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Nonlinear response analysis of long-span bridges under turbulent winds

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ABSTRACT: The nonlinear response of a long-span bridge under turbulent wind is analyzed in time domain. This includes aerodynamic nonlinearities with respect to the effective angle of wind incidence. The analysis framework incorporates unsteady characteristics and spanwise correlation of aerodynamic forces utilizing a rational function approximation. The turbulence effects on the flutter response and the interaction between flutter and buffeting responses are investigated. A comparison with conventional linear approach is made through response analysis of a long-span suspension bridge.

1 INTRODUCTION

Analytical prediction of wind induced buffeting response and flutter instability have predominantly been conducted in the frequency domain and based on the linear theory (Jones et al. 1998 and Chen et al. 1999). The frequency domain approach in general is limited to linear structures excited by the stationary wind loads which does not account for aerodynamic nonlinearities. However, for most bridge deck sections, the aerodynamic force parameters are highly sensitive to the angle of incidence (e.g., Matsumoto et al. 1998). Even for small level of turbulence, the effective angle of incidence due to structural motions and wind fluctuations may vary to a level such that the nonlinearity of aerodynamic forces may not be neglected. In such cases, the reliability of conventional linear approach using the linearized aerodynamic forces around the static position needs further verification.

Time domain approach is most appropriate for the analysis involving structural and/or aerodynamic nonlinearities. A nonlinear aerodynamic force model with their dependence on the angle of incidence has been proposed by Diana et al. (1999). This nonlinear model incorporates frequency dependent characteristics by decomposing the total response into components with different frequencies. These unsteady aerodynamic forces can be readily incorporated in the time domain by utilizing a rational function approximation (Chen et al. 2000).

Wind tunnel tests indicated that turbulence can both stabilize and destabilize the flutter instability depending on the shape of bridge deck and the characteristics of wind fluctuations. A number of analytical studies by randomizing the dynamic pressure and using stochastic approach have been conducted to predict the turbulence effects on flutter (e.g., Lin and Li, 1993). Such an ad hoc implementation of the turbulence component may not accurately represent the physics of the problem because turbulence may significantly modify the flow structure and lead to modifications in the aerodynamic force - generating mechanisms (Nakamura 1993). Diana et al. (1999) have analytical investigated turbulence effects on flutter by assuming that turbulence alters the effective angle of attack, which impacts the self-excited forces.

In this paper, a time domain approach for predicting the buffeting and flutter responses with aerodynamic nonlinearities is presented. The turbulence has been separated into low-frequency (large scale) and high-frequency (small scale) components. The effects of low-frequency turbulence are considered to alter the effective angle of incidence hence the aerodynamic forces. The main effects of high frequency turbulence are considered to alter the aerodynamic force-generating mechanism, and are modeled by directly using the aerodynamic parameters measured in turbulence flow conditions. The frequency dependent unsteady characteristics of aerodynamic forces have been incorporated by using a rational function approximation technique (Chen et al. 2000). A comparison with conventional linear approach is made through response analysis of a long-span suspension bridge.

2. NONLINEAR AERODYNAMIC FORCES

The nonlinearity of the aerodynamic forces depends on the value of the effective angle of incidence, which consists of the contribution of wind fluctuations and the static and dynamic structural motions. The effective angle of incidence and the associated aerodynamic forces can be separated into low-frequency (including static) and high-frequency components. The low-frequency components of aerodynamic forces , i.e. lift (downward), drag (downwind) and pitching moment (node-up) consists of the frequency components below the lowest natural frequency of structure. These can be expressed using the quasi-steady theory due to high value of the reduced velocity as shown in the following nonlinear form (including static components)

$$L_{bl} = F_{L_l} cos\phi_l - F_{D_l} sin\phi_l$$

$$D_{bl} = F_{L_l} sin\phi_l + F_{D_l} cos\phi_l \qquad M_{bl} = F_{M_l} \qquad (1)$$

$$F_{L_l} = -\frac{1}{2}\rho V_r^2 B C_L(\alpha_{e1}) \qquad F_{D_l} = \frac{1}{2}\rho V_r^2 B C_D(\alpha_{e1})$$

$$F_{M_l} = \frac{1}{2}\rho V_r^2 B^2 C_M(\alpha_{e1}) \qquad (2)$$

$$V_r^2 = (U + u_l - \dot{p}_l)^2 + (w_l + \dot{h}_l + b_1\dot{\alpha}_l)^2 \qquad (3)$$

