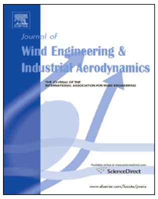
J. Wind Eng. Ind. Aerodyn. 147 (2015) 345–357

Contents lists available at ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

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



Near-ground turbulence of the Bora wind in summertime

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ARTICLE INFO

Keywords:
Gusty Bora wind
Turbulence
Turbulence intensity
Reynolds shear stress
Turbulence length scales
Field measurements

ABSTRACT

Bora is a strong, temporally and spatially variable downslope wind that blows along the Eastern Adriatic Coast and many other dynamically similar places around the world. Bora mean velocity rarely exceeds 20 m/s, while its strong gusts create significant problems for engineering structures, traffic and agriculture. Previous meteorological and geophysical studies laid foundations on Bora large- and mesoscale motions, but further research is necessary to fully understand and resolve Bora turbulence in a form usable for engineers. In this study, unique high-frequency measurements, carried out simultaneously in three heights on a meteorological tower in the hinterland of the city of Split, Croatia, are analyzed for a single summertime Bora episode. Time histories and vertical profiles are studied for turbulence intensity, Reynolds shear stress and turbulence length scales in comparison with values recommended in major international wind engineering standards. Turbulence intensity and Reynolds shear stress proved to be not that sensitive to meandering of the mean wind velocity, as the observed values remain within the same range during the time record. This trend applies on mean wind velocities larger than 5 m/s, as for smaller velocities the spread of values increases considerably. Turbulence length scales are observed to increase with increasing mean wind velocity and vice versa. With increasing height from the ground, turbulence intensity and absolute Reynolds shear stress decrease, turbulence length scales increase, all in agreement with the atmospheric physics. However, while turbulence intensity, Reynolds shear stress and longitudinal turbulence length scales generally agree well with the values recommended in international standards for the respective terrain type, turbulence length scales related to lateral and vertical velocity fluctuations are much larger than the standard values.

1. Introduction

The gusty Bora wind characteristics are quite unknown to the wind engineering community, thus preventing accurate prediction of Bora wind loads on structures and vehicles. While most of the previous Bora research is performed for the Adriatic Coast, this type of wind commonly blows in other world regions as well, such as Japan, Russia, Kurdistan, Iceland, Austria, Rocky Mountains in the Northern America, etc. (e.g. Jurčec, 1981; Neiman et al., 1988; Àgústsson and Ólafsson, 2007; Jackson et al., 2013) thus making the Bora research globally applicable.

Along the Eastern Croatian Coast, Bora blows from the North East across the mountain ranges, from Trieste to Dubrovnik and further South (e.g. Yoshino, 1976; Makjanić, 1978; Bajić, 1988, 1989; Tutiš, 1988; Vučetić, 1991; Belušić and Klaić, 2004, 2006). Generally, Bora is a very strong, commonly dry and always gusty wind, which significantly influences optimal functioning of transportation networks, the agriculture, local wind energy yield as well as the fatigue of energy structures (e.g. Kozmar et al., 2012a, 2012b, 2014, 2015). While previous geophysical and meteorological studies laid ground on the macro- and meso-scale features of the Bora (Jurčec, 1981; Smith, 1987; Grubišić, 2004; Grisogono and Belušić, 2009), further work is necessary to fully elucidate Bora turbulence in a form usable for wind engineers.

Bora mean wind speed, usually between 5 m/s and 30 m/s, is not that significant to wind engineers as the Bora gusts that can sometimes reach velocities up to three or even five times the average wind speed (e.g. Petkovšek, 1987; Belušić and Klaić, 2004, 2006; Grisogono and Belušić, 2009; Večenaj et al. 2010; Belušić et al., 2013). Spatially and temporally very variable, Bora is more common in winter when it can last from just a few hours up to several days (e.g. Jurčec, 1981; Poje, 1992; Enger and Grisogono, 1998; Jeromel et al., 2009). Due to its extreme spatial variability, a precise and strict definition of the Bora wind is not available (e.g. Poje, 1992; Horvath et al., 2009; Večenaj et al., 2012). Nevertheless,

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http://dx.doi.org/10.1016/j.jweia.2015.09.013
0167-6105/

a certain data series is considered to belong to Bora event if the recorded time series of the horizontal wind component has the azimuth from the first quadrant and remains persistent for at least three hours with the mean wind speed larger than 5 m/s and the standard deviation comparable to the mean value.

