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A PARAMETRIC AND TOPOLOGICAL STUDY ON THE USE OF VISCOELASTIC MATERIAL FOR FLUTTER SUPPRESSION

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Abstract: Emergence of flutter compromises not only the long term durability of the wing structure, but also the operational safety, flight performance and energy efficiency of the aircraft. Effective means of flutter prevention are, therefore, mandatory in the certification of new flight vehicles. This work intends to address the application of viscoelastic material for flutter suppression in a typical section under quasi-steady and unsteady aerodynamic loads. A numerical procedure is proposed to solve the set of non-linear equations. A parametric study showing the influence of the temperature on the stiffness, damping and flutter velocity of the system is also carried out using different viscoelastic based damping arrangements. The preliminary results indicate that the aeroelastic behavior of the system is significantly affected by the temperature and viscoelastic damping arrangement.

1. INTRODUCTION.

As a direct result of modern market requirements for lighter, faster and cheaper aircraft, the development of lighter structure designs is required. As new materials, such as composites, are increasingly used as primary wing structure materials, it's also seen an increase of flexibility of the wing as a whole. This increase of flexibility creates a challenge for safety, once it affects significantly the aeroelastic behavior of the structure.

One of the main concerns in aeroelastic safety of an aircraft is to avoid wing flutter, which not only decreases fatigue durability, but also it can lead to catastrophic structural failures. Flutter is characterized as a dynamic instability of the structure when the elastic and inertial forces of the structure and the external forces caused by the flow have positive feedback, leading to an augmentation of the amplitude of vibrations. The occurrence of flutter is directly related to inertia, damping and stiffness of the wing and the fuselage of an aircraft. The control of these parameters is necessary for the safe design of an aircraft.

Studies in aeroelastic behavior of aircraft wings have been done since the early 30's [1] but the control of flutter through the application of viscoelastic materials is a very recent topic of study [2]. Remarkably, most of the studies related to control of flutter is based on active control [3]. In this type of control, the vibration is measured and an actuator is used to prevent flutter. The advantage in passive control is that it is not required to measure the vibration in situ, which makes unnecessary the use of precise measuring instruments.

2. CHARACTERIZATION OF VISCOELASTIC PROPERTIES.

Viscoelastic materials are materials that have properties normally comparable to that of a elastic solid and that of a viscous fluid. The most popular mathematical model for viscoelastic materials properties is the complex modulus of elasticity [4]. The real part of this modulus is called storage modulus, and the imaginary part is called the loss factor. This last is a direct relation between the materials properties and the films ability to damp vibration.

It's widely known that viscoelastic materials exhibit a great dependence on environmental factors and dynamic properties [5]. The two most influential, and therefore, presented in this article, are the temperature and the frequency of vibration. In the present paper, a constitutive model formulation based on the complex modulus of elasticity approach is presented. The constitutive model used here is a semi-empirical model defined by the manufacturer for the 3 M™ ISD112 viscoelastic film where the shear modulus, G, and loss factor, α_t, dependence on frequency, ω, and temperature, T, are given by Eq. 1 and Eq. 2.

$$G(\omega) = B_1 + B_2/(1 + B_5(i\omega/B_3)^{-B_6} + (i\omega/B_3)^{-B_4}) \tag{1}$$

$$\log \alpha_t = a\left(\frac{1}{T} + \frac{1}{T_0}\right) + 2.303\left(\frac{2a}{T_0} - b\right)\log\frac{T}{T_0} + \left(\frac{b}{T_0} - \frac{a}{{T_0}^2} - S_{AZ}\right)(T - T_0) \tag{2}$$

Where:

$$B_1 = 0.4307\ MPa;\ B_2 = 1200\ MPa;\ B_3 = 1543000;\ B_4 = 0.6847; B_5 = 3.241;$$

$$B_6 = 0.18;$$

$$T_0 = 290\ K;\ T_L = 210\ K;\ T_H = 360\ K;\ S_{AZ} = 0.05956\ K^{-1};\ S_{AL} = 0.1474\ K^{-1};$$

$$S_{AH} = 0.009725\ K^{-1};$$

$$C_A = (1/T_L - 1/T_0)^2;\ C_B = (1/T_L - 1/T_0); C_C = (S_{AL} - S_{AZ});$$

$$D_A = (1/T_H - 1/T_0)^2;\ D_B = (1/T_H - 1/T_0);\ D_C = (S_{AH} - S_{AZ});\ D_E = (D_B C_A - D_A C_B);$$

$$a = (D_B C_C - C_B D_C)/D_E\ ;\ b = (D_C C_A - C_C D_A)/D_E\ ;$$

The constitutive model is incorporated into a dynamic model for a typical section under unsteady aerodynamic loads. Figure 1 shows the shear modulus and loss factor dependence on frequency of vibration for the viscoelastic material used in this paper.

