



Analytical solution of mean top tension of long flexible riser in modeling vortex-induced vibrations

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ABSTRACT

The vortex-induced vibration (VIV) of flexible long riser with combined in-line and cross-flow motion has been studied using a wake oscillator in this paper. The analytical solution of mean top tension of long flexible riser is evaluated and compared with experimental results, and good agreement is observed to verify its validity. Then the nonlinear coupled dynamics of the in-line and cross-flow VIV of a long tension-dominated riser were analyzed through wake oscillator model with the consideration of variation of the mean top tension. The in-line and cross-flow resonant frequencies, lift and drag coefficients, dominant mode numbers, amplitudes and instantaneous deflections are reported and compared with experimental results, and excellent agreements are observed. The comparison of mode numbers between the calculation with and without consideration of variation of mean top tension shows that the proposed analytical solution of the mean top tension can produce a better prediction of multi-mode VIV.

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1. Introduction

Deep water, string-like, marine risers subject to strong ocean currents, suffer from vortex-induced vibration (VIV), where vortex shedding interacts with the structural properties of the riser, resulting in large amplitude vibrations in both in-line (IL) and cross-flow (CF) directions. When the vortex shedding frequency approaches the natural frequency of a marine riser, the cylinder takes control of the shedding process causing the vortices to be shed at a frequency close to its natural frequency. This phenomenon is called vortex shedding lock-in or synchronization. Under lock-in conditions, large resonant oscillations will reduce the fatigue life significantly.

Despite continued research work on the mathematical model of description of the VIV, the lock-in phenomenon has remained elusive. Computational fluid dynamic codes have been developed and are capable of capturing some insight of the VIV, but the large requirement of the computing capacity gives rise to the limitation of modeling the deep water riser, whereas in some cases the length has exceeded more than 1500 m.

Alternatively the semi-empirical model for VIV response analysis has been used prevalently in the engineering. These models normally use the hydrodynamic force coefficients as a database, such as drag coefficient, lift coefficient, added mass coefficient and hydrodynamic

damping coefficient. These coefficients are obtained from rigid cylinder model tests with forced motions. All these models are based on the assumption that in one mode there is a dominant resonant frequency. However, for the deep water risers, shear flow and travelling waves will cause multiple modes and dense spectrum of the response frequencies. Consequently, a safety factor has been used widely in the design of the risers.

A second type of semi-empirical model is the wake oscillator model which was created by Birkhoff and Zarantanello [1]. Instead of direct application of the measured fluid forces to the equation of structural motion, wake oscillator models couple the equation of structural motion with a nonlinear oscillator equation that describes the CF fluid force. Three different coupling terms, including acceleration, velocity, and displacement coupling, were evaluated by Facchinetti et al. [2]. Violette et al. [3] and Xu et al. [4] performed the VIV prediction along the spanwise extent of a slender structure under uniform flow, non-uniform flow and linearly sheared flow, and good agreement was achieved. The wake oscillator has been extended to predict IL dynamic response beside the CF response in recent literatures [5,6]. Guo et al. [7] and Li et al. [8] performed dynamic response analysis of VIV of a long flexible riser with the consideration of influence of top tension and internal flow, and the comparison with experimental results presented a successful application of such wake oscillator. Meng and Chen [9] implemented a wake oscillator model to analyze the three-dimensional vibration behaviors of an inclined extensible steel catenary riser (SCR). Srinil [10] successfully carried out numerical prediction of vortex-induced vibration of variable-tension vertical risers in linearly sheared currents through a wake oscillator model. A

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comparison between laboratory measurements and blind predictions of eleven different numerical models was carried out by Chaplin et al. [11] to analyze the capability of different numerical tools to predict VIV. The response prediction of Orcina wake oscillator code was between 85% and 105% of the corresponding measurements, which has the same capability of predicting CF displacements and curvatures as empirical models (such as VIVA, VIVANA, VICOmo, SHEAR7 and ABA-VIV), but better than the codes based on CFD (such as Norsk Hydro, USP, DeepFlow and VIVIC). Wake oscillators also have been shown to be able to model VIV of vortex-induced waves along cables [3,12].

