AEROSERVOELASTIC MODELING OF A FLEXIBLE WING FOR WIND TUNNEL FLUTTER TEST

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Abstract. *This paper presents the design of a flexible wing that employs an active control system for flutter suppression. The design of this wing considers that all pitch and plunge loads are resisted by an aluminum longeron whose dimensions is specified according to the wind tunnel available for the flutter test and using NASTRAN. The same software is used for the determination of the various modes of pitch, plunge and their couplings. The airfoil is the NACA 0012. In this modeling the flutter speed is found using ZAERO software. For aerodynamic modeling, a panel method, such as doublet lattice method, is used and the same software gives this support. An active control system that makes flutter suppression by piezoelectric actuation is used during the wind tunnel tests. The purpose of this study is a future comparison between the results obtained herein and those that will be determined further from wind tunnel test.*

Keywords*: aeroservoelasticity, wind tunnel, flutter, flexible wing, active control*

1. INTRODUCTION

This paper presents the design of a flexible wing for flutter active control studies. Flutter is an auto-excited phenomenon which occurs the coupling of two or more vibration modes that, due to aerodynamic forces, deflects the lifting surface so all the applied load will be reduced. This is alternated with a reduction of the surface deflection and the restoration of original load, which generates a cycle and this oscillations increase exponentially until the structure collapse. So, flutter is the interaction between structural dynamics and aerodynamic characteristics of the wing, in this case (Scalan and Rosenbaum, 1951).

As flutter is a destructive phenomenon, there are a lot of studies in prevention actively or passively. The passive control implies in a stiffness increase which results in a heavier structure (Silva, 1994). Due to this, active control uses modern control techniques so, with no mass increase, the flutter can be suppressed by changing lift distribution over the surface. In some cases, the aileron and flaps can be used for this purpose. However, the wing designed herein will use piezoelectric (PZT) actuators so that will bend. The PZT has the capability to develop an electrical charge when subjected to a mechanical strain and vice-versa. In this case, it is necessary to know the electrical charge to be imposed so the wing will suffer a strain in bend, suppressing flutter (Heeg, 1992). PZT have also other applications in study, especially in vibration.

The purpose of this study is to present the study of a flexible wing so the flutter suppression using PZT can be investigated further. This paper can be divided in the following parts: wind tunnel description, wing design and PZT characteristics.

2. WIND TUNNEL

As the dimensions of the wing depend on the wind tunnel the test will be conducted, the first step of this study is the selection of the wind tunnel, according to availability. The wind tunnel available is the Education and Research Wind Tunnel located on ITA (Instituto Tecnológico de Aeronáutica). The main characteristics of this tunnel are: test section is 1,00m by 1,28m, 80 m/s (280km/h) maximum speed, 0,23 maximum Mach number and 200 hp power. This wind tunnel is closed circuit and permits the wing viewing. The wing will be fixed on a lathe adapted to work as a turn table, which is located in the wind tunnel floor.

3. WORK STEPS

Before the wing be tested in wind tunnel, it is necessary to make a ground vibration test (GVT) in order to compare the natural frequencies obtained theoretically via NASTRAN. If the theoretical results are near that obtained by GVT, the procedure can go on, and the next step will be the wind tunnel test. The first wind tunnel test is for flutter velocity validation. The theoretical result will be presented here and is calculated using ZAERO software. With the theoretical results validated (vibration modes, natural frequencies and flutter velocity), the next stage is to design the controller and, finally, the wind tunnel test with the PZT actuators.

4. WING DESIGN

The wing is designed using two software's: NASTRAN for Windows and ZAERO. The iterative process was based on Dowell and Tang's publication (2002) which is a study of gust response for high aspect ratio wing. They used the same flexible wing for other experimental studies. The idea was very similar: make all loads resisted only by a longeron which, because of the small dimensions involved, will be a metal plate, the aerodynamic format will be provided by a symmetrical airfoil such as NACA 0012, which is easier to build and, to provide the pitch and plunge coupling, a mass will be positioned on wing tip, reducing torsional stiffness (Coura, 2000).

4.1. Theoretical Fundaments

The structural finite element model is created using the NASTRAN for Windows software, which is possible to drawn a model very similar from the real one. In this case, the longeron is modeled with plate elements with determined thickness, at its tip there is a slender body, which gravity center is modeled with a mass element with determined mass and inertias and this mass is fixed to the plate using rigid elements, where independent node is the same as mass element node and the independent nodes are those nearby that node, on wing tip.

