Damping stay-cable transverse vibration using shape memory alloys and magneto rheological dampers

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Abstract. Passive dampers consume no external energy and they are able to stabilize a flexible structure. Another advantage of such devices is the limited maintenance required. Examples of passive devices include shape memory alloys (SMA) and magneto rheological (MR) dampers. This paper addresses the damping of stay cables by using super-elastic shape memory alloys (SMA). The model of a cable-damper is presented. The responses of stay cable model with/without one SMA damper free or subjected to harmonic excitation are numerically investigated. The effectiveness of the use of SMA dampers and their capability to reduce the cable vibrations are demonstrated. Finally, a numerical comparison between the performances of a SMA damper and a magneto rheological damper (MR) is provided.

Keywords: Stay cable, passive control, SMA damper, MR damper.

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1 Introduction

Stay cables are the basic structural components of stayed-cable bridges. Owing to their large flexibility, relatively small mass and extremely low damping, stay cables frequently exhibit large-amplitude vibrations under the action of wind (Hikami and Shiraishi, 1988), wind-rain (Hikami and Shiraishi, 1988; Peil and Dreyer, 2006) and support motion (Sun et al, 2003; Yamaguchi and Fujino, 1998). The stay cable vibrations may have extremely large amplitudes and can lead to the fatigue of the cables, with a consequent reduction of their service life. Therefore, the mitigation of the dynamic response induced by environmental loads is of vital importance in terms of safety and serviceability. Various mitigation measures have been developed and implemented around the world: treating the cable surface with different techniques to improve the aerodynamic properties, adding crossing ties or providing mechanical dampers (Yamaguchi and Fujino, 1998; Ni et al, 2000; Johnson et al, 2003).

Mechanical dampers are widely used since they provide a significant damping force and present an easy replacement. According to their energy consumption, they are classified as passive, active, and semi-active. Passive dampers consume no external energy and, in general, have low maintenance requirements. An example of passive devices is the magneto rheological (MR) damper (Wu and Cai, 2005; Duan et al, 2003; Christenson et al, 2002).

Another candidate is the superelastic Shape Memory Alloy (SMA) damper, which has the advantages of large damping capacity, self-centering ability, high fatigue and corrosion strength, and high damping capacity, namely, in the vibration control of stay cables subjected to wind and wind/rain loads (Auricchio et al, 1996; Humbeeck and Kustov, 2005; Saadat et al, 2001). The SMA shows an interesting behavior not present in traditionally material, the superelasticity, which is the capability of undergoing large inelastic deformations and of recovering their shape by releasing applied loads (?) without residual strain (Song et al, 2006).

To explore the potentials of SMA-based dissipators in passive structure control, in this paper we study the damping the of stay cables vibrations in a cable-stayed bridge, by using a SMA energy dissipation device with superelastic hysteresis. The first part of the paper presents the Galerkin approximation of the general equations of a stay cable subjected to dynamical loading and controlled by a damper, SMA or MR, in the transverse direction. The second part focuses on the comparison between the MR and the SMA energy dissipation devices to control the cable's free and harmonic transverse vibrations.

2 Dynamic equation of an inclined stay cable

At equilibrium position, we consider a uniform stay cable of length L suspended between two supports A and B of different heights. In Fig. 1, the A-B line is inclined of an angle θ with respect to the horizontal. The cable is subjected to a transverse concentrated force f_c due to an external damper, applied at the point x_c . The cable is assumed to have a uniform cross-section area A along its length.

Under the assumptions of small deflections and of linear elastic constitutive behavior, the Galerkin approximation based on the free modes of the structure provides the following expressions of the non-dimensional modal participation factors $\alpha_i(t)$ (Soltane, 2009)

$$m_i\ddot{\alpha}_i(t)+\left(k_i+\frac{EA}{L}\frac{m^2g^2\cos^2\theta}{T^2}m_i\right)\alpha_i(t)=F_{yi}-f_c(t)\varphi_i(x_c),\quad i=1......N. \tag{1}$$

Here T is the static cable tension, m the mass of the cable per unit length, g the acceleration due to gravity, and E is the Young modulus. The modal shape functions φ_i are assumed to satisfy the geometric boundary conditions $\varphi_i(A)=\varphi_i(B)=0$.