The occurrence of the long lasting Bora is commonly associated with a persistent cyclone over the Adriatic region or/and a high pressure center over the Central or Eastern Europe, as the continental air is drawn by the cyclone from the lower troposphere across the mountains (e.g. Jurčec, 1981; Heimann, 2001; Belušić et al., 2013). Simultaneously, the air from the Pannonia Basin and the Central Europe is forced across the mountains towards the Adriatic by the anticyclone. A short lasting Bora can be triggered by the passage of the cold front across the Adriatic. Depending on the intensity and evolution of the cyclogenesis and its synchronization with the upper tropospheric flow, shallow or deep Bora may occur (e.g. Grisogono and Belušić, 2009). Bora can be cyclonic, bringing clouds with high possibility for precipitation, anticyclonic, related to fair weather, and frontal (e.g. Jurčec and Visković, 1994). The frequency of the Bora occurrence in the Eastern Adriatic decreases from North West to South East (e.g. Poje, 1992), and its strength weakens seaward from the shore in a way that it is rarely stormy in the Western Adriatic (e.g. Enger and Grisogono, 1998).

Development of advanced measuring techniques and numerical atmospheric models contributes to the progress of the Bora research, causing a change in basic understanding of the triggering system for a severe Bora. Originally, a katabatic-type perspective prevailed (e. g. Yoshino, 1976; Jurčec, 1981), while the issue with this approach was that simple katabatic flows are generally unable to continuously create mean wind velocities of around 20 m/s and larger that is characteristic to Bora. At this moment, a hydraulic theory of strong to severe Bora with orographic wave breaking is commonly accepted in the mesoscale community, at least for the North Eastern Adriatic coast (Smith, 1987; Enger and Grisogono, 1998; Grubišić, 2004; Grisogono and Belušić, 2009). It was previously reported that the strong Bora flow can be treated, to a very good approximation, as a nonlinear hydraulic flow, which also means a lack of significant stratification effects (Klemp and Durran, 1987; Smith, 1987). A strong resonance between the flow and underlying terrain allows for the wave breaking phenomena to diminish stratification effects near the surface (e.g., Grisogono and Belušić, 2009). Quasi-periodic behavior is a typical characteristic of downslope windstorm gusts (Petkovšek, 1976, 1982, 1987; Rakovec, 1987; Neiman et al., 1988). Belušić et al. (2004, 2006, 2007) showed that Bora pulsations usually emerge between 3 and 11 min. Due to the less complex orography with minor influence from the upwind mountains on the incoming flow, Bora has historically been more studied over the Northern Adriatic (e.g. Grisogono and Belušić, 2009; Belušić et al., 2013).

Near surface Bora wind profile agrees well with the power-law and logarithmic-law approximations (Lepri et al., 2014). A decrease in the power-law exponent and aerodynamic surface roughness length, and an increase in friction velocity with increasing Bora wind velocity indicates a rural-like velocity profile for larger wind velocities and urban-like for smaller wind velocities. Due to strong mechanical mixing, Bora proved to be nearly neutrally thermally stratified. While for friction velocity and the power-law exponent the arithmetic mean and the median yield similar values independent on the averaging period, the more robust median proved to be more suitable when determining the aerodynamic surface roughness length.

In this study, detailed high-frequency Bora wind measurements carried out on a meteorological tower close to the city of Split, Croatia, at the Eastern Adriatic Coast, are analyzed to resolve some fundamental properties of the Bora turbulence. A particular focus is on the Bora turbulence intensity, Reynolds shear stress and turbulence length scales.

