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Identification and application of six-component aerodynamic admittance functions of a closed-box bridge deck

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ABSTRACT

A colligated residue least square method of auto and cross spectra (CRLSMACS) is presented for identifying six-component aerodynamic admittance functions (AAFs) base on common force and pressure measurement tests in the passive grid-generated turbulent flow. The incomplete spanwise correlation of the buffeting force on the sectional model in the turbulent flow is corrected. The six-component AAFs of a flat closed-box deck of a single-tower cable-stayed bridge are identified with the presented method for the service states without/with wind barriers and the construction state under 0° wind attack angle, respectively. The buffeting responses of the bridge are then calculated for both the service and typical construction sates by using a finite element approach based on the quasi-steady buffeting theory with the tested six-component AAFs to consider the unsteady effect of buffeting forces. The calculated buffeting responses are finally compared with and found to agree well with those obtained via full bridge aeroelastic model tests, verifying the feasibility of the proposed CRLSMACS as well as the reliability of the identified six-component AAFs and the calculated buffeting responses.

1. Introduction

Although buffeting forces are essentially unsteady, they are conventionally modelled at first in light of the quasi-steady theory and then modified by introducing so-called aerodynamic admittance functions (AAFs) with six components for normal wind case and eighteen components for yaw wind cases to consider their unsteady behaviours (Sears, 1941; Scanlan and Jones, 1999; Xu et al., 1998; Chen et al., 2000). Because the normal wind case is traditionally considered in most buffeting analyses, the six AAF components related to the buffeting lift force (L_b), drag force (D_b) and torsional moment (M_b) as well as the longitudinal and vertical fluctuating wind speeds (u, w), i.e., χ_{fa}($f = L, D, M$, $a = u,w$), are paid the most great attention to and are discussed or investigated most often, as done in this paper. For bluff bodies, such like the most of common bridge decks, the AAFs can be obtained via wind tunnel test or computational fluid dynamics (CFD) method in conjunction with a proper identification algorithm (Matsuda et al., 1997; Hatanaka and Tanaka, 2002; Tubino, 2005; Costa, 2007; Peila and Behrensb, 2007). Up to now, there have been several algorithms for the AAF identification based on tested fluctuating aerodynamic forces and wind velocities, such as equivalent AAF method or called auto spectral method (Larose, 1999; Diana et al., 2004; Gu and Qin, 2004), cross-spectral method (Zhao and Ge, 2015), zero-separation method (Chen et al., 2009), separated frequency-by-frequency method (Han et al., 2010), etc.

The equivalent AAF method only uses the one of the three auto spectral equations of buffeting forces (S_f) for solving three pairs of unknown variables of AAF related to the three component of buffeting force(χ_{fu}, χ_{fw}, f=D,L,M). Thus, it has to assume that the two AAF components in each pair, related to a same force component and the fluctuating wind velocities u and w, are equal to each other, i.e., $\chi_{fu} = \chi_{fw} = \chi_f$. Furthermore, this method can then only obtain the module value of one equivalent AAF for each force component, $|\chi_f|$, which can ensure the reproduced force auto spectrum to be equivalent to the real or tested one. In this method, $|\chi_f|$ is actually a weighted average of $|\chi_{fu}|$ and $|\chi_{fw}|$, and is often much closer to $|\chi_{Du}|$, $|\chi_{Lw}|$ or $|\chi_{Mw}|$ for common bridge decks because the weighting factors of the three AAFs in the spectral equations are often much larger than those of the others.

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The cross spectral method employs only three pairs of two equations of the cross spectra between one of the three buffeting force components and each of the two fluctuating wind speeds to solve the three pairs of two complex AAF components, six in all, and doesn't consider the auto spectral conditions. However, the results of the solved AAF components are often very discrete or random and have lower accuracy because the correlation between the buffeting forces and the fluctuating wind speeds is normally very weak and the values of cross spectra show strong random behaviours. This may sometimes result in significant discrepancies between the reproduced buffeting force auto spectra by using the identified six AAF components and the testes ones.

By utilizing the fact that the aerodynamic coefficients $(C'_D - C_L)^2$, C_L^2 and C_M^2 before the χ_{Dw} in the S_D expression, the χ_{Lu} in the S_L expression, and the χ_{Mu} in the S_M expression, respectively, equal to zero at certain but maybe different small wind attack angles, the zero-separation method solves three AAF components of $|\chi_{Du}|$, $|\chi_{Lw}|$ and $|\chi_{Mw}|$ at first by using the tested data of buffeting force spectra at the above-mentioned small attack angles. Then, by assuming that the AAFs doesn't depend on the wind attack angle within a small range, this method solves the rest three AAF components of $|\chi_{Dw}|$, $|\chi_{Lu}|$ and $|\chi_{Mu}|$ by using the tested data of buffeting force spectra at other small wind attack angles different from the above-mentioned small attack angles corresponding to the zero value of $(C'_D - C_L)^2$, C_L^2 and C_M^2. However, the independency assumption of AAFs from the wind attack angle in this method is still oppugned, considering the flutter derivatives for unsteady self-excited forces of bridge decks are quite sensitive to wind attack angle.

