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RESEARCH MODEL DESIGN FOR NUMERICAL-EXPERIMENTAL STUDY OF HIGH ASPECT RATIO WING AEROELASTIC RESPONSE

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Abstract. *The search to improve the performance of the aircraft has lead, among other things, the increase of wing aspect ratio. As a consequence of this solutions, the wing these solutions have the consequence an increased flexibility and, in some cases, resulting in aeroelastic problems. Among all methods used to study aeroelastic responses, the use of research models is highlighted. Reseach models for wind tunnel testing is a way to test different solutions for circumventing aeroelastic problem. As an example, the use os shape memory alloy propertires such as stiffness control an pseudoelastic properties are strategies to improve aeroelastic performance. Aiming to study the flutter response of a flexible wing of high aspect ratio, this article was intended to design, construct and test a model for this purpose, using a numerical-experimental methodology suitable for testing shape memory alloy arrangements for aeroelastic control. At first, the structure was modeled in finite elements, using Nastran, to obtain the aeroelastic response through the ZONA6 method, finally these numerical results were correlated with the experimental results. The flutter condition was evaluated analyzing the damping and coupling frequency. The numerical and experimental results reveal good approximations for the flutter velocity and oscillation frequency.*

Keywords: *aeroelasticity, flutter, flexible wing, wind tunnel.*

1. INTRODUCTION

Defined as the result of unsteady self-excited vibrations, *flutter* is an aeroelastic phenomenon that can lead to catastrophic structure failures due to the resulting dynamic efforts much higher than the static forces acting on such structures. The structure draws energy from the airflow and increases its own response amplitudes, resulting in excessive deformations and often structural failure (Whight and Cooper, 2015). Concerned with such destructive potential, a great number of studies looking for a flutter active or passive control has been developed since the 20th century (Tang and Dowell, 2001). These studies usually employ experimental tests using scaled models in Wind tunnels facilities.

In aeronautics sciences, the usage of small-scale models has been a very common practice since its beginning. Just to mention some pioneers related to aeroelastic experimental researches, Manfred Rauscher in 1927 began to introduce them in a wind tunnel at the Massachusetts Institute of Technology - MIT (Garrick and Reed, 1981), while Frazer and Duncan (1929) began to conduct experiments with aeroelastic models two years later at the Royal Aeronautical Society - RAS facilities.

In parallel, Perring (1928) also used this technique to determine the flutter velocity of a two wing seaplane (biplane) that featured flutter of wing-aileron type. The 1:3 scale model was tested in the RAE-7-ft tunnel and presented the same mass distribution of the prototype, but a significant lower stiffness (1/9) than the real airplane. This was the first model to demonstrate the efficacy of wind tunnel tests to correlate model experimental results and real scale prototypes behavior.

In a posterior work, Frazer and Duncan (1931) tested a model of three degrees of freedom of a flexible wing in which the mass of the wingtip could easily be changed (in position and amount) to alter the model dynamics. The aileron was freely articulated in order that the wing could flex and twist without restriction. This work has been used for decades as a methodological reference to study flutter and is known as the flutter bible.

More recently, Yeager and Kvaternik (2001) suggested that the scale models can be split into two groups: the research models and the prediction models. The first group does not represent any particular aircraft and, among other purposes, provides data for testing analytical models for structure behavior prediction. Their main result is the informational data about flutter trends in respect to certain dynamic and geometrical parameters. In the other hand, the prediction models are based on actual aircraft characteristics and have the purpose to evaluate the aeroelastic behavior of the actual airplane structure. Usually, one model is designed to elucidate only one aeroelastic phenomenon.

The accumulated knowledge by the pioneers of Aeroelasticity on scaled models and the improvement of this field of science did evolve the way to set up the aeroelastic tests which is nowadays known as *testing programs*. These programs formalize the procedures to explore several aeroelastic problems and aspects, such as the occurrence of aeroelastic phenomena within the flight envelope of the aircraft, according to the aeronautical regulatory norms; the aeroelastic characteristics of new constructive techniques and innovative materials; the evaluation and validation of computer codes and problem-solving techniques; and the development of active controls to decrease the harmful effects of aeroelastic responses (Ricketts, 1990; Tang and Dowell, 2016, p. 1).

