Ocean Engineering 139 (2017) 74–84

Contents lists available at ScienceDirect

Ocean Engineering

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

Cross-flow vortex-induced vibration of a flexible riser transporting an internal flow from subcritical to supercritical

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ARTICLE INFO

Keywords:
Internal flow effect
Vortex-induced vibration
Mode transition
Buckling-flutter coupled instability

ABSTRACT

This study aims to model and explore the IFE (Internal Flow Effect) on the CF (Cross-Flow) VIV (Vortex-Induced Vibration) of a flexible riser transporting an axial single-phase internal flow. The simulation model employs the nonlinear equations describing the coupling of axial and transverse vibrations of a fluid-conveying pipe as the structural model, and adopts a distribution of van der Pol oscillators to create the VIV effect. The governing equations can be solved via a Galerkin-based multi-mode approach combined with the Houbolt's finite difference scheme. The developed code has been validated for VIV effect and IFE from subcritical to supercritical region. The Argand diagram of a flexible riser is plotted at first, and the varying natural frequencies with the increase of internal flow velocity and the critical internal flow velocity can be obtained. Then simulations of the flexible riser at two uniform currents with the increase of internal flow velocity in a transition range from being subcritical to supercritical are conducted. The IFE on CF VIVs are examined by the space-time modifications of riser responses and dominant vibration frequency for which the mode switching and sharing can be identified. It has demonstrated that internal flow influences the vibration amplitude and the dominant vibration frequency. Internal flow can trigger new natural modes and switch the role of the most predominant one. Moreover, a buckling-flutter coupled instability is captured where the riser is experiencing a static divergence and a Hopf bifurcation via the first natural mode.

1. Introduction

A marine riser, typically transporting crude oil, natural gas and other undersea economic resources in the offshore structural system, is inevitably subject to the severe environmental forces resulting from currents and waves. The riser is inherently an extensible and flexible tubular structure, and as ocean recourse exploration expands into deep waters, it becomes much longer and slenderer. Then the dynamics start exhibiting new dynamic features which requires more careful analysis for the safety of offshore operations. For example, although the basic mechanism of VIV is well documented in the literature (Sarpkaya, 2004; Williamson and Govardhan, 2004; Gabbai and Benaroya, 2005), the mixture of standing and travelling waves occurs in the VIV (Vortex-Induced Vibration) of a flexible riser which is far from being well understood (Vandiver et al., 2009). With the increase of the aspect ratio and flexibility of a marine riser, IFE (Internal flow Effect) becomes more significant which has attracted great attention over decades (Atadan et al., 1997; Chatjigeorgiou, 2010). IFE has been well investigated employing variable fluid-conveying pipes in the air (Païdoussis, 2014), and the critical value of internal flow velocity of a simply-supported one at which it starts losing stability by buckling depends on the rigidity and length of the pipe. Hence, the internal flow velocity may exceed the critical value of a highly flexible marine riser. This study is thus motivated to examine the IFE on the VIVs of a flexible riser in a transition range of internal flow velocity from being subcritical to supercritical.

Stimulated by the fact that internal flow induced forces (e.g., centrifugal and Coriolis accelerations) can cause additional vibrations in the course of pipe motions, IFE on VIVs has been analyzed by scaled experiments and simulations. For a cantilevered pipe discharging fluid, the VIV can be affected remarkably by the open flow from which the pipe can gain or lose energy Meng et al. (2017). For a pinned-pinned riser, it is measured that IFE can increase the vibration amplitudes and decrease the vibration frequency in scaled experiments (Guo and Lou, 2008). Keber and Wiercigroch (2008) investigated the effect of a weak structural nonlinearity on the dynamics of a marine riser undergoing CF (Cross-Flow) VIV, and demonstrated that the internal flow can increase the stiffness effect of structural nonlinearity. Meng and Chen (2012) examined the IFE on the CF

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http://dx.doi.org/10.1016/j.oceaneng.2017.04.039
Received 16 October 2016; Received in revised form 5 March 2017; Accepted 23 April 2017

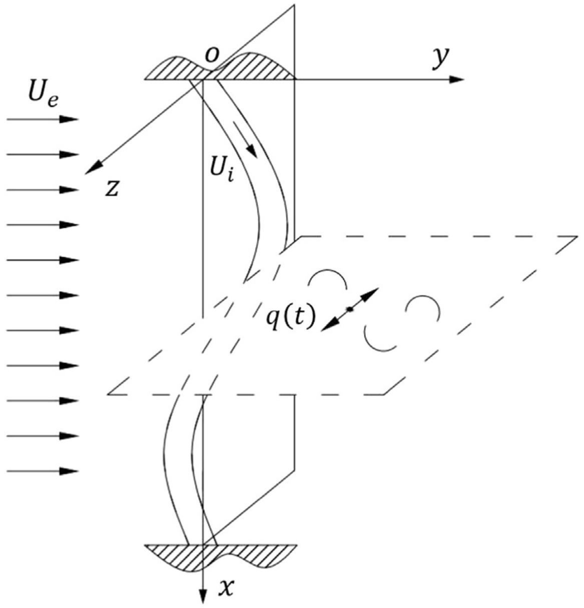

Fig. 1. Sketch of a fluid-conveying riser undergoing VIV.

