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Nonlinear free vibrations and vortex-induced vibrations of fluid-conveying steel catenary riser

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ABSTRACT

This paper presents a model formulation that can be used for analyzing the three-dimensional vibration behaviors of an inclined extensible steel catenary riser (SCR). The virtual work-energy functional, which involves strain energy due to axial stretching and bending rigidity of the riser and virtual work done by the gravitational, inertial and external drag forces, is formulated. The method of Galerkin finite element is used to obtain the mass and stiffness matrices. Then the eigenvalue problem is solved to determine its natural frequencies and corresponding mode shapes. A new nonlinear model capable of analyzing the vortex-induced vibration of SCR in the ocean current was addressed. The unsteady hydrodynamic forces associated with cross-flow vibrations are modeled as distributed van der Pol wake oscillators. Depending on the vortex-excited out-of-plane modes and system fluid-structure parameters, the parametric studies are carried out to determine the maximum response amplitudes of SCR, along with the occurrence of the mode transition phenomenon. The obtained results highlight the effect of internal fluid velocities and top tension on the nonlinear dynamics of riser undergoing vortex-induced vibration.

1. Introduction

As one of cable-like structures, steel catenary risers (SCRs) are widely used in offshore installation, exploration and production. Because of their promising technological and commercial solutions, SCRs have become primary candidates used with floating production platforms for future ultra deepwater oil and gas industry.

In the literature, there are many papers related to slender riser analysis as reviewed by Refs. [1–3], but most of them omit the effects of bending stiffness, axial deformation and the influence of internal fluid. It is conceivable that the combined actions of all the effects become more important for behavior of extensible steel catenary risers. In such cases, those effects should be carefully examined, and large strain analysis is essential. However, hitherto a mathematical treatment for the large strain analysis that takes into consideration the combined actions of those effects has not been elucidated.

The influence of internal fluid on the dynamic behavior and stability of risers has been studied by many researchers in recent years. Reviews of these studies are briefly mentioned herein. Irani et al. [4] presented the dynamic analysis of risers with internal steady fluid and nutation dampers in three dimensions using finite element method. The results indicated that the internal fluid reduced the stiffness of marine risers, and provided a negative damping mechanism. Moe and Chucheepsakul [5] studied the effect of internal fluid on vertical risers neglecting a bending rigidity. They showed that the natural frequencies were slightly reduced at a low internal fluid rate but significantly reduced at a very high fluid rate; these results can also be seen in Refs. [6,7]. Patel and Seyed [8] studied the internal slug fluid induced vibration of flexible risers. They concluded that the effect of slug fluid was significant for moderate to large water depths or in the large pressure area, and the slug fluid caused additional source of cyclic fatigue loading. Wu and Lou [9] studied the effects of internal fluid and rigidity on riser dynamics using the singular perturbation technique. Seyed and Patel [10] presented a detail treatment on the equations governing internal fluid and pressure effects on the risers and showed an overlap in mode of action of pressure and internal fluid forces. Huang [11] derived the governing equation of kinematics of transported mass inside an extensible riser in three approaches. Chucheepsakul and Huang [12] investigated the effects of transported mass on riser equilibrium configurations with large displacements for the cases of specified top tensions and specified arc-length. Almost all of the aforementioned works, the studies were limited to the marine risers neglecting extensibility, this restriction may not yield an accurate analysis. Furthermore, the study of effect of transported

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mass on vortex-induced vibration of steel catenary risers has not been reported.

One of the key issues in the analysis and design of steel catenary risers in the ocean current is to estimate and control the fatigue damage due to vortex-induced vibration. In spite of the numerous frequency- and time-domain analysis tools for predicting nonlinear dynamic responses of risers undergoing VIV are available in industry, the state-of-the-art comparisons of VIV responses still exhibit significant discrepancies between theoretical predictions and experimental measurements [13,14]. More importantly, not much is actually known about VIV behavior of SCRs. A prediction of fatigue damage of SCR has been shown by [15] based on the combined use of mode superimposition and frequency-domain approach. It has been realized that higher mode contributions are quite important to the damage rate. Due to the lack of empirical data on VIV of inclined and curved cylinders, the STRIDE joint industrial project has been initiated [16,17] to perform advanced testing on the VIV of towed curved pipes with/without strakes in water-tank and open-water environment. The corresponding experiment data have subsequently been considered by [18] in order to validate the theoretical finite element modeling. Because the experiment provides highly amplitude-modulated signals whereas the analysis tool provides steady-state responses, they have encountered the difficulty in making a direct comparison between analytical and experimental results even in the case of uniform flow. As a result, some discrepancies occurred and a number of experimental observations could not be theoretically explained. Ref. [19] pointed out the significance of using the time-domain approach with the inclusion of structural nonlinearities in the VIV analysis of SCRs.

