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Modeling and nonlinear dynamics of fluid-conveying risers under hybrid excitations

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ABSTRACT

The nonlinear dynamical responses of a vertical riser concurrently subjected to hybrid excitations, namely, vortex-induced vibrations (VIVs) and base excitations are investigated. The riser conveying fluid is placed in a uniform cross-flow and subjected to direct harmonic excitations. A van der Pol wake oscillator is used to model the fluctuating lift coefficient. The extended Hamilton's principle and the Galerkin procedure are used to derive a nonlinear distributed-parameter model for a vertical riser under a combination of vibratory base excitations and vortex-induced vibrations. Linear and nonlinear analyses are performed to investigate the effects of internal fluid velocity, cross-flow speed, and base acceleration on the coupled frequency, onset speed of synchronization, and vibration amplitudes of the riser. The results show that when the cross-flow speed becomes in the synchronization region, vibration behaviors of the riser change from aperiodic to periodic motions, with a jumping phenomenon between these two kinds of motions. It is also demonstrated that the amplitude of the riser can be increased or decreased under combined effects of vortex-induced vibrations and base excitations compared to the separate effect of vortex-induced vibrations or base excitations. The results also show that an increase of the base acceleration results in a wider synchronization region and a significant effect associated with the quenching phenomenon.

1. Introduction

Fluid-structure interaction (FSI) problems have been with us since time immemorial. In most cases, flow-induced vibrations are annoying or damaging to equipment and personnel and hence dangerous, e.g. leading to the collapse of bridges and high buildings, the flutter responses of slender structures, the destruction of pipelines and nuclear-reactor internals, the risk of developing cardiovascular diseases due to blood flow, or the severing of offshore risers (Berryman, 2013; Dai, Wang, & Ni, 2013; Li, 2012; Païdoussis, 1998; Taelman, Degroote, Swillens, Vierendeels, & Segers, 2014; Wang, Liu, Ni, & Wu, 2013, 2014; Yang, Ji, Yang, & Fang, 2014).

Among various FSI problems, vortex-induced vibrations (VIVs) of cylindrical structures placed in cross flows have been investigated extensively and intensively due to their practical use and significance in engineering applications (Abdelkefi, Hajj, & Nayfeh, 2012; Gabbai & Benaroya, 2005; Mehmood, Abdelkefi, Hajj, Nayfeh, & Akhtar, 2013; Païdoussis, Price, &

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de Langre, 2011; Dai, Abdelkefi, & Wang, 2014). It is well-known that self-excited large oscillations of bluff bodies are observed as the vortex shedding frequency is close to the natural frequency of the structure, which severely can lead to fatigue failure of these structures. Some of the fluid-loaded systems which can undergo vortex-induced vibrations range from hanging strings in air to marine structures, such as cables and risers placed within ocean currents. Comprehensive reviews and discussions of such aeroelastic phenomenon were summarized by Chen (1987), Blevins (1990), Williamson and Govardhan (2004), Williamson and Govardhan (2008), Païdoussis et al. (2011) and Wu, Ge, and Hong (2012).

The pioneer experimental study of vortex-induced vibrations of elastically-mounted rigid cylinders was performed by Feng (1968), who found that the lock-in (also known as synchronization) of the cylinder occurs over a range of cross-flow velocities. Based on their experimental studies on elastically-mounted rigid cylinders, Williamson and Roshko (1998) and Khalak and Williamson (1996) reported that different vortex shedding modes in the wake of the cylinder can take place, such as 2s, 2p, p+s, and 2p+2s. They also showed that three amplitude response branches can be obtained in the response of a cylinder under vortex-induced vibrations which are initial, upper, and lower branches. On the other hand, Brika and Laneville (1993) performed an experimental investigation on vortex-induced vibrations of a long flexible cylinder. They showed that the hysteresis loop is characterized by only two branches and each branch is associated with a particular vortex shedding mode. These studies on elastically-mounted rigid cylinders and flexible cylinders give a clear idea that the appearance and disappearance of vortex-shedding modes and branches depend on the type of elastic cylinders. These results oblige researchers to develop accurate analytical models depending on the considered elastic bluff body to correctly understand the physical aspect difference between these elastic cylinders.