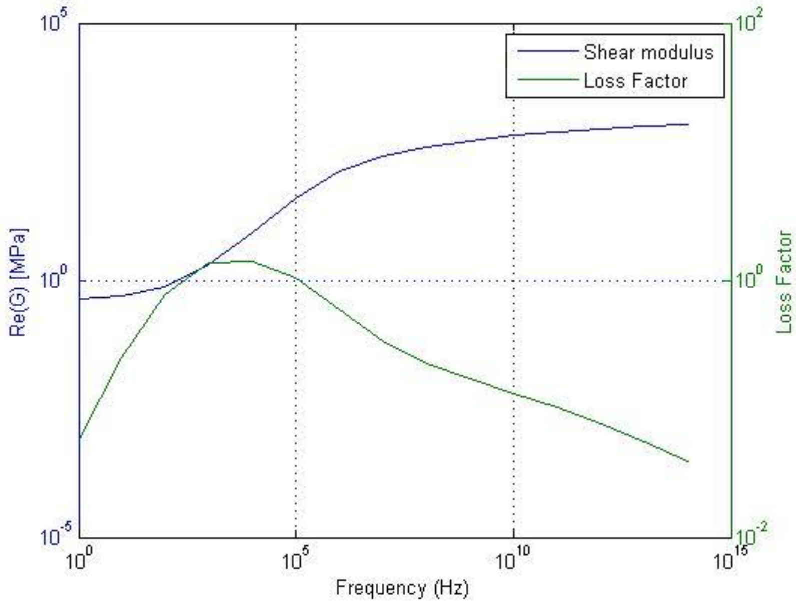

Figure 1: Variation of shear modulus (blue) and loss factor (green) with frequency for the

3 M^{TM} ISD112 viscoelastic material

As it can be noted in Figure 1 the loss factor shows a considerable dependence on the frequency usually related to flutter occurrences, up to 100 Hz. Therefore can be assumed that the higher the frequency of flutter, the higher the amount of energy dissipated by the viscoelastic material will be.

The relation between temperature, frequency and loss factor can be seen in Figure 2. The temperature has an effect over the loss factor that is dependent on the frequency. For typical aircraft temperature operation envelopes varying between -50°C and 40°C, and typical frequency of flutter, up to 100 Hz, the loss factor can vary between $10^{-1.4}$ and $10^{0.17}$.

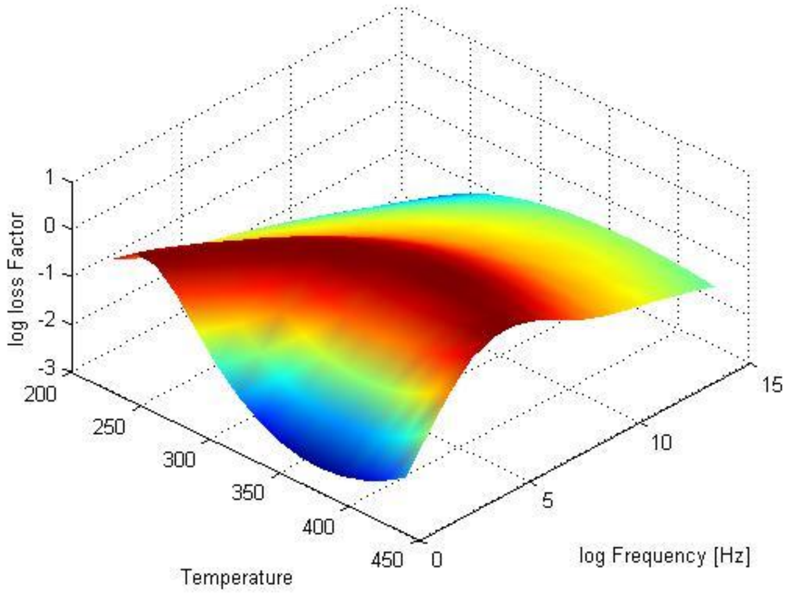

Figure 2 : Loss factor (log) vs. Temperature [K] vs. Frequency (log[Hz]) for the 3 M^{TM} ISD112 viscoelastic material

