Vortex ring breakdown induced by topographic forcing

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Abstract. Detailed measurements of the vortex breakdown within a strongly forced impinging jet are presented, with the goal of studying the effects of a small topographic disturbance on the breakdown and turbulence structure. This work is related to an ongoing effort to understand the dynamics of sediment suspension within a landing rotorcraft where a mobile boundary is subject to rapid erosion and deposition. The current work compares the results of a uniform surface to that of a small radial fence placed upstream of the vortex impingement location. The result is a dramatic increase in the coherence of the three-dimensional looping exhibited by the secondary vortex, leading to a more organized and strongly perturbed mean flow. Specifically, a triple decomposition of the velocity fluctuations indicates a very intense periodic stress in the vicinity of the impingement site, followed by a significant decay. Conversely, the random component of the fluctuating stresses gradually increases to modest levels as the coherent contributions decrease, eventually becoming greater than the coherent stress. The fence produces a bifurcation in the flow through the perturbation of the secondary vortex, which in turn creates a high- and low-speed streak on either side of the fence. The subsequent dynamics leads to increased fluctuating stress in the high-speed region, and a dramatically lower stress in the low-speed region, favoring preferential erosion on either side of the topographic disturbance.

1. Introduction

The problem of rotorcraft brownout is created when a helicopter lands in a dusty environment: the rotorcraft downwash wake is sufficiently intense to suspend large amounts of sand and silt, drastically impairing pilot visibility (Figure 1). These flows are characterized by intense vortices shed from the tips of the rotor blades, which are advected in the downwash and subsequently interact with the ground-plane in a turbulent stagnation point flow. The sediment suspension process is thought to be dominated by the local dynamics of these large-scale features. This poses a significant problem for accurate prediction of the flow as most sediment suspension models are based upon assumptions of a quasi-equilibrium development. In addition, the 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 strong coupling between the evolution of the air and sediment phases.

In order to improve our understanding of the coupled two-phase fluid mechanics of how these flow entrain sediment, the current work examines a simpler prototype model flow. A forced impinging jet facility has been constructed that is capable of generating repeatable coherent vortex rings superimposed within a axisymmetric stagnation point flow, either with an immobile solid surface, or in the presence of a mobile sediment bed. While this flow lacks
the complexity of a real rotorcraft wake, it retains the leading order elements of an intense vortex impinging on a planar surface in the presence of a turbulent wall jet. Extensive prior work on this prototypical flow has characterized the complete interaction between a traveling vortex ring and a wall positioned normal to the ring’s direction of motion. Inviscid theory predicts a vortex ring created by a forced jet will move hyperbolically toward a ground plane (Milne-Thompson 1962). A vortex ring approaching the ground plane will locally increase the velocity in the ground boundary layer, creating an adverse pressure gradient radially outward of the impinging vortex (Elliot et al. 1983). The adverse pressure gradient causes separation just downstream, forming a counter-rotating secondary vortex ring (Magarvey and McLatchy 1964). The primary and newly formed secondary vortex act together as a dipole lifting off of the ground as a “vortex rebound.” The rebound creates structures of wall normal velocity crucial in uplifting and bombarding sediment particles. The secondary vortex ring is shown to wrap around its primary counterpart while forming azimuthally unstable waves (Walker et al. 1987). These waves are stretched by the primary vortex, causing the secondary vortex to form “leg” structures under the primary ring (Luton and Ragab 1997). The instability and complexity of this wrapping event drives the need for 3-Dimensional studies of vortex-ground interactions.

The novelty of the current work originates with the addition of a topographic disturbance to the otherwise planar surface to assess its influence on the flow evolution. Qualitative imaging of flows with mobile sediment beds show that radial sediment streaks are quickly formed as the vortex ring interacts with the mobile grains, leading to the appearance of a radial “fence” like structure (Figure 2). Although the origin of these streaks is also of interest, the current work is focused on understanding how the presence of a radial “fence” influences the development of the secondary vortex, the primary vortex breakdown, and the subsequent turbulent flow downstream of this event. Although two-phase experiments are also being conducted, we concentrate here on the influence caused by the change in the planar wall boundary condition, and not the suspended sediment. Towards this end, single-phase flows are examined with a smooth flat boundary as a baseline condition, and are subsequently compared to those generated by placing a small artificial radial “fence” (1 × 1 × 15 mm) just upstream of the point where the primary vortex makes its closest approach.
2. Experimental Facility and Procedure

The impinging jet facility consists of an axisymmetric supply plenum, turbulence management section, and contoured nozzle (exit radius $R = 0.05$ m), suspended in a small test chamber ($0.91 \times 0.91 \times 1.82$ m), as shown in Figure 3. The mean centerline exit velocity was set to 11.5 m/s. The jet was forced by a loudspeaker fit to the plenum inlet, which modulated the exit flow and organizes the free shear layer at the outlet into coherent vortex rings. The ground plane was positioned at a stand-off distance of 10 cm below the nozzle outlet. Vortex ring size and development is greatly influenced by the forcing amplitude and frequency of the signal sent to the loudspeaker (Aydemir et al 2010). Care was taken to ensure the forcing conditions of the jet produced strong, stable vortices. One-half period of a sine wave pulse with smoothed end transitions (half-peak duration of 6.66 ms) was sent to the speaker at a pulse repetition frequency of 2 Hz. The forcing amplitude was selected to provide a peak-to-mean velocity amplitude of 0.73. Higher forcing amplitudes and lower forcing frequencies caused instabilities and coherent trailing vortex tails to develop in the flow.

