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The use of viscoelastic supports to whirl-flutter control in aeroelastic systems

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Abstract. The search for greater flight efficiency and net-zero emissions has driven the need for new aircraft concepts. In this context, distributed electric propulsion (DEP) offers a promising approach by enabling alternative propulsion systems. Furthermore, electric motors allow for a wide range of possible propeller configurations. An example of this is NASA X-57 Maxwell test aircraft. However, this solution introduces structural challenges due to the potential for aeroelastic instabilities such as whirl flutter, a phenomenon that occurs when a system experiences gyroscopic effects caused by a rotating component coupled to a flexible structure. To mitigate these instabilities, this work proposes the use of viscoelastic supports (VES) in the propeller pivoting point. Due to its characteristics, the use of VES tends to reduce the transmission of vibrations from the rotating parts to the surrounding structure. The VES are modeled in the frequency domain, using a complex stiffness that depends on both frequency and operating temperature. The system is modeled by 2 degrees of freedom system and the numerical results obtained using MATLAB software. The viscoelastic stiffness is characterized considering both parameters (frequency and temperature), and its influence on the whirl flutter speed is evaluated.

Keywords: aeroelasticity, viscoelastic supports, vibration control, whirl flutter.

1 Introduction

With the objective of decreasing in-flight emissions in commercial aviation, recent studies have been focused on the idea of hybrid or fully electric aircraft [1]. Electric aircraft generate the necessary lift and thrust using propellers distributed along the wingspan, known as Distributed Electric Propulsion (DEP). This type of aircraft typically feature high aspect ratio wing to enhance the aerodynamic efficiency and minimize the weight of the aircraft. However, this solution increases possibility of aeroelastic instabilities, and it must be carefully analyzed.

Therefore, the search for an effective whirl flutter control is fundamental to ensure safety during flight and open ways for structural and propulsion improvements. One approach to achieve this is by passive control using viscoelastic materials, due to its high capacity of dissipate energy. This type of control has proven to be very effective in different applications, as may be seen in Xímenes [2], Bastos and Vasconcellos [3], and focusing in viscoelastic materials in Ribeiro et al [4], Martins et al [5], Al-Dulaijan et al [6], Shu et al [7], Fang et al [8].

2 Aeroelastic model

The 2 degrees of freedom (2-DOF) model is composed by the whirl flutter model, presented in Reed and Bland [10]. The aeroelastic model is presented for the configuration of one single propeller attached to a rigid wing, which means the influence of typical section degrees of freedom are not considered.

2.1 Propeller mounted on a rigid typical section

It is considered a propeller flexibly mounted on a rigid typical section, that is, the influence of typical section DOF and aerodynamics will be neglected. The 2-DOF (pitch – θ and yaw – ψ) model for the propeller is presented in figure 1 [11].

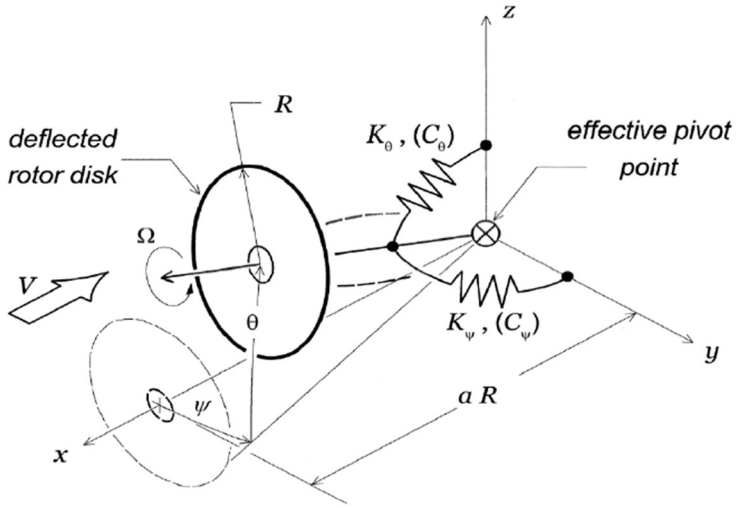


Figure 1. Schematic model of the propeller.

