

Wind induced effects on bluff bodies in turbulent flows: nonstationary, non-Gaussian and nonlinear features

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ABSTRACT: Notwithstanding the developments made in recent decades in bluff body aerodynamics and aeroelasticity, which have enhanced our abilities to better understand and capture the effects of turbulent wind on structures, we are at an appropriate juncture to reflect on these developments, reassess their merits and shortcomings, and identify the need for embarking on different modeling philosophies and paradigms. In this context, there is a need to revisit the current paradigms and to look for improved understanding concerning the nature of wind fields, the associated aerodynamics and the resulting load effects in recognition of the following emerging realities: non-stationarity/non-homogeneity/transient wind events; non-Gaussianity; nonlinearity of structural and aerodynamic origins; unsteady/transient aerodynamics. Also, one needs to take note of recent advances in analysis and identification tools, and modeling frameworks, which promise to offer better understanding of the underlying complexities associated with the preceding themes. This paper discusses these issues and illustrates their significance in bluff body aerodynamics and aeroelasticity from the perspective of wind effects on built infrastructure.

KEYWORDS: Turbulence; Bluff body; Nonstationarity; Non-Gaussianity; Nonlinearity; Modeling

1 INTRODUCTION

The assurance of structural safety and reliability under wind loads requires accurate modeling of wind load effects relying heavily on our understanding of bluff body aerodynamics and aeroelasticity. The intractability of wind-structure interactions amidst complex urban topography has precluded analytical treatment of the subject with rather few exceptions such as buffeting effects ([Davenport 1967](#); [Zhou and Kareem 2001](#); [Kwon and Kareem 2009](#)). Therefore, physical modeling of wind effects in boundary layer wind tunnels has served as a most effective tool for ascertaining these load effects ([Cermak 1975](#)). Accordingly, the last few decades have witnessed significant advances in wind tunnel technology, full-scale monitoring, sensors/transducers, instrumentation, data acquisition systems, data fusion and mining strategies, laser Doppler-based technologies, geographical information and positioning systems (GIS) & (GPS) and information technologies, which have increased our ability to better monitor and process gathered information for improved understanding of the complexities and nuances of how wind interacts with structures, the attendant load effects and their modeling. On the other hand, in the last few decades, there have been major developments in the computational area to numerically simulate flow fields and their effects on structures. Developments in computational methods, e.g., stochastic computational mechanics, have led to useful tools to further advance the role of numerical analysis. The availability of high-speed computers, individually, in networked clusters, or in the cloud has enhanced the portability and interoperability of computational codes, to most research laboratories and design offices. Rapid advances on all fronts have accordingly led to advances in our understanding of aerodynamics and aeroelasticity and associated load effects and, as a consequence, have improved the prospect of developing the next generation of load simula-

tion facilities and wind tunnels, database enabled design aids, web-based e-technologies and codes and standards.

These developments have undoubtedly enhanced our abilities to better understand and capture the effects of wind on structures. It is appropriate time, however, to reflect on these developments, reassess their merits and shortcomings, and identify the need for embarking on different modeling philosophies and paradigms as called for by the recent observations. In this context, the rest of this paper will identify and discuss a few selected frontiers in bluff body aerodynamics and aeroelasticity with particular reference to wind loads on structures and the challenges these pose to the fluid dynamics and wind engineering communities. These topics include non-stationarity/non-homogeneous/transient wind events; non-Gaussianity; nonlinearity of structural and aerodynamic origins; unsteady/transient aerodynamics and the relevant modeling frameworks and identification tools. Improved understanding of turbulence effects on bluff bodies is stressed.

2 NONSTATIONARY/TRANSIENT WINDS

Most extreme wind events are nonstationary in nature and are often highly transient, e.g., wind fields in hurricanes, tornadoes, downbursts and gust fronts. Therefore, the most critical issue in wind field characteristics concerns the transient wind events, e.g., gust-fronts generated by downdrafts associated with thunderstorms. The significance of these transient wind events and their load effects can be readily surmised from an analysis of thunderstorms databases both in the U.S. and around the world, which suggest that these winds actually represent the design wind speed for many locations ([Twisdale and Vickery 1992](#); [Brooks et al. 2001](#)).

The mechanics of gusts associated with convective gust-fronts differs significantly from conventional turbulence (driven by momentum) both in its kinematics and dynamics. A survey of full-scale studies in the meteorological field suggests that winds spawned by thunderstorm, both on the updraft side as tornadoes and on the downdraft side as downburst, fundamentally differ from the synoptic winds in neutrally stable atmospheric boundary layer flows. The key distinguishing attributes are the contrasting velocity profile with height and the statistical nature of the wind field. In gust-fronts, the traditional velocity profile does not exist; rather it bears an inverted velocity profile with maxima near the ground potentially exposing low- to mid-rise structures to higher wind loads (e.g., [Wood and Kwok 1998](#); [Letchford and Chay 2002](#); [Butler et al. 2010](#)). This is compounded by the inherent transient nature of energetic convective gusts, raising serious questions regarding the applicability of conventional aerodynamic loading theories. Although the size of gust-fronts may be relatively small and their effects rather local, the fact remains that they can produce significantly damaging winds. The famous Andrews Air force base downburst of 1983 clocked peak gusts of 67 m/s, whereas, ASCE Standard provisions list 50-year recurrence winds of 40-45 m/s in this region ([Fujita 1985](#)). Accordingly, one should question the appropriateness of a design based on conventional analysis frameworks in codes and standards, which generically treat these fundamentally different phenomena in the same manner.

The major challenge in this area is at least twofold, i.e., firstly, the nature of flow fields in rain bands, the eye wall of hurricanes, downdrafts and gust fronts needs to be better quantified, and secondly, analysis and modeling tools to capture these features need to be established. Design loads are based on the mean wind speed for a given site and direction and rely on the assumption that the fluctuations in the mean are characterized by a statistically stationary process, which has led to useful and practical simplifications. The gust-fronts generated in thunderstorms/downdrafts differ from the large-scale (extratropical/ depressional) storms as the mean wind speed exhibits sharp changes and in some cases changes in wind direction. This leaves the assumption of stationarity open to serious criticism.

Besides this departure in statistical attributes of the wind field, gust-fronts are likely to be associated with rapid and substantial changes in the local flow around structures and will likely be correlated over a larger area. These changes in the kinematics and dynamics of the flow field would potentially result in higher aerodynamic loads. These attributes further complicate the concept of “gust factors” which in some forms are central to most wind load assessments. The gust factor concept used for extratropical winds must be revisited as the period used to evaluate average wind speed for thunderstorm winds must be shortened to obtain meaningful results. Longer periods, such as an hour, if used for thunderstorm winds may result in gust factor values almost 2-3 times the corresponding values in extratropical winds. Current efforts toward glean-ing information regarding the thunderstorm outflow characteristics through modeling non-stationary winds would aid in better capturing the salient features of winds in transient events (Gast et al. 2003; Wang and Kareem 2004a; Chen and Letchford 2005a). In a recent study, Kwon and Kareem (2009) presented a new framework to capture the flow field in a gust front and its attendant load effects.

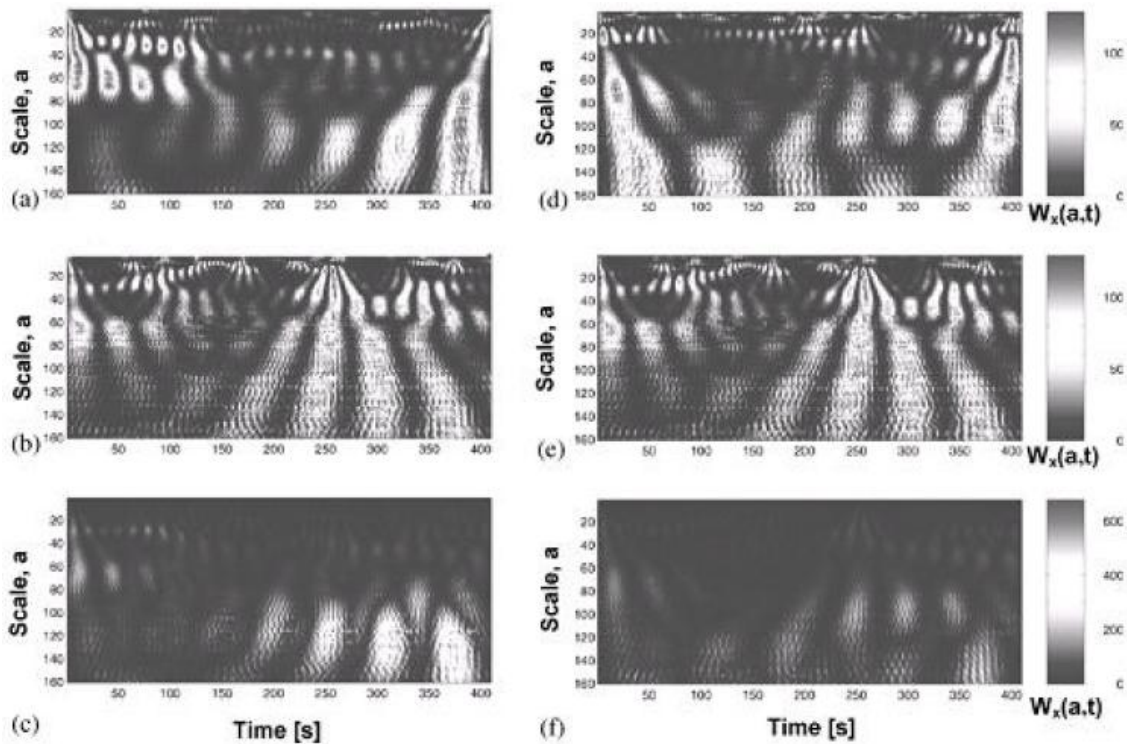


Figure 1: (a) Scalogram of upstream wind velocity 1; (b) scalogram of rooftop pressure; (c) coscalogram of these two correlated processes; (d) scalogram of upstream wind velocity 2; (e) scalogram of rooftop pressure; (f) coscalogram of these two uncorrelated processes (after Gurley and Kareem, 1999)

