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Original Research Paper

Wavelet packet analysis of particle response to turbulent fluctuation

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ABSTRACT

The fluid–particle synchronous measurements in a boundary layer wind tunnel were conducted to determine the particle concentration response to turbulent velocity fluctuation. Three groups of natural sand samples (diameter of 300–500, 100–125 and 63–80 μm) were employed in the experiments. Consecutive instants of saltating particles were recorded by using a high-speed digital camera at 2000 frames per second and a constant-temperature hot-wire anemometer was used to measure the turbulent fluctuation simultaneously. The particle concentration in the saltation layer was calculated by the dynamic-threshold binarization algorithm. The results confirm that the concentration fluctuation is a fairly typical stochastic process, and the low-frequency variation of particle concentration is closely related to the turbulent fluctuation. Moreover, a method was developed to apply wavelet packet transform to two-phase data analysis from the viewpoint of frequency-domain energy structure. Further analysis shows that the concentration fluctuation is predominant in the low frequency band less than 250 Hz. In addition, the particle concentration response to the turbulent fluctuation is significantly correlated with the particle diameter. For the fine particles (63–80 μm), medium particles (100–125 μm) and coarse particles (300–500 μm), the highest response frequencies of particle concentration variation to the turbulent fluctuation are 60, 40 and 30 Hz, respectively, which demonstrates that an appropriate sampling rate is crucial in saltation measurement. These qualitative and quantitative results are beneficial to understand the fluid–particle interaction mechanism.

1. Introduction

Wind is the essential drive to cause aeolian sand transport and desertization. The blown sand movement is influenced by the magnitude and frequency of wind. Under natural conditions, wind is commonly turbulent and often rapidly fluctuating, giving an inner boundary layer of highly variable properties [1,2]. Complex turbulent flow is inherent to natural aeolian environments. Consequently, almost all kinds of sand-drifting wind account for turbulence with intense fluctuation [3,4]. Turbulent characterization is really important for sediment transport research as instantaneous peaks in velocity components that exceed time-averaged shear velocity above a sand surface may be sufficient to initiate particle entrainment [5,6]. As an instantaneous phenomenon, the startup of a particle is closely related to the instantaneous (turbulent) velocity rather than the mean velocity [7]. In the wind-tunnel experiment by Leenders et al. [8], fairly good correlations between the horizontal wind component and saltation were found, compared to poor correlations between the kinematic stress and saltation. This result is consistent with the conclusion of the field studies conducted by Sterk et al. [4] and Schönfeldt and von Löwis [9]. Consequently, these studies have spurred a move away from the empirical approach of using mean flow properties for analyzing sediment transport toward investigations of high-frequency instantaneous measurements in gas–solid two-phase flow. To determine the frequency requirement of instantaneous measurements, researchers must analyze the fluctuation rule of airflow and saltating sand particles and confirm the response frequency of saltation transport to turbulence. It is an important precondition for realizing the two-phase simultaneous measurement.

Although many laboratory and field results on the response of sand transport to variations in wind velocity have been reported [10–12] and several studies have been directed specifically at the response frequency of saltation transport to airflow [8], considerable uncertainty still remains in existing literatures. Little attention has been devoted to the sampling frequency requirements for the saltation transport measurements. Almost all studies about the response frequency of saltation transport to airflow were derived from the earlier research of Butterfield [13] and Spies et al. [14]. Moreover, the time-domain analysis, including the mass flux ratio between steady and unsteady wind and the cross-correlation

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coefficient between wind velocity and saltating particle, was applied in the above research to evaluate the response frequency of saltation transport to airflow. Because of the intermittency of saltation and the uncertain time lags between the velocity fluctuation and the saltation response, these factors based on time-domain analysis are unable to estimate the response frequency of saltation to wind fluctuation correctly. Hence it is reasonable to doubt the authenticity and applicability of the experimental and numerical results obtained with time-domain analysis. In contrast, Fourier Transform and Wavelet Transform have been employed as frequency-domain analysis tools to analyze measured data in recent years. In particular, Bass has employed Wavelet Transform to analyze the sand transport intensity and the wind speed [15], which is an innovative study in the field of aeolian sediment dynamics.

In this study, we used a high-speed digital camera to acquire image sequence of aeolian sand particle and a thermal anemometer to measure turbulence fluctuation simultaneously. From image sequence, we calculated the instantaneous particle concentration of saltation transport and carried out a frequency-domain analysis of both phases by using wavelet packet analysis. The purpose of this work is to report insights into the particle response to turbulent velocity fluctuation.

