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Time-varying hydrodynamics of a flexible riser under multi-frequency vortex-induced vibrations

Chang Liu [a,b,c], Shixiao Fu [a,b,*], Mengmeng Zhang [a,b], Haojie Ren [a,b]

[a] State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
[b] Collaborative Innovation Centre for Advanced Ship and Deep-Sea Exploration, Shanghai 200240, China
[c] Department of Mechanical Engineering, Johns Hopkins University, Baltimore, MD 21218, USA

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ABSTRACT

This paper proposes the Forgetting Factor Least Squares (FF-LS) method for identification of time-varying hydrodynamics of a flexible riser under multi-frequency vortex-induced vibrations (VIV). Differing from the traditional least squares method used to identify hydrodynamics, with equal weights on all sampled data, this method introduces a forgetting factor to give higher weight to data closer to the present moment. FF-LS allows the possibility of handling the time-varying parameters. By following this procedure for all sampled data of a flexible riser undergoing multi-frequency VIV, the corresponding time-varying hydrodynamics in the Cross-Flow (CF) direction will be obtained considering multi-frequency coupling. The results show that, under multi-frequency coupling, vortex-induced force coefficients of flexible risers change periodically and differ from coefficients at the basic frequency usually used in VIV prediction. This difference is a result of the coupling effect between the basic frequency and high frequency. Time-varying coefficients considering multi-frequency coupling contain steady components and vibration components whose frequencies are the sum of coupling frequencies and the difference of coupling frequencies. To show the advantages of time-varying hydrodynamics, we compare forces reconstructed from different vortex-induced force coefficients, assuming vortex-induced force obtained from the inverse analysis is the real force. The results show that time-varying vortex-induced force coefficients considering a coupling effect between multiple frequencies can accurately reconstruct vortex-induced force, while the sum of vortex-induced force coefficients under multiple frequencies will produce the cross-term that overestimates the vortex-induced force.

1. Introduction

When predicting vortex-induced vibration (VIV) of a flexible riser, the construction of the vortex-induced force directly determines the accuracy of the VIV prediction results. The existing semi-empirical prediction models for VIV are based on the vortex-induced force coefficients database obtained from the one degree of freedom forced oscillation test of the rigid cylinder (pure CF or pure IL) (Gopalkrishnan, 1993; Larsen et al., 2007). The vortex-induced force coefficients database includes the excitation coefficient and added-mass coefficient.

In the real case, VIV exists in the in-line (IL) direction and cross-flow (CF) direction, and VIV in these two directions is strongly coupled. This coupling introduces strong coupling of hydrodynamics in the two directions as well. Through a low

* Corresponding author at: State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University, Shanghai 200240, China.
E-mail address: shixiao.fu@sjtu.edu.cn (S. Fu).

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mass-ratio two-dimensional free vibration experiment, Jauvtis and Williamson (2004) revealed the characteristics of VIV responses considering the coupling effect of the CF direction and IL direction. Differing from the VIV in the one-dimensional free vibration test, the 2T vortex shedding mode (a triplet of vortices being formed in each half cycle) in the wake vortex was observed. Dahl et al. (2007) further states that multi vortex patterns are the primary contributor for the high-frequency (third-order) component in the lift force. To obtain a database of VIV that more accurately predicts the VIV response in the CF direction of the riser, Dahl (2008) carried out the two-dimensional forced oscillations of rigid cylinders which provided the hydrodynamics coefficient database for the calculation of vortex-induced force, especially the third-order high-frequency forces. However, the database is relatively sparse, and the accuracy of the vortex-induced vibration predictions based on this database has not yet been validated.

