Comparison of various modeling schemes for bridge aerodynamics and aeroelasticity

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ABSTRACT: This paper compares five analytical models available in the literature systematically together with a new developed model for bridge aerodynamic/aeroelastic analysis. The models under consideration are quasi-steady (QS) theory based model, corrected QS theory based model, linearized QS theory based model, semi-empirical linear model, hybrid model and the proposed modified hybrid model. Physical significances of each approach in capturing the bridge behavior are highlighted. The interaction between the turbulence and the bridge deck motions is investigated. All these models are utilized in the time domain for consistency.

KEYWORDS: Comparison; Model; Bridge; Aerodynamics; Aeroelasticity

1 INTRODUCTION

The catastrophic failure of the original Tacoma Narrows Bridge has been pivotal in drawing attention to research in the aerodynamic/aeroelastic behavior of long-span bridges. The intense oscillation of the deck of the original Tacoma Narrows Bridge is actually the galloping in torsional degree of freedom (usually refers to torsional flutter). As a result, it is convenient to illustrate this phenomenon based on the QS theory. However, an obvious shortcoming of the QS theory is that it cannot take into the unsteady effect of fluid-structure interaction.

A familiar approach to consider the fluid memory effects is to modify the steady-state coefficients based on the unsteady effects measured in the wind tunnel and hence to improve the simulation accuracy (Diana et al. 1993). On the other hand, in order to circumvent dealing with nonlinear differential equations, QS theory based formula is usually linearized to qualitatively evaluate the wind-induced aerodynamic/aeroelastic forces. The parameters (consists of steady-state coefficients and their first-order derivatives) of this linearized QS theory based formula has their corresponding unsteady analytical expressions for the structure with streamlined cross-section, such as Theodorsen function (Theodorsen 1935).

However, for the cross-sections of bluff body, it is questionable to obtain the analytical expressions for the parameters based on some basic, simplified mechanism (such as potential theory and Kutta condition) due to the flow separation and other bluff-body aerodynamic issues. As a result, the parameters based on the wind-tunnel tests (e.g., aerodynamic admittances and flutter derivatives) is commonly utilized (Scanlan and Tomko 1971). This semi-empirical, linear, unsteady scheme has been applied extensively to simulate bridge aerodynamic and aeroelastic behaviors since its invention. It is emphasized that the QS theory based model could take into account the nonlinearity but no fluid memory while the conventional semi-empirical model could account for the fluid memory but no nonlinearity. Hence, a hybrid scheme has been proposed to simulate both the unsteady and nonlinear effects in wind-bridge interaction (Chen and Kareem 2003). Though the hybrid model could reasonably account for the nonlinear effect, it compromises the consideration of unsteady effect in the low frequency part. A modified hybrid model is proposed in this research, where the steady-state coefficients are modified based on their hysteretic features observed in wind tunnel. As a result, this new model could involve the higher-order memory effect (represented by hysteretic loop) when QS theory (nonlinear effect) is utilized.
2 IMPLEMENT OF VARIOUS MODELS

The coordinate system of the wind-bridge interaction system for analysis in all these models is shown in Fig. 1. A unit-length section of a modern bridge deck subjected to a turbulent wind flow is considered here and the aerodynamic/aeroelastic loads are established based on “strip theory”. The incident turbulent wind consists of mean wind velocity \( U \) and \( W \) and fluctuations \( u \) and \( w \) in horizontal and vertical direction, respectively. The bridge cross-section has horizontal motion \( p \), vertical motion \( h \), and torsional motion \( \alpha \) under the turbulent wind. The wind-induced effects considered are lift force \( L \), drag force \( D \) and moment \( M \).