Simulation of non-stationary events like gust fronts and hurricane wind fields can be accomplished by the generic summation of trigonometric time series approaches, but it is computationally inefficient, since, due to lack of ergodicity, ensemble averaging requires simulation of a large number of time series. The (proper orthogonal decomposition) POD based approach offers computational expediency, but thus far has been explored to only account for the amplitude modulations (Chen and Letchford 2005b). The wavelet-based simulation offers an alternative, which may better capture both time and frequency modulations (Wang and Kareem 2004a; 2004b; 2005). The dual nature of wavelet transforms, being a simultaneous transform in time and frequency, justifies its recent extension to civil engineering applications. The transform can be

adapted to a number of situations where Fourier transforms (for frequency domain analysis) or Hilbert transforms (for time domain system identification) are traditionally used to define quantities of interest. When considering the time and frequency information in tandem, wavelets can be used to determine the times and frequencies at which signal energy content is strongest by examining scalograms and co-scalograms (Gurley et al. 1997; Gurley and Kareem 1999; Kareem and Kijewski 2002). Fig. 1 displays a coscalogram comparison for full-scale pressure measured on a building and the two upstream wind velocity records. The first record is monitored simultaneously with the pressure time history under consideration and the second is from a different wind event. Fig. 1 (a-c) shows the scalogram and coscalograms of wind pressure and the first wind velocity, which is knowingly correlated. Note the pockets of white beyond 250 seconds revealing timevarying pockets of correlation in different frequency bands. This may be compared to a similar analysis for wind pressure and velocity that is known to be uncorrelated, for which no marked white pockets, indicative of correlation, are present. The presence of subtle light pockets, indicative of spurious correlation, present in both the correlated and uncorrelated examples in Fig. 1 is due to a lack of ensemble averaging (Kareem and Kijewski 2002).

3 NON-GAUSSIANITY

The wind velocity could be well represented as a Gaussian process, which is verified by numerous experiments and field observations. As a result, with the assumption of linear relationship between the input (wind velocity) and output (structure response), many of the studies encompassing analysis and modeling of wind effects on structures have assumed that the involved random processes are Gaussian. In general, for large structures the assumption of Gaussianity may be valid as a consequence of the Central Limit Theorem. However, the regions of structures under separated flows experience strong non-Gaussian effects in the pressure distribution characterized by high skewness and kurtosis. Fig. 2 illustrates the nature of pressure fluctuations on the windward and roof regions, where the rooftop region distinctly exhibits non-Gaussian features as noted in the time history of pressure fluctuations. It is also noteworthy that the bending moments (bottom time history) at the supports also exhibit non-Gaussian features despite the fact that the bending moments result from the summation of several force components. The departure from the Central Limit Theorem stems from the fact that the loads over the structures are correlated, which is in contradiction to the premise of the theorem.

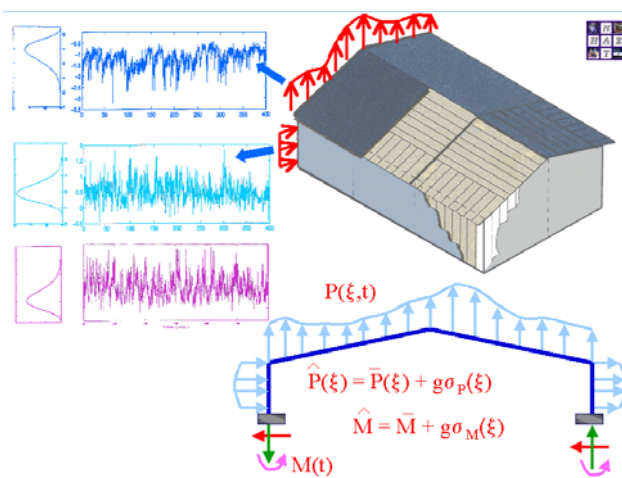


Figure 2: Schematic of pressure fluctuations on a building envelope

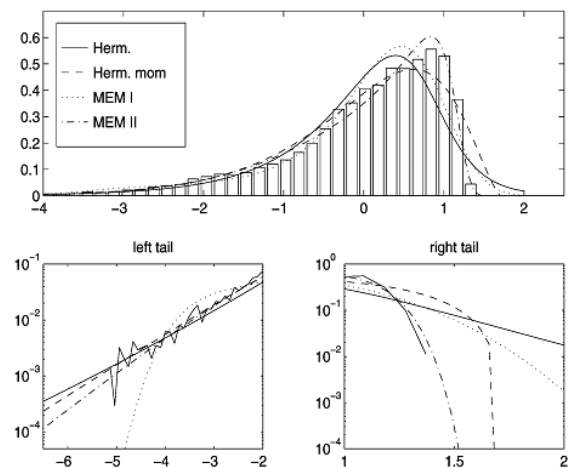


Figure 3: Top - PDF of pressure fluctuations in a separated region; Bottom - Close up of the tail regions (after Gurley et al. 1997)

The probability density function (PDF) of pressure fluctuations with large skewness observed in separated flow regions is critical to the modeling of loads on cladding and components, as well as loads on main load-resisting systems (Fig. 3). Often researchers have attempted to use the lognormal distribution for pressure fluctuations, but this fails to represent the tail region with high fidelity (Gurley et al. 1997). Among different alternatives, including the Maximum Entropy based model, it is noted in Fig. 3 that the Hermite moment-based distribution provides the best match to the data, especially for the negative tails (Gurley et al. 1997). This model also captures the significance of non-Gaussian pressure fluctuations for determining the equivalent constant pressure for glass design (Gurley et al. 1997), while providing a useful format to account for non-Gaussianity in the estimation of wind induced fatigue damage, as characterized by a correction factor (Gurley et al. 1997). The non-Gaussian effects result in enhanced local loads and may lead to increased expected damage in glass panels and higher fatigue effects on other components of cladding (Gurley et al. 1997).

Progress in quantifying and simulating the non-Gaussian effects of wind on structures has been elusive due to the limitations of traditional analytical tools (Gurley et al. 1996; Grigoriu 1998). Earlier work based on correlation distortion has been based on an inverse mapping of the desired PDF, a summary of which may be found in Gurley et al. (1996). In Gurley and Kareem (1997), a simulation approach, which is significantly more robust than the correlation distortion schemes, was presented. The non-Gaussian features and the frequency contents in the form of the first four moments and the target power spectral density (PSD) of the process were used; alternatively analytical expressions or other estimates of the distribution may be employed. The approach is named the spectral correction method relying on a few iterations to match both the spectral and probabilistic features. Fig. 4 shows an example of a simulation run based on a measured time history of a highly skewed full-scale pressure measurement. Also included are the PDF and PSD of the target and the simulated records which show good agreement. Additional follow-up work in this broad framework can be found in Grigoriu (1998), Deodatis and Micaletti (2001) and Masters and Gurley (2003). This approach has been extended to multi-variate processes including conditional simulations and random fields (Gurley and Kareem 1998a; 1998b; Gurley et al. 2001).

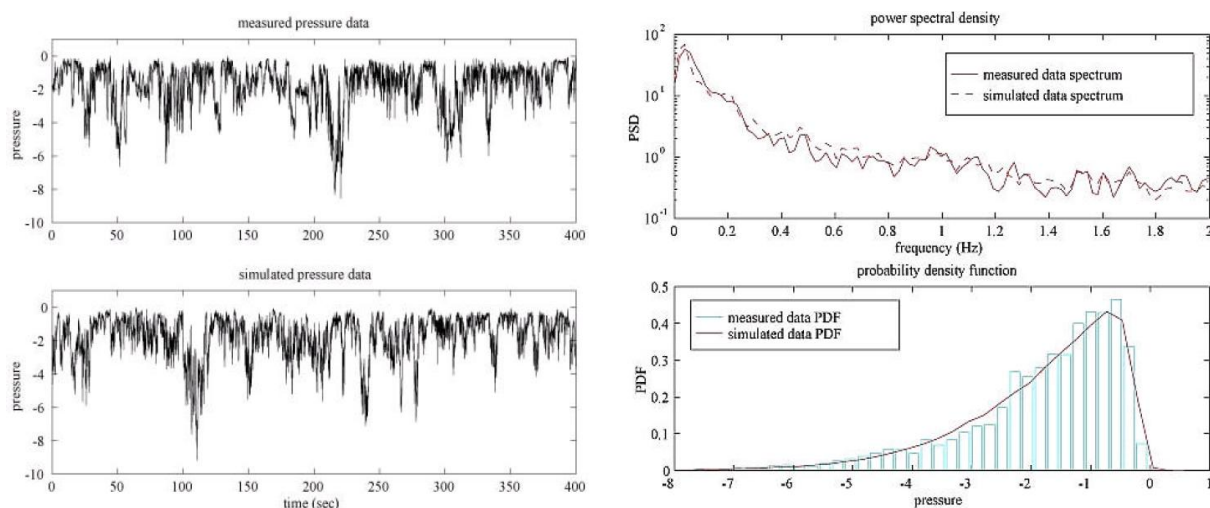


Figure 4: Left - Measured and simulated pressure time histories; Right - Comparison of PSD and PDF of simulated and measured time histories (after Gurley, et al. 1997)

Inasmuch as these techniques are based on static transformations, they may fail to encapsulate any memory that may be present in the target signals. A Volterra series-based scheme offers

an alternative that ensures preservation of memory. However, the Volterra kernels needed for such simulation may not always be available (Gurley and Kareem 1997). A class of single point non-Gaussian processes, e.g., pressure fluctuations at a location, can also be simulated through manipulation of the phase and utilization of neural networks (e.g., Gurley et al. 1996; Seong and Peterka 1998).