In this context, this work aims to develop a research model to study the flutter phenomenon in high aspect ratio flexible wing. The model was designed taking in mind its final objective, i.e., the evaluation of the viability and technical performance of shape memory alloy wires to control the wing structure aeroelastic responses, reducing internal stresses and structural displacements of the structure.

2. METODOLOGICAL REFERENCE

The wing scaled model used here was inspired in the experimental bench mounted by Tang and Dowell (2001) with the proposed modifications by Arantes (2009) and Westin (2010). These model concepts contain basically the same components, namely, a spar to resist the aerodynamic stresses and to ensure torsional and bending stiffness and ribs with the NACA0012 aerodynamic profile. The coupling of bending and torsional modes was forced by a mass slender body located at wing tip resulting in a lower torsional natural frequency.

The model presented by Tang and Dowell (2001) presented a wing structure with features that provide the occurrence of flutter without compromising its integrity or the occurrence of failure when subjected to flow. To do so, they adopted a steel frame with rectangular section (or scale length x width x thickness: 457.2 mm x 12.7 mm x 1.27 mm) and 66 discontinuities introduced to reduce its torsional stiffness. The structure also counted with eighteen ribs with NACA 0012 profile in aluminum plate (thickness x chord: 2.54 mm x 50.8 mm) and ribs of balsa wood arranged between aluminum ribs to keep the aerodynamic profile along the wingspan. The slender body at the wing tip was machined in aluminum (diameter x length: 9.5 mm x 101.6 mm) with its ends in bronze and paraboloidal shape. The function of this body is to increase the mass moment of inertia, decreasing the natural frequency of the set when submitted to this type of effort, making possible the coupling of the torsion and bending vibrating modes (Tang and Dowell, 2001).

The main alteration proposed by Arantes (2009) and Westin (2010) was the replacement of construction materials of the spar, ribs and aerodynamic fairing. The steel wing frame was replaced by an aluminum spar, the aluminum by balsa wood for the ribs and the aerodynamic fairing was built with Depron™ instead of the balsa wood. There were also changes in the position of the center of mass of the ballast in relation to the wing elastic axis. The elastic axis was moved along the wing chord and the ballast dimensions also were changed.

3. DESIGN OF THE EXPERIMENTAL MODEL

During this procedure, some requirements must be observed to design the model, such as the geometric constraints and maximum speed of the wind tunnel testing section and the restrictions on the application of shape memory materials (SMA). The SMA wires were applied to the wing model fixing them at the two wing extremities - root and tip. When tensioned, these wires generate a compressive force along the wingspan, demanding care in order to avoid structural buckling.

The wires act in pairs and are represented by the colored straight segments shown in Figure 1. The first setting (C1) is represented by the red line, the second (C2) by the green lines and the third (C3) by the blue lines. The fourth (C4) wire configuration consists of the combination of all the previous ones. The C1 and C2 sets were thought to act only in flexion vibration modes, the C3 to both bending modes, but focused on torsion as the wires crosses each other in a X configuration.

On the characteristics of the experimental facility, the available wind tunnel is an opened, blower and subsonic type. Its test section is 0.7 m long and 0.6 m high and wide and the fan is a turbine EAS/1250 model with 1.2 m diameter, power and maximum flow of 25HP and 43000 m³/h, respectively, maximum rotational speed of 1150 rpm and

maximum air speed of 33 m/s. Mounted at the Laboratory of Aerospace Structures at the ITA (LAB – AESP) this bench was a courtesy to the authors to perform the research presented here.

To analyze the characteristics of the spar used in the model proposed by Tang and Dowell (2001) and the alterations by Arantes (2009) and Westin (2010), it was found that the buckling load supported by the spar is too small, making unviable the insertion of the SMA wires. To work around this problem, the spar thickness was increased. After this modification, the wing stiffness was also altered and a revision of the aeroelastic system design was necessary to suit the research proposal. This new conception involves material specification used in aerodynamic wing sections (ribs) and the ballast resizing.

