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Time domain model for calculation of pure in-line vortex-induced vibrations

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ABSTRACT

A time domain model for prediction of cross-flow vortex-induced vibrations (VIV) of slender structures with circular cross section has been under development since 2012. As an extension of this work, a time domain model for pure in-line VIV is here proposed, with the same underlying theory. The in-line force model, consisting of added mass, damping and excitation, is based on empirical data from forced oscillation tests of rigid cylinders. Damping and excitation is tuned to give the best fit of the excitation force coefficient calculated from experiments, whereas a strip theory approach is utilized to determine the force is phase with cylinder acceleration, i.e. added mass. The excitation force model represents the time varying drag force induced by vortex shedding, and consists of two frequency-regions with positive excitation. Within these regions the excitation force is able to synchronize with the response vibrations, so that energy is transferred to the cylinder. Numerical simulations are performed to compare the present model with experimental results of free oscillations of rigid and flexible pipes with circular cross section, in uniform current. For the flexible cylinder case, a simple linear finite element structural model is combined with the in-line force model. The numerical simulations and the experiments are seen to match fairly well, both concerning frequency content, amplitude ratio and dominating vibration mode. Some discrepancies are observed, mostly concerning amplitude ratio. However, due to the complexity of VIV as a phenomenon, and the simplicity of the present model, it is concluded that the results are satisfactory. Consequently, this paper shows that the original idea of synchronization between excitation force and cylinder response is seen to work, not only for cross-flow VIV, but for pure in-line VIV as well.

1. Introduction

Vortex-induced vibrations (VIV) is a fluid-structure interaction phenomenon experienced by a large variety of slender marine structures subjected to current. Viscous effects result in flow separation and vortex shedding on the surface of the structure and in the wake, which changes the pressure field and induces alternating lift and drag forces. As the body is free to move, vibrations may occur. VIV is a concern due to accumulation of fatigue damage and drag amplification. It is particularly important for the oil and gas industry where life time evaluation of free spanning pipelines and risers may be limited by VIV.

Research on VIV has been substantial over the last decades, both experimentally and numerically (Gabbai and Benaroya, 2005). Traditionally the cross-flow vibrations have been given most attention among researchers, as indicated in the reviews by Sarpkaya (2004) and Williamson and Govardhan (2004). This is probably due to significantly larger response amplitudes than what is observed in the in-line direction. However, in later years, in-line vibrations, and the combination of cross-flow and in-line VIV have

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become a larger focus area. In the review by Bearman (2011) a cylinder free to move in both transverse and in the undisturbed flow direction is compared to a cylinder constrained to vibrate in cross-flow only. On the experimental side (Dahl et al., 2010) performed free oscillation tests of rigid cylinders free to vibrate in cross-flow and in-line direction, and dual resonance was observed for a wide parametric range. Aronsen (2007) did forced harmonic motion tests, where the in-line amplitude was half the cross-flow amplitude. Flow velocity, phase angle and absolute value of the amplitude were varied. However, as also discussed by Larsen (2011), the study showed large scatter indicating the importance of higher harmonics. As part of the development of the Ormen Lange field on the Norwegian continental shelf, experiments were performed, and a study of combined in-line and cross-flow VIV for free spanning pipelines was carried out by Søreide et al. (2001) and Nielsen et al. (2002). Later, the experiments were used as basis for the Ph.D.-thesis by Aglen (2013).

Pure in-line VIV is important for free spanning pipelines in particular. As the frequency of the hydrodynamic force in the in-line direction is significantly higher than that of the transverse force, in-line vibrations are induced at lower current velocities. This was confirmed experientially by MARINTEK as part of the Ormen Lange field development reported by Huse (2001). Designed to avoid cross-flow VIV by sufficient structural stiffness, free spanning pipelines will mainly experience accumulation of fatigue damage as a consequence of pure in-line vibrations (Larsen, 2011). In King and Prosser (1973), King (1974) and Currie and Turnbull (1987), it is emphasized that vibrations in the flow direction is important for pile-supported marine structures, braced members, jacket legs and delivery tubes, as it can cause unpleasant working environment for the staff, but also fatigue failure and structural collapse. Pure in-line VIV was also studied by Aronsen (2007) experimentally, where rigid cylinders were given a forced harmonic motion. Post-processing of the results gave a description of added mass and excitation force as function of amplitude ratio and frequency, which can be used as basis for semi-empirical prediction tools of pure in-line VIV.

