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An efficient modeling methodology of piezoaeroviscoelastic systems for vibration-based energy harvesting and subsonic flutter suppression

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An efficient modeling methodology of piezoaeroviscoelastic systems for vibration-based energy harvesting and subsonic flutter suppression

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In the open literature the flutter suppression and vibration-based energy harvesting using, respectively, viscoelastic materials and piezoelectric transducers have been studied by several authors. However, most of the available archives are limited to supersonic flight conditions and, furthermore, few papers have investigated the consequence of using the concept of piezoaeroviscoelasticity on the subsonic flutter suppression and electrical power generation, which motivates this contribution. Thus, the focus is placed on the mathematical modeling and numerical investigations of a two degrees of freedom typical wing section subjected to an unsteady airflow containing discrete viscoelastic mounts and attached to a resistive piezo-shunted circuit. In the modeling of the piezoaeroviscoelastic problem, the complex modulus approach combined with the concept of shift factor and reduced frequency has been retained to represent the frequency- and temperature-dependent behavior of the viscoelastic substructure. To model the unsteady aerodynamic

loadings acting on the typical section, it was assumed the well-known linearized thin airfoil theory. Numerical simulations were performed for some design parameters and subsonic flight conditions to demonstrate the main features and capabilities of the proposed modeling methodology and the possibility of increasing the dynamic stability and power generation of the piezoaeroviscoelastic airfoil. In addition, a parametric study has been performed with the aim of evaluating the degree of influence of operating temperature and resistance on the stability and power generation.

Keywords: Flutter suppression, energy harvesting, subsonic aeroelasticity, airfoil section, viscoelastic materials, piezo-shunt-damping circuits.

1. Introduction.

In the open literature, several works have demonstrated the possibility of using the concept of piezoelectricity and viscoelasticity for vibration and noise mitigation. Most of the works involving piezoceramics, it can be found cantilever beams and plates coupled with them and attached to external mono- or multi-modal shunt circuits [1-3]. Among the fundamental early studies in this field, the papers by Hagood and von Flotow [4] and Wu [5] are of great relevance. In the same way, viscoelastic materials have been successfully applied to mitigate undesirable vibrations and noise in configurations known as passive or active constraining viscoelastic layers or discrete viscoelastic mounts, as discussed in the books by Nashif and Jones [6] and Mead [7], and in the papers [8-10].

Also, in the context of aeroelasticity, viscoelastic and piezoelectric materials have been used for dealing with the problem of flutter suppression and vibration-based energy harvesting. However, most of the available archives appearing in the literature are limited to supersonic flight scenarios and, furthermore, few authors have studied the consequence of using the concept of piezoaeroviscoelasticity to improve the dynamic stability and power generation of subsonic aeroelastic systems. In most of the cases, it is due to the difficulty in considering the inherent complex frequency- and temperature-dependent behavior of the piezoaeroviscoelastic system in subsonic regimes, which motivates the present study. Thus, the focus is placed on the mathematical modeling and numerical investigations of a two degrees of freedom typical wing section subjected to an unsteady airflow containing discrete viscoelastic mounts and attached to a resistive piezo-shunted circuit device for the purposes of flutter suppression and energy harvesting.

In aeronautical and aerospace industries, the engineers are frequently faced with the increasing demand for efficiency and performance of products, among other factors such as safety and comfort of aircrafts. It has motivated the interest in applying the so-called new alloys and composite materials to construct more flexible and lighter structural components, but with the disadvantage of increasing the possibility of flutter occurrence due to the increasing on the interaction between inertia, elastic and aerodynamic loadings acting on aeroelastic systems [11].

Hence, more recently, much effort has been done on the use of efficient control strategies for flutter boundary prediction and suppression, especially regarding the use of passive control approaches in view of their low-cost of maintenance and application. For example, several studies can be found on the application of piezoelectric and viscoelastic materials with the aim of limiting the aircraft flight envelopes by suppressing the flutter phenomenon to avoid catastrophes. In this way, Scott and Weisshaar [12] have used piezoceramics patches combined with shape memory alloys for flutter suppression of flat panels under supersonic airflows. The authors in [13] have applied piezoelectric devices with a multi-input-multi-output feedback controller strategy for flutter suppression of a composite plate subjected to a supersonic regime. Leão et al. [14] have developed an optimal design strategy for a multimode resonant piezo-shunted system in series topology to increase the supersonic flutter of a composite flat panel.

Others interesting studies on the use of piezoelectric patches coupled with passive shunt circuits for flutter suppression and can be found in [15-17]. Clearly, it must be not disregarded the extensively use of piezoelectric transducers for vibration-based energy harvesting, as discussed in references [18-22]. For instance, Hafezi and Mirdamadi [23] presented a novel design strategy for a cantilever beam with an airfoil to extract energy from wind. They have investigated the trade-off between the onset of flutter instability and energy output, using both linear and nonlinear aeroelastic models. Amaral et al. [24] have studied the influence of nonlinear terms on flutter speed and power output of an aeroelastic energy harvester device using piezoelectric transducers. The results showed that, the nonlinear stiffness increases the flutter speeds, while nonlinear piezoelectric coupling increases electrical power. Also, they have shown that, more energy is harvested from pitch motion than plunge motion, highlighting the importance of accounting for nonlinear effects in harvester design systems. Sarvilha and Barati [25] have studied the wake-induced vibration of a thin piezoelectric actuator for vortex-based energy harvesting to obtain optimal configurations for enhancing the dynamic response and voltage output of the piezoelectric actuator, offering new insights for capturing the internal flow energy. Erturk et al. [26] have used a piezo-shunted device with a load resistance as aeroelastic control strategy and energy harvester from aeroelastic vibrations for a simple two degrees of freedom typical wing section in a subsonic flight.