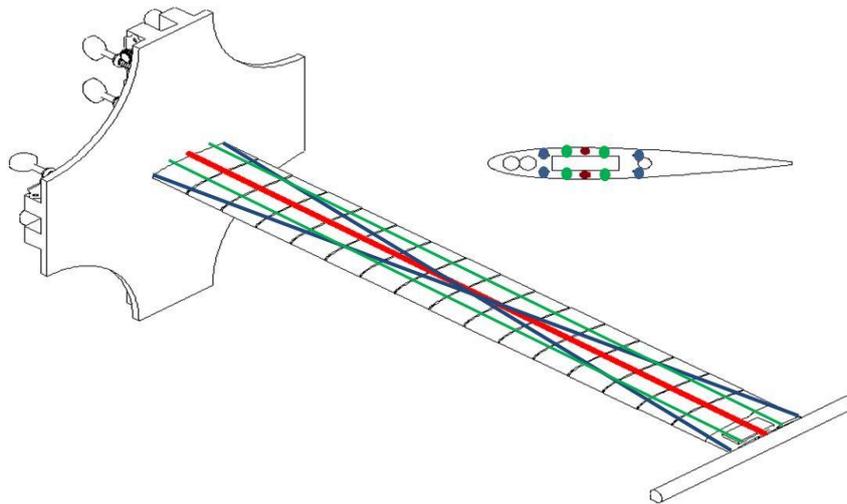


Figure 1. Wire arrangement in the research model.

The wire arrangement in search template the model project was held initially in virtual environment before leaving for constructions and wind tunnel tests. To that used two softwares: NASTRAN/PATRAN and ZAERO. The structural model was developed using a commercial finite element package very widespread (MSC NASTRAN/PATRAN), it developed a CAD model of the Stringer with dimensions (457 mm x 12.7 mm x 3.40 mm). Plate elements, with certain thickness, were used to represent the stringer (CQUAD4), concentrated mass element (CONM2) for the ballast of the tip and ribs, and to connect them to the structure rigid elements (RBE2). The opposite end to the concentrated mass is declared as perfect, bezel setting a condition of stringer engaged in free balance as shown in Fig. 2.

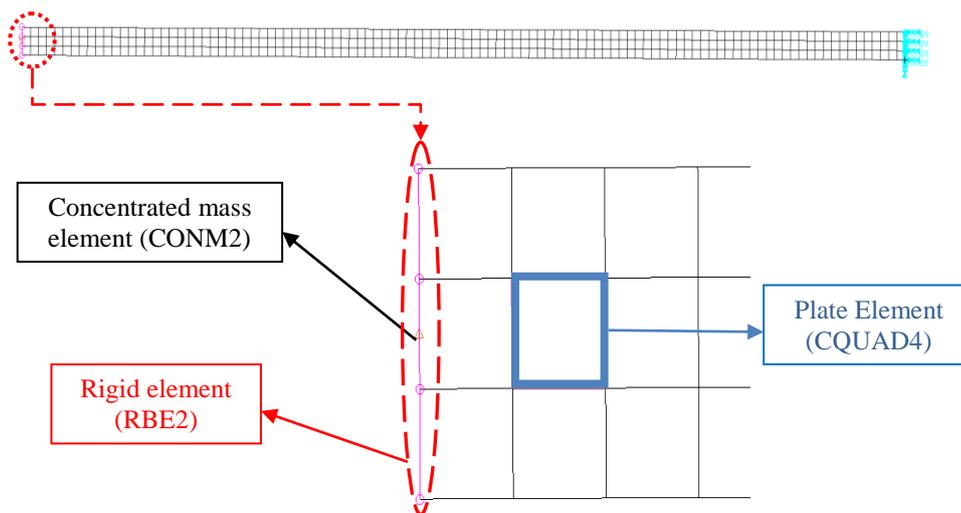


Figure 2. FEM model of the stringer.

