A Tribute to Jack E. Cermak – Wind Effects on Structures: A Reflection on the Past and Outlook for the Future

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ABSTRACT: This paper pays tribute to the "father of wind engineering," Jack E. Cermak, for his many valuable and pioneering contributions to the subject, followed by a reflection on the recent developments in wind effects on structures and an outlook for the future. This discussion encompasses the following topics: modeling of wind field; structural aerodynamics; computational methods; dynamics of long-period structures; model- to full-scale monitoring; codes/standards and design tools; damping and motion control devices.

KEYWORDS: Wind Effects; Dynamics; Structural Engineering; Turbulence; Wind Tunnel; Boundary Layer; Sensors; Full-scale Measurements; advanced technologies; e-technologies

1 INTRODUCTION

This paper highlights 50 years of wind engineering contributions by Dr. Jack E. Cermak, University Distinguished Professor, emeritus, Colorado State University, Colorado. As many of his contributions have facilitated the advancements witnessed over the last several decades in wind engineering research and practice, a sampling of these areas are provided subsequently in this paper. Fittingly, as we pay tribute to the "father" of our profession and its evolution, we should close with an outlook toward future developments in these areas.

2 JACK E. CERMAK TRIBUTE

Throughout the world, Dr. Cermak is considered the "father of wind engineering." In 1959, he founded the Fluid Dynamics Laboratory at Colorado State (Fig. 1) where he pioneered the physical modeling of wind-structure interactions in boundary layer wind tunnels (1). The technique Cermak pioneered has now become a quintessential part of the overall design procedure for the design of structures to withstand wind gusts, which is today applied to projects from low-rise and high-rise buildings, long-span bridges, roofs, chimneys and towers to offshore structures, defense/aerospace installations and even sports apparel and arenas. Dr. Cermak has since served as a consultant and principal investigator for wind tunnel tests on over 500 new building projects. These projects include some of the signature structures around the globe, including his work in 1963, on the World Trade Center Towers. In 1999, the laboratory founded by Dr. Cermak was recognized by the *Engineering News-Record* as one of the 125 engineering innovations in the 125 years between 1874 and 1999.

Fig. 1. (left) Design and construction of wind tunnel – J. E. Cermak, H. Maynard and E. Plate (right) WTC model in the wind tunnel --- Front row: A. Davenport, M. Yamasaki, J. Skilling, L. Robertson; Back row: M. Levy and J. E. Cermak (photos have been revised)

Dr. Cermak has a distinguished career as an engineering educator as well; he has advised over forty doctoral students, who in turn are contributing to the fields of structural and environmental engineering. This has led to generations of students influenced by him, e.g., several of his great-grand students have completed their doctoral studies and are beginning their careers in academia and industry.

Dr. Cermak has chaired many of ASCE's key technical committees earlier in his career and lately has done it again as a second round of his service to the profession. He also served as chair of the Committee on Natural Disasters for the National Research Council, which drew the agenda for post disaster investigations of natural disasters and their impact on built and social infrastructures. He has served as the Regional Editor (USA) of the *Journal of Wind Engineering and Industrial Aerodynamics*, Elsevier since its initial publication in 1973. This journal serves as a major source of research findings and design information for the effects of wind on structures. He has authored or co-authored more than 650 papers and reports.

In 1973, Dr. Cermak's pioneering research led to his election to the National Academy of Engineering. He was also selected to be among one of the twelve University Distinguished Professors at Colorado State in 1986 and in 1990 and was elected as an honorary member of the American Society of Civil Engineers. Chi Epsilon, the Civil Engineering Honor Society, also elected him as National Honor member in 1994. Through the contributions of his friends, ASCE last year instituted Jack E. Cermak Medal, administered by the Engineering Mechanics Division and the Structural Engineering Institute, for outstanding contributions to the area of wind effects on structures. The author is humbled by the honor of being the initial recipient of this award.

Dr. Cermak founded the Wind Engineering Research Council, which is renamed now as the American Association for Wind Engineering, serving also as its first President. He also was one of the lead organizers of the first United States meeting on the effects of wind on structures at Cal Tech in the early seventies. This meeting has grown to a major quadrennial conference serving those interested in the recent developments in wind effects on structures.

Dr. Cermak's "tour of duty" netted numerous prestigious awards and honors. A sampling of these includes awards from Sigma Xi, ASCE Aerospace Division, Structural Engineering Institute, ASME Distinguished Lecturer, Senior Research Award from ASEE, ASCE's Ernest E. Howard Award, and a citation from the National Society of Professional Engineers.

2.1 *Cermak "Father of Wind Engineering"*

The author is sure that most of you would agree with William Shakespeare that "there is something in the wind." However, while Shakespeare's fascination with wind was mostly poetic, Cermak's interest is primarily pragmatic. Initially Cermak's efforts in this field were confined to basic research concerning the development of scaling laws for physically simulating boundary layer flows in long test section wind tunnels. In the early sixties, it became apparent to him that an atmosphere simulated in laboratory could be applied to a host of practical problems. The first such example involved the investigation of the cause and recommended treatment for the 20 mph gusts wreaking havoc on the playing field of San Francisco's then new Candlestick Park. Known as "the cave of wind" in 1961 All Star game, baseball's best players committed seven errors and the relief ace was nearly thrown off the mound. This was all blamed on the capricious winds. The wind tunnel study showed that the geographic features and the stadium itself created this perilous condition and presented remedial solutions to revamp the Candlestick Park. It was also noted that if the park had been built one playing field length to the north, much of the problems would have been avoided.

Wind Engineering came of age during the mid-1960s with a study of the then to-be-built World Trade Center Towers (WTC) in New York City (Fig. 1). This study by Cermak of the twin towers would be the first comprehensive study of the wind loading on a structure that could take a large variety of atmospheric variables into account. Colorado State received this project because, at that time, it was the only institution in the world with a boundary layer wind tunnel. Cermak gleaned personal and professional satisfaction from that project, as he believed that his group created something that was useful to society in general. However, Cermak attributed the subsequent mushrooming of wind tunnel studies only in part to the greater confidence in their predictive capabilities and recognized another contributing factor: in spite of all the mathematical and engineering sophistication possible with analytical modeling and computational tools, wind analysis still managed to evade the quantification essential for design. The demand further escalated with the advent of taller, slimmer, thinner-skinned buildings, which are more sensitive to the dynamics of wind actions unlike the masonry edifices built earlier. As the Boston Hancock Tower's difficulties became known, the issues of wind effects on tall buildings came to the forefront of engineering practice. As a result, the problems of Boston's John Hancock have been viewed by some as the tall building community's Tacoma Narrows, though others still blame it on structural issues.

In summary, Cermak's contributions in the scaling of atmospheric flows served were pivotal in the emergence of a once obscure science that has now secured an important role in the design of structures, as wind tunnels are now a customary design tool in Civil Engineering akin to their aerospace counterparts used in the development of aircrafts and aerospace structures. In recognition of this monumental pioneering contribution, the design and research communities are indebted to Cermak for his vision, drive and certitude that led to these developments. The writer would like to express his gratitude for the support, guidance, advice and above all the freedom of exploration Cermak provided during author's graduate studies, which has since then served as a catalyst for promoting creativity in his professional career. The subsequent sections of this paper will now address many of the issues that framed Dr. Cermak's great career and served as the springboard for the current areas of research and future directions.

3   WIND EFFECTS ON STRUCTURES: THE CURRENT STATE-OF-THE-ART

The assurance of structural safety and reliability under wind loads requires accurate modeling of wind load effects. In an earlier review article entitled, "Wind Effects on Structures: A

Probabilistic Viewpoint" (2), among others, it was emphasized that the intractability of wind-structure interactions amidst complex urban topography has precluded analytical treatment of the subject. Therefore, physical modeling of wind effects in boundary layer wind tunnels has served as the most effective tool for ascertaining these load effects. Since then, there have been major developments in the computational area to numerically simulate flow fields and their effects on structures. These developments have been complemented by other areas, e.g., stochastic computational mechanics, which have lent useful tools to further advance the role of numerical analysis (3-4). The availability of high-speed computers, individually or in networked clusters, has enhanced the portability of computational codes, once the monopoly of supercomputers, to most laboratories and some design offices. On the other hand, the last decade has witnessed advances in wind tunnel technology, full-scale monitoring, sensors/transducers, instrumentation, data acquisition systems, laser Doppler-based technologies, geographical information systems (GIS), global positioning systems (GPS) and information technologies, which have increased our ability to better monitor and process gathered information for improved understanding of the complexities and nuisances of wind effects on structures and their modeling. Rapid advances on all fronts have accordingly led to the prospect of improved codes and standards, the next generation of load simulators, new versions of wind tunnels, database assisted design aids and web-based e-technologies.

