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A time domain prediction method for the vortex-induced vibrations of a flexible riser

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ABSTRACT

In this paper, a time domain prediction method from experimental data is proposed for vortex-induced vibration (VIV) of flexible risers. The nonlinear factors, couplings among axial tension, VIV response in cross flow (CF) direction and the hydrodynamic force, have been taken into account in this method, with a simplified tension variation model and empirical hydrodynamic force model. The hydrodynamic force, including the excitation force in the excitation region and the damping force in the damping region are the function of excitation coefficients, non-dimensional VIV amplitude and frequency based on vibration experiment data. Iterations are performed to achieve balances between the hydrodynamic forces and the VIV responses of a riser. Moreover, a new added mass coefficient of 2.0 from model tests of flexible pipes is applied, where the predicted VIV response frequencies reveal higher accuracy. Comparison between the predicted results and the experimental results under uniform flow of 2.8 m/s and shear flow of 2.0 m/s are conducted, which verifies the feasibility and reliability of the proposed method. In addition, by comparing the prediction results with and without coupling between axial tension and VIV responses, it is found that this coupling effect is of importance to VIV prediction and can improve VIV prediction accuracy, especially under the case of high flow velocity and high vibration mode.

1. Introduction

As the exploitation of offshore oil resources moves into deeper water, risers are becoming increasingly slender. Under the action of ocean currents, vortices generate and alternately shed from the sides of flexible-slender risers. This vortex shedding phenomenon leads to periodic pressure variation around the riser, producing a vortex-induced force. If the frequency of the vortex-induced force is close to one of the natural frequencies of the risers, a significant vibration will be induced in the risers. This vibration is termed as vortex-induced vibration (VIV). VIV can result in severe fatigue damage in the riser and decrease its service life. Thus, it is important to accurately predict the VIV of risers.

There have been lots of available methods to predict VIV of slender structures, which can be divided into three types: computational fluid dynamics (CFD) method, wake-vibrator model and semi-empirical prediction method [15]. The CFD method is an ideal method to study the complex vortex-induced vibration problem [12,18]. The CFD method calculates the hydrodynamic force in the cross flow direction and in-line direction, and the vortex-induced vibration response is solved by the combined fluid force equation

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and the structural response equation of the beam. However, grid quality of the flow field and structure in CFD method should be very high, requiring particularly large amount of calculation. Even a 6 m test riser case would take several months for each flow velocity case [2,4–6]. Therefore, the CFD method is mainly used for the interpretation of some experimental phenomena. The practical applications in engineering projects also entail further studies and exploration.

The wake-vibrator model describes the fluid force generated by the wake flow field as a nonlinear Van der Pol equation. The structure responses of the riser are obtained by solving this equation as well as the structural vibration equation [8,11,13,32]. The main challenges for the wake-vibrator model are that the coefficients in the wake equation are empirical coefficients, and difficult to be determined.

The semi-empirical prediction method can be divided into the frequency domain method and the time domain method. The semi-empirical frequency-domain prediction method takes the “lock in” state of the riser as a research object, and the energy balance of the riser is obtained by the balance of “response amplitude-response frequency-hydrodynamic coefficient”. The semi-empirical frequency-domain prediction method has been widely used in marine engineering, and were developed as several industrial software, such as VIVA [14,23], VIVANA [14] and SHEAR7 [24]. However, these frequency domain prediction methods cannot take nonlinear factors into account, such as axial force variation, multi-frequency coupling, pipe-soil coupling and so on, which are coupled with the VIV response of flexible risers and are of vital importance to VIV prediction and fatigue analysis. Thus semi-empirical time domain prediction methods are proposed [16,20,21,28,29]. These methods mainly focused on the non-linear ‘lock-in’ criterion, and some of them take geometry nonlinearity of structures into consideration [22]. However, the hydrodynamic coefficients used in these method are still obtained from forced oscillations tests of rigid cylinders. Recently, some progresses have been made on the identifications of the hydrodynamics of a flexible pipe undergoing VIV by Ref. [19]; where large differences between the hydrodynamics identified from the flexible pipe and those from the forces oscillation tests have been observed. Therefore it becomes necessary to develop a base, where we can take the advantage of these new observations on hydrodynamic coefficients and implement them into the time domain VIV prediction models.

In this paper, a time domain prediction method from experimental data is proposed for vortex-induced vibration of flexible risers. A new added mass coefficient of 2.0 is used based on identified values from model tests of flexible pipes. Couplings between axial tension, CF VIV responses, and the hydrodynamic forces are considered via simplified tension variation model, and in this method. The hydrodynamic forces are further divided into excitation forces in excitation region, and damping forces in damping regions. Both of them are functions of hydrodynamic coefficients, non-dimensional VIV amplitude and frequency, which is the same as that used in hydrodynamic coefficients identification by Ref. [19]. Iterations are carried out to achieve balances between hydrodynamic forces and VIV responses of the riser. Comparison between predicted results and the experimental results under uniform flow of 2.8 m/s and shear flow of 2.0 m/s are conducted to verify the feasibility and reliability of the proposed method. The coupling effects of axial tension and VIV responses are further investigated.

2. A time domain prediction method

2.1. The prediction model

A submerged flexible riser with time-varying tension T is illustrated in Fig. 1. The central axis of the riser lies on the x-axis. The direction of the flow is parallel with the x-y plane and orthogonal to the riser. The governing equation of the riser can be represented as:

$$(M + M_a)\ddot{u}(t) + C\dot{u}(t) + (K_b + K_T)u(t) = F_{VIV,CF}(t) \tag{1}$$

Where M, and C are global mass matrix and damping matrix of the riser, respectively. The damping matrix C is obtained based on Rayleigh damping model, and natural frequencies of the first and second dominant modes are applied to obtain parameters of Rayleigh damping model. M_a is the added-mass matrix; a new added mass coefficient of 2.0 at each node of the riser is adopted, further description about added mass coefficients is presented in Section 2.6. The stiffness matrix K_b is the stiffness matrix contributed by bending stiffness while K_T is the time-varied stiffness matrix related to tension. And the tension variation is accounted in the stiffness matrix K_T and the detailed descriptions can be found in Section 2.2. $F_{VIV,CF}$ is the vortex induced force on the riser, which includes the excitation force under all excitation frequencies in the exciting region and the hydrodynamic damping force in the damping region in CF direction, as illustrated in Fig. 2.

In Eq. (1), u, $\dot{u}$, $\ddot{u}$ are the displacement matrix, velocity matrix and acceleration matrix of the riser, respectively. In this paper, IL VIV or the effects of these vibrations on CF VIV are not considered for the sufficient experimental data which obtained from CF and IL coupled VIV tests are unavailable. It is worth mentioning that this method can also be used to predict VIV in IL direction when the corresponding hydrodynamic coefficients are available. Thus, the FEM model is simplified into a 2-degree freedom model. The displacement vector, velocity vector and acceleration vector on node x_i at time t_j can be expressed as:

$$\begin{aligned} u(x_i, t_j) &= \{z(x_i, t_j) \quad \theta_y(x_i, t_j)\}^T \\ \dot{u}(x_i, t_j) &= \{\dot{z}(x_i, t_j) \quad \dot{\theta}_y(x_i, t_j)\}^T \\ \ddot{u}(x_i, t_j) &= \{\ddot{z}(x_i, t_j) \quad \ddot{\theta}_y(x_i, t_j)\}^T \end{aligned} \tag{2}$$

In this paper, the governing equation is solved step by step in time domain using the Newmark-β method with coefficients $\gamma = 0.5$