3. APPLICATION OF VISCOELASTIC MATERIAL IN AEROELASTIC STRUCTURES.

The method of applying the viscoelastic material in aeronautical structures is in the form of a film. It's not the objective of this study to analyze the form of application of the film or the area in the aeronautical structure that the film must be applied. Figure 3 shows the simplified structural idealization adopted for the viscoelastic film in translational and torsional damping.

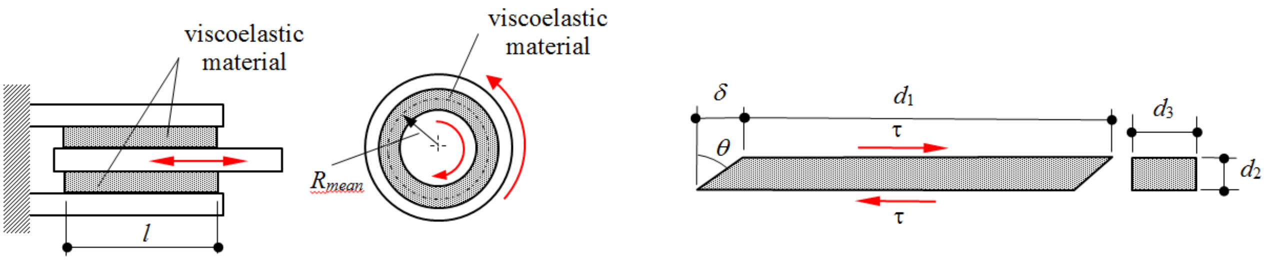

Figure 3 : Structural idealization model for the viscoelastic material. [6]

To incorporate this structural idealization in the unsteady aeroelastic model that will be used to calculate flutter velocity, a link between the characteristics of the film and the stiffness matrix of the model must be made. A new matrix is then introduced in the model, a matrix of stiffness of the viscoelastic material, were the new parameters of K_{hv} and $K_{\alpha v}$, defined in Eq. 3 and Eq. 4 respectively are introduced.

$$K_{hv} = P_h . G_v(T, \omega) \tag{3}$$

$$K_{\propto v} = P_{\propto} . G_v(T, \omega) \tag{4}$$

where :

$$P_h = \frac{d_1 . d_3}{d_2} , \qquad P_{\propto} = \frac{r_{mean} . d_3}{d_2}$$

and $G_v(T, \omega)$ is the stiffness of the viscoelastic material, dependent on the temperature and frequency.

For this study, the simplified two degrees of freedom (DOF) shown in Figure 4 was adopted.

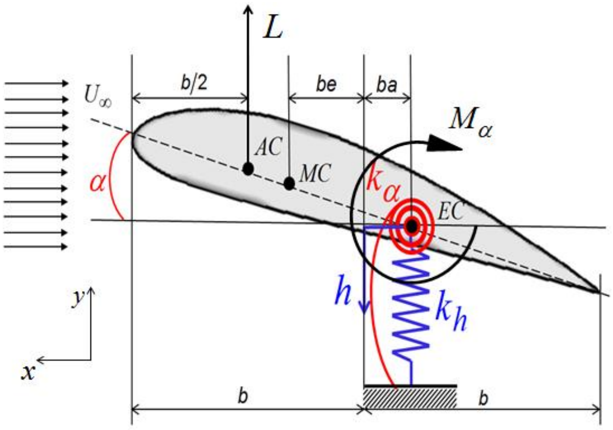

Figure 4 : Physical model of a 2 DOF airfoil.

The flutter velocity is known as the critical speed of the fluid in which one of the modes of vibration of the structure becomes negatively damped, therefore resulting in an augmentation of energy leading to potentially catastrophic results. For this study a simplified unsteady aeroelastic model was used [8].