![Figure 1: Coordinate system of the wind-bridge interaction system.](image)

Suppose vertical translation and rotational motion are considered, the governing equations of the motion of bridge deck cross-section are modeled by a two-degree-of-freedom oscillator as

\[
\begin{align*}
\dot{\mathbf{h}} + 2\zeta_\alpha \omega_\alpha \mathbf{h} + \omega_\alpha^2 \mathbf{h} &= \mathbf{F}_L, \\
\dot{\mathbf{h}} + 2\zeta_\alpha \omega_\alpha \dot{\mathbf{h}} + \omega_\alpha^2 \mathbf{h} &= \mathbf{M}_z
\end{align*}
\] (1a; b)

where the over dot indicates the derivative with respect to time; \( \zeta \) and \( \omega \) represent the damping ratio and natural frequency, respectively; \( m \) is the effective mass and \( I \) the effective mass moment of inertia; \( F_L \) and \( M_z \) are wind-induced effects (aerodynamic/aeroelastic forces or moments) and the simulation of these effects is emphasized in this research.

2.1 Quasi-steady (QS) theory based model

QS theory based model describes the flow-structure interaction with a static nonlinear relationship between the status of the system (e.g., incident flow and structure) and the flow-induced forces exerted on the structure. Based on the QS theory, the lift force and torsional moment per unit span in the global bridge axes are expressed as (Miyata et al. 1995)

\[
\begin{align*}
F_L &= F_L \cos(\phi) - F_D \sin(\phi), \\
M_z &= M
\end{align*}
\] (2a; b)

\[
\begin{align*}
F_L &= -\frac{1}{2} \rho \alpha_u \mathbf{D} \mathbf{C}_D(\mathbf{a}), \\
F_D &= \frac{1}{2} \rho \alpha_u \mathbf{D} \mathbf{C}_D(\mathbf{a}), \\
M &= \frac{1}{2} \rho \alpha_u \mathbf{D} \mathbf{C}_D(\mathbf{a})
\end{align*}
\] (3a; b; c)

where \( \rho \) is air density; \( B \) is the bridge deck width; \( \mathbf{C}_L \), \( \mathbf{C}_D \) and \( \mathbf{C}_M \) are nondimensional steady-state coefficients which are conveniently obtained with static wind-tunnel tests, where \( \mathbf{C}_M \) is respect to the center of the cross-section; \( V_r \) is the relative wind velocity calculated as

\[
V_r = \sqrt{(U + u)^2 + (W + w + \dot{h} + m \dot{\alpha})^2}
\] (4)

and \( \alpha_e \) is the dynamic angle of attack calculated as

\[
\alpha_e = \mathbf{a}_e + \alpha + \phi
\] (5)

where \( \mathbf{a}_e \) is the wind angle of attack when bridge deck is at the equilibrium position (also involving potential incident wind angle); \( \alpha \) is the torsional displacement of the bridge deck under turbu-
lent wind; and $\phi$ is the "dynamic" angle of attack induced by the bridge deck motions and wind fluctuations (here the terminology "effective angle of attack" refers the situation that only deck motions contributes the angle of attack) and could be calculated as

$$\phi = \arctan \left( \frac{W + w + h + m_1 B \dot{\alpha}}{U + u} \right)$$

(6)

The parameter $m_1$ value is selected to appropriately define an equivalent stationary state for the rotational motion.

### 2.2 Corrected QS theory based model

An obvious shortcoming of the quasi-steady theory based model is that it cannot take into account the unsteady effect. In order to improve this model, a corrected QS theory based model has been advanced where a coefficient is introduced to account for the unsteady effects (Diana et al. 1993). Based on the corrected QS theory, the lift force and torsional moment per unit span in the global bridge axes should be revised as

$$F_y = F_y^0 \cos(\phi) - F_y^1 \sin(\phi); \quad M_z = M$$

(2a; b)

$$F_y = \frac{1}{2} \rho u^2 B \left[ C_{y0}(\alpha) + \int_{\alpha_{ref}}^{\alpha_y} \frac{d \bar{C}_{y0}(\alpha)}{d \alpha} d\alpha \right]; \quad F_z = \frac{1}{2} \rho u^2 B \left[ C_{z0}(\alpha) + \int_{\alpha_{ref}}^{\alpha_z} \frac{d \bar{C}_{z0}(\alpha)}{d \alpha} d\alpha \right]; \quad M = \frac{1}{2} \rho u^2 B \left[ C_{m0}(\alpha) + \int_{\alpha_{ref}}^{\alpha_m} \frac{d \bar{C}_{m0}(\alpha)}{d \alpha} d\alpha \right]$$

(7a; b; c)

The parameter $k_1$ is determined by the unsteady effect of the wind-bridge interaction.

