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On the assessment of aeolian vibrations of damped electrical conductors

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Abstract. Aeolian vibrations are one of the main sources of wear damage and fatigue failures of overhead conductors and guard wires. Stockbridge dampers are often installed along the spans of electrical transmission lines to mitigate aeolian vibrations. The dynamic response of Stockbridge dampers is typically affected by a significant degree of variability, mainly due to the manufacturing process, which determines uncertainties in the identification of the mechanical parameters of a damper model. The present paper discusses the impact of these uncertainties on the prediction of the severity of aeolian vibrations within the framework of Monte Carlo simulations.

Keywords: Aeolian vibrations, Electrical Transmission Lines, Stockbridge dampers, Energy Balance Method

1 Introduction

Conductors and guard wires of overhead transmission lines are very sensitive to vortex-induced vibrations. Such phenomenon, also known as “aeolian vibrations” in the community of transmission line engineers, has been since long recognized as a major cause of wear damage and fatigue failures of both conductors and other line components [1].

In order to mitigate the severity of aeolian vibrations, Stockbridge dampers are typically installed along the spans of overhead transmission lines. These dampers are characterized by a markedly nonlinear dynamic behavior and a significant variability of their mechanical properties, Several modeling approaches have been recently proposed in the literature to deal with nonlinearities of the Stockbridge dampers response, e.g. [2-4]. Most of these formulations are computationally expensive and require identification of a significant number of parameters from experiments. A simpler, yet effective, approach was first proposed by Pivovarov and Vinogradov [5] and later restated and extended by Foti et al. [6, 7]. The Stockbridge damper is described through a reduced-order dynamic model based on an application of the Bouc-Wen phenomenological hysteretic model. The model developed in [6, 7] requires identification of a small number of parameters from experimental tests and has been successfully used in [7], along with an implementation of the Energy Balance Method (EBM) [1], to assess the severity of aeolian vibrations of a reference overhead transmission line span.

The present paper focuses on the effect of the uncertainties related to the damper model parameters on the predicted values of aeolian vibrations and their possible impact on the efficiency of the damping device.

2 The Stockbridge damper model

Stockbridge dampers are made of a short stretch of cable, also known as messenger cable, with two counterweights attached at its free ends. The messenger cable is then connected to the conductors or guard wires of the electrical transmission (primary cable, in the following) line through a metallic rigid clamp (see e.g. [2] for further details). The clamp subdivide the messenger cable in two branches. If the two branches of the messenger cable have the same length and the two counterweights are identical, the Stockbridge damper is said to be symmetric; asymmetric otherwise.

Whenever the clamp is set in motion, the two branches of the messenger cable behave as two uncoupled cantilevers with lumped translational and rotational masses attached to their end sections. By neglecting the inertia of the messenger cable, whose mass is much smaller than the mass of the counterweights, and focusing on the special case of symmetric Stockbridge dampers to keep the presentation as simple as possible, the force F_d exerted by the damper on the primary cable can be expressed as:

$$F_d = (2m_d + m_c)\, v_c{}' + 2m_d\, u_1{}'' - 2m_d\, e\, \mathrm{u}_2{}'' \tag{1}$$

where: m_c is the mass of the clamp; m_d and e are, respectively, the mass of the counterweight and the eccentricity of its centroid with respect to the end section of the messenger cable; v_c is the vertical velocity of the clamp; u_1 and u_2 are, respectively, the relative vertical displacement of the counterweight with respect to the clamp and its rotation; a prime denotes derivation with respect to the time (cf. [2, 7]).

The dynamics of the counterweights, then, is approximately described through the following decoupled equations of motion:

$$u_i{}'' + F_i/M_i = Q_i/M_i, \quad i = 1, 2 \tag{2}$$

where: M_i is the generalized mass associated to the i-th degree-of-freedom ($M_1 = m_d$, $M_2 = I + e^2 m_d$ where I is the centroidal mass moment of inertia of the counterweight); Q_i is i-th generalized external force due to the motion of the clamp ($Q_1 = -m_d\, v_c{}'$, $Q_2 =$

$e\, m_d\, v_c'$); and F_i is the i-th generalized restoring force exerted by the messenger cable on the counterweight. In order to model the hysteretic behavior of the messenger cable, the restoring forces are modeled through an application of the phenomenological Bouc-Wen model:

$$F_i / M_i = \alpha_i\, \Omega^2_{0,i} + (1\text{-}\alpha_i)\, \Omega^2_{0,i}\, u_{0,i}\, z_i \qquad (3)$$

$$u_{0,i}\, z_i = u_i' - |u_i'|\, z_i \qquad (4)$$

where: z_i is a non-dimensional hysteretic variable (with values in the range [-1,1]); $\Omega_{0,i}$, α_i and $u_{0,i}$ are the parameters of the model. The proposed damper model, hence, is characterized by a total number of six unknown parameters (three for each degree-of-freedom of the counterweight).

