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New Model for Vortex-Induced Vibration of Catenary Riser

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ABSTRACT

This paper presents a new theoretical model capable of predicting the vortex-induced vibration response of a steel catenary riser subject to a steady uniform current. The equations governing riser in-plane/out-of-plane (cross-flow/in-line) motion are based on a pinned beam-cable model accounting for overall effects of bending, extensibility, sag, inclination and structural nonlinearities. The empirically hydrodynamic model is based on nonlinear wake oscillators describing the fluctuating lift/drag forces. Depending on the potentially vortex-induced modes and system parameters, a reduced-order fluid-structure interaction model is derived which entails a significantly reduced computational time effort. Parametric results reveal maximum response amplitudes of risers, along with the occurrence of uni-modal lock-in phenomenon.

KEY WORDS: Catenary riser; vortex-induced vibration; wake oscillator, fluid-structure interaction, reduced-order model; empirical coefficient; uniform current.

INTRODUCTION

Steel catenary riser (SCR) has become a primary candidate for future ultra deepwater oil/gas industry because it offers the most promising technological and commercial solution. One of the key issues in the analysis and design of SCRs is to estimate and control the fatigue damage due to vortex-induced vibration (VIV). Nevertheless, current industrial knowledge of VIV prediction is still based on an empirical science and on a simplified linearized model of straight (e.g., top-tensioned drilling/production) risers and pipelines. Therefore, many uncertainties arise when designing the SCRs which are actually flexible inclined cylinders, having initial sags and varying curvatures. As a matter of fact, SCRs are substantially different from top-tensioned risers (TTRs), in view of the current flow direction relative to the pipe axis, which is arbitrary and different from 90^o when the flow aligns with the SCR plane of curvature. Moreover, a slender long beam-cable system has multiple natural frequencies which potentially give rise to different in-plane/out-of-plane multi modes in cross-flow/in-line VIV.

Nowadays, numerous frequency and time domain tools for predicting nonlinear dynamic responses of straight vertical risers experiencing VIV are available in industry. In spite of this, the state-of-the-art comparisons of VIV responses still exhibit remarkable discrepancies (Larsen and Halse, 1997; Chaplin et al, 2005), and not much is really known about the VIV of SCRs. Perhaps, the simplest and cost-effective way to deal with the hydrodynamics and to recreate the associated fluid forces acting on the underwater cylindrical body is to implement a phenomenological wake oscillator model. Essentially, this empirical model contains some parameters deduced from experimental data.

In this study, we utilize a new nonlinear wake oscillator model of Skop and Balasubramanian (1997) which has been developed based on some experimental collections of both elastically-mounted rigid and flexible cylinders subject to uniform flow. It has recently been used in predicting the VIV responses of horizontally suspended cables (Kim and Perkins, 2002). To overcome some limitations of a typical vertical riser model, we propose a general and realistic theoretical model valid for SCRs with arbitrary sags and inclinations. By coupling the wake oscillators to the riser nonlinear equations, a reduced-order model governing the hydro/elastic-cylinder interaction is derived and solved in the time domain, based on the potentially vortex-induced modes. In particular, we aim to predict the uni-modal lock-in phenomenon and the attainable maximum amplitudes of SCRs due to both cross-flow and in-line VIV in a sub-critical flow range of the Reynolds number (Re).

FLUID-RISER INTERACTION MODEL

With reference to a fixed Cartesian co-ordinate system, Fig. 1 displays a 3-D continuum model of SCR connected from a stationary floating structure to a seabed with simply pinned-pinned supports. A horizontal offset X_H and water depth Y_H define a chord inclination angle of riser (i.e. $\theta_r = \tan^{-1} Y_H/X_H$). Riser properties are spatially uniform, with mass/length (m), viscous damping coefficient (c), hydrodynamic diameter (D), effective bending (EI) and axial (EA_r) stiffness. As an initial consideration, the steady incoming flow, having density (ρ) and normal velocity (V), is considered to be uniform in the Z^+-direction perpendicular to the SCR plane (XY) of initial equilibrium curvature. Following the Strouhal number (St) law, this entails a single natural frequency (rad/s) of vortex shedding or wake (ω_s) behind the stationary riser, i.e. $\omega_s = 2\pi \mathrm{St} V/D$, where St ≈ 0.2 for sub-critical flow.