THIN AEROELASTIC WING FINITE ELEMENT MODEL UPDATING WITH EXPERIMENTAL MODAL ANALYSIS RESULTS

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Abstract. *This paper describes an update procedure of a numerical thin wing model. This wing is used as an aeroelastic test bench to characterize the wing instabilities such as: LCO (Limit Cycle Oscillation), flutter and divergence. In order to perform a numerical aeroelastic analysis and predict when the phenomena will occur in wind tunnel, the extremely thin wing has its structure modeled based on Finite Element Method (FEM). The instrumentations, such as the cable and the accelerometer, applied to monitor the aeroelastic phenomena need to be incorporated in the numerical model. In this work, the cable mass is considered uniformly distributed over the wing and accelerometer mass as lumped mass. The dynamics parameters are extracted from an Experimental Modal Analysis through the Single-Input Single-Output (SISO) procedure. Minimizing an error function, based on least square method, the equivalent elastic modulus is adjusted interactively with purpose of reproducing numerically the wing dynamic behavior when compared with experimental results. Numerical and experimental results are compared with different boundary conditions in order to evaluate the updating model representativeness. According to the comparison, the model was successfully adjusted with this updating procedure.*

Keywords: *Experimental modal analysis, numerical modal analysis, finite element method, numerical updating*

1. INTRODUCTION

Several numerical models have been proposed in order to describe the aeroelastic phenomena [Clark *et al.* (2005)]. These phenomena are resulted from inertial, structural and aerodynamic load interaction [Bisplinghoff *et al.* (1955)]. Dynamic instabilities; such as flutter, divergence, and limit cycle oscillation (LCO); may occur due to this interaction that can cause catastrophic aeronautic disaster. Models try to predict when these instabilities may occur.

Normally, the structure is represented by discretized numeric formulation based on finite element method, for example, beam element presented on Cook *et al.* (1989). The aerodynamic loads acting in the structures is interpolated and a numerical analysis, using for example Doublet Lattice Method [Albano and Rodden (1969)], is used to predict the aeroelastic phenomena. Aeroelastic wind tunnel tests are widely performed in order to verify the numeric model, because these tests are a safe and efficient way to study the aeroelastic phenomena and to verify the model representitivity [de Marqui, C *et al.* (2007)].

Recently, High Aspect Ratio Wing (HARW) is considered for unmanned aircraft [Patil *et al.* (1999)]. In order to simulate the nonlinear effects of this wing type in wind tunnel, an extremely thin wing is proposed by Jaworski (2009) and Westin (2010). The instrumentations need to be incorporated on the numeric model.

Some updating procedures using experimental results found in Maia *et al.* (1997) allow to adjust the numerical model in order to describe the dynamic behavior of the structure. According to Ewins (1986), for *comparison of experiment and prediction* can be used some procedures: *comparison of response properties*, *comparison of modal properties*, *comparison of natural frequencies*, *comparison of mode shapes - numerical* and *comparison of mode shapes - graphical*.

In this paper is presented a methodology to update a numerical model of a thin wing using *comparison of mode shapes - numerical*. This thin wing is used to investigate experimentally LCO phenomena. The wing is modeled numerically based on the FEM with a beam formulation. The natural frequencies and normal modes are obtained from an eigenvalue problem solution. The numeric results are compared with the natural frequencies extracted from a Ground Vibration Test (GVT). Maintaining the same mass properties the stiffness is adjusted in order to compute the same results.

2. METHODOLOGY

The wing used to investigate the LCO phenomena is schematically shown on the Fig. 1. The wing is clamped on the root. The instrumentations, such as cable and accelerometer, need to be incorporated in both numerical and experimental models. The cable is considered on the numerical model as distributed mass along the wing. On the other hand, the accelerometer is considered as a lumped mass on its location point.

In order to evaluated the updated procedures, three cases are considered with different Boundary Condition (BC), as presented in Tab.1. The proper mass and stiffness matrix used in the numeric model are obtained using first BC case. The other models are used to verify whether the numeric model is widely representative.