The unsteady aerodynamic model is calculated by the ZONA 6 method (Zona Technologies, 2011) where all the dipoles are distributed at the panes surce ans a control point located at centroid of each panel. The ZAERO™ is utilized to solve this problem by the coupling between the aerodynamic and structural models using the SPLINE function.

To proper work, the ZAERO™ code must have as input: the generalized mass and stiffness matrices, the displacement eigenvectors, associated vibration modes to natural frequency (all of there were outputs of NASTRAN code), furthermore, the geometric model, reduced frequencies, panel quantities and velocity. The ZAERO™ output are the generalized aerodynamic forces and flutter velocity calculated by the k method.

With various aeroelastic systems parameters and defined flow field, it is time to evaluate the required slender body to the desired analysis: that one that gives a small *wind-off*¹. At this time, some slender bodies with many different diameter, length and materials whose gives different mass and inertia moments were checked. The decision point about the slender body was taken into account the main capability to excite the bending and torsion modes coupling, occurring the flutter phenomenon inside the available wind tunnel velocity range. Together the slender body design, the position of its own gravity center between the elastic axis was carefully set, in order to slow down the critical flutter velocity.

After many simulations, the final aeroelastic system is shown at Figure 3 and it is composed by the stress rib, anchorage rib and the fill ribs. The fill ribs were used to ensure the wing profile along span and were made of 3 mm polystyrene plates laser cut. The joint of each nine fill ribs makes the “sections”. On the other hand, each section is 1 mm spaced from the next to not interfere the spar dynamic and also the flow, as Westin (2010) do. The slender body and spar are also part of the system.

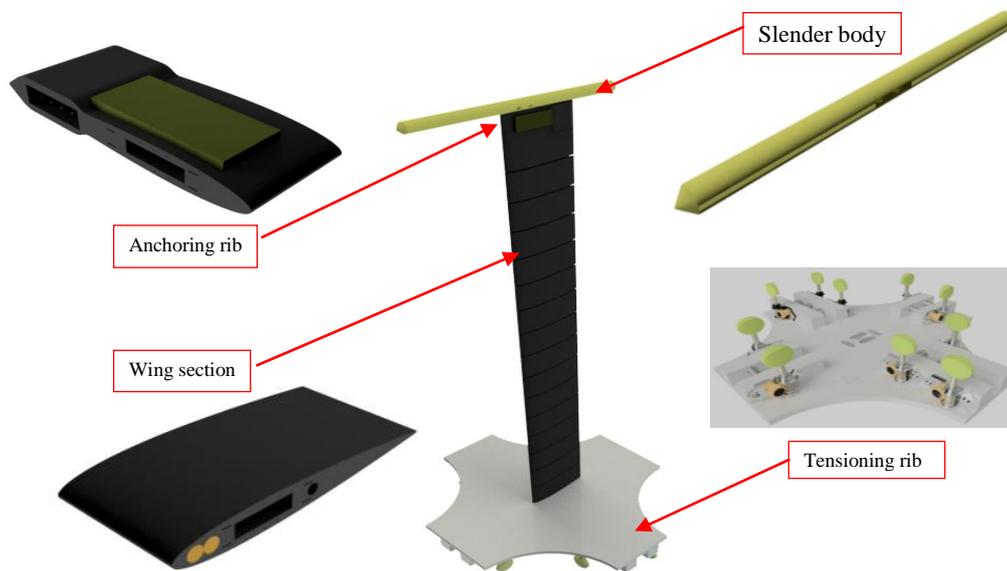


Figure 3. Major components of the flexible wing model.

At wing sections, two small brass cylinders (orange circles at wing sections in Fig. 3) are positioned near the leading edge to change the gravity center from 7.991 mm position behind the elastic axis to 0.348 mm position in front of it. This configuration ensures the flutter occurrence and the cylinders dimensions are 3.17 mm diameter and 27 mm length.

At Figure 3, the anchorage rib fix the wires and has the electric system to activate the SMA wires by heating process with Joule effect. The stress rib stresses the wires similar as guitar string stress system. Both were manufactured in ABS by 3D printing machine.

