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Investigation on influence factors of buffeting response of bridges and its aeroelastic model verification for Xiaoguan Bridge

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ABSTRACT

A time-domain procedure for analyzing buffeting responses of bridges is presented and implemented in ANSYS, formulated taking into account the self-excited forces, aerodynamic admittance functions (AAFs) and the coherence of buffeting forces. The buffeting forces simulated based on the span-wise coherence of buffeting forces and also considering the aerodynamic admittance functions, together with the steady aerodynamic forces are applied as external loads to the structural model to analyze the buffeting responses in time domain. In order to account for self-excited forces, elemental aeroelastic stiffness and aeroelastic damping matrices for spatial beam elements are derived following the quasi-steady theory and are incorporated in buffeting analysis through the user-defined *Matrix27* element in ANSYS. The procedure is applied to the Xiaoguan Bridge, China, during the longest double cantilever stage of construction. The wind tunnel tests of four typical bridge section models are performed to measure the aerodynamic parameters of the bridge including the steady aerodynamic coefficients and aerodynamic admittance functions. The bridge aeroelastic model testing is also carried out, and coherence functions of buffeting forces are derived from the measured buffeting forces. The measurement results of the displacements and internal forces are compared with those obtained from the analytical predictions. The influence factors, including aeroelastic effect, aerodynamic admittance functions and coherence of buffeting forces, are studied in some detail. It is shown the present method inclusive of above factors gives much closer predictions of buffeting responses to the experimental results.

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1. Introduction

Buffeting is a type of vibration motion induced by turbulent wind. As natural wind is turbulent in nature, wind fluctuation is random and thus the wind pressures along the bridges are also random in time and space. Depending on spectral distribution of the surface force vectors, certain vibration modes of a bridge may selectively be excited. In fact, buffeting responses are related not only to the wind field property and structural dynamic characteristics, but also to the geometrical shape of bridge sections and the interaction between wind and bridge motions. A large buffeting response may cause fatigue problem at bridge joints, discomfort to users, and even affect the bridge safety. Therefore, an accurate prediction of buffeting response of slender structures due to strong winds becomes increasingly important [1,2].

The seminal work due to Davenport [3] and Scanlan and Tomko [4] laid the spectral theoretical framework for predicting buffeting responses of flexible civil engineering structures under turbulent wind. Davenport also suggested the use of aerodynamic admittance functions (AAFs) to account for the frequency-dependent buffeting forces. Following their work, external wind loads are commonly modeled as a combination of three actions at present: (i) a quasi-steady component caused by mean incoming wind; (ii) a self-excited component due to structure-wind interaction; and (iii) a buffeting part associated with turbulent component of incoming wind. During the past several decades, many efforts regarding wind load models have been made to achieve better understandings of wind-induced buffeting. The representation of the unsteady self-excited forces has been commonly made in the frequency-dependent format via flutter derivatives [5–10] as well as in the frequency-independent formats via indicial functions [11] and rational functions [12–18]. In the unavailability of experimentally determined flutter derivatives, the unsteady self-excited forces may be approximately expressed, as a result of quasi-steady linear theory, by steady aerodynamic coefficients and their derivatives with respect to wind attack angle, as suggested by Miyata et al. [19] and also recently adopted by several researchers (e.g. [20–22]).

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The advancements in modeling of the buffeting forces are generally accompanied by the developments of the aerodynamic admittance functions invoked to relate buffeting forces to the incoming wind turbulent component, and of the coherence of buffeting forces used to account for its imperfect span-wise correlations. Regarding the aerodynamic admittance functions for bluff bodies, Sears function analytically derived for a thin airfoil was usually employed for a vertical wind turbulent component, or the approximate phenomenological relationships between flutter derivatives and aerodynamic admittance functions as noted by Scanlan and his coworkers [23–26] and verified by Hatanaka and Tanaka [27], may also be applied when lacking of measurement data. However, experimental studies have shown that the aerodynamic admittance functions for realistic bridge sections are different from the Sears function [28,29]. An experimental comparison of aerodynamic admittance functions for a thin plate and different streamlined bridge decks was performed by Larose and Livesey [30]. Larose and Mann [31] analytically obtained the aerodynamic admittance functions for a thin airfoil considering two wave-numbers and compared analytical results with experimental ones obtained for a family of streamlined deck sections. Diana et al. [32,33] developed the concept of complex aerodynamic admittance functions and identified three complex aerodynamic admittance functions associated with vertical gusts by using an active turbulence generator. The coherence of buffeting forces must be also incorporated in the formulation of buffeting forces to account for the imperfect correlation of wind pressure along the bridge deck, and it is commonly taken as the coherence of wind turbulent components in the literature. Recent studies, however, have pointed out that the coherence of buffeting forces is stronger than that of wind turbulence and that buffeting analysis based on wind turbulence coherence may underestimate buffeting responses [31,34,35]. In general, although very complicated formulations regarding buffeting analysis have been developed in the frequency/time domain, full-bridge wind tunnel validation or field validation of analytical results remains relatively small in the literature [36].

