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Stochastic modelling of cross-flow vortex-induced vibrations

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ABSTRACT

Semi-empirical models are commonly used to predict vortex-induced vibrations (VIV). The empirical parameters are traditionally found from forced harmonic motion tests of short rigid cylinders in one degree of freedom, which is a significant simplification of the three dimensional VIV experienced by flexible cylinders. Still, the models may provide satisfactory estimates of the response of slender marine structures exposed to current. At least in terms of root mean square (r.m.s.) of displacements and strains, dominating frequency and dominating mode, accurate predictions are possible. However, VIV of long slender beams, especially in sheared current, show large response variability in time and space, which appears to be of a random nature. Semi-empirical models that predict steady-state VIV are hence unable to reflect the non-stationary response observed in experiments, even though the time and space averaged result might be well represented.

In this work, a previously published semi-empirical time domain model for cross-flow vortex-induced vibrations is modified to describe the stochastic nature of the response of long slender beams subjected to stationary current. The mean non-dimensional frequency of the synchronization model (previously constant) is taken to be a simplified Gaussian process, where standard deviation and spectral frequencies are input. The stochastic synchronization model allows the response to jump between different eigenfrequencies and corresponding modes, and still predict mean and r.m.s. values close to the deterministic model. Its performance is verified through simulation of an experiment with a long riser in sheared flow. The response sensitivity with respect to standard deviation and spectral frequencies is investigated. The study indicates that for a proper choice of empirical coefficients, the chaotic response of the riser can be quite realistically simulated in terms of frequency variation and, to some extent, amplitude modulation.

1. Introduction

Slender marine structures, such as anchor lines, risers and pipelines, need sufficient structural integrity in order to withstand forces induced by the ocean environment. As oil and gas exploration moves into deeper waters, ocean currents may become the main force contributor. When the current show a sufficient degree of stationarity, shear forces between the body surface and external flow will lead to flow separation and vortex shedding. The consequence is high frequency response, known as vortex-induced vibrations (VIV), acting to lower the fatigue life of slender structures significantly. It is hence important to have accurate VIV prediction tools in structural design.

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Even though a flexible slender structure exposed to a time independent current may seem like a fairly simple problem to address, extensive research tells a different story. The difficulty rise from a complex vortex shedding process which is highly three dimensional and turbulent even at fairly low Reynolds number. In addition, interaction between structural response and hydrodynamics makes the vortex shedding process completely different from that of a fixed structure. More than a decade ago, Sarpkaya [14] concluded that the experimental focus of VIV researchers was still on flexibly mounted rigid cylinders restricted to move in cross-flow only. Since then, several experiments with flexible pipes both in uniform and sheared current have been conducted [2,12,24], allowing for complicated phenomena such as multi-mode vibrations, combination of standing and travelling waves, interaction between cross-flow and in-line motion causing higher harmonics, and time and space variations in the response process [25]. Realistic modelling of the latter is the topic of this paper.

Time and space variability of high mode VIV has been experimentally examined by several authors. Modarres-Sadeghi et al. [10] utilized data from experiments by the Norwegian Deepwater Programme (NDP) of long slender risers [2], separating the response into three branches. The VIV could be entirely quasi-periodic with statistically stationary properties, in the sense that one frequency and mode occupied the entire structure for the whole time window, typically in combination with higher harmonics. Observations of other time signals showed a response consisting of time intervals of periodic motion, and other periods of chaotic response with a broad frequency spectrum and no clear peak frequency. The last branch of VIV was seen to be purely chaotic, without time windows of quasi-periodic motion. The variability of high mode VIV was also recognized by Baarholm et al. [1] after post-processing experimental data from a large-scale model test of a tensioned riser.

From the previous discussion, it is clear that high mode VIV of flexible pipes behaves rather chaotic, which suggests that prediction tools should be stochastic rather than deterministic. By Swithenbank [15], a concept called time sharing was introduced as a method to improve reliability of VIV prediction tools, such as SHEAR7 [22] and VIVANA [13]. The intention was to model time variability of dominating frequency, rather than a constant spatial variation, in cases where several natural frequencies were in range of excitation. Time sharing can be considered as a step towards stochastic modelling of VIV. However, it predicts periodic stationary response in the sense that the riser jumps straight from one frequency to another, and the time at each frequency is predefined. To quantify the length of the time intervals associated with each frequency, and how the vibration amplitude depends on frequency variability, Swithenbank and Larsen [16] used laboratory tests of a riser in uniform and sheared flow. As one single frequency would dominate a large portion of the pipe, high amplitude VIV was seen. When the dominating frequency experienced a shift in time, a multi-frequency response would develop, associated with a drop in amplitude of vibration. Swithenbank and Larsen [16] concluded that the energy contained in the system was a main driving factor in determining the duration of high and low amplitude state.

There has been other attempts to model the stochastic nature of VIV. For instance, a van der Pol wake oscillator with a random spatial parametric variation was developed by Mukundan et al. [11], in order to predict fatigue damage for the NDP experiments. This stochastic prediction tool was able to provide a rough estimate of fatigue damage found directly from the measurements. Lie et al. [9] proposed a method for analysis of combined cross-flow and in-line response, using a time sharing approach combined with a stochastic model of displacement amplitudes. The method was based on frequency domain analysis and could potentially include the effect of higher harmonics in addition to the fundamental frequency. However, the method needed data from experiments with simultaneous cross-flow and in-line VIV, which was not available at the time of publication.

The starting point of the stochastic VIV analysis presented below is a previously published semi-empirical time domain model. It has shown to produce realistic estimates of the structural response through simulation of several experiments of flexible pipes in uniform, sheared and oscillatory flow [17,18,20]. Recently, heave induced VIV of an SCR with non-linear bottom contact was simulated. The response was in good agreement with measurements [19]. The fundamental idea of the model is the way synchronization between hydrodynamic force and response is handled. For a (constant) range of non-dimensional frequencies, the hydrodynamic force will synchronize with the structural velocity providing a positive energy transfer from the water to the structure.

In this paper, the original semi-empirical time domain model is referred to as deterministic, and the new model as stochastic. The stochastic feature is to make the mid-point of the synchronization range a slowly time-varying Gaussian process. This allows the flexible pipe to shift between eigenfrequencies and their corresponding modes, in an attempt to model time and space variability measured in high mode VIV experiments. The stochastic process introduces two new empirical coefficients, i.e. the standard deviation and the upper limit of spectral frequencies included in the process. Sheared flow experiments with a bare riser from the NDP tests are used to verify the new stochastic approach against the measurements. Response sensitivity with respect to the two new empirical coefficients is performed, trying to realistically capture both amplitude modulation and frequency variations the riser experiences.

2. Deterministic hydrodynamic force model

The hydrodynamic loading per unit length was by Thorsen et al. [19] defined as:

$$\mathbf{F}_n = C_M \rho \frac{\pi D^2}{4} \dot{\mathbf{u}}_n - (C_M - 1)\rho \frac{\pi D^2}{4} \ddot{\mathbf{x}}_n + \frac{1}{2}\rho D C_D \left|\mathbf{v}_n\right| \mathbf{v}_n + \frac{1}{2}\rho D C_v \left|\mathbf{v}_n\right| (\mathbf{j}_3 \times \mathbf{v}_n) \cos\varphi_{\text{exc}}. \tag{1}$$