CWE-8
June 7-11, 2026
London, ON, Canada

Efficient stochastic reconstruction of experimental wind loads using proper orthogonal decomposition

Xisheng Lin [a], Matiyas Bezabeh [b], Djordje Romanic [c], Un Yong Jeong [d]

[a]McGill University, Montréal, QC, Canada, xisheng.lin@mail.mcgill.ca
[b]McGill University, Montréal, QC, Canada, matiyas.bezabeh@mcgill.ca
[c]McGill University, Montréal, QC, Canada, djordje.romanic@mcgill.ca
[d]Gradient Wind, Ottawa, ON, Canada, unyong.jeong@gradientwind.com

SUMMARY

Performance-based wind design requires a large number of statistically consistent wind load realizations to support probabilistic performance assessment. Spectral representation methods are widely used for this purpose, but conventional Cholesky-based implementations can become computationally expensive and numerically fragile when applied to high-dimensional experimental datasets. This study proposes an FFT-accelerated proper orthogonal decomposition-based algorithm for fast and efficient stochastic simulation of wind loads. The method is evaluated using three examples: an empirically prescribed spectral model, an experimental high-frequency pressure-integration dataset, and a hybrid empirical-experimental dataset based on high-frequency force-balance measurements. Results show that the proposed method reduces simulation time by approximately 2–40 times compared with Cholesky-based approaches. Further speedups of 4–11-fold are achieved through modal truncation while maintaining good agreement with the target spectra. Moreover, the proposed method demonstrates improved numerical stability when applied to experimental data and supports the joint simulation of multiple wind load components.

Keywords: *Performance-based wind design, Proper orthogonal decomposition, Stochastic reconstruction*

1. INTRODUCTION

Performance-based wind design (PBWD) requires accurate estimation of small structural failure probabilities, which can be obtained through Monte Carlo simulation that demands a large number of statistically consistent wind-load realizations. To generate these realizations, the Cholesky decomposition-based spectral representation method (SRM) has been widely adopted, which, however, can be time-consuming with increasing simulation points (Deodatis and Shields, 2025). To improve efficiency, the fast Fourier transform (FFT) was introduced to speed up the summation process. Zhao et al. (2021) proposed a spatio-temporal two-dimensional (2D) FFT method that further accelerates the simulation by 5–20 times. However, most studies including Zhao et al. (2021) adopted test cases where empirical equations define the cross power spectral density (XPSD) matrix. In practical PBWD applications, SRM is often used for the stochastic reconstruction of wind-tunnel data, where numerical stability can be affected by measurement noise and finite-sample effects. These issues have not been systematically investigated in previous studies.

Proper orthogonal decomposition (POD) has also been proposed as an alternative to Cholesky decomposition (Chen and Kareem, 2005). By providing a reduced-order representation, POD enables substantial computational savings through modal truncation. However, a systematic formulation that integrates POD with FFT acceleration, together with a quantitative assessment of its efficiency and numerical stability relative to Cholesky-based approaches, remains lacking.

To address these limitations, this study formulates a POD-based SRM algorithm accelerated by FFT. Both empirical and experimental examples are included to test its efficiency and numerical stability. The results are also systematically compared with Cholesky-based SRM implementations using conventional 1D FFT acceleration and the 2D FFT method proposed by Zhao et al. (2021).

2. PROPOSED METHOD

The proposed algorithm is presented subsequently. The inputs include a floor-by-floor XPSD matrix estimated from empirical equations or experimental data, the time and frequency step sizes, a discrete frequency vector, and the number of retained POD modes. The output is wind load time histories. At each ω_k, eigenvalue decomposition is performed on $\mathbf{S}(\omega_k)$ to construct complex spectral amplitudes $\mathbf{B}(:,\omega_k)$, which is then transformed into the time domain through inverse FFT, with the resulting time history length constrained by $2\pi/(\Delta\omega\Delta t)$ (Deodatis and Shields, 2025).

Algorithm POD-based SRM with FFT acceleration

```
Input: $\mathbf{S}(\omega_k)$, $\Delta t$, $\Delta\omega$, $\omega_k$, $N_m$,
Output: $\mathbf{f}(t)$
1: For each discrete frequency $\omega_k$:
    2: Perform eigenvalue decomposition to obtain POD modes: $\mathbf{S}(\omega_k) = \mathbf{V}(\omega_k)\mathbf{D}(\omega_k)\mathbf{V}^T(\omega_k)$
    3: Retain the first $N_m$ POD modes
    4: Generate random phase angles $\theta_j(\omega_k) \in [0, 2\pi]$
    5: Construct complex spectral amplitudes: $\mathbf{B}(:,\omega_k) = \sqrt{2\Delta\omega}\mathbf{V}_{N_m}(\omega_k)\mathbf{D}_{N_m}^{1/2}(\omega_k)\exp(i\boldsymbol{\theta})$
6: End For
7: Obtain the time histories by inverse FFT of length $2\pi/(\Delta\omega\Delta t)$: $\mathbf{f}(t) = \mathrm{Re}\{\mathrm{IFFT}(\mathbf{B})\}$
```

3. TEST EXAMPLES

3.1. Example description

Three examples are considered to evaluate the performance of the proposed method, representing empirical, experimental, and hybrid empirical-experimental scenarios, as shown in Figure 1. The first "empirical" example follows the 50-story building adopted by Zhao et al. (2021), where the XPSD matrix is defined using Kaimal's two-sided spectrum (Kaimal et al., 1972) and Davenport's coherence function (Davenport, 1967), as given by:

$$S(z,\omega) = \frac{200}{4\pi}\frac{z}{U(z)}\frac{u_\tau^2}{\left[1+50\omega z/2\pi U(z)\right]^{5/3}}, \tag{1}$$

$$coh(z_i, z_j, \omega) = \exp\left[-\frac{\omega}{2\pi}\frac{C_z\left|z_i - z_j\right|}{\frac{1}{2}\left[U(z_i)+U(z_j)\right]}\right], \tag{2}$$

where z is building height, $U(z)$ is reference wind speed, u_τ is friction velocity, and C_z is a constant set at 7. This example validates our reproduction of Zhao et al. (2021)'s method. The second "experimental" example uses a 45-story building, for which floor-by-floor wind load spectra (see Figure 2a) are directly obtained from high-frequency pressure-integration wind-tunnel tests conducted at Western University (Bezabeh et al., 2020). The third “empirical-experimental” example adopts a 40-story building, where only base moments’ spectra S_{M_x} (see Figure 2b) and coherence $coh(M_y, M_x)$ are available from a high-frequency force balance test conducted at Gradient Wind Inc. (Jeong et al., 2026). The floor-level load spectra are indirectly generated by:

$$S_{xy}(z_i, z_j) \cong coh(M_y, M_x) coh\left(z_i, z_j\right) \psi_i \psi_j \frac{\sqrt{S_{M_y} S_{M_x}}}{\sum_{i,j=1}^{N}\left[z_i z_j coh\left(z_i, z_j\right) \psi_i \psi_j\right]}, \tag{3}$$

where ψ_i is wind load distribution function and is assumed to be linear along height.

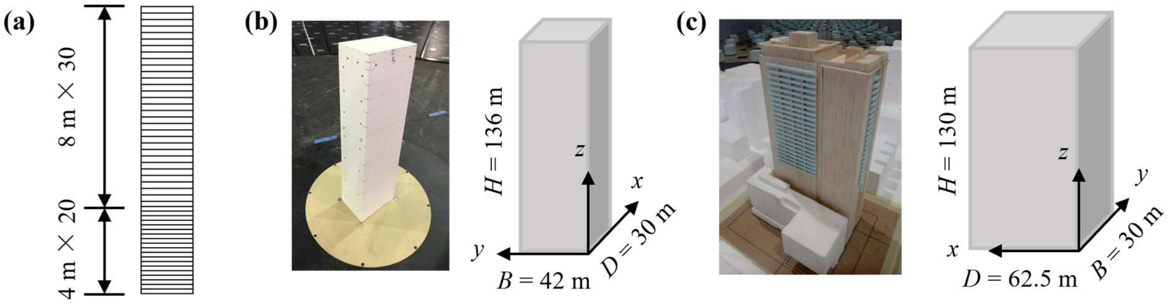

Figure 1: Three test examples on tall buildings with XPSD defined by: (a) empirical equations, (b) experimental measurements, and (c) a hybrid empirical-experimental model [image courtesy of Jeong et al. (2026)]

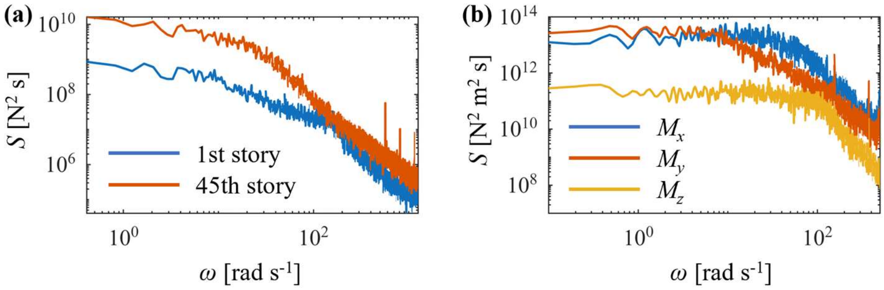

Figure 2: PSD of (a) along wind loads in Example 2 and (b) base moments in Example 3

3.2. Efficiency improvement

Table 1 compares the efficiency of the tested methods. For Cholesky-based methods, the application of 2D FFT reduces the simulation time by 5–7 times compared to 1D FFT, which is consistent with the ratio reported in Zhao et al. (2021), confirming successful reproduction of their methods. For the proposed POD-based method with full modes, simulation efficiency improved by 10–40 times compared with Cholesky with 1D FFT and by 2–6 times with 2D FFT. Further acceleration is obtained by modal truncation. When only 20% of the dominant POD modes are retained, the simulation time is reduced by an additional 4–11 times, while maintaining acceptable accuracy, as shown in Figure 3. All methods reproduce the target spectra with good agreement. Even for POD with only 20% modes, the simulated spectra match the target, with noticeable deviations appearing only in the relatively less influential high-frequency range (the zoom-in area).