### 2.3 Linearized QS theory based model

Both QS and corrected QS theory based model need to deal with nonlinear differential equations when implemented to calculate the bridge deck responses. In order to circumvent this complexity, QS theory based formula is usually linearized at the static equilibrium position to qualitatively evaluate the wind-induced aerodynamic/aeroelastic forces. Based on the linearized QS theory, the lift, drag and torsional coefficients should be approximated as

$$C_{y0}(\alpha) \equiv C_{y0}(\alpha) + (\alpha + \phi) C_{y1} \left| \alpha \right|; \quad C_{z0}(\alpha) \equiv C_{z0}(\alpha) + (\alpha + \phi) C_{z1} \left| \alpha \right|; \quad C_{m0}(\alpha) \equiv C_{m0}(\alpha) + (\alpha + \phi) C_{m1} \left| \alpha \right|$$

(8a; b; c)

where prime indicates the derivative with respect to angle of attack. With some manipulations, the lift force and torsional moment per unit span based on the linearized QS theory in the global bridge axes could be expressed as

$$F_y = \frac{1}{2} \rho u^2 B \left[ C_{y0}(\alpha) + \int_{\alpha_{ref}}^{\alpha_y} \frac{d \bar{C}_{y0}(\alpha)}{d \alpha} \right] \left[ C_{y1} \left| \alpha \right| + \left( \frac{m B \dot{\alpha}}{U - u} \right) \left( \frac{\alpha}{\alpha} \right) \right]; \quad M = \frac{1}{2} \rho u^2 B \left[ C_{m0}(\alpha) + \int_{\alpha_{ref}}^{\alpha_m} \frac{d \bar{C}_{m0}(\alpha)}{d \alpha} \right] \left[ C_{m1} \left| \alpha \right| + \left( \frac{m B \dot{\alpha}}{U - u} \right) \left( \frac{\alpha}{\alpha} \right) \right]$$

(9a; b)

where the first term in the bracket represents static effect; the second term aerodynamic effect and the third term aeroelastic effect.

### 2.4 Semi-empirical linear model

In order to take into account the unsteady effect within a linear framework, the so-called semi-empirical scheme was developed by Scanlan (e.g., Scanlan and Tomko 1971) using wind tunnel tests of a sectional bridge model to account for the aeroelastic effects. On the other hand, the spectral analysis in this linear framework is developed by Davenport (e.g., Davenport 1962) to account for the aerodynamic effects, in which the coefficients of the corresponding linearized terms are also measured based on wind-tunnel test (or based on linearized QS theory). The lift force and torsional moment of frequency domain per unit span based on the semi-empirical linear model in the global bridge axes could be expressed as
where the subscript "b" indicates the buffeting forces (or moment) while "s" indicates the self-excited forces (or moment). The buffeting forces (or moment) induced by turbulent wind are expressed as

\[ F_b = (C_l + C_d) \frac{w(t)}{U} + 2C_d \frac{u(t)}{U} + 2C_m \frac{w}{U} + 2C_m \frac{u}{U} \]  

and the self-excited forces (or moment) induced by the bridge deck motions are expressed as

\[ F_s = K_l \frac{h}{U} + K_d \frac{h}{U} + K_m \frac{h}{U} + K_m \frac{h}{U} + K_m \frac{h}{U} + K_m \frac{h}{U} + K_m \frac{h}{U} + K_m \frac{h}{U} \]

where \( K_l \), \( K_d \), and \( K_m \) are aerodynamic transfer functions (modulus is referred as aerodynamic admittance function) between wind fluctuations and buffeting forces (or moment), which are functions of \( K \), wind angle of attack and deck shape; \( h/\omega \) is dimensionless reduced frequency with \( \omega \) as circular frequency of bridge deck vibration; the coefficients \( H'(K) \) and \( A'(K) \) are aerelastic transfer function (flutter derivatives), which are also functions of \( K \), wind angle of attack and deck shape.