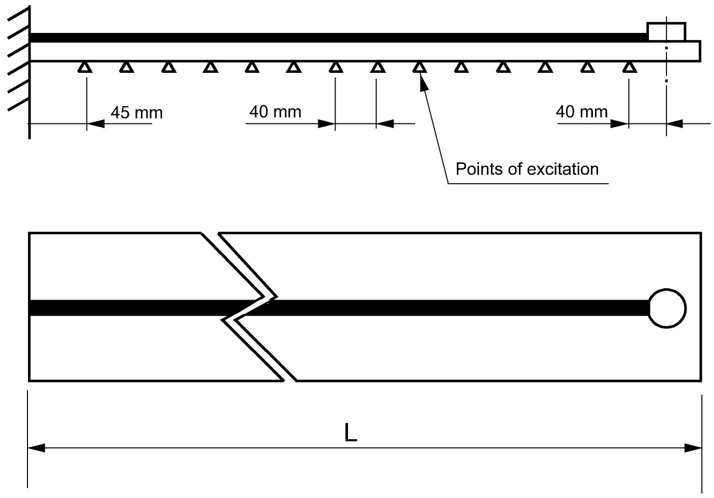

Figure 1. Experimental Modal Analysis setup for the wing model

Table 1. Study cases with different boundary conditions

Cases	1	2	3	4
L [mm]	482	402	322	562
number of *beam element*	24	20	16	28
number excitation points	12	10	8	14

The experimental set-up was mounted in order that the same boundary condition presented in the Tab. 1 could be reproduced. The modal properties for each BC case are extracting from experimental modal analysis.

2.1 Experimental modal analysis

Initially, the EMA set up is created as follows: the thin wing is clamped on other extremely rigid structure. The instrumentations, an accelerometer and a cable used to monitor aeroelastic phenomena, are glued on the wing. The cable is fixed near the neutral elastic line of the thin wing using an adhesive tape. The accelerometer is fixed on the wing tip using bee wax as suggest Ewins (1986).

In order to estimated the Frequency Response Functions FRF, the Single-Input Single-Output (SISO) procedure is performed with an impulsive input using a dynamometric hammer and. Several excitation points are 40 mm equidistant from each other to choose the best excitation location to estimate the FRF. The nearest root point has a 45 mm far to the root, due to the hammer test head size, as shown in Fig. 1. The natural frequencies ω_e are extracted from peak-amplitude method shown by Oliveira (2010).

This procedure is performed to the BC presented in the Tab. 1.

2.2 Numerical modal analysis

The numerical model is created using *beam element*. The pre-processor MSC/PATRAN^{TM} is employed to generate the *beam mesh*. The data used to create numerical model is shown in Tab. 2. The model is schematically presented by the Fig. 2 .

In order to define the number of *beam element* used in the numerical model, it is adopted the same distance between the two excitation points used in EMA (Fig. 1) . Thus, the number of *beam element* used for the cases 1, 2, 3 and 4 is shown in Tab.1.

The cable mass and accelerometer mass properties are added to the model. The cable mass is considered uniformly distributed on the wing. Therefore, the total mass allows to calculate an equivalent *beam element* density property.

The accelerometer mass is considered as lumped mass and it is concentrate on its c.g.(center gravity) location. Its mass property is presented by the Tab. 2.

The eigenvalue problems are solved using MSC/NASTRAN^{TM} to obtain the numerical natural frequencies and normal modes after each updating model realization.

Table 2. Main data of the wing model

Thin wing		
item	unit	value
thickness	mm	1.05
chord	mm	12.62
Wing Material		
item	unit	value
Aluminum	—	Al 1050 H16
Modulus of Elasticity	GPa	69.0
Density	g/cm^3	2.705
Poison ratio	1	0.3
Accelerometer		
item	unit	value
Type	—	IECP*
Made by	—	Brüel & Kjaer
model	—	4517-002
Frequency range	Hz	1 - 20k
mass	g	1.02
Cable		
item	unit	value
mass	g	1.15

