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PTV measurement of the spanwise component of aeolian transport in steady state

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ABSTRACT

This paper outlines and validates an improved particle tracking technique (PTV-EPAS) with automated trajectory detection capabilities, and then reports on a novel set of wind tunnel experiments aimed at measuring all three velocity components simultaneously. In order to study a fully adjusted particle cloud, the entire floor of the tunnel was filled with quartz sand (median diameter 550 μm) and the freestream velocity set to 8 ms^{-1} at an elevation of 0.35 m, above the threshold for particle entrainment at 6.5 ms^{-1}. This produced a friction velocity (u^*) of ~0.38 ms^{-1} with $u^*/u^*_t = 1.3$. Measurement of particle trajectories aligned at a spanwise angle (θ) relative to the mean airflow along the center-line of the wind tunnel involved incrementally adjusting the light sheet orientation from 0° to 60°. Three replicate experiments were carried out for each of 13 angles. Only 12% of all 2×10^5 trajectories sampled were strictly aligned with the mean streamwise air flow, while 95% were contained within 45°. As θ increases, a greater proportion of the particle transport consists of slow moving ejecta that ascend from and then impact the bed surface at higher angles than observed for saltation.

1. Introduction

Geomorphologists have long recognized that sand transport by wind is fundamentally three-dimensional (3D) in nature. From micro-scale ripples and flutes etched into ventifact surfaces to large-scale dunes, evidence of this three-dimensionality is preserved in aeolian bedforms that are ubiquitous in dryland regions of the world. Over the last decade or more, considerable effort has been invested in studying the spatial components of the transport process, as for example, in CFD simulation of the airflow structures surrounding such bedforms (e.g. Jackson et al., 2011), and in observation of the horizontal instability of sand streamers associated with vortical structures present in the shearing flow near the bed surface (e.g. Baas and Sherman, 2005).

At the particle scale, however, the perspective remains primarily two-dimensional (2D). While some progress has been made very recently in extending numerical models to a 3D framework (e.g. Yang et al., 2010), no direct measurements have as yet captured simultaneously all three components (x-streamwise, y-spanwise, z-vertical) of the motion of individual sand grains. For the purposes of the present paper, saltation is recognized as the motion of particles in a succession of ballistic jumps that are governed by gravity and fluid drag. Saltators rise sufficiently high into the airflow to attain a forward acceleration by the wind, and upon impact with the surface, may splash other particles (reptators) out of the bed. High speed photography suggests that any given particle may engage in a continuum of transport modes before finally coming to rest on the bed surface (e.g. roll-hop-slide-roll etc.). In general, the existing techniques for observing the flight of discrete sand particles have been restricted to situations involving unrealistically low particle concentrations, as for example, constrained by either low wind speeds near the threshold for entrainment or particle supply limitation imposed by a short fetch length.

The current paper presents an improved particle tracking (PTV) technique; validates it using direct two-dimensional velocity measurements obtained with a Laser Doppler anemometer (LDA); and then, presents a novel investigation of all three particle velocity components (u_x, u_z, u_y) measured simultaneously in wind tunnel experiments wherein the boundary-layer was fully saturated with saltating sand grains. We begin, however, with providing a brief context for this work which reviews the existing technologies and selected measurements of saltation dynamics in 2D.

2. Literature review

2.1. Technologies for the measurement of particle motion

With regard to capturing data on particle motion within a saltation cloud, there are three principal technologies available: Laser

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List of symbols

x	streamwise direction
y	spanwise direction
z	vertical direction (elevation)
r	particle image radius
d	particle diameter
ρ	particle density
m_j	particle mass associated with the jth trajectory
n_k	total number of particle trajectory segments sampled within the kth plane
n_j	total number of particle images (where $i = 1, 2, 3\ldots n_j$) representing the jth trajectory
N	total number of trajectories sampled within the particle cloud; may be segregated into subpopulations of ascending versus descending particles
A	area, e.g. field of view within the light sheet
θ	spanwise angle of the laser light sheet within the xy plane, i.e. at 0° the light sheet is oriented parallel to the airflow
α	angle of the particle's trajectory relative to the bed surface, where α_2 is the impact angle, α_1 the ejection angle and α_{50} the median angle
k	θ slice counter
t	time
U	mean velocity for a given particle along its flight path; equivalent to the instantaneous velocity (U') when the particle is not accelerated
U_{50}	median velocity based on the 50th percentile for a distribution of U
U_h	horizontal velocity of given particle moving parallel to the light sheet
u	velocity component for a given particle, where subscripts x (streamwise), y (spanwise) and z (vertical) indicate the orientation of the vector according to the axis convention shown in Fig. 1
U_∞	Mean wind velocity within the freestream flow
u^*	friction velocity
u^*_t	threshold friction velocity
E	kinetic energy of a given particle (with directional components specified by subscripts x, y or z)
E_k	kinetic energy of all particles sampled within the kth spanwise plane
KE	total kinetic energy sampled over the full range of values for θ

Where specified, subscripts 1 and 2 refer to ascending and descending particles, respectively.

