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Experimental and analytical study of galloping of a slender tower

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Many previous studies have been conducted to investigate wind-induced galloping of slender structures or structural members. While some recent studies have examined the particular problem of galloping involving coupling between vibration components about the principal axes, few occurrences of such vibrations of full-scale structures have been reported. This paper presents a comprehensive investigation that incorporates full-scale and wind tunnel experiments and an analytical formulation to study the galloping oscillation of a type of slender tower. The full-scale and wind tunnel experiments were conducted to assess the characteristics of the oscillations, their correlation with the wind characteristics, as well as the core parameters that influence the interaction between the tower and the wind. Based on the results from the experiments, a state-space model for coupled galloping of slender towers is formulated. This model enables the prediction of the susceptibility of a slender tower to galloping instability through an evaluation of the net damping resulting from the wind-structure interaction. The tower subjected to monitoring in the full-scale study is used as an example structure in an illustrative application of the analytical model.

1. Introduction

Slender towers and poles are frequently used as structural supports for objects such as luminaires and telecommunication antennae. Such structures are often flexible and low in inherent damping. As a result, they can be susceptible to a number of types of aeroelastic phenomenon, such as vortex-induced vibration (e.g., [1,2]) caused by vortices shedding from the surface of a structure at a frequency that locks in with a natural frequency of the structure, buffeting due to the turbulence in the wind [2], and galloping induced by aerodynamic forces that are in phase with the velocity of the structural motion [3]. Of these three types of phenomenon, galloping can be particularly problematic, as the amplitude of this type of vibration can reach many times the cross-sectional dimensions of a slender structure and potentially lead to structural failures. Furthermore, many slender towers consist of structural members with cross-sectional shapes that are known to be prone to gallop. Examples of such shapes include square and rectangles of various aspect ratios.

Many studies, including full-scale and wind tunnel experiments as well as analytical formulations, have been conducted to study galloping of slender structures or structural members. The early investigations focused on the across-wind vibration and neglected both translational oscillation in the along-wind direction and torsional motion. In a celebrated work, Den Hartog investigated the across-wind galloping of transmission lines with an ice coating based on the quasi-steady assumption of wind loading [4]. It resulted in the now well-known Den-Hartog criterion, which has been used broadly to evaluate the propensity of a structural member with a certain cross-sectional shape to gallop in the across-wind direction. A number of subsequent studies, also based on the quasi-steady approach, were conducted to enable the prediction of the across-wind galloping amplitude of a structure subjected to wind loading. Parkinson et al. [5,6] formulated the nonlinear equation of galloping motion of a single-degree-of-freedom (SDOF) prismatic body by expressing the aerodynamic damping as polynomials of the oscillation velocity, and used the Krylov-Bogoliubov method (e.g., [7]) to solve this equation for the steady-state across-wind vibration amplitude. Building upon this formulation, Novak et al. [8–11] conducted a series of investigations that utilized a method based on the principle of energy balance to further study the problem of across-wind galloping of full-scale elastic bodies in a uniform or sheared flow with or without consideration of wind turbulence. In one of these studies [10], Novak investigated three categories of across-wind galloping instability associated with three distinct types (i.e., positive, zero and negative) of slope of the across-wind force coefficient versus wind angle of attack curve. This study revealed the possibility of across-wind galloping instability even when the Den Hartog criterion is

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not satisfied. In a later study, Richardson [12,13] developed a method that is also based on energy considerations for the prediction of across-wind galloping amplitude. In the formulation of this method, the across-wind force coefficient is expressed as a Fourier series instead of a polynomial.

The early analytical studies were accompanied by extensive wind tunnel experiments that were conducted to reproduce the scenarios of across-wind galloping considered in the analytical formulations (i.e., SDOF or distributed parameter systems, uniform or sheared flow, smooth or turbulent flow) [5,8–11,14]. The results of these experiments were in general able to validate the predictions by the analytical models.

In the studies that followed the early investigations, the effects of a number of specific factors, such as the turbulence of the wind (e.g., [14–18]) and the variation of square and rectangular cross-sectional shapes (e.g., [17–19]), on the onset and amplitude of across-wind galloping were addressed. In addition, both analytical formulations (e.g., [20,21]) and wind tunnel tests [22] were also conducted to investigate the across-wind oscillation of a prismatic cylinder when the wind speed for the onset of across-wind galloping is close to that for lock-in vortex-induced vibration. It was revealed that the across-wind oscillation that occurs in this situation differs from both vortex-induced vibration and galloping in the dependence of the vibration amplitude on wind speed.