In this case, considering a rotating system, there is the addition of the gyroscopic matrix in system's equation of motion.

$$[M_p]\ddot{q}_p + ([C_p] + [G(\Omega_{rpm})])\dot{q}_p + [K_p]q_p = Q_p \tag{1}$$

Where

$$[M_p] = \begin{bmatrix} I_{\theta,p} & 0 \\ 0 & I_{\psi,p} \end{bmatrix} \qquad [C_p] = \begin{bmatrix} C_\theta & 0 \\ 0 & C_\psi \end{bmatrix}$$
$$[K_p] = \begin{bmatrix} K_\theta & 0 \\ 0 & K_\psi \end{bmatrix} \qquad [G] = I_x\Omega \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \tag{2}$$
$$q_p = \begin{bmatrix} \theta \\ \psi \end{bmatrix} \qquad Q_p = \begin{bmatrix} M_\theta \\ M_\psi \end{bmatrix} = \begin{bmatrix} M_{y,p} - \alpha R F_z \\ M_{z,p} + \alpha R F_y \end{bmatrix}$$

In this formulation, parameter α is the ratio between rotor radius R and pivoting point, I_x is moment of inertia on the propeller rotating axis. F_i and M_i are lateral forces and aerodynamic moments acting on the propeller and are given by equations:

Aerodynamic coefficients c_{ij} are obtained as can be seen in Bland and Reed [10], Houbolt and Reed [14] and Rose and Rodden [15]. Effective angles between propeller DOF and the wind are expressed, for a 2-DOF system as

Thus, it is possible to find final equation of motion for the propeller attached on a rigid wing, expressed in equation 3.

$$[M_p]\ddot{q}_p + ([C_p^{aero}] + [C_p] + [G(\Omega_{rpm})])\dot{q}_p + ([K_p^{aero}] + [K_p])q_p = 0 \tag{3}$$

Considering

$$[C_p^{aero}] = \begin{bmatrix} C_{aero1} & 0 \\ 0 & C_{aero1} \end{bmatrix} \qquad [K_p^{aero}] = \begin{bmatrix} K_{aero1} & -K_{aero2} \\ K_{aero2} & K_{aero1} \end{bmatrix} \tag{4}$$

$$C_{aero1} = -\frac{N_b}{2} K_\alpha R \frac{(A_3 + a^2 A_1)}{\Omega} \qquad K_{aero1} == \frac{N_b}{2} K_\alpha R \alpha A_1' \qquad K_{aero2} = \frac{N_b}{2} K_\alpha R A_2' \tag{5}$$

2.2 Composed system: the use of viscoelastic supports in rotating systems

In this work, the use of viscoelastic support is proposed to passive control in an aeroelastic system subjected to whirl flutter. The control will be added in the points indicated in figure 2, adapted from Cecrdle [13].

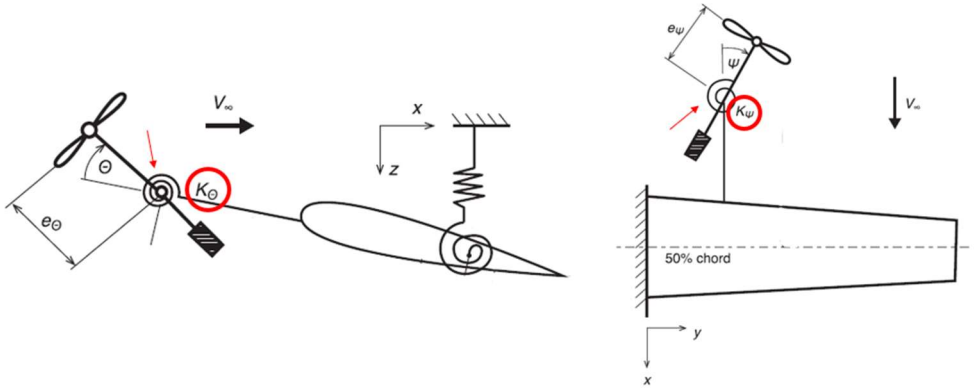


Figure 2. Insertion point of the viscoelastic material.

