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Experimental validation of a stochastic simulation model for non-Gaussian and non-stationary wind pressures using stationary wind tunnel data

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SUMMARY:
Over the past decade, growing interest in performance-based wind design has given rise to several frameworks. Notwithstanding these efforts, there exists no experimentally validated model for the stochastic simulation of non-Gaussian and non-stationary wind pressures given stationary wind tunnel data collected at discrete directions. Such a model would enable the capability to capture hurricane-induced aerodynamic effects associated with time-varying wind speed and direction. A recent study proposed a theoretical formulation to simulate direction-wise pressure processes based on the wind tunnel data followed by a filter-based transition model for combination. The direction-wise simulations are stationary non-Gaussian realizations while the transition model applies a linear-interpolation-based filter for the time-averaged components and a nonlinear-interpolation-based filter for the fluctuating components. Although this procedure represents a significant development towards evaluating hurricane-induced structural/envelope response, the validity, particularly of the transition models, and accuracy of the approach remains unknown and provide the motivation for this study which is focused on the experimental validation through carefully designed experiments carried out at the University of Florida boundary layer wind tunnel.

Keywords: Non-stationary wind simulation, Stochastic simulation, Computational Wind Engineering

1. INTRODUCTION

The fast-developing field of performance-based wind engineering has witnessed significant contributions over the past decade (Spence and Arunachalam, 2022). Underpinning the performance-based approach is the explicit evaluation of the performance objectives over a wide range of wind intensities in the presence of the inevitable uncertainties affecting the system and the loads (Arunachalam and Spence, 2022, 2023). However, there exists no experimentally validated model for the computer simulation of non-Gaussian and non-stationary (NG-NS) pressures given the standard stationary wind tunnel data collected at discrete wind directions. A recent study by Ouyang and Spence (2021) formulated a theoretical filter-based transition model to merge realizations of non-Gaussian and stationary (NG-S) stochastic pressure vector process associated with each discretized direction in the time domain to produce a single realization of the target NG-NS vector process. This study concerns the validation of the theoretical procedure using experimental data to quantify the approximation errors.

2. SIMULATION OF NON-GAUSSIAN STATIONARY VECTOR PROCESSES

2.1. Simulation by Spectral Representation and Translation Process Theory

Wind pressures on a building are a stochastic spatio-temporally varying process that may be modeled as a stochastic multivariate process for a given incident direction of the approaching wind. For a fixed hourly mean wind speed at the building height, it may further be assumed as stationary but non-Gaussian. In the context of a Monte Carlo type analysis wherein a large number of sample function evaluations is required, a second-order spectral representation method (SRM) can be adopted that generates ergodic samples that are asymptotically Gaussian (Shinozuka and Deodatis, 1991). Given the high-dimensional nature of the pressure vector process, i.e., for a large number of pressure taps, the proper-orthogonal-decomposition-based SRM is attractive as it permits the truncation of higher-order modes and enables reduced-order modeling of the process (Chen and Kareem, 2005). The availability of wind tunnel data is useful not only in specifying an accurate cross-power spectral density (CPSD) matrix for SRM but also in calibrating non-Gaussian CDFs to 'translate' the Gaussian stationary processes to non-Gaussian stationary (NG-S) processes corresponding to a given wind direction, α (Ouyang and Spence, 2019).

2.2. Wind Tunnel Data

In this study, a rectangular mid-rise building with a plan aspect ratio, $B : D$, of $1 : 2$, and height to breadth, $H : B$, of $5 : 3$ is considered. For the simulation of NG-S pressures, the CPSD matrices are obtained using 50 minutes of measurements recorded at the Natural Hazards Engineering Research Infrastructure (NHERI) wind tunnel at the University of Florida. The CPSD matrices were constructed for discrete wind directions in the range 0° to 90° in 10° increments. Similarly, the non-Gaussian CDFs were estimated with 15 minutes of data. Using a large amount of data ensures smooth, well-averaged CPSDs so that negligible error is associated with the spectral-representation-based simulations. It is noted that a kernel-Pareto mixture was adopted to describe the target non-Gaussian distribution (Zhao et al., 2019).

3. SIMULATION OF NON-GAUSSIAN AND NON-STATIONARY VECTOR PROCESSES

3.1. Estimation Using a Simulated Set of Direction-wise Stationary Vector Processes

The procedure proposed in Ouyang and Spence (2021) for the simulation of the NG-NS vector process is actually an estimation technique given a set of direction-wise NG-S realizations that can be described in the following steps: (i) discretize the time-varying wind direction, $\alpha(t)$, into $\alpha_i, 1 \leq i \leq N_s$, directions for which wind tunnel data is available; (ii) generate realizations of NG-S pressure processes corresponding to each discretized direction and corresponding duration; (iii) merge the random realizations corresponding to N_s wind direction segments. In particular, in the last step, filter-based transition models are used to estimate a realization of the target non-stationary, non-Gaussian process in the following manner:

$$\mathbf{C}_p(t) = \psi^{(i)}(t)\bar{\mathbf{C}}_p^{(i)} + \sqrt{\psi^{(i)}(t)}\left(\mathbf{C}_p^{(i)} - \bar{\mathbf{C}}_p^{(i)}\right) + \psi^{(i+1)}(t)\bar{\mathbf{C}}_p^{(i+1)} + \sqrt{\psi^{(i+1)}(t)}\left(\mathbf{C}_p^{(i+1)} - \bar{\mathbf{C}}_p^{(i+1)}\right) \tag{1}$$

