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Nonlinear aerodynamic forces on thin flat plate: Numerical study

Lin Huang [a,b], You-Lin Xu [b,*], Haili Liao [c]

[a] School of Civil Engineering, Ningbo University of Technology, Ningbo, Zhejiang 315016, China
[b] Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong, China
[c] School of Civil Engineering, Southwest Jiaotong University, Chengdu, Sichuan 610031, China

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ABSTRACT

This paper first presents a numerical simulation of nonlinear aerodynamic forces on a thin flat plate through an integration of the computational fluid dynamics (CFD) method and the forced asymptotic oscillation method. The thin flat plate is forced to have either asymptotic torsional oscillation or asymptotic vertical oscillation of increasing amplitude. A multiple-domain mesh technique together with unstructured dynamic meshes is used in the CFD simulation to accommodate large amplitude oscillations of the plate. The instantaneous frequencies and amplitudes of the aerodynamic forces are then identified from the simulated asymptotic aerodynamic force time histories using the continuous wavelet transform (CWT) in terms of the CWT ridges. Extensive numerical studies are finally performed to examine the feasibility of the proposed approach. The results show that the CFD method used in this study can properly simulate nonlinear aerodynamic forces on the plate. The amplitude of the aerodynamic force depends on the amplitude of the forced oscillation and there are high-order harmonic aerodynamic forces of higher frequency than the forced oscillation frequency, both indicating the nonlinearity of aerodynamic forces. The results also show the flutter derivatives associated with self-excited aerodynamic forces depend on the amplitude of forced oscillation in addition to reduced velocity.

1. Introduction

Linear aerodynamic force model is widely used in traditional buffeting and flutter analysis of long-span cable-supported bridges, but this linear model may fail to completely address the challenges posed by aerodynamic nonlinearities and turbulence effects (Kareem, 2008) on modern cable-supported bridges with increasing span. Diana et al. (1999) proposed a nonlinear aerodynamic force model to investigate turbulence effects on flutter and buffeting response and to incorporate frequency dependent characteristics. This nonlinear model was then validated by their experiments using an active turbulence generator (Diana et al., 2005). To address nonlinear aerodynamic forces, Chen and Kareem (2001, 2003a) separated the aerodynamic forces into the low- and high-frequency components in accordance with the effective angle of incidence. Conventional flutter and buffeting analysis is then retained for high frequency components with the low-frequency dynamic angle of attack considered. One of the unresolved issues with this approach concerns the identification of the demarcation between the low and high frequencies (Wu and Kareem, 2011). Zhang et al. (2002) considered the effects of large deformations of the bridge deck caused by mean wind forces on aeroelastic behaviour of the bridge. Later,

* Corresponding author. Tel.: +852 27666050; fax: +852 23659291.
E-mail addresses: tl_723_hl@163.com (L. Huang), ceylxu@polyu.edu.hk (Y.-L. Xu), hlliao@home.swjtu.edu.cn (H. Liao).

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Diana et al. (2008) further proposed a rheological model in the time domain to reproduce nonlinear aerodynamic forces due to large changes in the angle of attack caused by turbulence and deck motion. They carried out wind tunnel experiments to verify this rheological model (Diana et al., 2010). Wu and Kareem (2011) utilized the artificial neural network framework with the embedded cellular automata scheme to capture the hysteretic nonlinear behaviour of aerodynamic systems.

When the nonlinear aerodynamic force model proposed by Chen and Kareem (2003a) is applied to a long-span suspension bridge, a gradual growth in response with increasing wind velocity around its flutter onset velocity is observed (Kareem, 2008). This numerical finding is similar to wind tunnel observation of vibration of a full-bridge aeroelastic model in turbulent flows around its flutter onset velocity, and such a large amplitude vibration around the flutter onset velocity is called a soft-type flutter (Chen and Kareem, 2003b). Because of large amplitude oscillations of a bridge deck during soft-type flutter, the aerodynamic forces cannot be properly predicted by the linear aerodynamic force model even though the effect of low-frequency dynamic angle of attack is considered. It is therefore necessary to investigate nonlinear aerodynamic forces on a bridge deck during soft-type flutter. Actually, in recent years nonlinear aerodynamic forces on airfoil or flap with large-amplitude oscillation have been investigated using the computational fluid dynamics (CFD) method (Amiralaei et al., 2011; Lu et al., 2013) and wind tunnel experiments (Lee and Su, 2011). As a first step of investigation, this paper selects a thin flat plate as a bridge deck configuration to determine nonlinear aerodynamic forces on the plate with large amplitude oscillation by integrating of the CFD method and the forced asymptotic oscillation method.

