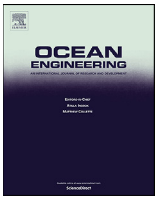
Ocean Engineering 148 (2018) 548–562

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng



Numerical analysis of Vortex-Induced Vibration for flexible risers under steady and oscillatory flows

Yuchao Yuan [a,b], Hongxiang Xue [a,b,*], Wenyong Tang [a,b]

[a] *State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University, Shanghai 200240, China*
[b] *Collaborative Innovation Center for Advanced Ship and Deep-Sea Exploration, Shanghai 200240, China*

ARTICLE INFO

Keywords:
Vortex-induced vibration
Flexible risers
Time domain
Steady flow
Oscillatory flow

ABSTRACT

Vortex-Induced Vibration (VIV) of flexible risers under unsteady flows is receiving increasing attention over the recent years. In this paper, an alternative time domain force-decomposition model for flexible risers is proposed to predict VIV response under both steady and oscillatory flows. Non-dimensional frequency range of [0.125, 0.25] is deemed as lock-in region. When lock-in occurs, the riser will be synchronized onto its own natural frequency closest to the non-dimensional frequency of 0.17. The hydrodynamic forces are time-varying and will be updated at each time step according to the riser's response amplitude and frequency. Firstly, the adopted lock-in region is verified well for uniform and sheared flow cases. Next, the same numerical model is also validated against experimental measurements when expanding to oscillatory flow conditions. VIV response with different *KC* numbers and maximum reduced velocities presents quite individual features, which can be reasonably explained from the VIV mechanism level. Then, the comparisons of VIV response between uniform and oscillatory flows are discussed and analyzed in essence. Finally, another large-scale riser is simulated under the designed oscillatory flows, and some new conclusions different from the small-scale risers are obtained.

1. Introduction

Vortex-Induced Vibration (VIV) of flexible risers in marine environment is a complicated fluid-structure interaction problem. When ocean current flows through, vortex would shed periodically around the riser, making the riser subjected to hydrodynamic forces. Due to the vortex shedding, the excitation force oscillates with a frequency $f_s = St \cdot V/D$ called Strouhal frequency, where D is the riser diameter and V is the current velocity. For a flexible riser, it will vibrate as a result of the oscillatory hydrodynamic forces, then disturb the surrounding flow and corresponding hydrodynamic forces. The most significant effect is that the vortex shedding may synchronize with the riser's motion, such that the frequency of the excitation force deviates from the expected Strouhal frequency. Consequently, the response amplitude would enlarge obviously, causing severe fatigue damage even structural failure. Therefore, it is imperative to make lots of efforts to broaden the understanding of VIV.

As there is still no well-accepted analytic method to solve the motion governing equations of viscous flow, experiments are the most effective source of the new insight of VIV mechanism temporarily. Typical laboratory experiments can be classified into free vibration of elastically mounted rigid cylinders (Song et al., 2016) and cylinder forced motions (Gopalkrishnan, 1993). Experiments with relatively long flexible structures were also performed, both under controlled simulation conditions (Trim and Braaten, 2005) and in field environments (Vandiver et al., 2006). These representative experiments are mainly in the view of steady flow situations. However, in the real marine environment, the subjected relative current velocity of the risers will generally be unsteady, either due to the wave-induced motion of top-end structures or the oscillations of incoming flow itself. VIV experiments under oscillatory flows had also been studied by several researchers for both rigid risers (Sumer and Fredsøe, 1988) and flexible ones (Fu et al., 2014). It turned out that VIV for risers under oscillatory flows presents more complicated features compared to steady flow situations.

There has been a sizable number of available methods to predict VIV response of slender structures, which can be divided into frequency domain and time domain approaches. The semi-empirical models such as SHEAR7 (Vandiver and Li, 2005) and VIVANA (Larsen et al., 2009) are the most recognized frequency domain prediction tools. Their prediction accuracy has been validated over the past decade. However, frequency domain approaches cannot take unsteady flow, moving boundary conditions, interaction between different response frequencies and

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[*] Corresponding author. State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University, Shanghai 200240, China.
E-mail address: hongxiangxue@sjtu.edu.cn (H. Xue).

https://doi.org/10.1016/j.oceaneng.2017.11.047
Received 24 July 2017; Received in revised form 20 November 2017; Accepted 26 November 2017

nonlinear structural behaviors into account. Therefore, time domain analysis is more considerable and applicable to a wider range of objects as well as conditions. CFD methods are potential and able to simulate different flow and boundary conditions, but generally complex and computationally demanding. Wake oscillator model usually uses a van der Pol oscillator to describe the wake. It was used by Chang and Isherwood (2003) to predict a riser's VIV under the unsteady flow generated by the platform heave motion. But like most wake oscillator models, how to find a set of controlled parameters such that the model can satisfy with diverse tests is still a difficult problem. Semi-empirical models have received increasing focus in the past years. Based on different forced vibration test data, Sidarta et al. (2010), Ma and Qiu (2012), Xue et al. (2015) and Yuan et al. (2017) successively developed several VIV time domain models. Liao (2001) developed a numerical method with reduced damping and wave propagation parameter to predict VIV of slender structures under unsteady flow. Resvanis (2014) recommended a non-dimensional parameter which can be used to determine whether the response under unsteady flow will be similar with that under steady flow. When it comes to the test validation for unsteady flow cases of numerical model, to the knowledge of the authors, it seems only Thorsen et al. (2016, 2017) developed a time domain semi-empirical approach and compared their numerical results with the test measurements of a TTR and an SCR under oscillatory flows. Therefore, such a research issue involved in this paper is still in its infancy at present.

