Particle Suspension by a Forced Jet Impinging on a mobile Sediment Bed

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Abstract Phase-resolved two-phase flow experiments have been conducted to predict particle suspension and sedimentation within coupled particle-laden flows relevant to rotorcraft brownout conditions. A hybrid PIV/PTV technique has been implemented to improve the performance in high particle concentration regions, while still retaining the flexibility inherent to PTV to resolve multi-valued velocity displacements within a given interrogation region. These processing tools have been optimized and their reliability has been validated using synthetic particle images in a prescribed Taylor-Green vortex flow model. The parametric space of investigation included particle image density, Stokes number and image delay times. Experiments have been conducted to study the interaction of a mobile sediment bed with characteristic flow structures similar to those within a rotor wake. The mobilization conditions and wall-normal flux of particulates by the vortex-wall interaction are reported and are correlated to the local vortex conditions such as proximity to the wall and subsequent decay. The effect of turbulent coupling between the particle and fluid momentum, as based on a point-particle drag law valid for dilute concentrations of particles are examined. The effect of the changing sediment bed profile on sediment erosion rates are also studied.

1. Introduction

Rotorcraft brownout is characterized by dust suspension that is uplifted during rotorcraft operations such as landing, takeoff or hover in a dusty environment. The downwash from the main rotor is strong enough to suspend large amounts of dust and sand and the resulting dust cloud can severely impair pilot’s visibility (Figure 1). One of the main flow features within the rotor wake are intense vortices shed from the tips of the rotor blades, which are advected in the downwash in a helical path and subsequently interact with the ground plane in a turbulent stagnation point flow (Johnson et al 2009). Mitigation of brownout requires a thorough understanding of the particle uplift behavior under brownout conditions as a function of wall/vortex interaction parameters and the initiation mechanisms of events like saltation and scouring. Most sediment suspension models are based upon assumptions of a quasi-equilibrium development, which are inadequate in predicting the suspension process in this highly transient flow. The simplest approach to entrainment modeling is to specify a minimum threshold surface-shear stress to initiate particle motion (Greeley et al 1985, Shao et al 2001), which is done by developing empirical models with idealized sediment particles. The data can be correlated with a functional form dictated by aerodynamic, gravitational, and inter-particle cohesive forces. In general, aeolian particle transport is characterized by three modes: 1) creep, in which particles roll along the boundary; 2) saltation, in which stochastic stress events are sufficient to temporarily lift a particle and initiate a bouncing trajectory but are insufficient to fully suspend the particle; and 3) suspension, where the particles become fully suspended in the turbulent flow (Bagnold 1941). The most common models for saltation are based on very idealized assumptions (Greeley and Iversen 1985) but the highly intermittent and transient nature of

Figure 1. Dust cloud formation around the landing zone under brownout conditions (photo courtesey Leishman 2010)
a rotorcraft wake calls all of these assumptions into question. Very little physical understanding in terms of laboratory scale experiments has been obtained about the mechanisms that govern sediment transport in these types of complex vortical flows. Furthermore, quantification of particle/turbulence interaction is necessary to examine the nature of a potentially strong coupling that may alter vortex dissipation process. Within the dust cloud, there are regions of dilute particle concentrations where the effect of particles on the fluid phase is negligible, but in regions of high mass loading, the suspended particles are capable of altering the carrier phase flow. Higher order interactions in the form of particle-particle collisions and particle-bed collisions must also be taken into account. Simulations of particle-laden flows under dilute conditions have shown that increasing particle loading increases the dissipation rate of fluid kinetic energy while the viscous dissipation in the fluid decreases with increased loading (Boivin et al 1998). When particles of different size classes are involved, preferential concentration of light particles in low-vorticity, high strain-rate regions tend to modify the fluid turbulent field differently when compared to heavier particles (Squires and Eaton 1990). Rapid erosion of sediment, and formation of topographic structures on comparatively short time-scales can potentially alter the boundary conditions from a nominally planar surface in significant ways, leading to a coupling between the evolution of the air and sediment phases. This paper will examine the influence of the mean fluid motion on particle suspension mechanisms and the role of vortex impingement and its subsequent dissipation on wall-normal particle flux. The coherence of the vortex will allow it to focus that energy in a highly localized and violent interaction at the bed surface. Evolution of bed surface over time will be examined to gain insight into locations of high shear on the bed surface along with the formation of topological structures on the surface and their influence on particle motion. The effect of particle volume fraction and slip velocity on the mean and fluctuating drag fields will also be reported.