2.5 Hybrid model

It should be noticed that it is intractable to determine the proper reduced wind velocity in the "corrected" quasi-steady theory. Therefore, usually only an unique value of the reduced velocity is utilized. In order to overcome this shortcoming of the corrected quasi-steady theory based model, band superposition model has been developed (Diana et al. 1995). However, this band superposition scheme is not easy to implement for the time-frequency mixed characteristics of the equations of motion and the measurement of the flutter derivatives under the incident wind condition with narrow-band turbulent fluctuations is not feasible. Besides, the interaction between each subrange cannot be considered. In order to further improve the "band superposition" scheme, a numerical analysis framework, which utilizes the rational function approximation scheme to obtain more efficient computational procedures, is proposed (Chen and Kareem 2003). Beside, this proposed scheme has a clear connection with the conventional linear analysis framework (here referred as semi-empirical linear model). This hybrid model simply combines "QS theory based model" and "semi-empirical linear model". Basically, the hybrid model linearizes the wind-induced force around a dynamic equilibrium angle of attack (or instantaneous angle of attack with low-frequency components) instead of a static angle of attack. Based on the hybrid model, the lift force and torsional moment per unit span in the global bridge axes are calculated by combining the forms of Eqs. (2) and Eqs. (10) and could be expressed as

\[ F_s = -\frac{1}{2} \rho B \left[ \frac{v^2}{U^2} \left\{ C_l (\alpha') \cos(\phi') + C_d (\alpha') \sin(\phi') \right\} \right] \]

\[ M_s = -\frac{1}{2} \rho B \left[ \frac{v^2}{U^2} \left\{ C_m (\alpha') \right\} \right] \]

where superscript "l" indicate the low frequency part based on a pinpoint presupposed and

\[ V' = \sqrt{(U + u')^2 + (W + w')^2 + (K + m_B a')^2} \quad \alpha' = \alpha + \alpha' + \phi' \]

Theoretically, the parameters in high frequency part should be measured in the dynamic wind-tunnel tests with turbulent incident wind condition.
2.6 Modified hybrid model (new)

Typically, the "static" wind-tunnel tests are featured with the identification of steady-state coefficients while the "dynamic" wind-tunnel tests are featured with the identification of aerodynamic transfer functions or aeroelastic transfer functions in bridge aerodynamics/aeroelasticity. A convenient approach to describe the results from "static" and "dynamic" wind-tunnel tests is to utilize the similar parameters, namely, steady-state coefficients and dynamic-state coefficients, respectively. Both steady- and dynamic-state coefficients are nonlinear with respect to angle of attack, while the dynamic-state coefficients also presents the hysteretic loop feature. As the fluct derivatives (or aerodynamic admittances), the dynamic-state coefficients with hysteresis are dependent on the angle of attack of the equilibrium position and reduced wind velocity. Assume all the components of bridge deck motions and wind fluctuations have the equal weighting on the wind-bridge interaction behavior, as applied in QS theory based model, the bridge aerodynamic/aeroelastic behavior could be described utilizing the dynamic-state coefficients with hysteresis (Diana et al. 2010). However, this assumption is questionable and the error introduced by this assumption is not always acceptable. Some attempts of accounting for different weights for various components of the dynamic angle of attack is to use higher-order artificial neural network (ANN) (Wu and Kareem 2011a). However, as a nonparametric model it is difficult to elucidate the physical meaning of the various weighting functions employed in the ANN model. A critical issue when utilizing the dynamic-state coefficients in bridge aerodynamics/aeroelasticity is that it is very difficult to find a proper frequency to define the reduced wind velocity, especially when wind fluctuations involved. A feasible approach to deal with this issue is to determine an averaged frequency for defining the reduced wind velocity under each mean wind velocity. Another feasible way is to utilize the concept of "band superposition". Different reduced wind velocities could be defined at each subrange to apply the appropriate dynamic-state coefficients measured in wind tunnel. Besides, this approach could improve the hybrid model which compromises the consideration of unsteady effect in the low frequency part to account for the nonlinear turbulence effect on the aeroelastic instability. Based on the modified hybrid model, the lift force and torsional moment per unit span in the global bridge axes should be revised as