(*) Internal eletronic circuit piezoelectric

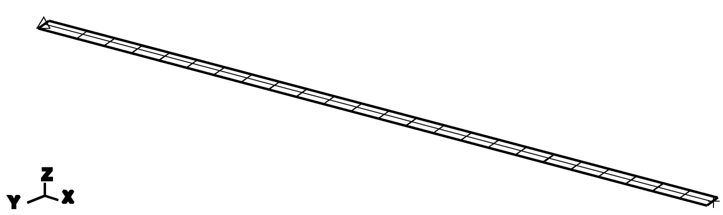

Figure 2. Wing mesh from the numeric model

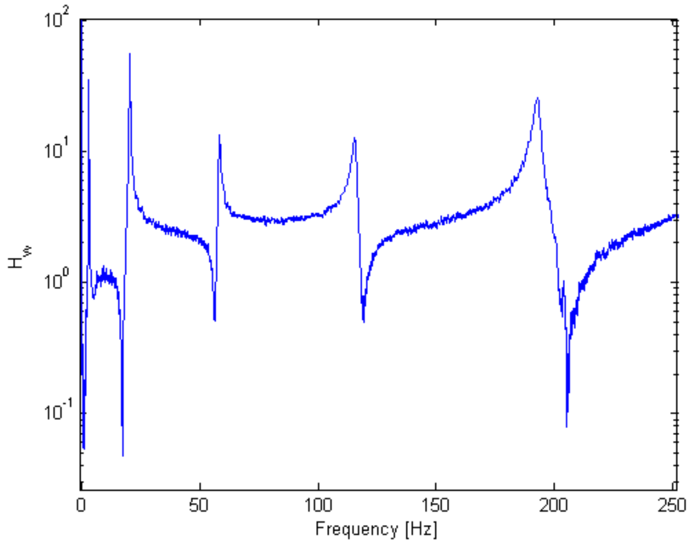

Figure 3. Frequency Response Function FRF estimated for case 1

Table 3. Natural frequencies obtained experimentally for each case

CASE	First mode	Second mode	Third Mode	Fourth Mode
1	3.17	20.44	58.28	115.83
2	4.50	29.56	85.00	168.83
3	6.83	45.33	130.78	—
4	2.33	15.22	43.28	85.61

2.3 Update procedure

The initial numerical state is defined with an equivalent mass and a standard elasticity E, shown in the Tab. 2. A numerical modal analysis is calculated as described on the section 2.2 and natural frequencies ω_n for fist modes are compared with natural frequencies extracted experimentally ω_e.

An error function based on square differences, Eq. 1, is used as criterion to assess the difference between both, numerical and experimental model.

$$e_{rr} = \sum(\omega_e - \omega_n)^2 \tag{1}$$

The model is adjusted iteratively, with different Young modulus E. Sucessive eigenvalue problem is solved until the error function converges to the minimum value.

3. RESULTS AND DISCUSSIONS

The natural frequencies ω_e are extracted from experimental modal analysis using the Peak Amplitude Method (PAM) implemented by Oliveira (2010). An example of FRF used is shown in the Fig. 3 for the case 1. These natural frequecies extracted are presented by Tab. 3

3.1 Error function evolution

In order to evaluate Young modulus variation ΔE, the error function is plotted as function of E as shown on the Fig. 4. From the figure E is defined as $69.2GPa$. This value yields the minimum error for the model consideration.

3.2 The model evaluation

Once the elasticity modulus is defined for the first case, the numerical modal analyses are performed for the other cases in order to evaluate the model quality. The predicted natural frequencies are plotted as function of experimental one, similar as presented in Ewins (1986). Observing the Figs. 5 - 8, it can be noted how far the model is from the real one. The assumption adopted on the model is valid for all cases and the properties of mass and stiffness agree among the cases as can be observed in the Fig. 9.