Viscoelastic materials present a complex stiffness, dependent on the frequency and temperature of operation, thus, propeller matrix K_p in equation 3 is replaced with VEM stiffness matrix $K_c(\Omega, \mathrm{T})$, which is defined as

$$K_c(\Omega, \mathrm{T}) = LG(\Omega, \mathrm{T}) \tag{6}$$

Where $L = \frac{A}{h}$ is the geometric factor for shear loading, A is viscoelastic shear area and h is material thickness. $G(\Omega)$ is the shear modulus, in case of tensile/compression loading, $L = \frac{3A}{h}$. This formulation is obtained from expression based on fractional derivative model shown in Bagley and Torvik [17] and Cruz [18].

$$G_c(\Omega, \mathrm{T}) \approx \frac{G_0 + G_\infty b_1 \left(i\Omega\alpha(\mathrm{T})\right)^\beta}{1 + b_1 \left(i\Omega\alpha(\mathrm{T})\right)^\beta} \tag{7}$$

In expression 7 G_0 and G_∞ represent, respectively, asymptotic lower and upper values of the real part of complex modulus, β is the order of the fractional differentiation, b_1 is the constant related to the relaxation time of the material, T is the operating temperature, Ω is circular variable frequency and α(T) is the frequency-temperature shift factor, which can be obtained from equation 8, proposed by Williams, Landell and Ferry [19].

$$\log \alpha(T) = \frac{-\theta_1 (T - T_0)}{\theta_2 + T - T_0} \tag{8}$$

Parameters θ_1 and θ_2 are characteristics from VEM, obtained for a reference temperature T_0.

System's response must be obtained in frequency domain, due to the frequency dependency of viscoelastic material. Thus, the equation of motion in frequency domain is written

$$\left\{-\Omega^2[M_p] + i\Omega\left([C_p] + [C_p^{aero}] + [G(\Omega_{rps})]\right) + \left([K_p] + [K_p^{aero}]\right)\right\} X(\Omega) = 0 \tag{9}$$

Where $[K_p]$ is complex and contain viscoelastic stiffness. This is defined as

$$[\mathrm{K}_p(\Omega, \mathrm{T})] = \begin{bmatrix} K_c(\Omega, \mathrm{T}) & 0 \\ 0 & K_c(\Omega, \mathrm{T}) \end{bmatrix} \tag{10}$$

For a given temperature and velocity, modal behavior is obtained for a range of operation frequency, resulting in auxiliary Campbell diagram for $\Omega_j x \Omega$. A line is drawn starting from zero, crossing the modal frequencies on the plot. The crossed values are the modal frequencies for that velocity. These values are found for each velocity, obtaining Campbell diagram, when doing the same process with the 45º line, it is possible to find critical speeds for the rotor.