After all the virtual tests and ensuring all the desired requirements of the research model, the part constructions and assembly were made.

No matter how careful is the manufacturing, small differences about the designed model and the manufactured model will exist. These shape, dimensions and properties differences lead to mass distribution, inertia moment and dynamic response changes due the excitations. These inaccuracies reflect in error between the theoretic or numeric results and experimental data.

Keeping in mind these slightly differences and trying to reduce them, the built system had his own dimension and mass measured, directly (like geometric dimensions and mass) or indirect (inertia moment and specific mass by CAD code). Now with all input variables for the aeroelastic numeric analysis at ZAERO™ and NASTRAN® softwares the codes were refreshed. The Tab. 1 present the main system dimensions, materials and properties.

¹*Wind-off* is the difference between the natural frequencies modes that couples in the absence of the aerodynamic load.

Table 1. Experimental wing model data.

Wing		Slender Body			Stringer	
Span (m)	0.457	Diameter (m)	0.00952		Length (m)	0.4570
		Length (m)	0.16748		Width (m)	0.0126
Chord (m)	0.05823	Mass (kg)	0.0941753		Thickness (mm)	3.3981
		Inertial Moments (10^{-6} kg.m ²)	I _x	1.065		Material
I _y	211.909		Elasticity Modulus (GPa)	59.5		
I _z	211.895		Poisson Coefficient	0.33		
Center of Gravity	26.04% chord	Material	Brass		Density (kg/m ³)	2607.54
		Offset (mm)	3.8			

4. MODAL EXPERIMENTAL ANALYSIS

The modal experimental analysis has made at the Laboratory of Structures at the Aeronautical Department of ITA. The equipments are: LMS – SCADAS acquisition system, PCB Piezotronics® 086C03 impact hammer and two Polytec® CLV-2534 laser vibrometers to check the system output velocity. The spar root was fix to an inertial base and the reflexive tapes were fix at twenty-six points to data acquisition.

Afterwards the model was excited by the impact hammer and the associated FRF's were extracted to determine the modal form and associated natural frequencies by the LMS Test Lab Modal Analysis software.

Table 2. Confrontation of experimental and theoretical results

Experimental					
Modes	1° F	2° F	3° F	4° F	1° T
Frequency (Hz)	3.835	30.494	91.972	189.283	30.494
Numerical					
Frequency (Hz)	3.6493	31.233	89.896	196.19	30.186
Error (%)	4.84	2.42	2.25	3.64	1.01

To check the results experimental data the methodology was applied at the complete research model so the NASTRAN® returned the shape modes and associated natural frequencies. The Tab. 2 shows results for the firsts five vibration modes and the Fig. 4 shows the proximity between the second bending mode and first torsion mode frequencies. All the error are less than 5%, and the torsion mode that is the most important frequency value has an error of nearly 1%.

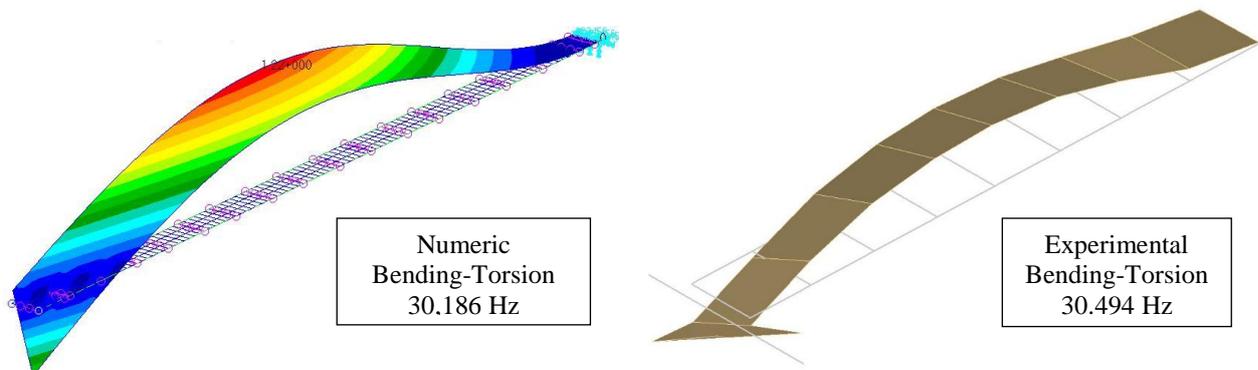


Figure 4. Visual comparison of numerical and experimental results for flexo-torsional coupling frequency.