2. Experimental Setup

Rotorcraft flow is extremely complex; the base flow consists of a downwash jet bounded by coherent tip vortices shed from the ends of each rotor blade. The convection of these vortices leads to a helical shape, which induces a swirl component to the downwash. As a first-order simplification of this more complex flow, the tip vortices can be approximated as vortex rings convecting towards the ground. In the current work, an impinging wall-jet is forced by modulating the flow at the exit plane to produce a highly coherent vortex ring. This is achieved by acoustically forcing the jet within the supply plenum using a loud speaker. While this flow retains the essential features of a coherent vortex embedded within an axisymmetric rotor downwash, a significant difference is that the rings themselves are nominally axisymmetric, and not helical as would be the case in a rotorcraft wake. The objective is to generate repeatable coherent vortex rings superimposed within an axisymmetric stagnation point flow in the presence of a mobile sediment bed.
A 12” 2000W subwoofer has been used as the forcing loudspeaker for the jet. The input voltage signal to the amplifier that controls the subwoofer is a sine wave generated by a function generator. In order to match velocity conditions and circulation strength found in an actual micro-rotor setup, a parametric study has been conducted to establish the operating point for this setup in terms of the mean axial jet velocity, the forcing amplitude and forcing frequency. The conditions for the tests reported here correspond to a mean jet exit velocity of about 4.1 m/s forced at a frequency of 50 Hz. The amplitude of the forcing was adjusted to give velocity fluctuation amplitude of ±4 m/s. The jet was positioned 2 jet nozzle radii ($R_{jet} = 5$ cm) above a 1.5 cm thick sediment bed made of 45-63 micron particles. The Stokes number defined in this case as,

$$St = \frac{\tau_p}{\tau_f},$$

where $\tau_f$ is the characteristic fluid time scale based on the diameter of the vortex core before it interacts with the ground plane (1.2 cm for the current conditions) and the peak-to-peak velocity across the vortex. $\tau_p$ is the Stokes time scale or particle relaxation time, i.e. the time a particle at rest needs to reach $1/e$ of the velocity of the surrounding fluid:

$$\tau_p = \frac{\rho_p}{\rho_f} \frac{d_p^2}{18v}$$

The Stokes number in this case is estimated to be 15.

### 3. Data acquisition and processing

Phase resolved particle imaging velocimetry (PIV) has been used to study the particle dynamics under replicated brownout conditions, giving a measure of the particle concentration, velocity and flux, in conjunction with the corresponding unsteady fluid structure and statistics. A single camera two-phase PIV system has been implemented to quantitatively study this flow field. The light source used in these experiments is a Litron Nano-L PIV laser operating at 532 nm. A 2048x2048 pixel, 14 bit CCD LaVision Imager Pro X4M camera has been used to capture the composite two-phase PIV images. Data has been recorded in two vertical planes; an upstream plane close to where the vortices first make their closest approach to the ground and a downstream plane where the vortex undergoes a rapid three-dimensionalization and dissipation due to its interaction with the ground plane. The field of view in both planes is 5.8cm×5.8cm. The imaging lens used is a Nikon 80-200mm f/2.8D ED AF Zoom Nikkor lens with the aperture open at f/8. The light sheet is about 1.5 mm thick in the field of view. The imaging system is phase locked with the forcing cycle of the speaker and images were recorded at 8 phase angles for each plane. A delay time of 50 µs between the image pairs has been used for the PIV measurement, which was selected as a compromise between the higher-speed fluid motion and the slower suspended particles. This delay time is too large to obtain good interrogations of the fluid motion using a 32×32 interrogation window, so a 64x64 window with 50% overlap was used. Sets of 275 images have been taken in two different vertical planes. Data processing steps involve image processing to separate the carrier and dispersed phase, followed by standard cross-correlation PIV on carrier phase and particle tracking on the dispersed phase.