4 NONLINEARITY

In the area of wind effects on structures there are three types of nonlinearities that are generally experienced, i.e., geometric, material and aerodynamic. The geometric nonlinearity is most prevalent in cable-suspended and guyed structures, i.e., suspension and cable stayed bridges and guyed towers and masts, and pneumatic structures. The material nonlinearities may arise from materials of construction, e.g., concrete and composites that do not follow linear constitutive relationships. These effects can be adequately modeled for most structures using finite element models.

The nonlinearity of aerodynamic and aeroelastic origins are prevalent in wind effects on structures. Customarily, in these situations, linearized solutions are invoked, e.g., the widely used gust loading factor in codes and standards is based on the Gaussian framework, thus the term containing the square of the velocity fluctuations is dropped from the formulation. Kareem et al. (1998) presented a gust loading factor, which included the square velocity term, using the Hermite moment-based distribution in place of the Gaussian distribution. Earlier attempts to capture this effect using Edgeworth series did not adequately represent the tail regions of the distribution.

A linear assumption is often used to compute the response of structures to buffeting forces when nonlinearity in aerodynamic loading arises from the squared velocity term, as alluded to previously and due to dependence of aerodynamic coefficients on the angle of attack. Currently, reliance on the quasi-steady theory is a method of choice to take into account aerodynamic nonlinearities. According to the quasi-steady (QS) assumption, aerodynamic forces on structures are expressed as a nonlinear memoryless transformation of the flow-structure relative velocity and the angle of attack, which are variable in time due to oscillation of the body and the presence of turbulence in the incoming flow. The projection of the aerodynamic forces on the shape-functions employed in the finite element or Galerkin discretization of the structure requires approximating the nonlinearities by polynomial expressions. This can be carried out through a Taylor series expansion (Denoël and Degée 2005) or by an optimization procedure aimed at minimizing some error measure (Carassale and Kareem 2010).

On the other hand, one of the challenges in aeroelastic analysis remains in the modeling of wind-induced forces that take into consideration nonlinearities in both structural dynamics and aerodynamics in an unsteady analysis framework. As the measured information utilized in the traditional analysis framework, e.g., flutter derivatives, wind spectra, and aerodynamic admittances, are all natural functions of frequency, the aerodynamic issues are conventionally analyzed in frequency-domain (Scanlan and Tomko 1971). These frequency-domain analysis approaches are not suitable for accommodating the computational challenges of the nonlinear considerations.

In order to consider the unsteady effect in time domain, the indicial function approximation (Scanlan et al. 1974) or rational function approximation (Bucher and Lin 1988) is utilized. One of the earliest performance of the bridge aerodynamic/aeroelastic unsteady analysis in time domain is carried out by Beliveau et al. (1977) based on the indicial function approximation. Recently, Chen et al. (2000) and Chen and Kareem (2001) conducted the bridge aerodynamic/aeroelastic unsteady analysis in time domain based on the rational function approximation.

The proposed time domain analysis framework by Chen et al. (2000) and Chen and Kareem (2001) incorporates the frequency-dependent characteristics of aerodynamic forces that have been often neglected in most of the previous studies in time domain aeroelastic analysis, potentially impacting the accuracy of the response estimates.

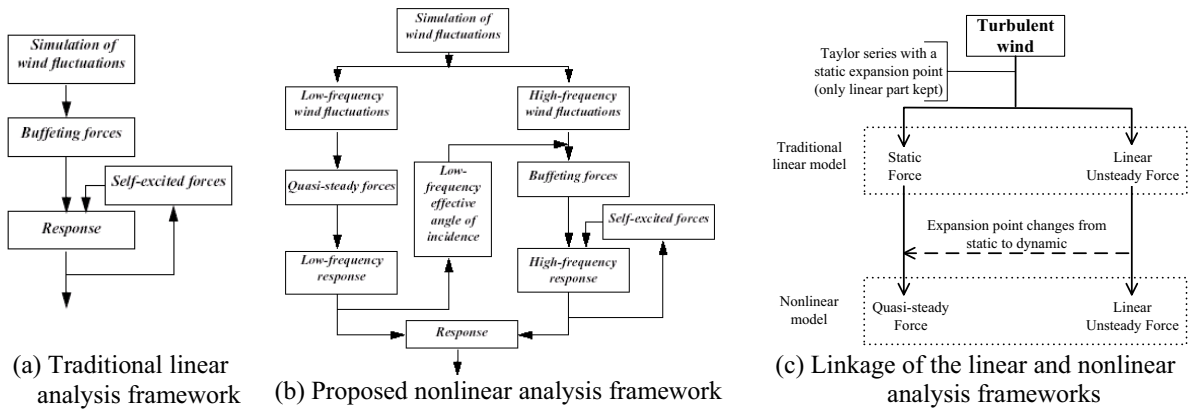


Figure 5: Traditional and nonlinear analysis frameworks ((a) and (b) after Chen and Kareem 2003)

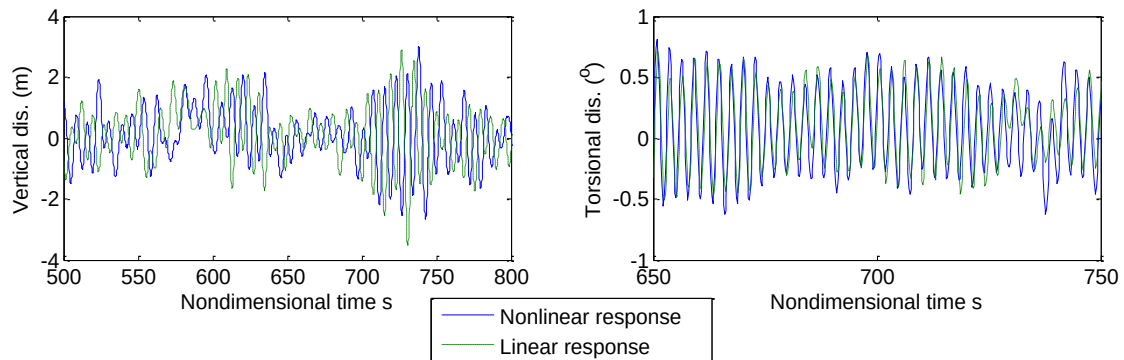


Figure 6: Time history of linear and nonlinear bridge deck responses

Furthermore, an advanced nonlinear aerodynamic force model and attendant analysis framework has been presented by Chen and Kareem (2003) that focused on the needs for modeling of aerodynamic nonlinearity of long span bridges. This nonlinear analysis framework transforms the problem into a full-time-domain formulation by means of a rational-function approximation and solves the equations of motion in the time domain through among others an integrated state-space approach. The aerodynamic forces are separated into the low- and high-frequency components in accordance with the effective angle of incidence corresponding to the frequencies lower than and higher than a critical frequency, e.g., the lowest natural frequency of the bridge. The low-frequency force component can be modeled based on the QS theory due to its high reduced velocity, while the high-frequency force component is separated into self-excited and buffeting components which are modeled in terms of the frequency dependent unsteady aerodynamic characteristics at the low-frequency spatiotemporally varying effective angle of incidence. Beside, this nonlinear scheme, proposed by Chen and Kareem (2003), has a clear connection with the traditional linear analysis framework. The traditional linear and advanced nonlinear analysis frameworks are summarized in Fig. 5 along with the basic relationship between these two analysis schemes. Actually, the advanced nonlinear scheme uses expansion of the aerodynamic force term about a dynamic position of the deck as opposed to a static position,

which represents the mean displaced position of the deck as employed in a traditional linear scheme. In other words, this nonlinear analysis framework represents piecewise linearization in a dynamic scheme as opposed to the static approach (Wu and Kareem 2011). The time histories of the nonlinear aerodynamic responses, namely vertical and torsional displacements for a long span bridge are presented in Fig. 6 compared with the traditional linear results.

5 HYSTERETIC NONLINEAR BEHAVIOR

The hysteretic nonlinear phenomenon is well known in vortex induced vibration of bluff bodies since it was initially observed experimentally by Feng (1968). Recently, the hysteretic phenomenon in the aerodynamic/aeroelastic forces on both the bridge decks and the cables of cable-stayed bridges has been a focus of interest (Diana et al. 2010; Wu and Kareem 2012a). The hysteretic behavior that appears in bridge aerodynamics/aeroelasticity suggests a higher-order memory in the system. Details of the hysteresis phenomenon, common to many fields, may be found in the literature (e.g., Brilliant 1958). The examples carried out by the authors indicate that the wind-induced responses of a typical modern bridge deck and of a stayed cable are significantly increased by introducing the hysteretic behavior in the respective response prediction schemes (Wu and Kareem 2012b; Wu et al. 2012). The hysteretic phenomenon could be modeled through a rheological model (Diana et al. 2010) or through a more generalized higher-order polynomial model based on the Moore-Penrose pseudoinverse identification scheme (Wu and Kareem 2012a). Fig. 7 presents the hysteretic phenomena observed in the lift forces acting on a bridge deck and on a typical stay cable based on wind-tunnel studies together with the numerically fitted model utilizing Moore-Penrose pseudoinverse identification scheme which shows a good agreement (Wu and Kareem 2012a).