With respect to an arbitrary static equilibrium position, any linear displacement of the elastic center (EC) is equal to h and any angular displacement of the same EC is equal α. Therefore the linear displacement of any point in the x-axis of the airfoil is given by Eq. 5.

$$z(x) = h + x\,\alpha \tag{5}$$

The kinetic energy of the airfoil can be then described as in Eq. 6.

$$K = \frac{1}{2} \int_{b}^{-b} \rho \left(\frac{dz}{dt}\right)^2 dx \tag{6}$$

This equation can also be written as a function of *h* and α after combining Eq. 5 and Eq. 6.

$$K = \frac{1}{2}\left(\dot{h}^2 \int \rho\, dx + 2\dot{h}\dot{\alpha} \int \rho x\, dx + \dot{\alpha}^2 \int \rho x^2 dx\right) \tag{7}$$

where:

$$m = \int \rho dx\,, \qquad m x_\alpha = S_\alpha = \int \rho x dx\,, \qquad I_\alpha = \int \rho x^2 dx$$

x_α is the distance between MC and EC of the airfoil.

The potential energy stored in the structure due to its elastic behavior, U is given by,

$$\mathrm{U} = \frac{1}{2}\mathrm{K_h h^2} + \frac{1}{2}\mathrm{K_\alpha \alpha^2} \tag{8}$$

The equations of motion for this system can be obtained by using the Lagrange based formulation,

$$\frac{\partial}{\mathrm{dt}}\left(\frac{\partial(\mathrm{K-U})}{\partial\dot{\mathrm{h}}}\right) - \frac{\partial(\mathrm{K-U})}{\partial \mathrm{h}} = \mathrm{Q_h}$$

$$\frac{\partial}{\mathrm{dt}}\left(\frac{\partial(\mathrm{K-U})}{\partial\dot{\alpha}}\right) - \frac{\partial(\mathrm{K-U})}{\partial \alpha} = \mathrm{Q_\alpha} \tag{9}$$

which leads to the following nondimensionalised system of equations,

$$\begin{bmatrix} 1 & \mathrm{x_\alpha} \\ \mathrm{x_\alpha} & \mathrm{r_\alpha^2} \end{bmatrix} \begin{Bmatrix} \ddot{\mathrm{h}}/\mathrm{b} \\ \ddot{\alpha} \end{Bmatrix} + \begin{bmatrix} \omega_h^2 & 0 \\ 0 & \omega_\alpha^2 \mathrm{r_\alpha^2} \end{bmatrix} \begin{Bmatrix} \mathrm{h}/\mathrm{b} \\ \alpha \end{Bmatrix} = \begin{Bmatrix} \mathrm{Q_h/mb} \\ \mathrm{Q_\alpha/mb^2} \end{Bmatrix} \tag{10}$$

where r_α is the section radius of gyration. The unsteady aerodynamic loads are based on linearized thin-airfoil theory and are given by,

$$Q_h = \mathrm{L} = \pi\rho \mathrm{b}^2\left(\ddot{\mathrm{h}} + \mathrm{V_0}\dot{\alpha} - \mathrm{b a}\ddot{\alpha}\right) + 2\pi\rho\mathrm{V_0 b C(k)}\left[\dot{\mathrm{h}} + \mathrm{V_0}\alpha + \mathrm{b}(0.5 - \mathrm{a})\dot{\alpha}\right] \tag{11}$$

$$Q_\alpha = \mathrm{M} = \pi\rho\mathrm{b}^2\left[\mathrm{b a}\ddot{\mathrm{h}} + \mathrm{V_0 b}(0.5 - \mathrm{a})\dot{\alpha} - \mathrm{b}^2\left({}^1\!/_8 + \mathrm{a}^2\right)\ddot{\alpha}\right] +$$

$$2\pi\rho\mathrm{V_0 b^2}(0.5 + \mathrm{a})\mathrm{C(k)}\left[\dot{\mathrm{h}} + \mathrm{V_0}\alpha + \mathrm{b}(0.5 - \mathrm{a})\dot{\alpha}\right] \tag{12}$$

where C(k) is the equation for lift deficiency of Theodorsen [1] and $k = \omega\mathrm{b}/\mathrm{V}$ is the reduced frequency. By assuming the hamonic motion ($h = he^{i\omega t}$, $\alpha = \alpha e^{i\omega t}$) and defining R as the ratio between the bending frequency ω_h and the twisting frequency ω_α and Ω as a ratio between ω, the frequency of vibration, and ω_α, the natural frequency of the torsional mode,