VIV of a steel catenary riser in the subcritical region, and mode transition phenomenon is captured. A notable work was carried out by Dai et al. (2013) who simulated the CF VIV of a hinged-hinged pipe conveying fluid in the subcritical and supercritical regimes, and inverse period-doubling bifurcations, periodic and chaotic motions were observed. However, there are some inadequacies in Dai et al. (2013) (see Section 2.2) which is another motivation of this study. In this paper, the simulation model is elaborated in Section 2. In Section 3, efforts are devoted to validate the developed codes for VIV effect and IFE of both subcritical and supercritical flows. In Section 4, The CF VIV responses of a flexible riser subject to two uniform currents with the increase of internal flow velocity are examined. In Section 5, there is a discussion of this study and future works are also suggested.

2. Simulation model

2.1. Riser model and system coordinates

The sketch of a fluid-conveying flexible riser subjected to a uniform current is illustrated in Fig. 1. It consists of a pipe of length L with mass per unit length m_p, density ρ_r, bending stiffness EI and axial stiffness EA. The internal fluid has a mass of M_i per unit length of the riser with density ρ_i and a constant velocity U_i. The external flow has a mass per unit length of M_e with density ρ_e. The internal and external diameters of the riser are D_i and D_e respectively which are relatively small compared to L. Correspondingly, the internal and external cross-sectional areas of the pipe are A_i and A_e. The external imposed tension is assumed to be T_0. The origin of the adopted coordinates are set at the top end of pipe O. An arbitrary point of the pipe can be expressed as $(s,\ 0,\ 0)$ in Lagrangian coordinate in the initial undefromed state and $(x_0,\ y_0,\ z_0)$ in Euler coordinate in the deformed condition. The deformations of the riser can be expressed as $(x,\ y,\ z)$ where $x = x_0 - X,\ y = y_0,\ z = z_0$. There is an incoming current U_e in the y direction and if the pipe is vertical, g is the gravity acceleration in the x direction. In the following sections, a prime stands for $\partial()/\partial s$ and an overdot denotes $\partial()/\partial t$ where t is time.

2.2. Non-linear structural model

In the IFE study of a simply-supported pipe, researchers always utilize a linear lateral equation which can predict the subcritical dynamics very well including the critical internal flow velocity at which the pipe loses its stability by a static divergence (Païdoussis, 2014). However, when the linear analysis approach applies to the supercritical dynamics, a paradoxes arise for the existence of post-divergence coupled-mode flutter via the first and second modes, and great efforts have been devoted to resolve it (Sadeghi and Païdoussis, 2009). Holmes (1978) obtained a nonlinear equation of motion by adding to the linear equation a nonlinear term representing the mean, deformation-induced tensioning and concluded that pipes supported at both ends cannot flutter. There is no question that the pipes supported at both ends cannot flutter. However, attention must to be paid to the order of approximation recalling that a mistake has led Holmes (1977) to the opposite conclusion which demonstrates how sensitive this type of analysis can be (Païdoussis, 2014). In the study of IFE on VIVs by Dai et al. (2013), the structural nonlinearities are accounted for by simply introducing a nonlinear term resulting from the coupling with axial deformation, and the post-buckling dynamics were not justified for the supercritical IFE. Assuming the strains along the pipe are small recorded as the first order, Semler et al. (1994) have derived the equations of motion describing the coupling of axial and lateral vibrations exact to the third order. The nonlinear model has been corrected (Païdoussis, 2014) and utilized by Sadeghi and Païdoussis (2009) in the supercritical region.

In many experimental and simulation studies of VIVs, the offshore cylinder system can be modelled as a linear system and the nonlinearity effects are restricted only to the fluid force. The most commonly used prediction tools, e.g., SHEAR7 and VIVANA, are traditionally developed based on linear structural models and the interaction between different response frequencies is difficult to account for. A rigid structure with low aspect ratio is always modelled as a linear spring-mass-damper oscillator (Khalak and Williamson, 1996; Facchinetti et al., 2004; Langre, 2006), and a flexible one is usually simplified as a linear tensioned linear Euler beam (Huera-Huarte et al., 2006; Song et al., 2016). This is valid for a rigid cylinder with large stiffness and a flexible one with imposed a large tensile force as the nonlinearity characteristics are hidden. For long flexible risers (Srinil and Wiercigroch, 2009; Srinil, 2010) or one cylinder subjected to a stepped-current (Lucor et al., 2006), the dynamics would become intrinsically nonlinear in the course of oscillation. The shortcoming of linear structural model has been underlined and the significant role of geometric nonlinearities has been highlighted (Keber and Wiercigroch, 2008; Srinil, 2010; Srinil and Zanganeh, 2012; Meng and Wang, 2017). Therefore, a detailed description of the structure is needed despite the fact that the computational time would be increased. To account for the geometrical nonlinearities, the nonlinear partial-differential equations of a cable can be utilized (Srinil, 2010). Nonlinear terms with calibrated coefficients can be added to the linear structure and the jump phenomena may disappear if the added cubic nonlinear terms are omitted (Srinil and Zanganeh, 2012). Keber and Wiercigroch (2008) have introduced a term representing the coupling of lateral and axial displacements, and they find that the geometric nonlinearity has a stiffening effect on the oscillation of the riser which becomes more pronounced when the internal flow is incorporated into the model.

Referring to Païdoussis (2014) and Xu et al. (2008), the nonlinear structural model accounting for the buoyancy effect, which describes the coupling of axial and transverse vibrations, can be obtained as: