

Statistical Characteristics of Tornado Wind Speeds from WindEEE Dome Experiment

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SUMMARY

This study examines wind speed data from experimentally simulated tornado-like vortices generated in the WindEEE Dome to quantify their statistical characteristics. Runs tests are first performed to examine the stationarity of the wind speed records. Empirical Mode Decomposition (EMD) is then applied to the wind speed time history to extract a smoothly time-varying mean wind speed component and the corresponding turbulent fluctuations. Based on this nonstationary framework, key statistical characteristics of the wind speeds, including gust factor, turbulence intensity, and peak factor, are defined and evaluated. Empirical cumulative distribution functions (CDFs) of the gust factor are constructed at different locations relative to the tornado center, from which characteristic fractiles (50%, 78%, and 95%) are extracted. The results indicate that median gust factors range from approximately 1.15 to 1.25, while the 95th-percentile values approach 1.35–1.40 for the tested configurations.

Keywords: Tornado, nonstationary time history, empirical mode decomposition, gust factor, cumulative distribution function

1. INTRODUCTION

Tornado-like vortices generate highly transient and turbulent flows in which wind speed at a fixed point can change dramatically as the vortex passes. Unlike synoptic boundary-layer winds, tornado winds are strongly nonstationary, and treating them as stationary can result in significant errors in estimating peak wind loads (Wang and Kareem, 2004). In the study of other nonstationary wind storms such as typhoons and hurricanes, it has become common practice to decompose wind records into a slowly varying mean component with superimposed turbulent fluctuations, providing a more appropriate representation of time-varying wind characteristics (Xu and Chen, 2004; Fang et al., 2024). However, the statistical characteristics of tornado wind fields that explicitly account for nonstationary effects remain largely unexplored.

This paper addresses this gap by applying a nonstationary decomposition approach to tornado-like wind flows generated in the WindEEE Dome. Statistical characteristics, including gust factor, turbulence intensity, and peak factor, are computed relative to the mean wind speed obtained from empirical mode decomposition, and empirical cumulative distribution functions of the gust factor are constructed to extract design values at different percentiles.

2. METHODOLOGY

2.1. Experimental Data

The dataset adopted in this study is taken from Kopp and Wu (2020), which comprises 87 simulations of a tornado-like vortex generated in the WindEEE Dome. All tests were conducted

using the identical control parameters, including swirl ratio, radial flow rate and translation speed. Tornado wind speed time histories were recorded at four probe locations, labeled A, B, C, and D, positioned across the vortex path, as shown in Figure 1. More details regarding the experimental setup and testing procedure are provided in Kopp and Wu (2020). It is also noted that only the resultant horizontal wind speed is considered in this study.

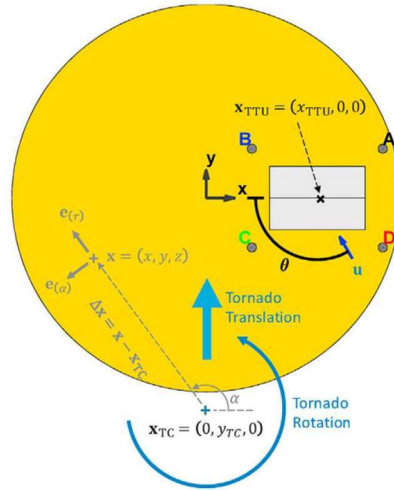


Figure 1. Schematic of Cobra probe locations (from Kopp and Wu, 2020)

2.2. Stationarity Test

Run tests are applied to the wind speed time series to examine the stationarity of the data. The runs test counts consecutive positive or negative fluctuations about zero to identify systematic trends in the data. When the time series were divided into sequential spatial segments of 10 mm, more than 90% of the segments failed the stationarity test. Even when finer segment length of 6 mm and 2 mm were considered, a significant proportion of segments remained nonstationary, particularly in regions associated with peak wind speeds. These runs test results presented in Table 1 provide quantitative evidence that tornado wind records are strongly nonstationary, indicating that conventional stationary wind models would lead to inaccurate estimates of peak wind speeds.

