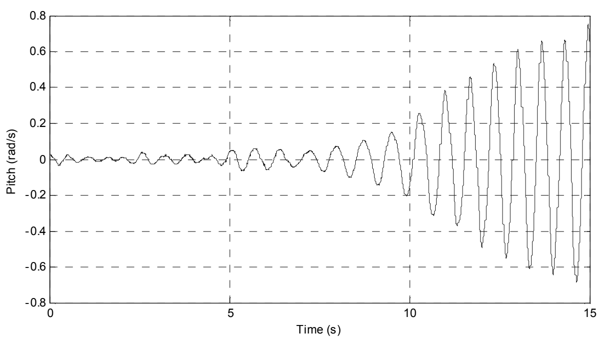

Figure 11. Pitch response measured during wind tunnel tests at velocity of 24 m/s.

This test shows the system behaviour only at the critical velocity. But some dynamical characteristics change with increasing wind tunnel flow velocity. In order to verify these changes other tests are performed. Basically, frequency response functions are obtained in several velocities showing the evolution of first bending and torsion modes with increasing speed. The input signal considered during these tests is the trailing edge position and the output signal is the acceleration measured in the wing trailing edge.

A B&K dual channel digital spectrum analyser type 2032 is employed to obtain the frequency responses. These responses are obtained from the wind tunnel off condition up to velocities as near as possible of the critical one. The signal input is a white noise generated in the dSPACE® system and sent to the trailing edge flap. This signal and the acceleration are processed in the spectrum analyser. This procedure is repeated for all intermediate test velocities. Some of the frequency responses obtained are shown in Figs.12, 13, 14, 15, 16 and 17.

In Fig. 12 is observed the frequency response obtained with the wind tunnel off condition. This frequency response shows the same frequencies for the first bending and torsion modes obtained during the EMA, as was expected.

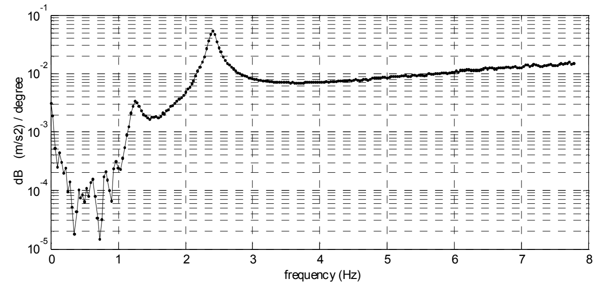

Figure 12. Frequency response measured with wind tunnel off.

In Figs. 13 to 17 is shown the evolution of the modes with increasing velocity. In these figures, it is clear the changes in the positions of the peaks relatives to the modes involved in the flutter. The shape of these peaks is also modified with increasing velocity, showing changes in the damping of these modes. Obviously, damping is increasing with velocity, but this tendency is expect to change abruptly at flutter velocity. In this case, the damping of one or of both modes involved in flutter goes to zero.

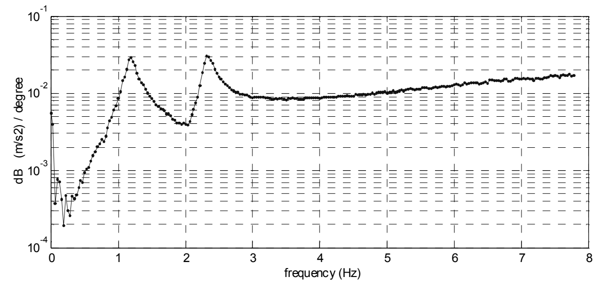

Figure 13. Frequency response measured at velocity of 10 m/s.

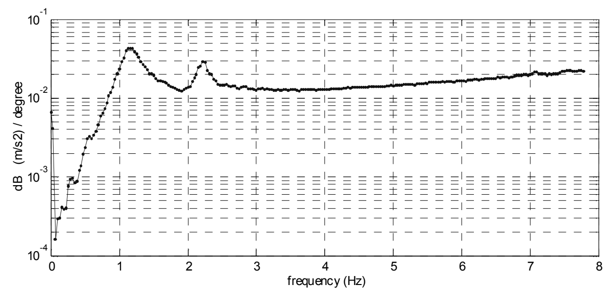

Figure 14. Frequency response measured at velocity of 15m/s.

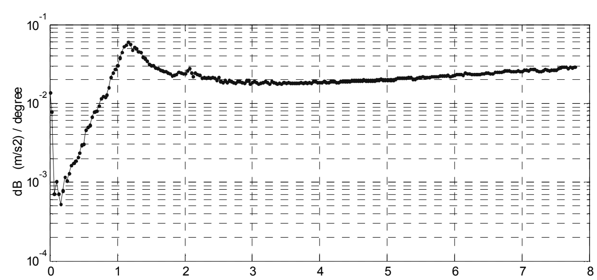

Figure 15. Frequency response measured at velocity of 20 m/s.