More recent studies investigated galloping oscillations that involve more than only across-wind translation. Jones was the first to systematically study the problem of galloping that involves coupling between across-wind and along-wind motions [23]. She formulated an eigenvalue problem that considers both the along-wind and the across-wind degrees of freedom, and provided a solution to this problem that can be used to evaluate the coupled galloping propensity of a segment with a particular cross-section. However, Jones' study, as well as a number of subsequent studies by other researchers (e.g., [24]), only dealt with the situation in which the natural frequencies of the modes of interest are identical and the mean wind direction coincides with one of the principal axes of the structure. Liang et al. [25] formulated the equations of coupled across-wind and along-wind galloping of a distributed parameter system in sheared flow. This formulation does not restrict the direction of wind or the natural frequencies of the structure. However, in solving the equations of motion, this study treated the motions about the two orthogonal axes as perfectly in phase. It resulted in an incorrect conclusion that coupled translational galloping occurs only when the natural frequencies of the participating modes about the principal axes of the structure are identical. Li et al. [26] further extended the formulation by Liang et al. to investigate the effect of turbulence on coupled translational galloping. This investigation, however, unrealistically assumed that the turbulence is fully coherent throughout the height of a boundary layer.

In a recent work, Nikitas and Macdonald [27] conducted a comprehensive review of the galloping problem. They also formulated and correctly solved the equations of coupled translational galloping of a dynamic system in smooth flow without restrictions on the natural frequencies or the direction of the wind. This formulation enabled an assessment of the galloping stability boundaries of a number of cross-sectional shapes. It was also used to investigate the effects of the tuning between the natural frequencies of the system in the directions of the principal axes on the aerodynamic damping and the trajectory of the galloping oscillation. The investigation of the trajectory, however, is trivial as this particular formulation is resulted from a linearization of the problem based on the assumption of small vibration amplitude and cannot be used to evaluate the characteristics of galloping oscillations of large amplitudes, at which the aerodynamic damping is inherently nonlinear. In another recent work, Raeesi et al. [28] further extended the formulation of coupled translational galloping to arrive at a model that considers both the nonlinearity of the aerodynamic damping and the unsteadiness of wind. However, this study focused on the galloping of a two-degree-of-freedom cylinder and did not consider the coupled galloping of full-scale structures or structural members, which would have involved treatment of factors such as the spatial correlation of the turbulence and the aerodynamic admittance.

In addition to the extensive investigations of coupled galloping involving translational degrees of freedom, a number of studies also highlighted the role of torsional motion in the galloping phenomenon. Using analytical formulations, Blevins and Iwan [29] and Blevins [30] studied the galloping response of a system with a translational degree of freedom and a torsional degree of freedom in smooth flow. Yu et al. [31,32] further investigated the problem of three-dimensional galloping that involves motions in two translational degrees of freedom and one torsional degree of freedom. The nonlinearity of the aerodynamic damping and that of the structural behavior are both considered in this investigation. The inclusion of torsion, however, is often unnecessary for the analysis of galloping of structures such as slender towers. In addition, the formulation proposed by Yu et al. only deals with the case in which the wind direction is along one of the principal axes of the structural member under consideration.

Despite the advancement in the analytical study of coupled galloping, there have been few experimental evidence of such vibration, especially the type that involves two-dimensional translation. In a forensic study conducted to investigate the failure of highway lighting poles [24], coupled-galloping of the type studied by Jones [23] was identified to be the mechanism of the problematic vibrations. However, no measurements were available to substantiate this conclusion and enable a more quantitative case study. Also, based on observations made in a series of wind tunnel tests of circular cylinders [33], coupled galloping was claimed to be the mechanism of large-amplitude vibrations of dry stay cables [34]. However, no definitive evidence of such vibration has been reported for prototype stay cables.

This paper describes the observed galloping of a slender tower with distinct natural frequencies along the directions of its two principal axes. The characteristics of the full-scale vibrations and their dependence on the wind characteristics, as well as the results of a series of wind tunnel experiments conducted to complement the full-scale study, are interpreted. In addition, this paper presents the formulation of an analytical model for coupled translational galloping in the form of a complex eigenvalue problem. Solving this eigenvalue problem results in the frequencies of the vibration and the net damping ratios of the wind-structure system, the latter of which can be used as a basis for the evaluation of coupled-galloping propensity of a structure. Using the full-scale tower subjected to monitoring as an example, the application of the analytical model in the assessment of the factors that affect coupled galloping of slender towers is illustrated.

2. Full-scale experiment

2.1. Full-scale structure and monitoring system

The study presented herein was initially motivated by many reported incidents of excessive wind induced-vibration and the resultant failures of a type of positive train control tower that are often seen along railways in the US. The main structural components of these towers are a base tube and a swing tube, which are both rectangular Hollow Structural Steel sections. The base tube rigidly connects to the foundation through a base plate, and the swing tube pivots about the top of the base tube to allow