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Finite time-Lyapunov based approach for robust adaptive control of wind-induced oscillations in power transmission lines

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ABSTRACT

Large amplitude oscillation of the power transmission lines, which is also known as galloping phenomenon, has hazardous consequences such as short circuiting and failure of transmission line. In this article, to suppress the undesirable vibrations of the transmission lines, first the governing equations of transmission line are derived via mode summation technique. Then, due to the occurrence of large amplitude vibrations, nonlinear quadratic and cubic terms are included in the derived linear equations. To suppress the vibrations, arbitrary number of the piezoelectric actuators is assumed to exert the actuation forces. Afterwards, a Lyapunov based approach is proposed for the robust adaptive suppression of the undesirable vibrations in the finite time. To compensate the supposed parametric uncertainties with unknown bands, proper adaption laws are introduced. To avoid the vibration devastating consequences as quickly as possible, appropriate control laws are designed. The vibration suppression in the finite time with supposed adaption and control laws is mathematically proved via Lyapunov finite time stability theory. Finally, to illustrate and validate the efficiency and robustness of the proposed finite time control scheme, a parametric case study with three piezoelectric actuators is performed. It is observed that the proposed active control strategy is more efficient and robust than the passive control methods.

1. Introduction

Flow-induced vibration of the suspended slender cables is a common challenging problem in many fields of the engineering such as power transmission lines, cable-stayed bridges, and sea bed oil risers and so on. In the practical engineering, undesired vibrations in the slender cable have adverse and even hazardous consequences. Power transmission lines are vulnerable to the wind-induced vibrations due to the long length and low structural damping. High amplitude, low frequency oscillations of the power transmission lines, also known as conductor galloping, is a devastating phenomenon which is caused by various wind excitation mechanisms such as wake galloping, vortex shedding vibrations and wind-rain vibrations [1]. Conductor galloping phenomena has undesired costly consequences such as short circuiting between different interphases, fatigue of the transmission lines, reduction of the hardware operational life, even collapse of the

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transmission towers and finally disruption of the power supply. Accordingly, designing a control scheme that guarantees the vibration suppression of the transmission line in the finite time has great importance.

Galloping oscillation is a flow-induced instability, which is self-excited and occurs at low frequencies. Slender, flexible structure which is exposed to a fluid flow is vulnerable to the galloping oscillation. Cable galloping might occur in specific cross sections that are potentially unstable because of their aerodynamics [2].

Conductor galloping occurs in the wind speed ranging from 5 to 15 m/s and it is the high-amplitude, low-frequency oscillation of the power transmission lines. The oscillations usually occur in the vertical plane, but horizontal or rotational motion with significant lower amplitudes, is also possible [3]. In this paper, due to above reasons and for model simplification, vertical vibrations are considered. Excitation frequency usually is in the range of fundamental harmonics, around 0.1 to1 Hz; and oscillations peak to peak amplitudes may be as large as 10 m; which leads to the devastating consequences such as failures and interruption of power supply as well as increase the maintenance cost of the hardware [4,5].

Due to the stochastic occurrence of the galloping phenomenon, it is hard to study its properties accurately. 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. Due to crescent nature of encrusted ice, the cable profile is changed which increases the tendency to oscillate [6,7].

In the past few decades, many efforts have been done to model and analysis the dynamics of the power transmission lines. Among the early works, determination of their natural frequencies and mode shapes [8], investigating the aero-elastic behavior of bundle conductors through wind tunnel experiments [9], parametric analysis of large amplitude free vibrations of a suspended cable [10] and a comparison of different mathematical models for transmission lines vibrations [11] have been carried out.

Afterward, a review on dynamic aspects, design and parametric study of transmission lines [12], galloping of bundle conductor using a three degree of freedom model [13], identification of galloping vibrations based on field observed data [14] and dynamic analysis of transmission lines using finite element method [15] have been performed. Recently, dynamic characteristics of transmission lines under turbulent downburst loading [16], measurement of their vibrations based on a heterodyne method [17], numerical investigation on galloping in the quad bundle conductors [18], characteristics of the rain-induced vibrations [19] and modeling of the ice shedding propagation with or without spacers [20], investigating the galloping phenomenon for single and quad conductor [21,22], comparison of a glaze icing model with experiments for the conductor icing [23], quasi-steady modeling of aeroelastic forces exerted by the wind in the galloping phenomenon [24] have been carried out.

Motivated by the adverse consequences of the galloping phenomenon, many admirable efforts have been carried out to suppress or attenuate the vibrations in power transmission lines. In this regard, passive, semi-active and active schemes are designed. Due to the simplicity and easy implementation, various passive controls 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 [1,4,5,12,25].

As a passive control method, vibration absorbers have been extensively used to reduce galloping vibrations. In the early studies of transmission lines, dampers design for vibrations caused by Karman vortex shedding [26] and optimum design of impedance value in Stockbridge dampers for dead-end spans [27] have been studied. Recently, the effect of bending stiffness on damping properties of the cable with tuned-mass-damper (TMD) [28], optimum design of damper scheme based on finite element simulations via ANSYS [29], dampers design based on energy balance method [30], vibration control of transmission lines based on the Euler-Bernoulli beam model [31], the effect of self-damping on Eolian vibrations [32], vibration control of cables with damped flexible supports [33], galloping vibrations suppression via optimum tuneable vibration absorbers [34], strings vibration suppression via spatial cross-section modulation [35] and nonlinear energy sink to suppress the vibration in the elastic string [36] have been presented.

Due to the limitation of the passive approaches in the structures with uncertainties, many researchers develop the active and semi active control approaches. In this regard, development of active boundary control of elastic cables [37] and string stabilization by optimal shaping and positioning of the actuators [38] have been investigated. Recently, using magneto-rheological (MR) dampers for semi-active control of cable vibrations [39], design of flexural self-damping in transmission lines [40], vibration control of the cables through optimal design of shape memory alloy dampers [41], cyclic application and removal of constraints [42] and integral barrier Lyapunov approach for vibration suppression in the flexible strings [43] have been accomplished.

However, in the most of the aforementioned researches, the nonlinearities and uncertainties are not taken into account. In the practice engineering, we have to deal with the uncertainties and modeling imprecisions. Neglecting the modeling uncertainties and nonlinearities in the dynamics of the transmission lines may lead to instabilities. Replacement of the governed distributed partial differential equation (PDE) with a finite set of the ordinary differential equations (ODEs), ice accumulation on the conductor, variation of the wind induced force, variation of the system nonlinearities due to the variation of the vibration amplitude are the most important sources of the uncertainties. Furthermore, the nonlinearities in the dynamic model should be considered due to the large amplitude vibrations. Moreover, in the most of the previous mentioned control schemes, the time of the convergence to the desired performance was not taken into account. In practice, to avoid the failure of the system, undesired vibrations should be suppressed as quickly as possible.

In this paper, motivated by the above discussions, nonlinear model of the power transmission line with unknown parameters is considered. Then, a Lyapunov based approach is proposed for the robust adaptive suppression of the galloping phenomenon in the finite time by using piezoelectric actuators. Finite time control scheme is used to ensure that the