Table 1: Average simulation time (s) for generating 15-min full-scale time histories

Example	Cholesky (1D)	Cholesky (2D)	POD (full modes)	POD (20% modes)
1	262.2	37.5	6.2	0.8
2	44.6	8.6	1.9	0.5
3	128.9	22.3	11.5	1.0

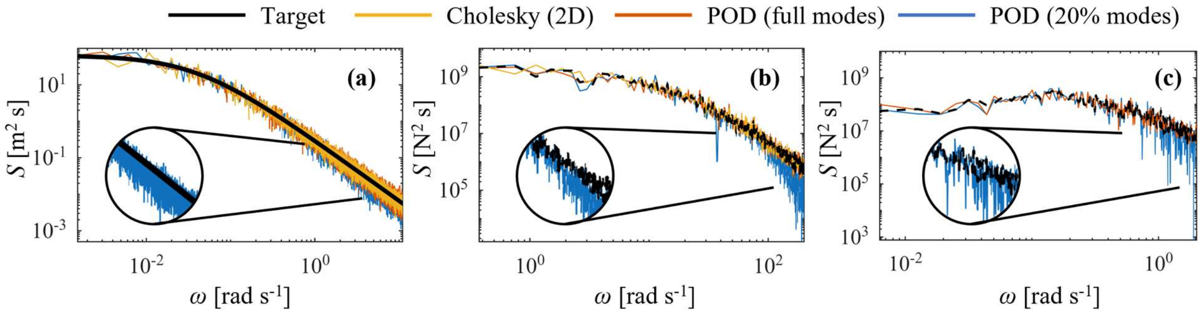

Figure 3: Comparison of PSD at the top story of the building for (a) Example 1, (b) Example 2, and (c) Example 3

3.3. Numerical stability

Beyond computational efficiency, the POD-based method also exhibits improved numerical stability when applied to experimental datasets. While all methods perform well for the “empirical” example, Cholesky-based methods encounter stability issues when XPSD matrices are estimated from experimental data in examples 2 and 3. In particular, Cholesky-based methods with a 2D FFT formulation yield invalid time histories at stories whose spectral characteristics differ significantly from those of adjacent stories. Additionally, this property prevents Cholesky-based methods from simultaneously handling multiple types of wind loads, such as along-wind, cross-wind, and torsional components. In contrast, the POD-based method remains numerically stable across all test cases and naturally supports joint simulation of multiple load components.

4. CONCLUSIONS

This study formulates a POD-based SRM algorithm with FFT acceleration, providing an efficient and numerically robust alternative to Cholesky-based spectral representation methods for stochastic reconstruction of experimental wind loads in performance-based wind design.

REFERENCES

Bezabeh, M.A., Bitsuamlak, G.T., Popovski, M., Tesfamariam, S., (2020). Dynamic response of tall mass-timber buildings to wind excitation. J. Struct. Eng. 146, 04020199.

Chen, X., Kareem, A. (2005). Proper orthogonal decomposition-based modeling, analysis, and simulation of dynamic wind load effects on structures. J. Eng. Mech. 131, pp. 325–339.

Davenport, A.G. (1967). The dependence of wind loads on meteorological parameters, International Seminar on Wind Effects on Buildings and Structures, Toronto, Canada, pp. 19–82.

Deodatis, G., Shields, M. (2025). The spectral representation method: A framework for simulation of stochastic processes, fields, and waves. Reliability Engineering & System Safety 254, 110522.

Jeong, U.Y., Dupelle, L., Hartlin, S. (2026). Wind load time history regenerated considering coherences for performance-based wind design of tall buildings. J. Wind Eng. Ind. Aerodyn. 269, 106283.

Kaimal, J.C., Wyngaard, J.C., Izumi, Y., Coté, O.R., (1972). Spectral characteristics of surface-layer turbulence. Quarterly Journal of the Royal Meteorological Society 98, pp. 563–589.

Zhao, N., Huang, G., Kareem, A., Li, Y., Peng, L., (2021). Simulation of ergodic multivariate stochastic processes: An enhanced spectral representation method. Mechanical Systems and Signal Processing 161, 107949.