Once the raw images are acquired, they are processed to separate the phase information and prepare them for interrogation (See Figure 4). The images are first pre-processed to remove reflections from the sediment bed by employing a sliding minimum background subtraction. In order to improve the signal to noise ratio, a uniform minimum intensity threshold is applied. The CCD of the camera saturates at 10000 counts while the noise floor under current illumination conditions is about 20 counts. A minimum threshold of 25 counts is employed to filter the sensor noise. A two-dimensional 3×3 median filter is applied on these images (Kiger and Pan 2000) and it is subtracted from the original image to generate the carrier phase (tracers only) image. The dispersed phase is then identified by first constructing an object identification mask. The template is produced by following the method developed by Khalitov.
and Longmire (2002) that employs two-dimensional intensity gradients along with saturation threshold criteria to identify the location of the dispersed phase particles in the original image, and subsequently extract the size and brightness of each object for use as discriminating criteria. The mask is constructed by applying a Gaussian smoothing function with pixel radius of 1.25 pix to the median filtered image to smooth the edges of the large and bright dispersed phase object images. With this information, a dispersed phase-only image is generated using a mask of identified particle locations and copying the intensity values from the original image onto these identified locations. Sample images with carrier-phase only and dispersed-phase only have been used to identify reliable separation criteria for the current imaging conditions to minimize cross-talk and maximize the number of correctly identified dispersed phase particles (see Figure 5). The tracers are generated from an atomized spray of Bis-2-Ethyl Hexyl Sebacate with a droplet size of about 1-2 microns. Using a size criteria of $A_p > 25$ pixels, and an average brightness criteria of $I_p > 200$ pixels gave a cross-talk error of 2%, while correctly identifying 95% of the dispersed phase particles.

**Figure 4. Phase separation algorithm**

**Figure 5. Size-brightness map of particles of different size classes and tracer particles**
The tracers images are then used the extract fluid velocity field by performing standard cross-correlation using LaVision’s Davis software (version 8.0.5). A multi-pass routine with interrogation window size of 64×64 pixels in the final pass has been used. In order to estimate the velocity field of the dispersed phase, a hybrid PIV/PTV algorithm has been implemented (Keane et al 1995) to improve the performance in high particle concentration regions, while still retaining the flexibility inherent to PTV to resolve multi-valued velocity displacements within a given interrogation window (see Figure 6). A coarse PIV pass is carried out on the dispersed phase images when the number of particle images in an interrogation window (64×64 pixels) is higher than a nominal threshold value to ensure that the cross-correlation information obtained is reliable (at least 5 particles in a single interrogation window). If the particle image concentration is low, this step is skipped and the displacement estimate at this window location is set to zero. The second image sub-window is shifted by this displacement in the appropriate direction and cross-correlation analysis is performed again. This process is repeated until the nearest integer value of the displacement goes to zero but if the value does not converge in three passes, the displacement estimate at that window is set to zero (Cowen et al 1997). At the end of each PIV pass, spurious vectors are identified using a universal outlier detection median test as outlined by Westerweel and Scarano (2005). In the subsequent PTV step, particles in the first image are paired with particles in the second image and the position of particle in the second image is estimated using the mean interpolated displacement (dx) obtained from the PIV pass. A 12×12 sub-window (I) is centered on each particle location and a correlation analysis is done to estimate the final displacement of the particle. In locations with no displacement estimate from PIV, a search window of size 16×16 pixels is used (maximum particle displacements were found to be 5 pixels).

![Figure 6. Hybrid PIV/PTV algorithm](image)

Synthetic images have been used to evaluate and optimize the performance of this algorithm with a parametric space that included particle image density (N_A: fraction of total area occupied by particles), Stokes number, delay time and the sizes of interrogation windows. To capture essential features of this flow field, especially in regions with large velocity gradients and regions where particle paths cross each other, a Taylor-Green vortex flow has been used to generate artificial images. The fluid velocity at location \((x,y)\) is given by
\[ U_f = U_0 \sin \left( \frac{2\pi x}{\lambda} \right) \cos \left( \frac{2\pi y}{\lambda} \right) \]

The non-dimensional equation of motion for the particle assuming Stokes drag, the effective force due to fluid stress generated by the macro-scale flow and added mass is given by

\[
\frac{dv}{dt} = \frac{u[y(t), t] - v}{St} + Ru.\n u + \frac{1}{2} Rv.\n u.
\]

In these equations, \( v(t) \) and \( y(t) \) are particle velocity and location; \( u(x,t) \) is Eulerian flow velocity field, and, for the cellular flow, it is independent of \( t \). \( R \) is the ratio of densities of the fluid to the particle and \( St \) is the Stokes number. Simplifying the above equation and substituting for \( u \) to extract particle velocities \( u \) and \( v \):

\[
\frac{du}{dt} = \frac{\sin x \cos y - u}{St} + R\sin x \cos x + \frac{1}{2} R(\cos x \cos y - v\sin x \sin y)
\]
\[
\frac{dv}{dt} = -\cos x \sin y - v + R\sin y \cos y + \frac{1}{2} (\sin x \sin y - v \cos x \cos y)
\]
\[
\frac{dx}{dt} = u, \quad \frac{dy}{dt} = v
\]

The particle initial velocity was set to zero. An integration time step of 0.01 was used and the time period for a fluid element at non-dimensional spatial coordinates of (1.4, 0.3) to complete a closed orbit from was 12 non-dimensional time units. Depending on the Stokes number and density ratio, the long time particle motion may or may not follow closed orbits (Wang et al 1992). Periodic boundary conditions have been used wherever the particles move out of the flow domain. The image size is 512x512 pixels. The parametric space for this study included variation of particle Stokes number, particle image area ratios and the delay time between the frames. It should be noted that the particle image size remains constant at 1 pixel (radius) and that there is no artificial background noise for all the cases.