Table 1: Run Test Results for All (87) Simulations

Bin Size (mm)	No. of Bins	Bins have $z \geq 1.96$	% of Bins having $z \geq 1.96$	Result
10	34,083	32,107	94.20	Non-stationary
6	56,555	45,581	80.60	Non-stationary
2	168,518	61,529	36.51	Non-stationary

2.3. Empirical Mode Decomposition (EMD)

Empirical Model Decomposition (EMD) is then applied to each wind speed time history to extract a time-varying mean component. EMD decomposes a signal into intrinsic mode functions (IMFs) and a residual, with the residual representing the lowest frequency component and thus interpreted as the evolving mean. Unlike conventional filtering approaches, EMD does not require a predefined window or cutoff frequency; instead, the decomposition adapts naturally to the dominant time scales present in the data. In the present experiments, the EMD-derived mean wind

increases from near zero to a maximum as the vortex core passes the measurement location and subsequently decays, as shown in Figure 2.

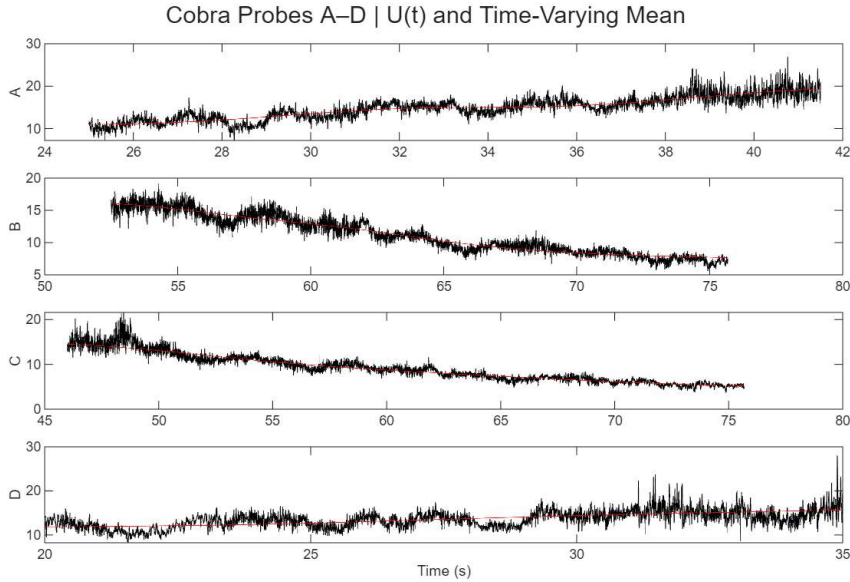


Figure 2. EMD-derived time-varying mean wind speed for each probe.

2.4. Gust Factor Computation

With the time-varying mean wind speed defined based on EMD, the gust factor is calculated using:

$$G_u = V_{max}/\bar{V} \quad (1)$$

where V_{max} is the instantaneous peak wind speed and \bar{V} is the EMD-derived time-varying mean wind speed. In addition, the turbulence intensity, defined as $I_u = \sigma_u/\bar{V}$ (where σ_u is standard deviation of wind speed) and the peak factor, defined as $g_p = (V_{max} - \bar{V})/\sigma_u$, were calculated for each time history from each probe. These metrics reflect run-to-run variability. To characterize this variability for design applications, empirical cumulative distribution functions (CDFs) of G_u were constructed at each location, and characteristic percentiles were extracted, including the 50th (median), 78th (intermediate) and 95th (extreme) percentiles. These percentile values are interpreted as probabilistic gust factors. In practice, a smooth probability distribution may be fitted to the empirical CDF, after which design percentiles can be obtained from the fitted distribution.