Notwithstanding these developments, which have enhanced our abilities to better understand and capture the effects of wind on structures, now is the time 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, the rest of this paper will critically assess a few selected areas and will either validate the current approaches to further improve our understanding and practice, or will suggest alternate paths that may lead us to more realistic modeling of loading environments and their effects on structures. These subjects include modeling of the wind field, structural aerodynamics, computational methods, dynamics of long-period structures, model- to full-scale monitoring, codes/standards and design tools, and damping and motion control devices.

4 WIND FIELD MODELING

The discussion of wind-structure interactions must first begin by discussing the means of describing the oncoming wind field. The following section will discuss the current treatment of velocity profiles over land and water, design wind speeds and the case for considering transient wind fields associated with gust-fronts.

4.1 *Velocity Profiles Over Land*

The mean wind profile of the lower portion of the planetary boundary layer is best described by a logarithmic law; however, most codes with a few exceptions employ a more convenient format involving the power law, which has its roots back to the early 20th Century. Despite the simplicity of the power law, it has been continually criticized for its empiricism and assumptions. On the other hand, the log law suffers from it inability to describe the wind profile beyond the bottom 10% of the boundary layer thickness which necessitates improvised descriptions above this elevation. The concept of gradient height, often invoked in the power law representation in codes and practice, may not be the true gradient height, as it may exhibit variations even in a particular flow regime due to spatial variations in the terrain characteristics. Some of the code/standard values for the gradient height represent a height that is convenient for

relating gradient level winds in different terrains (5). Therefore, on the one hand, winds at these elevations may be adequate for establishing equivalence of gradient level winds in different terrains, but on the other hand, these may fall short of meeting the strict definition of the gradient level winds where the velocity fluctuations are expected to diminish. These compromises are requisite in codes and standards, where simplicity and ease in application without significant loss of accuracy are essential features. It is also important to note that though the log law has a firm theoretical basis for fully developed flows in the inner boundary layer; it does not represent a peak gust profile, which is the basis of wind speed description in a few standards.

4.2 *Velocity Profiles over Water*

The problem of defining a boundary layer profile over the ocean in hurricanes is very critical. The primary difference between the flow over ground and the ocean is that in latter case the boundary, i.e., wave surface, is translating and deforming as opposed to being stationary. In case of hurricanes, this is further compounded by the fact that convective cells in the rain bands may add additional turbulence structure of a convective origin. Data over the ocean suggests that the mean velocity profile and the structure of mechanical turbulence are similar to the smooth terrain despite the presence of large waves. The large waves practically move as fast as strong winds, therefore, the contribution of waves to the surface roughness is small and is comparable to small waves that break and are at times sheared off from the surface, contributing to the ocean surface spray thus transferring momentum. Therefore the wind flow field and its characteristics are not much influenced by the exact form of the sea surface; rather these are sensitive to the energy loss and momentum transfer due to surface friction. The wind stress coefficient has been defined to characterize ocean surface roughness. The literature suggests that it increases with wind speed, e.g., (6). However, Amorocho and DeVries (6, 7), predicated it upon the wave breaker density to follow growth processes, which are limited by a state of saturation, and their measurements suggested that the drag coefficient reaches an asymptotic value. One of the limitations of all these studies was that these were based on winds below those experienced in hurricanes and data was extrapolated to predict conditions at higher winds.

In recent years a number of GPS sondes have been dropped in the hurricane wind field to catalog the wind velocity profile. Powell et al., (8) have carefully processed and analyzed the GPS sonde data. Though affected by convective scale features and the launch location of the sondes, their study has shed light on the air-sea interaction with emphasis on the surface drag. In the author's opinion, this study has confirmed the assertion of Amorocho and DeVries that the surface drag coefficient levels off as wind speeds increase. These findings may have profound influence on the characterization of wind fields in hurricanes, thus impacting a number of application areas. Notwithstanding, these results are really valid only in open waters far from the coastline. Therefore, additional work continues through drop sondes and measurements from surface buoys and from a network of mobile and fixed measurement sites in the coastal zones for obtaining reliable data to establish realistic filling models to represent the decay in surface winds as the wind moves from sea to land surface. In combination with computer models, information from these measurements would provide a much higher resolution portrait of the wind field in coming years, thus reducing the level of uncertainty we currently experience.

It is also important to investigate the hurricane wind field model to quantify the evolution of localized convective cells that are characterized by excessive rain bands and strong gusts. These intense drafts may facilitate stretching of vortices induced by winds of different speeds spiraling towards the low-pressure region. The stretching process may enhance the rotational speeds, which in combination with the winds bounding these vortices, may lead to localized intensification of wind speeds. Some in the meteorological community dispute this theory of

localized intensification; however full-scale mapping using the next generation of GPS sondes may help to resolve these controversial opinions and aid in quantifying these conditions.

4.3 *Design Wind Speeds*

The current design wind speed estimates suggested in codes and standards are based on the extreme value statistical analysis of measured wind data. These estimates have inherent uncertainties of both climatological and micrometeorological origins, manifested as modeling, sampling and observational errors (9). The prediction of extreme wind speed plays a major role in design standards and is a currently a subject of some debate as to the choice of distribution, i.e., those with finite tails or infinite tails. The Generalized Extreme Value (GEV) distributions characterized by shape, location and scale parameters offer a flexible framework for fitting data and other families of extreme value models, i.e., Gumbel, Fretchet and reverse Weibull can be re-parameterized within the GEV family of models. The restriction of GEV in modeling maxima over a block of sampled data, e.g., yearly maximum, can be overcome through other characterizations such as the peaks-over-threshold method based on Generalized Pareto distribution to include the excess values in the data above a high threshold. In the U.S., recent work based on peaks-over-threshold method has shown the efficacy of the reverse Weibull distribution for modeling extreme winds over earlier modeling based on Fretchet and Gumbel distributions (9). Notwithstanding these developments, there are other studies that do not suggest any conclusive evidence for choosing reverse Weibull over Gumbel. In order to address the difficulty of estimating confidence intervals on the point estimates of extreme values, bootstrapping has been shown to be a valuable analysis tool (10). The theorized climate change, poses yet another dilemma for design engineers. The question surfaces as to the reliability of extreme wind estimates at high recurrence intervals based on limited years of data, which is fraught with statistical and climatic uncertainties. The overall topic of extreme value analysis is of great interest as it impacts the design of structures; therefore, discussions and research should continue with the promise of yielding more reliable estimates of extreme wind speeds.

4.4 *Stationary versus Non-stationary/Transient Winds*

The most critical issue in wind field characteristics concerns transient wind events, e.g., gust-fronts generated by downdrafts associated with thunderstorms. Thunderstorms databases both in the U.S. and around the world suggest these winds comprise the design wind speed for many locations (11-12). The mechanics of gusts associated with convective gust-fronts differs significantly from conventional turbulence (driven by momentum) both in its kinematics and dynamics. The key distinguishing attributes are the contrasting velocity profile with height and the transient nature of the wind field itself. These flow field attributes are much different from the steady boundary layer wind simulations in wind tunnels that have formed the basis of all wind loading codes globally. 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 profile with maxima near the ground potentially exposing low- to mid-rise structures to higher wind loads. This is compounded by the inherent transient nature of energetic convective gusts that rapidly increase in amplitude and direction raising serious questions regarding the applicability of conventional aerodynamic loading theories. Extreme loads on structures are potentially sensitive to the influence of transient flows,

i.e., the load coefficients may be enhanced by the form of gust and rapid changes in the local flow and the load effects are likely to be correlated over larger areas than in conventional flows. These aerodynamic consequences clearly call for a careful examination of traditional design loads.