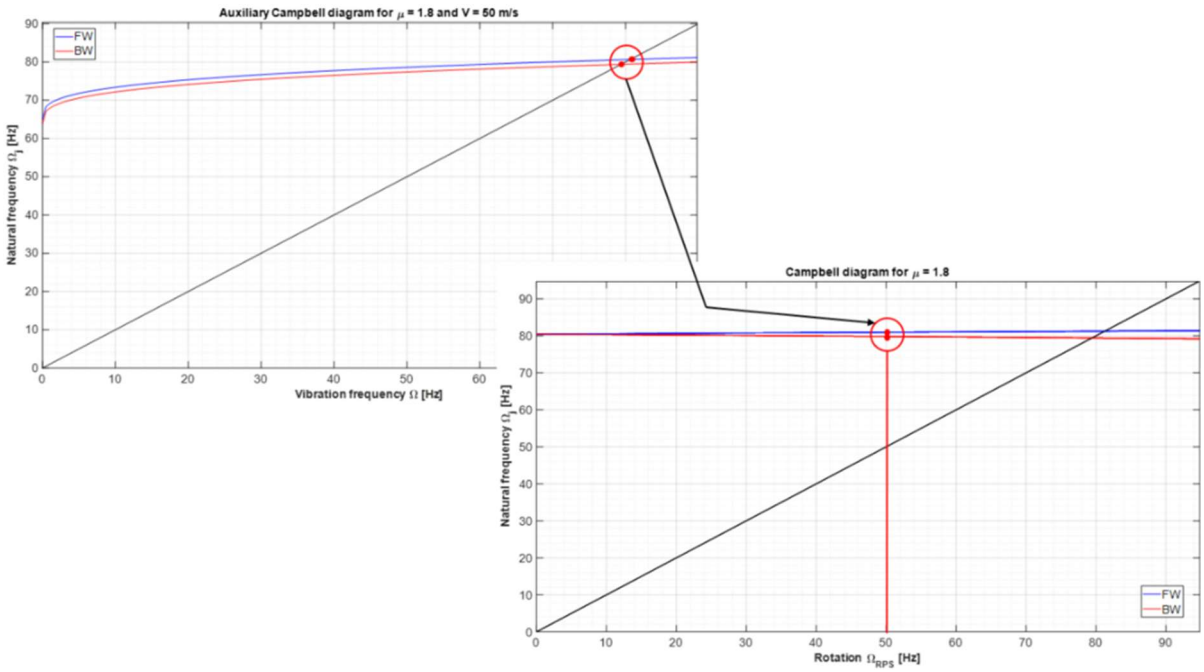


Figure 4. Auxiliary Campbell to obtain natural frequencies for each velocity

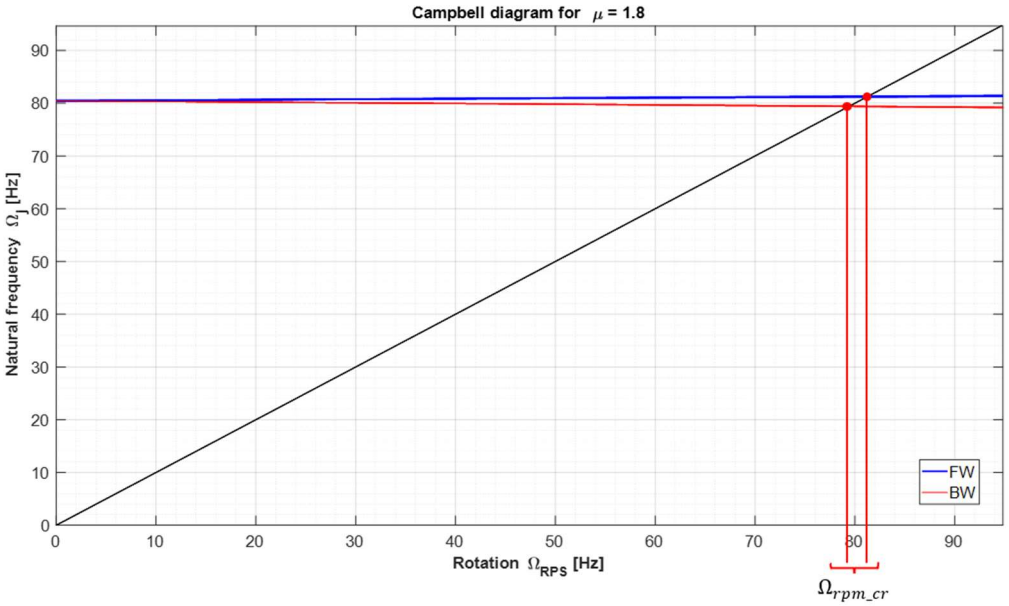


Figure 3. Campbell diagram. Crossed frequencies correspond to critical speeds.

3 Results

The parameters considered to this work were extracted from Bennett and Bland [12] and are presented in table 1. The author also emphasized that the results for this system are reliable for velocities until $Mach = 0.25$, so this was taking into consideration.