where $t \in [T_i, T_{i+1}]$ is the transition duration between $\alpha(T_i) = \alpha_i$ and $\alpha(T_{i+1}) = \alpha_{i+1}$; $\mathbf{C}_p(t)$ is the estimated realization of the target vector process, $\bar{\mathbf{C}}_p^{(i)}$ is the time-averaged component of the realization of the NG-S process associated with α_i, and $\psi(t)$ are the transition filter functions describing the weights of the weighted average expressed by Eq. (1). Ouyang and Spence (2021) assumed that the transition filter functions take the form of a linear function in time (with special considerations at the boundaries). With this assumption, it can be shown that the resulting realization will have statistics up to the second-order (i.e., mean, auto- and cross-correlations) varying in a near-linear manner (with respect to the statistics of $\mathbf{C}_p^{(i)}$ and $\mathbf{C}_p^{(i+1)}$) in the transition region. This study focuses on validating the transition models and therefore, the accuracy of the estimation approach. If linear functions for $\psi^{(i)}$ do not sufficiently capture the stochastic properties of the target vector process, alternate formulations for $\psi^{(i)}$ and/or Eq. (1) will also be considered.

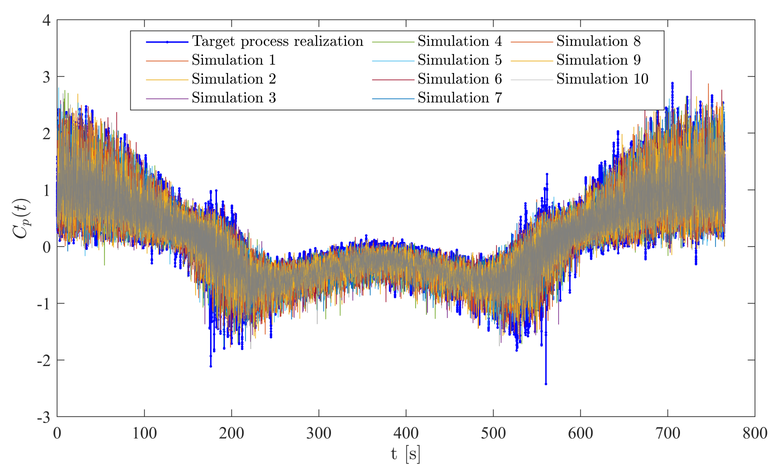

Figure 1. Comparison of a realization of the true pressure coefficient process with 10 simulations.

3.2. Experimental Validation

For the experimental validation, a series of tests on a scaled model were conducted at the NHERI boundary layer wind tunnel. Specifically, pressure data were recorded while continuously varying the wind direction (i.e., rotating the turntable) during the test. Different $d\alpha/dt$ were considered together with different rates of change of the mean reference wind speed to test the validity and sensitivity of the errors to these rates. For every test combination, 20 repetitions were performed to obtain the ensemble statistics of the true NG-NS vector process. Fig. 1 shows a single realization of the true $C_p(t)$ for pressure tap 153 (located near the center of the side facing the approaching wind at $\alpha = 0°$) along with 10 simulations generated by merging the direction-wise stationary process realizations. This comparison is made for $d\alpha/dt = 0.5°/s$ and a constant mean reference wind speed. Fig. 2 demonstrates the validity of the linear interpolation assumption of the mean and variance of the NG-S process locally in the transition region. Here, the true mean and variance refer to the ensemble mean and variance at any given time calculated from the 20 wind tunnel realizations of the target process. In this work, rigorous error measures, such as those based on normalized auto- and cross-correlations, will be defined to quantify the accuracy of the simulations for every pressure tap, pair of taps, and the different test conditions.

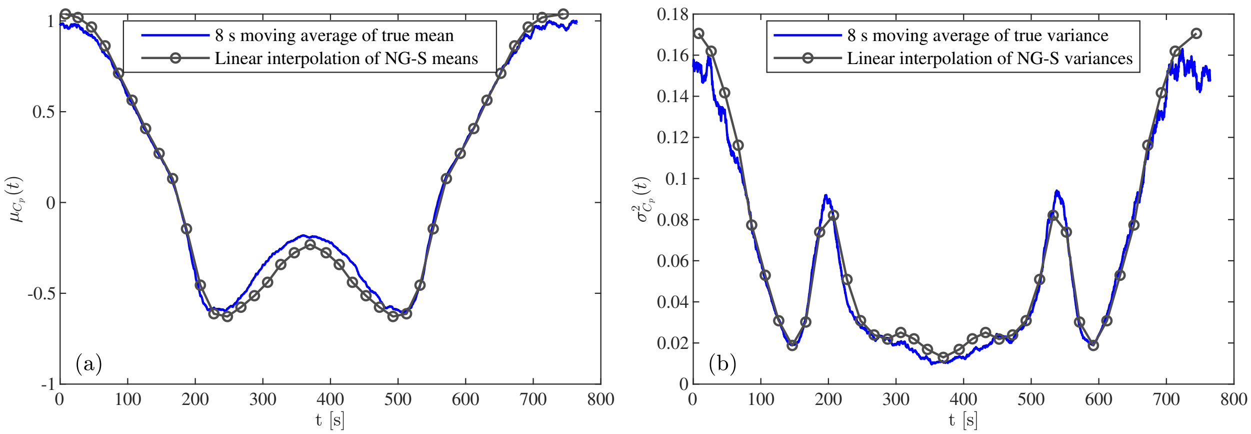

Figure 2. Demonstration of the linear interpolation assumption for: (a) mean of C_p; (b) variance of C_p.

4. CONCLUSION

The objective of this work was to validate a stochastic simulation model for correlated NG-S pressure processes using experimental data recorded at the University of Florida NHERI wind tunnel. The preliminary results indicate a good performance of the filter-based transition model which will be rigorously quantified in this work. The output of this work will be a significant advancement for performance-based wind engineering in enabling the capability to faithfully model hurricane-induced aerodynamics associated with a stochastic hazard model characterized by time-varying wind speed and direction.

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