5 STRUCTURAL AERODYNAMICS

Having addressed the descriptions of the oncoming wind field, the following section focuses on the characterization of the resulting wind loads on bluff bodies. Upon impacting the windward face, the wind is then deflected around the structure and accelerated such that it cannot negotiate the sharp corners and thus separates from the building, leaving a region of high negative pressure. This separated flow forms a shear layer on each side, and subsequent interaction between the layers results in the formation of discrete vortices, which are shed alternately. In certain cases involving flexible structures, response deformations can alter the aerodynamic forces, thus setting up an interaction between the elastic response and aerodynamic forces commonly referred to aeroelasticity. 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 the wake aeroelastic effects. The current challenges are to address aerodynamics in transient flows. In the following a brief discussion in these areas is provided with an outlook for the treatment of transient conditions.

5.1 *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 and the alongwind buffeting load effects. The quasi-steady theory fails to relate approach flow and the ensuing pressure fluctuations on surfaces in separated flow regions. In an attempt to identify admittance functions for wind pressures, it is noted (13) that the quasi-steady theory fails to model the spectral descriptions of pressures under separated flow regions despite the inclusion of the square of the fluctuating velocity term. 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.

5.2 *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 the distortion of the wind field, the flow separation, the vortex formation and the 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. 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 in the section on dynamics. 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.

In attempts to relate the incident turbulence to pressure fluctuations in separated regions, higher-order modeling via bi-spectral approach has been utilized, which has identified some correlation, but has not provided a functional relationship (14). It is noteworthy that that the intermittent nature of the unsteady aerodynamic relationship is vitiated using Fourier based analysis (14). Higher-order bi-spectral analysis utilizing a wavelet basis offers promise to capture intermittent relationship between the incident turbulence fluctuations and the attendant pressures under separated flows (4, 15). Thus challenges remain in establishing transfer functions that could relate, at higher-orders in a localized basis, the complexities inherent to bluff body aerodynamics. Another important challenge remains in better understanding and quantification of inclined cable aerodynamics, which is complicated by the axial flow behind the cables and the water rivulets (16).

5.3 *Transient Flow Aerodynamics*

Earlier and recent studies in fluid dynamics had pointed out an overshoot in aerodynamic loads on cylinders in unsteady flows (17-18). 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 (19). The exposure of trains/trucks suddenly emerging from a tunnel to the energetics of gust-fronts can lead to drastic aerodynamic modifications, i.e., force sign reversal, which have led to serious considerations for their operation and safety. As another example, a recent study by Yalla and Kareem (www.nd.edu/~nathaz) concerning pressure distribution on a wall exposed to periodic waves, large overshoots in pressure were noted due to sudden action of wave slamming on the wall, which subsequently settled to normal hydrodynamic pressure levels. This trend is further confirmed in recent experiments involving simulated gust-front utilizing a translating wall jet, which suggest that surface pressures over a cube significantly exceed the quasi-steady estimates (20). 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.

6 COMPUTATIONAL METHODS

The wind loads on structures discussed in the previous section, and the ensuing response, can be modeled, analyzed and simulated in a number of ways, as discussed in this section, with specific examples which include proper orthogonal decomposition (POD), simulation and probabilistic modeling, CFD, time-frequency analysis, system identification, and the outlook for future analysis frameworks.

6.1 *Proper Orthogonal Decomposition*

The application of the POD theorem has led to the development of many useful techniques with a wide range of applications. A number of researchers have used POD to expand pressure fields

on buildings and structures (3). POD has also been used in the simulation of multi-variate random processes (21-22), and it has been extended to problems in probabilistic dynamics (23-24) and in reduced-order modeling of dynamic load effects (25). Other related stochastic approaches have been used to facilitate identification of optimal signatures of turbulent energy and in arriving at low-order dynamical systems in turbulent flows (26). These approaches hold the promise of providing useful analysis and interpretation tools in wind effects studies.

6.2 *Modeling of Probability Density Function*

In wind engineering applications, large skewness in the probability distribution of negative pressures is observed in separated flow regions. An implicit assumption of Gaussian distribution would clearly underestimate the dynamic load effects. Peterka and Cermak (27) and others have demonstrated that in negative pressure regions, the probability density function (PDF) was skewed. Therefore, the PDF of pressure is critical to the modeling of loads on cladding and components, as well as loads on main load-resisting systems. The latter is significant, as often it has been implied that the integral load effects approach Gaussian processes due to the Central Limit Theorem (CLT). However, due to the presence of correlation in the local pressures, the CLT breaks down, thus resulting in non-Gaussian load effects in various response measures, e.g., base moments. Often researchers have attempted to use the lognormal distribution for pressure fluctuations, but this fails to represent the tail region with high fidelity (14). Among different alternatives, the author and his colleagues have found that the Hermite moment-based distribution provides the best match to the data (14). This model also captures the significance of non-Gaussian pressure fluctuations for determining the equivalent constant pressure for glass design (14, 28), while providing a useful format to account for non-Gaussianity in the estimation of wind induced fatigue damage, as characterized by a correction factor (14). The widely used gust loading factor is based on the Gaussian assumption, since the term containing the square of the velocity fluctuations is dropped from the formulation. Kareem et al. (29) presented a gust loading factor, which included the square velocity term, using the Hermite moment-based distribution. Earlier attempts to capture this effect using Edgeworth series did not adequately represent the tail regions of the distribution. In future loading formats, especially for the background loading involving relatively stiffer structures, a non-Gaussian gust factor approach would be more relevant since a Gaussian factor would underestimate loads (14).

6.3 *Simulation of Random Pressures*

Simulation of random wind and pressure time histories are essential for time domain analysis of structures. The conditional simulations or stochastic interpolation schemes can be used to simulate or interpolate data in between measured locations. Simulated data can also be an important source of information for the next generation of building codes utilizing large databases for estimating design loads. Simulated time histories are also important for actively generating turbulence and transient flow features involving multiple fans or test facilities using multiple actuators to generate effects of a desired wind field (30).

The simulation of stationary Gaussian processes can be accomplished using spectral, time series and other techniques, such as state space modeling. A summary of these techniques can be found in Kareem (3). Simulation of non-stationary events like gust fronts and hurricane wind field can be accomplished by the generic summation of trigonometric time series approach, but it is computationally inefficient, since, due to lack of ergodicity, ensemble averaging requires simulation of a large number of time series. The wavelet-based simulation offers an alternative, which may better capture both time and frequency modulations. Li and Kareem (31) presented

an efficient fast Fourier transform-based technique to simulate nonstationary processes through decomposition of the cross-spectral matrix into a weighted summation of basic functions and time-dependent weights simulated by FFT.

On the other hand, the progress in the simulation of non-Gaussian processes has been elusive. Earlier work based on correlation distortion has been based on an inverse mapping of the desired probability density function, a summary of which may be found in Gurley et al. (36). In Gurley and Kareem (33), a new simulation approach, which is significantly more robust than the correlation distortion schemes, is presented. The non-Gaussian features and the frequency contents in the form of the first four moments and the target power spectral density of the process are used; alternatively analytical expressions or other estimates of the distribution may be employed. The approach is named the spectral correction method, which, following a nonlinear transformation relies on a few iterations to match both the spectral and probabilistic features. This approach has been extended to multi-variate processes including conditional simulations and random fields (34-36).

Since 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 (33). 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 neural networks (32).

Future challenges in this area lie in the simulation of large vectors of data, which may be used in a design database, and in simulations that preserve memory inherent to the process. In the former case some space reduction techniques combined with linear stochastic estimation may be invoked to accomplish the task of simulating large correlated data sets.

6.4 *Computational Fluid Dynamics*

The Large Eddy Simulation (LES) framework is emerging as a numerical scheme of choice for the solution of Navier-Stokes equations. For example, recent studies have shown that the simulated pressure field around prisms has convincingly reproduced experimentally-observed characteristics, with respect to variations in the mean and RMS pressure coefficients, drag force and regions of flow reattachment, even as the aspect ratio of the prism is varied (37-38). 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 fronts, including modeling of aeroelastic instabilities, CFD techniques for practical applications, and modeling of urban roughness and terrain effects (39-40). 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. Like the burgeoning growth of structural analysis software packages, in the next decade, we may see the emergence of prototype CFD based tools, which will further evolve with time to eventually gain the public's confidence, just like their counterparts in structural mechanics, through validations with experiments both at small- and full-scale.

