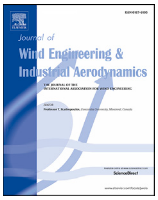
Journal of Wind Engineering & Industrial Aerodynamics 169 (2017) 94–105

Contents lists available at ScienceDirect

Journal of Wind Engineering & Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia



Near surface wind longitudinal velocity positively skews with increasing aerodynamic roughness length

P.L. Fernández-Cabán, F.J. Masters*

Engineering School of Sustainable Infrastructure & Environment, Univ. of Florida, USA

ARTICLE INFO

Keywords:
Near-surface winds
Non-Gaussian
Suburban terrain
Quadrant analysis
Exposure coefficient

ABSTRACT

Analysis of anemometric observations collected during the 1999–2016 Atlantic hurricane seasons and boundary layer wind tunnel (BLWT) measurements indicate that the near surface wind behavior deviates from Gaussian as surface roughness increases. Quadrant analysis of the Reynolds stress clearly demonstrates the linkage between the longitudinal skewness and downward transfers of momentum (sweep events) in strong winds, which previous studies have also observed. Modern wind load provisioning and BLWT similarity requirements do not explicitly account for this effect, although the experimental configuration of typical wind tunnel development sections may correctly simulate the phenomena. Here we quantify how the observed positive skewness affects the terrain exposure coefficient profile for ASCE 7. The results demonstrate the need to update peak factor calculations to accurately predict extreme winds acting on low-rise buildings in built-up terrain.

1. Introduction

The findings of this paper refute the dominant assumption in wind engineering that the surface (<25 m) wind field exhibits Gaussian behavior over all terrain types. Results from 17 years of anemometric observations in tropical cyclones and recent boundary layer wind tunnel (BLWT) experiments indicate that the skewness (γ_{3u}) of the longitudinal velocity component increases with aerodynamic roughness length (z_0)—a phenomena not currently addressed by exposure conversion factors in wind load provisioning nor in standards to commission facilities for BLWT modeling, e.g. ASCE/SEI 49-12 and AWES-QAM-1-2001. The cause is attributed to the prevalence of sweeps, i.e. downward and forward departures from the mean longitudinal flow, that positively skew the velocity. This mechanism, in part, also explains why field studies (e.g., Baldocchi and Hutchison, 1987; Baldocchi and Meyers, 1988; Maitani and Shaw, 1990) have observed variations in high order moments near the canopy of suburban regions. Our observations strongly corroborate with previous findings originating from field measurements (e.g., Chen, 1990; Rotach, 1995; Rotach et al., 2005; Shaw et al., 1983) and the BLWT (e.g., Finnigan, 2000; Zhu et al., 2007; Raupach, 1981; Böhm et al., 2013), which have documented the dominance of large coherent structures within and just above the canopy of the turbulent boundary layer, and the effect of these structures on the third moment of the longitudinal and vertical velocity components.

The study extends the work of Balderrama et al. (2012), expanding its dataset to include targeted field measurements in suburban terrain and ultrasonic anemometer measurements at five levels spanning 5–15 m. It also incorporates new approach flow data collected in a novel BLWT that can rapidly reconfigure the roughness element grid to achieve a user-specified z_0 for a user-specified geometric scale. The results suggest the standards should be conservatively updated to incorporate a linear change in γ_3 from [0.46, 0.0] over [4.4, 24.6] m, holding $\gamma_3 = 0.46$ below this extent. Applying the non-Gaussian up-crossing rate defined in Kareem and Zhao (1994) to the wind speed (pressure) conversion described in Masters et al. (2010), we find up to a 14% increase in the pressure loading on suburban low-rise structures (ASCE 7-10, 2010).

2. Methodology

2.1. Field experiments in landfalling tropical cyclones

The study's field data originate from near-surface wind field observations collected during 1999–2016 Atlantic tropical cyclones by the Florida Coastal Monitoring Program (FCMP), a multi-institution consortium that includes the University of Florida, Clemson University, Florida International University, and the Insurance Institute for Business & Home Safety. Balderrama et al. (2011, 2012) describe the program in detail.

The dataset includes records from 86 deployments of portable weather stations in 25 named storms. The current study incorporates 13

---

* Corresponding author.

E-mail addresses: plfernandez@ufl.edu (P.L. Fernández-Cabán), masters@ce.ufl.edu (F.J. Masters).

http://dx.doi.org/10.1016/j.jweia.2017.06.007
Received 31 December 2016; Received in revised form 17 May 2017; Accepted 14 June 2017

Table 1
FCMP datasets included in this study in addition to those analyzed in Balderrama et al. (2012).

Year	Tropical Cyclone	Station ID	Latitude	Longitude	Town	Anemometry
2016	Matthew	T1	+28.1947	−80.5944	Satellite Beach, FL	3-Axis Propeller
2016	Matthew	T2	+32.7141	−79.9664	Charleston, SC	Ultrasonic
2016	Matthew	T2	+27.1889	−80.2411	Stuart, FL	Ultrasonic
2016	Matthew	T3	+32.7902	−79.9881	Charleston, SC	Ultrasonic
2016	Matthew	T3	+28.1937	−89.6056	Satellite Beach, FL	Ultrasonic
2016	Matthew	T5	+27.1802	−80.2295	Stuart, FL	3-Axis Propeller
2016	Hermine	T2	+29.6735	−83.3746	Steinhatchee, FL	Ultrasonic
2016	Hermine	T3	+29.6731	−83.3798	Steinhatchee, FL	Ultrasonic
2016	Hermine	T5	+29.6728	−83.3703	Steinhatchee, FL	3-Axis Propeller
2014	Arthur	T2	+35.2322	−75.6215	Hatteras, NC	Ultrasonic
2012	Sandy	T3	+39.3208	−74.5953	Linwood, NJ	Ultrasonic
2012	Isaac	T3	+29.6487	−90.6940	Houma, LA	Ultrasonic
2012	Isaac	T2	+29.5385	−89.7751	Bohemia, LA	Ultrasonic

