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Control of vertical oscillations of a cable by a piecewise linear absorber

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ABSTRACT

Design tools for fabrication of nonlinear (nonsmooth) passive absorbers for controlling vertical modes of taut cables are presented. The design takes into account the effects of the gravity and activation of the nonlinear absorber. In detail, the slow invariant manifold of the system is tuned which lead to design of the absorber. The paper is followed by several numerical and experimental results showing the efficiency of such nonsmooth absorbers in controlling targeted vertical modes of cables.

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1. Introduction

Design procedure for mechanical and structural systems seeks for their acceptable and controlled behaviours against dynamic loads. The structural control process is globally spread from active to passive systems. In the passive control procedure, the vibratory energy of main equipments are localized/transferred to secondary systems/elements. These control systems are divided into linear and nonlinear categories. The Tuned Mass Damper (TMD) [1] is a linear passive control solution which can be tuned at the exact frequency of main oscillators for reducing their vibratory energies in acceptable levels. However, the TMD (apart being heavy) is very efficient for a narrow frequency width and it creates additional resonances for the overall system [2]. Stockbridge dampers [3] are examples of such systems which are endowed to reduced vortex induced vibrations in transmission lines [4,5]. Roberson [6] considered an absorber system which its restoring forcing function (F) was sum of linear and cubic parts i.e. $F(\alpha) = \lambda_1\alpha + \lambda_2\alpha^3$. Their design criterion was to place the working frequencies inside the suppression band. They proved that the suppression band of the nonlinear absorber system is wider with respect to the corresponding linear one [6]. Many different types of nonlinear absorber systems have been developed during past decades. One of them is named as Nonlinear Energy Sink (NES) [7,8] where its restoring forcing term is purely nonlinear having "no linear" part which in its early developments possessed purely cubic nonlinear term [9]. Since then, different type of such nonlinear devices have been developed, such as vibro-impact [10–12], piecewise linear [13–15] and absorbers with hysteresis and geometrical nonlinear-

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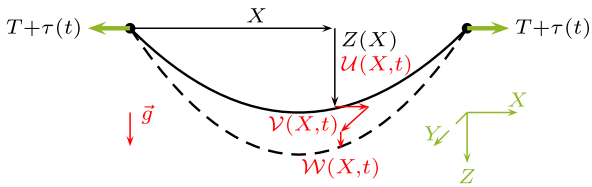

Fig. 1. Schematic of the cable under study from Irvine model [31].

ities [16]. The efficiency of such nonlinear absorbers in controlling main structural systems and equipments has been proved experimentally as well [17–21]. Vibration mitigation of cables is of highly interest due to their extreme nonlinear behaviours and their applications in different systems such as bridges and transport systems. The vibration control of a horizontal mode of the stay-cable via a NES with cubic nonlinearity is studied by Weiss et al. [22]. There are other passive control systems for mitigation of vibration of cables which use other technologies. As representative examples we can list some of them as it follows: Tirelli and Anthoine [23] developed a device namely state switched inducer which is composed of a linear spring and a unilateral contact system connected in series [24]. Egger and Caracoglia [25] did a numerical and experimental investigations on control of the stay-cable via a resilient damper model [26] consisted of multiple mass-element pendulum damper. Then, Egger et al. [27] considered other models of resilient dampers including multiple mass-particle and multiple mass-element string dampers. Analytical and numerical studies of the passive control of a stay-cable via a nonlinear system with a general odd nonlinearity of the restoring forcing function is studied by Izzi et al. [28]. After derivation of governing system equations, they adopted and energy-based approach where the nonlinear law of the absorber has been replaced by a linear equivalent law leading to definitions of universal design curves.

This paper deals with passive control of a vertical mode of a cable by a nonsmooth absorber taking in the gravitational field. Design tools for this goal are presented and an absorber is fabricated and mounted on a cable for controlling the oscillations of its first vertical mode. The paper is followed by obtained numerical experimental results. Organisation of the paper is as it follows: Mathematical modelling of the cable and identification of its mechanical properties are presented in Section 2. In Section 3 theoretical study of the compound system, i.e. the cable and the coupled nonsmooth absorber is presented. In detail, the system is project on one of its modes which should be controlled. The slow invariant manifold of the system is detected and a design procedure for tuning parameters of the nonlinear absorber is presented for controlling an indented mode of the cable. In Section 4 experimental results on the passive control of a vertical mode of the cable by the designed absorber are presented and discussed. Finally, the paper is concluded in Section 5.

2. Cable modelling

The first step of this work is using an appropriate cable model (e.g. as shown in Ref. [29]) which describes its real behaviours [30]. This model will permit to represent the cable under study by a single degree-of-freedom (dof) system (the dof to be controlled) for preparing easy-to-use design tools of the nonlinear vibration absorber in the next sections. After choosing and explaining a theoretical model, a modal analysis is performed on the real cable to fit its mechanical parameters.

2.1. Theoretical cable model

To theoretically describe the cable response, the Irvine cable model [31] is used, see Fig. 1. The two reasons of this choice is the simplicity of this linear model and its possibility to describe cables with small sag (if necessary for future applications). The studied case is a cable fixed between two points at the same level, separated by a length L while the length of the cable is $L' > L$. With the hypothesis of a uniform cable, m_l is it mass per unit length. The other parameters are the Young modulus E and the section area A of the cable. This dynamic model describes small displacements around the approximate static catenary profile of cable with small sag ratio, less than $\frac{1}{8}$. The catenary profile is obtained with hypothesis of inextensibility of the cable and absence of flexural rigidity under gravitational field $\vec{g}$. This profile is given by a function $X \rightarrow Z(X)$, where X is the horizontal abscissa and $Z(X)$ is the vertical position of the cable.

As summarised in Fig. 1, at any time t the point $(X, 0, Z(X))$ exhibits small displacements $(\mathcal{U}(X,t), \mathcal{V}(X,t)\, \mathcal{W}(X,t))$ so that:

$$\begin{aligned} \mathcal{X}(X,t) &= X + \mathcal{U}(X,t) \\ \mathcal{Y}(X,t) &= \mathcal{V}(X,t) \\ \mathcal{Z}(X,t) &= Z(X) + \mathcal{W}(X,t) \end{aligned} \tag{1}$$

These small displacements create an additional cable tension $\tau(t)$ on anchor described by:

$$\mathcal{T}(t) = T + \tau(t) \tag{2}$$

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