6.5 *Time-Frequency Analysis*

As many physical processes of interest to civil engineers manifest nonstationary and nonlinear features, their complete characterization may not be accomplished via Fourier transforms, necessitating a new analysis framework in the time-frequency domain. The dual nature of
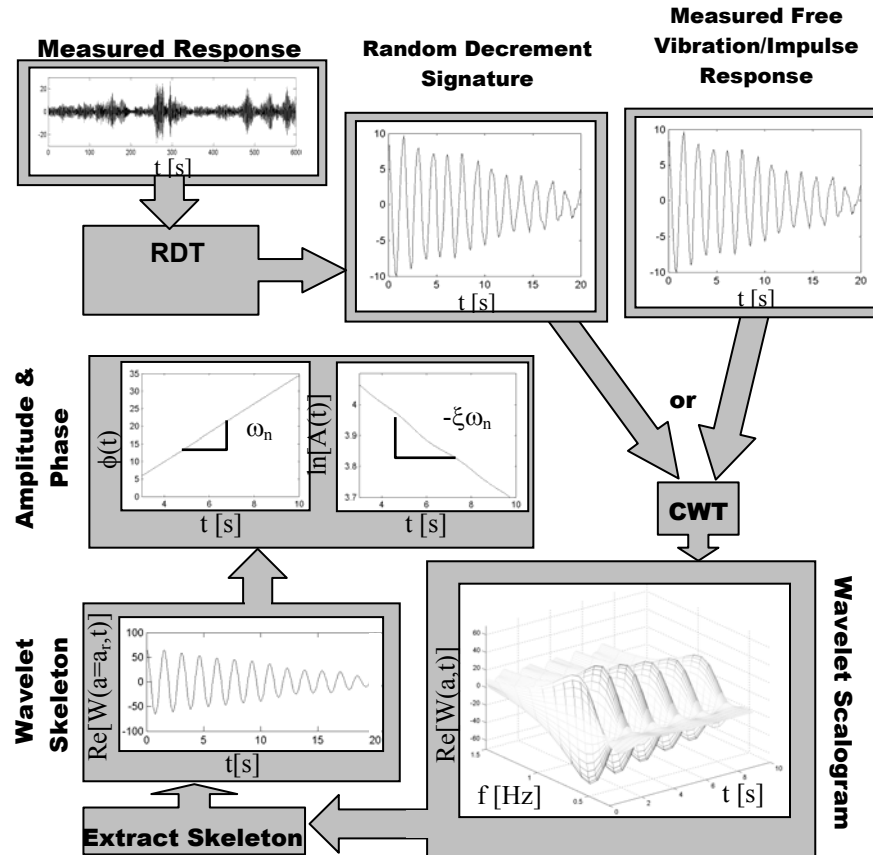
Fig. 2. Wavelet system identification framework, Track A for ambient vibrations or Track B for measured free vibration or impulse response (4)

wavelet transforms, being a simultaneous transform in time and frequency, justifies its recent extension to the analysis of stochastic processes of interest to civil engineering, adapting the transform to a number of situations where Fourier transforms (for frequency domain analysis) or Hilbert transforms (for time domain system identification) were 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, through examination of scalograms and coscalograms (15). 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 (41). However, by exploiting the dual potential of wavelets, other analysis 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 (42). 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 (4).

Recently, in order to capture intermittent correlation, a wavelet coherence measure was introduced used to produce a time-frequency display of the coherence between signals intermittently correlated, e.g., pressure and velocity fluctuations (4, 41). In this study, the analysis developed for first-order correlation detection was further extended to higher-order correlation through a bicoherence measure, as some of the processes under investigation may not be linearly related, e.g., wind velocity fluctuations and associated pressure fluctuations. Detailed

examples given in (4, 41) affirm that the wavelet-based technique is capable of identifying both first- and second-order correlation while effectively reducing the presence of noise in both simulated and measured data. The robustness of the provided thresholding techniques is further established, as it is shown to alleviate the presence of spurious coherence, even in cases where variance and leakage are prevalent. Though relatively intensive, this approach facilitates the removal of significant levels of all of the various contributing noise sources.

Wavelet-based system identification and instantaneous spectral analysis offer very invaluable tools that permit the tracking of nonlinear characteristics in structural frequency and damping. Such tracking of time-varying frequency content is typically accomplished by monitoring the instantaneous frequency of the signal and extracting ridges from wavelet scalograms to form the Wavelet Instantaneous Frequency Spectra discussed in Kareem and Kijewski (4). The complex coefficients associated with these ridges can be used directly in a traditional system identification approach based on analytic signal theory to identify the instantaneous frequency, and in the case of free vibration decay or random decrement signatures, damping. Frequency domain perspectives from the wavelet coefficients are also insightful, as the wavelet instantaneous frequency and bandwidth can be respectively tracked to monitor the mean frequency and its deviation as they evolve in time (4).

For the sake of an example, even in situations where free vibration decays are not directly available, this wavelet-based system identification approach may still be implemented. As shown in the example in Fig. 2, the Random Decrement Technique is used to preprocess the response of a structure under random excitation, in this case the acceleration of a full-scale tower under typhoon winds, yielding a Random Decrement Signature (RDS) proportional to the free vibration response of the structure. The signature in its current form contains the contributions of multiple modes and measurement noise and is not the smooth stable decay one would expect from a single-degree-of-freedom oscillator. However, processing this through the continuous wavelet transform permits the dominant mode to be readily identified and isolated. The wavelet skeleton associated with this mode yields the anticipated decay associated with the system. Note that both the wavelet scalogram and skeleton are complex-valued, though only the real component is shown in Fig. 2 for simplicity. This slope of the skeleton's phase and amplitude may be analyzed to determine the natural frequency and damping, respectively, as discussed previously. As shown in (42), the frequency was estimated at 0.645 Hz and critical damping ratio at 0.0151, though showing some slight variations. These findings were consistent with those observed in free vibration testing.

In summary, just as the Fourier transform has introduced spectral analysis to the practicing engineer, current efforts are focused on ushering in a new analysis framework in the time-frequency domain, bringing innovative mathematical tools such as wavelet transforms to practicing engineers, permitting accurate analysis without the restrictions of stationarity. The extension of wavelet transforms to the estimation of time-varying energy density permits the tracking of evolutionary characteristics in the signal and the development of measures like wavelet-based coherence to capture intermittent correlated structures in signals. Further, the wavelet's dual nature, being a simultaneous transform in the time and frequency domains, can be exploited to permit the adaptation of a number of traditional system identification and analysis schemes. Though the application of wavelet transforms in Civil Engineering is in its infancy, its future shows great promise as a tool to redefine the probabilistic and statistical analysis of wind effects. Despite the merits of these analyses, it should be noted that a number of processing concerns must be addressed in order to obtain reasonable results, particularly for the class of signals of relevance to Civil Engineering (42).

7 DYNAMICS OF LONG-PERIOD STRUCTURES

While wind loads impact a variety of Civil Engineering structures, long-period structures in particular require careful treatment due to their dynamic sensitivity, often requiring the type of wind tunnel investigations made possible by Jack Cermak. This section highlights the developments and challenges wind presents for tall buildings, bridges and offshore structures.

7.1 *Dynamic Wind Effects on Buildings*

Under the action of wind, tall buildings oscillate simultaneously in the alongwind, acrosswind and torsional directions. The alongwind response has been successfully treated using quasi-steady and strip theories in terms of gust loading factors (5); however, the acrosswind and torsional loads cannot be treated in the same manner as alongwind loads, since they cannot be related in a straightforward manner to the fluctuations in the approaching flow. Accordingly, most current codes and standards provide little guidance for the acrosswind and torsional response. Unfortunately, for many high-rise buildings, these responses may exceed the alongwind in terms of both serviceability and survivability designs. Modern trends towards unconventional architectural shapes with innovative structural systems have led to buildings dynamically more sensitive to torsional loads resulting from asymmetrical wind pressures, and static and/or dynamic coupling among modes. There has been a significant focus over the years on developing load descriptions on buildings relying on high frequency force balance (HFFB), or multi-point pressure scan systems. The spectral and time-history information derived from these studies has been traditionally employed in a random vibration model to predict response predictions. In case of slender structures, or those with complex coupled modes, reliance has been made on aeroelastic balance studies or multi-level aeroelastic model of structures to address the concerns surfacing from motion-induced loads and coupled motions, respectively. While these experimentally derived procedures met practical design needs, researchers have been active in developing analytical procedures based on the concept of the gust loading factor following the original work of Davenport (5). These developments have led to initial formulations for 3-D gust loading factor, which is summarized in the section on codes/standards and design tools. Future challenges remain in developing load effects on buildings with unusual configurations, shapes, layouts and architectures or with large appendages, e.g., the buildings initially proposed to replace the WTC in New York City.