VIV hydrodynamic force coefficients are the kernel of semi-empirical models. The formulations of the coefficients include no restriction on the time variability of the incoming current velocity. For an unsteady flow, it can be thought meeting steady flow condition during each tiny time interval. That means the existing hydrodynamic force coefficient databases available for steady flow cases should be theoretically applicable under unsteady flow situations, as long as the calculated time increment is short enough. In this paper, an alternative force-decomposition model of VIV for flexible risers is proposed to predict the structural response under steady and oscillatory flows. All the associated hydrodynamic force coefficients originate from forced vibration experimental data (Gopalkrishnan, 1993). The most important component is applying existing hydrodynamic force coefficient database to unsteady flow cases. Another novel attempts are improving hydrodynamic force formulation and adopting new lock-in region, making them perform well under oscillatory flows, no longer just applicable for steady flow cases in the previous researches. Moreover, the proposed numerical model is validated well against laboratory experiments under uniform, sheared and oscillatory flows respectively. This paper is structured as follows. Section 2 is the description of the proposed numerical model and analysis methodology. In Section 3, the experiments by Song et al. (2016) and Lie and Kaasen (2006) are used for comparisons to evaluate the prediction accuracy of the proposed model for steady flow cases. In Section 4, by comparing with the experiments in Fu et al. (2014), the same numerical model is proved compatible for oscillatory flow situations. The different VIV features between uniform and oscillatory flows are analyzed in Section 5, and the reasonable explanations for all the interesting response characteristics are given as well. Two designed oscillatory flow cases of the large-scale riser model in Trim and Braaten (2005) are simulated in Section 6 for the further investigation on VIV response under oscillatory flow. Finally, the main conclusions are drawn in Section 7. It is worth mentioning that the main contributions of this paper are not developing an original approach but improving the existing VIV semi-empirical model to handle more realistic and complicated unsteady (e.g. oscillatory) flow cases, explaining the time-varying response characteristics under oscillatory flow with the VIV mechanism, and revealing the universal features of VIV under oscillatory flow for a relatively large-scale riser.

2. Numerical model and analysis methodology

The proposed force-decomposition model originates from Wang et al. (2013) and Xue et al. (2015), nevertheless this paper improves the hydrodynamic force formulation and updates the lock-in region, making the present numerical model applicable for more extensive (including unsteady flow) cases.

A large aspect ratio of length to diameter is a universal feature of flexible risers. Thus, the riser can be considered as a flexural elastic structure satisfying the Euler-Bernoulli beam hypothesis. The governing differential equation for the riser in the cross-flow direction could be expressed as Eq. (1) in the Cartesian coordinate system, where x-axis is parallel with current velocity, y-axis is perpendicular to the incoming flow direction and z-axis is along the riser's axial direction.

$$\left(m+\frac{\pi}{4}C_a\rho_f D^2\right)\frac{\partial^2 y}{\partial t^2}+\left(c_s(f_r,t)+c_f\left(A^*,f_r,t\right)\right)\frac{\partial y}{\partial t} + EI\frac{\partial^4 y}{\partial z^4}-\frac{\partial}{\partial z}\left(T_a(z,t)\frac{\partial y}{\partial z}\right)=F_y\left(A^*,f_r,t\right) \tag{1}$$

where m is the mass per unit length of the riser, C_a is the added mass coefficient which is generally assumed as a constant e.g. 1.0 in this paper, $\rho_f$is the fluid density, c_s and c_f are the structural and hydrodynamic damping coefficients, $A^*$is the non-dimensional response amplitude to riser's diameter D respectively, $f_r$is the non-dimensional frequency equal to$f\cdot D/V$, $f$is the response frequency, E is the elastic modulus, I is the moment of inertia, T_a is the effective axial tension, F_y is the VIV excitation force.

The VIV excitation force F_y is in phase with the riser's velocity and depends on the response amplitude, vibration frequency and current velocity. Assuming that the excitation force acting on riser element follows sinusoidal rule in one period, it could be expressed as Eq. (2):

$$F_y=\frac{1}{2}C_V\left(A^*,f_r,t\right)\rho_f D|V(t)|V(t)\cos 2\pi ft \tag{2}$$

where C_V is the excitation force coefficient and V is the instantaneous current velocity.

Compared with the existing VIV semi-empirical models, Eq. (2) replaces$V^2$with$|V(t)|V(t)$to take the time-varying velocity and direction of unsteady flow into account.

2.1. Excitation force model

To obtain the excitation force coefficient C_V, a function of non-dimensional amplitude and frequency based on forced vibration experimental data is proposed. Gopalkrishnan (1993) carried out a series of cylinder forced vibration tests in MIT towing tank, and gave the contour of VIV excitation force coefficient. This database has been well verified and used by several relatively mature frequency domain software like SHEAR7 and VIVANA, but only limited to steady flow cases before this paper.

Fig. 1 is the contour of VIV excitation force coefficient in phase with velocity (Gopalkrishnan, 1993), where the thick line marks the important boundary corresponding to $C_V=0$. The non-dimensional frequency of VIV excitation center is approximately 0.17, where corresponds to the largest excitation force coefficient. Note that, when C_V is negative, the excitation force is deemed to transfer into hydrodynamic damping, which will be described in detail as follows. Strouhal number of this series of forced vibration experiments is 0.193.

2.2. Damping model

The total damping considered in the proposed VIV model consists of structural damping and hydrodynamic damping. The structural damping coefficient c_s is typically expressed in Eq. (3):

$$c_s=4\pi mf\xi \tag{3}$$

where$\xi$is the structural damping ratio.