For the case of viscoelastic materials, the open literature also includes many works dealing with their application for flutter suppression, as addressed in references [27-30]. For instance, Martins et al. [31] have developed a hybrid approach for aeroelastic control, combining passive and active techniques to prevent flutter in a simplified wing model. The passive control involved viscoelastic materials used as resilient elements, while the active control uses a flap-like surface governed by a proportional-derivative control law. In that work, the authors have demonstrated the potential of viscoelastic materials to enhance aeroelastic stability in practical aerospace applications.

Again, based on the literature review, surprisingly enough, most of the available studies regarding the use of piezoelectric and viscoelastic materials in aeroelastic are restricted to supersonic flight conditions. Also, nothing was reported on the possibility of using both viscoelastic and piezo-shunt-damping devices for vibration-based energy harvesting and flutter suppression in subsonic aeroelasticity. Thus, all these aspects have motivated the interest into this study.

To demonstrate the capabilities and main features of the proposed methodology, it is used herein a 2D typical wing section containing discrete translational and rotational viscoelastic mounts and a resistive shunted piezoceramic. In the development of the foundations, it is shown all the mathematical developments of the piezoaeroviscoelastic system subjected to a subsonic airflow and the numerical resolution method to solve the resulting equations of motion in frequency-domain to predict the subsonic flutter speeds and electrical power. In addition, a parametric study have been performed to evaluate the influence of operating temperature and load resistance on the piezoaeroviscoelastic airfoil responses under study.

2. The piezoaeroviscoelastic model in frequency-domain.

In this section the formulation of a 2D typical wing section incorporating discrete viscoelastic springs and attached to a piezoelectric material coupled with an external shunt circuit is presented. Figure 1 illustrates the airfoil system of interest here composed by two structural degrees of freedom (DOFs), namely h and θ associated to the plunge and pitch motions, respectively. The system is attached to a piezoelectric patch coupled with a load resistance, R, in addition to translational and rotational viscoelastic springs, having the following complex stiffnesses coefficients, k_h^* and k_θ^*, respectively. In the same figure, it is shown the aerodynamic, aa, and elastic, ea, axes and the center of gravity, cg, of the 2D airfoil. It is important to mentioning that the relative position of these three axes influences strongly the flutter speeds of the airfoil, as discussed in [30].

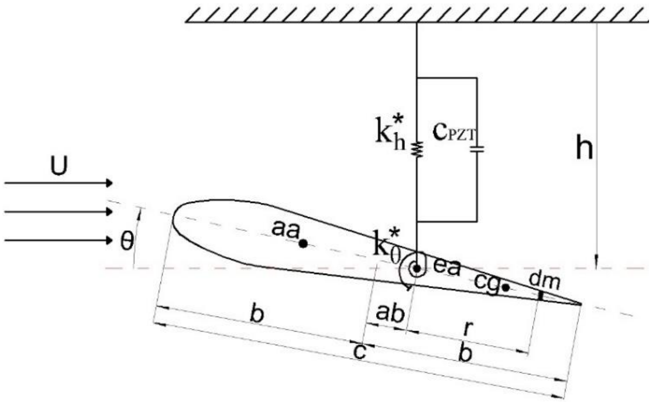

Figure 1 – Illustration of the airfoil with viscoelastic and piezo-shunt damping devices.

For a transverse displacement of the elastic axis, $z = h + r\theta$, with r its distance from a small mass, $dm = \rho dr$, it is possible to formulate the kinetic and strain energies, as given in Eqs. (1.a) and (1.b):

$$T=\frac{1}{2}\left(m+m_f\right)\frac{dh}{dt}^2+mx_\theta\frac{dh}{dt}\frac{d\theta}{dt}+\frac{1}{2}mr_\theta^2\frac{d\theta}{dt}^2 \tag{1.a}$$

$$U=\frac{1}{2}k_h^*h^2+\frac{1}{2}k_h^*\theta^2+\frac{1}{2}\int_{V_{pzt}}\varepsilon_1\sigma_1 dV_{pzt}-\frac{1}{2}\int_{V_{pzt}}D_3E_3 dV_{pzt} \tag{1.b}$$

where m is the mass of the airfoil per span length, l, x_θ is the cg coordinate from ea and r_θ is the radius of gyration. Clearly, for a more realistic situation, the fixture mass, m_f, should be considered in the analysis to represent the connection between the airfoil to the plunge motion. But, for an ideal representation, as given in Fig. 1, $m_f=0$.

By applying the piezoelectric constitutive equations [32] on the plunge DOF for the piezoelectric device, it can be found the following relations for its mechanical stress and electrical displacement, $\sigma_1=C_{11}\varepsilon_1-e_{13}E_3$ and $D_3=e_{13}\varepsilon_1+\chi_{33}E_3$, respectively, where $\varepsilon_1=h/L_{pzt}$ and $E_3=-\phi/t_{pzt}$ represent, respectively, the mechanical strain and electric field. ϕ is the electric potential, L_{pzt} and t_{pzt} are the length and thickness of the piezoelectric patch, C_{11} is its elastic property, and e_{13} and χ_{33} designate, respectively, the electromechanical coupling coefficient and electrical permissivity of the piezoelectric material. Thus, Eq. (1.b) can be rewritten as follows:

$$U=\frac{1}{2}k_h^*h^2+\frac{1}{2}k_\theta^*\theta^2+k_{h\phi}h\phi-\frac{1}{2}k_{\phi\phi}\phi^2 \tag{1.c}$$

where $k_{h\phi} = e_{13} V_{pzt} / \left(L_{pzt} t_{pzt} \right)$ is the so-called electromechanical coupling term, and $k_{\phi\phi} = \chi_{33} V_{pzt} / t_{pzt}^2$ is the equivalent capacitance. Now, the Hamilton's Principle can be used to generate the piezoaeroviscoelastic equations (2) in time-domain, accounting for the virtual works done by the non-conservative aerodynamic loadings in plunge and pitch displacements, $\delta W_h = -Q_h \delta h$ and $\delta W_\theta = -Q_\theta \delta\theta$, respectively, and the electrical force, $\delta W_\phi = -Q_\phi \delta\phi$, where Q_ϕ is the electrical charges.

