Materials Research Proceedings 73 (2026) 142-146 https://doi.org/10.21741/9781644904459-28

Innovative Viscous Damper Design for Stay Cable Control: The Hysteretic Maxwell Model

Selsebil SOLTANE[1,a *], Othman BEN MEKKI[1,b]

[1]Université de Tunis El Manar, Ecole Nationale d'Ingénieurs de Tunis, LGC, Tunisia

[a]selsebil.soltane@enit.utm.tn, [b]othman.benmekki@enit.utm.tn

Keywords: Viscous Damper, Hysteretic Maxwell Model, Stay Cable Vibration Control

Abstract. This study develops an optimized Hysteretic Maxwell model to capture the nonlinear behavior of viscous dampers while maintaining a limited number of parameters. Following experimental calibration across various frequencies, the model's performance is validated through numerical simulations of the longest stay cable on the Rades-La Goulette bridge. Results show that the proposed model significantly outperforms the standard Maxwell formulation in mitigating both free and forced vibrations, directly enhancing aerodynamic stability. Furthermore, a comparative assessment demonstrates that this optimized viscous damper provides superior modal damping compared to magnetorheological (MR) systems, offering a highly efficient alternative that bypasses the need for complex external power supplies.

Introduction

While high-performance materials allow for flexible designs, they make long stay cables vulnerable to vibrations [1], requiring diverse mitigation strategies. Among these, viscous dampers are widely used; however, their actual performance often deviates from standard linear predictions due to inherent nonlinearities and hysteresis [2].

To capture these dynamics, various mathematical frameworks have been developed. The Maxwell model (spring and dashpot in series) and the Kelvin-Voigt model (in parallel) are widely used to represent elastic and dissipative components [3]. However, these classical models often fail to account for the frequency-dependent behavior of damper polymers. While fractional derivative models offer high precision in describing such frequency dependency [4], their mathematical complexity often limits practical application. Consequently, the simplified Maxwell model incorporating a damping exponent has emerged as a highly efficient alternative, providing an accurate depiction of nonlinear behavior and superior displacement reduction compared to linear models [5].

Building on this framework, the present study proposes a parametric nonlinear model based on the simplified Maxwell approach. The model parameters are identified using experimental data fitting across three characteristic frequencies [6]. The effectiveness of the proposed model is then validated by simulating the free and forced vibration responses of a stay cable from the Rades-La Goulette bridge. Finally, a comprehensive sensitivity analysis evaluates the influence of key parameters on energy dissipation and compares the results with magnetorheological (MR) damper performances.

The proposed model for viscous damper

The simplified Maxwell model captures both the linear and nonlinear behaviors of a viscous damper using the following equation:

$$F_d^M = C\,\mathrm{sgn}(v_d)\,|v_d|^a \quad (0 < a \leq 1) \tag{1}$$

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A viscous damper's force F_d^M depends on piston velocity v_d, a damping coefficient C, and a damping exponent a. While a = 1 defines linear behavior, other values dictate nonlinear behavior (Fig. 1), prompting a mathematical transformation to fully model the damper's hysteretic loop across piston velocity $v_d \in [-v_h, v_h]$ by:

$$F_d^{HM} = \begin{cases} C\ \mathrm{sgn}(v_d - v_0)\left[1 - \exp\left(-\mathrm{sgn}(v_d - v_0)\frac{v_d - v_0}{n}\right)\right]|(v_d - v_0)|^a & \text{for } \dot{v}_d < 0 \\ C\ \mathrm{sgn}(v_d + v_0)\left[1 - \exp\left(-\mathrm{sgn}(v_d + v_0)\frac{v_d + v_0}{n}\right)\right]|(v_d + v_0)|^a & \text{for } \dot{v}_d > 0 \end{cases} \quad (2)$$

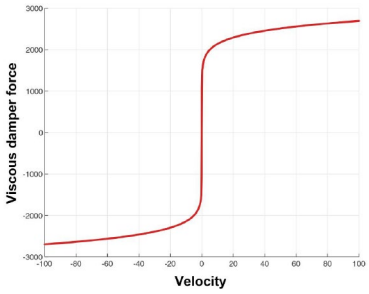


Fig. 1: Simplified Maxwell model.

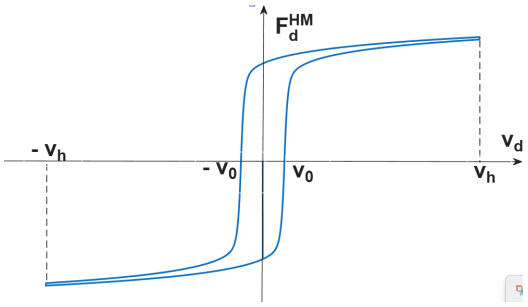


Fig. 2: The hysteretic Maxwell model.