Much work has been done for investigation of VIV prediction of long slender structures using wake oscillator model. However some of the important factors have not been evaluated quantitatively, such as the variation of top tension. The purpose of the present study is to present an analytical solution of the mean top tension of long flexible riser under vortex-induced vibration. The nonlinear coupled wake oscillator model has been used to simulate the dynamic response of long flexible risers. A comparison between model and experimental results from literature shows the validity of the present analytical solution.

2. Model description

2.1. Wake oscillator model

The marine riser model can be idealized as a beam with low flexural stiffness. The deflection of a generic beam is described by means of the Euler–Bernoulli beam equation. A Cartesian reference with its origin at the bottom of the riser has been used, in which the x axis is parallel to the flow velocity, z coincides with the vertical axis of the riser in its undeflected configuration and y is perpendicular to both (see Fig. 1). The dimensionless coupled fluid–structure dynamical system is represented as

$$\frac{\partial^2 y}{\partial t^2} + \left(\frac{r_s}{m\Omega_f} + \frac{\gamma}{\mu} \right) \frac{\partial y}{\partial t} - c^2 \frac{\partial^2 y}{\partial z^2} + b^2 \frac{\partial^4 y}{\partial z^4} = Mq, \quad (1)$$

$$\frac{\partial^2 q}{\partial t^2} + \varepsilon (q^2 - 1) \frac{\partial q}{\partial t} + q = A_s \frac{\partial^2 y}{\partial t^2}, \quad (2)$$

$$\frac{\partial^2 x}{\partial t^2} + \left(\frac{r_s}{m\Omega_f} + 2\frac{\gamma}{\mu} \right) \frac{\partial x}{\partial t} - c^2 \frac{\partial^2 x}{\partial z^2} + b^2 \frac{\partial^4 x}{\partial z^4} = N \left(C_{Dm} + \frac{C_{D0}}{2} g \right) \quad (3)$$

$$\frac{\partial^2 g}{\partial t^2} + 2\varepsilon (g^2 - 1) \frac{\partial g}{\partial t} + 4g = B_s \frac{\partial^2 x}{\partial t^2} \quad (4)$$

$$\frac{C_{Dm}}{C_{D0}} = 1 + 1.043 \left(\frac{2Y_{rms}}{D} \right)^{0.65} \quad (5)$$

where $y = Y/D$, $x = X/D$, and $z = Z/L$. D and L denote diameter and length of riser model, respectively. The time-averaged drag coefficient on a cylinder vibrating at or near the vortex shedding frequency is also a function of CF vibration amplitude [13], and some of them have been evaluated by Huang and Sworn [14]. The expression widely used for the increase in the drag coefficient with vibration is shown in Eq. (5) which is based on the results from field experiment with long flexible cylinders carried out by Vandiver [15]. This relation could couple the IL drag force with the CF response. Y_{rms} is the standard deviation of the anti-node displacement in diameters. The dimensionless tension c , bending stiffness b and mass number M , N are given by:

$$c^2 = \frac{T_{top}}{m\Omega_f^2 L^2}, \quad b^2 = \frac{EI}{m\Omega_f^2 L^4}, \quad M = \frac{C_{L0}}{2} \frac{1}{8\pi^2 St^2 \mu}, \quad N = \frac{1}{8\pi^2 St^2 \mu}. \quad (6)$$

q , g are reduced fluctuating lift and drag coefficients, $q = 2C_L/C_{L0}$, $g = 2C'_D/C_{D0}$; C_L denotes lift coefficient. We separate the drag