Parameter	Symbol	Unit	Value
Rotor radius	R	m	0.2572
Rotor radius / Length of propeller axis	α	-	0.7776
Nonrotating parts moment of inertia	I_p	$kg.m^2$	0.0859
Moment of inertia on the propeller rotation axis	I_x	$kg.m^2$	0.0116
Blade chord	c	m	0.0556

Lift curve slope	$c_{l\alpha}$	-	2π
Air density	ρ	kg/m^3	1.0872
Stiffness in pitch DOF	K_θ	Nm/rad	287.15
Stiffness in yaw DOF	K_ψ	Nm/rad	282.18
Damping coefficient in pitch DOF	g_θ	-	0.003
Damping in yaw DOF	g_ψ	-	0.003

In Figure 5 the V-g-f diagram for the system without the VES is presented. The critical speed is 21.73 (m/s) for backward mode.

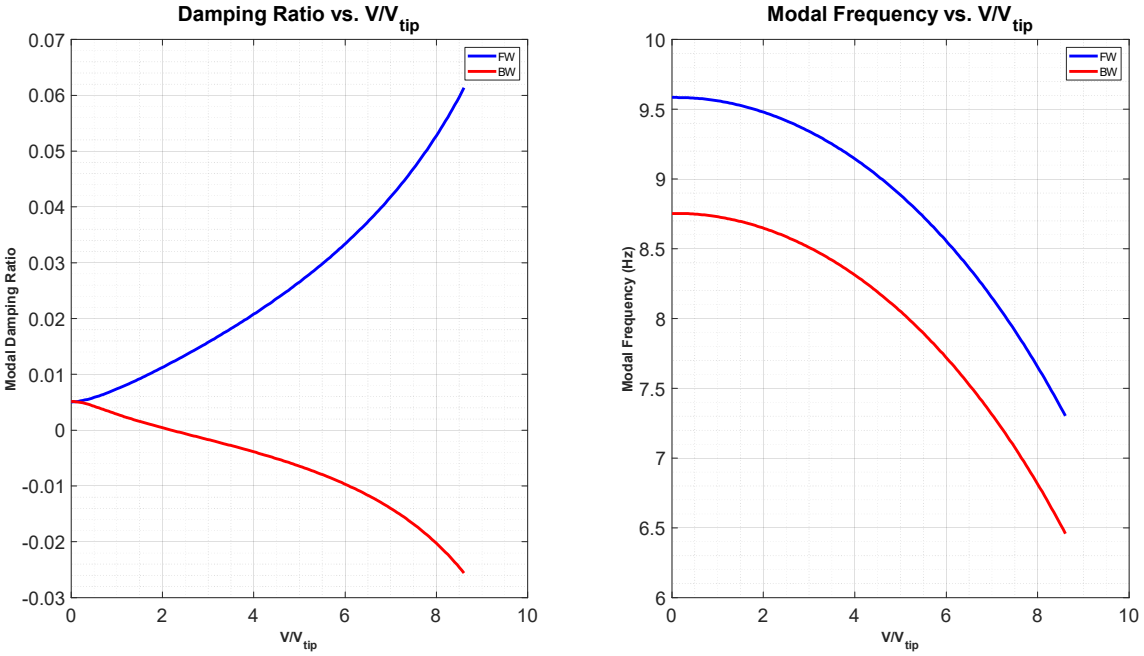


Figure 5. V-g-f diagram for the system without VEM

The VES were modeled using Neoprene due to its characteristics in lower temperatures, and geometric factor is $L = 0.0031$. Initially, it was considered the temperature of 293 K. In this case, the system remains stable for all the velocity range considered, can be checked in figure 6.