$$\left(m + m_f \right) \frac{d^2 h}{dt^2} + m x_\theta \frac{d^2 \theta}{dt^2} + k_h^* h + k_{h\phi} \phi = Q_h \tag{2.a}$$

$$m x_\theta \frac{d^2 h}{dt^2} + m r_\theta^2 \frac{d^2 \theta}{dt^2} + k_\theta^* \theta = Q_\theta \tag{2.b}$$

$$k_{h\phi} h + k_{\phi\phi} \phi = Q_\phi \tag{2.c}$$

By assuming harmonic motions for h, θ and ϕ, at frequency, ω, and for a given temperature, T, and using the Ohm' Law, $Q_\phi(\omega) = -\phi(\omega) / (j\omega R)$, in Eq. (2.c), it leads to following Eq. (3), representing the relation between the voltage across the load resistance and the plunge motion:

$$\phi(\omega) = \frac{-j\omega k_{h\phi}}{1/R + j\omega k_{\phi\phi}} h(\omega) \tag{3}$$

Equations (2.a) and (2.b) can be rewritten in the following matrix form:

$$\left(\begin{bmatrix} k_h(\omega,T)+k_{sht}(\omega) & 0 \\ 0 & k_\theta(\omega,T) \end{bmatrix} - \omega^2 \begin{bmatrix} m+m_f & mx_\theta \\ mx_\theta & mr_\theta^2 \end{bmatrix}\right)\begin{Bmatrix} h(\omega,T) \\ \theta(\omega,T) \end{Bmatrix} = \begin{Bmatrix} Q_h(\omega) \\ Q_\theta(\omega) \end{Bmatrix} \quad (4)$$

In Eq. (4), $k_{sht}(\omega) = -j\omega k_{h\phi}^2 / \left(1/R + j\omega k_{\phi\phi}\right)$ designates the stiffness of the shunt circuit, and $k_h(\omega,T) = k_h^e + E(\omega,T)k_h^v$ and $k_\theta(\omega,T) = k_\theta^e + G(\omega,T)k_\theta^v$ are the frequency- and temperature-dependent stiffnesses of the discrete viscoelastic springs, formed by elastic contributions, k_h^e and k_θ^e, and viscoelastic parts for which the complex *moduli*, $E(\omega,T)$ and $G(\omega,T)$, have been factored-out of their stiffnesses coefficients, $k_h^v = (\pi/2)\left[\left(R_e^4 - R_i^4\right)/\left(R_e - R_i\right)\right]$ and $k_\theta^v = L_m h_m / t_m$, for the translational and rotational springs, respectively, accounting for their geometrical characteristics, according to the illustration given in Fig. 2. Also, by assuming the widely used hypothesis of constant Poisson ratio for isotropic polymers, $G(\omega,T) = E(\omega,T)/\left(2(1+\nu)\right)$.

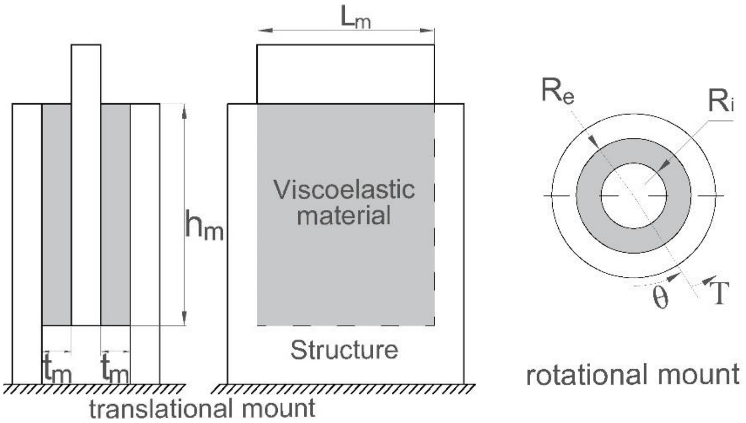

Figure 2 – Illustration of translational and rotational viscoelastic mounts.

By defining the following terms, $\omega_h^2 = k_h/m$, $\omega_\theta^2 = k_\theta/\left(mr_\theta^2\right)$, $\omega_{sht}^2 = k_{sht}/m$, $\beta = \left(m + m_f\right)/m$, and $\bar{x}_\theta = x_\theta/b$ and $\bar{r}_\theta = r_\theta/b$, with b the airfoil's semi-chord, and multiplying the 1st and 2nd rows of Eq. (4) by $1/\left(mb\right)$ and $1/\left(mb^2\right)$, respectively, after performing some mathematical manipulations, it leads to Eq. (5):

$$\left[\boldsymbol{K}\left(\omega,T\right) - \omega^2\boldsymbol{M}\right]\boldsymbol{X}\left(\omega,T\right) = \begin{Bmatrix} Q_h/mb \\ Q_\theta/mb^2 \end{Bmatrix} \quad (5)$$

where $\boldsymbol{K}\left(\omega,T\right) = \begin{bmatrix} \omega_h^2\left(\omega,T\right) + \omega_{sht}^2\left(\omega\right) & 0 \\ 0 & \bar{r}_\theta^2\omega_\theta^2\left(\omega,T\right) \end{bmatrix}$, $\boldsymbol{M} = \begin{bmatrix} \beta & \bar{x}_\theta \\ \bar{x}_\theta & \bar{r}_\theta \end{bmatrix}$ and $\boldsymbol{X}\left(\omega,T\right) = \begin{Bmatrix} h\left(\omega,T\right)/b \\ \theta\left(\omega,T\right) \end{Bmatrix}$.