$$\alpha_{e1} = \alpha_s + \phi_l \qquad \phi_l = arctan\Big(\frac{w_l + \dot{h}_l + b_1\dot{\alpha}_l}{U + u_l - \dot{p}_l}\Big) \qquad (4)$$

where ρ is air density; U is mean wind velocity; $B = 2b$ is the bridge deck width; C_L, C_D and C_M are the mean static coefficients; u_l and w_l are low frequency components of wind fluctuations in the longitudinal and vertical directions; h_l, p_l, and α_l are the corresponding low frequency components of the vertical, lateral and torsional displacement, respectively; α_s is static angle of bridge deck section; α_{el} is the low frequency component of the effective angle of incidence; and $b_1 = b/2$.

When the low frequency responses are comparatively small and negligible (it is the case for most long-span bridges), α_{e1} can be simplified as

$$\alpha_{e1} = \alpha_s + arctan\Big(\frac{w_l}{U + u_l}\Big) \qquad (5)$$

The high-frequency component of the aerodynamic forces can be expressed by the linearization around the low frequency effective angle of incidence α_{e1}. They can be further separated into self-excited force and buffeting force components. The self-excited forces per unit length induced by arbitrary structural motion, and the buffeting forces corresponding to arbitrary fluctuations, can be expressed in terms of convolution integrals as detailed in Chen et al. (2000).

For the lift components,

$$L_{seh}(t) = \frac{1}{2}\rho U^2 \int_{-\infty}^{t} \Big(I_{L_{seh}}(\alpha_{e1}, t-\tau)h_h(\tau)$$

$$+I_{L_{sep}}(\alpha_{e1}, t-\tau)p_h(\tau) + I_{L_{se\alpha}}(\alpha_{e1}, t-\tau)\alpha_h(\tau)\Big)d\tau \qquad (6)$$

$$L_{bh}(t) = -\frac{1}{2}\rho U^2 \int_{-\infty}^{t} \Big(I_{L_{bu}}(\alpha_{e1}, t-\tau)\frac{u_h(\tau)}{U}$$

$$+I_{L_{bw}}(\alpha_{e1}, t-\tau)\frac{w_h(\tau)}{U}\Big)d\tau \qquad (7)$$

where subscript h denotes the high frequency component; I indicates the aerodynamic impulse functions, which are associated with indicial aerodynamic functions and related to the flutter derivatives and admittance functions (Chen et al. 2000); They also depend on the effective angle of incidence and the approach wind fluctuations. By using the rational function approximation technique to express the flutter derivatives and admittance functions, the time histories of unsteady aerodynamic forces can be calculated, and spanwise correlation of the aerodynamic forces can also be included in the time domain analysis (Chen et al. 2000).

3. SOLUTION OF EQUATION OF MOTION

The static deformation is firstly calculated by static analysis. Using the simulated wind fluctuations at the center of each element, the low frequency components of wind fluctuations are then derived by low-pass filters. The corresponding buffeting responses to the quasi-steady nonlinear forces are calculated. At each time step and for each element the low frequency component of the effective angle of incidence is calculated and the associated aerodynamic parameters are determined for the calculation of the linear unsteady aerodynamic forces. An iterative calculation procedure is necessary for treating both the low-frequency and high-frequency responses. For most of long span bridges, the low-frequency buffeting responses are negligible, therefore Eq. 5 can be used for reducing computational effort.

Structural nonlinearities can also be readily accounted for in the analysis. For linear structures, a mode generalized approach can be utilized to benefit from the reduction in computational effort by limiting the analysis to selected modes.

Table 1 Flutter onset velocity (m/s)

Mode No.	$\alpha_{e1} = 0$	$\alpha_{e1} = \alpha_s$
(a) Frequency domain		
mode 2, 8, 10	72.1	74.1
mode 1-15	74.8	76.3
(b) Time domain		
mode 1-15	74.9	76.5