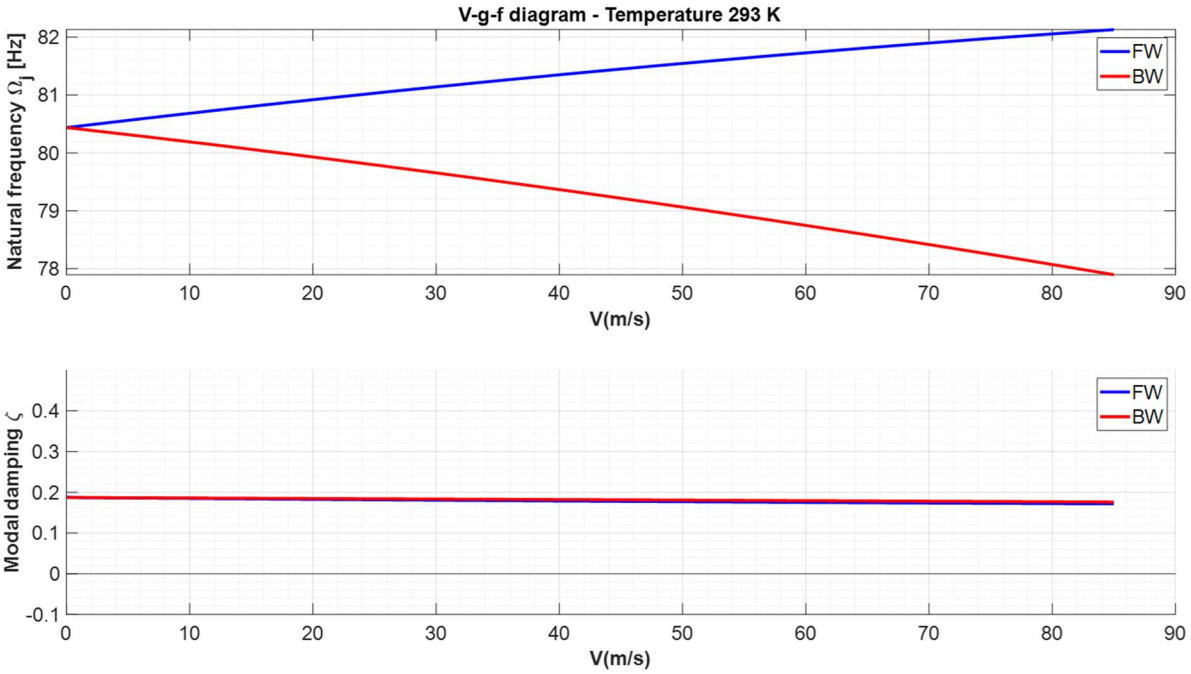


Figure 6. V-g-f diagram for the system with addition of VEM, for T = 293 K.

In second case, temperature was decreased to 253 K, values for modal damping increase, as expected for this configuration of VEM (Figure 7), and stability is maintained for all velocity range, as happen in previous case.

