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Aeroelastic galloping response of square prisms: The role of time-delayed feedbacks

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ABSTRACT

In this paper, the aeroelastic galloping responses of an elastically mounted square prism is investigated based on a theoretical model, principally focusing on the effect of additional time-delayed feedbacks. The results have indicated that the time-delayed feedback force plays a dramatic role in controlling the aeroelastic galloping responses. With increasing gain of the feedback force, the amplitude of galloping responses would always increase. With increasing time delay of the feedback force, however, it is found that galloping responses of the square prism may be either amplified or suppressed, depending on the value of the time delay chosen.

1. Introduction

Flow-induced vibration of structures is of practical interest to many fields of engineering (Alberdi-Muniain, Gil-Negrete, & Kari, 2013; Berryman, 2013; Chen, 1987; Li, 2012; Paidoussis, 2008; Paidoussis, Price, & de Langre, 2011; Willamson & Govardhan, 2004; Şimşek, 2010). For example, it can cause complex vibrations in pipes/tubes in contact with internal or/and external fluid flows (Dai, Wang, & Ni, 2013a; Dai, Wang, Qian, & Ni, 2013b; Ghayesh, Paidoussis, & Amabili, 2013; Modarres-Sadeghi & Paidoussis, 2013; Paak, Paidoussis, & Misra, 2013; Paidoussis, 1998; Paidoussis & Li, 1993; Rinaldi & Paidoussis, 2012; Wang, 2012; Wang, Liu, Ni, & Wu, 2013; Yu, Paidoussis, Shen, & Wang, 2013; Zhou, 2012); it influences the safety of slender risers bringing oil from the seabed to the surface; it can lead to catastrophic oscillation and collapse of bridges (e.g., the famous Tacoma Narrows Bridge); and it can cause large-amplitude vibrations of tethered structures in the ocean. Indeed, under certain conditions the vibration may be self-excited, and it is usually referred to as an instability. These instabilities are of great importance to designers and operators of the systems concerned because of the significant potential to cause safety hazard. Thus, the practical significance of flow-induced vibrations has led to a large number of fundamental studies, some aspects of which are discussed in books by Blevins (1990), Chen (1987), Paidoussis (1998), Paidoussis (2004) and Paidoussis et al. (2011).

In particular, the flow-induced vibrations treated in this paper are associated with cross-flow, that is, flow normal to the long axis of the structure. Among others, a specific problem vulgarly known as galloping and in some other circles as a dancing vibration, that is fundamentally and technologically important, will be treated. As a paradigm for such galloping systems, we shall consider here a square prism restrained to move transverse to the flow, as Fig. 1(a) shows. As reported by Paidoussis et al. (2011), galloping may be defined as a velocity-dependent, damping-controlled instability, giving rise to transverse or torsional motions of bluff bodies.

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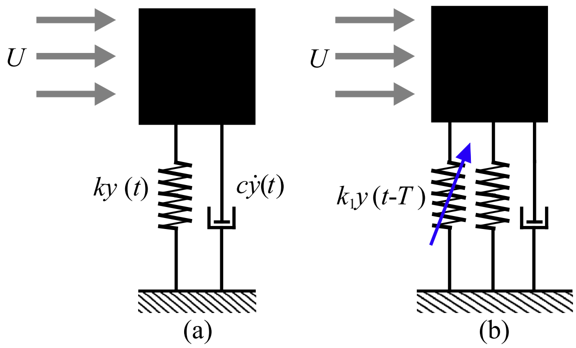

Fig. 1. (a) Schematic of a typical galloping system subjected cross-flow; (b) schematic of a modified galloping system with an additional time-delayed feedback control.

There is a very rich literature on galloping. Den Hartog (1956) was the first to study and explain the galloping phenomenon. He used a quasi-steady hypothesis to describe the aerodynamic forces. A criterion for the occurrence of galloping was also provided. After Den Hartog's work, the effects of various system parameters on the galloping responses of different structures were investigated (see, e.g., Alonso, Meseguer, & Prez-Grande, 2007; Barrero-Gil, Sanz-Andres, & Roura, 2009; Naudascher & Rockwell, 1994). Perhaps the most notable book is provided by Blevins (1990), wherein many of the pertinent references on the topic may be found. Some of the earlier references may also be found in several reviews of the topic by Parkinson (1971), Parkinson (1974) and Parkinson (1989). In a recent book chapter by Paidoussis et al. (2011), the mechanism of galloping was extensively discussed and many references on this topic were provided.

In this paper, we will pay much attention to investigate the amplitude of galloping responses of square prisms. For that purpose, a new impetus of time-delayed feedback controls for controlling the oscillatory amplitude of galloping will be provided, to sharing it with the wider research community.

The first element in this new impetus is related to the vibration suppression of fluid–structure interaction (FSI) systems with control signals involving time delays. Actually, during vibration control of mechanical systems, time delays arising in the control signals may inevitably exist (Zhao & Xu, 2007). From a mechanical point of view, thus, it is indeed of interest to study the dynamics of a system subjected to cross-flow-induced galloping and with time-delayed feedbacks.

The second impetus comes from renewable energy technology, specifically the use of flow-induced vibrations for energy harvesting (Akaydin, Elvin, & Andreopoulos, 2012; Mackowski & Williamson, 2013; Xie, Yang, Hu, Hu, & Chen, 2011; Yang, Zhao, & Tang, 2013). Indeed, there has been of interest in the concept of harvesting energy from galloping vibrations (Abdelkefi, Hajj, & Nayfeh, 2013). For example, Barrero-Gil, Alongso, and Sanz-Andres (2010) discussed for the first time the use of galloping as an alternative to extract energy from the fluid flow. In their energy harvester, a spring-mounted prismatic rigid body prone to gallop under the action of an incoming flow in the transverse direction was used. In a work by Abdelkefi, Hajj, and Nayfeh (2012), they devised a galloping-based piezo-aeroelastic energy harvester consisting of an elastically-mounted square cylinder and a piezoelectric transducer attached to its transverse degree of freedom.

It is noticed that in the design of energy harvester from aeroelastic galloping, high amplitudes of the harvesting system have the potential to extract much more energy from the flow. Thus, the method of amplifying the amplitude of galloping responses becomes very important; this, of course, has served to revitalize interest in the topic of this paper.

The objective of this work is to investigate the effect of time-delayed feedbacks on the galloping responses of a square prism subjected to cross flows. Particularly, we aim to focus on the attainable amplitude of galloping responses by introducing the time-delayed feedbacks. Following a description of the mathematical modeling of transverse galloping in the next section (Section 2), we study the amplitude dependence on the gain and time delay of the feedback controls (Section 3). Finally, some conclusions are drawn in Section 4.

2. Problem

Let us consider a flexibly supported square prism which could be modeled as a mass-dashpot-spring system, as shown in Fig. 1(a). The prism is assumed to move in the direction transverse to the flow; the cross-section of the prism is uniform along its length (normal to the plane of the paper). It has a mass per unit length (or section mass) m, mechanical damping ratio ζ and natural circular frequency of oscillations ω_N. It is also supposed that the body is sufficiently slender to consider bidimensional flow, and that the incident flow is free of turbulence. The prism would be subjected to flow-induced vibration due to the aero-dynamic force per unit length F_y.

Then, the equation governing the dynamics of the system shown in Fig. 1(a) is given by