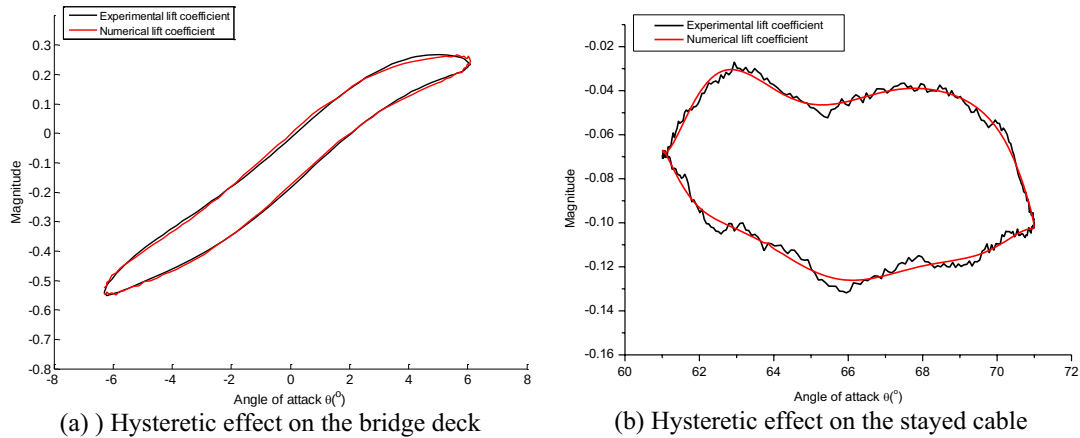


Figure 7: Modeling the hysteretic behavior related to the lift coefficient (after Wu and Kareem 2012a)

However, both of these schemes are based on a unique independent variable, namely the effective angle of attack. In other words, these schemes assume that all other interacting components (bridge deck motions and turbulences) that are represented by this unique independent variable have equal weighting on the bridge aerodynamic behavior, which poses an unwarranted constraint in the aerodynamic force description (Wu and Kareem 2011). On the other hand, Wu and Kareem (2011) proposed a neural network model to simulate the hysteretic nonlinear behavior, which can be easily expanded for a single term input parameter to several input parameters through introduction of added weights and neurons as illustrated schematically in Fig. 8.

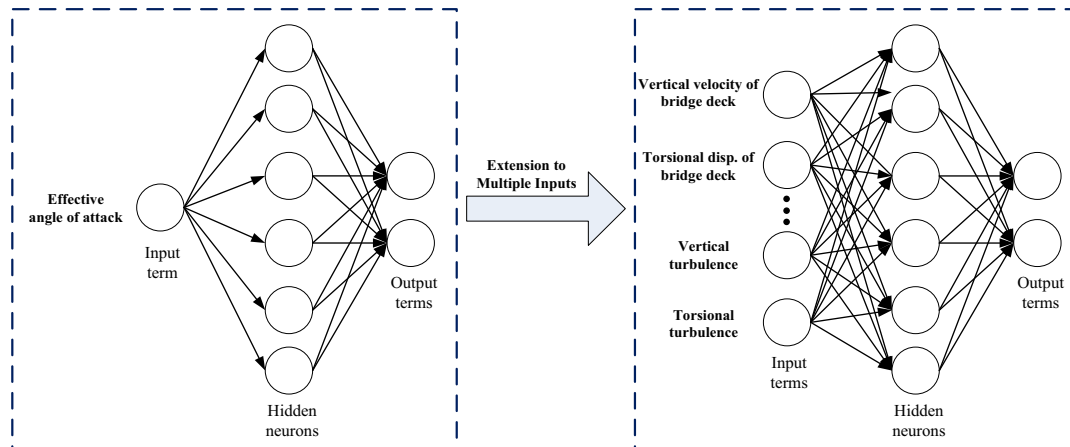


Figure 8: Schematic of the neural network for hysteretic nonlinear phenomenon

This data-driven model is determined by input-output information, which automatically captures intrinsic aerodynamic/aeroelastic nonlinearity and structural nonlinearity of the wind-bridge interaction system, as shown in Figure 9. Besides, the hysteretic nonlinearity modelling capability is enhanced through the higher-order neurons in the hidden layer, which results from the power terms of the first-order terms themselves as well as their cross terms. The cellular automata optimization scheme is applied to determine the configuration of the neural network with the aim of modelling bridge aerodynamics and aeroelasticity (Wu and Kareem 2011).

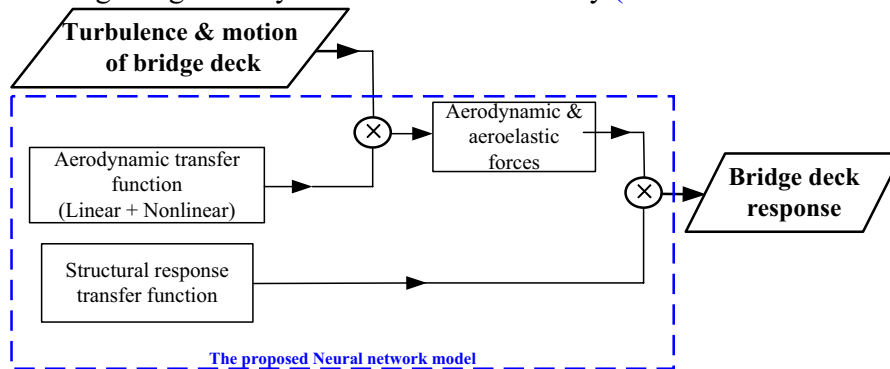


Figure 9: Integration of structural and aerodynamic nonlinearities via neural network model

6 ROLE OF TURBULENCE

The role of turbulence in the aerodynamics of stationary bluff bodies has been extensively documented in the literature (e.g., Gartshore 1973; Lee 1975; Kareem and Cermak, 1979; Saathoff and Melbourne 1989; Nakamura 1993). More recent studies investigating the effects of turbulence on rectangular sections have focused on both stationary and/or oscillating prisms with applications to improved understanding of building and bridge aerodynamics to turbulence (Larose 1993; Haan and Kareem 2009). Studies have shown that the flow around bluff bodies is governed by the separation and reattachment of the shear layers and by vortex shedding. The shear-layer thickness and the body size are length scales associated with these two phenomena, respectively. Turbulent eddies on the order of these scales are most effective at altering flow structure. The main effect of small-scale turbulence is to cause earlier reattachment of the flow through enhanced mixing in the shear layers. Turbulence in the range of the body scale can enhance or weaken vortex shedding depending on the body geometry. A schematic diagram of the multi-

scale fluctuations involved in typical bluff body wind interactions is shown in Fig. 10. Clearly there are three distinct bands of frequency characterized by the incident, shear layer or near wake and the wake fluctuations.

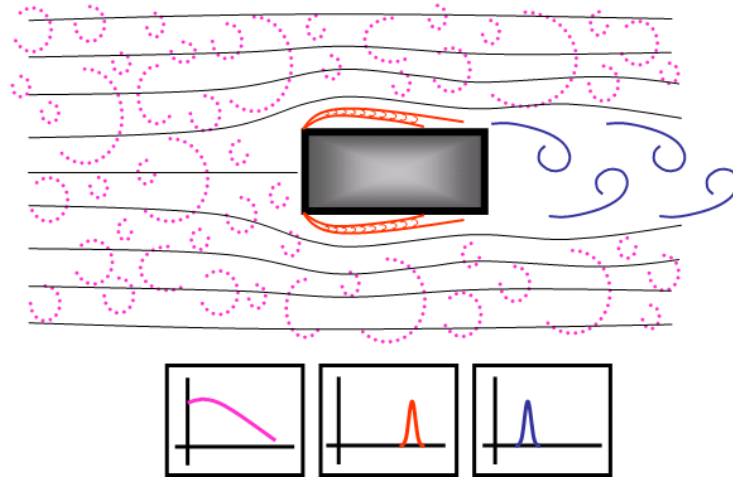


Figure 10: Schematic of flow around a bluff cross-section highlighting three distinct regions of fluctuations

Current fundamental and applicable research in turbulence effects on bluff bodies is summarized in Fig. 11, while only a selected few topics will be discussed in the following sections.

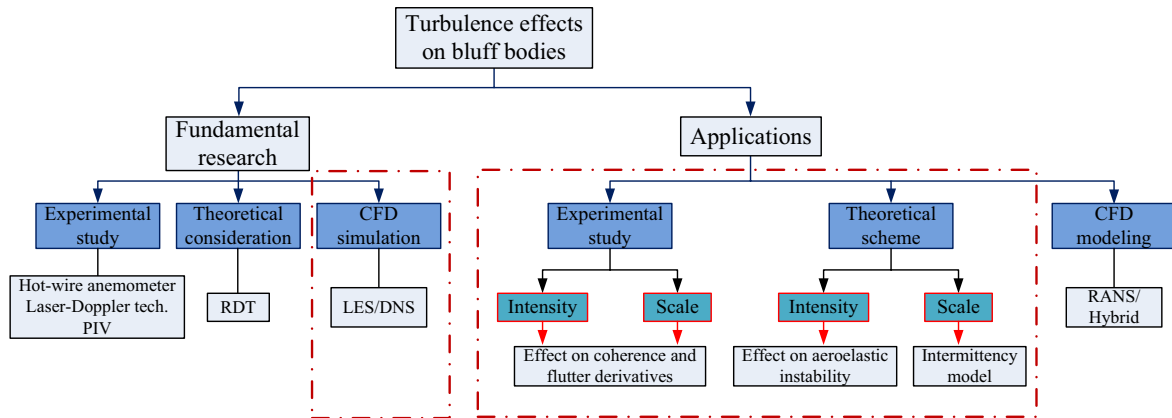


Figure 11: Current studies of turbulence effect on bluff bodies

6.1 Fundamental research

Although the "rapid distortion theory" (RDT) presents promising features to simplify the nonlinear nonlocal turbulent flow controlled by Navier-Stokes equation, this linear partial differential equation is still mathematical intractable as applied to the bluff bodies (Hunt et al. 1990). While current fundamental understanding of turbulence effect on bluff bodies mainly relies on the experimental studies involving significant improvement of the data acquisition systems, such as the Hot-wire anemometer, Laser-Doppler based technologies and particle image velocimetry (PIV), there have been remarkable developments in the area of computational wind engineering centered on the flow around bluff bodies involving 2-D and 3-D prisms and the role of turbulence (e.g., Murakami and Mochida 1999; Yu and Kareem 1997; Tamura and Ono 2003). The Large