Ath this time, by considering the Theodorsen's unsteady potential theory [33] for thin airfoils, the non-stationary aerodynamic lift, Q_h, and pitching moment, Q_θ, as defined by Eqs. (6), can be introduced into Eq. (5) to obtain the complex eigenproblem (7), which must be solved using an iterative resolution method, as shown in Section 4.

$$\frac{Q_h}{mb} = \frac{\omega^2}{\mu}\left[L_h\frac{h}{b} + \left(L_\theta - gL_h\right)\theta\right] \quad (6.a)$$

$$\frac{Q_\theta}{mb^2} = \frac{\omega^2}{\mu}\left\{\left(M_h - gL_h\right)\frac{h}{b} + \left[M_\theta - g\left(L_\theta + M_h\right) + g^2L_h\right]\theta\right\} \quad (6.b)$$

where $L_h = 1 - i2C/k$, $L_\theta = 0.5 - i(1+2C)/k - 2C/k^2$, $M_\theta = 3/8 - i/k$ and $M_h = 0.5$ are functions of the reduced frequency, $k = \omega b/U$, and the Theodorsen's coefficient, $C(k)$, where U is the airflow speed, $\mu = m/(\pi\rho b^2)$, and $g = 0.5 + a$. Details on the computation of, $C(k)$, can be found in [14].

$$\left[\boldsymbol{K}(\omega,T) - \lambda\left(\boldsymbol{M} + \frac{1}{\mu}\boldsymbol{A}(k)\right)\right]\boldsymbol{X}(\omega,T) = \boldsymbol{0} \qquad (7)$$

where $\lambda = \omega^2$ and $\boldsymbol{A}(k) = \begin{bmatrix} L_h & L_\theta - gL_h \\ M_h - gL_h & M_\theta - g(L_\theta + M_h) + g^2 L_h \end{bmatrix}$.

3. Complex modulus approach.

As discussed in introduction, the main difficulty in the modeling of aeroelastic systems with viscoelastic materials under subsonic airflows is the fact that, their dynamic behavior depends strongly on temperature and frequency. To overcome this drawback, it is used here the complex modulus approach in conjunction with the concept of reduced frequency and shift factor, according to the frequency and temperature superposition principle (FTSP) [6]. Based on it, the complex modulus of linear viscoelastic materials is given by Eq. (8).

$$G(\alpha_T\omega,T) = G'(\alpha_T\omega,T)\left[1 + i\eta(\alpha_T\omega,T)\right] \qquad (8)$$

where $\eta = G''/G'$ is the loss factor, and G' and G'' are the storage and loss *moduli*, respectively, which are computed for a given frequency and temperature of the system. α_T is the shift factor, which is a function of the operating temperature.

Here, it is used the well-known 3M ISD112™ polymer, where Drake and Soovere [34] have proposed expression (9) for the complex modulus, valid for the following temperature and frequency intervals, $210 \le T \le 360K$ and $1.0 \le \omega \le 1.0\times10^6\ Hz$:

$$G(\omega,T) = 0.4307 + \frac{1200}{1+3.241\times\left(\dfrac{i\omega\alpha_T}{1543000}\right)^{-0.18}+\left(\dfrac{i\omega\alpha_T}{1543000}\right)^{-0.6847}}\left[MPa\right] \quad (9)$$

where $\alpha_T = 10^{\left(-3758.4\times\left(\frac{1}{T}-0.00345\right)-225.06\times\log(0.00345\times T)+0.23273\times(T-290)\right)}$.

Figure 3 shows that, for a given oscillation frequency, as the operating temperature of the 3M ISD112™ increases, its loss factor is strongly affected, causing a significantly reduction on its damping performance.

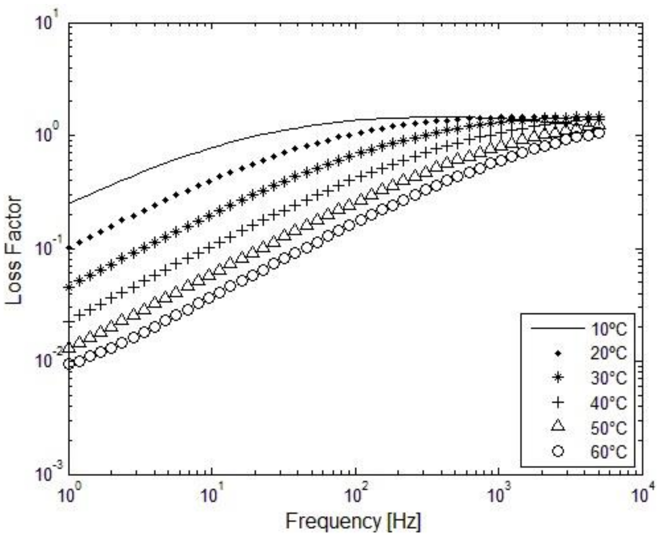

Figure 3 – Influence of the operating temperature on the loss factor for the 3M-ISD112.

4. Iterative resolution scheme.

Since the stiffness matrix, $\boldsymbol{K}(\omega,T)$, is frequency- and temperature-dependent in addition to the dependence of aerodynamic matrix, $\boldsymbol{A}(k)$, on the Theodorsen's term, the complex eigenproblem (7) is solved herein by using an efficient iterative resolution method, as summarized in Fig.4, for dealing with piezoaeroviscoelastic systems under subsonic airflows, where the oscillation frequency, ω, used to compute these matrices is given by solving Eq. (7) that becomes unstable as the airflow speed, U, increases [26].