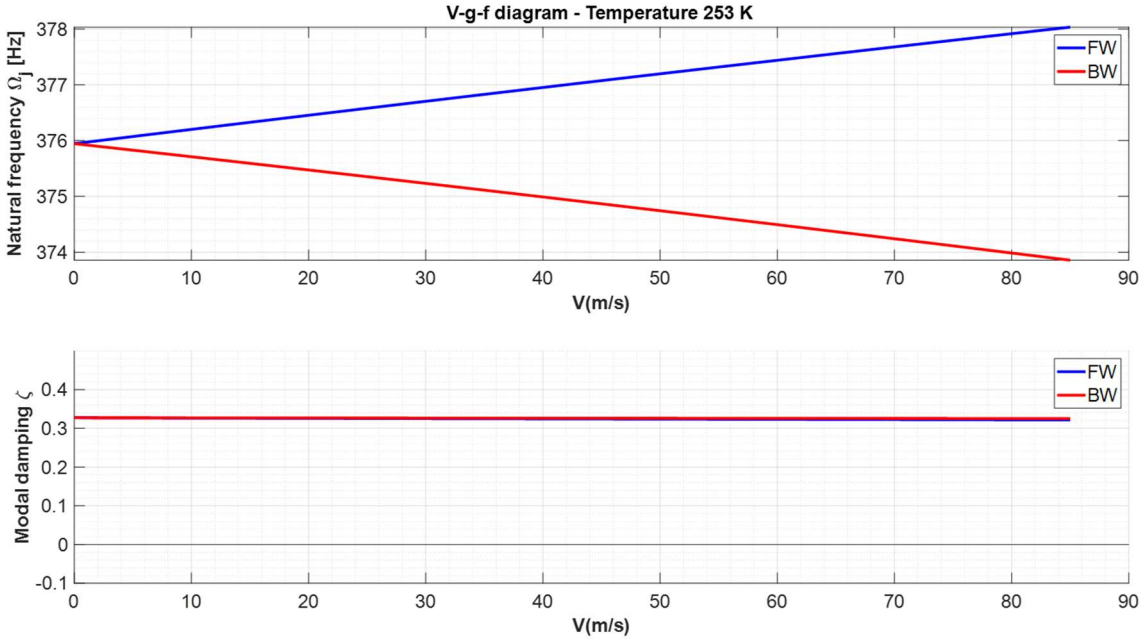


Figure 7. V-g-f diagram for the system with addition of VEM, for T = 253 K.

Third case was evaluated for higher temperature (333 K). Values for modal damping decrease, but still stable for the velocity range (Figure 8).

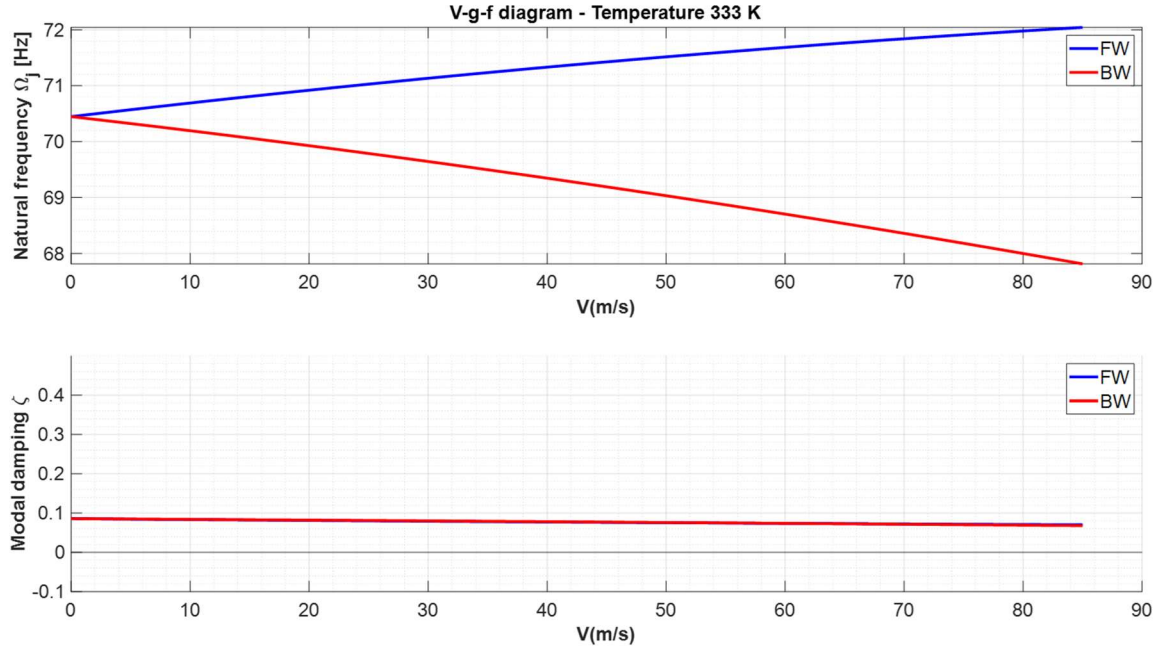


Figure 8. V-g-f diagram for the system with addition of VEM, for T = 333 K.

4 Conclusions

In the optimal project of viscoelastic supports for whirl-flutter control, it is important to consider system parameters, and work temperature, which must be carefully evaluated when using this type of solution. In numerical studies viscoelastic materials have shown to be a possible solution to stabilize systems subjected to whirl-flutter. Future work tends to project and fabricate experiments to validate the obtained results.

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