Doppler Anemometry (LDA), Particle Imaging Velocimetry (PIV), and Particle Tracking Velocimetry (PTV). LDA is useful for obtaining population statistics, but does not track individual particles and cannot be used at elevations (z) in close proximity to a sand bed (e.g. $z < 3$ mm) where its photosensor becomes overloaded. PIV can track individual sand particles, but only for sequential high speed images that are paired. The displacement distance measured is in the order of several particle diameters (or less) and generally represents an insignificant fraction of the ballistic trajectory. PIV is unable to perform reliably in flows where there is a high density of sand particles of various sizes.

PTV is widely regarded as the most desirable method for obtaining information about saltation dynamics as this technology can track a particle's displacement and velocity throughout a portion of its ballistic trajectory, in rare instances from ejection through to impact (or a complete 'life cycle'). The basis of this methodology involves a thin (~1.5 mm) laser light sheet aligned parallel to the wind direction (Fig. 1), within which saltating particles are illuminated as they pass through it. Their paths are recorded with a high speed camera oriented perpendicular to the sheet. The image of a given particle in one camera frame is then correlated with other images of the same particle across sequential frames to produce a record of the grain's trajectory during the entire sampling period. From this record, particle velocity, angle and acceleration/deceleration can be calculated during ascending and descending phases. The evolution of PTV has yielded numerous papers that examine selected aspects of saltation at a micro-scale in 2D, as for example, particle spin (White and Shulz, 1977), surface collision (Gordon and McKenna Neuman, 2009), and ejection and impact statistics (Zhang et al., 2014). Similar to LDA and PIV technologies, however, existing PTV systems generally perform poorly in airflows with a high density of particles, especially near the bed surface where the particle concentration is highest (Liu and Dong, 2004) and in saturated or transport limited conditions.

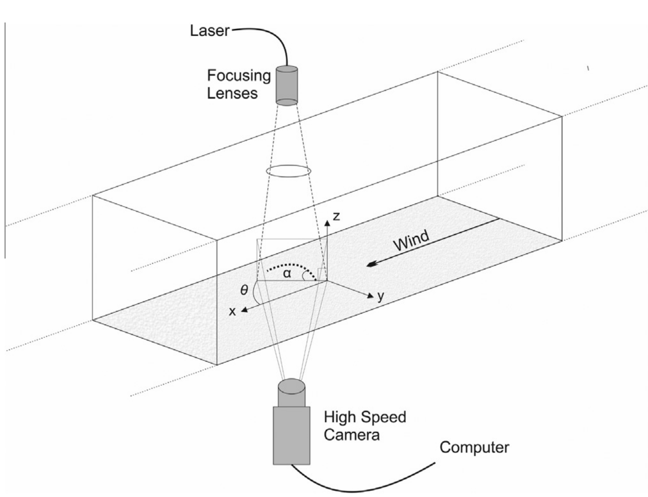

Fig. 1. Schematic of PTV system configuration, along with directional naming conventions.

The earliest PTV experiments were conducted using cine film photography with manual particle identification and tracking (Rice et al., 1995, 1996; White and Shulz, 1977). While the high speed of these film cameras (~3000 fps) was suitable for capturing the full range of particle velocities possible, they could only sample in relatively low saltation densities as typical of those generated by emissions from either a short tray or narrow strip of sand. Manual processing of the images was subjective, and due to its labor intensive nature, not feasible for processing large data sets. Over the last decade, scientific-grade, digital cameras have replaced film in the application of PTV in wind tunnel experiments (Zhang et al., 2007; Wang et al., 2008; Beladjine et al., 2007). The digital images captured by these cameras have the advantage that particles can be automatically detected and assigned spatial coordinates using a range of commercial and customized computer programs. However, the manual assignment of particle images to trajectories remains a constraint in the analysis of very large populations of saltators. A further disadvantage of early digital PTV technology was that cameras delivering both high resolution and a high frame rate were very costly. As a result, they were largely inaccessible to aeolian researchers, so that compromises were often made that affected the quality of the work. Within the last four years, a