7.2 *Long Span Bridges*

Innovative aerodynamic tailoring of deck sections and advanced aeroelastic analysis frameworks are fundamental to the cost effective design of bridges with increasing complexity and span. Recent experiences have clearly demonstrated that traditional truss and box sections cannot be extended economically to longer spans. Further, the innovative sections with attractive aerodynamic performance, meant to take the place of more traditional sections, tend to exhibit aerodynamic nonlinearities. This situation is complicated by the fact that there is no conclusive evidence concerning the stabilizing or destabilizing effects of turbulence on the aerodynamics of bridges. So while current analytical methods have proven their utility for past and current designs, their inability to fully analyze bridges with innovative sections and long spans, which are characterized by aerodynamic nonlinearities, turbulence effects and the spanwise coherence of aerodynamic forces, limits the utility of state-of-the-art analysis procedures, thus requiring a comprehensive nonlinear analysis framework. The design of future, longer spans will require a multi-mode, coupled framework for flutter and buffeting analysis, which can accommodate the

effects of turbulence and aerodynamic and structural nonlinearities, as discussed later in this section. Certainly these analytical tools must be complemented by extensive wind tunnel and full-scale testing.

7.2.1 *Multimode Coupled Aeroelastic Analysis*

The aerodynamic forces on bridges can be represented in most cases by a linear approximation and expressed in terms of time-averaged static and time-varying self-excited and buffeting force components, characterized by flutter derivatives and admittance functions in the frequency domain (43). Akin to other structural dynamics problems, expressing structural equations of motion in terms of reduced-order structural modal coordinates is computationally effective. The mode-by-mode approach has proven its utility in many applications, despite neglecting aerodynamic coupling among structural modes. However, experience shows that bridges with longer spans generally require a multimode, coupled analysis framework, e.g., (44-46). In such a framework, the changes in modal frequencies, damping ratios, mode shapes and overall flutter behavior due to the aeroelastic effects associated with increasing wind velocity can be estimated through a complex eigenvalue analysis. This type of multimode approach offers useful insights into inter-mode aerodynamic coupling, enhancing the understanding of multimode, coupled aeroelastic response.

7.2.2 *Time-Domain Prediction of Aeroelastic Response:*

One of the challenges in aeroelastic analysis remains in the modeling of aerodynamic forces induced by non-stationary wind fields acting on bridges located in complex topographies, as well as in the consideration of nonlinearities in both structural dynamics and aerodynamics and the ubiquitous issues related to turbulence (47). Traditional analysis approaches are not suitable for accommodating these computational challenges. Chen et al. (46) proposed a time domain framework incorporating 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.

7.2.3 *Nonlinear Aeroelastic Analysis Framework:*

For many innovative bridge sections, even at low levels of turbulence, the effective angle of incidence 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. Wind tunnel studies using full-bridge, aeroelastic models have often shown flutter onset velocity boundaries to be sharply defined in smooth flows, whereas it exhibits rather gradual flutter boundaries in turbulent flows. A recent experimental study supports the full correlation of self-excited forces tacitly assumed in most current analytical approaches (48). This implies that the turbulence-induced changes in flutter instability of bridges cannot be explained entirely due to a decrease in the coherence of self-excited forces, as suggested in Scanlan (49). An advanced nonlinear aerodynamic force model and attendant analysis framework have been presented by Chen and Kareem (50) that focused on the needs for modeling of aerodynamic nonlinearity and effects of turbulence on long span bridges. 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. 3). This suggests that the effects of turbulence on the flutter of full-bridges may in part be attributed to aerodynamic nonlinearities, i.e., nonlinearities in the self-excited forces.
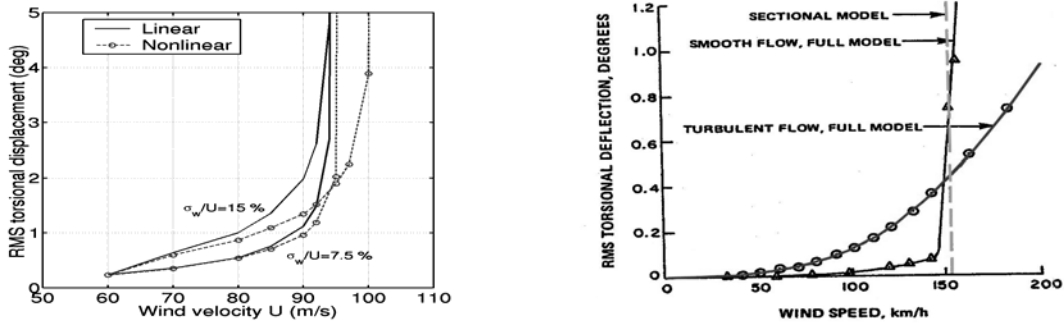
Fig. 3 Left-Torsional response vs. wind velocity; Right-Lions' Gate Bridge torsional response (88)

7.2.4 *Cable Vibration*

Several cable-stayed bridges have experienced wind-and wind-rain induced vibrations, with a potential of fatigue failure. This in part can be attributed to extremely low level of damping in these cables. While addition of dampers may ameliorate this elusive phenomenon, which has mired the performance of otherwise functional bridges, no consensus has been reached as to the underlying mechanism responsible for these vibrations (16, 51). Currently, a number of studies are attempting to unveil the mechanisms based on fluid dynamics as well as instituting measures to mitigate these vibrations through augmented damping. Interestingly, the amount of damping required to mitigate these vibrations is very low.

7.3 *Compliant Offshore Platforms*

The wind-induced dynamics of offshore systems plays a major role in their design and operation. Low natural frequencies of compliant offshore platforms in the horizontal plane, e.g., a tension leg platform, articulated tower platforms and Spar buoys, for deep water oil recovery have increased the importance of accurately predicting the effects of wind on these structures. Kareem (52) examined the dynamics of these compliant systems and presented computationally efficient time and frequency domain analyses that consider the combined actions of wind, waves, and currents. It was noted that the wind-induced response could not be evaluated in isolation and that the predicted response was sensitive to the nonlinear and non-Gaussian load effects, inducing coupling among several force and the platform response components. The response estimates provided good comparison with experimental data obtained in a wind/wave tunnel. More recent developments and directions for future analysis work can be found in (53-54). A number of proprietary studies are in progress with a focus on comparing the predicted response of platforms to full-scale measurements.

8 MODEL- TO FULL-SCALE MONITORING

The ability to model and simulate wind effects on structures by the aforementioned techniques, especially for dynamically-sensitive structures, is only as accurate as the data upon which our understanding and these techniques are based. As Jack Cermak's work demonstrated, this often requires reliable model-scale experimental data to estimate loads and response, while shedding light on the physical processes involved in wind-structure interactions. Therefore, this section overviews the current spectrum of monitoring programs from model- to full-scale to address

research needs and discuss the role of e-technologies and advanced sensing initiatives in further enhancing our ability to efficiently collect large stores of experimental data.

8.1 *Scale Models in Wind Tunnel*

Despite the computational advances, wind tunnels remain, at this juncture, the most effective means of estimating wind effects on structures. Scale model tests in wind tunnels are absolutely essential, especially when dealing with novel designs or designs for which dynamic and aeroelastic effects are difficult to anticipate. This primarily concerns long-span bridges and tall buildings, though wind sensitivity is not limited to these classes of structures. The pioneering work of Cermak has led to appropriate modeling of the wind environment, which necessitates various scaling considerations (1, 55-56). Ideally, these scaling requirements are most conveniently met when the boundary layer is simulated over a long fetch with scaled floor roughness. A large number of this type of wind tunnel has been developed over the years, especially in Japan, with specialized versions of these tunnels built in Japan, Italy and China for large-scale, full-aeroelastic bridge model tests. Similarly, to study the effects of wind on offshore installations, wind tunnels with a wave tanks have been constructed in Canada and Hong Kong.