Eddy Simulation (LES) framework is emerging as a numerical scheme of choice for the solution of Navier-Stokes equations (Murakami and Mochida 1999). For example, recent studies have shown that the simulated pressure field around prisms has convincingly reproduced experimentally-observed characteristics. This is true with respect to variations in the mean and RMS pressure coefficients of the drag force and regions of flow reattachment, even as the aspect ratio of the prism is varied (Murakami 1999; Yu and Kareem 1997). Other computational schemes like detached eddy and hybrid simulation schemes are offering other opportunities for improved simulations (Wei and Kareem). Fig. 12 shows instantaneous contours of vorticity for prisms of aspect ratios: 3:1 and 1:3 based on 3D LES schemes. In Fig. 13 time histories of the drag and lift forces along with their respective PSD and time-frequency scalograms are shown. Examination of the drag and lift force time histories for the selected aspect ratios reveal distinctive features both above and below the critical aspect ratio of 0.62. For aspect ratios below the critical value intermittent behavior (periods of low and high drag force) occurs, while beyond the critical value, the drag force has less intermittence. The corresponding spectral descriptions show a global distribution of energy. The scalograms (Fig. 14) reaffirm the intermittent bursts of energy for aspect ratio 3:1 and relatively more evenly distributed fluctuations for the 1:3 prism.

One of the challenges remaining in this field entails the inclusion of surrounding structures to capture the influence of flow modification, shielding and interference, as well as the simulation of inflow turbulent boundary layer flow conditions. Recently, advances have been made in these areas, including modeling of aeroelastic instabilities, CFD techniques for practical applications, and modeling of urban roughness and terrain effects (Tamura et al. 2002; Tamura and Ono 2003). Coupled with computer aided flow animations, such simulation techniques may in the near future provide “numerical wind tunnels” to analyze the evolution of flow around structures and estimate attendant load effects. More recently, developments in CFD on the cloud are evolving (vortex-winds.org).

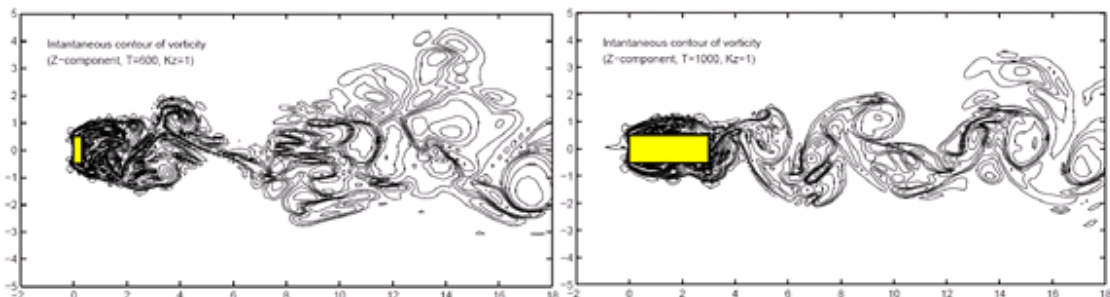


Figure 12: Instantaneous vorticity contours for rectangular prisms with aspect ratio; Left - 0.3 and Right - 3.0 (after Yu et al. 2006)

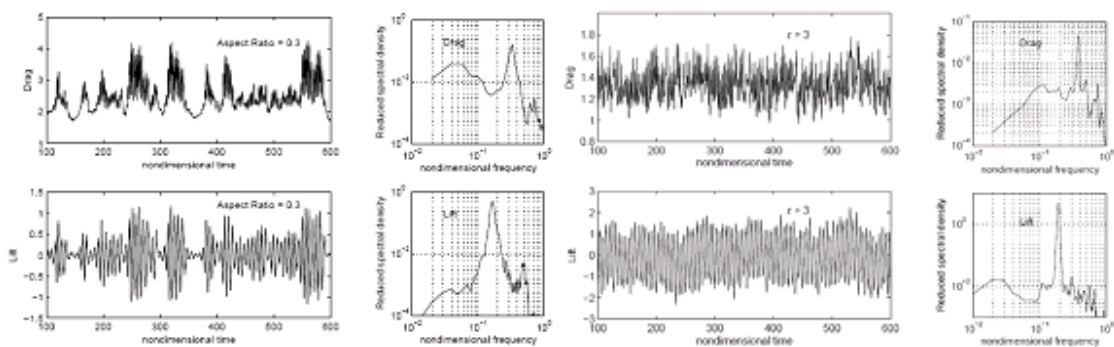


Figure 13: Drag and lift force fluctuations and respective PSD for prisms with aspect ratios: Left 0.3; Right 3.0 (after Yu et al. 2006)

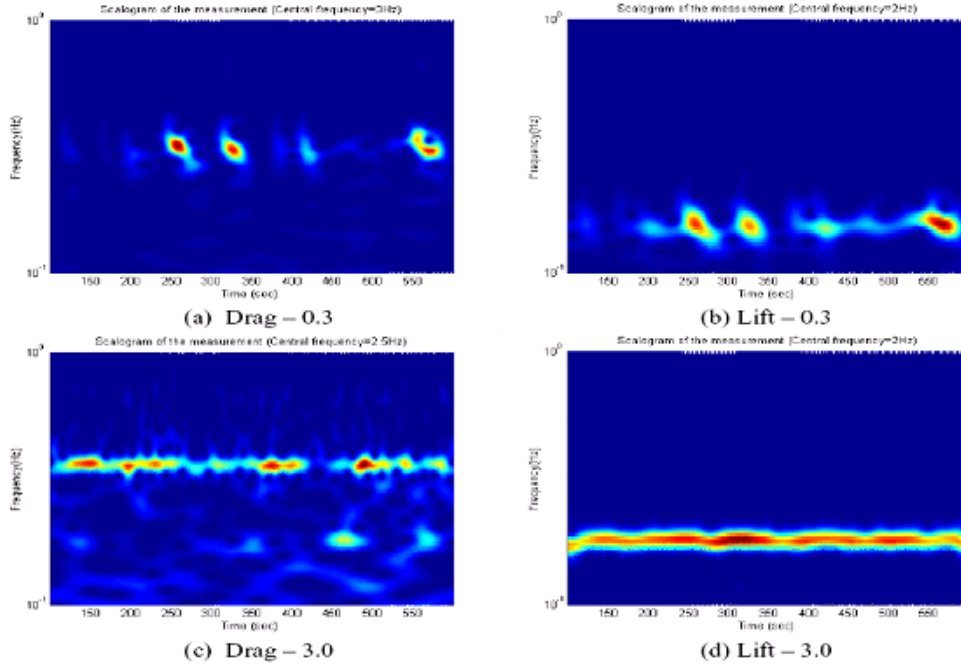


Figure 14: Wavelet based scalogram of drag and lift fluctuations for aspect ratio 0.3 (a, b) and 3.0 (c, d), respectively, (after Yu et al. 2006)

6.2 Applications

While the turbulence simulation based on LES or direct numerical simulation (DNS) is limited to a relative low Reynolds number due to the extremely computational consumption together with the intricacies of the inlet turbulence modeling, applications of CFD modeling based on various turbulence models have been developed in bluff body aerodynamics. However, the following sections will focus on the improved understanding of the turbulence effects on bluff bodies based on the experimental studies and on the theoretical schemes.

6.2.1 Experimental study

Because bridges and buildings often have rectangular or near rectangular shapes, a notable amount of wind tunnel work has been done studying varieties of rectangular bodies and the shear layers separating from them. Most of this work has been done for stationary bodies, but some has been for prisms in motion. While experimental studies focusing on the effects of turbulence on bridge aerodynamics (e.g., Scanlan and Lin 1978; Huston 1986; Matsumoto et al. 1991; Larose et al. 1993; Haan et al. 1999) have typically noted an increase in critical wind velocity with added turbulence, several studies have reported destabilizing trends associated with turbulence (Matsumoto et al. 1991; Huston 1986). The cause of these disagreements remains to be conclusively determined and signifies the limitations in current understanding of the problem (e.g., Scanlan 1997; Chen et al. 2000; Haan and Kareem 2009).

Recent experimental studies put significant attention on the turbulence effects on the flutter derivatives and on the correlation of the wind-induced forces. Scanlan and Lin (1978) first investigate the turbulence effect on the bridge aeroelasticity experimentally by utilizing the flutter derivatives under turbulence wind condition. Observation indicates there is no distinct difference of flutter derivatives resulting from laminar and turbulent flow conditions. It should be noted that the turbulence in wind tunnel cannot reproduce the natural condition accurately. Specifically, the

turbulence integral scale in wind tunnel will be very small compared with the reasonable one based on the scale law.

It is well known that not only the turbulence intensity but also turbulence scale will contribute the effect on the bluff body. Gartshore (1973) investigate the turbulence scale effects on various prisms by emphasizing the modification of the shear layer. Besides, Nakamura (1993) pointed out the small-scale turbulence could influence torsional flutter through resulting in earlier reattachment of flow on the solid surface. Recently, a detailed investigation of the turbulence effects on the aerodynamics of an oscillating prism in wind tunnel indicates the turbulence intensity and turbulence scale will simultaneously affect the flutter derivatives with different mechanisms (Haan and Kareem 2009). The former mainly changes the flutter derivatives which are sensitive to the pressure phase such as A_2^* (weighting the contribution to the moment from torsional velocity) while the latter mainly changes the flutter derivatives which are sensitive to the pressure amplitude such as A_3^* (weighting the contribution to the moment from torsional displacement) (Haan and Kareem 2009).