Even though there exist guidelines for analysis of VIV for free spanning pipelines and risers (DNVGL, 2006, 2010), the methods are inaccurate, designed to give conservative results. Hence more specialized analysis tools are developed. Numerical solution of Navier–Stokes equation can produce a complete picture of the fluid enclosing the structure, and can hence be used to calculate VIV. As an example, Bourguet et al. (2011) uses three-dimensional direct numerical simulation to analyze a long cylindrical tensioned flexible beam at low Reynolds number. In general CFD is extremely time consuming. Thus the engineering world still rely on semi-empirical models, where the hydrodynamic VIV forces are calculated from empirical coefficients. VIVA (Triantafyllou et al., 1999), SHEAR7 (Vandiver and Li, 2005) and VIVANA (Passano et al., 2014) are all semi-empirical VIV models solving the equation of motion in frequency domain.

Marine risers and free spanning pipelines are highly non-linear structures and can undergo large deflections and experience non-linear soil-pipe interaction. The frequency response method is limited to treat a linearised problem, so time domain is the preferred solution scheme with no restrictions in the structural modelling. Lie (1995), Finn et al. (1999) and Mainçon and Larsen (2011) have proposed VIV models in time domain, but none of which have been accepted as engineering tools by the industry. Also, the Van der Pol oscillator equation used to describe the fluctuating force coefficient, is utilized as basis for several numerical studies. Even for pure in-line VIV, a numerical study of a damped mass-spring model combined with a forcing term where the drag coefficient satisfies a Van der Pol equation, has been conducted (Currie and Turnbull, 1987).

During the last few years, a new semi-empirical time domain method for prediction of cross-flow VIV has been developed by Thorsen et al. (2014a). The model has later been extended, also to include in-line VIV in combination with transverse vibrations (Thorsen et al., 2014b). The way the excitation force synchronizes to the cylinder velocity to obtain lock-in, is the most remarkable aspects of this time domain model. In Thorsen et al. (2014a), the model is seen to produce realistic results for both forced and free oscillation tests of rigid cylinders, and free oscillations of flexible cylinders. Through several case studies, a high degree of realism is found for numerical simulations of flexible pipes with circular cross section in uniform and sheared current (Thorsen et al., 2014b, 2015a, 2015b), and in oscillating flow (Thorsen et al., 2016).

In this paper, a new semi-empirical time domain model for pure in-line VIV is proposed, strongly based on the cross-flow model by Thorsen et al. (2014a). The hydrodynamic force is modelled as the sum of damping, excitation and added mass tuned to fit empirical data by Venugopal (1996) and Aronsen (2007) in the subcritical flow regime. Hydrodynamic damping is modelled as frequency-independent, which simplifies the numerical code, and still produces a damping force in acceptable agreement with Venugopal (1996). Since pure in-line VIV is characterized by two separate regions of different vortex shedding processes, two excitation force terms are utilized. They can synchronize with the cylinder velocity for a frequency range determined from forced oscillation experiments by Arosen (2007), to provide energy to the cylinder under lock-in conditions. As the excitation force tries to synchronize with the cylinder velocity, there are time instants at which the excitation force is in phase with the acceleration. This contribution, plus an additional added mass term from potential theory of circular cylinder sections, provides the total force in phase with cylinder acceleration.

1.1. Circular cylinder subjected to current

A cylinder subjected to current will experience alternating vortex shedding for Reynolds number (Re) larger than 40 (Sumer and Fredsøe, 2006). If the cylinder is fixed, the Strouhal number ($St = \frac{f_v D}{U}$) gives the relationship between the vortex shedding frequency f_v, the diameter of the cylinder D, and the current velocity U. The Strouhal number depends on Reynolds number and the cylinder's surface roughness (Achenbach and Heinecke, 1981). At least in the subcritical flow regime, i.e. $300 < Re < 3.0 \cdot 10^5$ (Sumer and Fredsøe, 2006), the value is fairly constant and approximately equal to 0.2. The alternating vortex shedding changes the pressure distribution around the cylinder, and behaves approximately sinusoidal. This gives rise to fluctuating forces. The force component in