\[
F_y = \frac{1}{7}\rho B \begin{cases} U^2 [C_u + V_{\text{hys}}^{\text{h}} \{ C_u^{\text{hys}}(\alpha^h) \cos(\phi^h) + C_D^{\text{hys}}(\alpha^h) \sin(\phi^h) \} ] \\ + V_{\text{hys}}^{\text{h}} \{ C_L^{\text{hys}}(\alpha^h) \cos(\phi^h) + C_D^{\text{hys}}(\alpha^h) \sin(\phi^h) \} ] \end{cases} ; \\
M_z = \frac{1}{7}\rho B \begin{cases} U^2 [C_u + V_{\text{hys}}^{\text{h}} \{ C_u^{\text{hys}}(\alpha^h) \} ] \\ + V_{\text{hys}}^{\text{h}} \{ C_L^{\text{hys}}(\alpha^h) \} ] \end{cases} \]

(19a; b)

where superscript "hys" indicates the dynamic-state coefficients with hysteresis; "h_n" indicate the wind fluctuations of high frequency part are divided into n subranges, and

\[
V_{\text{hys}} = \sqrt{(U + w)^2 + (W + w + h + m_B \delta h)^2} ; \quad \alpha^h = \alpha + \phi^h ; \quad \phi^h = \arctan \left( \frac{W + w + h + m_B \delta h}{U + w} \right) \]

(20; 21; 22)

Due to a lack of the experimental data, only the dynamic-state coefficients with hysteresis in the subrange with low-frequency fluctuation components is utilized in this research.

3 RESPONSE ANALYSIS

In this section, the aeroelastic and aerodynamic responses of a long-span cable supported bridge have been calculated with the six models discussed in the preceding content. The time histories of wind fluctuations is simulated utilizing the spectral representation scheme with prescribed power spectral density (PSD) function and turbulence integral scales and intensities. Low-pass and high-pass elliptic filter are utilized to separate the wind fluctuation into low- and high- fre-
frequency parts. The steady- and dynamic-state coefficients with angle of incidence are measured in wind tunnel and simulated based on the nonlinear least square and the Moore-Penrose pseudoinverse techniques, respectively. All the aerodynamic parameters in frequency domain are transferred into time domain based on the indicial function approximation.

3.1 Aerodynamic analysis

3.1.1 Comparison of aerodynamic responses based on various models

The aerodynamic responses of this bridge deck under turbulent wind condition are investigated based on the various models previously discussed. Fig. 2 presents the comparison of time histories of the calculated aerodynamic responses based on each model under the mean wind velocity 60 m/s with $I_u=15\%$ and $I_w=8\%$.

Fig. 3 presents the root-mean-square (RMS) values of the vertical and torsional displacements. Since the semi-empirical linear model is the conventional model utilized for bridge aerodynamics/aeroelasticity, it is treated as a reference model in this research. As discussed in the preceding section, for bridge aerodynamics/aeroelasticity, QS theory based model takes into account nonlinear effect but no fluid memory; corrected QS theory based model considers nonlinear effect with linear fluid memory at a fixed reduced frequency; linearized QS theory based model accounts for linear effect but no fluid memory; semi-empirical linear model considers linear effect with linear fluid memory; hybrid model considers nonlinear effect with linear fluid memory and modified hybrid model accounts for nonlinear effect with nonlinear memory (or higher-order memory featured by hysteresis).

Based on the results calculated by each model, in general it could be concluded that: (1) the aerodynamic responses based on the hybrid or modified hybrid models are close to the semi-empirical linear model, which indicates the nonlinearity or higher-order fluid memory effects captured by these two models in this case is small; (2) the aerodynamic responses based on the corrected QS model are closer to the semi-empirical linear model (larger for the vertical responses and smaller for the torsional responses in this case) compared to those based on the QS model, which indicates the corrected QS model could uncertainly improve the calculated responses by take into account the fluid memory at a fixed reduced frequency; (3) the fluid memory consideration has more significant effects on the torsional degree of freedom rather than the vertical degree of freedom as the relative difference between the torsional responses calculated by the linearized QS model and semi-empirical linear model is larger compared with the relative difference between the vertical responses; (4) the static nonlinearity consideration has more significant effects on the vertical degree of freedom rather than the torsional degree of freedom as the relative difference between the vertical responses calculated by the linearized QS model and QS theory based model is larger compared with the relative difference between the torsional responses. In a sense, the contribution to the aerodynamic responses from fluid memory effects is larger than that from nonlinear consideration based on this comparison. It should be noticed that the relative large torsional response based on the modified hybrid model is due in part to the contribution of
the limit cycle oscillation (LCO) response resulting from subcritical behavior, which indicates the aeroelastic instability resulting from the low-frequency part in the hybrid and modified hybrid models.