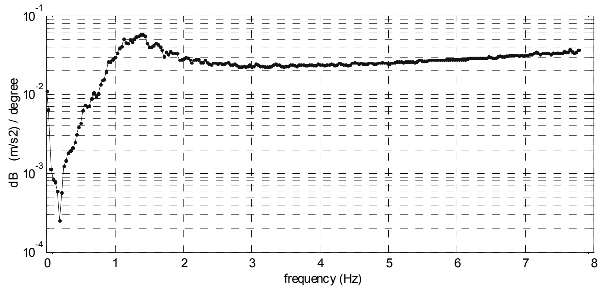

Figure 16. Frequency response measured at velocity of 23 m/s.

Figure 17 shows clearly that the pitch and plunge modes are getting coupled at a frequency of 1.5 Hz. This tendency shows that flutter is being achieved at the velocity of the test. This is the most difficulty measurement because the system is almost having an self-sustained oscillatory behaviour. We can assume this velocity as the flutter critical one.

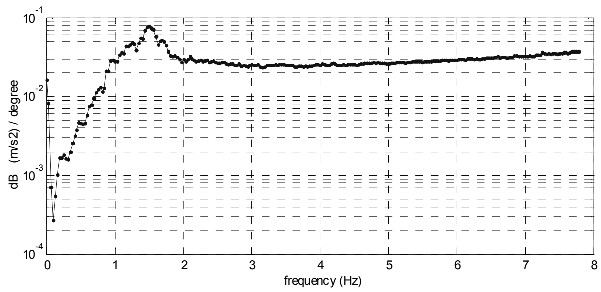

Figure 17. Frequency response measured at velocity of 24 m/s.

In Fig. 18 one can verify all frequency responses obtained during these tests. These frequency responses clearly present the evolution of the modes involved in flutter and the coupling at flutter velocity.

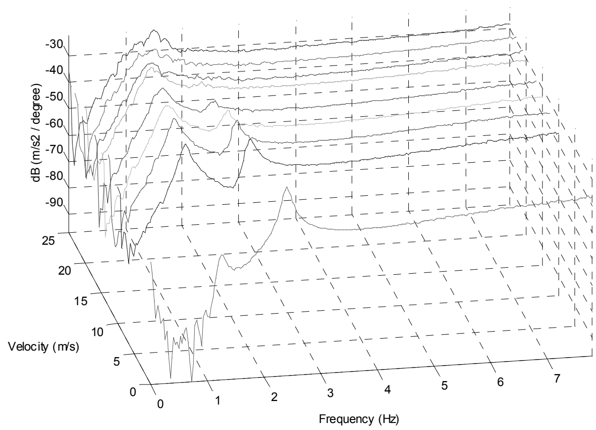

Figure 18. Frequency responses evolution with velocity increasing.

In a qualitative point of view, the frequency responses presented in Fig. 18 give a clear idea of the flutter mechanism of this work. The Extended Eigensystem Realization Algorithm (EERA) is employed to quantify the variation of frequencies and damping values with wind tunnel increasing velocity relative to the modes involved in flutter (Rebolho, 2006). This is a time domain algorithm that uses the input and output signals to identify the system. By inspecting the damping evolution with airspeed variation using EERA one can predict when flutter is expected to occur.

The identification process is performed using the trailing edge signal as the input one and the signals measured by the extensometers as the output. These data were measured in the frequency domain simultaneously to the tests performed to obtain the frequency responses of Fig. 18. An example of the input and output signals are shown in Figures 19 to 21.

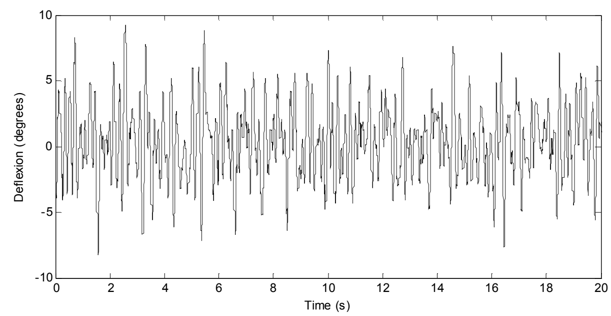

Figure 19. Input signal applied during the identification process.

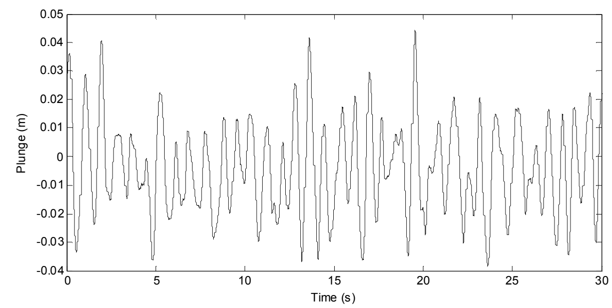

Figure 20. Plunge output signal used in the identification process.