In view of the sinusoidal form $\varphi_i(x)=\sin\left(\frac{i\pi x}{L}\right)$ of the shape functions, the modal masses, the modal rigidities and the external excitation take the forms

$$m_i=m\frac{L}{2},\quad k_i=\frac{T\pi^2i^2}{2L},\quad F_{yi}=\int_0^L F_y(x,t)\sin\left(\frac{i\pi x}{L}\right)dx\ .$$

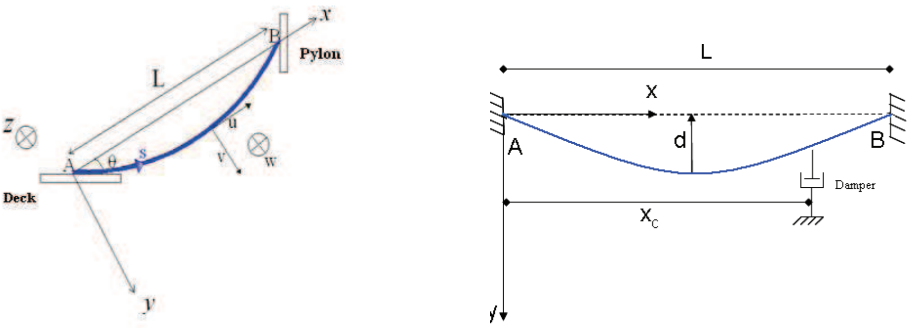

Figure.1. In-plane inclined stay cable attached with one transverse damper

3 Hysteretic model for the SMA damper

To describe the superelastic behaviour of the SMA damper, we consider the one dimensional model proposed by (Auricchio and Sacco, 1997). The stress strain curve shown in Figure 2 is obtained fron the following properties of the SMA element: $E = 50000 MPa$, $\sigma_s^{AS} = 500 MPa$, $\sigma_f^{AS} = 600\ MPa$, $\sigma_s^{SA} = 250\ MPa$, $\sigma_f^{SA} = 200\ MPa$, $\varepsilon_L = 8\,\%$.

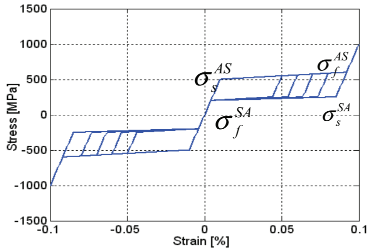

Figure.2. Hysteresis loops in the one-dimensional model

4 Mechanical model of the MR damper

The MR damper is schematized by the viscoplastic Bingham rheological model, which consists of a Coulomb frictional element placed parallel with a viscous damper c_0 , see Figure 3. The force f_c generated by this device is

$$f_c = f_y sign(\dot{x}) + c_0 \dot{x}, \tag{2}$$

where f_y is the Coulomb friction force and x is the piston displacement.

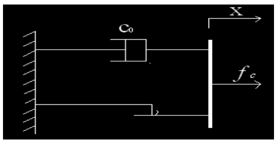

Figure.3. Rheological Bingham Model

Figure 4 illustrates the force vs. velocity and force vs. displacement for f_y= 0.62 *N*, c_0 = 1 *Ns/m* at the voltage 0 V (Ni *et* al, 2000). The MR damper primarily exhibits the characteristics of a viscous device: the force-displacement relationship is approximately elliptical and from the force vs. velocity it is observed the rigid-viscoplastic behavior.

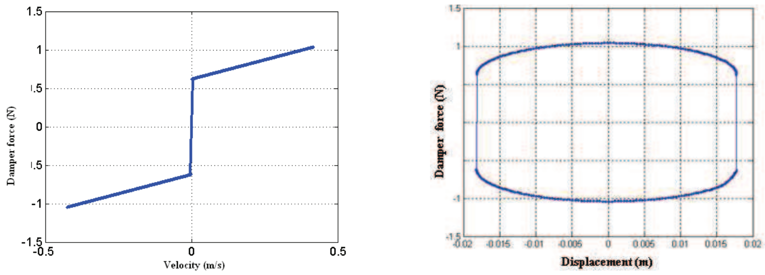

Figure.4. MR damper: force versus velocity (left), and force versus displacement (right)

5 Comparison between the performances of the SMA and the MR dampers

To investigate the performance of the SMA damper parameters and its location on the damping capability and control efficiency of SMA dampers, the stay cable model, which was built and which will be studied in the Civil Engineering Laboratory of the University of Tunis (ENIT), was used to carry out the investigation in this study. We proceed with solving the equation of motion (1) of the system stay cable/SMA in the first mode. Due to its hysteretic behaviour, the SMA damper force $f_c(t)$ is coupled and cannot be solved independently. Therefore, a Newmark numerical method programmed in MATLAB is used to compute the dynamic response of the cable.