For the separated frequency-by-frequency method, the mixed sinusoidal fluctuating wind flow composed of a single-frequency longitudinal component and a single-frequency vertical component is to be generated at first with an actively vibrating airfoil grid system at a single frequency. The frequencies of the longitudinal and vertical components of the fluctuating wind velocity are reported by Han et al. (2010) to be separated, and just to be double of and equal to the frequency of the grid vibration, respectively. Then, the values of three AAF components related to u at the double-time frequency and the values of the other three AAF components related to w at the single-time frequency can be determined according to the auto spectral equations of fluctuating aerodynamic forces and the tested data. The values of AAFs at other frequencies can further be identified by changing the vibrating frequency of the grid system. However, the results obtained by the first author during the similar tests show that in the most cases, both the two fluctuating velocities generated by such a vibrating airfoil grid system normally contain a series of multiple-frequency components, and cannot be separated in frequency domain, unless the vibrating amplitude of the airfoil grid is rather small, which will consequently lead to the weak intensities of the fluctuating velocities and lower measurement accuracy of the fluctuating forces. Actually, this is because the disturbance of wind flow from the vibrating grids, thus the intensities of the both generated fluctuating wind velocities are nonlinear, and the nonlinearity will become stronger with the increase of the vibrating amplitude of the grids. Furthermore, compared with that of other methods based on the tests in the passive grid-generated turbulent flow, this method has huge testing workload because of adopting the frequency scanning way.

To overcome the shortcomings of the above methods for AAF identification, a new method, called colligated residue least square method of auto and cross spectra (CRLSMACS), is presented for identifying six-component AAFs base on common force and pressure measurement tests in a passive grid-generated turbulent flow. Furthermore, the authors are going to introduce the identification of six-component AAFs of the closed-box deck of a single-tower cable-stayed bridge by using this new method and the verification of the identified AAFs as well as the method via comparing the calculated buffeting responses of the bridge with those obtained through wind tunnel tests of full bridge aeroelastic model for the service and longest-double-cantilever states.

2. Basic principle of CRLSMACS

2.1. Definitions of colligated residues of auto and cross spectra

For each component of buffeting forces, an equation set, comprised of auto spectrum of the buffeting force, the cross spectra between the buffeting force and one of the longitudinal and vertical fluctuating wind velocities, u and w, can be established based on the corresponding measured data as follows.

For the drag force:

$$S_D = \left(\frac{\rho UB}{2}\right)^2 \left[4C_D^2|\chi_{Du}|^2 S_u + (C'_D - C_L)^2|\chi_{Dw}|^2 S_w + (C'_D - C_L) \times \left(\chi_{Du}^*\chi_{Dw}S_{uw} + \chi_{Du}\chi_{Dw}^*S_{wu}\right)\right] \quad (1a)$$

$$S_{Du} = \rho UB\left[C_D\chi_{Du}^*S_u + 0.5(C'_D - C_L)\chi_{Dw}^*S_{wu}\right] \quad (1b)$$

$$S_{Dw} = \rho UB\left[C_D\chi_{Du}^*S_{uw} + 0.5(C'_D - C_L)\chi_{Dw}^*S_w\right] \quad (1c)$$

For the lift force:

$$S_L = \left(\frac{\rho UB}{2}\right)^2 \left[4C_L^2|\chi_{Lu}|^2 S_u + (C_D + C'_L)^2|\chi_{Lw}|^2 S_w + 2C_L(C_D + C'_L) \times \left(\chi_{Lu}^*\chi_{Lw}S_{uw} + \chi_{Lu}\chi_{Lw}^*S_{wu}\right)\right] \quad (2a)$$

$$S_{Lu} = \rho UB\left[C_L\chi_{Lu}^*S_u + 0.5(C'_L + C_D)\chi_{Lw}^*S_{wu}\right] \quad (2b)$$

$$S_{Lw} = \rho UB\left[C_L\chi_{Lu}^*S_{uw} + 0.5(C'_L + C_D)\chi_{Lw}^*S_w\right] \quad (2c)$$

For the torsional moment:

$$S_M = \left(\frac{\rho UB^2}{2}\right)^2 \left[4C_M^2|\chi_{Mu}|^2 S_u + (C'_M)^2|\chi_{Mw}|^2 S_w + 2C_M C'_M \left(\chi_{Mu}^*\chi_{Mw}S_{uw} + \chi_{Mu}\chi_{Mw}^*S_{wu}\right)\right] \quad (3a)$$

$$S_{Mu} = \rho UB^2\left[C_M\chi_{Mu}^*S_u + 0.5C'_M\chi_{Mv}^*S_{wu}\right] \quad (3b)$$

$$S_{Mw} = \rho UB^2\left[C_M\chi_{Mu}^*S_{uw} + 0.5C'_M\chi_{Mw}^*S_w\right] \quad (3c)$$

where, $S_f(f = D, L, M)$ are the auto spectra of distributed buffeting forces; $S_a(a = u, w)$ are the auto spectra of fluctuating wind velocities; $S_{fa}(f = D, L, M; a = u, w)$ are the cross spectra between the distributed buffeting force and the fluctuating wind velocity; $\chi_{fa}(f = D, L, M; a = u, w)$ are the aerodynamic admittance functions between the distributed buffeting force and the fluctuating wind velocity; S_{uw} and S_{wu} are the cross spectra between the fluctuating wind velocities u and w, respectively; ρ is the air density; U is the mean wind speed; B is the characteristic width of bridge deck; $C_f(f = D, L, M)$ are the aerodynamic coefficients of aerodynamic drag force, lift force and torsional moment; C'_f is the derivatives of aerodynamic coefficients with respect of wind attack angle. The superscript * represents the conjugate operation of a complex variable.

Then, the colligated spectral residue functions for the buffeting drag force, lift forces and torsional moment are defined, respectively, as follows.

The residual function for the drag force:

$$R_D\left(\chi_{Du}^{Re}, \chi_{Du}^{Im}, \chi_{Dw}^{Re}, \chi_{Dw}^{Im}\right) = w_1\varepsilon_{DD}^2 + w_2\left[\left(\varepsilon_{Du}^{Re}\right)^2 + \left(\varepsilon_{Du}^{Im}\right)^2\right] + w_3\left[\left(\varepsilon_{Dw}^{Re}\right)^2 + \left(\varepsilon_{Dw}^{Im}\right)^2\right] \quad (4a)$$