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An investigation into the hydrodynamics of a flexible riser undergoing vortex-induced vibration

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ABSTRACT

In this study, a method to obtain the hydrodynamic forces of a flexible riser undergoing vortex-induced vibration (VIV) based on measured strain is proposed. The tensioned riser is approximated as an Euler–Bernoulli beam, and an inverse method is adopted for the calculation of the hydrodynamic forces in the cross flow (CF) and inline (IL) directions. Based on these hydrodynamic forces, and combined with the VIV velocities and accelerations of the riser, the excitation and added-mass coefficients are obtained through a least-squares method. As an illustration example, the hydrodynamic characteristics of a flexible riser model undergoing VIV in a uniform flow are investigated. Results indicate that VIV leads to non-uniform distribution of the drag coefficient and amplifies the drag coefficient along the riser. Similar distribution of the energy transfer coefficient has been found between the entire riser and that of the CF direction. For synchronized VIV occurring in both CF and IL directions, the energy transferred from the fluid is all dissipated by the structural damping, and hence leads to the energy balance in both CF and IL directions. It further shows that the excitation coefficients on flexible riser undergoing VIV do not agree with those of the forced oscillation tests: excitation coefficients sometimes even become negative within the normally excitation regime, and are related with not only the non-dimensional frequency and amplitude but also the phase angles between the CF and IL vibrations. The added-mass coefficient of flexible risers does not keep a constant value of 1.0 anymore, but depends on the non-dimensional frequency and amplitude of vibration.

Introduction

As the exploitation of offshore oil resources moves into deeper waters, the risers transferring oil from the seabed to facilities on the surface are becoming increasingly slender (Basim and Mekha, 2011). Under the action of ocean current, vortices are generated and alternately shed from the sides of these flexible, slender risers. This vortex shedding leads to periodic pressure variation around the risers, producing a vortex-induced force. If the frequency of the vortex-induced force

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is near one of the natural frequencies of the risers, a significant vibration will be induced in the risers, which is normally termed as vortex-induced vibration (VIV). The vibrating risers would in turn affect the fluid flow distribution, which affects the distribution of the hydrodynamic forces along the risers. For instance, VIV can disrupt the hydrodynamic force distribution along the risers in the inline (IL) direction, and make the drag coefficient increase from 1.2 (the drag coefficient of a stationary, rigid cylinder at sub-critical Reynolds numbers) to 4.0 (Zhao and Wang, 2010).

Moreover, VIV in the IL and cross-flow (CF) directions are always strongly coupled. This kinematic coupling leads to an interaction of the vortex-induced forces in the two directions. Previous research has shown that VIV in the IL direction results in an additional peak in the excitation coefficient in the CF direction (Marcollo and Hinwood, 2006). Sumer and Fredsoe (2006) noted that when the VIV amplitude in the CF direction exceeds approximately 0.2–0.3*D*, the vortex shedding becomes ordered and the strength of the vortex shedding increases. The increase in CF VIV amplitude would also amplify the vortex-induced force in the IL direction. This observation suggests that CF and IL VIV coupling significantly complicates the hydrodynamics on the risers.

Since hydrodynamics of risers subjected to VIV are not well understood so far, a factor of safety greater than 10 is normally used in the riser design to prevent failure (API RP 2RD, 1998). However, with the development of oil and gas resources into deeper waters, the structural integrity of risers cannot be insured simply by increasing the safety factor. Hence, investigations into the hydrodynamic characteristics of flexible risers undergoing VIV, including the mean drag force in the IL direction and the vortex-induced forces in both CF and IL directions, are becoming more necessary.

Computational fluid dynamics (CFD) is an ideal method to study complex fluid-structure interaction problems such as VIV (Kaiktsis et al., 2007; Sarpkaya, 2004). Yamamoto et al. (2005) developed a quasi-3*D* model to investigate the hydroelastic behavior of oscillating, flexible cylinders and estimated the hydrodynamic forces using a discrete vortex method. Evangelinos et al. (2000) used a direct numerical simulation (DNS) based on spectral elements to simulate the 3*D* flow over rigid and flexible cylinders and calculated the hydrodynamic forces acting on a flexible cylinder. However, these numerical results have not been verified with experiments. Furthermore, CFD requires detailed meshes for both the fluid and the structure, which leads to large effort of computation. For example, one study involving a 6-meter-long riser required several months to complete (Chen et al., 2007). Hence, the use of CFD methods to analyze the hydrodynamic forces on a flexible, slender riser is still limited so far.

Several researchers conducted scale-model tests to investigate VIV and the hydrodynamic characteristics of flexible risers. Soni (2008), Yin and Larsen (2010) studied forced oscillations of a smooth, rigid cylinder, where the oscillations replicated the motion at various points on a flexible riser as measured from flexible riser model tests. Based on these experiments, the hydrodynamics of flexible risers undergoing VIV in uniform and shear flows were studied. The measured hydrodynamic loads on the cylinder in the CF and IL directions were proportional to those from an actual riser at the corresponding cross sections. However, this experimental method was based on strip theory, and the interactions between cross sections were ignored. The discrepancies between the results for the model and the actual flexible riser deserve further study. To predict the VIV in the CF direction more accurately, Mukundan (2008) parameterized the database of excitation coefficients obtained from the forced oscillation experiments of Gopalkrishnan (1993). Using an optimization method to minimize the error between the response from an empirical model of VIV and the test results, Mukundan (2008) established a new database of excitation coefficients in the CF direction. The new database had a larger excitation range, and the main excitation region overlapped the secondary excitation region. However, this method could not capture higher-order harmonic force components in the CF direction or the vortex-induced force in the IL direction. Huera-Huarte et al. (2006) analyzed the fluid forces by inputting displacement measurements at various sites into a finite element analysis of a vertically tensioned riser subjected to a stepped current. However, the coefficients of the vortex-induced force, including both the excitation and added mass coefficients, were not analyzed further. Wu et al. (2008, 2009) obtained the vortex-induced force on a flexible riser in the CF direction using an inverse estimation method based on a state-space formulation of a finite element beam model and an inverse method based on optimal control theory, respectively. However, the two methods were not employed to analyze the hydrodynamic forces on the riser such as the mean drag force and the vortex-induced force in the IL direction.

The existing database describing vortex-induced forces is based on forced oscillations of a rigid cylinder in only the CF or IL direction in a two-dimensional flow. An actual riser undergoing VIV, however, experiences kinematic coupling in the CF and IL directions and a three-dimensional flow field. The differences in the hydrodynamics of a rigid cylinder undergoing forced oscillations in a single direction and those of a flexible riser require further investigation. How to obtain the hydrodynamics more accurately requires more investigation.

In this study, a method to obtain the hydrodynamic forces and coefficients for a flexible riser undergoing VIV is presented. Vibrations of the riser in both CF and IL directions are described by on Euler–Bernoulli beam vibration equations. The CF and IL displacements, as well as velocities and accelerations, are obtained by modal superposition method based on measured strain signals. Consequently, the hydrodynamic forces in two directions, including the mean drag force in the IL direction and the vortex-induced forces in both CF and IL directions are obtained by inverse analysis procedures. Based on the VIV responses and the vortex-induced forces in two directions, a least squares method is further employed to calculate the hydrodynamic force coefficients in two directions, namely excitation coefficients and added-mass coefficients. The use of this proposed method is illustrated by the investigation of the hydrodynamic forces and hydrodynamic coefficients in CF and IL directions of a flexible riser undergoing VIV in uniform flows.