Particle image density \( N_A \) is defined as the fraction of the total area occupied by particle images. Particle identification effectiveness is close to 100% for low particle image densities \( N_A \sim 0.001 \) and it decreased to 88% when the image density increased ten fold \( N_A \sim 0.01 \), in large extent due to particle image overlapping (see Figure 7). Most of the snapshots from actual experiments fall between these two extremes. Results indicate that the performance of hybrid algorithm is better at higher particle image densities when compared to standard PTV. Performance efficiency \( (F) \) is defined as a fraction of total vectors calculated that deviate less than 5% from true displacements. For Stokes number of 0.01 and constant delay time, about 4% of calculated displacements were deemed spurious for moderate to high particle image densities. A maximum performance efficiency improvement of about 7% is seen at high particle image densities in estimating particle displacements, when compared to standard PTV for this case (Fig. 8a). However, performance efficiency decreases with increasing Stokes number for all particle image densities as shown in Fig.8b.

\[\text{Figure 7. Particle identification effectiveness with increasing } N_A\]
Results and discussion

Using the regular-spaced carrier phase PIV data, fluid velocity is extracted at each particle location by performing bi-cubic interpolation. These particle-sampled statistics are then binned on a regularly spaced grid to determine Eulerian statistical average quantities. In order to obtain higher spatial resolution in the wall-normal direction for dispersed phase statistics, a rectangular grid with aspect ratio of 4:1 has been used. Statistics have been excluded at cells where the total number of particles is below 15 in order to reduce noise. There is “jitter” in the location and strength of the primary vortex as it interacts with the ground and dissipates. As a result, the primary vortex becomes sufficiently incoherent that triggering off of the original forcing signal no longer has much relevance to the location of the flow structure. Nonetheless, some averaged structure is still visible, and hence is presented. In this section, phase averaged statistics at four phase angles and time-averaged statistics are presented. Shown in Fig. 8 are particle volume fraction contours for the upstream and downstream planes as a percentage of the total number of particles suspended at that particular phase angle. Most of the particle concentration is directed radially outward and the maximum height these particles get suspended is about 0.2 radii above the bed. In the downstream plane, the vortex has more or less dissipated and lost its coherence and the particles are getting suspended to greater heights (0.4 radii above the ground). Shown in the foreground are the mean slip velocity vectors, defined as the mean of difference between instantaneous fluid velocity (interpolated to the particle location) and particle velocity. Slip velocity is one of the parameters that can be used to quantify particle-fluid interaction and fluctuations in the slip velocity play an important role for the drag on the particles that is crucial for the particles to remain in suspension. The slip velocity vectors are directed radially out and towards the ground as the vortex is approaching the bed in the upstream plane. As the vortex dissipates and particles get suspended in the downstream plane, the average slip magnitude becomes 30% larger.

Multiplying the particle volume fraction with the mean vertical particle velocity gives a mean wall-normal flux of the particles as shown in Fig. 9. As the vortex approaches the sediment bed, it creates an adverse pressure gradient in the boundary layer, typically resulting in separation and formation of a secondary counter-rotating vortex (Geiser and Kiger 2011). It should be noted that the negative vortex cannot be directly seen in the fluid streamlines due to the large concentration of sediment particles present. The particle motion, however, is consistent with the presence of negative vorticity. At the point of closest approach, large velocity gradient causes a high shear region resulting in the ejection of sediment particles as seen by the increase in vertical flux. There is a pocket of recirculation at \( r/R=2.3 \) with a negative wall-normal flux indicating that the ejected particles are moving towards the sediment bed enhancing saltation phenomenon. The steady state settling velocity of these particles assuming
Stokes drag is about 0.15 m/s and the mean downward velocity in the region of negative flux is 0.2 m/s which indicates that the negative vorticity, even though not directly visible, has its effect on the suspended particles (see streamlines in Fig. 9). As the vortex dissipates and reaches the downstream plane, the positive flux becomes dominant, and results in large amounts of sediment getting uplifted. It is important to note that the vortex by now has become highly incoherent and phase averaged quantities would be dominated by a periodicity of the vortex or “jitter” induced fluctuations.