$$\boldsymbol{r_\alpha^2 = \frac{I_\alpha}{m}}\,, \qquad \boldsymbol{\omega_h^2 = \frac{K_h}{m}}\,, \qquad \boldsymbol{\omega_\alpha^2 = \frac{K_\alpha}{m}}, \qquad \boldsymbol{R = \frac{\omega_h}{\omega_\alpha}}\,, \qquad \boldsymbol{\Omega = \frac{\omega}{\omega_\alpha}}$$

the set of equilibrium equations can be written as follows,

$$-\Omega^2\begin{bmatrix}1 & \bar{x}_\alpha\\ \bar{x}_\alpha & \bar{r}_\alpha^2\end{bmatrix}\begin{Bmatrix}h/b\\ \alpha\end{Bmatrix}+\begin{bmatrix}R^2 & 0\\ 0 & \bar{r}_\alpha^2\end{bmatrix}\begin{Bmatrix}h/b\\ \alpha\end{Bmatrix}=$$

$$\frac{\Omega^2}{\mu}\begin{bmatrix}L_h & L_\alpha-\left(\frac{1}{2}+a\right)L_h\\ M_h-\left(\frac{1}{2}+a\right)L_h & M_\propto-\left(\frac{1}{2}+a\right)(L_\propto+M_h)+\left(\frac{1}{2}+a\right)^2(L_\propto)\end{bmatrix}\begin{Bmatrix}h/b\\ \alpha\end{Bmatrix} \tag{13}$$

with,

$$\bar{x}_\alpha=\frac{x_\alpha}{b},\quad \bar{r}_\alpha=\frac{r_\alpha}{b},\quad \mu=\frac{m}{\pi\rho b^2 l},\quad L_h=1-i2\frac{C(k)}{k},$$

$$L_\alpha=\frac{1}{2}-i\frac{1+2C(k)}{k}-\frac{2C(k)}{k^2},\quad M_h=\frac{1}{2}\quad M_\alpha=\frac{3}{8}-i\frac{1}{k},$$

$$k=\frac{\omega b}{V_0}$$

With the addition of the viscoelastic stiffnesses in pitch and plunge, the equations of motion for the unsteady aerodynamic model reads,

$$-\Omega^2\begin{bmatrix}1 & \bar{x}_\alpha\\ \bar{x}_\alpha & \bar{r}_\alpha^2\end{bmatrix}\begin{Bmatrix}h/b\\ \alpha\end{Bmatrix}+\left[\begin{bmatrix}R^2 & 0\\ 0 & \bar{r}_\alpha^2\end{bmatrix}+\frac{1}{m\omega_\alpha}\begin{bmatrix}P_h G(\omega,T) & 0\\ 0 & P_\alpha G(\omega,T)\end{bmatrix}\right]\begin{Bmatrix}h/b\\ \alpha\end{Bmatrix}=$$

$$\frac{\Omega^2}{\mu}\begin{bmatrix}L_h & L_\alpha-\left(\frac{1}{2}+a\right)L_h\\ M_h-\left(\frac{1}{2}+a\right)L_h & M_\propto-\left(\frac{1}{2}+a\right)(L_\propto+M_h)+\left(\frac{1}{2}+a\right)^2(L_\propto)\end{bmatrix}\begin{Bmatrix}h/b\\ \alpha\end{Bmatrix} \tag{14}$$

which can be written in a matrix compact form as follows,

$$\Big\{\{[\mathbf{K}]+[\mathbf{K}^{\mathbf{v}}(\boldsymbol{\omega},\mathbf{T})]\}-\boldsymbol{\omega}^{\mathbf{2}}\{[\mathbf{M}]+[\mathbf{A}(\boldsymbol{\omega})]\}\Big\}\{\boldsymbol{\varphi}\}=\{\mathbf{0}\} \tag{15}$$

3.1. Solution method for the resultant nonlinear eigenvalue problem.

For the solution of the nonlinear eigenvalue problem an iterative numerical method was applied, in which an initial frequency is set to zero as initial guess for trigging the iterative process. During the iterations, new values of frequency are calculated and compared to the frequencies obtained in the previous iteration. If this difference is less than a predefined tolerance, the iterative method is stopped and a frequency values are determined. This method is illustrated in Figure 5.