3.1.2 Comparison of aerodynamic responses under various turbulent wind conditions

Fig. 4 presents the RMS values of aerodynamics responses based on various models under different mean wind velocities with the turbulence intensity $I_u=15\%$ and $I_w=8\%$.

As shown in this figure, it is obvious that these six model could be divided into two groups based on the calculated aerodynamic responses. One group cannot take into account the fluid memory effects (including QS theory based and linearized QS models) and the other group could account for the fluid memory effects (including semi-empirical linear, hybrid and modified hybrid models), while capability of the reasonable consideration for the fluid memory based on the corrected QS model is uncertain. The results based on no memory consideration group are obviously larger than those based on memory consideration group, which indicates the fluid memory effect consideration reduces the aerodynamic responses at various wind velocities. On the other hand, the hybrid model based results are close to those calculated from the semi-empirical linear model, which indicates that the hybrid model may not fully characterize the nonlinear effects at various wind velocities. Besides, the comparison of the responses based on QS theory and linearized QS theory at various wind velocities indicates that the static nonlinearity (without coupling fluid memory effect) has significant effects on the vertical aerodynamic responses at various wind velocity while it has less effects on the torsional responses in this case. However, it is not necessary that this observation is also applicable for the dynamic nonlinearity effects (with coupling fluid memory effect). The differences of the results based on various models are more significant at higher wind velocity. The ripples in the corrected QS theory based result at some wind velocities are due to the relatively intense change of the correct coefficient $k_1$ while the large oscillations of the modified hybrid based results at wind velocity 60 m/s and 65 m/s is due to the subcritical behaviors. It should be noted that the observations discussed in the preceding content is based on that all other models are compared with the selected reference model, i.e., the semi-empirical model, which may not provide the "true" answer for the bridge aerodynamics/aeroelasticity.
Fig. 5 presents the RMS values of aerodynamic responses based on various models under different turbulence intensities with the mean wind velocity 40 m/s. As indicated in this figure, in general the incremental values of the aerodynamic responses based on the models which can consider the fluid memory effect are less than those based on the models which cannot account for the fluid memory effect. Besides, as the turbulence intensity is larger than 15%, there is intense nonlinear increases of the aerodynamic responses for most of models.

3.1.3 Motion induced effects on the aerodynamic responses
It is well known that the motion induced effects will change the effective structural dynamic parameters (mass, stiffness and damping ratio) and hence affect the aerodynamic responses. The aerodynamic responses discussed in the preceding content actually involves the aeroelastic effects. In order to investigate the motion induced effects on the aerodynamic responses for various models, the aerodynamic responses coupled with the aeroelastic responses are compared with the aerodynamic responses neglecting the motion induced effects as shown in the Fig. 6.

It is obvious that the motion induced effects are larger when the wind velocity increases. It seems there are more significant motion induced effects in the vertical degree of freedom in this case. In general, the motion induced effects will reduce the aerodynamic responses. However, for the torsional responses based on the semi-empirical linear and hybrid models the motion induced effects increase the aerodynamic responses. The errors of neglecting the motion induced effect for the aerodynamic responses based on the no memory consideration models are larger than those for the aerodynamic responses based on the memory consideration models.

