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On the modeling and analysis of a vibration absorber for overhead powerlines with multiple resonant frequencies

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ABSTRACT

Stockbridge dampers are primarily used to suppress or reduce Aeolian vibrations of transmission lines. The number of resonant frequencies characterizes the effectiveness of the Stockbridge damper. Aeolian vibrations refers to the vibration of conductor cables in the range of 3–150 Hz. Unlike the primitive Stockbridge damper which has only two resonant frequencies, the asymmetric Stockbridge damper exhibits up to four resonant frequencies. The numerical simulations and parametric studies conducted previously showed a correlation between the increase of natural frequencies and the change in the geometry of the counterweight. This paper presents an analytical model of a novel Aeolian vibration damper with an increased number of resonant frequencies. The analytical model is used to deduce the resonant frequencies of the damper. A 3D finite element model is developed to validate the analytical model. The natural frequencies and the subsequent mode shapes of both analytical and finite element models are presented. Experiment is conducted to validate the proposed models.

1. Introduction

Aeolian vibrations can cause fatigue and eventual failure of the transmission line. These are the most common kinds of vibrations observed in transmission lines and are caused by vortex shedding due to the laminar flow of wind. These low amplitude vibrations are characterized by frequencies between 3 and 150 Hz. The vibrations are noticed in the vertical plane, causing alternating bending stresses and eventual failure of the conductor cable. The catastrophic failure of the transmission line from Cowal junction to Longwood in London was due to Aeolian vibrations [1]. Several other recent incidents in Ontario and Manitoba were attributed to Aeolian vibrations [2,3]. I.F.Lazar et al., address this issue in their work on vibration suppression of cables [4].

The Stockbridge damper is one of the most common used dampers in controlling Aeolian vibrations. The conventional damper has two counter weights connected by a messenger cable. This assembly is hung from the conductor cable using an aluminum clamp. The absorption of energy is possible only if the natural frequencies of the damper are tuned to cover the range of Strouhal frequencies. The primitive Stockbridge damper developed by George H. Stockbridge in 1925, is termed as symmetric Stockbridge damper or 2R damper since the counter weights on both sides are symmetric, and the system possesses two resonant frequencies in the Strouhal frequency range [5]. The modern asymmetric Stockbridge damper or the 4R damper has unequal counterweights, and possesses four resonant frequencies [6]. Fig. 1 shows a commercially available asymmetric Stockbridge damper. It has unequal counter weights, and the length of the messenger cable on both sides is also unequal.

One of the leading concerns in designing new transmission lines is the efficiency of the Stockbridge damper. With a growing need for better dampers, design improvements have gained enormous attention [6]. Tuning the counterweights, length, and cross-section of the messenger cable can increase the number of resonant frequencies (i.e. natural frequencies falling within the range of the entire Strouhal frequency spectrum) of the Stockbridge damper, thus resulting in a significant performance improvement.

Numerous authors have developed mathematical models for asymmetric Stockbridge dampers [7–9]. Among them, the latest was developed by Barry et al., [10], in which the authors presented explicit expressions for the frequency equation and mode shapes of an asymmetric Stockbridge damper.

A common approach used by several researchers is to experimentally determine the natural frequencies from the impedance curve [11–23]. The technical preliminary considerations showcase two

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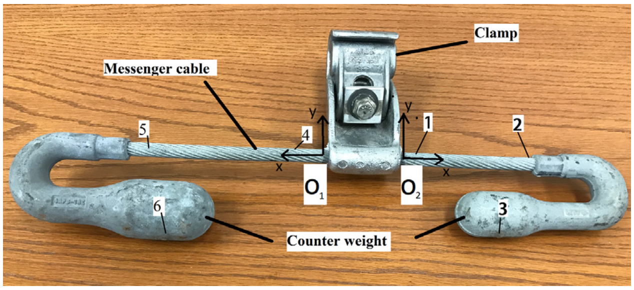

Fig. 1. Asymmetric Stockbridge damper.

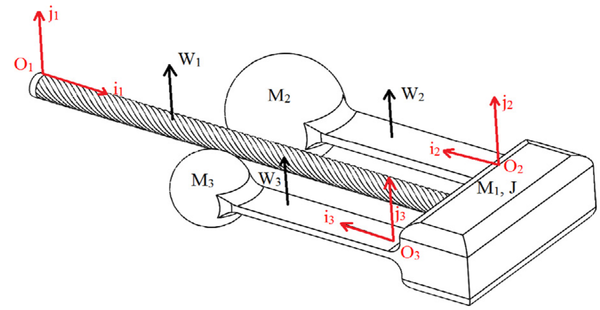

Fig. 3. Schematic of the quarter model of Vibration damper.

methods of testing- the basic method and the direct method. The basic method is based on measuring the energy loss due to the damper, with the stockbridge damper attached to a test span of the cable. On the other hand, in the direct method, the stockbridge damper is directly mounted on an electro dynamic shaker, and only vertical excitation is imposed to determine the resonant frequencies [24,25]. The sources also mention that the basic method is desirable for an analysis of the whole system(cable and damper). The direct method is preferred to basic method out of technical and economic considerations. In the experiments conducted by Wanger et al., a constant displacement of 1 mm peak to peak was used with a frequency sweep between 2.5 and 35 Hz [26]. Lara-Lopex et al., also conducted similar experiments with a constant peak to peak displacement of 2.7 mm [27]. However, the measurement standards, as mentioned in requirements and tests for Stockbridge type aeolian vibration dampers (IEC 61 897) recommend testing the Stockbridge damper at a constant velocity [28].

