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A simplified method for time domain simulation of cross-flow vortex-induced vibrations

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ABSTRACT

A new method for time domain simulation of cross-flow vortex-induced vibrations of slender circular cylindrical structures is developed. A model for the synchronization between the lift force and structure motion is derived from already established data for the cross-flow excitation coefficient. The proposed model is tested by numerical simulations, and the results are compared to experimental observations. When a sinusoidal cross-flow motion is given as input to the algorithm, the generated force time series are generally in good agreement with experimental measurements of cross-flow force in phase with cylinder velocity and acceleration. The model is also utilized in combination with time integration of the equation of motion to simulate the cross-flow vibration of a rigid cylinder. The resulting amplitude and frequency of motion as functions of reduced velocity are compared to published experimental results. In combination with the finite element method, the model is used to simulate cross-flow vibrations of a flexible cylinder in shear flow. Comparison with experiments shows that the model is capable of reproducing important quantities such as frequency, mode and amplitude, although some discrepancies are seen. This must be expected due to the complexity of the problem and the simple form of the present method.

1. Introduction

Slender structures such as marine risers and mooring lines are subjected to vortex-induced vibrations (VIV) when placed in a current flowing around the structure. The vibrations are a result of the oscillating fluid forces arising from the shedding of vortices. Such vibrations may lead to rapid accumulation of fatigue damage, and it is therefore important for the safety of offshore operations such as drilling and hydrocarbon production to be able to predict the time varying stresses caused by VIV.

The topic of VIV has been subjected to extensive research during the second half of the 20th century, and much of the work has been reviewed by Bearman (1984), Sarpkaya (2004), Williamson and Govardhan (2004) and Wu et al. (2012). Studies have traditionally focused on the cross-flow oscillations and fundamental frequency response, however in more recent publications, authors have focused on cylinders free to oscillate in both transverse and in-line directions (Jauvtis and Williamson, 2004; Dahl et al., 2006) and higher order force and vibration components (Vandiver et al., 2006; Modarres-Sadeghi et al., 2010). It has also been recognized that the VIV response of risers can be chaotic, meaning that it is non-periodic with a broad band spectrum (Modarres-Sadeghi et al., 2011).

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When it comes to prediction of VIV for slender structures there is a large number of available methods, which according to Lie et al. (2011) can be divided into three classes: computational fluid dynamics (CFD), wake oscillator models and semi-empirical models. As demonstrated by Bourguet et al. (2011), CFD methods are promising, but generally complicated and computationally demanding. Wake oscillator models, as described by e.g. Facchinetti et al. (2004) use a Van der Pol oscillator to describe the wake. Results obtained using this model show a qualitative agreement with experimental observations, but it is difficult to find a set of parameters such that the model conforms to both free and forced vibrations (Ogink and Metrikine, 2010).

The most commonly used prediction tool in design of marine risers are the semi-empirical models, such as SHEAR7 (Vandiver and Li, 2005) and VIVANA (Larsen et al., 2009). The basis for these programs is the use of databases for hydrodynamic forces, e.g. added mass, damping and excitation (lift) coefficients. The formulation restrict these methods to stationary, harmonic response in the frequency domain, hence only linear structural behavior is allowed, and interaction between different response frequencies is difficult to account for. Also, these tools are unable to predict VIV caused by unsteady flows such as waves, and cross-flow and in-line motion is considered separately, neglecting the interaction between the two.

Semi-empirical time domain methods for simulation of riser VIV have been developed by Lie (1995) and Finn et al. (1999). A challenge with these methods is the need to estimate the vibration frequency of the riser for every time step, based on the previous time history. Recently, Mainçon (2011) proposed a totally new method for time domain prediction of VIV. He applied an artificial neural network in order to predict the instantaneous hydrodynamic force based on a compressed form of the recent velocity history. The results obtained in the study were promising, but in some cases the model adopted a non-physical pattern of vibration, indicating that the algorithm has stability issues.

In this paper, an alternative method for time domain prediction of VIV is presented. The most important element is the proposed synchronization model, which effectively simulates how the lift force changes its instantaneous frequency to obtain lock-in. Another key component is a new damping model, based on the model by Venugopal (1996), but put in an alternative form to avoid frequency dependence. Combined with a finite element model of the structure, the hydrodynamic force model makes a powerful tool for time domain simulation of VIV, and it is shown through numerical investigation that the method produces results very similar to those observed in various types of experiments. The formulation includes no restrictions on the time variation of the incoming current velocity, and therefore enables the study of VIV in waves and other unsteady flows, although this has presently not been investigated. The formulation also has potential for incorporating the interaction between cross-flow and in-line hydrodynamic forces and motion, as well as drag amplification and higher order frequency components. However, these issues will not be addressed further in the present research. In this initial stage of development, focus will be on cross-flow response in stationary flow.

2. Hydrodynamic force model

2.1. Hydrodynamic forces on circular cylinders

A cylinder placed in a flowing fluid will experience forces in the direction of the flow as well as perpendicular to the flow. The force component in the direction of the flow is called drag, while the perpendicular component is usually termed lift. For a single cylinder positioned in an otherwise undisturbed flow, the mean of the lift force is zero, while the drag force oscillates around a non-zero mean value. The case with a fixed cylinder in uniform incoming flow was thoroughly studied by Bishop and Hassan (1964) and many others since then, see e.g. Sumer and Fredsøe (1997) for a comprehensive review. In summary, the lift forces are a result of the fluctuating pressure which in turn is related to the vortex shedding process. It is found to vary almost sinusoidally with the same frequency as the vortex shedding frequency, $f_s = \mathrm{St}\, U/D$, where St is the Strouhal number, U is the incoming undisturbed fluid velocity and D is the cylinder diameter. Stochastic variations in amplitude and frequency are seen, hence the forces are only approximately sinusoidal. The drag force has a significant non-zero mean value, while the fluctuating part oscillates at twice the vortex shedding frequency with a small amplitude, only around 10% of the lift force (Hallam et al., 1977). The drag and lift force are usually expressed in terms of the non-dimensional coefficients $C_d = F_d/\left(\frac{1}{2}\rho D U^2\right)$ and $C_l = F_l/\left(\frac{1}{2}\rho D U^2\right)$ where ρ is the fluid density and F_d and F_l are the drag and lift force per unit length. The mean value and the amplitude of the coefficients are found mainly as functions of the Reynolds number and the cylinder's surface roughness, while the turbulence level in the incoming flow and specific experimental conditions such as aspect ratio, end terminations and blockage effects have some influence on measurements as well. Curves for the coefficients and the Strouhal number have been established through extensive research (see e.g. Norberg, 2003), though it should be mentioned that values for the lift coefficient from various researchers show significant scatter.

The complexity of the problem increases considerably when the cylinder is allowed to oscillate. This subject has perhaps been studied even more than the stationary cylinder case, and typical experiments consist of freely oscillating spring supported cylinders (Khalak and Williamson, 1999; Vikestad, 1998) and cylinders forced to move in specified patterns (Sarpkaya, 1978; Yin, 2013). The last category of experiments has served two purposes: To increase the understanding of the vortex-shedding process as well as to create a database of force coefficients which can be used in prediction tools. The reason why the moving cylinder case is more challenging to predict than the fixed case is that the cylinder motion disturbs the flow. The most important effect is possibly that the frequency of the vortex shedding may adjust itself, and synchronize

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