Start by defining: T, R, $\boldsymbol{M}$, $Err = 100$ and $tol = 1\times 10^{-6}$

1. For $k = [4 - 0.01]$

- *Compute:* $C(k)$ and $\boldsymbol{A}(k)$
- *Initial frequencies:* $\omega^0 = \omega_{sht}^0 = 0.1$

2. While $Err > tol$

- *Compute:* $G(\omega,T)$, $\omega_{sht}^2(\omega)$, $\omega_h^2(\omega,T)$, $\omega_\theta^2(\omega,T)$
- *Compute:* $\boldsymbol{K}(\omega,T)$ and $\boldsymbol{A}(k)$
- *Solve Eq.* (7) to obtain eigensolutions $(\lambda, \boldsymbol{X})$
- *Compute* $\omega = \omega_\theta \big/ \sqrt{\mathrm{Re}(\lambda)}$ *and damping factor* $g = \mathrm{Im}(\lambda)/\mathrm{Re}(\lambda)$
- *Actualization,* $\omega_{sht} = \omega$, *and error value,* $Err = \left|\omega_{sht}^0 - \omega_{sht}\right|$
- *End While*

3. Voltage to plunge amplitude ratio, (ϕ/h), *from Eq. (3)*

4. Normalized power, $(\phi/h)^2 / R$

5. Vg diagram: $(\omega \times U)$ *and* $(g \times U)$

Figure 4 – Main steps of the iterative method for subsonic flutter and power predictions.

After defining the temperature and load resistance, for each reduced frequency, k, corresponding to an airspeed, U, it is computed the complex eigenvalues, $\lambda = \omega^2$, and eigenvectors, $\boldsymbol{X} = [h \;\; \theta \;\; \phi]^T$, accounting for the error and tolerance values adopted by the user for the convergence. The critical flutter speed is predicted by analyzing the typical Vω and Vg plots, representing the evolution of the natural frequencies for plunge, ω_h, and pitching vibration modes, ω_θ, versus the airflow speed, U, and the damping parameter, g, versus, U, respectively. The subsonic flutter occurs at $g = 0$.

5. Numerical applications and discussions.

To perform dynamic stability and energy harvesting analyses with the 2D airfoil incorporating discrete viscoelastic springs and piezo-shunt damping device subjected to a uniform subsonic airflow, as illustrated in Fig. 1, the nominal values of the system parameters are defined following Erturk *et al.* [2]: (a) for the typical section: $\bar{x}_\theta = 0.504$; $\bar{r}_\theta = 0.504$, $\beta = 2.597$, $\left(\omega_h^e / \omega_\theta^e\right) = 3.33$, $\mu = 29.6$, $b = 0.125m$, $\rho = 1.225\, Kg/m^3$, $l = 0.5m$, $\omega_\theta^e = 15.4\, rad/s$, $a = -0.5$; for the PZT-5A element: $k_{h\phi} = 1.55 \times 10^{-3}\, N/V$, $k_{\phi\phi} = 120 \times 10^{-9}\, F$; (iii) for discrete viscoelastic springs: $k_h^v = 1.25 \times 10^{-6}\, N/m$ and $k_\theta^v = 1.25 \times 10^{-7}\, N/m$.

In all simulations that follow, it has been assumed a range of reduced velocity of $[0.25 - 2]$ with an arbitrary chosen step of, 0.001, and a tolerance value of, 1×10^{-6}, for the convergence. It is important to highlighted that, these conditions are not related to a specific flight envelope in any way but give insights on the subsonic flutter and harvester studies of interest here.

Since the region of interest from the point of view of the piezoaeroviscoelastic airfoil is the critical velocity, it is important to characterize firstly the subsonic flutter boundary of the purely airfoil section without viscoelastic and piezoelectric materials. Thus, for the airfoil section without any control device, the Vω and Vg graphs are shown in Fig. 5. These curves were constructed by solving the complex eigenproblem (7) for the purely airfoil system, according to the iterative method discussed in Fig. 4. It can be seen that, as the airflow speed increases, the subsonic flutter phenomenon occurs at an airspeed of approximately, $7.06\, m/s$, where the damping parameter assumes the value of, $g = 0$, characterizing the coalescence of the pitch and plunge modes of the airfoil. Moreover, it is perceived that, for these subsonic flight conditions, it is the plunge mode the responsible for the dynamic instability.

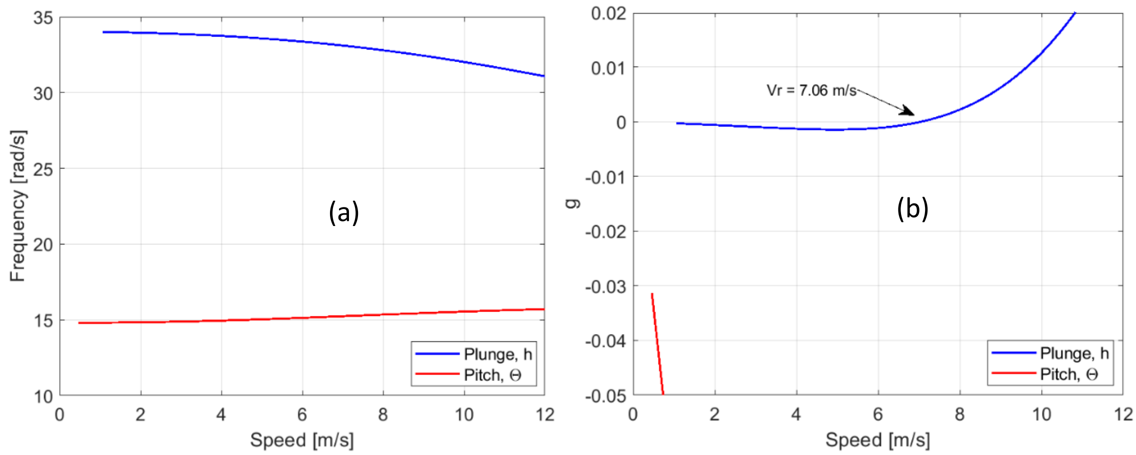

Figure 5 – Vω (a) and Vg (b) plots for the 2D airfoil section without control systems.