After the modal analysis in absence of fluid flow the flutter tests begins. At first, the numeric analysis at ZAERO™ than the experimental analysis. The methodology already explained, the ZAERO™ outputs the velocity, damping and frequency (V-g-f) data relative to each mode provided by NASTRAN®. At Fig. 5 (a) the damping and (b) frequency, both related to the velocity to the second mode (first torsion mode) and third mode (second bending mode). At Fig. 5 (a) the artificial damping is slightly negative but becomes zero at 14.74 m/s, and this is the critical flutter velocity. At the same time, the Fig. 5 (b) corroborates this statement with the coalescence trend to couple of the two modes.

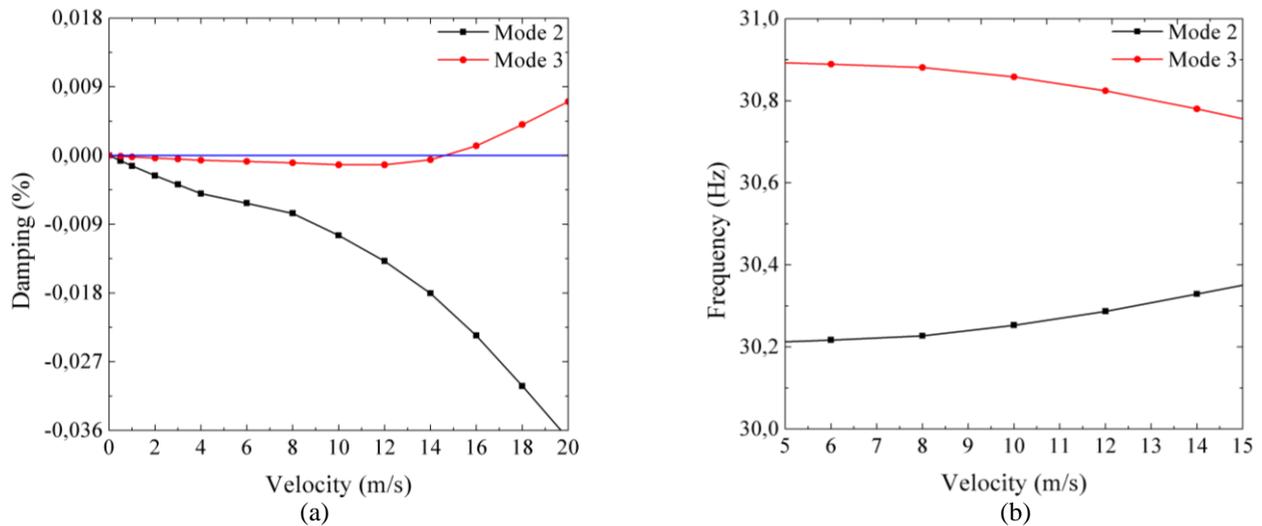


Figure 5. Artificial damping evolution (a) and frequency (b) of second and third modes.

For the experimental measurement of flutter velocity, the research model was clamped in an inertial base and the vibrometers were positioned. The model was tested at the air flow velocities of 6.0 and 14.0 m/s, measured by a Pitot tube and a Testo 512 model 056051283 digital manometer. The PoliMax extraction technique was used in the FRFs to obtain the system modal parameters; in this way, the damping behavior and natural frequency modes were evaluated, mainly the coupling modes, the second and third modes, as shown in Tab. 3 and Fig. 6.

Table 3. Measured values of damping and coupling frequency.

