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Wake oscillator model for assessment of vortex-induced vibration of flexible structures under wind action

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ABSTRACT

The wake oscillator model is considered to be the most proper semi-empirical model for qualitatively or even quantitively assessing the vortex-induced vibration of a structure in the design stage. However, the complexities in parameter determination limit its usage in real engineering fields. Moreover, this kind of model is traditionally used to describe the experimental phenomena of two-dimensional cross-section models, the gaps between the results of two-dimensional cross-section model tests and the prototype responses of the three-dimensional real structures should be filled up. In this paper, a detailed study of the wake oscillator model is firstly presented, which demonstrates the influences of model parameters on the VIV features described by the wake oscillator model. Then, a new method for conveniently identifying the model parameters in the wake oscillator model is proposed. Besides, a new procedure, based on the wake oscillator model, for interpreting the wind tunnel test results into real structures is also proposed. The results are validated by wind tunnel tests and compared with field measurements.

1. Introduction

Bluff bodies submerged in the flow fields are impacted by the periodically shedding vortices from their surface. The periodic shedding vortices can result in fluctuations in the pressures around the bluff body, which is characterized by the Strouhal number $S_t = fD/U$. When the frequency of vortex shedding is close to the structural natural frequency, "synchronization" or "locked-in" phenomenon occurs. The shedding frequency no longer follows the Strouhal law, but is entrained by the structural natural frequency in a limited range of flow velocities. The practical significance of vortex-induced vibration (VIV) has led to a large number of fundamental studies. These extraordinary studies have revealed some fundamental mechanisms of VIV. For example, different amplitude branches exist in the "lock-in" region, which is characterized by different wake modes; the phase jump phenomenon accompanies with the transition between these branches; the mass-damping parameter, Reynolds number, and some other parameters obviously influence the VIV of bluff bodies, etc. These studies are well discussed in some comprehensive reviews (Bearman, 1984; Billah, 1989; Gabbai and Benaroya, 2005; Sarpkaya, 1979, 2004; Williamson, 1996; Williamson and Govardhan, 2004).

Due to the nonlinearities in the fluid–structure interaction, vortex-induced vibration exhibits limit cycle oscillation (LCO). Even though VIV does not always cause a catastrophe, it seriously influences the fatigue life and may cause a loss of usability of the structure. Therefore, careful attentions should be paid to predict the VIV of a structure in the design stage.

To make a careful prediction of VIV in the design stage, the most direct way is to solve the Navier–Stokes equations rigorously with the presence of arbitrarily shaped moving boundaries. However, real domain VIV of flexible structures is characterized by structural eigenmodes and the spanwise coherence of VIV forces. From the numerical point of view, computational limits arise for simulating a three-dimensional (3D) flexible structure with large aspect ratio.

A compromising way is to adopt some mathematical models, based on "strip" assumption, to model the two-dimensional (2D) VIV force on a slice of the structure, and apply it on the 3D real structures. To model the 2D VIV force, one can adopt some advanced modeling techniques, like the reduced order modeling (ROM) techniques (Wu and Kareem, 2013), or adopt some semi-empirical models. The traditional semi-empirical models have very simple forms of formula and usually do not have special requirements on experimental or CFD calculation techniques. Thus, these kinds of models can be adopted to qualitatively or even quantitatively assess the VIV of real structures in the design stage.

The semi-empirical models, according to Billah (1989), can be divided into two main categories: the single degree of freedom

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models and the two degree of freedom models. The single degree of freedom models can be further classified into the negative damping models (D'Asdia et al., 2003; Goswami et al., 1993b; Larsen, 1995; Marra et al., 2011; Scanlan, 1981, 1998; Vickery and Basu, 1983) and the force-decomposition models (Griffin, 1980; Iwan and Botelho, 1985; Sarpkaya, 1978). The two degree of freedom models can also be further divided into two main subclasses: the wake oscillator models (Facchinetti et al., 2004; Hartlen and Currie, 1970; Skop and Griffin, 1973) and the Milan oscillator models (Diana et al., 2006; Falco et al., 1999).

Among these models, the wake oscillator model is considered to be the most proper semi-empirical model for simulating the VIV of bluff bodies. The wake oscillator model can simulate some basic features of VIV, such as limit cycle oscillation, "lock-in" phenomenon, and amplitude branches. However, the parameter determination for such kind of model is quite complex, which limits its usage in real engineering fields. Besides, the wake oscillator model is traditionally used to describe the VIV phenomenon of 2D structures, for example, the cross-section models. Nevertheless, there exists a gap between the results of cross-section model test and the prototype responses of the 3D real structure. This gap should be filled up when predicting the prototype responses of a 3D real structure through the results of 2D cross-section model test.

In this study, a new method for conveniently identifying the model parameters in the wake oscillator model is proposed. The model parameters in the wake oscillator model are determined through adjusting them to make the predicted amplitude branch by the wake oscillator model to best simulate the experimental results. Besides, a new procedure, based on the wake oscillator model, for interpreting the wind tunnel test results into real 3D structures is also proposed.

This paper is organized as follows: in Section 2, the wake oscillator model used for simulating the VIV of bluff bodies submerged in air is discussed in detail; in Section 3, the parameter determination method is proposed; in Section 4, this procedure is validated by wind tunnel tests; and in Section 5, the procedure for interpreting the wind tunnel test results into prototype responses of real structures is proposed.