The unsteady aerodynamic model is calculated using Doublet-Lattice Method. This is a panel method which all dipoles are distributed on the ¼ line of each panel and the downwash induced by the other panels is measured at the ¾ line of each panel. To solve this problem, the ZAERO software is used and it already splines both aerodynamic and structural models. The ZAERO inputs are the displacement eigenvectors, generalized mass and stiffness matrices, the vibration modes with their associated natural frequencies (which are the outputs of NASTRAN), the model geometry, reduced frequencies, panels' quantity and the velocity range desired. The ZAERO outputs are the generalized aerodynamics forces and, for this inputs, it is possible to determinate flutter velocity by k-method.

An important static phenomenon is observed in some cases namely divergence. The divergence occurs if the dynamic pressure of the process is extremely high. The divergence collapses the structure too, and the divergence velocity equation is:

$$V_D = \sqrt{\frac{2K_\theta}{\rho S e C_{L_\alpha}}} \tag{1}$$

where K_θ is the torsional stiffness, ρ is the air density, S is the plan form area, e is the elastic center position and C_{L_α} is the slope of the curve C_L *versus* α. From Equation 1 is possible to observe that, when the area increases, the divergence velocity decreases.

The k-method, or V-g-f method, assumes that there is an artificial damping, necessary to grantee that the eigenvalues problem solution of the Equation 2 represents a simple harmonic movement (Karpel, 1981). As the artificial damping is introduced, the new flutter determinant can be calculated, plotting damping and frequency curves as function of velocity. The Equation 2 is shown above:

$$\left[-\omega^2[\bar{M}] + (1 + ig_s)[\bar{K}] - q_\infty[Q(ik)]\right]\{q(i\omega)\} = 0 \tag{2}$$

In Equation 2, ω is the natural frequency, q_∞ is dynamic pressure, $[\bar{M}]$ is generalized mass matrix, $[\bar{K}]$ is generalized stiffness matrix, $[Q(ik)]$ is aerodynamic influence coefficients matrix, g_s is the damping and $\{q(i\omega)\}$ is generalized coordinates vector. As the artificial damping is assumed, it is important to notice that this damping has no physical meaning outside flutter condition. The ZAERO software already plots the V-g-f graphic.

4.2. Dowell and Tang's model

The main difference from Dowell and Tang's model is the absence of flanges in the plate, so the construction will be easier. Their model is a rectangular no swept wing. In this wing, the metal plate was made of steel with 0,457m in length, 0,0127m in width and 0,00127m in thickness. The slender body is an aluminum bar, 0,0095m in diameter and 0,1016m in length; there are paraboloidals fore body made of brass resulting in inertias I_x, I_y and I_z equal 0,3783x10^{-5} kgm^2, 0,9753x10^{-4}kgm^2 and 0,9753x10^{-4}kgm^2, respectively. This model is represented in Figure 1:

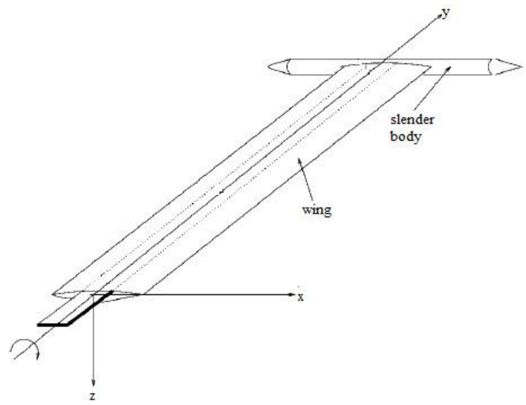

Figure 1. Wing representation (Dowell and Tang, 2002)

As can be seen, the longeron dimension is different of the chord dimension. The longeron is 0,0127m in width and the chord is 0,05m. The wing span and the longeron length has the same size.