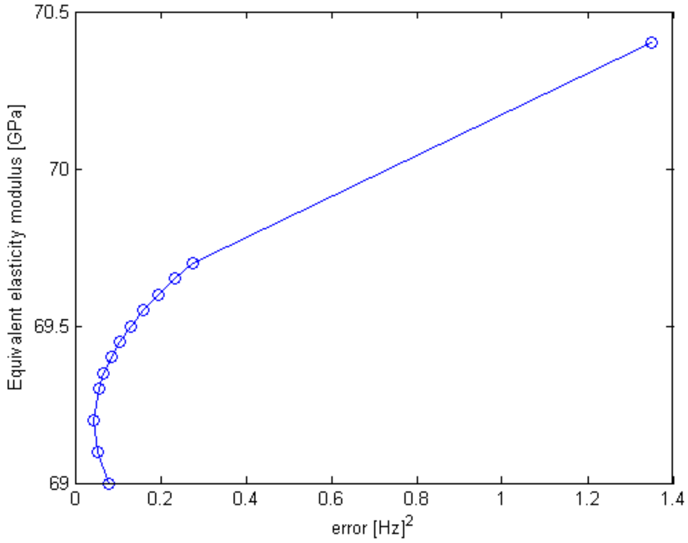

Figure 4. Error variation in function of young modulus E

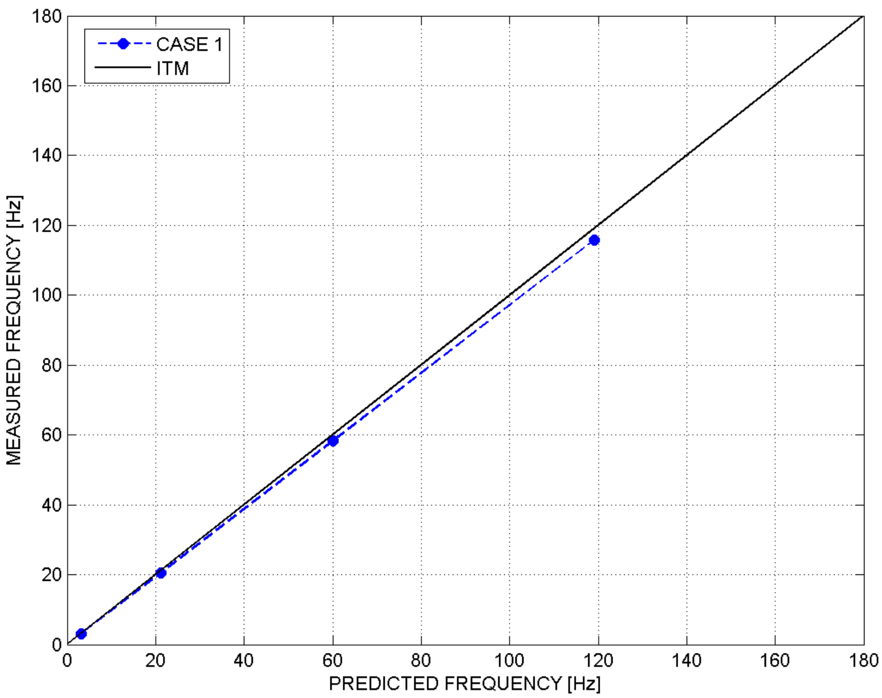

Figure 5. Predicted and Measured comparison - Case 1

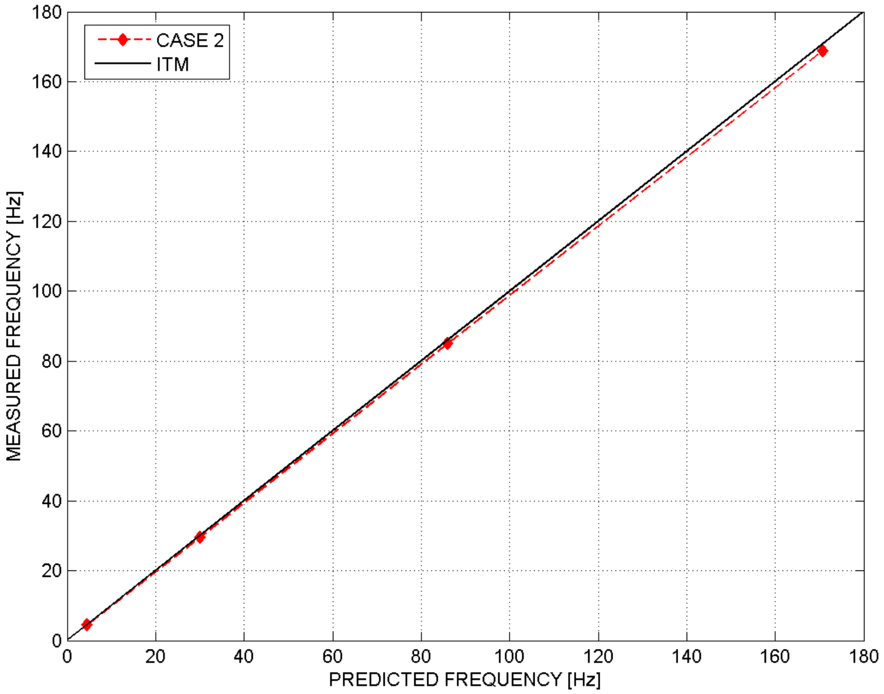

Figure 6. Predicted and Measured comparison - Case 2

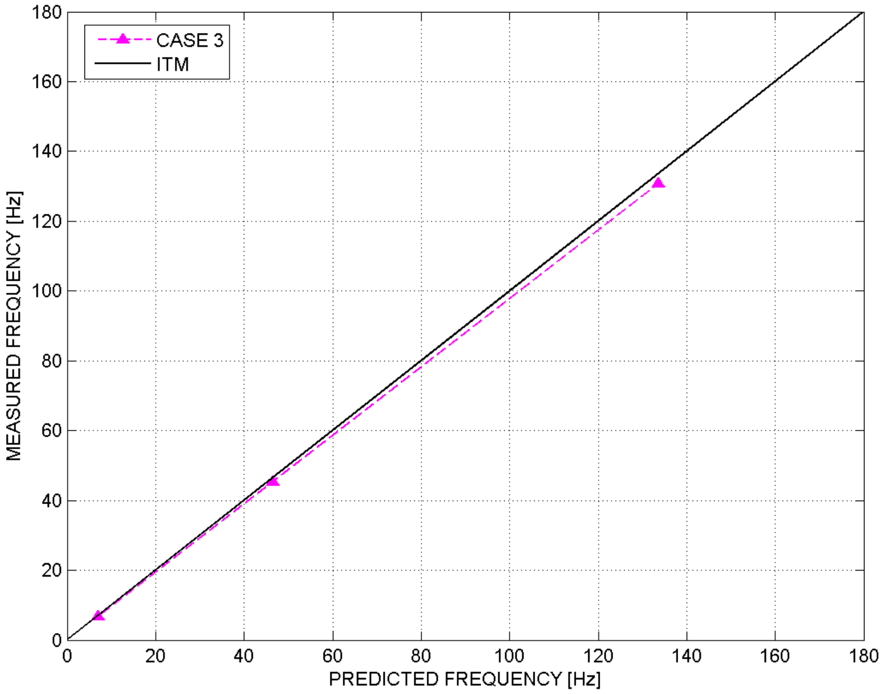

Figure 7. Predicted and Measured comparison - Case 3

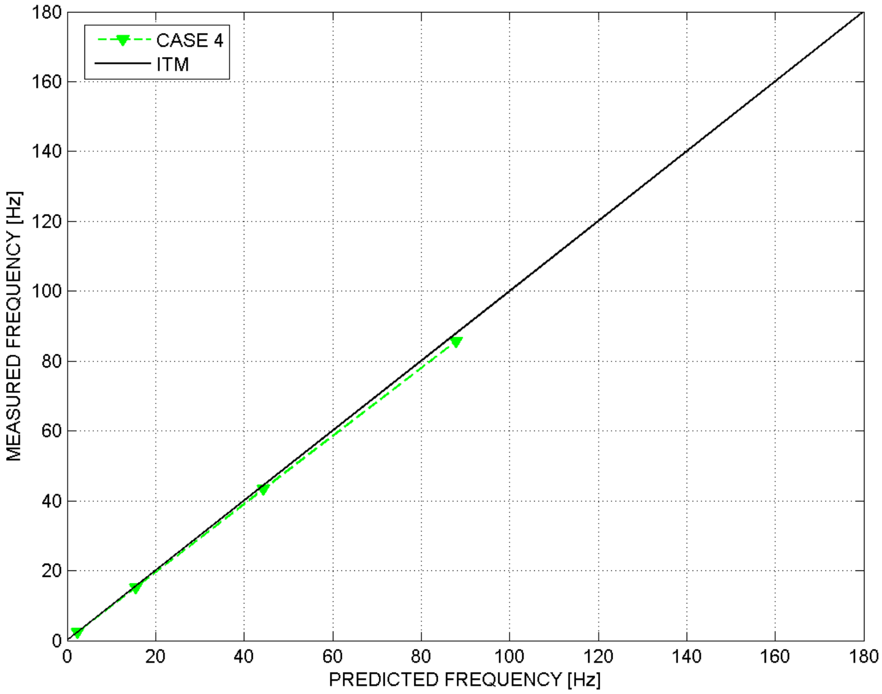

Figure 8. Predicted and Measured comparison - Case 4