Both active and passive devices have been used to generate turbulent boundary layer flows in shorter test sections. Active devices like air jets, flapping vanes, airfoils and individually controlled multiple fan facilities are capable of generating a wide range of turbulence parameters. More recently efforts are underway to generate vortical flows like tornadoes and thunderstorm outflows and other transient features using active and passive devices, including moving or pulsating jets (55). The NatHaz laboratory is developing a transient flow field simulator (TFFS) to generate sudden changes in wind speed to mimic gust-fronts utilizing a battery of low inertia, AC servomotor driven and individually computer-controlled fans in a wind tunnel-type test section with tailored transient flow features.

8.2 *Pressure/ Force/Displacement/Acceleration Measurements*

Regarding the instrumentation in scaled model testing, significant advances have taken place both in sensors and data acquisition systems. High sensitivity sensors at low cost have allowed synchronous scanning of pressures over building models for capturing individual point pressure variations as well as the integral loads. These scanning devices are a major leap forward from earlier systems involving statistical integration with a limited number of pressure transducers or spatial averaging using pneumatic and PVDF films (58-59). A space-time portrait of pressure field over a long rectangular section is shown in two flow conditions in Fig. 4. The addition of turbulence, shown in the figure on the right, tends to shift the separation bubble towards the leading edge. Scans like these help to better visualize in real-time the evolution of pressure fields over bluff structures. Similarly, the HFFB has revolutionized wind tunnel testing of most high-rise structures, as it has evolved from earlier versions involving foil-strain gauged beam type balances to present day ultra-sensitive piezoelectric load cells (60-62). However, both pressure scanning systems and HFFB do not account for negative aerodynamic damping, which may become important for structures that experience significant lateral displacements. Future developments in laser vibrometers and GPS-like pseudolites -- indoor navigational systems -- would aid in further advancing our ability to measure structural displacements. Researchers would be able to draw similar benefits from advances in wireless accelerometers and load cells.
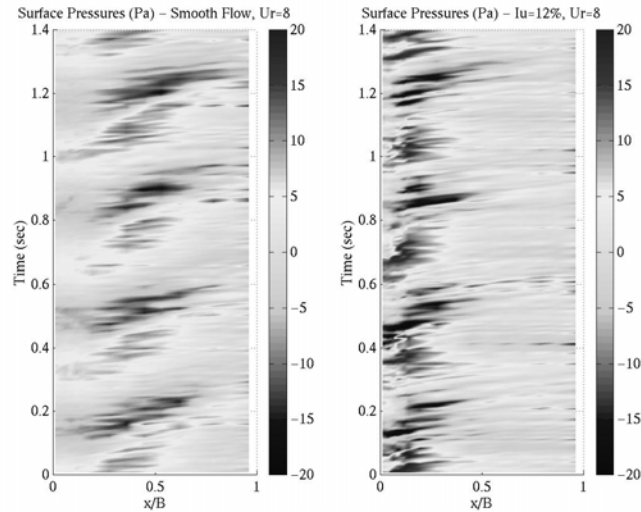
Fig. 4 Surface plots of the temporal and spatial evolution of surface pressure on a rectangular cylinder undergoing torsional oscillations (48) (*x* represents the stream-wise direction and *B* the deck width).

8.3 *Full-scale Monitoring*

Although scale model studies are often useful, they are at times incapable of capturing the underlying characteristics of structural response and require validation from full-scale observations. In the new era of high-rise buildings and long-span bridges, design challenges continually rise that motivate the need for better understanding of the dynamic behavior of these structures through full-scale monitoring. Historically, structural performance has been monitored in full-scale either through instrumentation or post-disaster investigations. Davenport (63) has summarized the full-scale measurements from a historical perspective and outlined many of the difficulties encountered, particularly in pressure measurements.

   More recently, there have a number of full-scale measurement programs in the U.S., which can be classified into two categories. The first category entails low-rise structures at the field station at Texas Tech, Outer Banks of North Carolina, and host of single-family dwellings in Florida. The inclusion of fixed and mobile towers to capture wind velocity field during the passage of hurricanes represents a unique feature of these studies. Most of these projects will be discussed in detail at the 11ICWE. The other category concerns a group of tall buildings in Chicago, for which the measured characteristics of tall buildings under a wide range of wind environments are being correlated with the behavior predicted via analyses performed as a part of the design process and wind tunnel testing (64; www.nd.edu/~windycty). Instrumentation in this project includes high sensitivity accelerometers, ultrasonic anemometers, and a Global Positioning System. Limited data collected thus far appears to be consistent with wind tunnel studies. Preliminary system identification of the dynamic properties of one of the buildings indicates that fundamental frequencies were accurately predicted by the finite element models and that the damping values displayed some amplitude dependence and were slightly lower than those assumed during design. The continued monitoring and analysis will enable a more complete description of damping over a range of amplitudes. It should also be noted that there are other proprietary full-scale sites being monitored for specific objectives.

8.4 *Advanced/E-Technologies*

It is envisaged that with the burgeoning growth and advances in wireless communication technologies, embedded sensors and information technologies will become a practical technology to enhance our capabilities for sensing and monitoring of wind load effects. These individual tetherless sensors would be a phenomenal development in eliminating the need of cables to connect to sensors, especially in occupied buildings. A near future development in this milieu involves integrated sensors comprising of sensing element, signal conditioning and micro-processor. The microprocessor aids in facilitating analog-to-digital conversion, digital processing and interfaces sensors to external environment. These systems can perform self-diagnostics, self-identification, or self-adaptation functions (66). Open hardware/software platforms of these so-called smart sensors are available, e.g., Open Berkeley-Mote Platform. These systems would generate a large amount of data; therefore the prospect of processing in the memory (PIM) architecture is a preferred mode of operation that requires special computational platforms. Efforts are also underway to invoke agent-based architecture for processing and communication of these embedded sensors. Such developments would present the next generation of structural monitoring and their heath assessment tools.

In addition, the face of wind engineering is being transformed through emerging information technologies that allow for the rapid transfer, archiving, display and interpretation of large amounts of data generated though extensive laboratory and full-scale monitoring programs. A number of commercial software packages and readily available freeware and shareware, along with a basic understanding of programming languages, enables today's researcher to rapidly and inexpensively transfer remote stores of data and create secured, interactive interfaces through the World Wide Web. In the full-scale study based in Chicago and described earlier, these technologies were exploited. PHP and JAVA programming was fused with MATLAB to create efficient yet computationally robust interfaces that convert, repair and display measured full-scale data on-the-fly (65). This interface will be coupled in the future with database query capabilities to allow users not only to search available data by date but also by the desired level of wind speed, wind direction or response to determine the data sets meeting specified characteristics or manifesting the largest levels of response. Such technologies reduce the labor-intensive organization, elementary processing and archiving of massive amounts of measured data.

9   CODES/STANDARDS AND DESIGN TOOL

The ultimate end of the research conducted by innovators such as Jack Cermak and others is to enhance the performance and safety of the built environment under wind. International codes and standards represent the most direct manner by which this research comes together in a form that dictates the daily design and construction of Civil Engineering structures. Most international codes and standards utilize some form of the traditional displacement-based gust loading factor for assessing the dynamic alongwind loads and their effects on tall structures. Although deriving themselves from a similar theoretical basis, considerable scatter in the predictions of codes and standards have been reported, e.g. (67). Unfortunately, the globalization of the construction industry and the prospect of developing unified international codes and standards make it increasingly important to better understand the underlying differences, prompting an in-depth investigation by Zhou et al. (68). The major international codes and standards: the US Standard (ASCE 7-98), the Australian Standard (AS1170.2-89), the National Building Code of Canada (NBC-1995), the Architectural Institute of Japan Recommendations (RLB-AIJ-1993) and the

European Standard or Eurocode 1993 were compared. It was found that the varying definitions of wind field characteristics, including mean wind velocity profile, turbulence intensity profile, wind spectrum, turbulence length scale, and wind correlation structure, were the primary contributors to the scatter in predicted response quantities. An example presented in Zhou et al. (68) highlights these differences. Current efforts are underway in trying to bridge these differences for better agreement between the predictions based on different major codes and standards. In the following section, some recent developments and future prospects related to codes/standards and design tools are discussed.