This model is simulated and the results are presented in Figures 2 and 3:

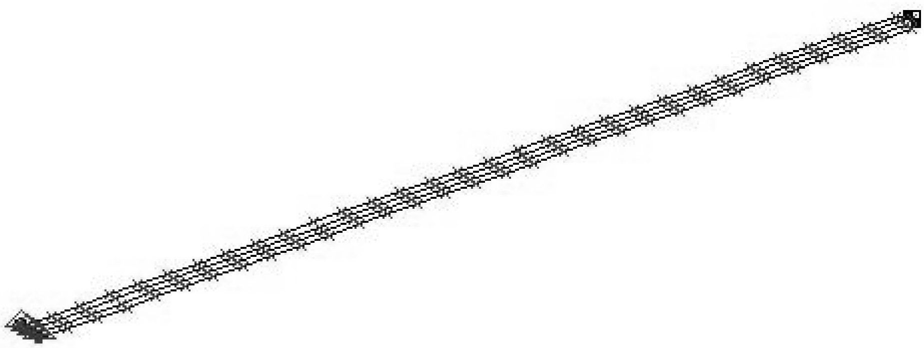

Figure 2. Model use for NASTRAN simulation

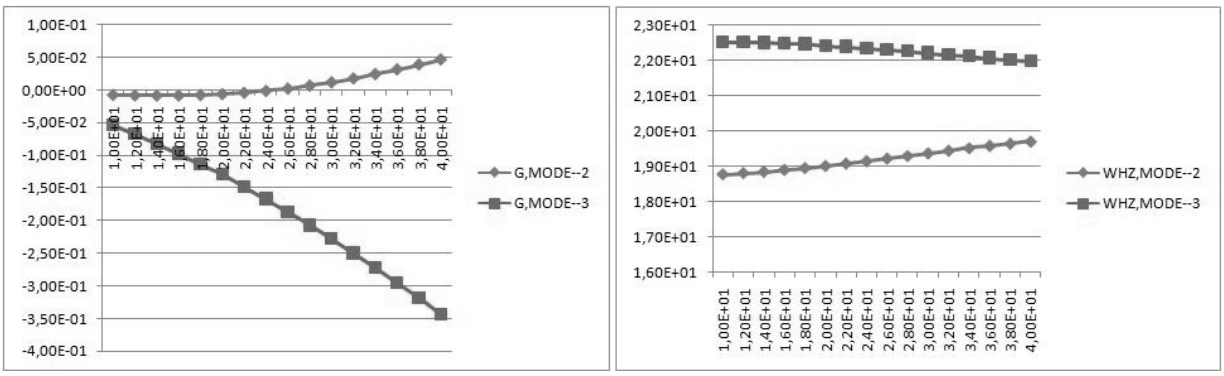

Figure 3. Simulation results: damping and frequency, respectively, *versus* velocity

From Figure 3 it is possible to observe that the flutter velocity is about 24m/s and occurs because of the third and fourth modes frequency coupling. According to k-method, the flutter velocity is given when the damping g is zero.

4.3. Model evolution

Because of the availability of aluminum plates, this was the selected material. There are two available thicknesses: 3mm and 1mm. In order to maintain the stiffness value close to that obtained by Dowell and Tang (2002), which is 0,4186Nm^2, the plate with 1mm is selected, because if a plate with 3mm was selected, the thickness will be greater than width. From Equation 3, the width is calculated:

$$EI = E\frac{bh^3}{12} \qquad (3)$$

where E is Young's modulus and b and h are dimensions of transversal section.

The slender body is changed too. As the material changed from steel to aluminum, the mass of the slender body, and the inertias, consequently, have been increased: 0,12474kg in mass and, I_x, I_y and I_z are, respectively, $9{,}2\text{x}10^{-6}$kgm^2, $4{,}2\text{x}10^{-4}$kgm^2 and $4{,}2\text{x}10^{-4}$kgm^2. The material change from aluminum with brass to lead in order to obtain this results.

The span is maintained, 0,45m, and the chord is 0,0668m so the bending stiffness is the same as Dowell and Tang (2002) model, but, in this model, the chord is at the same size as longeron width (Figures 4 and 5):