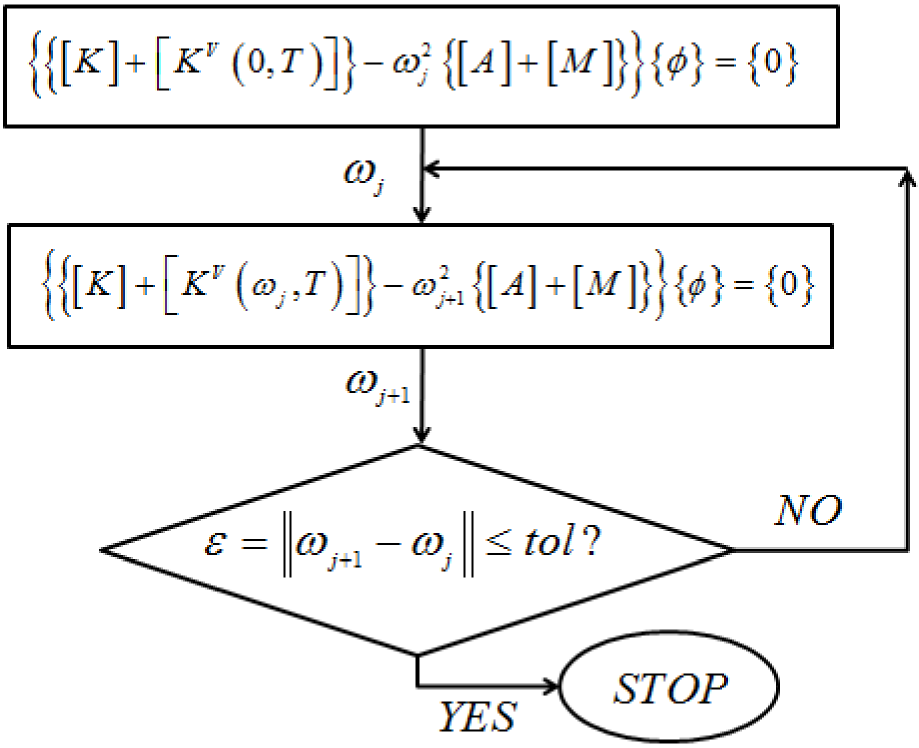

Figure 5 : Iterative method for solution of the nonlinear eigenvalue problem.

4. NUMERICAL SIMULATIONS

The typical section parameters used in the simulations are listed in Table 1. The parameters used for the viscoelastic material were the same presented in section 2.

Parameter	x_α	R_2	r_α	μ	a	b [m]	ω_α [Hz]	m [Kg]
Value	0.1	0.71605	0.5	75	-0.2	0.15	65	6.494

Table 1: Typical section parameters

With the utilization of this numerical procedure of iterative solution, the dynamic response of the airfoil can be calculated. Results for the flutter velocity of the typical section with and without the viscoelastic treatment are presented in Figures 6-9.

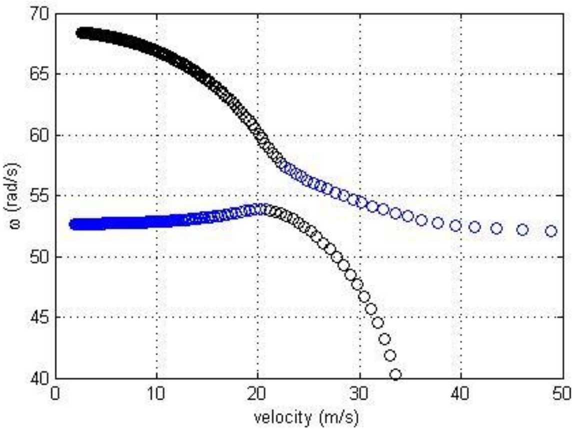

Figure 6: Frequency of the flexural and torsional mode vs. flow velocity.

