International Journal of Mechanical Sciences 87 (2014) 163–178

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

journal homepage: www.elsevier.com/locate/ijmecsci

Semi-active control of forced oscillations in power transmission lines via optimum tuneable vibration absorbers: With review on linear dynamic aspects

Navid Asmari Saadabad, Hamed Moradi *, Gholamreza Vossoughi

Centre of Excellence in Design, Robotics & Automation, Department of Mechanical Engineering, Sharif University of Technology, Tehran, Iran

ARTICLE INFO

Article history:
Received 5 November 2013
Received in revised form
10 May 2014
Accepted 6 June 2014
Available online 13 June 2014

Keywords:
Transmission lines
Galloping
Optimum vibration absorber
Semi-active control

ABSTRACT

Due to flexibility, relatively small weight and low energy-dissipative characteristics of cables, they are vulnerable to external excitations such as wind, wind–rain, earthquake and traffic loadings. Among them, galloping phenomenon is one of the most important sources of electrical/mechanical failures in power transmission lines. In this paper, tuneable vibration absorbers (TVAs) are used to suppress galloping forced vibrations (as a semi-active control approach). Using mode summation technique, mathematical model of the hybrid problem including the transmission line and an arbitrary number of absorbers is presented. Developing a sophisticated multi-loops optimization algorithm, best values of the absorbers' parameters (their location and stiffness, not necessarily symmetric) are found such that the transmission line deflection is minimized. Simulation results are presented in time and frequency domains. According to the results, designed TVAs act efficiently in suppressing galloping forced vibrations, especially under resonance conditions. Finally, global optimum design of TVAs is presented through a lookup diagram for a wide range of harmonic excitations. Since the optimal algorithm is developed in an extensive and general user-friendly manner, TVAs design can be accomplished for other industrial applications of flexible cables; under various excitations.

1. Introduction

Suspended cables are extensively used in several fields of engineering such as extra-high voltage transmission lines, cable-stayed bridges and mooring cables. In the case of transmission lines, flexible long cables with low structural damping are susceptible to wind-induced oscillations. These large amplitude oscillations may be caused by various wind excitation mechanisms such as wake galloping, vortex shedding vibrations and wind–rain vibrations. Connection failure, fatigue and corrosion of cables and consequently their lifespan reduction and increase in maintenance costs are the adverse effects of frequent and excessive vibrations. Therefore, suppression of cable vibrations via passive/active control methods is an essential issue in retrofitting the existing transmission lines or designing of new installations.

Conductor galloping is the high-amplitude, low-frequency oscillation of power transmission lines due to wind [1]. Cables are oscillating most commonly in the vertical plane, although horizontal or rotational motion is also possible. The excitation frequency is in the range of low-order harmonics, around 0.1–1 Hz; and the oscillations can exhibit amplitudes in excess of 10 m. Large vibration amplitudes cause the phase conductors to infringe operating clearances, leading to the flashover (due to breakage of atmospheric insulation) [2,3]. Also, this undesirable motion leads to the high loading stress on insulators and electricity pylons, raising the risk of mechanical/electrical failures and interruption of the power supply.

Since galloping occurs sporadically both in time and location, its investigation is not straightforward. Also, quantitative data related to weather condition, icing type, single/bundle conductors, frequency and amplitude ranges are difficult to determine. The initiative mechanisms of galloping are not clear, but it is often thought to be caused by asymmetric conductor aerodynamics due to ice build-up on one side of the cable [4–6]. Due to crescent nature of encrusted ice, the cable profile is changed which increases the tendency to oscillate.

According to the above sources of galloping vibrations, it should be mentioned that galloping is generally an instability phenomenon that is self-excited and occurs at low frequencies. Galloping can arise in any lightweight, flexible structure exposed to a flow. Cable galloping might occur in specific cross sections that are potentially unstable because of their aerodynamics [7].

* Corresponding author. Tel.: +98 21 66165545; fax: +98 2166000021.
E-mail addresses: hamedmoradi@sharif.edu, hamedmoradi@asme.org (H. Moradi).

http://dx.doi.org/10.1016/j.ijmecsci.2014.06.006
0020-7403/

Many investigations have been devoted to the dynamic modeling, design and behavior analysis of power transmission lines. In the early works, mathematical and experimental analysis of transmission lines vibration [8], determination of their natural frequencies and mode shapes [9], development of a simple model for wind-induced vibrations [10] and investigating the aero-elastic behavior of bundle conductors through wind tunnel experiments [11] have been carried out. Also, the effect of conductor geometry on galloping vibrations [12], galloping of a two-dimensional section model of a two-conductor bundle [13], free vibrations of suspended cables with flexible supports [14], parametric analysis of large amplitude free vibrations of a suspended cable [15,16] and a comparison of different mathematical models for transmission lines vibrations [17] have been presented.

In addition, a review on dynamic aspects, design and parametric study of transmission lines [18], cable galloping model for thin ice accretions [19], galloping of bundle conductor using a three degree of freedom model [20], identification of galloping vibrations based on field observed data [21] and dynamic analysis of transmission lines using finite element method [22] have been performed. Recently, dynamic characteristics of transmission lines under turbulent downburst loading [23], measurement of their vibrations based on a heterodyne method [24], characteristics of the rain-induced vibrations [25] and modeling of the ice shedding propagation with or without spacers [26] have been presented.