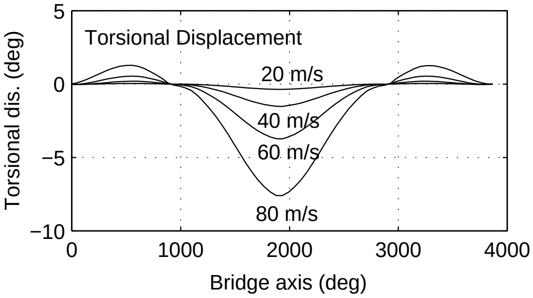

Fig. 1 Static torsional deformation

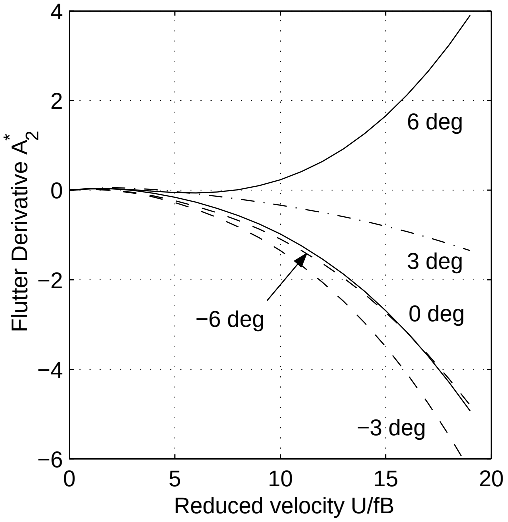

Fig. 2 Flutter derivative A_2^* at different angles of incidence

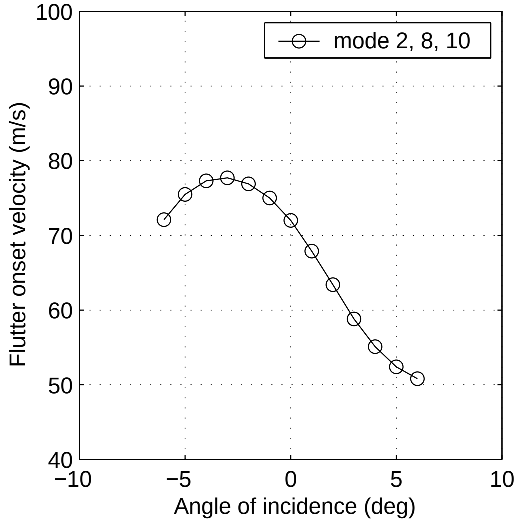

Fig. 3 Flutter onset velocity vs. effective angle of incidence

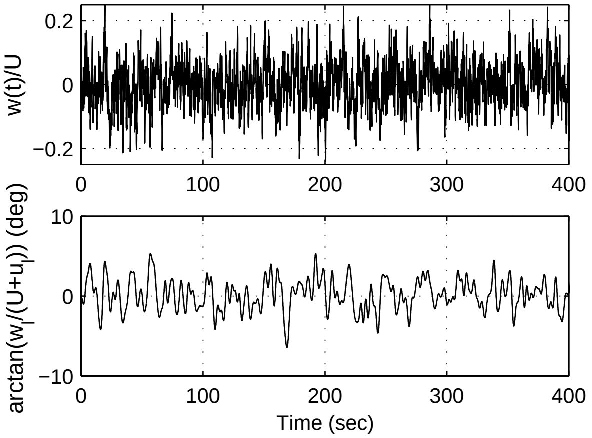

Fig. 4 Vertical wind fluctuation and low-frequency effective angle of incidence

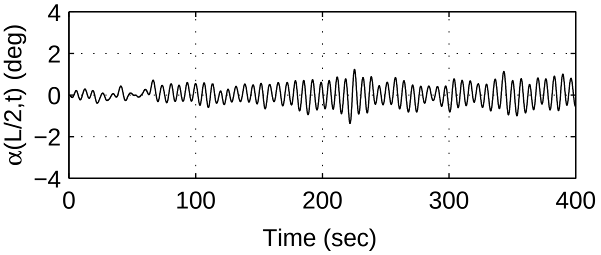

Fig. 5 Buffeting torsional displacement (Linear, U=60 m/s, main span center)

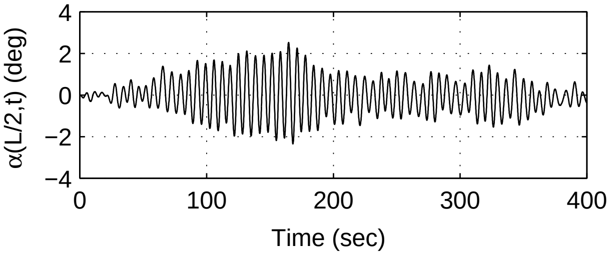

Fig. 6 Buffeting torsional displacement (Nonlinear, U=60 m/s, main span center)