Recently, an investigation into vortex-shedding patterns and fundamental wake topology when the flow past a stationary curved circular cylinder has been carried out by [20,21]. As a result of pipe curvatures, the computational simulations highlight different kinds of wake characteristics depending on the pipe (convex or concave) configuration and its orientation with respect to (aligned with or normal to) the incoming flow. When the flow is uniform and normal to the curvature plane, the cross-flow wake dynamics of curved pipes behave qualitatively similar to those of straight pipes. This is in contrast to the case of flow being aligned with the curvature plane where wake dynamics change dramatically. For this reason, in our study, the current flow approaching the SCRs is assumed to be steady, unidirectional, uniform and aligned with the curvature plane of inclined cylinder (Fig. 1).

Several wake oscillator models have been proposed in the literature. The models generally have the following characteristics: The oscillator is self-exciting and self-limiting; the natural frequency of the oscillator is proportional to the free stream velocity such that the Strouhal relationship is satisfied, and the cylinder motion interacts with the oscillator. The modeler's desire is to obtain the equations of the cylinder oscillator and the fluid oscillator by independent means and then use them together to predict the response of the combined fluid–elastic system [22].

Hence it is the objective of this research: first to show how to formulate nonlinear models of steel catenary risers in Cartesian coordinate by relying upon the large strain theory; second to carry out the free vibration analysis by the linear dynamic model based on the nonlinear static analysis; next the vortex-induced vibration (a linear dynamic model which was nonlinear with respect to loads—the Matteo Luca Facchinetti wake oscillator model) under influence of different factors is investigated.

2. Geometrically nonlinear equations of riser motion

The following assumptions are stipulated in the present mathematical modeling to simplify the formulation and to focus on

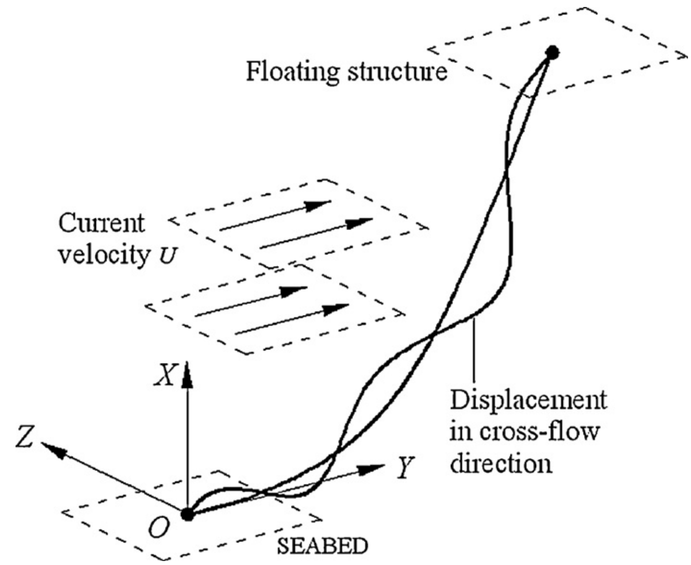

Fig. 1. A model of catenary riser subject to uniform current flow.

the critical effects induced by internal fluid, external flow and large extensibility, which produce differences between previously published models and the present one: the risers are sufficiently thick-walled to suppose that, ideally, their cross-sections remain circular after change of cross-sectional size due to the Poisson's ratio effect, so that the elastic rod theories are usable, and Brazier's effect or flattening of bent tubes is negligible; Longitudinal strain is large, but shear strain is insignificant for elastic rods with high slenderness ratio; The internal and external fluids are inviscid, incompressible, and irrotational. Their densities are uniform along arc lengths of the pipes.

2.1. *Deformation of riser*

With reference to the global Cartesian coordinate system, Fig. 2 depicts a general 3-D continuum model of SCR connected from a stationary floating structure to a seabed with simply pinned-pinned supports. A horizontal offset y_V and water depth x_H define a chord inclination angle of riser (i.e., $\theta_r = \tan^{-1} x_H/y_V$). Under the marine environment, only specified time independent loading (i.e., gravity force, static current and centrifugal force due to transported fluid) is considered, the riser forms a single catenary configuration with the unstreched state being its initial condition. Due to the extensibility, unstreched state translates to equilibrium, which is considered as an initial state of riser. Subsequently, due to the disturbances, such as wave, time dependent current, and internal fluid, the riser displaces to the third state. u_1 is the vertical displacement, u_2 and u_3 are the horizontal displacements in *XY* plane and *XZ* plane, respectively. The strain at any material point of riser is zero in the unstreched state, equal to ε_0, $\bar{\varepsilon}$ at the equilibrium and displaced state, respectively. The steady incoming uniform external flow, having density ρ_e and normal velocity U, is in the Y-direction collateral to the SCR plane (*XY*) of initial equilibrium curvatures. Following the Strouhal number S_t law of a stationary cylinder, the flow entails a single natural frequency (rad/s) of vortex shedding in the wake ω_f, i.e., $\omega_f = 2\pi S_t U/D$, where $S_t = 0.2$ being assumed for a sub-critical flow condition with $300 \prec R_e \prec 3 \times 10^5$ [23].

2.2. *Virtual work formulation*

2.2.1. *Virtual strain energies*

(1) The strain energy U_a due to axial deformation is caused by two actions: one is by the axial tension and the other is by the