2. Experimental methods and instrumentation

2.1. Wind-tunnel setup and boundary-layer simulation

The experiment reported here was performed in a boundary-layer wind-tunnel, as shown in Fig. 1. Dong et al. [16] and Yang et al. [17] carried out some important wind tunnel tests with respect to the particle velocity in blown sand cloud. Their experimental setups were referenced in this study. The blowing sand wind-tunnel had a test section 7.4 m long with cross-sectional dimensions 0.7 m (width) × 0.6 m (height). The spires and roughness elements were installed at the entrance of the test section to simulate a neutral atmospheric boundary layer. Several effects arising from the constraints imposed upon the free development of both the boundary layer and saltation by the limited height (H) and length (x) of small wind-tunnels are apparent. From detailed experiments, Owen and Gillette [18] demonstrated that H must be sufficient to meet the minimum Froude number criterion ($Fr = u_\infty^2/(gH) \leqslant 20$, where u_∞ is the incident free-stream velocity). In addition, a minimum entrance length ($x/H = 5$) and an absolute minimum entrance length ($x/\delta = 25$, where δ is boundary layer height) were suggested by White and Mounla [19] for the establishment of an equilibrium saltation and a constant friction velocity.

As the bed materials, natural sand samples were sieved into three categories: coarse (300–500 μm), medium (100–125 μm) and fine (63–80 μm) grains. The selected sand samples were spread over a sand tray with a dimension of 6 m (length) × 0.5 m (width) and 0.02 m in depth. The sand tray was set at 1.4 m downwind from the start of the test section to establish a fully developed aeolian sand flow. Free-stream wind velocity was measured with a Pitot tube at the entrance of the test section. In order to meet the requirements for Fr, the free-stream wind velocity in the wind-tunnel was less than 11 ms^{-1}. Furthermore, relatively low particle concentration was desired because the particle motion could be distinguished accurately by the image processing below. Then the reference free-steam velocities (U_0) were 5.6, 6.0 and 6.5 ms^{-1} for the fine sand, 6.8, 7.2 and 7.5 ms^{-1} for the medium sand, 9.2, 9.5 and 9.8 ms^{-1} for the coarse sand, respectively.

A Dantec hot-wire anemometry (connected with 55P11 probe) was used to measure the velocity profiles of the simulated oncoming flow at 7, 8 and 9 ms^{-1} (Fig. 2a). The wind profiles within the boundary layer at different velocities accord with the logarithmic law very well (Eq. (1)). The thickness of the boundary layer in the test section is around 0.25 m. The profiles of steamwise turbulence intensity ($T_u = \sqrt{\overline{u'^2}}/U_0 \times 100\%$) are shown in Fig. 2b. The maximum turbulence intensity near the ground surface is around 11%.

$$\frac{\bar{u}(z)}{u_*} = \frac{1}{\kappa}\log\left(\frac{z}{z_0}\right) \tag{1}$$

where $\bar{u}(z)$is the time averaged velocity and a function of the height above the surface z; u_* is the friction speed; κ is von Kármán's universal constant; and z_0 denotes the effective roughness length.

2.2. Simultaneous measurement of wind velocity and particle concentration

In this experiment, the particle concentration and simultaneous wind velocity were measured by a high-speed digital camera and a constant-temperature hot-wire anemometer, respectively (Fig. 1). The main idea is to abstract accurate particle concentration data from raw sand particle image. This work is an extension of classical particle image velocimetry (PIV) and particle tracking velocimetry (PTV) method. Therefore, the setup requirement is the same as that for PTV measurement. A thin cold light sheet (5 mm) illuminated the vertical center-plane of the test section. The depth of the field of the camera lens is slightly bigger than 5 mm. Consecutive particle images were captured at a frame rate of 2000 fps (frames per second) and with an exposure time of 1/3000 s by a high-speed

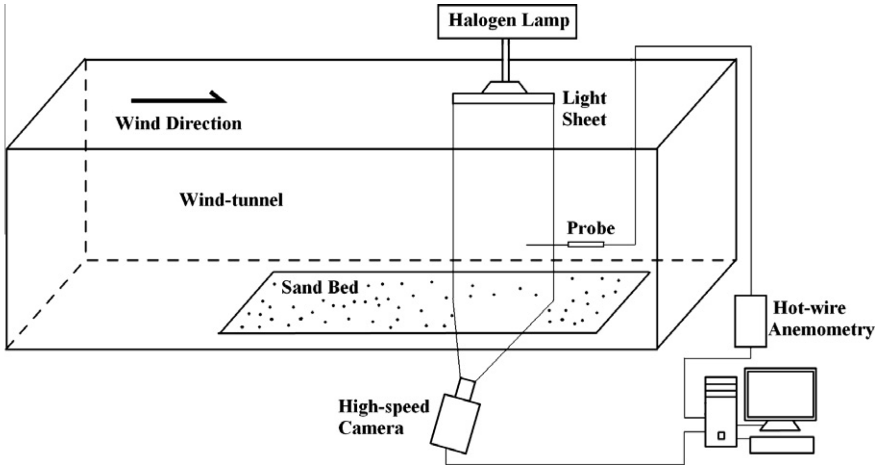

Fig. 1. Test apparatus, particle-motion visualization and air-velocity measurement systems.