Various control methods, especially passive approaches, have been developed to suppress galloping vibrations. In the early works, providing sufficient phase-to-phase spacing between lines to prevent flashover; improving icing and aerodynamic characteristics by using smooth faced conductors; using anti-gallop devices to convert the lateral motion to a less damaging twisting one; boundary control of conductor galloping and melting the ice through increasing the power transfer have been suggested [1–3,18,27,28].

As a passive control method, vibration absorbers have been extensively used to reduce galloping vibrations. In the early studies of transmission lines, the effect of Stockbridge dampers' location on maximum strains [29], optimization of the two types of dampers for galloping control [30], dampers' design for vibrations caused by Karman vortex shedding [31], design of damping devices based on modal analysis [32,33], optimum design of impedance value in Stockbridge dampers for dead-end spans [34] and vibration control of sagged cables under harmonic excitation [35] have been studied. Recently, the effect of bending stiffness on damping properties of the cable with tuned-mass-damper (TMD) [36], design of an optimal damper for bridge stay cables [37], optimum design of damper scheme based on finite element simulations via ANSYS [38], dampers design based on energy balance method [39], vibration control of transmission lines based on the Euler–Bernoulli beam model [40], the effect of self-damping on Aeolian vibrations [41] and vibration control of cables with damped flexible supports [42] have been presented.

Semi-active and active control approaches are the other methods of this area. Development of appropriate describing functions for the control problem [43], vibration control of the string with energy dissipation and impulsive feedback support [44], active boundary control of elastic cables [45] and string stabilization by optimal shaping and positioning of the actuators [46] have been investigated. Recently, using magneto-rheological (MR) dampers for semi-active control of cable vibrations [47–50], design of flexural self-damping in transmission lines [51], vibration control of the cables through optimal design of shape memory alloy dampers [52] and cyclic application and removal of constraints [53] have been accomplished.

However, in the majority of previous researches, dynamics of the transmission lines has been locally studied on its cross section; as a two degree of freedom (2DOF) lumped model. Under practical conditions where a relatively long transmission line is used, this assumption is not sufficiently accurate. This is because the transmission line is a continuous system, containing infinite number of vibration modes. When the control procedure is developed to suppress the dominating mode, the rest of the structural modes may be excited, resulting in a spill-over problem. Moreover, due to sporadic occurrence and unpredictable nature of the galloping, many of previous control approaches fail to demonstrate a satisfactory behavior.

In this paper, optimum tuneable vibration absorbers (TVAs) are designed to suppress galloping forced vibrations induced by wind excitation. For simplicity, the expression of galloping forced vibration is used throughout the paper. The hybrid continuous model of transmission line and TVAs is presented based on mode summation. In this semi-active control method, a simultaneous multi-loops optimization algorithm is developed to determine the best values of TVAs' parameters such that transmission line deflection is globally minimized (locations are not necessarily symmetric). Through analysis of the problem in the time/frequency domains, an efficient lookup diagram for TVAs' design is presented for a wide range of excitations.

2. Performance description of the transmission lines under environment excitations

Transmission lines vibrations are generally caused by two major mechanisms of excitation: wake induced oscillations and vortex excitation [13,17,18,31,32,54]. In the first mechanism, wake induced oscillation of sub-conductors, i.e., the leeward conductor in a multi-conductor configuration, has been observed (but generally limited to quad conductors). Under unstable conditions, the sub-conductors move in anti-phase ellipses with a horizontal major axis of the order of 0.2 m at a frequency about 1 Hz [18]. To predict the onset of instability, linearized flutter theory can be applied; showing relatively good agreement with experiments. This type of oscillations can lead to the spacer damage and conductor fatigue. To suppress wake induced oscillations, flexible spacers including the high damping elements can be used.

The second Aeolian mechanism of transmission lines vibration is the high vortex excitations of conductors. The alternate shedding of vortices from the conductor in steady wind conditions leads to this kind of excitation. The shedding frequency directly depends on the wind speed and conductor diameter [18]. Vibrations induced by von Karman vortex shedding, also called flutter, are observed in the high frequency range of 10–50 Hz [17,31,32,54]. Resonance conditions occur when the frequency of vortex shedding matches one of the natural frequencies of the conductor (albeit in a high mode). However, conductor self-damping, which increases with frequency and wind turbulence, limits the vibrations. These small but high frequency amplitudes produce secondary bending stresses in the conductor, especially at the support ends. This may lead to fatigue failure at suspension clamps or at the spacers. Since approximately 1940 the Stockbridge damper and its modified versions have been used for the damping of this type of vibrations.

According to the field observations, any of mentioned mechanisms may be activated depending on the type of freezing precipitation, parameters adopted for the design, wind excitation patterns and intensity. For instance, experience in North West Europe suggests that galloping mainly occurs with bundle conductors in conditions of wet snow [18]. On the other hand, the laminar wind patterns in desert areas may lead to the development of vortex excitation. Often steady uniform wind patterns create vortex shedding leading to dynamic forces on transmission