3 The Energy Balance Method

The technical approach to the assessment of aeolian vibrations of electrical transmission lines relies on an application of the Energy Balance Method (EBM). Focusing on a reference span of the line between two support towers, the conductor or guard wire is modeled as a tensioned cable restrained by rigid supports and equipped with one of more dampers along its length. In the following, the attention will be focused on the particular case of a cable with length L and equipped with a single Stockbridge damper, attached at a distance x_d<<L from one of the supports. Generalization to more complex case is, however, relatively straightforward (see [8]).

The EBM is based on the assumption of mono-modal steady state vibrations. For each natural frequency (f_n) of the coupled cable+damper system, the single-peak antinode amplitude of vibration (A_n) is obtained by imposing the balance between the average power per vibration cycle imparted by the wind to the vibrating cable (P_w), the one dissipated within the cable (cable self-damping, P_c) and that dissipated within the damper (P_d). This energy balance, gives a non-linear algebraic equation that can be solved, at each vibration frequency f_n, to get the antinode vibration amplitude A_n:

$$P_w(f_n, A_n) - P_c(f_n, A_n) - P_d(f_n, A_n) = 0 \quad \rightarrow \quad A_n = A_n(f_n) \qquad (5)$$

In the present work, without loss of generality, the wind input power and the cable self damping are calculated, respectively, through the empirical equation recommended in [9] and the theoretical equation derived in [10] under the assumption of micro-slip between contacting wires of the vibrating cable.

The power dissipated within the damper can be calculated as:

$$P_d(f_n, A_n) = ½\, \mathrm{Re}[Z_d]\, v_c^2 \qquad (6)$$

where Re[Z_d] is the real part of the impedance function of the damper. By adopting the classic taut string model to describe the vibrations of the cable, v_c can be easily related to the vibration frequency (f_n) and antinode vibration amplitude (A_n):

$$v_c = 2\pi f_n A_n \, |\sin[(2\pi f_n)/\Omega_1 \cdot (1 - x_d/L)]| \tag{7}$$

where Ω_1 is the fundamental circular frequency of vibration of the bare cable.

The impedance function of the damper can be experimentally determined by performing a sweep test with constant clamp velocity on an electrodynamic shaker. As an alternative, if the mechanical parameters of the damper model presented in Section 2 are known, the impedance function can be calculated by performing a numerical sweep test [7].

4 Application example

The formulation presented in Section 2 and 3 is herein applied to the benchmark span already considered in [7]. The cable is a ACSR Bersfort 48/7 conductor (diameter D = 35.6 mm, mass per unit of length 2.375 kg/m, Rated Tensile Strength RTS =180 kN) strung at the 40% of its RTS. The length of the cable is L=450 m and a symmetric Stockbridge damper is attached at a distance x_d=0.01L from one of the supports. The geometric and mechanical properties of the damper are fully reported in [7]. The parameters of the damper model were identified in [7] to match the impedance functions experimentally determined in [11] and read: $\Omega_{0,1}$ = 96.7 rad/s, $\Omega_{0,2}$ = 319 rad/s, $\alpha_1 = \alpha_2$ = 0.25, $u_{0,1} = 2 \cdot 10^{-3}$ m, $u_{0,2} = 7.5 \cdot 10^{-3}$ rad. These values will be referred to, in the following, as the nominal values of the model.

Preliminary analyses have shown that, for the application herein considered, the dependence of the damper impedance function on the clamp velocity has a minor impact on the predicted values of the aeolian vibration amplitude (cf. [7]). Based on this remark, the impedance function of the damper has been pragmatically evaluated for a single reference value of the clamp velocity: v_c=100 mm/s.

Fig. 1(a) and (b), respectively, show the real part of the impedance function of the damper calculated for the nominal values of the parameters $\Omega_{0,i}$, α_i and $u_{0,i}$ (i=1, 2) and the non-dimensional vibration amplitude predicted by the application of the EBM. The vibration amplitudes calculated for the bare cable model are also reported in Fig. 1(b) for comparison purposes. As it can be clearly appreciated from Fig. 1, the damper is mostly effective in a range of frequencies centered around its first resonant frequency (which is associated to the translational degree of freedom u_1).