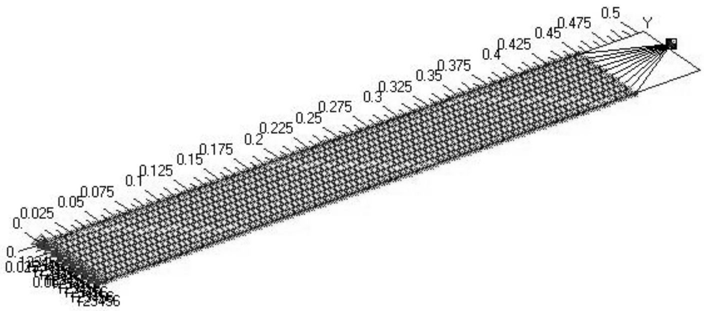

Figure 4. NASTRAN model of the wing with 0,0668m in chord

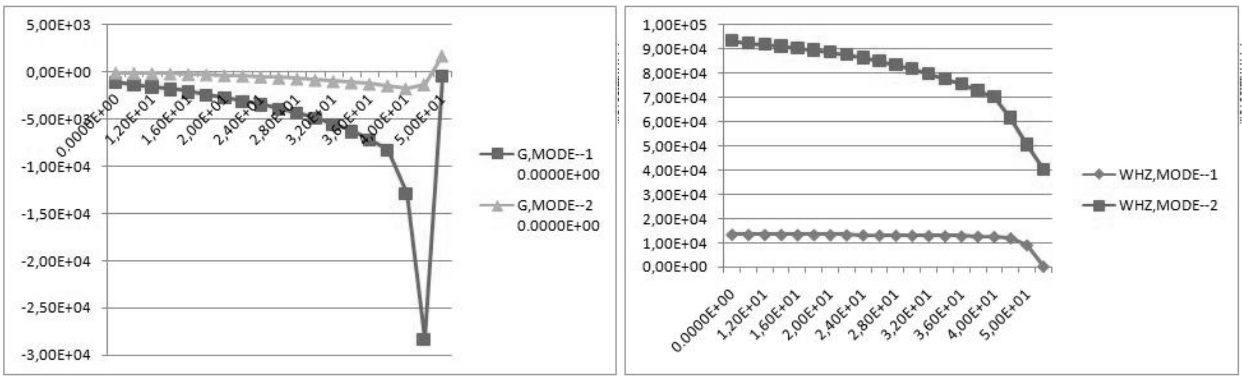

Figure 5. Damping and frequency *versus* velocity, respectively, obtained from k-method

These results show the presence of a divergence near the flutter velocity. The divergence velocity occurs when the frequency is zero, so, the damping is much smaller than expected. For this case, the divergence velocity is 45m/s while the flutter velocity is about 53m/s.

In order to try to avoid this divergence, the lift must be increased, so one possibility is to increase the chord to 0,08m (Figures 6 and 7):