Figure 8. Particle volume fraction (percentage) with slip velocity vector field in the foreground
Instantaneous bed profiles are extracted as a function of time as shown in Fig. 11. From these, one can see the formation of a scour hole upstream ($x/R=1.5$) of the point of closest approach ($x/R=2.3$). Although the rapid growth of the scour hole implies a maximum mobilization of the particulates in this region, it does not correspond with any appreciable vertical flux (as shown in Fig. 9) indicating a large phase delay. This is also supported by the fact that large pockets of vertical flux (Fig. 9) are seen further
downstream ($x/R>3.2$). The lowest point in the valley on the stoss side moves in the direction of the flow as time progresses, which is a common phenomenon seen in evolution of sand dunes (Bagnold 1941). The mean erosion rate or the cumulative erosion over time is defined as the total amount of sediment eroded per unit time in the current field of view centered around the first scour valley. The instantaneous erosion rate is defined as the amount of sediment eroded at different instants of time per unit time. These are shown in Fig. 12a and it suggests that the mean erosion rate decreases rapidly initially but then stabilizes and decreases slowly. The instantaneous rate however peaks after a period of time before decreasing and it is probably a result of the vortex interacting with the bed at a critical angle causing high shear along the bed surface, resulting in rapid erosion; however further studies are necessary to confirm this hypothesis. Denudation rate, defined as the rate at which the bed height is changing, is estimated from these profiles (Figure 12b). It has been observed that it is highest at $x/R$ of about 1.6 for this particular case, which is just upstream of the point of impact of the vortex on the sediment bed. Even though large numbers of particles are ejected upstream of the point of impact, they get deposited close to the crest of the denudation, hence the denudation rate is lower at the point of closest approach of the vortex.

From point-particle drag law for dilute concentrations of particles, the overall drag on particles in suspension is proportional to the local particle concentration and the square of slip velocity:

$$D \propto c \frac{\pi d^2}{4} \frac{1}{2} \rho \left( \Delta u^2 \right)$$

where $c$ is the local particle concentration, $\Delta u$ is the slip velocity, $d$ is the particle diameter and $\rho$ is fluid density. Expanding the right hand side of the drag equation into mean and fluctuating components will result in,

$$D \propto \hat{c} \Delta u \bar{u} + \hat{c} \Delta u \bar{u}^2 + c \Delta u \bar{u} + c \Delta u \bar{u}$$

where $\hat{c}$ is the mean particle volume fraction, $c'$ is the fluctuating component of the volume fraction. Estimation of fluctuations in particle volume fraction requires converged time average statistics and hence the last two terms are not reported here. The first two terms are highlighted in Figures 13a and 13b, which are related to the turbulent coupling between the particle and fluid momentum. The mean drag component is dispersed into the upwash region of the flow and reaches a maximum as a large positive flux of particles gets ejected from the surface in the upstream plane. In the downstream plane, slip velocity contributes greatly to the mean drag component. The fluctuating component is highest along the bed surface indicating large transient variations in particle concentrations and slip velocities near the point of impingement in the upstream plane.
Figure 13. (a) Contours of mean drag (b) Contours of fluctuating drag
Conclusions

Detailed dual phase PIV measurements of a forced impinging jet on a mobile sediment bed have been studied with the goal of understanding the process of particle mobilization and sediment suspension. Simultaneous velocity measurements of the fluid and dispersed phase in two vertical planes were analyzed to examine the role of vortex interaction and its subsequent breakdown on sediment transport process. The results show a predominantly radial scouring of sediment particles, which eventually get entrained, by the vortex into suspension near the point of closest approach. There is a region of negative vorticity downstream of the point of impingement due to flow separation that results in negative particle flux. Deposition of these suspended particles downstream is confirmed by examination of the evolution of bed surface profiles over time. These profiles indicate that the cumulative and instantaneous erosion rates are highest when the bed is flat and it decreases with time as a scour valley forms just upstream of the point of impingement. Mean and fluctuating particle-fluid drag components were estimated and it was found that the mean drag component is dispersed into the upwash region of the flow and reaches a maximum as a large positive flux of particles gets ejected from the surface in the upstream plane. Conversely, the fluctuating drag component is highest along the bed surface indicating large transient variations in particle concentrations and slip velocities near the point of impingement in the upstream plane.

References