Instead of directly dealing with the turbulence effect on the flutter derivatives, Haan and Kareem (2009) investigated the distribution of the pressure field around the prism in both chordwise and spanwise directions, including their correlations and in bridge related studies the correlation of the pressure field in comparison with upstream turbulence. In the following, a summary of some of the findings of this recent study, which has not been widely reported in the literature thus far, is presented. It brings out some useful observations and important ramifications for the current state of the art of aerodynamic analysis of long span bridges (Haan and Kareem 2009). In this study, grid generated turbulence was used to study the effects of both turbulence intensity and turbulence scale on aerodynamic forces. By examining the unsteady pressure distributions over the bridge model rather than the flutter derivatives alone, a clearer understanding of how turbulence affects the unsteady forces was obtained. Both increasing turbulence intensity and turbulence scale decreased the amplitudes of self-excited pressure fluctuations. The basic shape of the chordwise distributions of pressure amplitude—a single hump shape—is shifted upstream with increasing intensity of the free stream turbulence. This shift, however, was only slightly affected by the turbulence scale. Fig. 15 shows a space time portrait of the pressure distribution highlighting this observation.

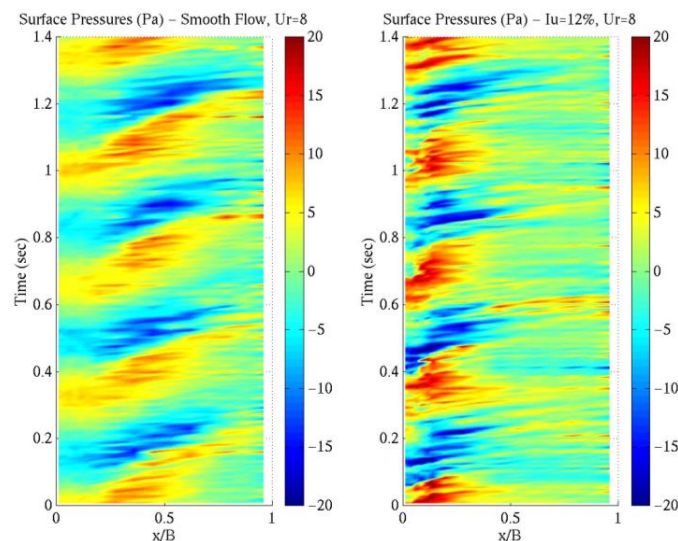


Figure 15: Surface plots of the temporal and spatial evolution of the surface pressure on a rectangular prism undergoing torsional oscillations (X/B - streamwise direction/deck width; left - smooth flow; right - turbulent flow) (after Haan 2009)

Haan and Kareem (2009) also observed that the phase values of the self-excited pressure (with respect to the body motion) had several regimes in the streamwise direction. Near the leading edge, phase was nearly constant. Downstream of this locale was a region where phase increased rapidly. Beyond this rapidly increasing phase zone was a region where the phase values leveled off and even decreased in some cases. While scale had little discernible effect on this phase value, turbulence intensity shifted the region of rapidly increasing phase toward the leading edge. The stabilizing effects of turbulence observed in the flutter derivatives were related to these turbulence-induced shifts in the pressure amplitudes and phase distributions. By tracking the integrands of expressions for lift and moment, specific changes in pressure amplitude and phase were linked to flutter derivative modifications. In addition, this upstream shifting in the unsteady pressure on the oscillating models was found to be similar to the behavior observed for pressure distributions over stationary models. This suggests that the vast amount of research done in bluff body aerodynamics on stationary bodies may aid in the understanding of oscillating body problems as well.

Prior to this study, no experimental study had justified the conventional analysis technique in which the aerodynamic forces are separated into flutter and buffeting components. Pressure measurements made on oscillating models allowed experimental assessment of this assumption. Overall, the assumption is quite close. Examination of the lift and moment spectra showed close agreement throughout the frequency range considered. Where the stationary and oscillating model spectra did not agree, however, the oscillating model values were larger. This oscillation-induced increase in the broadband energy occurred mainly for frequencies above $fD/U = 0.1$ although some differences were observed for lower frequencies as well. Quantitative analysis of these differences showed that oscillating model buffeting forces could have RMS values as much as 10% higher than their stationary model counterparts. This difference decreased for increased turbulence intensity and increased turbulence scale. For the flow with the highest intensity and scale considered, these differences were only around 2-3%. Observation of the streamwise distribution of such differences revealed that the location of oscillation-induced broadband increase was upstream of reattachment—for this case, this meant upstream of the location of the maximum RMS pressure value. This implies that bodies which experience separation over smaller portions of their surface may exhibit less significant differences between stationary and oscillating model buffeting levels.

Through both coherence measurements and correlation calculations of self-excited force components, the self-excited forces were found to have near unity coherence over the entire spanwise separation range considered. It was noted that cases with larger turbulence length scale showed a slightly lower correlation than those of smaller scales, the estimated 95% confidence intervals of ± 0.03 puts all results within the statistical spread of the others suggesting no influence of length scale. The conventional assumption of self-excited forces being fully correlated in the spanwise direction was thus supported by the results of this study. Of course, this also means that the often-suggested hypothesis that a decrease in spanwise correlation of the self-excited forces causes the turbulence-induced increase in the critical flutter velocity is not supported by the current results. Although the stabilizing effect of spanwise correlation loss may be apparent for single-mode torsional flutter (Scanlan 1997), it is not obvious that this will apply to multi-mode coupled flutter cases. Correlation loss along the span may stabilize a deck by reducing negative damping effects, and yet it may destabilize a deck by reducing favorable damping (Chen and Kareem 2003). This issue will become even more important as bridge spans grow longer and multi-mode flutter becomes more probable. A conclusive investigation of self-excited force coherence would require much longer span lengths to observe whether appreciable changes occur for longer spanwise separations. Coherence calculations also showed that the broad band

coherence of the oscillating model matched that of the stationary model to within the uncertainty of the experiment.

While spanwise correlation of pressure and buffeting forces on static models in turbulent flows have been measured by a number of researchers, little if any experimental work has been done on the spanwise behavior of the self-excited forces. Full correlation of the self-excited forces is generally assumed in the response analysis, as alluded to earlier by findings in Haan et al. (1999). This suggests, however, that the turbulence-induced behavior of full-bridge models mentioned previously cannot be explained entirely due to a decrease in self-excited force coherence. In view of this, there is a clear need for improved knowledge of the basic physical phenomenon. Analysis framework based on recent developments in bridge aerodynamics may facilitate improved understanding in the subject area (Chen and Kareem 2006a; 2006b; Wu and Kareem 2011)

6.2.2 *Theoretical scheme*

Although both the effects of turbulence in the incoming flow and the signature turbulence should be taken into account, there is no well developed scheme to account for the effect of signature turbulence except utilizing the CFD technique. On the other hand, the incoming turbulence effect can be well represented utilizing the theoretical Küssner function or Sears function for streamlined structures, or employing the measured admittance function for bluff bodies. However, the incoming turbulence effects on aeroelastic instability is not able to be considered based on these schemes. With some ad hoc assumptions, turbulence intensity effect on the aeroelastic instability could be considered either based on randomizing the dynamic pressure and invoking stochastic approaches, or through the incorporation into the effective angle of attack based on the QS concept.

Lin and Ariaratnam (1980) and Bucher and Lin (1988) theoretically demonstrated the turbulent intensity effect on aeroelastic instability by solving the linear stochastic differential equations based on Itô's differential calculus. The second-moment stability is emphasized in this analytical scheme. It is proved that the turbulence with small intensity has uncertain (either "stability" or "destability") effect on the bridge aeroelasticity while the turbulence with larger intensity has "destability" effect on the bridge aeroelasticity. However, this analytical scheme has some obvious limitations, such as the turbulence is assumed to be Gaussian stationary process with small turbulence intensity and the solutions are assumed as Markov processes. More importantly, only the along-wind turbulence component is considered while the vertical turbulence component is neglected which is usually considered as more important role contributing to turbulence effect.

On the other hand, the QS theory based models can also take into account the turbulence intensity effect after integrating the fluctuation into the effective angle of attack. For many innovative bridge sections, even at low levels of turbulence, the effective angle of attack due to structural motion and incoming wind fluctuations may vary to a level such that the nonlinearities in the aerodynamic forces may no longer be neglected. However, the QS assumption based model is a well-known memoryless system, where the unsteady effect is not considered.

The nonlinear analysis framework proposed by Chen and Kareem (2003) could incorporate the effects of turbulence on long span bridges. In this analysis framework, the low frequency force component can be modeled based on the quasi-steady theory, while the high-frequency force component can be modeled by utilizing the traditional unsteady scheme. Actually, the effects of low-frequency turbulent fluctuations are taken into account analytically through the QS concept with the effective angle of attack and the effects of high-frequency turbulent fluctuations could be considered experimentally through the measured flutter derivatives under turbulent wind condition.

Flutter studies utilizing full-bridge models have often shown critical velocity boundaries to be sharply defined in smooth flows and higher or nonexistent in turbulent flows. Under turbulent wind condition, there are some observations that the flutter instability will not happen suddenly with a distinct flutter boundary as the Scanlan's linear analysis predicts. One possible illustration of this phenomenon is the turbulence, not only the oncoming turbulence but also the signature turbulence, build up the exchange of energy between different structural modes with more complicated manners, which leads to the gradual incidence of flutter (Scanlan and Jones 1990). The proposed analysis framework by Chen and Kareem (2003) is able to investigate this behavior quantitatively. Within this framework, the effects of turbulence on flutter are modeled through the changes in the effective angle of incidence caused by turbulence and its influence on the self excited forces and the flutter instability. The application of this framework to a long span suspension bridge, with aerodynamic characteristics sensitive to the angle of incidence, revealed a gradual growth in response with increasing wind velocity around the flutter onset velocity, which is similar to the wind tunnel observations of full-bridge, aeroelastic models in turbulent flows (Fig. 16).