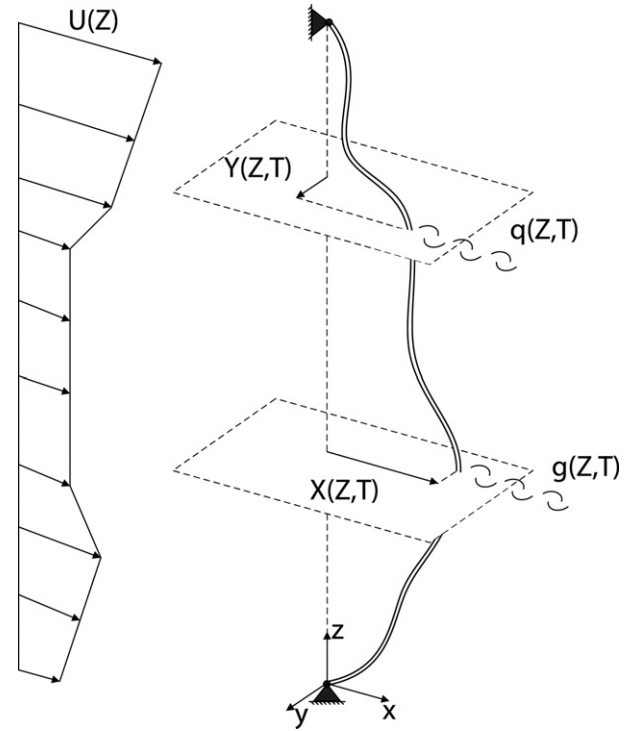


Fig. 1. Model of coupled structure and wake oscillators combining in-line and cross-flow motion.

coefficient C_D into two terms: one is the mean drag coefficient C_{Dm} and the other is the fluctuating drag coefficient C'_D . The C_{Dm} is the time averaged mean of the drag coefficient C_D and C'_D is obtained by removing the time averaged mean C_{Dm} , i.e. $C_D = C_{Dm} + C'_D$. The coefficients C_{L0} and C_{D0} denote amplitude of fluctuating lift and drag coefficients for a fixed rigid cylinder subjected to vortex shedding. The values of $C_{D0} = 1.5$ and $C_{L0} = 0.8$ were selected in all cases [13,16]. Ω_f and Ω_i are CF and IL reference angular frequencies, and $\Omega_i = 2\Omega_f$.

The values of the van der Pol parameter ε and scaling parameter A_s and B_s can be derived from experimental results from Facchinetti et al. [2]. Under the acceleration coupling model the value of ε is set as 0.3 according to a best-fitting on the lock-in bands for synchronization of vortex shedding with transverse cylinder vibration. The value of the combined parameter $A_s/\varepsilon = 40$ is proposed from a least-squares interpolation between lift magnification and the imposed structure motion amplitude, thus setting $A_s = 12$. $B_s = 3$ is an empirical coefficient in the present simulation.

The riser model was pin-ended, hence displacements and curvatures were zero at each end with the following set of boundary conditions:

$$y(0, t) = 0, \quad y(1, t) = 0, \quad x(0, t) = 0, \quad x(1, t) = 0 \quad \forall t \\ \frac{\partial^2 y(0, t)}{\partial z^2} = 0, \quad \frac{\partial^2 y(1, t)}{\partial z^2} = 0, \quad \frac{\partial^2 x(0, t)}{\partial z^2} = 0, \quad \frac{\partial^2 x(1, t)}{\partial z^2} = 0 \quad \forall t \quad (7)$$

2.2. The variation of mean top tension

As for a pin-ended cylinder towed in a water tank, the applied axial tension T_{top} is in fluctuation due to IL and CF vibrations. Using Hooke's Law, the mean top tension T_{mean} can be defined as

$$T_{mean} = T_{ini} + E A_c \frac{\Delta L}{L}. \quad (8)$$

where T_{ini} is initial tension force, $\Delta L = S - L$, L and S denote initial length and instantaneous length of the cylinder model, respectively;

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