5.1. The airfoil with piezoelectric coupling.

Here, it is investigated the subsonic flutter response of the airfoil with a PZT-5A piezoceramic attached on its plunge DOF to be coupled with an electrical load resistance.

Firstly, for each load resistance the airflow speed is slowly increased from 0 m/s to 12 m/s in order to construct a plot of the critical velocity as function of the resistive. Figure 6 presents the critical flutter speed versus load resistance of the piezoaeroelastic airfoil, showing the short-circuit ($R \to 0$) to the open-circuit ($R \to \infty$) flutter velocities from 7.06 m/s to 7.32 m/s, respectively. It is important to highlighted that, this small increasing in the critical flutter velocity due to the shunt-damping mechanism obtained here is in agreement with the numerical results appearing in reference [2]. Moreover, it can be clearly perceived that, the load resistance value of, $300 k\Omega$, leads to an increasing in the dynamic stability of the airfoil of, 6.8%, resulting in a critical flutter speed of, $7.54\, m/s$. At this time, it must be mentioned that, these observations are in agreement with those appearing in [26]. Thus, it demonstrates the effectiveness of the piezo-shunt device in increasing the flutter boundary of aeroelastic systems under subsonic flight conditions.

By examining the voltage to plunge motion ratio versus load resistance shown in Fig. 7, according to Eq. (3), it exhibits a linear asymptote behavior until a value of, $10\, V/mm$, for the optimal resistance of, $300\, k\Omega$, for flutter suppression. This kind of motion is similar to that observed in classical harmonic base-excitation experiments with piezo-energy-harvesters devices, as discussed in [22]. It is important to mentioning that, these observations are in agreement with those appearing in [26].

The normalized electrical power to plunge motion versus load resistance is given in Fig. 8, where the optimal load resistance of, $300\, k\Omega$, that leads to the maximum electrical power output of, $0.33\, mW/mm^2$, causes a considerable increase in the flutter speed of 6.8%, as shown in Fig. 6. Thus, these numerical results demonstrates clearly the effectiveness of the piezoelectric energy harvesting of increasing the flutter boundary of the piezoaeroelastic airfoil.

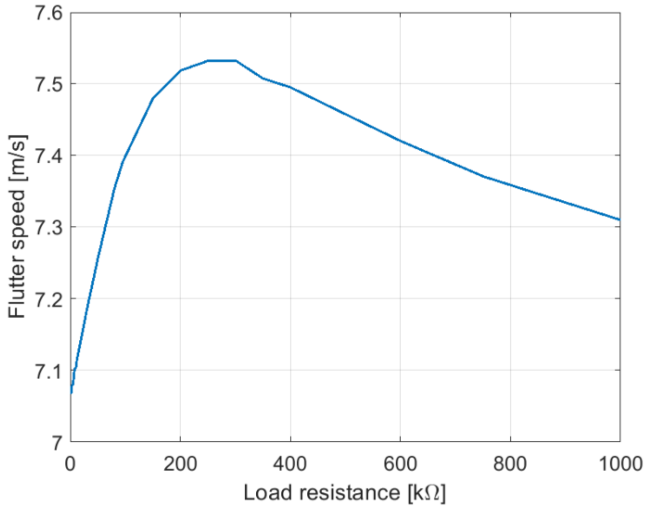

Figure 6 – Flutter speed vs resistance for the piezoaeroelastic airfoil.

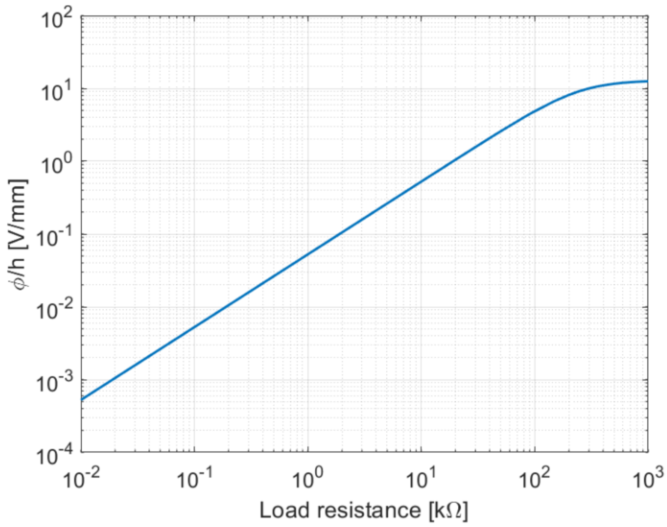

Figure 7 – Voltage output to plunge motion vs resistance for the piezoaeroelastic airfoil.

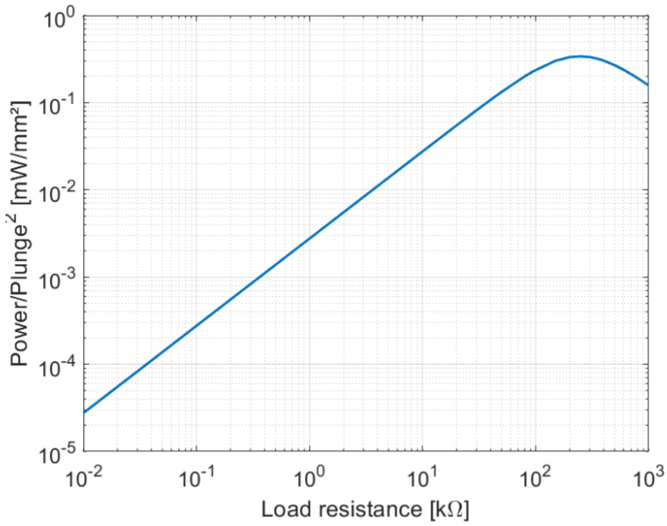

Figure 8 – Power to plunge motion ratio vs resistance for the piezoaeroelastic airfoil.