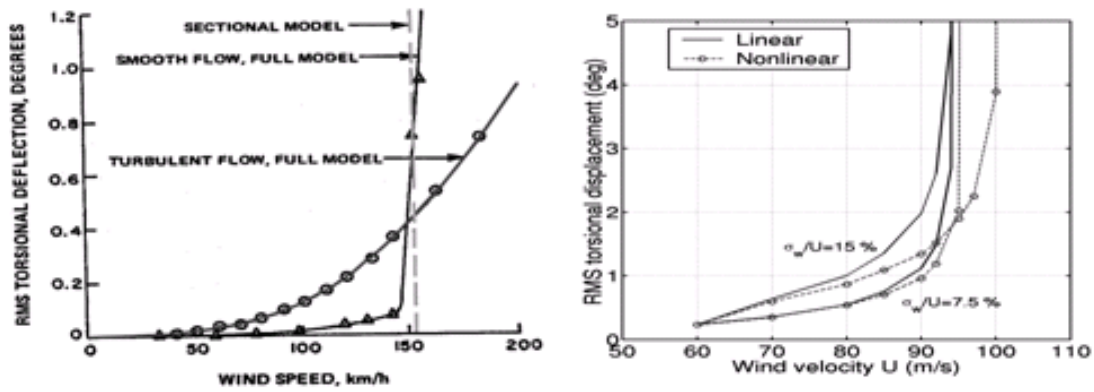


Figure 16: Left - Torsional response of Lions' Gate Bridge (Irwin 1977); Right - Linear and nonlinear predicted response of a bridge (after Chen and Kareem 2003a)

Currently there is no theoretical consideration of the turbulence scale effect on the bluff bodies. However, recently development of the intermittency modeling in turbulent flows may shed some light on this consideration. As a violent discontinuous nature of turbulence, internal intermittency seems only change the velocity statistics slightly (a slightly wider PDF compared with Gaussian distribution), while it has significant effects on the statistics of the velocity difference (a considerably larger PDF tail compared to Gaussian distribution). Conventional simulation scheme such as spectral representation cannot consider the multi-scale property of turbulence while the wavelet based expansion has been applied to simulate the intermittency with promising results (Kitagawa and Nomura 2003; Yin et al. 2012). The simulated PDFs of different scales (represented by the wavelet coefficients) in turbulence are presented in Fig. 17 compared with the measured results. These tails of PDFs can make significant contributions to higher-order moments, which impact the rare events. The simulation with intermittency consideration will directly contribute to the inlet turbulence modeling. Though the small scales contains little energy, it is well known that the intermittency in turbulence has significant effect on the transport and diffusion of material by the turbulence (Ecke 2005), which could be important to the environmental wind engineering community. The QS assumption may describe adequately the effects of large scales, which has high accuracy in galloping modeling. On the other hand, there is no theoretical analysis to investigate the effect of small scales on the bluff bodies. While it is reasonable to ignore the turbulence effects with the scale significantly smaller than the struc-

tural dimensions, there is demand to advance the analysis approach for the turbulence effects with comparative scale sizes. The simulated turbulent flow with intermittency consideration could be utilized in the analysis of aerodynamics and aeroelasticity in time domain, where the turbulence scale effect could be investigated in detail.

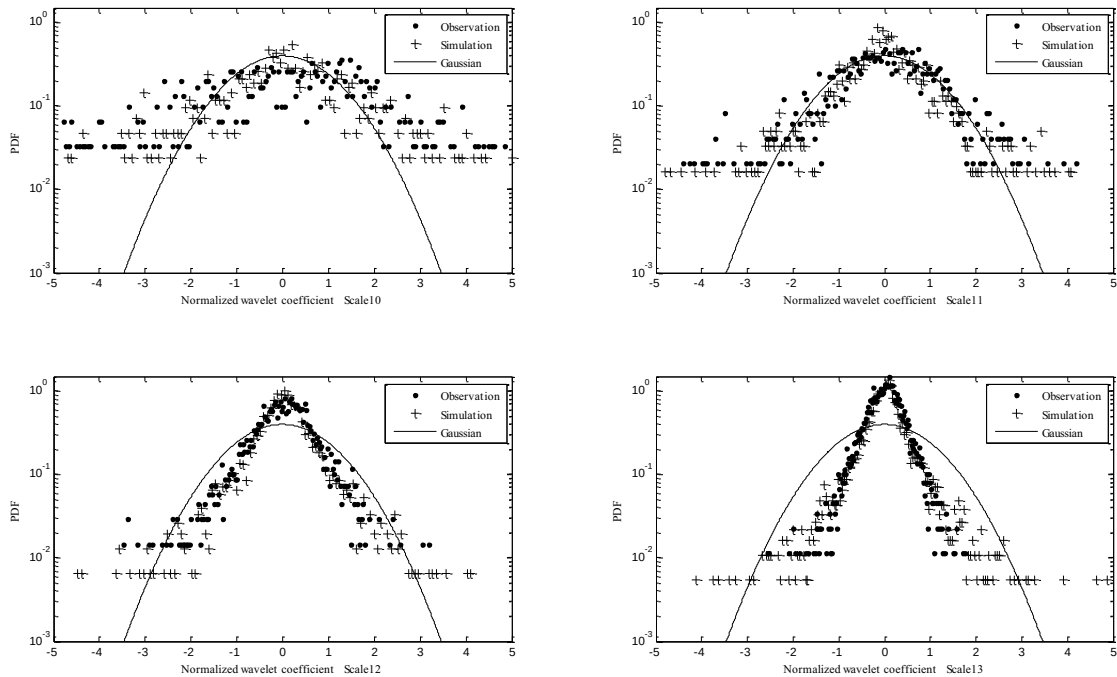


Figure 17: PDFs of wavelet coefficients at typical scales

In closing this section, it is very important to note that the preceding anthology of the role of turbulence on the bluff body aerodynamics of prismatic bodies, with applications to buildings and bridges, excluded a vast amount of literature concerning circular cylinders which is available in a number of review articles. On the other hand, although there is strong correlation between the circular cylinder and the bluff bodies with prismatic shape, the difference between them is unnegligible. For example, bridge deck, which features a significant afterbody, has fixed separation points instead of moving separation points varying as Reynolds number and oscillation frequency and amplitude. Besides, the torsional force induced by the wake vortices may be more important for prismatic bodies since this structural geometry possesses a long afterbody. Hence, wake-vortex-induced effect of prismatic bodies may differ significantly from that of the circular cylinder.

7 CHANGING DYNAMICS OF AERODYNAMICS

The subject of aerodynamics has been treated traditionally by invoking quasi-steady and strip theories and has been extended to unsteady aerodynamic theories for loads originating from wake aeroelastic effects. The current challenges are to address aerodynamics in transient flows. In the following, a brief discussion of these areas is provided with an outlook for their treatment of transient conditions, and lessons one may learn from aerodynamics in nature.

7.1 *Quasi-steady Aerodynamics*

Quasi-steady and strip theories offer reliable estimates of load effects when the dominant mode of loading is attributed to buffeting, e.g., surface pressure responding to large-scale, low frequency turbulence for the alongwind buffeting load effects. The quasi-steady theory fails to relate the approach flow and the ensuing pressure fluctuations on surfaces in separated flow regions. The shortcoming of the theory stems from the fact that it does not account for the wind-structure interactions at several scales, which may introduce additional components, thus highlighting the need for unsteady aerodynamics. The quasi-steady theory has been successfully applied to the analysis of galloping behavior of structures, often observed in structures exposed to winds at high reduced velocity, e.g., ice coated transmission line cables and cables experiencing skewed winds.

An obvious shortcoming of QS theory is that it cannot take into the unsteady effect of fluid-structure interaction. In order to take into account the fluid memory effects based on the static wind-tunnel tests, Steinman (1950) introduced phase correction factors resulting from pressure distribution graphs of stationary titled straight models (for the effects of vertical velocity and wind angle of attack) and horizontal curved models (for the effects of angular velocity). A more 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). This corrected QS theory could partially include the fluid memory consideration, which indicates that the flow around a structure is not only dependent on the instantaneous relative states (structural motions and flow fluctuations) but also on their previous time history. Actually, it is difficult to select an appropriate frequency to calculate the reduced wind velocity in the corrected QS scheme especially as the bridge aerodynamic effects involved. In order to overcome this shortcoming of the corrected QS theory, a more detailed scheme named “band superposition” was proposed by Diana et al. (1995), where the aerodynamic/aeroelastic forces are linearized about a reference value of the effective angle of attack.

7.2 *Unsteady Aerodynamics*

Notwithstanding the improved knowledge of wind effects on structures over the past few decades, our understanding of the mechanisms that relate the random wind field to the various wind-induced effects on structures has not developed sufficiently for functional relationships to be formulated. Not only is the approach flow field very complex, the flow patterns generated around a structure are complicated by distortion of the wind field, flow separation, vortex formation and wake development. Nonlinear interaction between the body motion and its wake results in the ‘locking in’ of the wake to the body’s oscillation, resulting in vortex-induced vibrations over a range of wind velocities. The stability of aeroelastic interactions is of crucial importance (Matsumoto 1999). In an unstable scenario, the motion-induced loading is further reinforced by the body motion, possibly leading to catastrophic failure. Depending on the phase of the force with respect to the motion, self-excited forces can be associated with displacement, velocity, or acceleration. Furthermore, aeroelastic effects can couple modes that are not coupled structurally, leading to more complex issues in bridge aerodynamics as discussed earlier. The intractability of these unsteady aerodynamic features has led to experimental determination of these effects using scale models in wind tunnels. These measurements have led to loading characterizations in terms of spectral distributions of local and integral load effects and aerodynamic flutter derivatives, which, when combined with structural analysis, yield measures of overall structural behavior.