Data was acquired using particle image velocimetry, PIV. Single and stereoscopic camera set-ups were utilized to retrieve 2 and 3 component velocity fields, with 2-component data acquired using a $1376 \times 1040$ pixel Lavision Imager Intense and 3-component data with a $2048 \times 2048$ pixel LaVision Imager Pro4M. For the 2-component single camera measurements, an 85mm lens was used with a 0.5 meter working distance to obtain a field of view of approximately $4.1 \times 4.7$ cm ($\Delta r \times \Delta z$). This field of view was processed with $32 \times 32$ pixel windows with no overlap giving a vector spacing of 0.67 mm. A $10 \times 10$ cm field of view was obtained for the 3-component fields using two 105 mm lenses separated by 60 degrees with the sensor 1 meter away from the imaging plane. To correct for the angle of the camera sensor, Scheimpflug mounts were attached to both cameras and calibrated for the imaging set-up. The 3-component images were processed with $32 \times 32$ pixel windows and no overlap giving a vector spacing of 1.473 mm. A laser sheet (approximately 1 mm wide) was employed in different locations to quantify vortex formation, trajectory, and ground interaction (Figure 4). A vertical laser sheet was used to illuminate fields of view between the jet and the ground plane for 2-component fields. For 3-component fields, 9 horizontal image planes spaced 1mm apart were imaged to create a volumetric data set, although only a single image plane located at $z = +1$ mm from the surface of the plate is discussed here. Image phase was specified via a triggering signal supplied from the forcing amplifier to the imaging hardware. The delay between each phase angle of the complete forcing
cycle was 1.4 ms.

3. Results and Discussion

Since the motivation of the current work is to understand the vortex/wall interaction in the context of sediment transport, emphasis will be placed on examining the near-wall flow dynamics and the resulting unsteady stresses. Given the strong and highly-coherent nature of the forced vortex, the flow will be quantified by using the standard triple decomposition of the flow variables (Hussein and Reynolds, 1971):

$$f(r, \phi, z, t) = \overline{f}(r, \phi, z) + \tilde{f}(r, \phi, z, t/T) + f'(r, \phi, z, t)$$

(1)

where $\overline{}$ is the time-average, $\tilde{}$ is the periodic component of the signal (with period $T = 0.5$ s referenced to the plenum forcing in the current work), and $'$ is the stochastic fluctuating component.

The external flow will first be examined briefly via the vertical plane measurements to provide general details of the vortex generation, its repeatability, and its approach to the wall surface. This will be followed by a detailed examination of the flow in a plane parallel to the wall, situated within the thin boundary layer at a location of $z/R = 0.02$.

3.1. Vertical plane, without radial fence

Ensembles of 50 images acquired at the same relative time delay were captured in vertical plane with a sufficient field of view to reveal the formation, propagation, and breakdown of the forced vortex. A total of 67 phase angles were recorded to cover the span of the speaker forcing period. The resulting quantitative evolution of the primary vortex is shown in Figures 5 and 6. Following a transient roll-up of the shear layer near the nozzle exit ($z/R = 2$), the vortex follows the expected hyperbolic trajectory, until reaching its point of closest approach to the wall at approximately $r/R = 2$. At this point, the secondary vortex is generated and subsequently induced into the outer flow. Note that the secondary vortex was not observed to orbit strongly around the primary vortex, unlike in typical impinging vortex ring studies (Orlandi & Verzicco, 1993), owing to the continual flow from the stagnating jet. Following interaction with the wall, the primary vortex begins to degenerate and quickly becomes three-dimensional.

The circulation of the primary vortex (Figure 6, obtained as the average of individual circulation measurements within the ensemble) quickly saturates near the nozzle, and then
Figure 7. Time-averaged radial velocity, $\bar{v}_r$, for a plane $z/R = 0.02$. The case with no radial fence is shown on the left, and the case with a radial fence is shown on the right (location indicated by grey stripe). The region used to calculate the azimuthal averages is shown by the black sector, and to sectional lines, AA and BB are indicated.

