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Three-dimensional vortex-induced vibrations of supported pipes conveying fluid based on wake oscillator models

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ABSTRACT

The present study develops a new three-dimensional nonlinear model for investigating vortex-induced vibrations (VIV) of flexible pipes conveying internal fluid flow. The unsteady hydrodynamic forces associated with the wake dynamics are modeled by two distributed van der Pol wake oscillators. In particular, the nonlinear partial differential equations of motion of the pipe and the wake are derived, taking into account the coupling between the structure and the fluid. The nonlinear equations of motion for the coupled system are then discretized by means of the Galerkin technique, resulting in a high-dimensional reduced-order model of the system. It is shown that the natural frequencies for in-plane and out-of-plane motions of the pipe may be different at high internal flow velocities beyond the threshold of buckling instability. The orientation angle of the postbuckling configuration is time-varying due to the disturbance of hydrodynamic forces, thus yielding sometimes unexpected results. For a buckled pipe with relatively low cross-flow velocity, interestingly, examining the nonlinear dynamics of the pipe indicates that the combined effects of the cross-flow-induced resonance of the in-plane first mode and the internal-flow-induced buckling on the IL and CF oscillation amplitudes may be significant. For higher cross-flow velocities, however, the effect of internal fluid flow on the nonlinear VIV responses of the pipe is not pronounced.

1. Introduction

Vortex-induced vibrations (VIV) phenomena have been with us for a long time. They occur in many engineering situations, such as bridges, transmission lines, offshore structures, heat exchangers, marine cables, production risers, moored structures, pipelines, cable-laying, and other hydrodynamic and hydroacoustic applications [1]. Indeed, vortex-induced vibrations have been known as a typical type of truly self-excited and self-sustained oscillations.

In most instances, vortex-induced vibrations are annoying or damaging to structures and personnel and hence dangerous, e.g., leading to the fatigue of offshore risers, causing the large-amplitude deformation of tethered structures in the ocean, or the destruction of heat-exchanger tubes. These examples are but a few in a large number of problems where vortex-induced vibrations take place. As pointed out by Paidoussis [2], in some cases, the repaired and supposedly 'cured' fluid-loaded system failed also. Thus, understanding either the cause of vortex-induced vibrations or the techniques for suppressing VIV, or both,

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is urgent for reliable estimations of the fatigue damage and safety. As discussed by Paidoussis et al. [3], the physics of vortex-induced vibrations is rich in complexity, and modelling VIV is not a trivial task. Consequently, engineering applications, as well as fundamental issues, sustain continuing researches in this field.

The study of vortex-induced vibrations of slender structures, either rigid or flexible, has a fine pedigree. Many studies were concerned with the vortex-induced vibrations of circular cylinders and pipes due to their typical geometric shapes. The VIV response is a very complex phenomenon which has been established experimentally by many researchers. A series of experimental studies by Feng [4], Chen and Jendrzejczyk [5], Brika and Laneville [6], Sarpkaya [7], and Khalak and Williamson [8] on rigid circular cylinders, illustrating the main characteristics of VIV, are perhaps among the kaleidoscopic experiments pertinent to the topic at hand. For instance, the famous experiment conducted by Feng [4] was in air condition with a single-degree-of-freedom cylinder. Both the mass ratio (mass/displaced mass) and Reynolds number (*Re*) are relatively large in the experiments. Another notable experiment by Khalak and Williamson [8] was conducted, however, in water with a relatively small mass ratio and *Re*. Feng's experimental data indicates that at higher Reynolds numbers, the response amplitudes of the cylinder have two branches (initial and lower), while Khalak and Williamson's experimental results showed that at lower Reynolds numbers the VIV responses have three branches (initial, upper, and lower), with a much larger peak amplitude and a broader synchronization range of cross-flow velocity.

