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Fatigue damage induced by vortex-induced vibrations in oscillatory flow

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A B S T R A C T

Vortex-induced vibration (VIV) of a flexible cylinder in oscillatory flow was experimentally investigated in an ocean basin. An intermittent VIV was confirmed to have occurred during the tests. The fatigue damage caused by VIV was calculated based on rain-flow counting and a standard S–N curve. There are 3 main observations for fatigue damage from VIV in oscillatory flow: 1) the damage varied significantly with the *KC* number, which is a unique feature for VIV in oscillatory flow. 2) Fatigue damage at small *KC* number cases was found to be larger compared to those at large *KC* numbers owing to the fact that number of vortex shedding cycles per half of the motion cycle is low, and damping within half of the motion cycle will hence become low. The fact that vortices from the previous cycle still are active during the next may also contribute to the large response at small *KC* numbers. 3) ‘Amplitude modulation’ and ‘mode transition’, two specific features for VIV in oscillatory flow, were found to have a strong influence on fatigue. Fatigue damage has also been calculated by an empirical VIV prediction model assuming that all cases have steady flow at an equivalent velocity. Finally, a simplified method for calculating fatigue damage from VIV in oscillatory flow based on steady flow conditions is proposed. A modification factor diagram is presented, but the scope of the present study is too limited to provide a good

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basis for a general model for this factor. A general model for how to apply results from constant current analysis to predict fatigue in oscillatory flow will therefore need further research.

1. Introduction

As oil and natural gas exploration and production extend to ever deeper waters, the cost of the riser systems and technological challenges increase rapidly. Use of steel catenary risers (SCR) is a potential solution for deep-water production systems. A steel catenary riser is a prolongation of a sub-sea pipeline attached to a floating production structure in a catenary shape. SCR lines are commonly subjected to fatigue loads, particularly in the touchdown zone, due to platform motions, waves and current. When the riser is exposed to fluid flow, vortices are generated in the wake of the riser. The alternate vortex shedding leads to oscillating cross-flow (CF) and in-line (IL) forces, which causes the riser to vibrate perpendicular and in-line to the ambient flow. Such vibrations are called vortex-induced vibrations (VIV), and will often be an important contributor to the fatigue damage of the riser system. VIV is also known to amplify drag forces. These issues have been thoroughly studied by researchers in the last three decades [1–13].

VIV can also occur at the sag-bend of a SCR due to the heave motions of the platform. The reason for this is that the riser will experience oscillatory flow due to its motions in still water. Heave-induced VIV was observed in the sag-bend close to the touch down point of a SCR from the model test performed by the joint industrial program called STRIDE [14]. Heave motions at various combinations of amplitude and frequency were applied at the top end of the SCR model. Intermittent VIV response and dynamic out-of-plane buckling were observed in the tests. The test results indicate that SCR and other types of Highly Compliant Rigid (HCR) risers can experience intermittent VIV induced by vessel heave motions, and the response will be influenced by soil structure interaction.

Another experiment with a steel catenary riser was performed by Gonzalez [15]. A small model representing the SCR on a semi-submersible was placed in a towing tank, and 48 out-of-plane forced motion cases with different amplitudes and frequencies were applied on its top end. The imposed harmonic motion at the top of the model was perpendicular to the SCR plane to minimize the influence of buckling close to the touch down point. The diameter of the riser cross-section was too small to apply accelerometers. Therefore, the reaction force at the top end of the SCR model was measured. The experiment revealed that resonance was observed when there was a match between at least two of the following frequencies: riser natural frequency, average shedding frequency and a multiple of the top motion frequency.

Sumer and Fredsøe [16] performed model tests to study the transverse vibrations of an elastically mounted rigid cylinder exposed to an oscillating flow. A *KC* number range from 5 to 100 and reduced velocity range from 0 to 16 were covered in the experiment campaign. The response characteristics of the cylinder were shown to vary extensively, depending on *KC* number as well as on the reduced velocity.

The most commonly used programs to predict VIV damage for slender marine structures are SHEAR7 [17], VIVA [18], and VIVANA [19]. These tools use empirical or semi-empirical solutions relying on hydrodynamic force coefficients found from VIV model tests, and the response is found by frequency domain analyses. Time domain VIV analysis tools have also been proposed [20,21], which requires proper coupling of the fluid loading and dynamic structural response. Numerical methods based on computational fluid dynamics (CFD) are also available. These solve the Navier-Strokes equation and apply the calculated pressure to a flexible beam model. However, very long simulation times are required, and some calibration of the software for high Reynolds number applications must be carried out. Despite the considerable research on VIV during the last decades, the whole process for predicting the load and response is still subject to a considerable amount of uncertainty. Therefore, high safety factors between 10 and 20 are required in the design process.

To the knowledge of the authors, there exists no riser analysis program for the prediction of heave-induced VIV for SCRs, partially due to the complexity of the problem. To further improve the