2. Wake oscillator model

For a bluff body submerged in air, the structural equation can be expressed as

$$m\ddot{y}+2m\xi\omega_n\dot{y}+m\omega_n^2y=\frac{1}{2}\rho U^2D\left(\tilde{C}_L+H_1^*\frac{\dot{y}}{U}\right) \tag{1}$$

where m is the mass of the structure; ξ is the mechanical damping ratio; ω_n is the natural frequency; D is the structural characteristic length; ρ is the air density; $\tilde{C}_L$ is the fluctuating lift coefficient; y is the displacement from its equilibrium position; and U is the mean wind velocity. The flutter derivative H_1^*, which denotes the "stall" effects of the flow field, is assumed to be a constant in the "lock-in" region, as done by Scanlan (1998).

As to the flow oscillator, the traditional Van der Pol type is followed, which is defined as

$$\ddot{\tilde{C}}_L-\omega_sG\tilde{C}_{L0}\dot{\tilde{C}}_L+4\omega_sG\tilde{C}_L^2\dot{\tilde{C}}_L+\omega_s^2\tilde{C}_L=f(y,\dot{y},\ddot{y}) \tag{2}$$

where $\tilde{C}_L$ denotes the excitation effects of the shedding vortices; $\omega_s=2\pi S_tU/D$ is the Strouhal frequency; $\tilde{C}_{L0}$ is the magnitude of $\tilde{C}_L$ on fixed structures. $f(y,\dot{y},\ddot{y})$ can be Ay, $A\dot{y}$, or $A\ddot{y}$, which represent displacement coupling, velocity coupling, or acceleration coupling, respectively.

According to the study of Facchinetti et al. (2004), the displacement coupling fails in simulating VIV under both high and low mass-damping conditions; the velocity coupling can only simulate VIV under high mass-damping conditions; the acceleration coupling can simulate VIV under both high and low mass-damping conditions. However, for the acceleration coupling, the maximum amplitude occurs in a small region where the velocity variable $\delta=\omega_s/\omega_n$ equals to 1. Besides, both the upper and lower boundaries of the "synchronization" region vary with the mass-damping parameter. Nevertheless, according to the experiments conducted in wind tunnels (Ehsan and Scanlan, 1990; Goswami et al., 1993a), only the upper boundary of the "synchronization" region changes with the variation of the Scruton number (mass-damping parameter), which is in accordance with the results simulated by the velocity coupling. Moreover, the mass-damping parameter of bluff bodies submerged in air is much higher than those submerged in water. Thus, taking everything into account, the velocity coupling is more proper than the other two cases in simulating the VIV of bluff bodies under wind action.

The coupled structural and flow oscillators can be transformed into non-dimensional forms with respect to dimensionless displacement $Y=y/D$ and dimensionless time $\tau=\omega_nt$, as follows:

$$\begin{cases} Y''+2\xi Y'+Y=M\delta^2\tilde{C}_L+2\pi M\delta S_tH_1^*Y' \\ \tilde{C}''_L-\delta G\tilde{C}_{L0}^2\tilde{C}'_L+4\delta G\tilde{C}_L^2\tilde{C}'_L+\delta^2\tilde{C}_L=FY' \end{cases} \tag{3}$$

where the mass parameter M is defined as $M=\rho D^2/(8\pi^2mS_t^2)$. The notation $\delta=\omega_s/\omega_n$ denotes the ratio of the Strouhal frequency to the structural natural frequency. It can also be expressed as $\delta=S_tU_*$, where $U_*=U/(f_nD)$ is the reduced wind velocity. H_1^*, G, and F are model parameters.

3. Parameter identification method

3.1. Numerical study of the model parameters

Before proposing the parameter identification method, firstly, we have to study the influences of model parameters on the VIV features described by the wake oscillator model. Thus, the structural responses of the wake oscillator model under different values of model parameters are numerically calculated. The structural parameters like M and ξ are adopted in accordance with the experimental report by NAVSEA (Ng et al., 2001), where $M=0.002$ and $\xi=0.0015$. The Strouhal number S_t and the magnitude of fluctuating lift coefficient $\tilde{C}_{L0}$ are adopted in accordance with Facchinetti et al. (2004), where $S_t=0.2$ and $\tilde{C}_{L0}=0.3$. The velocity variable δ is gradually increased from 0.8 to 2 with an interval of $\Delta\delta=0.005$ to pass through the lock-in region, and is also gradually decreased from 2 to 0.8 with an interval of $\Delta\delta=-0.005$ to pass through the lock-in region. At each velocity δ_i, the wake oscillator model is numerically solved by the 4th-order Runge–Kutta method with an initial condition of $\left[Y_0=A(\delta_{i-1}),\quad Y'_0=0,\quad \tilde{C}_{L0}=0.3\quad\text{and}\quad \tilde{C}'_{L0}=0\right]$, where $A(\delta_{i-1})$ is the steady-vibration amplitude at δ_{i-1}. The dimensionless time step is 0.01, the dimensionless calculation time length is set to be 10,000 or more (if necessary) to reach the steady-vibration state. Results are shown in Fig. 1.

As illustrated in Fig. 1, the wake oscillator model has significant amplitude responses when gradually increasing the wind velocity to pass through the lock-in region and insignificant amplitude responses when gradually decreasing the wind velocity to pass through the lock-in region. These two different amplitude responses of the wake oscillator model are usually defined as the amplitude branches. The amplitude responses generated by increasing the wind velocity to pass through the lock-in region is defined as the initial branch, and the amplitude responses generated by decreasing the wind velocity to pass through the lock-in