The stay cable model used to carry out this investigation has the geometrical and mechanical proprieties: m = 0.55Kgm^{-1}, L = 4m, θ = 27.5°, E = 0.910^{11}N/m^2.

The considered SMA damper with radius R_{SMA} = *0.1mm* and length L_{SMA} = *0.2m* was installed on the cable at location x_c= *0.1L* from the left end. These parameters are optimized in reference (soltane, 2009).

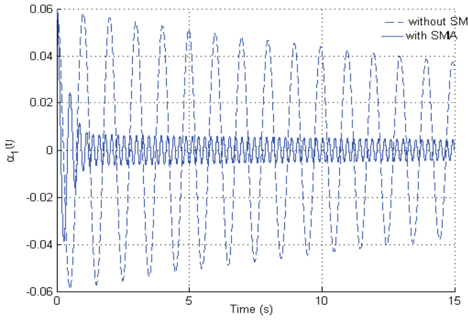

Figure .5. Effect of SMA damper on the first mode response of free vibrations of the stay cable

It can be seen from Figure 5 that the SMA damper accomplishes a significant response reduction, thanks to hysteretic performance, as compared to the case without damper. It can be also observed that the SMA reduces the vibration amplitude very quickly. However, it can be noted from this simulation that the SMA damper is not able to control the small vibration because the SMA deformation is smaller than 1%: the SMA has purely an elastic behavior and the hysteresis is not yet built. Consequently, the SMA model chosen does not damp the small vibrations of the cable. However, this is not a real disadvantage in practice since one focuses on the large vibrations for cable-stayed bridges.

Figure 6 illustrates the response of the cable controlled by MR damper and by SMA damper. It can be seen that the SMA damps significantly better that the MR damper.

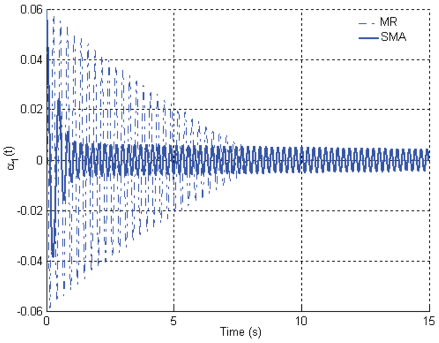

Figure.6. Comparison between SMA damper and MR damper to control the stay cable free vibrations

In order to compare the performance of the two dampers, when the cable is subjected to an external force, we consider a harmonic excitation on the cable. The associated Fourier spectrum of the cable controlled by the two dampers separately at the position x_c=0.1L is shown in Figure 7. SMA damper is able to damp the harmonic excitation much better than MR one. It is worth nothing that the peak value of the displacement is located at 2 Hz, which is the cable natural frequency.

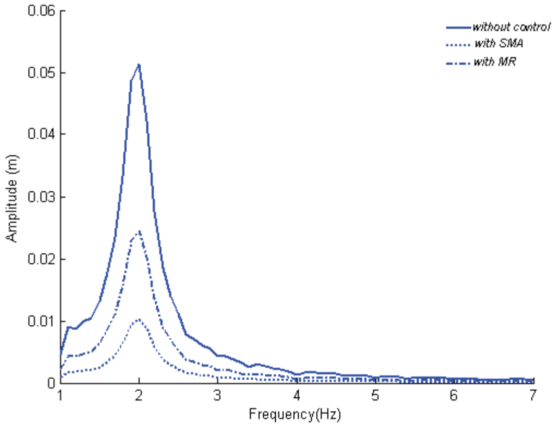

Figure.7. FFT of displacement response of the cable with SMA and MR damper.

4 Conclusions and perspectives

Mechanical dampers are very useful to reduce vibrations. Taking a typical short cable as an example, the numerical investigations show that both MR and SMA dampers are efficient in vibration reduction. Comparison shows that, in mitigating excessive vibrations, either caused by wind or a combination of wind and rain or by the motion of supported structures, the SMA damper is more effective than the MR damper operating in the passive mode. Due to its large energy dissipation ability, the SMA damper can be a good energy absorber for structural vibrations. Knowing that the capacity of energy dissipation is closely related to the SMA damper parameters, it is useful to optimize the feature, the section, the length and the position of the SMA dampers to control several modes passively.

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