3.2 Aeroelastic analysis

3.2.1 Critical flutter wind velocities
The stability issue is critical in bridge aeroelasticity as most researchers have attribute the catastrophic failure of the Tacoma Narrows Bridge to flutter behavior, which is a typical phenomenon of the bridge aeroelastic instability. Fig. 7 presents the critical flutter wind velocities $U_{cr}$ cal-
culated utilizing these six models under the uniform wind condition. Based on the calculated $U_{cr}$ of various models, in general it could be concluded that: (1) the linear memory effect consideration could increase the aeroelastic response (reduce the critical wind velocity of instability) since the $U_{cr}$ calculated by linearized QS theory based model (no memory) is larger than semi-empirical linear model (linear memory); (2) the nonlinear memory effect consideration could reduce the aeroelastic response (increase the critical wind velocity of instability) since the $U_{cr}$ calculated by modified hybrid model (nonlinear memory) is larger than hybrid model (linear memory); (3) the nonlinear effect consideration involved in the hybrid scheme could reduce the aeroelastic response (increase the critical wind velocity of instability) since the $U_{cr}$ calculated by hybrid model (nonlinear) is larger than semi-empirical linear model (linear). In a sense, the contribution to the aeroelastic response from fluid memory effect is larger than that from nonlinear consideration based on the comparison of the results of these models. However, it should be noticed that while the fluid memory effect (especially linear) is considered well through the unsteady parameters (e.g., flutter derivatives) the nonlinear effects are not fully characterized with an appropriate approach.

3.2.2 Turbulence effects on the instability

Suppose the turbulence effects on instability are considered in two aspects: the effect on the nonlinearity and the effect on the fluid memory. As the linearized QS model cannot take into account either nonlinearity or fluid memory, the turbulence will not affect the instability based on the linearized QS model. However, though the semi-empirical linear model could take into account the fluid memory effect, the turbulence effects will not significantly change the instability based on this model since the aerodynamic and aeroelastic responses are simply summed based on the superposition theory. Generally, the turbulence consideration will increase the critical flutter wind velocities as its effects on the nonlinearity have more significant contribution on the aeroelastic responses, which is demonstrated in the results based on the QS and corrected QS models as shown in Fig. 8. This observation indicates the turbulence effects reduce the aeroelastic responses due to static nonlinearity. On the other hand, if the turbulence effects on the fluid memory have more significant contribution on the aeroelastic responses, the situation becomes more complicated. In this situation, the turbulent fluctuations will reduce the critical flutter wind velocities generally. However, as the turbulence intensity increases, the critical flutter wind velocities slightly increase, as demonstrated in the results based on the hybrid and modified hybrid models. This observation indicates the turbulence effects increase the aeroelastic responses due to fluid memory, and this effect is larger for the smaller turbulence intensity. Another possible mechanism for this complicated situation in the hybrid and modified hybrid models is that the turbulence effect on the nonlinearity involved in these model increase significantly as the turbulence intensity becomes larger, which results in the slight increase of the critical flutter wind velocities compared to those with smaller turbulence intensity. Besides, the higher-order fluid memory consideration will significantly reduce the instability based on QS.
theory as the subcritical wind velocity in the modified hybrid model is 53 m/s under the uniform inflow condition while that in the hybrid model is 87 m/s. On the other hand, the low-frequency components of the wind fluctuations with small turbulence intensity (e.g., $I_u=5\%$) will slightly change (either reduce or increase) the subcritical wind velocity (from 53 m/s to 52 m/s in the modified hybrid model and from 87 m/s to 88 m/s in the hybrid model) while the low frequency components of the wind fluctuations with larger turbulence intensity (e.g., $I_u=15\%$) will increase the subcritical wind velocity (from 53 m/s to 59 m/s in the modified hybrid model and from 87 m/s to 91 m/s in the hybrid model).

Figure 8. Critical wind velocity under various inflow conditions.

4 CONCLUDING REMARKS

Six models for bridge aerodynamics/aeroelasticity, namely the QS theory based model (nonlinear effect but no fluid memory), the corrected QS theory based model (nonlinear effect with linear fluid memory at a fixed reduced wind velocity), the linearized QS theory based model (linear effect but no fluid memory), the semi-empirical linear model (linear effect with linear fluid memory), the hybrid model (nonlinear effect with linear fluid memory) and the modified hybrid model (nonlinear effect with nonlinear fluid memory), are investigated in detail. It is noted that the consideration of the linear and nonlinear unsteadiness (fluid memory) and the nonlinearity in the wind-bridge interaction significantly changes the bridge aerodynamic/aeroelastic responses.

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6 REFERENCES