The rigid cylinder forced oscillation test conveniently establishes a hydrodynamic coefficient database for vortex-induced vibration predictions, but the flexible riser differs from a rigid cylinder because of the coupling effect of the CF and IL direction and the three-dimensional flow field effect (Marcollo and Hinwood, 2006; Sumer and Fredsøe, 2006). For the flexible riser scaled model test, Vandiver et al. (2009, 2006) found a high-order response at three times the basic frequency in the CF direction and four times the basic frequency in the IL direction, which indicates high-frequency vortex-induced force exists in a real flexible riser. This high-frequency force causes high-frequency VIV response. Hu et al. (2014) also found the high-order response in laboratory experimental VIV signals from the Norwegian Deepwater Program (NDP) high mode test (Trim et al., 2005). Furthermore, Zheng et al. (2014) found that by including third-order higher harmonic components, there is a fatigue damage increase of up to 50% compared with the damage due to the first-order harmonic stress only and the fatigue damage increases by another 20% due to a wide-spread Power Spectrum Density (PSD). Using buoyancy elements and strakes also cause multiple lock-in frequencies to compete with each other (Fang et al., 2014; Li et al., 2013, 2011; Lie et al., 1998). Wu et al. (2016) obtained the vortex-induced force and its coefficients at the lock-in frequency in the CF direction of a riser using the beam finite element equation and the inverse analysis based on the optimal control theory. Focusing on the lock-in frequency, Song et al. (2016) used the method of modal analysis combined with the Euler beam dynamic response equation to analyze hydrodynamic force. Strain information measured from a flexible riser scaled model test is used to obtain the hydrodynamic characteristics at the lock-in frequency. For the vortex-induced force and VIV response at a single frequency, the hydrodynamic load is decomposed into excitation force in phase with the velocity and added-mass force in phase with the acceleration. These two force components are normalized to the excitation coefficient and the added-mass coefficient, respectively. Vortex-induced force coefficients obtained at a single frequency can be used to accurately reconstruct the hydrodynamic force at a specific frequency.

However, hydrodynamic characteristics of a flexible riser under the multi-frequency coupling are not considered in the papers mentioned above because effective analysis methods are not available. Using only vortex-induced force coefficients under a single frequency cannot accurately reconstruct the real vortex-induced force or predict the multi-frequency VIV precisely either.

This paper proposes the Forgetting Factor Least Squares Method (FF-LS) for identification of time-varying hydrodynamics of a flexible riser under multi-frequency vortex-induced vibrations (VIV). Differing from the traditional least squares method used to identify hydrodynamics (Song et al., 2016) with equal weights on all sampled data, this approach introduces a forgetting factor to give higher weight to data closer to the present moment (Section 2). FF-LS allows the possibility of handling time-varying parameters. By following this procedure for all sampled data of a flexible riser undergoing multi-frequency VIV (Section 3), the corresponding time-varying hydrodynamics considering multi-frequency coupling is obtained. Characteristics of time-varying vortex-induced force coefficients under multi-frequency coupling are also analyzed.

2. Time-varying hydrodynamics identification

2.1. Time-varying hydrodynamics identification method

When flexible risers undergo vortex-induced vibration, the frequency where the power spectral density of the VIV response in the CF direction reaches maximum value is regarded as the basic frequency (henceforth, all basic frequency is thus defined). Vibration in the CF direction usually consists of multi-frequency vibrations that are odd times of the basic frequency ω, 3ω, $5\omega\ldots$, while vibration in the IL direction consists of multi-frequency vibrations that are even times of the basic frequency 2ω, 4ω, $6\omega\ldots$. The vibrations that are three times or more of the basic frequency in the CF direction and four times or more in the IL direction are called high-frequency response (Vandiver et al., 2009). Recently, more complicated characteristics such as chaotic type motions are observed in the vortex-induced vibration of the long riser (Li et al., 2011; Zheng et al., 2014). Therefore, this paper considers more general cases, where we express displacement response time history of the riser in the CF and IL directions as follows:

$$\begin{aligned} y\,(z,t) &= \sum_i y(z,t,\omega_i) \quad i = 1, 2, 3\ldots \\ x\,(z,t) &= x_0(z) + \sum_i x(z,t,\omega_i) \quad i = 1, 2, 3\ldots. \end{aligned} \tag{1}$$

In the above equation, z is the axial position of a flexible riser, t denotes time, ω_i is the ith response frequency, $y(z,t,\omega_i)$ represents the time history of displacement at the position z in the CF direction at a single vibration frequency ω_i. Similarly,