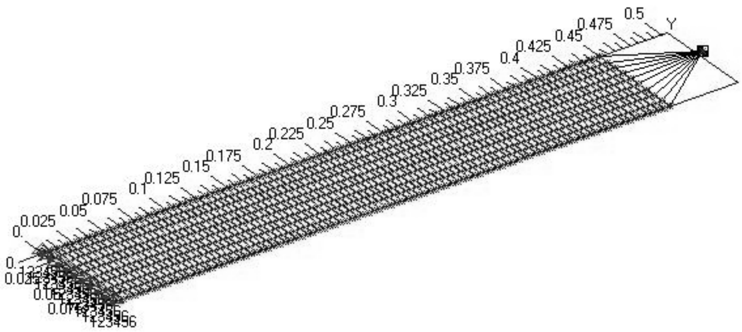

Figure 6. NASTRAN model of a 0,08m chord wing

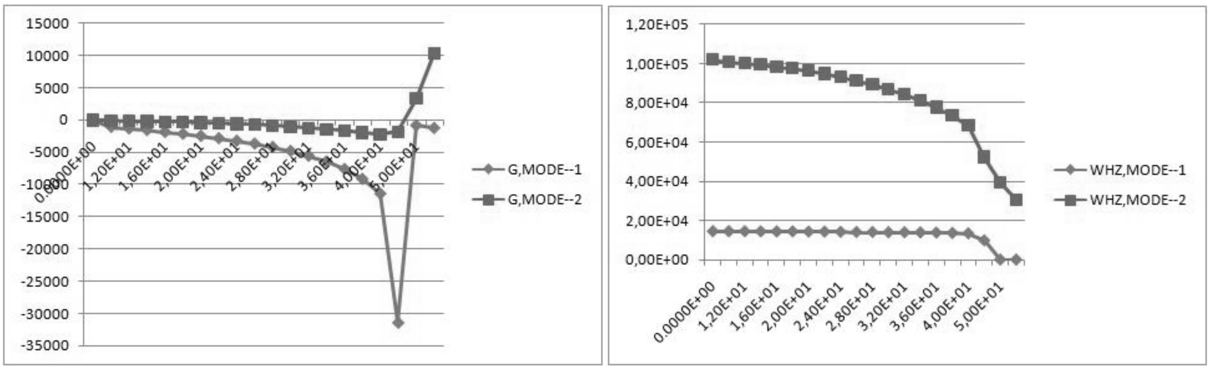

Figure 7. Damping and frequency *versus* velocity graphics from k-method

According to Figure 7, the divergence still occurs. The divergence velocity is 45m/s, like the other case, and the flutter velocity is about 46m/s. The divergence velocity is the same and the flutter velocity became smaller.

A solution for the divergence problem is to sweep the wing. According to Weisshaar (1995), when the reference axis is rotated, the loads on the wing changed, changing the divergence velocity. This happen because the effective angle of attack has two components: one because of torsion and the other because of bending and in this bending term appears the sweep contribution. Equation 4 is the effective angle of attack:

$$\alpha = \theta - \phi tan\Lambda \quad (4)$$

where θ is the pitch angle (torsion contribution), ϕ is the plunge angle (bending contribution) and Λ is the sweep angle. The divergence dynamic pressure for sweep wings is:

$$q_d = \frac{K_\theta / SeC_{L_\alpha}}{cos^2\Lambda\left[1-\left(\frac{b}{e}\right)\left(\frac{K_\theta}{K_\phi}\right)\frac{tan\Lambda}{2}\right]} \quad (5)$$

where K_ϕ is he bending stiffness and b is the chord length. From Equation 5, when the sweep angle increases, the dynamic pressure increases and, consequently, the divergence velocity. However, if the sweep angle is big, the flutter occurs sudden, with the frequencies almost parallels the entire velocity range. The model presented in Figure 8 shows a 45° sweep wing, but with the same slender body used by Dowell and Tang (2002) and is totally positioned on the wing:

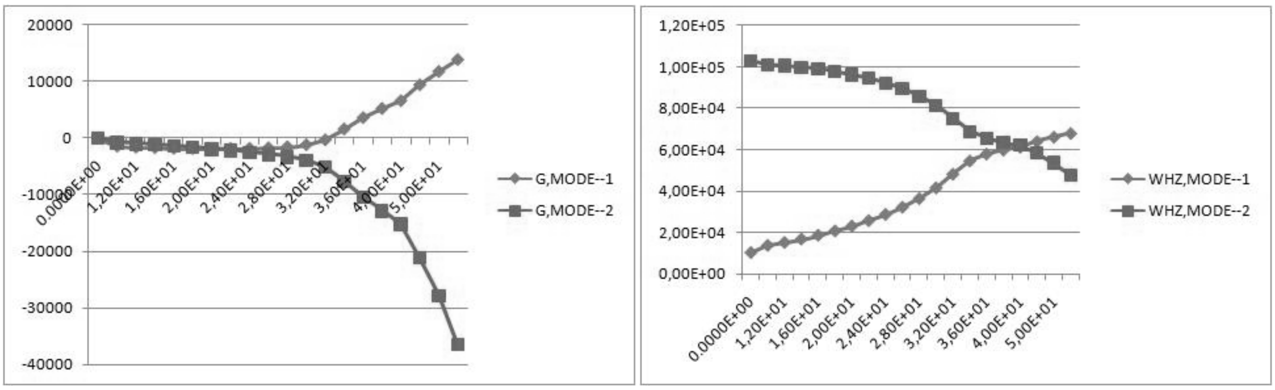

Figure 8. Damping and frequency *versus* velocity, respectively

As showed in Figure 8, the frequencies curves of modes 1 and 2 suddenly go to the same value. This kind of flutter has more energy than those which smoothly approximate from each other. After modeling some cases varying the mass and inertias of the slender body and varying the sweep angle, can be concluded that the best model is that shown in Figures 9 and 10 which has 10° of sweep angle:

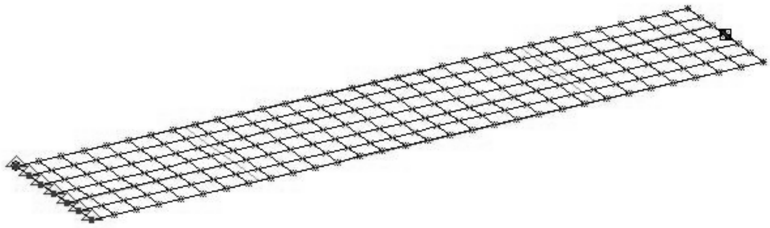

Figure 9. NASTRAN model with 0,08m in chord and 0,45 in span

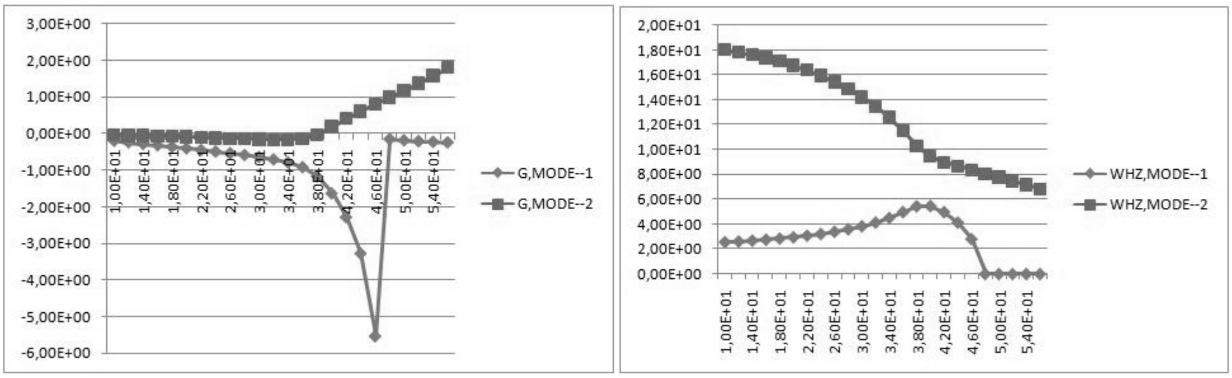

Figure 10. Damping and frequency results obtained from k-method

It is possible to see from Figure 10 that the divergence still appears, but this velocity is greater than flutter velocity (the divergence velocity is 46m/s while the flutter velocity is about 39m/s) and this difference is safe for the wind tunnel operation. Another conclusion about Figure 10 is that the vibration modes are coupling in such a way acceptable. It is neither smooth as showed on Figure 3 nor abrupt like that in Figure 8. The slender body gravity center is positioned on the tip of the wing and is made of aluminum and brass, like the first, used by Dowell and Tang (2002).

These are some of the various iterations done until get the model showed on Figure 9. After this design, it is important to do a ground vibration test to validate the vibration modes and a wind tunnel test to validate the flutter velocity. It must be remembered that all the graphics showed above, though plotted using Excel, get their data from ZAERO, in an output file.

5. PIEZOELECTRIC CHARACTERISTICS

As described before, the piezoelectric materials, or PZT, are usually ceramic materials which have the ability of deforming elastically when an electrical field is applied and this deformation is perpendicular to the electrical potential. The advantages are the ability to adhere the surface and the force exerted can be very large. These advantages make the use of PZT on active flutter suppression possible. When the deformation occurs, the lift distribution is altered too, changing the flutter velocity. Heeg (1992) studied the applicability of the use of PZT in suppressing flutter, and did wind tunnel tests. However, the model used was a rigid wing in a flexible assembly so the PZT were fixed there. The conclusions about it were favorable to the use of them. Modeling of the PZT is represented by the following electromechanical constitutive relation (Nam *et al.*, 1996):

$$\{D\} = [d]^T\{T\} + [\epsilon^T]\{E\} \tag{6}$$
$$\{S\} = [s^E]\{T\} + [d]\{E\} \tag{7}$$

where $\{D\}$ is the electric displacement, $\{S\}$ is the strain, $\{T\}$ is the stress, $\{E\}$ is the electric field intensity, $[d]$ is the piezoelectric constant, $[s^E]$ is the elastic compliance matrix and $[\epsilon^T]$ is the dielectric constant.

The PZT have to be strategically located on the plate (longeron) surface in such a way that these points will be actuators. Nam *et al.* (2001) presented the modeling of a composite wing using PZT, optimizing the electrical power and the best geometry for flutter suppression.