2. Methodology and the data

Turbulence intensity, as a measure of magnitude of turbulence intensity in the x-, y- and z-directions in height z is respectively defined as provided in Simiu and Scanlan (1996),

$$I_u = \frac{\sqrt{\overline{u'^2(z)}}}{\overline{u}_z} \quad I_v = \frac{\sqrt{\overline{v'^2(z)}}}{\overline{u}_z}, \quad I_w = \frac{\sqrt{\overline{w'^2(z)}}}{\overline{u}_z} \tag{1}$$

by applying the Reynolds decomposition,

$$u(t) = \overline{u} + u'(z), \quad v(t) = \overline{v} + v'(z), \quad w(t) = \overline{w} + w'(z), \tag{2}$$

where $\overline{u}$, $\overline{v}$, $\overline{w}$ are time-averaged mean wind velocities in the longitudinal x-, lateral y- and vertical z-direction respectively; z in subscript is the height, while u', v' and w' are the respective fluctuating wind velocity components.

Turbulent Reynolds shear stress represents a measure for transporting the retarding forces exerted on the wind near the Earth's surface. It is calculated by using the fluctuating velocity correlations $-\rho\overline{u'v'}$, $-\rho\overline{v'w'}$, $-\rho\overline{u'w'}$, where ρ is the air density.

The length scale of turbulence represents a comparative measure of the average size of a wind gust (e.g. Holmes, 2007). The length scales of turbulence in the x-direction related to u', v', w' fluctuations are calculated from the time scale of turbulence using autocorrelation functions and assuming the validity of Taylor's frozen turbulence hypothesis (e.g. ESDU 74030, 1976)

$$T_i = \int_0^{\infty} R_{ii}(\tau)d\tau. \tag{3}$$

Here, R$_{ii}$ represents the autocorrelation function, τ represents incremental time lag and $i = u'$, v', w'. Taylor's hypothesis of frozen turbulence implies that for mean wind speed $\overline{V}_z$ larger than the fluctuating wind velocity component along the x-axis, $u(t)$, the turbulence field can be considered to be frozen in space and convected past a point with the mean wind velocity $\overline{V}_z$. Assuming the validity of Taylor's hypothesis of frozen turbulence, turbulence length scales for $i = u'$, v', w' components measured along the x-axis are defined as (e.g. ESDU 74030, 1976)

$$^{x}L_i = T_i \cdot \overline{V}_z \tag{4}$$

The measurements analyzed in this study were performed on Pometeno brdo, a location in the hinterland of the town of Split, Croatia (Fig 1a). The exact geographical coordinates of this measurement site are 43°36′28.9″N, 16°28′37.4″E with the elevation 618 m above the sea level. The main hill axis extends from North West to South East. The hill is less steep at the leeward side than on the windward side. In the vicinity of the measurement place there are a few crevices and sinkholes several tens of meters deep. The vegetation around the tower consists mostly of brushwood and shrubbery not higher than 2 m. The location is easily accessible by several regional roads.

In the time period between April 2010 and June 2011, Eastern, Northern and vertical wind velocity components as well as the ultrasonic temperature were measured using Windmaster Pro (Gill instruments) ultrasonic anemometers on a 60 m high meteorological tower at three height levels, i.e. 10 m, 20 m and 40 m (Fig. 1b). Each anemometer was mounted on one end of the 2 m long aluminum boom whose other end was fixed to the tower in such a way that the anemometers were facing the main Bora wind direction. The measurements were sampled at the frequency of 5 Hz and collected using Campbell Scientific data logger CR1000, while the whole system was solar powered.

An isolated summertime Bora wind event analyzed in this study lasted from July 24 to 27, 2010, in the overall duration of 62 h. During this particular Bora episode, the wind was long lasting and relatively strong, with mean hourly wind velocities larger than 15 m/s. During