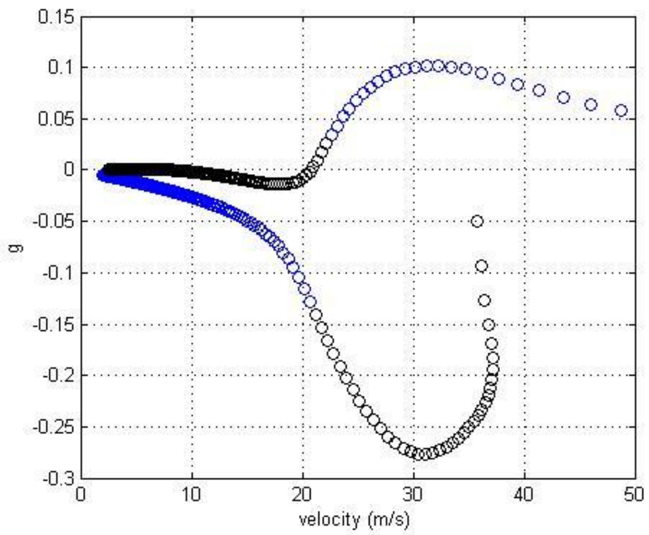

Figure 7 : Damping of each mode vs. flow velocity.

As shown in Figure 7, the moment where flutter occurs is when damping, g, becomes positive, in this case, at approximately 21 m/s. When applying the viscoelastic material it's noticed that this velocity increases, meaning the retardation of flutter due to the damping provided by the viscomaterial film.

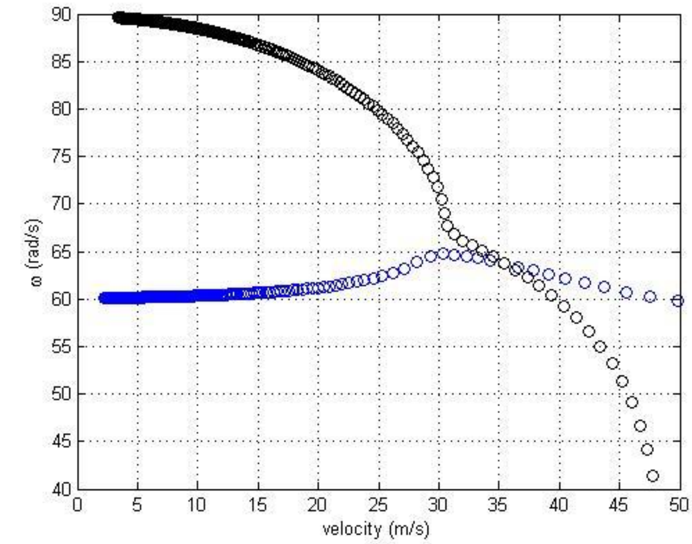

Figure 8 : Frequency of flexural and torsional modes vs. flow velocity with viscoelastic treatment ($P_h=P_\theta=10^{-4}$).

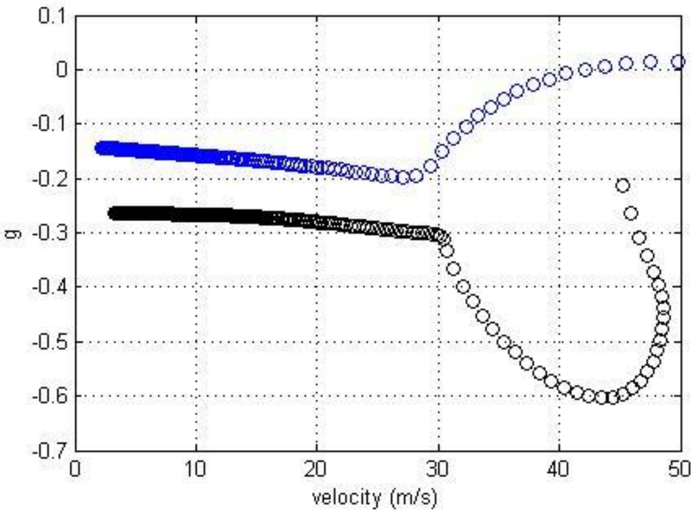

Figure 9 : Damping of each mode vs. flow velocity with viscoelastic treatment ($P_h=P_\theta=10^{-4}$).

As predicted, and observed in Figure 9, the presence of the viscoelastic material suppressed flutter, now at about 42 m/s.