3. RESULTS AND DISCUSSION

Using the EMD-derived time-varying mean, gust factors G_u were computed for all 87 simulations. Ensemble cumulative distribution functions of G_u were then constructed for each probe location. The distribution of gust factors for 50% percentile during the tornado passage is presented in Figure 3. For probe A, located near the core radius corresponding to maximum wind speed, the median gust factor is $G_{u,50} \approx 1.16$, while a 95th-percentile value is $G_{u,95} \approx 1.28$. Similarly, probe D, also situated near core radius, exhibits $G_{u,50} \approx 1.19$ and $G_{u,95} \approx 1.40$. Probes B and C show slightly lower gust factors, with median values of approximately 1.13–1.14 and 95th-percentile

values of approximately 1.23–1.25. Overall, most gust factors lie between 1.1 and 1.3, with extreme values approaching 1.4. The turbulence intensity I_u typically ranges from 5% to 10% across the tested cases, increasing to approximately 15% near the vortex core. From a spatial perspective, the largest gust factors occur inside the core radius corresponding to the maximum wind speed. This behavior arises because the mean wind speed decreases slightly within the core region while turbulent fluctuations remain strong, thereby increasing the gust factor G_u .

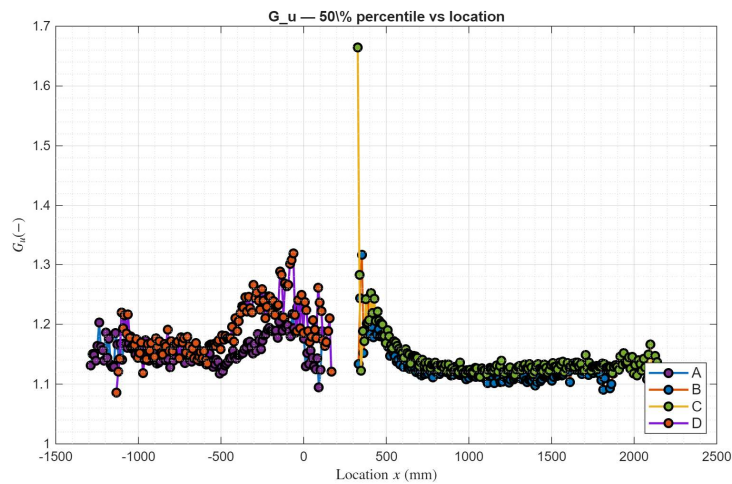


Figure 3. Gust factors corresponding to the 50th percentile at different locations.

4. CONCLUSIONS

This study provides a comprehensive statistical characterization of tornado wind speed data. Runs tests confirm that the experimentally simulated tornado wind flows are strongly nonstationary. EMD is shown to be an effective tool for extracting the transient mean wind component from each record, yielding a physically meaningful pulse-shaped representation of the tornado passage. Key turbulence metrics are computed relative to these adaptive mean wind speed. The resulting gust factor G_u has median values in the range of 1.15–1.25, with 95th-percentile values reaching about 1.35–1.40 for the tested configurations. Spatially, the largest gust factors occur slightly inside the tornado core.

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5. REFERENCES

- Fang, G., Liu, Z., Pang, W., Zhao, L., Xu, K., Cao, S., Ge, Y., 2024. Probabilistic gust factor model of typhoon winds. *J. Struct. Eng.*, 150(1): 04023205.
- Kopp, G.A. and Wu, C.-H., 2020. A framework to compare wind loads on low-rise buildings in tornadoes and atmospheric boundary layers. *J. Wind Eng. Ind. Aerodyn.*, 201: 104164.
- Wang, L. and Kareem, A., 2004. Modeling of non-stationary winds in gust fronts. In: *Proc. 9th ASCE Specialty Conf. on Probabilistic Mechanics and Structural Reliability (PMC)*, pp. 1–9.
- Xu, Y.L. and Chen, J., 2004. Characterizing nonstationary wind speed using empirical mode decomposition. *J. Struct. Eng.* 130(6): 912–920.