The CFD methods have been successfully applied to determine aerodynamic forces on various types of bridge decks in small amplitude motion. One of the widely used CFD methods is the grid method, which includes the finite difference method (Fujiwara et al., 1993), the finite volume method (Vairo, 2003), and the finite element method (Jeong and Kwon, 2003). To simulate the motion of a bridge deck in the grid method, two dynamic mesh algorithms are often used. In the first algorithm, all the meshes in the computational domain synchronously move with the bridge deck model while the relative motion of wind flow to the model is considered through the transformation of coordinates (Fujiwara et al., 1993). In the second algorithm, the shapes of meshes close to the deck model are deformed at each iteration time while the connectivity of all the nodes remains unchanged (Vairo, 2003). Since large amplitude oscillation of the plate is considered in this study, the above two dynamic mesh algorithms may not be efficient and an improved algorithm called the domain decomposition algorithm proposed by Huang et al. (2009) will be used in this study. This algorithm was further applied by Brusiani et al. (2013) to extract the aerodynamic derivatives of a bridge deck. Similar dynamic mesh strategy was used by Fransos and Bruno (2006) and Bruno and Fransos (2008). Furthermore, considering of the concerned soft-type flutter, an asymptotic oscillation of varying amplitude rather than a harmonic oscillation of constant amplitude is applied to the thin flat plate in this study.

The previous experimental results also show that the motion amplitude would affect the self-excited forces on the plate (Noda et al., 2003). Therefore, the continuous wavelet transform (CWT) rather than the fast Fourier transform (FFT) will be used to extract instantaneous features of nonlinear aerodynamic forces on the plate. Haase and Widjajakusuma (2003) used the complex Morlet wavelet (Grossman and Morlet, 1985) to analyse the transient vibration behaviour of structures. Wang. et al. (2007) applied the complex Morlet wavelet to investigate the non-stationary features of flow-induced forces on two side-by-side oscillating cylinders. Curadelli et al. (2008) also selected the complex Morlet wavelet to detect structural damage by means of the instantaneous damping coefficient identification. The complex Morlet wavelet will be used in this study to identify the instantaneous frequencies and amplitudes of the aerodynamic forces on the thin flat plate from the simulated aerodynamic force time histories.

2. Numerical simulation of nonlinear aerodynamic forces

2.1. Dynamic mesh algorithm

To determine nonlinear aerodynamic forces on an oscillating thin flat plate of large amplitude with uniform flow inlets, a dynamic mesh algorithm – called the domain decomposition algorithm – is used in this study (Huang et al., 2009). The domain decomposition algorithm has been validated by the wind tunnel test results of typical bridge deck sections in forced harmonic oscillation of small amplitude and by the theoretical results for thin flat plates (Huang et al., 2009). This method has also been applied to identify flutter derivatives of a bridge deck in a linear combination of multi-frequency oscillations and validated by wind tunnel test results (Huang and Liao, 2011). The two-dimensional computational domain of the thin flat plate is shown in Fig. 1. To ensure the computation accuracy of aerodynamic forces on the plate, a circle domain is created surrounding the plate. Very fine and fixed structured quadrangular meshes are assigned within this domain to connect the plate, and the whole circle domain has the same movement as the plate during its oscillation. To accommodate large amplitude motion of the plate, a small rectangular domain is then created to cover the circle domain. Between the rectangular domain and the circle domain is a dynamic mesh region, in which triangular meshes are used. The size of dynamic mesh region is determined by the plate width and its oscillation amplitude. The meshes in this region will be deformed at every iteration time step. The size and shape of the triangular mesh are adjusted according to the early work of Batina (1990). Finally, a large rectangular domain is created to cover the dynamic mesh region with relatively coarse and fixed structured rectangular meshes.