9.1 *New Gust Loading Factor*

The gust loading factor has been used extensively to determine equivalent static wind loads (ESWL). In its most general form, the factor represents the ratio between the expected maximum mean value of a random variable and its mean value. Although this generalized definition is applicable to any load effect, the GLF, as it is traditionally envisioned, is actually based on the displacement response. Unfortunately, this formulation has shortcomings when applied to long period structures. The ESWL in this format is of the same distribution as the mean wind load, contradictory to the common understanding of ESWL for flexible structures, where the resonant response dominates, thereby necessitating that the ESWL should distribute in accordance with the structural mass and mode shape. Consequently, when using the traditional GLF, structural displacements are determined with accuracy, while other response quantities, such as base shear, are not (69).

In response to this concern, a GLF cast in terms of base bending moments or MGLF is introduced (69), which allows the mean base bending moment to be factored by the MGLF and distributed to the other floors in a manner similar to the convention used in earthquake engineering for the distribution of base shear. In addition to providing a realistic framework for gust loading factors, particularly for long period structures, the approach more importantly accommodates nonlinear and non-uniform mass distributions, circumventing the need for exact mode shape correction, resulting in a computationally efficient scheme that directly approximates non-ideal mode shapes.

Further, this approach based on the base bending moment has been adapted to the acrosswind and torsional response calculations, using new aerodynamic loads database in an electronic frameworks (70). This development offers a convenient framework for the 3-D gust loading factor in a format very familiar to design engineers (70-71).

9.2 *Equivalent Static Wind Loads*

There are a number of equivalent static load descriptions available in the literature, e.g., (72). Recently, a new framework for evaluating the equivalent static wind load (ESWL) for any given peak response of a building characterized by uncoupled motions in the three primary directions was presented in Chen and Kareem (73). This includes a new description of the background loading based on the gust loading envelope, whereas the resonant component was described in terms of the inertial loading. In this scheme, the proposed background load based on the gust loading envelope offered a very simplified load description in comparison with the load-response-correlation approach whose spatial distribution exhibits a clear dependence on the response component of interest (74). It also provided a physically more meaningful and efficacious description of the loading as compared to the conventional gust response factor approach. The ESWL for the total peak response was then expressed as a linear combination of the background and resonant components. It was demonstrated that the proposed equivalent

static load in terms of the external fluctuating wind load and the inertial load description provided a convenient and meaningful load description for future applications to building codes and standards.

9.3 *Implications of Gust-front Velocity Profile*

Design loads are based on the mean wind speed for a given site and direction and rely on the assumption that the ratio of the fluctuations to the mean is a statistically stationary process, which has led to useful and practical simplifications. However, 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 violation in statistical attributes of the wind field, gust-fronts will 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 result in higher aerodynamic loads. Current efforts toward gleaning information regarding the thunderstorm outflow characteristics would certainly aid in better defining wind field associated with these transient wind events (75).

One can argue that the current design codes are adequate, in general, and there is no overwhelming view that these are not. This is notwithstanding limitations due to reductive formats and simplifications in codes. Structures are vulnerable to the actions of extreme winds and may experience some level of failure in extreme winds, which can be attributed to under-design lacking necessary redundancies, poor construction, and deterioration due to aging rather than simply under specification of wind speeds. Aerodynamic studies in oscillatory flows and recent initial studies in impinging, translating or pulsating jet flows provide sufficient evidence that indeed there is load enhancement.

One possible scenario to account for the changes in load effects in gust-fronts would be through quantifying wind speeds that would embody the effects associated with gust-fronts. A comparison with design winds may provide guidance regarding the need for any refinements in wind speed that bear practical significance. Such augmentation in wind speed nonetheless should not be to account for poor design or construction practice; rather it could be clearly defined as a practical step to account for load increase without changing the historic force/pressure database. Such changes may be warranted for all or limited cases depending additional research involving transient flows.

9.4 *Aerodynamic Loads Database*

Most standards and codes traditionally have relied on reductive formats and simplifications, which lead to tables and plots to describe wind loads on structures. The level of accuracy inherent in codified information in this format and the uncertainty associated with interpolation or extrapolation of information may compromise the overall accuracy in the code-specified load effects. This has recently led to the initial development of database-assisted design procedures, which offer convenient meshing with existing analysis software. Primarily, such databases rely on wind tunnel-derived data, which may be couched in analysis portals to provide desired loads effects. One such example, concerning tall buildings, manages information via an "e-database" of aerodynamic wind loads. This was introduced by Zhou et al. (70), based on HFBB measurements on a host of isolated tall building models, and is currently accessible to the worldwide Internet community via Microsoft Explorer at the URL address http://www.nd.edu/~nathaz. Through the use of this interactive portal, users can select the
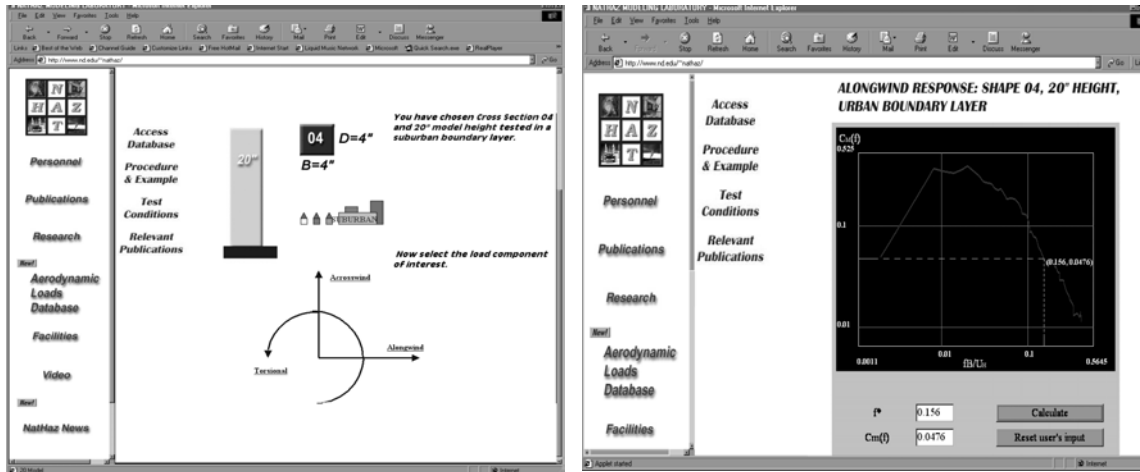
Fig. 5 Screen displays from the interactive database: (left) Selection of building and flow Conditions; (right) Display of the load spectrum (70).

geometry and dimensions of a model building, from the available choices, and specify an urban or suburban condition. Upon doing so, the aerodynamic load spectra for the alongwind, acrosswind or torsional response is displayed with a Java interface permitting users to specify a reduced frequency of interest and automatically obtain the corresponding spectral value. In Fig. 5, two screen displays from the interactive web are presented. When coupled with the supporting web documentation, examples and concise analysis procedure, the database provides a comprehensive tool for computation of the wind-induced response of tall buildings, suitable for possible inclusion in codes and standards as a design guide in the preliminary stages. Another example concerns low-rise buildings, in which a user-friendly tool for designers and code writers founded upon database-assisted design is used (76).

Finally, in this section it is important for the wind engineering community to begin working on a paradigm change, i.e., from prescriptive to performance-based as other areas concerning environmental loads on structures are moving expeditiously in that direction.

10 DAMPING AND MOTION CONTROL DEVICES

This section addresses inherent damping in structures, its quantification and the role of auxiliary damping in taming potentially lively structures.

10.1 *Structural Damping*

With the advancement of modern structures to new heights with greater dynamic sensitivity, the issue of serviceability, occupant comfort and fatigue has come to the forefront in design, making damping now more than ever, a critical design parameter. Despite its significant role, damping continues to be an enigma in design (77). As damping does not relate to physical properties of the structure in a direct way like mass and stiffness, it cannot be estimated with much uncertainty in design. While the examination of existing structures has resulted in international databases of actual damping values, there is considerable scatter in the data, partly attributed to the amplitude dependence of damping, but more so due to errors in the identification of parameter (78-81). This is complicated by the fact that much of the full-scale data results from ambient excitations, providing the analyst with no measured input for the system identification. As a result, system

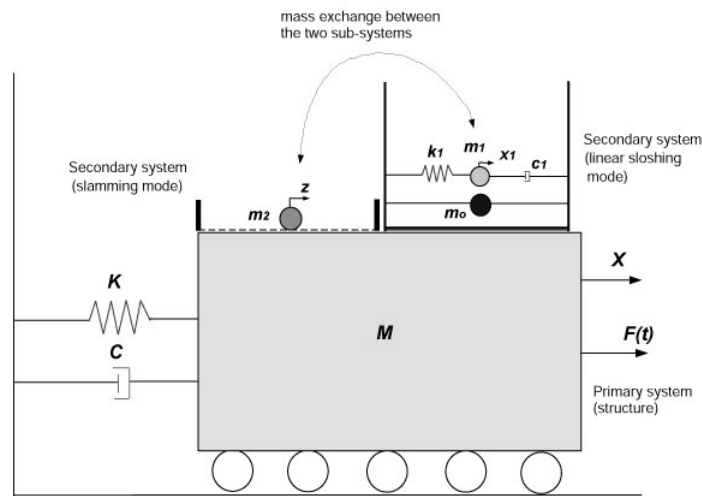SLOSHING-SLAMMING DAMPER ANALOGY

Fig. 6 Sloshing-Slamming damper analogy (85)

identification must be conducted using 'unknown input' system identification schemes or those that only make some general assumptions about the nature of the input.