This paper presents a novel vibration damper using analytical and finite element models. The messenger cable is modeled as a Euler-Bernoulli beam, and the cable is assumed to behave linearly. The governing equations of motion and boundary conditions are derived using Hamilton's principle. The frequency equation is obtained analytically and experiment is conducted to validate the proposed model. It is should be noted that the present work is an extension of the work by Vaja et al. [29].

2. Analytical model

A full scale solid model of the vibration damper is shown in Fig. 2.

The mathematical model of the whole Vibration damper will be enormous. To simplify the computation, a half model of the vibration damper is used. Fig. 3 shows the schematic of the half model of the vibration damper. Three coordinate systems(O_1, O_2, and O_3) are used. The model is treated as a three-beam and three-mass system. The first coordinate system O_1 is at the clamp with mass M_1 at the other end. The second and third coordinate systems are on either sides of the mass M_1, with mass M_2 and mass M_3 at their respective extreme ends. The mass M_1 is considered to have rotation about axis perpendicular to the length of messenger cable, while mass M_2 and M_3 are considered to be point masses. The vibration displacement along the j coordinate is given by

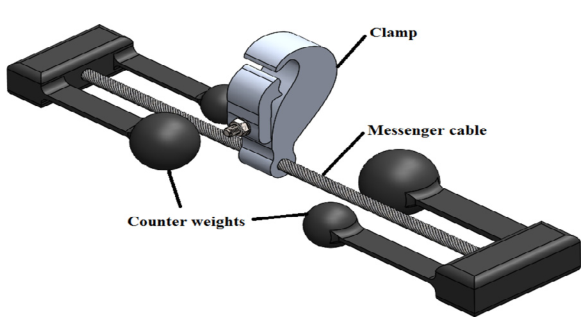

Fig. 2. Vibration damper.

W_1, W_2 and W_3 respectively in the first, second and third coordinate systems.

The kinetic and potential energy of the system are given by Eqs. (1) and (2), respectively

$$T = \frac{1}{2}m_1\int_0^{L_1}\dot{W}_1^2(x_1, t)dx + \frac{1}{2}M_1\dot{W}_1^2(L_1, t) + \frac{1}{2}J\dot{W}_1'^2(L_1, t) + \frac{1}{2}m_2\int_0^{L_2}\dot{W}_2^2(x_2, t)dx + \frac{1}{2}M_2\dot{W}_2^2(L_2, t) + \frac{1}{2}m_3\int_0^{L_3}\dot{W}_3^2(x_3, t)dx + \frac{1}{2}M_3\dot{W}_3^2(L_3, t) \tag{1}$$

$$V = \frac{1}{2}EI_1\int_0^{L_1}W_1''^2(x_1, t)dx + \frac{1}{2}EI_2\int_0^{L_2}W_2''^2(x_2, t)dx + \frac{1}{2}EI_3\int_0^{L_3}W_3''^2(x_3, t)dx \tag{2}$$

The primes in the above equations represent differentiation with respect to x, and differentiation with respect to time is represented by dots. E is Youngs modulus, I_1, I_2 and I_3 are the area moment of inertia of the messenger cable and beams respectively. J is the rotational inertia of the mass M_1, L_1 is the length, and m_1 is the mass per unit length of the cable. L_2, L_3 are the lengths and m_2, m_3 are the mass per unit length of the beams respectively. Using Hamilton's principle, the equations of motion of the system are obtained as

$$EI_1W_1^{IV} + m_1\ddot{W}_1 = 0 \tag{3}$$

$$EI_2W_2^{IV} + m_2\ddot{W}_2 = 0 \tag{4}$$

$$EI_3W_3^{IV} + m_3\ddot{W}_3 = 0 \tag{5}$$

Assuming the system exhibits harmonic motion, the following equations can be written

$$W_1(x_1, t) = F(x_1)e^{i\omega t} \tag{6}$$

$$W_2(x_2, t) = G(x_2)e^{i\omega t} \tag{7}$$

$$W_3(x_2, t) = H(x_3)e^{i\omega t} \tag{8}$$

where ω is the natural frequency and the mode shapes are given as

$$F(x_1) = a_1\sin\beta_1x_1 + a_2\cos\beta_1x_1 + a_3\sinh\beta_1x_1 + a_4\cosh\beta_1x_1 \tag{9}$$

$$G(x_2) = a_5\sin\beta_2x_2 + a_6\cos\beta_2x_2 + a_7\sinh\beta_2x_2 + a_8\cosh\beta_2x_2 \tag{10}$$

$$H(x_3) = a_9\sin\beta_3x_3 + a_{10}\cos\beta_3x_3 + a_{11}\sinh\beta_3x_3 + a_{12}\cosh\beta_3x_3 \tag{11}$$

Since the cable is fixed at the left end, the displacement and slope at this point are zero. Therefore the boundary conditions at $x_1 = 0$ are:

$$W_1(0, t) = 0; \tag{12}$$

$$W_1'(0, t) = 0; \tag{13}$$

At $x_1 = L_1$ the right end of the cable meets the mass M_1. At this point the displacement is assumed to be equal, but the slope is opposite in direction due to the choice of reference coordinate. Hence,