This model uses three key velocity-dimensioned parameters: a scale factor v_0 that determines the overall width of the loop, the maximum reached piston velocity v_h, and a regularization parameter n that dictates the exponential growth of the damping force. The resulting hysteresis loop (Fig. 2) is characterized by an upper curve, which represents the damping force as the piston's velocity decreases, and a lower curve, which shows the force as the velocity increases.

Experimental identification of model parameters

The five parameters (C, v_0, v_h, n, a) of the Hysteretic Maxwell model (Table 1) are identified via least-squares optimization using experimental data from a rotatable-blade viscous damper [6]. Simulated responses under various sinusoidal excitations (frequencies of 0.6–1.8 Hz, amplitudes of 2–15 mm) closely match the experiments, validating the model's accuracy (Fig. 3).

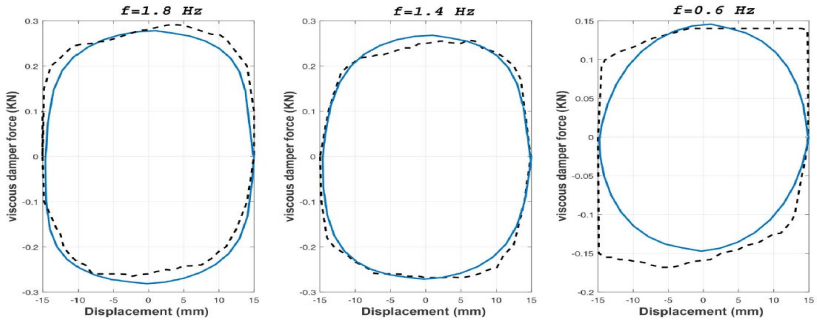


Fig. 3: Validation of model predictions (solid line) against experimental measurements (dashed line).

Table 1. Calibrated parameters for the Hysteretic Maxwell

f	C [N.s/m]	v_0 [m/s]	n [m/s]	a	v_h [m/s]
1.8	1000	0.05	0.01	0.5	0.22
1.4	970	0.05	0.02	0.5	0.22
0.6	550	0.05	0.1	0.3	0.22

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Vibration Control of a Stay Cable Using a Viscous Damper

To analyze the dynamics of the inclined stay cable equipped with a viscous damper (Fig. 4), the system's motion is simplified into a single-degree-of-freedom model using the Galerkin method. By focusing specifically on the fundamental mode with the sinusoidal shape function $\phi_i = \sin\left(\frac{i\,\pi\,x}{L}\right)$, the partial differential equation governing the transverse vibrations is reduced to the following discretized ordinary differential equation:

$$m_1\,\ddot{\alpha}_1(t) + \left(k_1 + \lambda^2 m_1\right)\alpha_1(t) = F_1 - F_d(t)\,\phi_1(x_d) \tag{3}$$

Where the system and modal parameters are defined as follows: $\alpha_1(t)$: non-dimensional modal participation factor, $m_1 = m_c\frac{L}{2}$: Equivalent modal mass (m_c: mass per unit length), L: cable length, $k_1 = \frac{T\pi^2}{2L}$: Equivalent modal stiffness (T: static tension), $\lambda^2 = \frac{E_c\,A_c}{L}\left(\frac{m_c\,g\cos\theta}{T}\right)^2$: cable characteristic parameter (E_c: Young's modulus,A_c: the cross-sectional area, , and θ :inclination angle), $F_1 = \int_0^L F_{ext,y}\,\phi_1(x)\,dx$: Generalized modal force ($F_{ext,y}$: external transverse forces), $F_d(t)$: External control force provided by the viscous damper, as defined in Eq.2 , $\phi_1(x_d) = \sin\left(\frac{\pi x_d}{L}\right)$: fundamental mode shape evaluated at the damper's location x_d. The damper's efficacy is evaluated on the Rades-La Goulette bridge's longest cable, S16 (properties in Table 2).

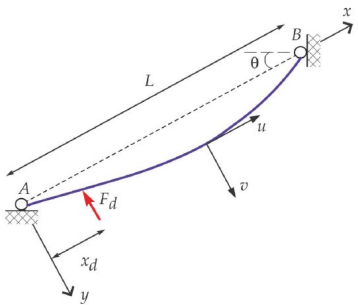


Fig. 4: Stay cable and viscous damper system.

