Editorial

# Bluff body aerodynamics: from linear to nonlinear

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## Editorial

Accurate modeling of wind-induced loads on bluff bodies is critical to ensure the functionality and survivability of wind-sensitive civil infrastructures. Notwithstanding the developments made in recent decades in bluff body aerodynamics and aero elasticity, which have enhanced our abilities to better understand and capture the effects of turbulent wind on structures, there is a need to revisit the current paradigms and to look for improved understanding concerning an appropriate simulation level from linear to nonlinear. Although the linear analysis methodologies cannot reveal some aerodynamic/aero elastic behaviors clearly, they have been proven to be valid with reasonable accuracy in many applications of structural wind engineering. On the other hand, modern bridge decks, super tall buildings with unusual profiles and flexible wind turbine blades all exhibit aerodynamic nonlinearities, which combined with unsteady effects limit the applicability of state-of-the-art analysis procedures. A main physical source of nonlinearity in bluff-body aerodynamics and aero elasticity is due to flow separation from the structure. For streamlined sections like an airfoil or a wind turbine blade, flow separation results from the large angle of attack (dynamic stall) or in the case of high flight speed of an aircraft shock motions in the transonic region (the shock motion itself also induces nonlinearity). For bluff sections like a bridge deck, flow separation is prevalent as the fluid motion around the deck cannot negotiate sudden changes in the deck profile (severe adverse pressure gradients).

The resulting nonlinearity may be classified as: (i) non-proportional relationship between amplitudes of the input and output; (ii) single-frequency input resulting in multiple-frequency output; (iii) amplitude dependence of aerodynamic and aero elastic forces; (iv) hysteretic behaviour of aerodynamic forces versus angles of attack. It is often believed that nonlinearity usually has favorable effects on the aero elastic systems due to limit-cycle oscillations, while nonlinearity also could result in unfavorable effects on the aero elastic systems. Nonlinear effects are usually exploited to offer a possible explanation for any differences observed between the linear analysis results and experiments although it is not always possible to delineate their relative contributions. For a specific aerodynamic or aero elastic system, it is important to first make a preliminary investigation to better understand general effects of nonlinearity and unsteadiness on the gust-, and motion-induced responses with recently developed analytical tools. The quasi-steady (QS) theory, first introduced to model galloping phenomenon, is central to a large class of aerodynamic and aero elastic analysis frameworks. The high amplitude oscillations of the original Tacoma Narrows Bridge deck were similar to galloping in a torsional degree-of-freedom (usually referred to as torsional flutter). Accordingly, it is convenient to illustrate this behavior by the QS theory. However, an obvious shortcoming of the QS theory is that it cannot take into consideration the unsteady features inherent in fluid-structure interaction with attendant fluid memory effects. The fluid memory indicates that the flow around the structure not only depends on the current relative states (structural motions and flow fluctuations) but also on their time histories. On the other hand, to circumvent dealing with nonlinear differential equations, the QS theory-based formula is usually linearized to qualitatively evaluate the aerodynamic/aero elastic forces, corresponding to equivalent analytical expressions existing for airfoils, i.e. the asymptotic form of the Theodorsen/Sears function. These functions can account for the unsteady effects, however, are mathematically intractable for sections like a bridge deck, due to flow separations and other aerodynamic considerations. This has led to the development of linear unsteady parameters, derived from dynamic wind-tunnel tests, commonly referred to as aerodynamic admittances and flutter derivatives. Since these early studies pioneered by Profs. Alan Davenport and Robert Scanlon, flutter analysis based on the linear analysis framework has been carried out through numerical and closed-form solutions. This semi-empirical, linear, unsteady scheme has been applied extensively both in research and design to investigate aerodynamic and aero elastic behavior of bridge decks under winds.

The QS theory-based models could take into account nonlinearity, but not the fluid memory, whereas conventional models based on Scanlan's flutter derivatives could account for the fluid memory effects, but not the nonlinearity. In light of these features, a hybrid methodology has been developed by research groups of Profs. Giorgio Diana and Ahsan Kareem to capture both the unsteady and nonlinear effects of wind-bridge interactions. The basic premise of this semi-empirical, nonlinear approach is that the low-frequency aerodynamic/aero elastic effects are simulated by the QS theory while the contributions at high frequencies are represented by conventional semi-empirical linear model. Though the hybrid model reasonably accounts for the nonlinear effects, it sacrifices the inclusion of unsteady effects at the low frequencies. Besides, the exact demarcation between the low- and high-frequency fluctuations currently lacks a rigorous treatment. The semi-empirical, linear, unsteady model is actually a time-linearized method, where a steady-flow field (statically nonlinear) is first determined, and then a small perturbation (linear) is added on this base flow; while the hybrid model extends the steady-flow field to a slowly fluctuating base flow. Unfortunately, this methodology does not always have a satisfactory representation of the full nonlinear equations which govern the fluid-structure interactions.

In the case of wind turbines, if the nonlinearity and unsteadiness are significant, conventional blade element momentum (BEM) theory for aerodynamic analysis is not suitable. Instead, the unsteady wake modeling, such as vortex wake model, need to be utilized. The current state of the art is to combine the vortex wake model (which is based on the incompressible potential flow theory) and the dynamic stall modeling (which indicates massive separation and intensive viscosity effects). Although this scheme shows a great promise of simulating aerodynamics of wind turbines, it may have its own limitation for prediction of power outputs. An alternate way is to utilize computational fluids dynamics. However, the computational effort is too high considering the three-dimensional nature of wind turbine aerodynamics. In light of this, low-dimensional modeling of the aerodynamics may offer a promise approach.

In light of the high computational efficiency and ability to retain essential physics, the low-dimensional models have been rapidly developed in this context over the last several decades. There are a number of low-dimensional models which have been successfully applied in engineering, such as the describing function, trajectory piece-wise linearization, artificial neural network, autoregressive moving average, Volterra series and proper orthogonal decomposition. Improvement in the efficiency and robustness of these low-dimensional models is a topic of cutting-edge research in aerodynamics community. In addition, selection of a proper scheme among a wide range of low-dimensional models to simulate nonlinear unsteady bluff-body aerodynamics and aero elasticity is quite challenging.

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## Conflict of interest

The author declares no conflict of interest.

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