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Non-linear time domain analysis of cross-flow vortex-induced vibrations

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ABSTRACT

A previously proposed hydrodynamic load model for time domain simulation of cross-flow vortex-induced vibrations (VIV) is modified and combined with Morison's equation. The resulting model includes added mass, drag and a cross-flow vortex shedding force which is able to synchronize with the cylinder motion within a specified range of non-dimensional frequencies. It is demonstrated that the hydrodynamic load model provides a realistic representation of the cross-flow energy transfer and added mass for different values of the non-dimensional frequency and amplitude. Furthermore, it gives a reasonable approximation of the experimentally observed drag amplification. The load model is combined with a non-linear finite element model to predict the cross-flow VIV of a steel catenary riser in two different conditions: VIV due to a stationary uniform flow and VIV caused by periodic oscillation of the riser top end. In the latter case, the prescribed motion leads to an oscillating relative flow around the riser, causing an irregular response. The simulation results are compared to experimental measurements, and it is found that the model provides highly realistic results in terms of r.m.s. values of strains and frequency content, although some discrepancies are seen.

1. Introduction

Elastic cylinders in fluid flow experience structural oscillations caused by vortex shedding, known as vortex-induced vibrations (VIV) [1]. The classic example is the elastically mounted rigid cylinder in a steady incoming flow, free to oscillate in the cross-flow direction [2]. In the offshore industry however, one is typically concerned with VIV of long slender structures such as risers and free spanning pipelines. Here, the VIV response may consist of several higher modes, in-line and cross-flow oscillations, and a combination of traveling and standing waves [3]. In addition, the incoming undisturbed flow may vary along the cylinder span.

To accurately predict riser VIV, two things must be in place. The first is a mathematical model that, given the hydrodynamic forces acting on the structure, can accurately predict the structural response. Secondly, one must be able to calculate the hydrodynamic forces along the structure, which will depend on the motion of the riser. The first part of the problem can be handled using the finite element method (FEM). If non-linear FEM is utilized, potentially important effects such as large displacements, time-varying geometric stiffness and changing boundary conditions may also be dealt with. The second part of the problem can be solved using computational fluid dynamics [4], but the necessary computer resources are large. Therefore,

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alternative semi-empirical methods have been developed, such as VIVANA, VIVA and SHEAR7 [5–7]. These are based on hydrodynamic coefficients measured in experiments, which is combined with a structural model to predict the VIV response in the frequency domain. Because the analysis is performed in the frequency domain, these methods require a linear structural model and stationary conditions (i.e. constant current velocity in time).

The limitations of the frequency domain methods prohibit realistic modeling of some problems. As an example, consider a steel catenary riser (SCR) suspended from a floating platform. The top end will be subjected to wave induced motions, which will cause the riser tension, and hence the geometric stiffness, to vary with time. Close to the bottom, a segment of the riser will go in and out of contact with the seabed, causing time-varying boundary conditions. If the wave induced motions are sufficiently large, vortex shedding will initiate due to the relative oscillatory flow [8]. Hence, the VIV response can be stationary in some parts (due to current) while in other parts it may be intermittent (due to relative oscillatory flow). In addition, internal slug flow may also cause riser vibrations [9], which will interact with the VIV response. To capture all these effects, a non-linear time domain analysis is required.

Several models exist which can be used to simulate VIV in time domain. One such model is the wake-oscillator, which is based on the assumption that the lift coefficient can be described by a forced Van der Pol oscillator. This idea was first suggested by Bishop and Hassan [10], and has been modified by many others since then (see e.g. Ref. [11] for a review). Such models have been used in a large number of studies, for instance to investigate the behavior of flexible structures with geometric nonlinearities [12]. However, it is difficult to find a consistent set of wake-oscillator parameters suitable for both forced and free vibrations [13]. Other time domain models have been developed by Lie [14], Finn et al. [15], Mainçon [16] and Xue et al. [17].

An alternative semi-empirical model for time domain simulation of VIV has been under development by Thorsen et al. [18–22], and the present paper is a continuation of this work. In combination with a finite element model, it has been shown that the model can be used to predict VIV of elastic cylinders in various current conditions, including oscillating flow. In these previous studies, the structural model was linear, and the mean in-line drag force was not included. The purpose of the present paper is to introduce a non-linear finite element model (including non-linear soil contact) for the structure, and to include the mean in-line drag forces (and the associated displacements). This should enable highly realistic prediction of the dynamic response of risers and other slender structures due to ocean currents in combination with prescribed oscillatory motions and possibly other loads (ocean waves are not considered here). To illustrate the applicability of the proposed model, it is utilized to simulate the cross-flow VIV of an SCR in two different conditions. The first is VIV due to a stationary incoming uniform flow. Secondly, VIV caused by periodic oscillation of the riser top end is considered. The results are compared to experiments.

2. Hydrodynamic load modeling

2.1. Morison's equation

This paper considers the dynamic response of slender circular structures exposed to currents. In addition, the structure can have velocities and accelerations induced by other loads or prescribed motions. A strip theory approach is used, such that the hydrodynamic force on a cylinder cross-section is calculated from velocities and accelerations at the same cross-section only. The relevant velocity vectors and coordinate system for computing the hydrodynamic force on a cylinder segment is shown in Fig. 1. The relative flow velocity is $\mathbf{v}=\mathbf{u}-\dot{\mathbf{x}}$, where $\mathbf{u}$ is the incoming flow velocity and $\dot{\mathbf{x}}$ is the velocity of the cylinder cross-

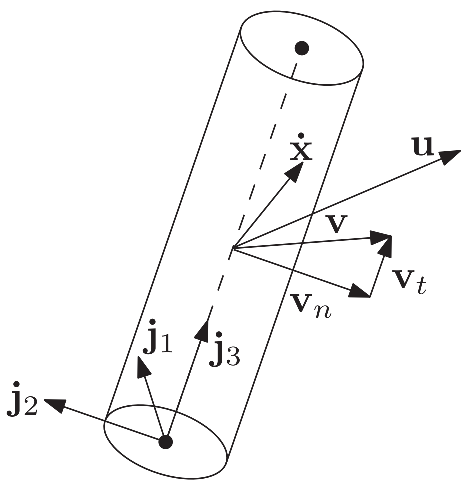

Fig. 1. A cylinder segment with local coordinate system and velocity vectors.