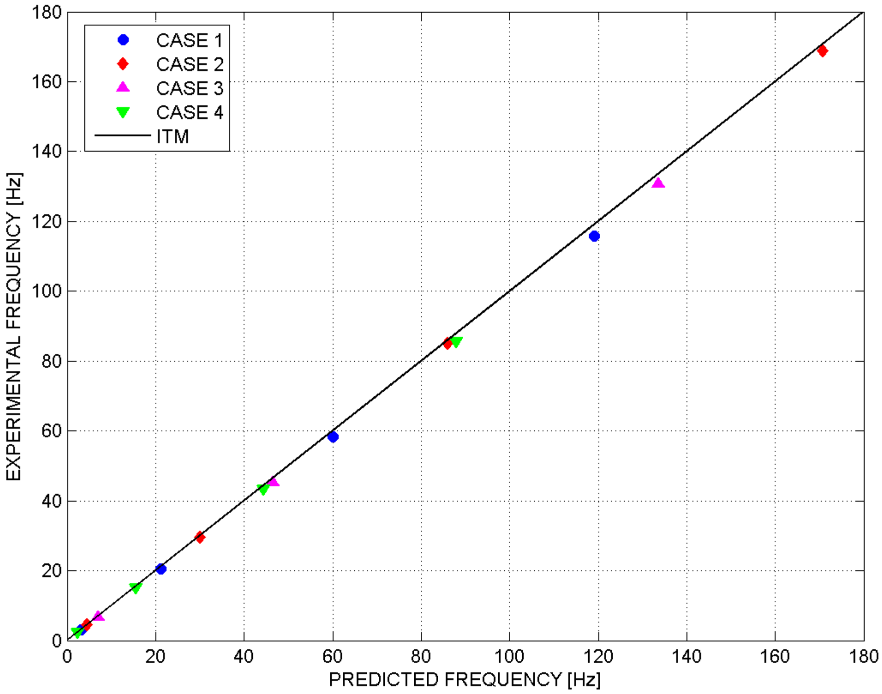

Figure 9. All cases - predicted and Measured comparison

4. CONCLUSIONS

It is possible to consider the instrumentation as part of the wing structure in order to perform aeroelastic measurements. To do this numerical updating procedure, some data from ground vibration test need to be considered. The procedure consists of measuring all the mass and the replace as a equivalent *beam element* mass through the equivalent density. The elasticity properties are iteratively adjusted with an equivalent Young modulus of elasticity until the differences between numerical and experimental natural frequencies to be minimized. The successful of this approach can be observed by the comparison experimental-numerical curves. The curves slopes trend to a 45 degrees as cited by references.

5. ACKNOWLEDGEMENTS

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7. Responsibility notice