Skop and Griffin (1975) firstly theoretically investigated the vortex-induced vibrations of flexible cylinders. Based on a normal mode approach, they extended the used models for elastically-mounted rigid cylinders to develop accurate models for flexible cylinders. Vortex-induced vibrations of a freely vibrating flexible cylinder were predicted by Wang, So, and Chan (2003), who employed a nonlinear fluid force model that is based on an iterative process and modal analysis approach. Skop and Balasubramanian (1997) and Facchinetti, de Langre, and Biolley (2004) proposed a wake oscillator model to evaluate the fluctuating lift coefficient of flexible circular cylinder structures. Applying the wake oscillator model proposed by Facchinetti et al. (2004), numerical investigations on vortex-induced vibrations of flexible cylinders were carried out by Mathelin and deLangre (2005) and Violette, de Langre, and Szydlowski (2007). Using direct numerical simulations to represent the fluid force, Newman and Karniadakis (1997) and Evangelinos and Karniadakis (1999) investigated the behavior of flexible cylinders when placed in cross flows. Some other studies on vortex-induced vibrations of flexible cylinder structures were contributed by Bokaian (1994), Zhou, SO, and Lam (1999), and Yamamoto, Meneghini, Saltara, Fregonesi, and Ferrari (2004).

Recently, few publications have been concerned with the vortex-induced vibrations of flexible pipes/risers conveying fluid due to the practical interest in marine risers. Keber and Wiercigroch (2008) investigated the effects of weak structural nonlinearity on the dynamical behavior of pipes subjected to vortex-induced vibrations. Meng and Chen (2012) explored the response of extensible steel catenary risers when subjected to vortex-induced vibrations. Both of the above studies showed that the internal and external flows can remarkably affect the dynamical response of pipes/risers. Recently, Dai and Wang (2012) and Dai, Wang, Qian, and Ni (2013) investigated the dynamic responses of pipes concurrently subjected to internal flows and cross-flows. They found that when the value of internal flows is beyond a critical value, more complicated dynamical behaviors of the cylinder such as quasi-periodic, periodic-n, and chaotic motions may occur.

Previous research studies have only considered the case when the flexible riser/pipe is subjected to vortex-induced vibrations. However, these fluid-conveying flexible risers may be subjected to different types of excitations, such as vortex-induced excitations, wave excitations, and base excitations. The cumulative effects of different excitations on the behavior of the riser can not be a simple superposition of the individual responses to these types of vibrations. This motivates the current work.

In this study, we investigate the dynamical responses of fluid-conveying circular cylindrical risers under a combination of vibratory base excitations and vortex-induced vibrations. A coupled nonlinear distributed-parameter model is derived based on the Hamilton's principle and Galerkin discretization and presented in Section 2. In Section 3, we determine the required number of modes in the Galerkin discretization to get convergence. Linear and nonlinear analyses are then performed in details in Section 4, in order to investigate the effects of cross-flow speed, internal flow velocity, and base acceleration on the coupled frequency, lock-in region, and dynamical responses of the riser system. Summary and conclusions are presented in Section 5.

2. Model formulation

The present system consists of a vertical riser simply-supported at both ends. The fluid-conveying riser is placed within a uniform fluid flow with flow speed, U_o, and subjected to an external harmonic base excitation, $z_b(t) = z_0\cos(\omega t)$, where z_0 is the amplitude of the base displacement and ω is the base excitation frequency, as shown in Fig. 1. It should be noted that the present riser system is supposed to only oscillate in the cross-flow direction. This assumption has been demonstrated to be quite reasonable due to the fact that the in-line oscillation amplitudes are generally one order smaller than the cross-flow oscillation amplitudes (Keber & Wiercigroch, 2008; Newman & Karniadakis, 1997; Zhou et al., 1999). Thus, based on performed experimental researches for flexible cylinders with simply supported ends (Huse, Nielsen, & Soreide, 2002; Marcollo & Hinwood, 2006; Moe & Wu, 1990; Sarpkaya, 1995), it was suggested that the cross-flow responses always dominate over the in-line responses in terms of amplitude.