Velocity (m/s)	Damping (%)					
	6	8	10	12	13	14
Torsion	0.73238	0.78022	0.97508	1.25962	1.34465	1.55272
Flexion	0.73704	0.53875	0.39050	0.21848	0.11713	0.05322
Velocity (m/s)	Frequency (Hz)					
	6	8	10	12	13	14
Torsion	28.7902	28.8001	28.7049	28.6248	28.6492	28.5979
Flexion	29.6988	29.64	29.5658	29.4568	29.3642	29.2751

At Figure 6 (a) an instability can be seen at the bending mode since the damping becomes about zero to the 14 m/s velocity representing thus the critical velocity V_{crit} ; the presented behavior at this same figure was used to identify the flutter boundary; another particular behavior is the frequency loss in function of velocity at Fig. 6 (b); the loss is seen in both modes but is more intense in the bending mode; this behavior is already expected because when the structure is in presence of air flow, a portion of stiffness is velocity-dependent; it is possible to see that the difference between the natural frequencies decrease as the velocity increases and this fact is an advantage to the flutter occurrence. The damping and frequency values can be seen at Tab. 3.

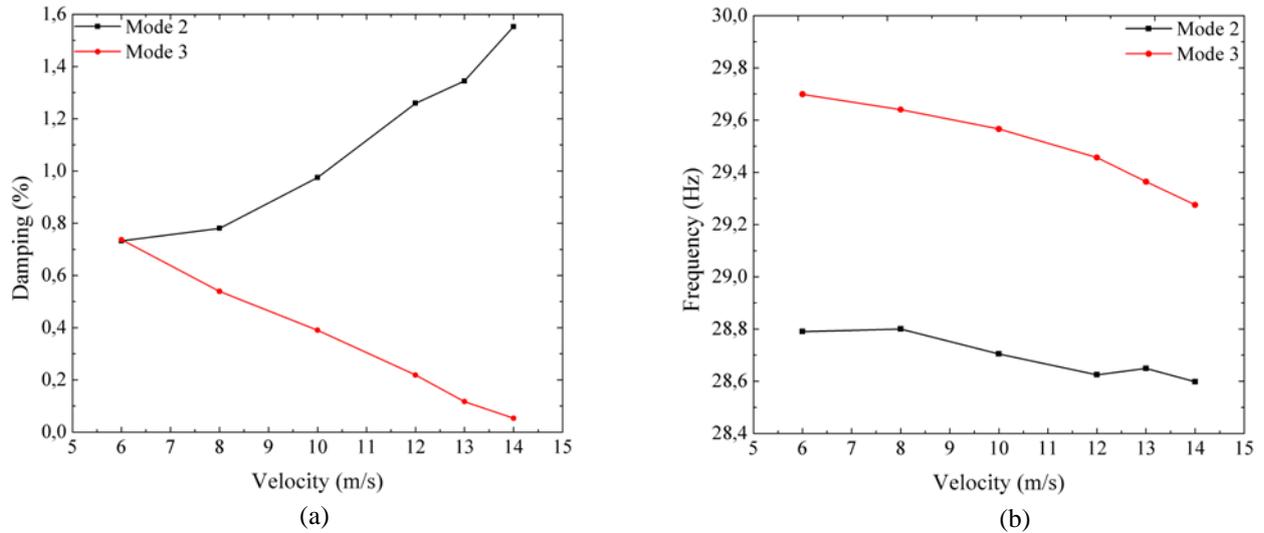


Figure 6. Experimental damping (a) and frequency (b) versus velocity for the second and third modes.

The Figure 7 shows the FRFs evolution as the speed is increased, keeping in mind that the flutter occurs at the V_{crit} , that the damping decrease as the velocity air flow increases and the coalescence of modes as the velocity reaches V_{crit} .

