Journal of Wind Engineering & Industrial Aerodynamics 170 (2017) 226–237

Contents lists available at ScienceDirect

Journal of Wind Engineering & Industrial Aerodynamics

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

Free vibration numerical simulation technique for extracting flutter derivatives of bridge decks

Fuyou Xu *, Zhanbiao Zhang

School of Civil Engineering, Dalian University of Technology, Dalian, 116024, China

ARTICLE INFO

Keywords:
Flutter derivatives
Free vibration
Numerical simulation
Bridge aerodynamics

ABSTRACT

A numerical simulation technique based on computational fluid dynamics (CFD) for determining the time-varying histories of free vibration displacements, velocities, and aerodynamic forces of bridge decks is presented. The weak coupling method is used to address the problem of fluid-structure-interaction (FSI). The flutter derivatives can be conveniently extracted using the numerically simulated displacements, velocities, and aerodynamic forces, which is similar to the procedure adopted in the forced vibration method. First, the identification accuracy of flutter derivatives is validated by comparison with the theoretical results for an ideal thin plate. Then, the flutter derivatives of two typical bridge deck sections, one streamlined and one bluff, are extracted by the proposed method. The results of the streamlined section show good agreement with other methods. However, for the bluff section, noticeable discrepancies exist between different methods. The mean angle of incidence in the free vibration method is shown to be responsible for these disagreements. The strengths of the newly-proposed approach are compared with those of the numerical and experimental forced vibration and experimental free vibration methods. This convenient and effective approach may serve as a building block for extracting flutter derivatives and better understanding of the aeroelastic responses of long-span flexible bridges.

1. Introduction

The flutter derivatives of bridge decks are critical parameters for flutter, buffeting, and vortex-induced vibration analyses of long-span flexible bridges. Rigid section models are commonly used to extract the flutter derivatives by using three conventional methods, i.e., the wind tunnel free vibration (Sarkar et al., 1994, 2009; Gu et al., 2000; Chen et al., 2002; Ding et al., 2010; Bartoli et al., 2009), the wind tunnel forced vibration (Falco et al., 1992; Noda et al., 2003; Chen et al., 2005), and the forced vibration numerical simulation (Walther and Larsen, 1997; Vairo, 2003; Mannini et al., 2016; Zhu et al., 2007; Xu et al., 2014a, 2016).

In wind tunnel experiments, flutter derivatives can be identified by free vibration and/or forced vibration technique. For the free vibration method, rigid section models are suspended by springs. Firstly, the natural modal parameters (mass, mass moment of inertia, frequencies, and damping ratios) at zero wind speed are extracted to construct the initial state-space matrix of the system. Secondly, the oscillating displacements at different (reduced) wind speeds are recorded to further construct the corresponding state-space matrices. Finally, the flutter derivatives can be extracted by subtracting the initial matrix at zero wind speed from the state-space matrices at a given (reduced) wind speed. However, the signal quality decreases at higher wind speed, and noticeable added angle of incidence may be incurred.

For the forced vibration method, a complicated driving apparatus is involved to force the rigid deck model to sinusoidally vibrate with specified frequencies and amplitudes. Force-measuring or pressure-measuring instruments are used to record the time-varying aerodynamic forces, and then the flutter derivatives can be extracted by using the appropriate methods such as the least-square method (LSM). Compared with the free vibration technique, where common acceleration and/or displacement sensors are sufficient to obtain the required data, the forced vibration apparatus are more complicated and expensive. A high-frequency balance or electronic scanning valve and acceleration or displacement sensors are needed to simultaneously record the time-varying signals. In order to reduce the inertial forces, and to increase the wind speed and vibration frequency, the models should be as light and rigid as possible. In fact, weight and rigidity are mutually exclusive, so that it is very challenging to design a light-weight and high-rigidity model. Admittedly, the extraction procedure for the sinusoidal constant-amplitude forced vibration is more convenient than that of the free vibration technique. However, the specified sinusoidal constant-amplitude forced vibration only corresponds with the critical flutter

* Corresponding author.
E-mail address: fuyouxu@dlut.edu.cn (F. Xu).

http://dx.doi.org/10.1016/j.jweia.2017.08.018
Received 18 April 2017; Received in revised form 25 August 2017; Accepted 27 August 2017

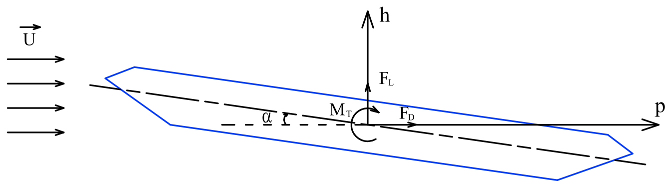

Fig. 1. Wind actions on a 2D bridge deck section.

state. For most cases, the vibrations are the exponentially modified sinusoidal styles, and the corresponding divergent or convergent ratio may have influence (more or less) on flutter derivatives, and this influence cannot be considered or involved by using the constant-amplitude forced vibration. Fortunately, the accuracy of flutter derivatives determined under constant amplitude motion is acceptable for decaying and building-up oscillations with not high damping ratios.

For the numerical simulation approach, the forced vibration style has been used for identifying the flutter derivatives. With the aid of computational fluid dynamics (CFD), at the given wind speed, oscillating frequency and amplitude, one can obtain the synchronous time-varying aerodynamic forces, displacements, and velocities. Then, the flutter derivatives can be extracted by the same way as that used for the experimental forced vibration method. Compared with the experimental one, the numerical technique has the following advantages: (1) A specialized testing apparatus is unnecessary, leading to greater convenience and lower cost; (2) The inertial forces are not included, and the quality of the aeroelastic forces and moments can be easily ensured. (3) Numerically-obtained sinusoidal oscillations can be very precise, whereas in wind tunnel tests, deviation between the prescribed and the real oscillations is unavoidable.