This is still an ongoing study, but it is intended to use this material not only on theoretical model but on the final wind tunnel test. To design the controller which the PZT must follow, all models must be on space-state, so the equations become easier, and this is done by rational functions approximation.

6. PRELIMINARY WING CONSTRUCTION

As the numerical results obtained by NASTRAN and ZAERO were good enough compared with the results reached by Dowell and Tang (2002) it is possible to construct the first wing model based on their original. The idea is similar, however using other materials. Three models, with the dimensions of the Dowell and Tang's wing model, were constructed, each one using different construction. It is necessary to properly evaluate them, so the one with the closest results from numerical model will be chosen.

All the models are constructed using the aluminum plate with the already specified dimensions and the loads must be supported only by it. The slender body differs from the original and it is all made on aluminum (Figure 11).

Figure 11: Slender body

On the first model, over the plate, there are balsa woods which are the responsible for give the aerodynamic format of NACA 0012, and between those airfoils, there is expanded polyurethane. A small gap between sections is necessary so the loads are transmitted only on the plate, imposing no damping. The whole model is covered by plastic, so the air flows smoothly. The Figure 12 shows this first wing model:

Figure 12: Wing model made by expanded polyurethane

The second model idea is very similar from the first, however using depron instead of expanded polyurethane. The depron is easier to work with than the other, but the geometric characteristics are better to maintain. After sanding, the surface has such a quality that there is no need to cover by any material. Figure 13 shows this model:

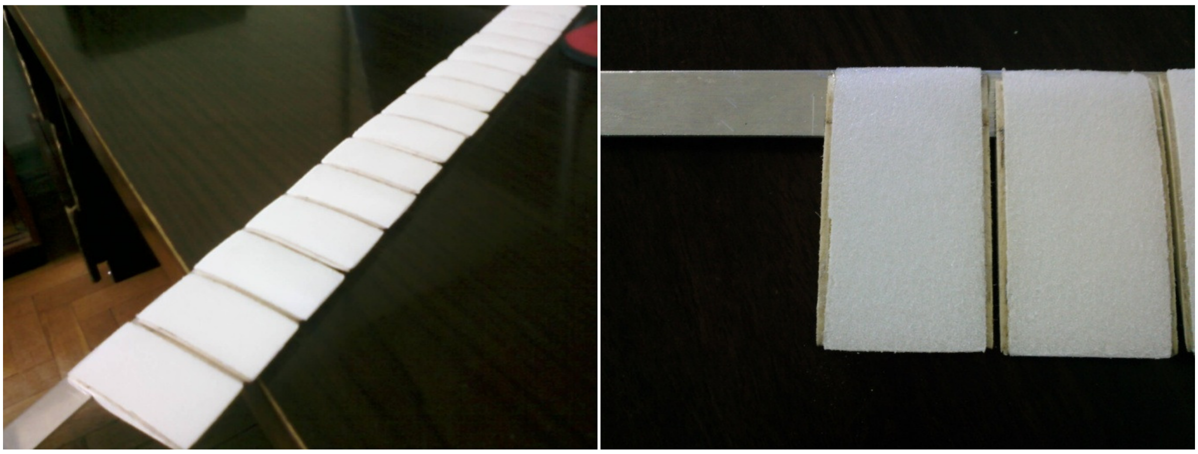

Figure 13: Wing model made by depron

The third model has as main objective to study the approach commonly used in aeroelasticity: for small perturbations the wing can be treated like a plan plate. To make this construction, two balsa wood plates (1mm each) are attached by the aluminum plate and then cuts are made so the loads are all transmitted along the aluminum. This is a very simple construction as can be seen in Figure 14:

Figure 14: Wing model made by balsa wood plate

As can be seen from the Figures 12 to 14, the depron model has better geometric characteristics than the others, but only preliminary tests can tell which one presents the closets results from theoretical model.

7. CONCLUSION

The flutter suppression study has been spotlighted because of its destructive nature. So the use of PZT materials has been studied as an active way to suppress flutter, instead of the passive suppression which increases the mass of the airplane in general.

The results obtained in this paper are important for the continuity of the development of the wing model to be tested in wind tunnel. This showed a small part of the iterative process of a flexible wing design, considering the materials available and the results obtained. From the analyses presented herein, it is possible to select the wing to be used for the next steps.

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