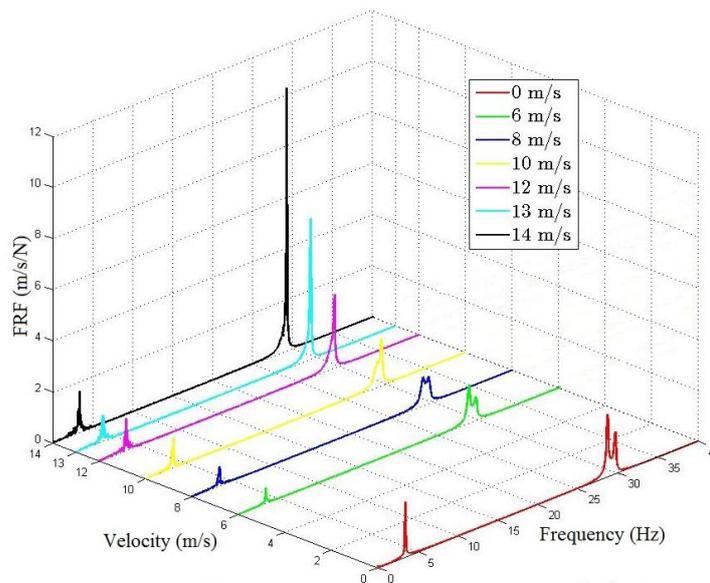


Figure 7. FRFs evolution as speed increasing.

5. CONCLUSIONS

Comparing the numeric and experimental results it was possible to check that the utilized methodology to design the research model was well efficient and effective, due to the lower error of 5.29% in the critic flutter velocity. Furthermore, the flutter presented a low energy mode as can be seen by the Fig. 5 (a) analysis that has a low inclination of the instable mode as it crosses the velocity axis.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

- Arantes filho, J. O. F., 2009. *Projeto e Modelagem Aeroelástica de uma Asa para Testes de Flutter em Túnel de Vento Subsônico*. Trabalho de Conclusão de Curso. (Graduação) – Instituto Tecnológico de Aeronáutica, São José dos Campos.
- Frazer, R.A. Duncan, W.J., “*The flutter of aeroplane Wings*,” R&M 1155,1929.
- Frazer, R.A. Duncan, W.J., “*The flutter of Monoplanes, Biplanes and Tail units*,” R&M 1255,1931.
- Garrick, I. E.; Reed, W. H. Historical Development of Aircraft Flutter. *Journal of Aircraft*, v. 18, n. 11, p. 897–912, 1981.
- Perring, W.G.A., “*Wing Flutter Experiments Upon Model of a Single Seater Biplane*,” R&M 1197, 1928.
- Ricketts, R. “Experimental Aeroelasticity - History, Status and Future in Brief”. In *31st Structures, Structural Dynamics and Materials Conference*. Anais.Reston, Virigina: American Institute of Aeronautics and Astronautics, 2 abr. 1990 <<http://arc.aiaa.org/doi/10.2514/6.1990-978>>.
- Tang, D. M.; Dowell, E. H. Experimental and Theoretical Study on Aeroelstic Response of High-Aspect-Ratio Wings. *AIAA Journal*, v. 39, n. 8, p. 1430–1441, 2001.
- Tang, D.M.; Dowell, E. H. Experimental Aeroelastic Models Design and Wind Tunnel Testing for Correlation with New Theory. *Aerospace*, v. 3, n. 2, p. 12, 2016.
- Westin, Michelle Fernandino, 2010. *Aeroelastic Modeling and Experimental Analysis of a Flexible Wing for wind Tunnel Flutter Test*. Dissertação (Mestrado) - Curso de Aeronautics And Mechanics Engineering, Instituto Tecnológico de Aeronáutica, São José dos Campos.
- Wright, Jan R.; Cooper, Jonathan E.,2015. *Introduction to Aircraft Aeroelasticity and Load*. Chichester: Wiley,2nd edition. 544 p. (Aerospace Series List).
- Yeager, W. T. Jr., Kvaternik, R. G. *A Histotical Overview of Aeroelasticity Branch and Transonic Dynamics Tunel Contributions to Rotorcraft Technology and Development*. Technical Memorandum, NASA/TM-2001-211054. August 2001.
- ZONA Technologies. (July de 2011). ZAERO Theoretical Manual, Version 8.5.

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