After showing the viscoelastic treatment capability of flutter suppression, a parametric study was carried out to analyze the variation of flutter velocity with the change in the dimensional parameters of the film, represented by P_h and P_α.

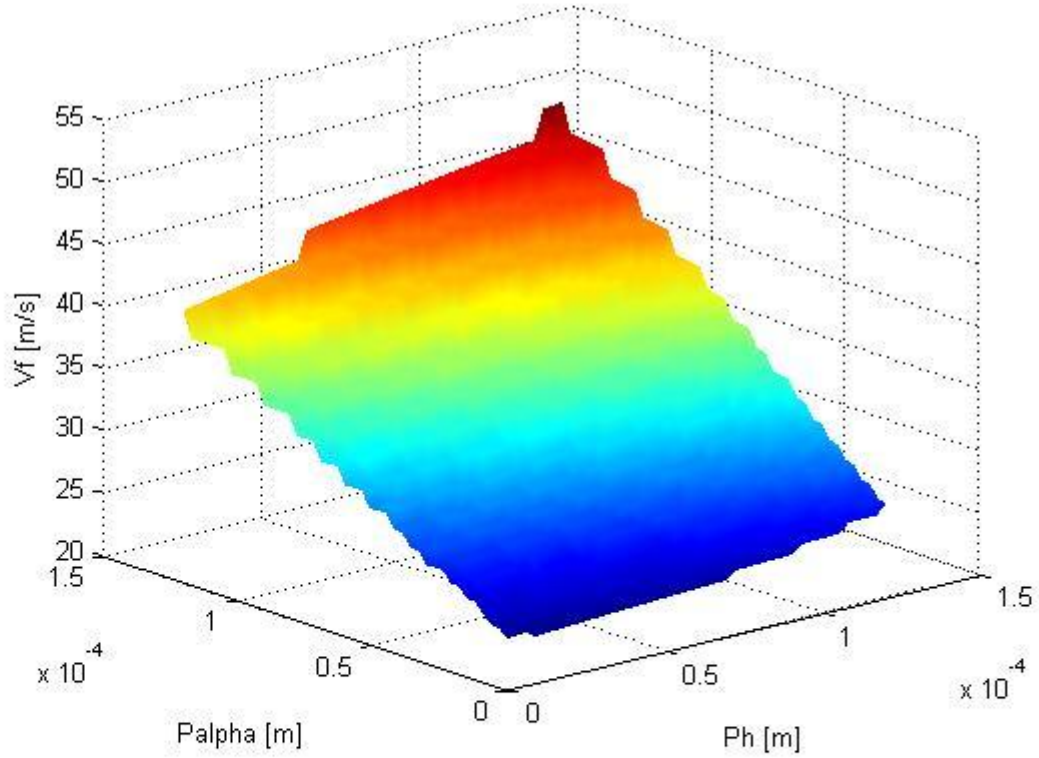

Figure 10 : Flutter velocity [m/s] vs. P_h [m] vs. P_α [m].

Figure 10 presents the variation of flutter velocity with the variation of the parameters P_h and P_α. It can be clearly seen in the plot that the flutter velocity considerably increases with the increasing in P_α and P_h. Furthermore the results also indicate that the parameter P_α has a greater influence on the damping of the system compared to the parameter P_h, since, for the same increase in the parameters, the flutter velocity increases more apparently with the increase in P_α. The preliminary results presented in this paper have indicated that viscoelastic materials are potential material candidates for passive flutter control in aeronautical structures. Further studies including the addition of viscoelastic layers in the surfaces of plates, shells and stiffened composite panels under supersonic flow are currently being investigated. The preliminary results also indicated a considerable increase in the velocity of flutter for panels and shells including viscoelastic treatment.

5. CONCLUDING REMARKS

As presented in previous sections, the application of viscoelastic material for suppression of flutter has proven itself plausible in the cases studied herein. The passive control based on viscoelastic material has shown to be efficient in a wide range of temperatures and frequencies usually experienced by typical aeronautical structures, proving the capability of this material to suppress flutter.

The parametric study also indicated that an increase in flutter velocity is expected with the application of viscoelastic material, with greater influence been observed with the application of viscoelastic in the torsional degree of freedom of the typical section.

6. ACKNOWLEDGEMENTS

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