However, the simulation accuracy of the numerical method also suffers certain suspicions, and the results seem to be not so convincing as those of experimental ones. The simulation accuracy depends on facets of the numerical modeling method such as mesh generation, turbulence model, and parameter settings. Nevertheless, many papers (Šarkić et al., 2012; Brusiani et al., 2013; Xu et al., 2014a,b) have verified that the numerical simulation technique guarantees desirable identification accuracy, especially for the streamlined deck sections. The traditional sinusoidal constant-amplitude forced vibration cannot reflect the real vibration behavior of bridge decks due to dampings. Based on the forced vibration method, Xu et al. (2016) investigated the influence of the oscillation decaying/diverging ratio (ξ) on the flutter derivatives of several typical deck sections by adopting exponentially modified sinusoidal oscillations. Results showed that the influence is non-negligible when $|\xi| > 0.1$.

To the authors' knowledge, no research has been conducted so far on the free vibration numerical simulation approach for identifying flutter derivatives. This study, for the first time, attempts to comprehensively investigate its feasibility and reliability. The numerical simulation of free vibration of bridge deck models will be elaborated in Section 2. The flutter derivative extraction procedure is introduced in Section 3. Further, Section 4 provides the extraction results, and compares with the theoretical and/or other numerical/experimental results. The advantages and disadvantages of the free vibration numerical simulation technique are summarized in Section 5. Finally, some concluding remarks are addressed.

2. Numerical simulation of free vibration

2.1. Governing equations for fluids

The 2-dimensional (2D) incompressible, transient airflow past a bridge deck can be solved by Reynolds Averaged Navier-Stokes (RANS) equations combined with the shear stress transportation (SST) $k-\omega$ turbulence model, which was developed by Menter (1994). In the present study, the Arbitrary Lagrange-Euler (ALE) formulations are used for governing equations in consideration of the dynamic mesh. By introducing the grid moving velocity u_{mi} along the *ith* coordinate direction, the ALE formulations for the mass and momentum conservation equations for incompressible flow can be expressed as:

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho (u_i - u_{mi})}{\partial x_i} = 0 \tag{1a}$$

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho \left(u_j - u_{mj}\right) u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu_{eff}\frac{\partial u_i}{\partial x_j}\right) + S_i \tag{1b}$$

where x_i and u_i are the *ith* coordinate in Cartesian coordinate system and fluid velocity component, respectively; $\rho$and$p$are the fluid density and the fluid pressure, respectively; S_i denotes the additional momentum source contributions, if any; μ_{eff} is the effective viscosity which includes both laminar and turbulent contributions.

2.2. Governing equations for a bridge deck

The position of a 2D rigid section model can be defined in terms of three components, i. e., p, h, α, where p and h are the translation displacement in lateral and heaving directions, respectively; α is the angular displacement about the centroid of the section, as shown in Fig. 1. The influence of the lateral motion p on the aeroelastic drag force, lift force, and twist moment are considered to be insignificant in most cases, thus p is omitted herein for brevity.

The aerodynamic equations for 2D analysis of a bridge deck can be expressed as:

$$m\left(\ddot{h} + 2\omega_{h0}\xi_{h0}\dot{h} + \omega_{h0}^2 h\right) = F_L \tag{2a}$$

$$I\left(\ddot{\alpha} + 2\omega_{\alpha 0}\xi_{\alpha 0}\dot{\alpha} + \omega_{\alpha 0}^2 \alpha\right) = M_T \tag{2b}$$

where $\dot{h}$ and $\ddot{h}$ are the heaving velocity and acceleration, respectively; $\dot{\alpha}$ and $\ddot{\alpha}$ are the angular velocity and acceleration, respectively; m and I are the mass and mass moment of inertia per unit length of deck model, respectively; ω_{h0} and $\omega_{\alpha 0}$ are the heaving and torsional natural circular frequencies, respectively; ξ_{h0} and $\xi_{\alpha 0}$ are the heaving and torsional mechanical damping ratio, respectively; F_L (upward, positive) and M_T (clockwise, positive) are the aerodynamic lift force and torsional moment, respectively.

2.3. Solutions for the fluid-structure interaction

The non-coupling method, weak coupling method, and strong coupling method are three major methods to solve the problem of fluid structure interaction (FSI). The non-coupling method solves the flow field and the structural equations separately, which is usually used in the situations where the modal mass is sufficiently large and the fluid and structure coupling effect is negligible. The strong coupling method solves all the variables in both CFD frame and computational structural dynamics (CSD) frame simultaneously, which is more reasonable theoretically. However, it is unfeasible in many cases for its tremendous costs of computation time. The weak coupling method uses a staggered calculation technique, which means that the CFD frame and CSD frame are alternately solved at each time step. It shows higher computational efficiency compared with the strong coupling method and provides a flexible connection between the existing developed fluid and structural solvers. In this paper, the weak coupling method is adopted for the simulation of free vibration. The flow field is solved by the commercial program *ANSYS Fluent 14.0*, and the structural dynamic equations are calculated using the fourth-order hybrid linear multistep scheme (Zhang et al., 2007).

The numerical simulation procedure in this paper includes three