



The critical frequency of the large-scale vortices and the background turbulence in desert area



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ABSTRACT

Based on the analysis of the experimental data obtained in a desert area, this study investigated the variations of the critical frequency discriminating the large-scale vortices and the background turbulence with the distance above the ground surface and the inflow velocity. The results show that the critical frequency decreases with the reciprocal of the wall-normal distance and increases linearly with the inflow velocity. The effect of the surface properties were also considered in this study, and finally the fitting formula of the critical frequency with respect to the wall-normal distance and the inflow velocity was given.

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1. Introduction

It has been widely accepted that the turbulence is characterized not only by randomness, but also by multi-scale coherent structures, i.e. the entire turbulent flow is superimposed by vortices with various scales. Wall turbulence researches have shown that isotropic turbulences exist in the outer region which is dominated by inertial vortices (Obukhov, 1951). In this region, energy is not dissipated but transported from large eddies to viscous vortices, and which is known as background turbulence due to their universality (Chen and Hu, 2003). Recent studies showed that there exists a kind of turbulent coherent structures called very-large-scale motions (VLSMs) extending a large scale in the streamwise direction in high Reynolds number wall-bounded turbulent flows (Kim and Adrian, 1999; Hutchins and Marusic, 2007; Guala et al., 2011), which also are anisotropic low-frequency orderly structures similar as the large-eddy structure (LSMs) (Kovaszny et al., 1970; Offen and Kline, 1974; Brown and Thomas, 1977; Hutchins et al., 2012) found previously. Therefore, the fluctuation u' in natural wind is

actually the superposition of large-scale anisotropic vortices and small isotropic background small vortices (Lykossov and Wamser, 1995; Chen and Hu, 2003), which can be written as:

$$u' = u'_l + u'_s$$

in which u'_l represents velocity contributed by anisotropic eddies, including large-scale coherent structures (LSMs and VLSMs), which are important to the energy, momentum and mass transportation (Robinson, 1991; Balakumar and Adrian, 2007; Serafimovich et al., 2011; Horiguchi et al., 2012), while u'_s is the random term representing small-scale fluctuations, i.e. small homogeneous isotropic eddies (Kolmogorov, 1941). Extracting the information of large-scale anisotropic eddies from turbulence signals is a key task in the study of turbulent coherent structures (Collineau and Brunet, 1993; Lykossov and Wamser, 1995; Chen and Hu, 2003; Zeng et al., 2010). Therefore, the determination of the critical frequency of the large-scale vortices and the isotropic background turbulence is very important for accurately discriminating the characteristic of turbulence structures.

In the existing studies, Collineau and Brunet (1993) measured the wind velocities and temperatures above an

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oak forest area at a height of 16.7 m and 11.05 m using ultrasonic anemometers, and the raw data were smoothed with a sliding window of 0.5 s for removing the small-scale fluctuations before detecting coherent motions. Based on the analysis of the power spectrum of the vertical wind velocities measured at 15 m above an ice surface, Lykossov and Wamser (1995) suggested that the critical frequency be 0.1 Hz. Chen and Hu (2003) pointed out that the critical frequency is about 0.088 Hz based on the analysis of experimental data obtained at 4 m height using the maximum energy method and the Mexi-hat wavelet. While Zeng et al. (2010) indicated that the critical frequency of the isotropic and anisotropic turbulences is about 0.01 Hz through analyzing of the three-dimensional wind velocities obtained by sonic anemometers at 3 heights, i.e., 47 m, 120 m and 280 m respectively above the urban boundary layer. The critical frequency suggested by different researchers have a large discrepancy from each other, for example, the criterions taken by Collineau and Brunet (1993) and Zeng et al. (2010) have a difference of nearly two orders of magnitude. It is noteworthy that the underestimation of the critical frequency will make parts of large-scale coherent structures be missed by the filtering process, and further underestimating the energy and momentum contributions of the large-scale structures. In addition, the effect of other factors (such as height and stream wind velocity) on the critical frequency is still not clear and requires further study.

In this paper, experimental observations are conducted at different heights above a desert surface, and the measurement data is decomposed using the wavelet method to get sub-scale turbulent fluctuating signals and their energy. Then the critical frequencies discriminating the anisotropic large-scale eddies and isotropic small eddies were revealed and their variations with horizontal velocities were obtained by the analysis of the three-dimensional wind velocity energy. In addition, the expression formula of the critical frequency was given by the consideration of the current height and the inflow wind velocity. Section 2 gives the introduction of the field experiment, and Section 3 describes the data selection and pretreatment method, Sections 4 and 5 respectively present the method to obtain the critical frequency of isotropic and anisotropic turbulences and the analysis results and the discussions, and finally Section 6 gives the conclusion.

2. Experimental setup and measurement

The field experimental observation site is located on a flat surface at the edge of the Badain Jaran Desert (38. 37.7° N, 102. 55.2° E), the variations of the surface topography were less than 1 m within 1 km and less than 2 m within 4 km, the kinetic roughness length was approximately 8.12×10^{-4} m, and the main wind direction was from the northwest. Measuring instruments were placed on a 50-m-high weather observation tower, as shown in Fig. 1, in which the CSAT-3D sonic anemometers produced by the U.S. Campbell company were used for measuring the synchronous near-surface three-dimensional wind velocities at different heights (Druihet and Durand, 1997), and the sampling frequency is 50 Hz. Measuring heights were: 0.5 m, 1.0 m, 2.0 m, 8.0 m, 16.0 m, 32.0 m and 47.0 m. In order to avoid the effect of the tower wake, the ultrasonic anemometer probe is set to point to the northwest direction (the tower surface is toward the north), so as to



Fig. 1. No. 3 meteorological tower located at the southeast edge of the Badain Jaran Desert and the local topography near the tower.

ensure that the probe is pointing toward the inflow direction during dust storms passing through this region.

3. Data selection and pretreatment

Actually, the field observation data are always affected by environmental factors. In order to obtain reliable data for turbulence analysis, data selection and pre-processing process were conducted for the turbulence data in this study, including the atmospheric stability judgment to select out the near neutral stratification data, and the noise exclusion process to exclude 'spikes' in raw data, as well as the wind direction adjustment.

3.1. Atmospheric stability

Atmospheric stability of the surface layer flow is determined by buoyancy $\left(-\frac{g}{T}\frac{w\theta}{T}\right)$ and wind stress $\left(\frac{u_*^2}{kz}\right)$, their ratio gives the Monin–Obukhov stratification parameter:

$$\frac{z}{L} = -\frac{kzg}{Tu_*^3} \frac{\overline{w\theta}}{T}, \quad (1)$$

in which L is the Obukhov length, T is the average temperature at the surface, k is the Karman constant, g is the acceleration of gravity, u_* is the friction velocity and $\overline{w\theta}$ is the kinematic heat flux.

For the observation data occurred at 06:00–18:00 on March 19, 2010, the stability parameter is shown in Fig. 2. It can be found that the parameter $|z/L| < 0.1$ from 6:00 to 10:00 is almost neutral and the effect of the buoyancy can be neglected (Nieuwstadt and Duynkerke, 1996). So the near surface layer is more like a flat-plate canonical turbulent boundary layer.

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