new field experiments that deployed upgraded 15 m portable weather stations (see Table 1), with suburban terrain being the primary study target. The original 10 m FCMP weather stations are equipped with anemometers at 5, and 10 m. Two custom arrays of three fixed axis anemometers (RM Young Model Number 27106R) collect wind velocity observations (3D wind speed and direction) at the 5 and 10 m levels. Dynamic characteristics of the anemometer's four-blade polypropylene helicoid propellers (Model Number 08234) include a 2.7 m, 63% recovery distance constant and a damped natural wavelength of 7.4 m. A wind monitor (RM Young Model Number 05103V) installed at the 10 m level serves as a redundant anemometer system to monitor the horizontal component of the wind. The wind monitor 50% recovery vane delay distance is 1.3 m, and it is rated for a 100 m/s gust survival. In 2010, two weather stations were upgraded with high-resolution ultrasonic anemometers (WindMaster Pro Model 1561-PK-020) installed at 5, 7.5, 10, 12.5, and 15 m above ground level. The units have a wind speed range of 0–65 m/s with a resolution of 0.01 m/s, and measure instantaneous u, v, and w wind components with a maximum sampling rate of 32 Hz. In this study, data were sampled at or resampled to 10 Hz.

2.2. Data processing

Data were segmented into contiguous non-overlapping 15-min time histories. Quality control included comparing the propeller measurements at an elevation of 10 m to the redundant wind monitor measurements at the same elevation to detect anomalies. Data segments with mean wind velocities below 5 m/s were removed to eliminate any effects from convection. The tower tilt correction described in Foken and Nappo (2008) was performed to align the anemometer coordinate system into the streamlines and towards the mean flow coordinate system. Negligible mean vertical and lateral wind components were verified to satisfy the requirements of an eddy-covariance method of analysis. Linear trend removal methods were performed on all 15-min records to remove first order non-stationarities.

Shear (friction) velocities for each data segment were calculated directly from the three measured orthogonal velocity components following Weber (1999):

$$u_* = \left(\overline{u'w'}^2 + \overline{v'w'}^2 \right)^{\frac{1}{4}} \tag{1}$$

The logarithmic mean velocity profile was then used to estimate the roughness length z_0:

$$z_0 = (z - d)\exp\left[-\frac{U(z)\kappa}{u_*} \right] \tag{2}$$

where $U(z)$ is the mean wind speed at elevation z, $\kappa = 0.4$ is von Kármán’s constant, and d is the zero-plane displacement height. Measurements were obtained at 2–5 levels, preventing direct estimation of d. Thus the heuristic method of Jackson (1981) was applied:

$$d = \overline{H} - 2.5z_0 \tag{3}$$

where $\overline{H}$ is the average roughness element height, nominally assumed to be 5 m, which is representative of locations surrounded by clusters of single family dwellings. Displacement height was assumed to be effectively zero for records with $z_0 < 0.15$ m.

For quality assurance, an independent procedure was performed to calculate z_o. A bounded nonlinear function minimization was applied to satisfy the logarithmic formulation of the mean velocity profile and the modified Harris and Deaves (1980) variance model described in Vickery and Skerlj (2005). Percent differences between the two procedures were in the range of 2–6% for records corresponding to suburban terrain ($0.15 \text{ m} > z_0 \geq 0.7 \text{ m}$).

Data records were stratified by surface roughness (exposure) categories defined in ASCE 7-10 (2010), i.e. B (suburban), C (open), and D (marine). Table 2 lists the number of 15-min records stratified by surface roughness and the mean wind speed at 10 m. Table 3 lists the corresponding mean roughness length estimates, which were obtained from Eq. (2) for $U(z = 10 \text{ m})$.

2.3. Conditional analysis of the Reynolds stress

Conditional (also known as quadrant) analysis of the Reynolds stress is useful to quantify the turbulent mechanisms of organized structures in the inertial sublayer and the roughness sublayer (RS), i.e. the region below the inertial sublayer affected by the coherent motions spawned by buildings, trees, etc. upwind (Lu and Willmarth, 1973). It applies conditional statistical averaging to partition the contribution of the mean Reynold stress into four quadrants based on the sign of the (mean-removed) longitudinal (u') and vertical (w') wind velocity components as

Table 2
Total number of 15-min records (z = 10 m) stratified into mean wind speed and roughness length based on ASCE 7–10 exposure categories.

Terrain Type	ASCE 7–10 Exposure	Roughness Length Regimes	No. of 15-min data segments			
			$5 \leq U < 15$	$15 \leq U < 25$	$U \geq 25$	Total
Suburban	B	$0.15 \text{ m} > z_0 \geq 0.7 \text{ m}$	507	233	105	845
Open country	C	$0.01 \text{ m} > z_0 \geq 0.15 \text{ m}$	483	350	760	1593
Very smooth	D	$z_0 < 0.01 \text{ m}$	73	129	499	701
Total			1063	712	1364	3139