Table 2. Properties of stay cable (S16)

L [m]	θ [°]	T [KN]	E_c [*Gpa*]	A_c [cm^2]	m_c [Kg/m]
55.4	16.5	4313.5	190	55.5	44

Numerical Results

Fig. 5 compares the first-mode dynamic responses at 1.8 Hz. The proposed Hysteretic Maxwell model outperforms the standard version by significantly accelerating vibration decay and reducing peak amplitudes to approximately 74.3%. These numerical results for free vibrations extend to forced excitations. Specifically, for an external force $F_{ext,y}(t) = 1.5\cos\left(\sqrt{\frac{k_1}{m_1}}\,t\right)$ the damper's hysteresis significantly enhances the cable's (S16) damping capacity. Detailed graphical evidence of this forced response was previously established in [7].

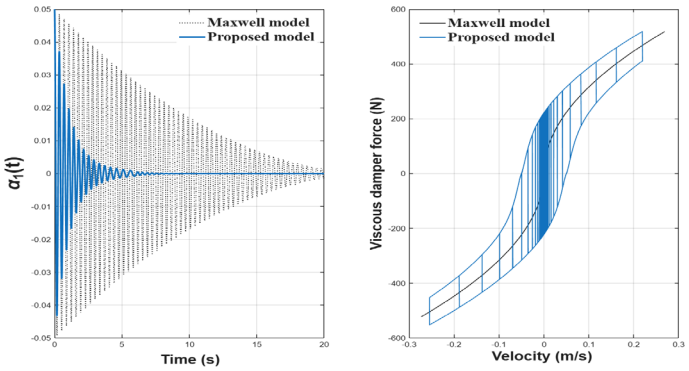
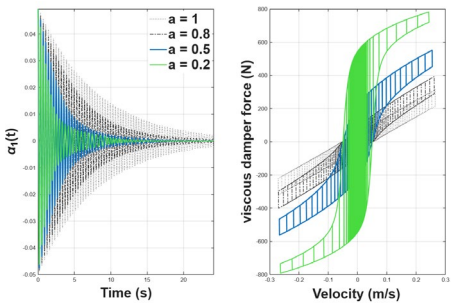
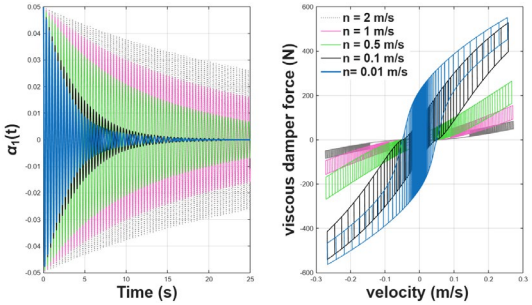


Fig. 5: Free vibration control comparison: standard Maxwell vs. proposed model.

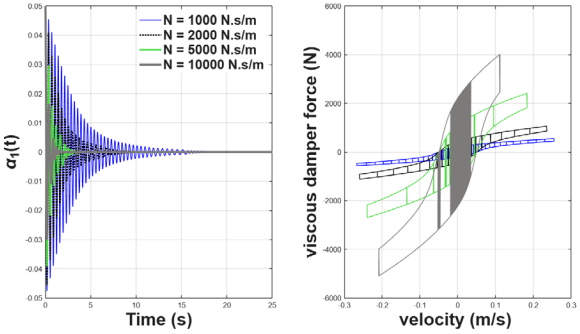
Parametric analysis (Fig. 6) shows that optimizing a, n, and C to expand the hysteresis loop directly maximizes energy dissipation. Notably, increasing the damping coefficient can reduce the maximum vibration amplitude by 89.5% within the first five seconds.



(a) n = 0.01 m/s, v_0= 0.05 m/s, C = 1000 N.s/m



(b) a = 0.5, v_0= 0.05m/s, C = 1000 N.s/m



(c) a = 0.5, v_0= 0.05 m/s, n = 0.01 m/s

Fig. 6: Hysteretic parameter effects on the first-mode vibration of the stay cable.

Performance is compared against a Magneto-rheological (MR) damper, characterized by the standard Bingham model. The optimized Hysteretic Maxwell model outperforms the MR damper, achieving faster decay and a 70% amplitude reduction, as illustrated by the comparative curves provided in [7].

Conclusions

In summary, this study develops and optimizes a hysteretic Maxwell model for viscous dampers to enhance the aerodynamic stability of cable-stayed bridges. Applied to the Rades-La Goulette bridge, this model significantly outperforms the simplified Maxwell model in mitigating both free and forced vibrations. Furthermore, a comparative analysis demonstrates that this viscous damper

offers superior performance compared to MR dampe. This highlights the viscous damper's practical superiority: delivering enhanced energy dissipation without an external power source.

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