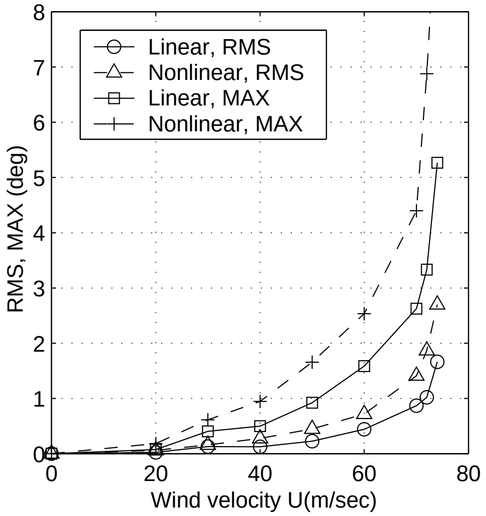

Fig. 7 Comparison of RMS and Maximum value of torsional displacement at main span center

4. EXAMPLE

An example long span suspension bridge with a main span of approximately 2000 m is used to demonstrate the effectiveness of proposed approach. Figure 1 shows the static torsional deformation at different mean wind velocity. Only the variation of the flutter derivative A_2^* with the angle of incidence is considered in this nonlinear analysis (Fig. 2).

The multimode coupled flutter analysis in frequency domain is conducted involving lower 15 natural modes, and only 1st and 2nd vertical bending and 1st torsional modes. Flutter analysis is also carried out in the time domain by the simulation of the free vibration of the bridge. Table 1 gives the estimated flutter onset velocity. Figure 3 shows the flutter onset velocity at different mean wind angles of incidence using the uniformly distributed value in the spanwise direction. Results indicate that this example bridge is very sensitive to the changes in the angle of incidence, and that the time domain flutter estimates are in good agreement with those of the frequency domain analysis.

An example realization of the vertical wind fluctuations and associated effective angle of incidence acting on the center of the main are shown in Fig. 4 (σ_u/U=10%, σ_w/U=7.5%, U=60 m/s). Figures 5 and 6 show the torsional buffeting at the center of main span by the linear and nonlinear analysis. Figure 7 show the comparison of the root-mean-square and maximum value of torsional buffeting at the center of the main span.

It is noted that the nonlinear analysis result are significantly larger for the buffeting response than those obtained by the linear analysis. The low-frequency turbulence destabilizes the flutter instability in this example. The current analysis framework can be readily used to account for the contribution of high-frequency turbulence by using aerodynamic force parameters obtained in a turbulent approach flow.

5. CONCLUSION REMARKS

A time domain approach for predicting the buffeting and flutter responses with aerodynamic nonlinearities is presented. Significant higher buffeting responses has been predicted by this nonlinear analysis then those obtained by the linear approach. The low-frequency turbulence indicated a destabilizing effects on the flutter instability. A coordinated experimental investigation is in progress for further validation of the proposed approach.

ACKNOWLEDGMENTS

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REFERENCES

Chen, X., Kareem, A. & Matsumoto, M. (1999). “Aerodynamic coupling effects on flutter and buffeting of bridges.” *Wind Engineering into the 21 Century*, Larose & Livesey (eds), Balkema, Rotterdam, 845-850.

Chen, X., Matsumoto, M. & Kareem, A. (2000). “Time Domain Flutter and Buffeting Response Analysis of Bridges.” *J. of Engrg. Mech.*, ASCE, 126(1)

Diana, G., Cheli, F., Zasso, A. & Bocciolone, M. (1999). “Suspension bridge response to turbulent wind: Comparison of new numerical simulation method results with full scale data.” *Wind Engineering into the 21 Century*, Larose & Livesey (eds), Balkema, Rotterdam, 871-878

Jones, N. P., Scanlan, R. H., Jain, A. & Katsuchi, H. (1998). “Advances (and challenges) in the prediction of long-span bridge response to wind.” *Bridge Aerodynamics*, Larose & Esdahl (eds), Balkema, Rotterdam, 59-85

Matsumoto, M., Yagi, T., Ishizaki, H., Shitato, H. & Chen, X. (1998). “Aerodynamic stability of 2-edge girders for cable-stayed bridge.” *Proceedings of 15th Nat. Symp. on Wind Engrg.*, JAWE, 389-394 (in Japanese)

Nakamura, Y. (1993). “Bluff-body aerodynamics and turbulence.” *J. of Wind Engrg. and Ind. Aero.*, Vol. 49, 65-78