In the past decade, a number of experimental attempts have been made to evaluate the VIV problems of flexible cylinders/risers under different flow conditions and some also assessed the effectiveness of VIV suppression techniques. Among these experimental studies, various important aspects such as, VIV amplitude, dominant mode and frequency, coupling between cross-flow (CF) and in-line (IL) responses, and fatigue damage, were some of the problems considered. For instance, in the experiment performed by Trim et al. [10], the riser is of length-to-diameter ratio $L/D = 1407$ and the uniform current was simulated by towing the gondola in one direction using the crane. For cross-flow velocity equal to 0.4 m/s, it was found that the CF and IL resonance responses were respectively dominated by the third and fifth modes of the riser. Chaplin et al. [11] provided laboratory measurements of vortex-induced vibrations of a vertical tension riser in a stepped current. The riser, 28 mm in diameter, 13.12 m long and with mass ratio (m^*) of 3.0, was tested in conditions when 45% of the lower part was exposed to a uniform current at speeds up to 1 m/s, while the upper part of the riser was in still water. The cross-flow vibrations were observed at modes up to the eighth while the corresponding in-line vibrations up to the twelfth. In the experiment apparatus of Song et al. [12], the riser model was horizontally installed on a towing carriage at a water depth of 1.5 m. The uniform current was simulated by towing the riser at a constant speed. The distributions of the root mean square (RMS) of non-dimensional VIV displacements in CF and IL directions were obtained. It was shown that at low cross-flow velocity (0.4 m/s), both IL and CF resonance responses were dominated by the first mode, while at high cross-flow velocity (2.8 m/s) the IL and CF resonance responses were respectively dominated by the seventh and fifth modes of the riser. The insights obtained from these experiments can provide good benchmarks for verifying theoretical, empirical or numerical models.

Apart from the numerous experimental investigations, there have been a number of computational fluid dynamics (CFD) studies on the vortex-induced vibrations of rigid and flexible cylinders/risers. Many possible numerical methods, such as quasi-three-dimensional (Q-3-D) method [13], discrete vortex method (DVM) [14], fully 3-D finite element method (FEM) [15], finite volume method (FVM) [16], finite-analytic Navier-Stokes (FANS) [17], and etc., have been utilized to simulate the vortex-induced vibrations of cylinders subjected to cross flows. However, as pointed by Wang and Xiao [8], fully 3-D fluid-structure interaction (FSI) simulations of VIV of risers subjected to various flow conditions were still quite limited. Thus, a great deal remains to be done.

The third possible predictive tool for vortex-induced vibrations is the utilization of theoretical (empirical) models. These theoretical models are based on some experimental results, essentially the experimental data on vortex shedding from stationary or oscillating cylinders, aiming at predicting the lock-in phenomena and vortex-induced vibrations of straight cylinders/risers, and more complicated 3-D configurations of pipelines. Paidoussis et al. [3] have proposed an easily understandable classification of available theoretical models. The first type is the so-called ‘forced system models’, where the external hydrodynamic force is independent of the structural motions, and therefore only depends on time. This type of theoretical models is based only on data from experiment with a fixed cylinder. The second type is ‘fluidelastic system models’, which consider that the hydrodynamic force depends on the structural displacements, velocities, and/or accelerations. The third type is the ‘coupled system models’, in which the hydrodynamic force depends on variables related to the wake dynamics. At the same time, the evolution of wake is related to the structural motions. Thus, unlike the forced system models, the latter two models can incorporate data from experiments with oscillating cylinders. The major limitation of the former two types of models is that the formulation bears no relation to the physics of wakes as global modes [3]. The third type of modes, however, considers VIV as resulting from the coupling of the structure and the wake. In recent years, indeed, the coupled system models have been widely used to simulate vortex-induced vibrations of rigid/flexible cylinders and flexible risers/pipes.

The system under consideration in this paper is a flexible pipe/riser conveying internal fluid, as shown diagrammatically in Fig. 1. In the presence of external cross flow, the topic of dynamical behavior of fluid-conveying pipes has received considerable attention in the past years. Actually, the knowledge gained from studying such pipe models is of practical interest in ocean engineering.

Perhaps the only available experiment work on cross-flow-induced vibrations of flexible pipes conveying fluid is attributed to Guo and Lou [18], who initiated to measure the non-planar motions of clamped-clamped pipes partially immersed in external currents. The effect of low internal flow velocity was considered. The figure-of-eight for bending strain was observed