5.2. The airfoil with discrete viscoelastic mounts.

Now, it is considered the viscoelastic dissipation mechanism on the translational and rotational springs mounted on the airfoil section for various values of temperature, since it is the most influent parameter affecting the damping performance of viscoelastic materials, as discussed in [27]. Thus, it is important to quantify the degree of influence of it on the flutter boundary for the aeroviscoelastic airfoil subjected to subsonic airflows.

By comparing the Vg curves for the aeroviscoelastic airfoil shown in Fig. 9 with the corresponding obtained for the airfoil supported on elastic springs (see Fig. 5), it can be concluded that, the viscoelastic damping has the favorable effect of increasing the critical flutter speed of the aeroviscoelastic airfoil, even for subsonic airflows. However, it makes evident the strongly influence of the temperature on the flutter boundary, since, for a temperature range of –15°C to 80°C, it has been observed an important variation on the critical flutter speed between 10.55m/s to 7.06m/s. Clearly, as shown in Fig. 3, as the operating temperature increases, the loss factor (damping capacity) of viscoelastic polymer reduces significantly. It can be verified by examining the results appearing in Fig. 10, which shows the critical flutter speed for a large number of temperature values. It is interesting to perceived that, as the operating temperature of the aeroviscoelastic airfoil increases, its flutter speed decreases accordingly until a value of the simple airfoil with elastic springs, as expected. Also, the flutter speed versus operating temperature for the aeroviscoelastic airfoil exhibits an asymptotical trend for higher temperature values.

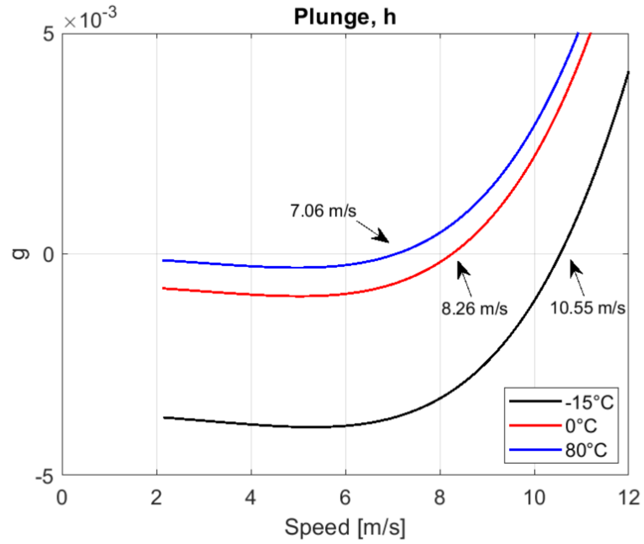

Figure 9 – Vg curves for various temperature values for the aeroviscoelastic airfoil.

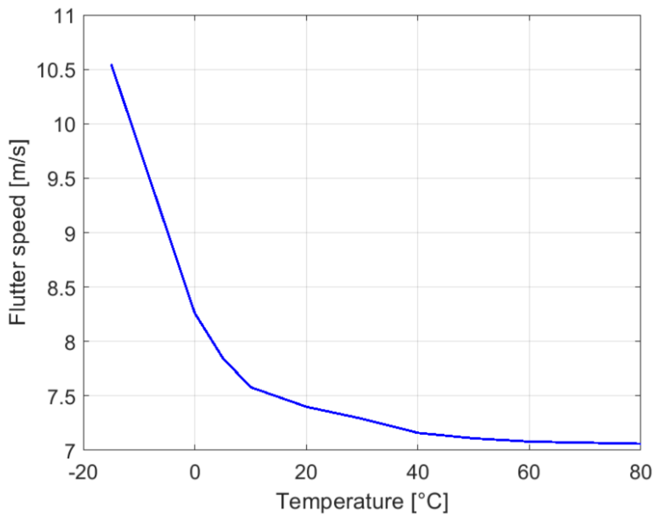

Figure 10 – Flutter speed vs temperature for the aeroviscoelastic airfoil.

5.3. The airfoil with viscoelastic and piezo-shunt damping devices.

Since the flutter suppression and energy harvesting from piezoaeroviscoelastic vibrations induced by subsonic airflows have investigated by few papers in the literature, now, it is study the airfoil with both viscoelastic and piezo-shunt devices. The main interest is to evaluate if these damping mechanisms used in conjunction might be useful in a piezoaeroviscoelastic system designed for flutter suppression and power generation.

Also, it enables to verify the proposed modeling methodology of piezoaeroviscoelastic systems under subsonic airflows. Thus, for the purposes of comparison, it is assumed the same flight conditions as adopted in previous sections, but for a temperature of 10°C.

By comparing the flutter speeds versus load resistance of the piezoaeroelastic and piezoaeroviscoelastic systems shown in Fig. 11, it can be seen the best performance of the piezoaeroviscoelastic airfoil, since it leads to a considerable increase in the flutter speed, when compared with the corresponding predicted by the piezoaeroelastic system. Thus, viscoelastic materials used in conjunction with piezo-shunt devices has favorable effect of increasing the flutter boundary of piezoaeroviscoelastic systems. However, as shown in Fig. 12, as the temperature increases, the stability is strongly affected due to the reduction on the loss factor of the viscoelastic part. Also, surprisingly enough, the power generation capacity is remarkably insensitive to the presence of the viscoelastic material, even when variations on the temperature are performed, as shown in Fig. 13.

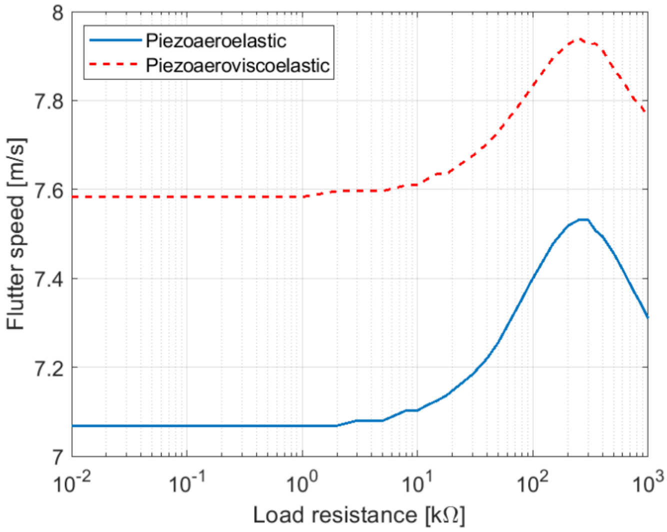

Figure 11 – Comparison between the flutter speeds vs resistance for the piezoaeroelastic and piezoaeroviscoelastic airfoils.

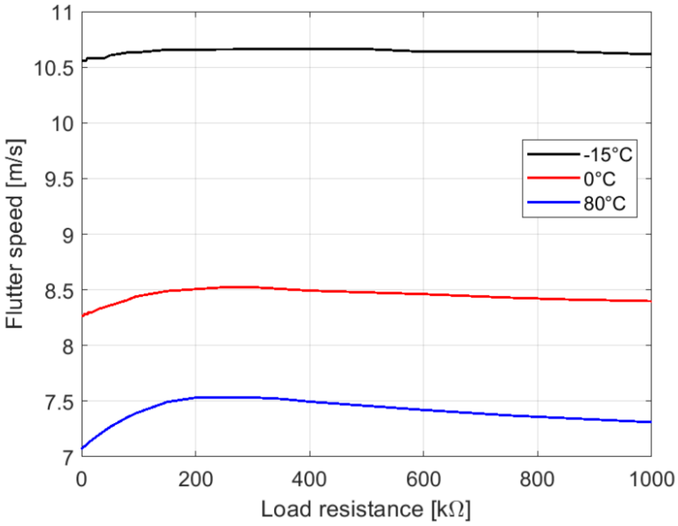

Figure 12 – Influence of the operating temperature on the flutter speed for the piezoaeroviscoelastic airfoil.

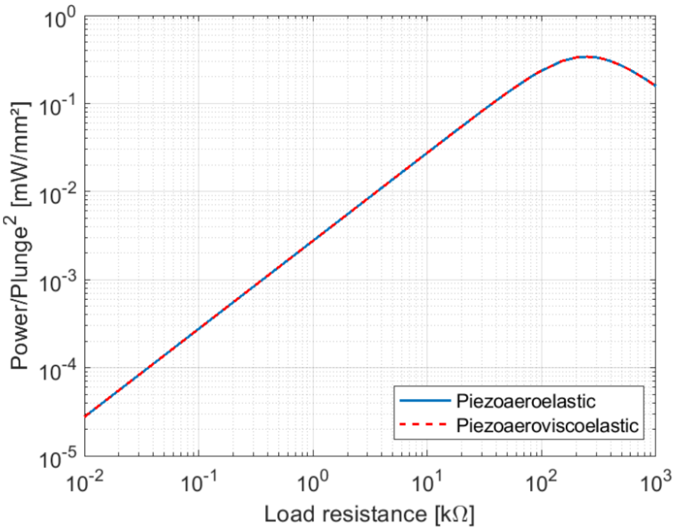

Figure 13 – Comparison between the power to plunge motion ratio vs resistance for the piezoaeroelastic and piezoaeroviscoelastic airfoils.

6. Concluding remarks.

This work has demonstrated the possibility of using both viscoelastic and piezo-shunt damping devices for flutter suppression and piezoelectric energy harvesting of aeroelastic systems under subsonic flight conditions. Firstly of all, it was implemented a typical section model containing two DOF's containing a piezoelectric element attached on its plunge motion and coupled with an electrical load resistance. By analyzing the critical flutter speed versus load resistance, it has been observed that, the optimal load resistance of, $300\,k\Omega$, that gives the maximum electrical power output of, $0.33\,mW/mm^2$, causes a reasonable increase in the critical flutter speed of approximately, 6.8%, when compared with the critical flutter speed of the simple airfoil without control system. Moreover, the voltage to plunge displacement ratio versus resistance exhibited a linear asymptote behavior similar to the corresponding obtained for harmonic base excitations of energy harvesters systems. These observations are in agreement with those appearing in reference [2].

For the case of the airfoil incorporating translational and rotational viscoelastic springs, the results make clear the performance of the viscoelastic material to suppress the flutter boundary, even in subsonic airflow conditions. However, as expected, as the temperature increases, the flutter speeds decreases accordingly due to the influence of higher temperatures values on the loss factor of viscoelastic materials. Thus, in practical applications of aeronautical interest, care must be taken with the adoption of viscoelastic polymers which are more insensitive to operating temperature variations.

In order to offer another possibility of increasing the dynamic stability and power generation of existing aeronautical components subjected to subsonic airflows, it has been implemented a piezoaeroviscoelastic airfoil. It has been demonstrated that, the use of viscoelastic and piezo-shunt damping devices simultaneously has the favorable effect of increasing the subsonic flutter speed of the piezoaeroviscoelastic system. Thus, it is a very promised strategy to be used in practice, since it has observed a considerable increase in the piezoaeroviscoelastic flutter boundary compared with the flutter generated for the piezoaeroelastic airfoil. However, care must be taken, since the temperature influences significantly on the flutter boundary of the piezoaeroviscoelastic system. Furthermore, the electrical power output is remarkably insensitive to the presence of the viscoelastic material, even when variations on the operating temperature are performed.

Hence, it is reasonable to state that, in terms of subsonic flutter suppression, the shunted piezoceramics combined with viscoelastic materials seem to be the best suited aeroelastic control strategy for this purpose, but not for electrical power generation in the context of energy harvesting system.

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