This restriction is often problematic and leads to a host of possible errors. The random decrement technique and spectral analysis are commonly invoked system identification techniques for this problem, e.g., (77, 79, 82). Although there is well-established theory regarding the bias and variance errors of power spectra and random decrement signatures, the theoretical error formulae give only approximate indications of errors inherent to the estimated dynamic properties. Kijewski and Kareem (83) utilized a bootstrapping approach to assess the quality of system identification by providing surrogate estimates of damping and natural frequencies to generate useful statistics and confidence intervals. Since the damping in structures cannot be engineered like the mass and stiffness, nor it can be accurately estimated until the structure is completed, resulting in a certain level of uncertainty. Therefore, the treatment of the propagation of damping uncertainty in the dynamic response analysis becomes essential (77).

10.2 *Auxiliary Damping Devices*

In structures, where the inherent damping is not sufficient, auxiliary damping devices may be introduced, offering somewhat more predictable, adaptable and reliable method of imparting additional damping to the system. In Kareem et al. (84), an overview of the state-of-the-art measures that reduce the structural response of buildings including a summary of auxiliary damping devices and their applications to buildings around the world is presented. These devices range from active and passive tuned mass dampers to a host of liquid damping technology, which is currently receiving considerable attention from design engineers. For wind applications, among all inertial devices, liquid dampers, i.e., liquid sloshing dampers and tuned liquid column dampers (TLCD), have demonstrated both effectiveness in controlling building/structural motions as well as utilitarian value, as the water can be used for fire extinguishing purposes, which otherwise has to be pumped up. The liquid sloshing has been modeled with different levels of sophistications, i.e., it ranges from simplistic models based on tuned mass damper analogy to the solution of shallow water equation representing sloshing. Despite these advances, most models need some tweaking to account for large damping at wave breaking. Yalla and
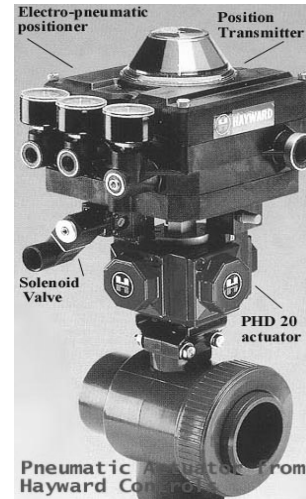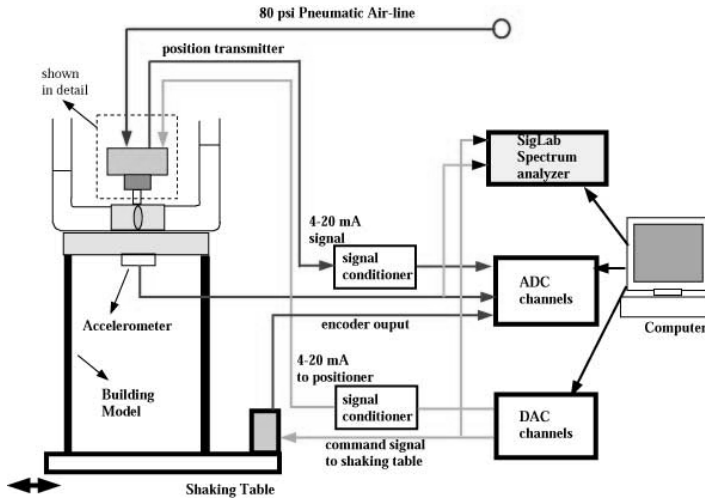
Fig. 7 Left: Semi-active control of TLCD; Right: Electro-pneumatic valve (86)

Kareem developed a mechanical analog of the sloshing action named sloshing-slamming damper, or S^2 damper (85). The model consists of linear sloshing model at low amplitudes of base excitation, whereas at higher amplitudes of motion, a part of its mass transforms from sloshing action to rolling between the tank walls, thus it acts as an impact damper (Fig 6). The impact action adds damping, thus explaining the high level of damping at large amplitudes. The non-optimal performance of TLCDs at a wide range of wind speeds is enhanced by introducing a semi-actively controlled electro-pneumatic valve (86) (Fig. 7).

The decision to use one damping system over another or not to use one at all can be better accomplished through a utility analysis (87). The future in damping technologies lies in distributed damping devices integrated in the overall structural system to resist the dynamic actions of wind as well as seismic action if needed. Some combination of viscous dampers, liquid dampers and tuned mass damper, placed at optimal locations, may offer a reliable and robust solution to controlling wind-induced motion as opposed to relying simply on one device. The use of these damping devices in future promises to impel buildings to reach even greater heights, while maintaining acceptable levels of motion. In addition to damping systems, wind-induced motions can be controlled via global design modifications, innovative structural systems, and utilization of efficient aerodynamic profiles, e.g., openings, set-backs, drop-off corners and sculptured building tops (84).

While the incorporation of such technologies permit contemporary structures to reach even greater heights, it is interesting to reflect and notice that these concepts are not new. Nearly 1200 years ago, Japanese utilized many of these concepts summarized here in the design of their famous pagodas, making these structures resistant to both the action of typhoons and earthquakes. The secret of their enduring strength and stability lies in their tapered configuration, the variation of their cross-section with height, and the fact that the energy dissipation occurs at each level, since the levels are not attached to one another and may independently slide back and forth. This is achieved using the 'shinbashhira,' the central pillar attached to the ground, which serves as a snubber, constraining each level from swinging too far in any direction. As the independent levels impact this fixture, energy is introduced, which is then dispersed through soil radiation damping. Thus the concept of secondary inertial system, friction and impact dampers, and aerodynamic tailoring are not so revolutionary. In fact, the same strategies exploited in

modern times for urban skyscrapers, today's counterpart of pagodas, have been ingeniously tapped by the ancient Japanese builders for centuries (84). Accordingly, a short journey into the past may be invaluable in crafting a brighter outlook for the future!

11   CONCLUDING REMARKS

This paper serves as a tribute to the lifelong contributions of Jack E. Cermak, "father of wind engineering," beginning with his pioneering role in the development of scaling laws and boundary layer wind tunnels for the simulation of the atmospheric boundary layer for wind engineering studies of tall buildings and space structures. Though his work was not limited to these fields, as he is equally recognized for his contributions in the area of modeling diffusion and dispersion of pollutants. On behalf of the wind engineering community, I would like to congratulate Cermak for completing a distinguished career of over a half-century in academia.

   As a fitting tribute to the "father" of our field, this paper chronicled the offspring of his pioneering work, through recent developments in wind effects on structures and an outlook for the future. Some of the overarching issues for the future encompass the modeling and impact of imperfect correlation, transient/nonstationary effects, non-Gaussian and nonlinear features and coupled load effects, their roles in the formulation of loads and their effects on structures. Advances in computational methods, with particular reference to CFD, time-frequency analyses, and POD, and in experimental methods, with improved sensing capabilities, based on wireless sensors, smart sensors, GPS, laser Doppler-based technologies and optical/sonic systems, would aid in effectively addressing the needs for robust and reliable design of the next generation of structures. Coupled with an embracing of advanced and e-technologies, the foundations laid by Jack Cermak, the growth of the field in the last several decades and the projected research paths described herein, will certainly elevate our abilities to a higher level of understanding, modeling, analysis, design and monitoring of wind effects on structures.

12   ACKNOWLEDGEMENTS

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