In order to get a first insight on the effect of the uncertainties related to the damper parameters, Monte Carlo simulations have been performed by considering each parameter as a random Gaussian variable with mean value equal to the nominal one and a coefficient of variation equal to 10%. The latter value is representative of the variability of the Stockbridge dynamic properties reported in the literature (cf. [9]).

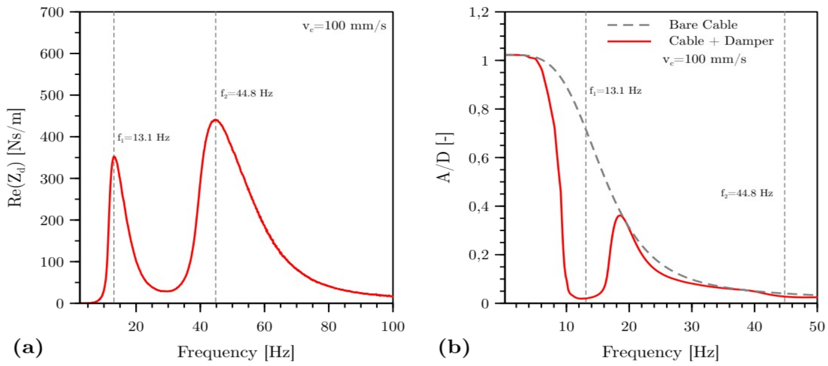

Fig. 1. Response evaluated by considering the nominal values of the damper mechanical parameters. (a) Real part of the impedance function; (b) Non-dimensional single-peak antinode vibration amplitude.

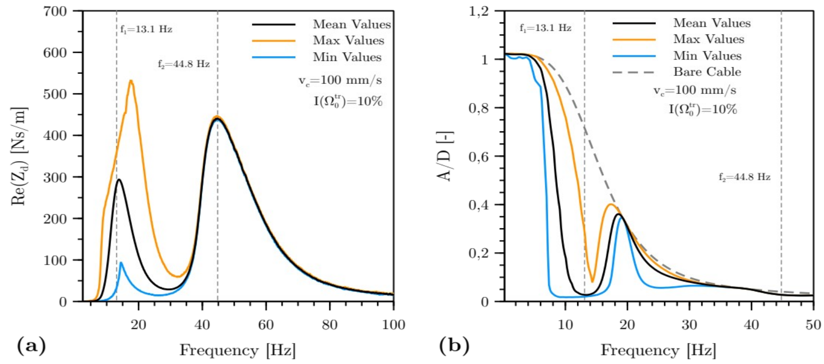

Fig. 2. Effect of a random variation of the parameter $\Omega_{0,1}$. (a) Real part of the impedance function; (b) Non-dimensional single-peak antinode vibration amplitude.

Numerical simulations have been performed by considering the random variation of a single parameter at time (setting the others at their nominal values). For each random variable, a population of 100 individual has been sampled. For each set of parameters, the impedance function of the damper has been numerically evaluated and the EBM applied to estimate the vibration amplitude.

The simulations have shown that the randomness of the parameters α_i and $u_{0,i}$ (i=1, 2) have only a very small impact on the computed vibration amplitudes, while the randomness of the parameter $\Omega_{0,2}$ affects aeolian vibrations only for frequencies higher than about 20 Hz, where the damper is only marginally effective.

Uncertainties on the parameter $\Omega_{0,1}$, on the other hand, significantly affects the computed values of vibration amplitude. Fig. 2(a) and 2(b), respectively, show the real part of the impedance function and the non-dimensional vibration amplitude predicted by the application of the EBM. In each figure the average and extreme values of the computed response parameter are reported as a function of the vibration frequency. Fig. 2(b) highlights that uncertainty on the parameter $\Omega_{0,1}$ leads to a significant scatter of amplitudes in the frequencies range 8-20 Hz, where the damper is supposed to be the most effective. Scatter of the results in this frequency band is by far greater than effects of damper nonlinearities, estimated in [7]).

5 Conclusions

The paper presents the preliminary results of a study on the effects of the uncertainties related to the mechanical properties of Stockbridge dampers on the predicted values of aeolian vibrations. Ongoing research will address the definition of design criteria for the damper and the line.

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