Concerning building aerodynamics, the most widely used wind tunnel technology involving the high frequency base balance (HFBB) does not include motion induced loads. Kareem (1982) noted in a validation study concerning the crosswind spectra derived from statistical inte-

gration of surface pressure that the response estimates computed by using the measured spectra began to depart from the estimated values based on aeroelastic model test of the same building at reduced velocities above 6. The damping estimates from the aeroelastic model suggested a constant increase in the negative aerodynamic damping. By including the negative aerodynamic damping, the response predictions provided a better comparison with the aeroelastic tests at higher reduced velocities. It is also important not to simply attribute all motion induced effects to aerodynamic damping. Indeed the motion of a structure also modifies the flow field around it. Particularly it tends to enhance the spanwise pressure correlation, which may lead to an increased forcing in comparison with that measured by a force balance. A recent study critically evaluates the role of several modeling parameters needed to accurately model aeroelastic effects for base pivoted models (Zhou and Kareem 2003).

In attempts to relate the incident turbulence to pressure fluctuations in separated regions, higher-order modeling via bispectral approach has been utilized, which has identified some correlation although it has not provided a functional relationship. It is noteworthy that the intermittent nature of the unsteady aerodynamic relationship is vitiated using Fourier based analysis (Gurley et al. 1997). Higher-order bispectral analysis utilizing a wavelet basis offers promise to capture intermittent relationship between the incident turbulence fluctuations and the attendant pressures under separated flows (Gurley et al. 2003). Thus, challenges remain in establishing transfer functions that could relate, at higher-orders in a localized basis, the complexities inherent to bluff body aerodynamics.

7.3 *Transient Aerodynamics*

Both earlier and more recent studies in fluid dynamics have pointed out an overshoot in aerodynamic/hydrodynamics loads on cylinders in unsteady flows (Sarpakaya 1963). It has also been noted that for the analysis of structures in non-stationary atmospheric turbulence, the traditional stationary analysis fails to account for possible transient overloads, e.g., the sharp changes in gusts were found to cause a transient aerodynamic force on a bridge model, which cannot be explained by a stationary statistical analysis. This clearly points at the need to critically assess the impact of abrupt changes in the wind field magnitudes and associated modifications in aerodynamics of structures and appraises the need for refining the current load descriptions.

7.4 *Aerodynamics in Nature: Some Lessons*

Natural objects with bluff profiles like trees, plants and jellyfish experience forces in a flowing medium like air or water. Often these objects have the ability to minimize drag by shape reconfiguration, e.g., palm trees bend and through their compliant action survive the fury of hurricanes. This is not an option available to most of the built environment as their shapes are fixed. In architectural and structural communities tapered, twisted and tilted towers are being built. The fixed shapes used in man-made structures are arrived at on the basis of aerodynamic considerations, but are undertaken a priori and the possibilities of changes in real-time during wind storm are not available. Other possible avenues of managing flow around buildings are possible by using biomimetics through introducing scalloped leading edges like whale flippers, which act like vortex generators.

Unfortunately, these fundamental phenomena in nature may not benefit the built environment. As in nature, more flexibility may help survive adverse environmental conditions through excessive bending, however, tall buildings or bridges may not be able to afford this luxury as they may lose their functionality, e.g., occupants of a building experiencing large excursions of motion may get symptoms of sea sickness leading to discomfort and in extreme cases nausea and

vertigo. However, such flexible behavior has been utilized in offshore drilling platforms, where the human comfort considerations are not as stringent.

8 IDENTIFICATION TOOLS

The higher-order spectrum is the Fourier transform of the higher-order correlation. It identifies nonlinear interactions among frequency components and also preserves the phase information, which is generally a more sensitive marker to identify the departure from linearity as compared to information related to amplitude (Ueda and Dowell 1984). For a linear system, the second-order information embedded in a power spectrum represents distribution of energy at different frequencies which fully characterizes a linear system in the frequency domain. The normalized value of the cross-power spectrum captures the phase relation at the same frequency between two different signals. However, for nonlinear system higher-order spectrum is needed because the power spectrum cannot portray the energy transformation between different frequency components which is a typical feature of nonlinear systems. Among these higher-order spectra, the bispectrum, the Fourier transform of triple correlation can capture quadratic nonlinearities. Further higher-order interactions can be tracked by trispectra and beyond, but each additional order adds significantly to the computational demand and need for added length of data sets. (e.g., Kim and Powers 1979; Gurley et al. 1996; Tognarelli 1999; Hajj and Silva 2004). A bispectrum is easy to visualize since it can be displayed as a three-dimensional (3-D) plot, whereas, further higher-order spectra can be only viewed in 3-D by slicing the hyper-dimension at different frequencies.

The auto-/cross-bispectrum and auto-/cross-bicoherence could be applied to both the pressure signal or the force signal obtained in wind-tunnel experiments. Fig. 18 presents the second-order spectrum of an aerodynamic force acting on a typical bridge deck obtain in a wind tunnel. The nontrivial values in the figure indicate nonlinear interactions between the frequency components, suggesting the presence of such interactions in the aerodynamics of bridge decks.

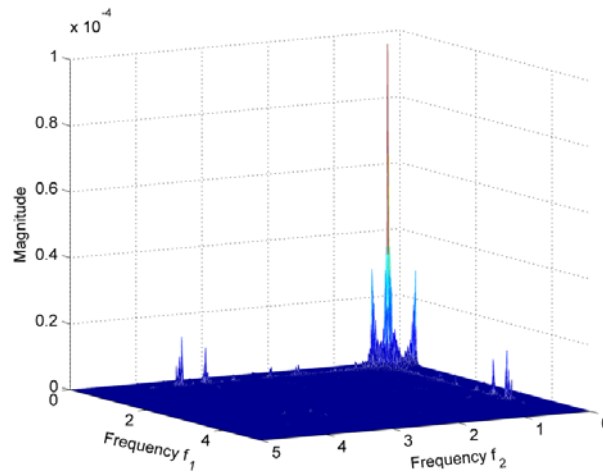


Figure 18: Auto-bispectrum of aerodynamic force on a bridge deck (after Wu and Kareem 2012a)

On the other hand, the evidence of nonlinear input-output relationship could be obtained in time domain through the second-order Volterra kernel, which corresponds to the double inverse Fourier transform of the higher-order transfer functions of the nonlinear system. Fig. 19 presents the linear and nonlinear Volterra kernels of a simulated bridge aerodynamic system, where the nontrivial values of the second-order kernel indicate that nonlinearity exists in the system.

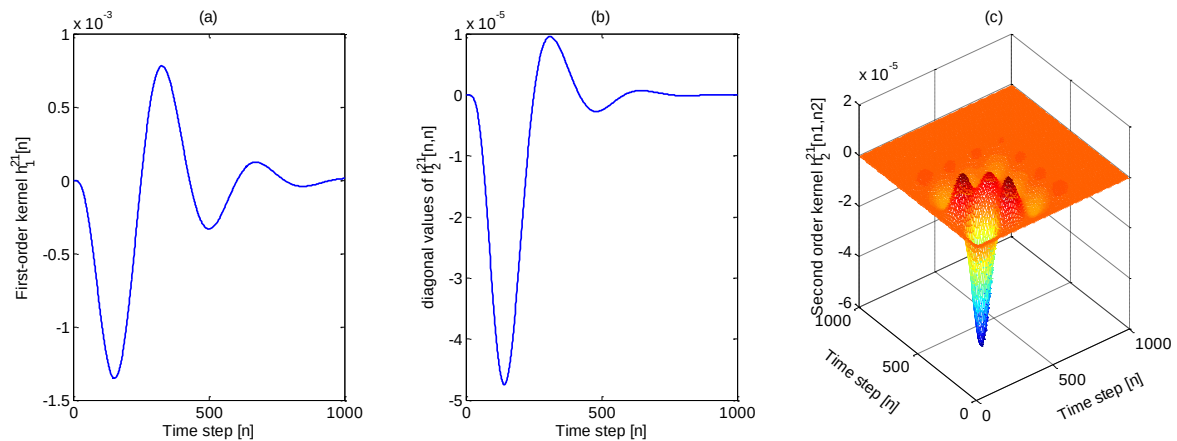


Figure 19: Linear and nonlinear Volterra kernels of a simulated bridge aerodynamic system (after Wu and Kareem 2012c)

More specific insights into the linear and quadratic interplay between two signals in both time and frequency can be gained utilizing wavelet coherence and bicoherence measures (Gurley et al. 2003). However, by exploiting the dual potential of wavelets, other analyses based primarily in either the time or frequency domain can also be performed. By tracking the variation of wavelet transform coefficients in the time domain, system identification can be readily performed (Kijewski and Kareem 2003). Similarly, the distribution of wavelet coefficients with frequency at a window in time provides a familiar spectral representation whose evolutionary properties can be monitored to provide insights into nonlinear behavior (Kareem and Kijewski 2002).

9 CONCLUDING REMARKS

This paper reflected on recent developments in aerodynamics and aeroelasticity of bluff bodies with a viewpoint concerning turbulent wind effects on structures. Some of the overarching issues for the future encompass the modeling and impact of imperfect correlation, transient/nonstationary effects, non-Gaussian and nonlinear features involving recent development of the modeling frameworks and identification tools. Improved understanding of turbulence effects on bluff bodies is stressed. Advances in experimental and theoretical methods with improved sensing capabilities based on wireless sensors, smart sensors, GPS, laser Doppler based technologies and optical and sonic systems would aid in effectively addressing some of the needs highlighted. With foundations steeped in bluff body aerodynamics and aeroelasticity theories and projected research paths imbued in advanced and e-technologies, our abilities will certainly be lifted up to a higher level of understanding, modeling, analysis, design and monitoring of wind effects on structures.

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