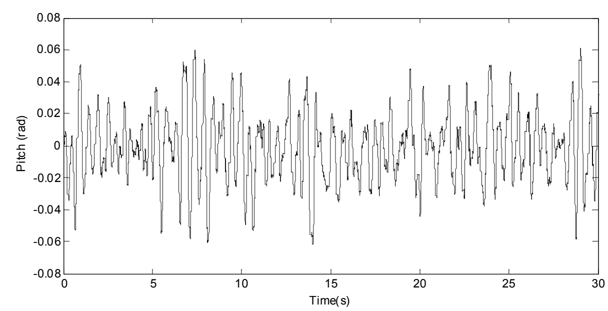

Figure 21. Pitch output signal used in the identification process.

The result of the identification process is the *V-g-f* plot presented in Fig. 22. This Figure shows the typical frequencies coalescence at flutter velocity. At the same velocity is also observed another typical flutter behaviour, the damping of the first torsion mode vanishes. For the frequency calculations, one can observe that the EERA method was able to provide good prediction. Nonetheless, for the damping factor identification the values per airspeed were more disperse. The damping values for pitch mode seems lesser disperse than those for plunge mode. The reasons for that are still not determined, and it must be object for ongoing investigation on flutter prediction with EERA. Although these results may be poorer than those for the frequency, the average damping values show curves that are consistent with the physics of the classical two-degrees of freedom flutter.

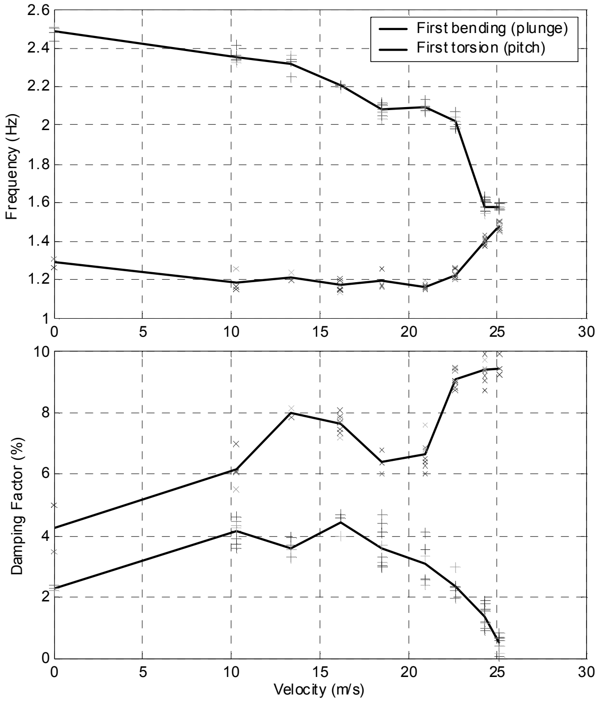

Figure 22. V-g-f plot of the system.

Conclusions

A flexible mount system is designed for flutter tests with rigid wings in wind tunnel. A design procedure is developed to assure that 2DOF flutter can be achieved during wind tunnel tests, which is the main scope of this work. This design procedure includes Finite Element, Aeroelastic Stability and Experimental Analyses.

The Finite Element model was developed as a design tool to the initial development of the system. As is verified in Tables 1 and 3 there are errors in frequencies determined by Finite Element and Experimental Modal Analysis/ERA analysis. These differences were expected since the finite element model is simplified and does not take in account some characteristics of the experimental system, like the mass of the electric motor. The connections of rods and flat plate strut considered in the finite element model are fixed-fixed end type. This condition is quite different in the experimental model. Even assuming these simplifications the finite element model was an important tool to the design and verification of the flexible mount system.

The dynamical characteristics of the flexible mount system and rigid wing were verified with an Experimental Modal Analysis. The Eigensystem Realization Algorithm was used to identify modal parameters from the experimental results. This procedure showed the rigid body pitch and plunge modes well defined and the other modes higher than these. This characteristic assures that the system will be as near as possible of a two-degree-of-freedom system when flutter is achieved.

The wind tunnel tests were done to verify the evolution of the modes involved in flutter with increasing velocity until flutter achievement. The frequency responses obtained in these wind tunnel tests confirmed the expected behaviour of the system, showing the modes coupling at flutter velocity. Time responses were also measured showing the self-sustained oscillatory behaviour of flutter.

The V-g-f plot obtained using the identification algorithm EERA showed in a quantitative way the evolution of frequencies and damping of the modes involved in flutter. The next step of this work is to perform real time identification using this algorithm. The main objective is the association of this identification algorithm with a control law in order to obtain a real time adaptive controller for flutter suppression.

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