In this study, a time-domain buffeting analysis procedure is formulated and implemented in the commercial finite element package ANSYS, taking into account the six complex aerodynamic admittance functions and coherence of buffeting forces. In recognizing the unavailability of flutter derivatives for the problem in study, the unsteady self-excited forces are approximately represented by the quasi-steady theory (e.g. [19,21]). Following this, aerodynamic stiffness and aerodynamic damping matrices in the consistent formulation for a spatial beam element are derived and are incorporated into the structural finite element model through *Matrix27* element in ANSYS to consider the aeroelastic effect on buffeting responses. Making use of Shinozuka's spectral representation method [37,38], the buffeting forces are simulated based on the buffeting force spectrum consisting of the buffeting force coherence and complex aerodynamic admittance functions. The steady aerodynamic forces and buffeting forces are applied as external loads to the integrated system model, namely the structural model incorporating *Matrix27* elements, and time-domain integration method is used to compute structural responses. The present method is applied to the Xiaoguan Bridge during the longest double cantilever construction stage. The steady aerodynamic coefficients and aerodynamic admittance functions for four typical cross sections are determined from rigid sectional model tests in wind tunnel. The wind-field parameters and coherence of buffeting forces are derived in the scaled full-bridge aeroelastic model experiments. For verification of the buffeting analysis procedure, the structural displacements and internal forces at the bottom of the piers are measured by means of laser displacement transducers and dynamic strain gauges, respectively, in the scaled full-bridge aeroelastic model experiments. The measurement results are compared with analytical predictions.

2. Equations of motion and quasi-steady aerodynamic forces

Consider a deck section in a turbulent flow and in motion at an instant time t. Based on the quasi-steady theory, the aerodynamic forces per unit span in the global axes are expressed as (e.g. [19,21])

$$\begin{aligned} F_y(t) &= \frac{1}{2}\rho U^2 B C_D + \frac{1}{2}\rho U^2 B\left[C_D\frac{2u(t)}{U} + (C_D' - C_L)\frac{w(t)}{U}\right] \\ &\quad - \frac{1}{2}\rho U^2 B C_D\frac{\dot{y}(t)}{U} - \frac{1}{2}\rho U^2 B(C_D' - C_L)\frac{\dot{z}(t)}{U} \\ &\quad + \frac{1}{2}\rho U^2 B(\eta B)(C_D' - C_L)\frac{\dot{\theta}}{U} - \frac{1}{2}\rho U^2 B C_D'\theta \end{aligned} \tag{1a}$$

$$\begin{aligned} F_z(t) &= \frac{1}{2}\rho U^2 B C_L + \frac{1}{2}\rho U^2 B\left[C_L\frac{2u(t)}{U} + (C_L' + C_D)\frac{w(t)}{U}\right] \\ &\quad - \frac{1}{2}\rho U^2 B C_L\frac{\dot{y}(t)}{U} - \frac{1}{2}\rho U^2 B(C_L' + C_D)\frac{\dot{z}(t)}{U} \\ &\quad + \frac{1}{2}\rho U^2 B(\eta B)(C_L' + C_D)\frac{\dot{\theta}}{U} - \frac{1}{2}\rho U^2 B C_L'\theta \end{aligned} \tag{1b}$$

$$\begin{aligned} M_x(t) &= -\frac{1}{2}\rho U^2 B^2 C_M - \frac{1}{2}\rho U^2 B^2\left[C_M\frac{2u(t)}{U} + C_M'\frac{w(t)}{U}\right] \\ &\quad + \frac{1}{2}\rho U^2 B^2 C_M\frac{\dot{y}(t)}{U} + \frac{1}{2}\rho U^2 B^2 C_M'\frac{\dot{z}(t)}{U} \\ &\quad - \frac{1}{2}\rho U^2 B^2(\eta B)C_M'\frac{\dot{\theta}}{U} + \frac{1}{2}\rho U^2 B^2 C_M'\theta \end{aligned} \tag{1c}$$

where ρ is the air density; B is the deck width; U is the mean wind velocity; $u(t)$ and $w(t)$ are the longitudinal and vertical turbulence wind components, respectively; $\dot{y}(t), \dot{z}(t), \dot{\theta}(t)$ are the deck velocities in the horizontal, vertical and rotational directions, respectively; C_D, C_L and C_M are the drag force, lift force and pitching moment coefficients; C_D', C_L' and C_M' are the derivates of C_D, C_L and C_M with respect to wind attack angle, respectively; and η (=0.25) is a factor representing the distance between the center of aerodynamic forces and deck mid chord.

Eq. (1) represents the three wind loading components acting on the bridge section, namely the steady aerodynamic forces, the buffeting forces due to the fluctuating wind components u and w, and the self-excited forces induced by interaction between bridge and wind motions. The steady aerodynamic forces can be directly inputted as external loads in ANSYS for time-domain buffeting analysis. The modeling of self-excited forces and buffeting forces is discussed in the following.

3. Modeling of self-excited forces

Referring to Fig. 1, a three-dimensional spatial frame element oriented in its own member axes (X_e, Y_e, Z_e) has the following 12 degrees of freedom x_i, where $i = 1, 2, \ldots, 12$. Based on the finite element method, the displacements $y(t), z(t), \theta(t)$ within the element are expressed as

$$\begin{bmatrix} y(x) & z(x) & \theta(x) \end{bmatrix}^{\mathrm{T}} = \begin{bmatrix} \mathbf{N}_y & \mathbf{N}_z & \mathbf{N}_\theta \end{bmatrix}^{\mathrm{T}} \mathbf{X}^e \tag{2}$$

where $\mathbf{X}^e = \{x_1, x_2, \ldots, x_{12}\}^{\mathrm{T}}$ is the displacement vector of the element e, as shown in Fig. 1. The shape functions for a three-dimensional spatial frame element are

$$\mathbf{N} = \begin{bmatrix} \mathbf{N}_y \\ \mathbf{N}_z \\ \mathbf{N}_\theta \end{bmatrix} = \begin{bmatrix} 0 & N_1 & 0 & 0 & 0 & N_2 & 0 & N_3 & 0 & 0 & 0 & N_4 \\ 0 & 0 & N_5 & 0 & N_6 & 0 & 0 & 0 & N_7 & 0 & N_8 & 0 \\ 0 & 0 & 0 & N_9 & 0 & 0 & 0 & 0 & 0 & N_{10} & 0 & 0 \end{bmatrix} \tag{3}$$

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