Gradually increases to a peak value $\Gamma = 0.74 \text{ m}^2/\text{s}$ while it continues to scavenge vorticity from the shear layer from the upstream and downstream sides while propagating towards the wall. This gives a Reynolds number for the vortex ring of $Re = \Gamma/\nu \approx 49,000$. Upon final approach, the ring begins to quickly lose circulation, until it exits the imaging region at $r/R = 2.6$ with a mean value of $\Gamma = 0.1 \text{ m}^2/\text{s}$.

3.2. Horizontal plane, within and without radial fence
Stereo PIV data was acquired from a plane located at $z/R = 0.02$, which spanned a region from $2 < x/R < 3.8$ and $-1 < y/R < 1$. Ensembles of 50 image pairs for each phase were acquired, with 37 phase angles resolved before, during, and after the impact with the wall. Note that this covers a span of approximately 0.05 s (or 10% of the cycle) between forced vortices, which will bias the statistics. Although not ideal, this would be representative of a case where the primary vortex is formed at a more frequent interval.

The dramatic influence of the fence can be seen in the time-averaged radial velocity field (Figure 7). For the case with no fence, the flow is nominally axisymmetric, albeit with notable azimuthal variation for $r/R > 3$ due to possible low-frequency variation in the outer flow and the relatively small number of samples. For the case with the fence, the radial velocity exhibits a sharp bifurcation downstream of the primary vortex impingement location ($r/R = 2$), leading to two high-speed streaks (marked BB in the figure) straddling on either side of a low-speed valley (line AA). The included angle between the two high-speed streaks is approximately 35°. Beyond $r/R \approx 3.4$ the mean radial velocity field appears quite similar to the case with no fence.

The cause of these streaks becomes apparent when examining the ensemble-averaged velocity fields and the various moments of the periodic and stochastic fluctuations (Figure 8). Examining first the ensemble-averaged wall-normal velocity, $\bar{v}_z$, it can be seen that the fence perturbs the secondary vortex to form a kink that bumps up into the higher speed primary vortex ($t - t_0 = 2.8 \text{ ms}$), as noted in previous literature on impacting vortex rings. This vorticity forms a dipole with an induced velocity that opposes the mean flow, and hence forms the low speed region noted...
Figure 8. Ensemble-averages of the wall-normal velocity and periodic and stochastic Reynolds stresses in a plane parallel to the wall at $z/R = 0.02$. Note that the color scale for the stress components is stretched quadratically to capture the large variation. The location of the primary (solid line) and secondary (dashed line) vortex core is indicated by the corresponding black line. Contours of the wall-normal vorticity component $\omega_z$ are shown at several positive (red) and negative (blue) thresholds ($\pm 1000$ to $\pm 4000$ 1/s in 1000 1/s increments).
Figure 9. Azimuthal- and time-averaged radial profiles. Mean velocity profiles (left), radial normal stresses (center) and wall-normal Reynolds stresses (right). Grey lines indicate the sectional profiles in the low-speed (AA) wake, and the high-speed (BB) streak noted in the mean radial velocity shown in Figure 7.

in Figure 7. The strength of the vorticity is significant, with peak values approaching 50% of the primary vortex. Note also that the vorticity contours shown in Figure 8 indicate only the wall-normal vorticity magnitude, and therefore represents a fraction of the three-dimensional magnitude (unless the vortex is oriented perpendicular to the page, which is not known from the current data).

By \( t - t_o = 5.4 \) ms, the original pair of vortices have spawned new opposite-signed partners and are beginning to move away from the radial plane where they originated. This is consistent with additional kinks developing in the secondary vortex and being pulled down into the lower speed region beneath primary vortex. Similar shear-instability-driven vortex dynamics have been noted in other systems, such as in free-shear mixing layers (Choi & Lasheras, 1989), where smaller vortices are reoriented and intensified as they are pulled in a straining field between larger neighbors. Also visible at this instance, is the strong upwelling between the primary and secondary vortex cores, flanked on either edge by significant but slightly weaker downwash on the opposite sides of the respective vortex cores.

As the primary vortex moves past \( r/R = 2.4 \) (\( t - t_o = 9.8 \) ms), the strength of the upwash starts to dramatically decrease and the dipole pairs of the secondary vortex continue to separate further from their plane of origin. Finally, by \( t - t_o = 23.8 \) ms, the vortex signature has decreased to less than 20% of its original value, and has lost nearly all azimuthal variation visible in the prior three instances shown.

The rest of Figure 8 follows the evolution of the Reynolds normal \( \overline{v_r v_r} \) and \( \overline{v_r v_z} \) and shear \( \overline{v_r' v_r'} \) stress contributions. As to be expected in a highly organized coherent structure, the periodic fluctuation stresses dominate their stochastic counterparts by a magnitude of 5 to 10 times in the early stages of development. Once the primary vortex begins to lose coherence (\( t - t_o = 9.8 \) ms), however, the stresses become more comparable in magnitude, with the stochastic contributions becoming dominant by the time the remnants of the vortex pass \( r/R > 3 \). This is consistent with a rapid decrease in the observed strength of the primary and secondary vortex, which can be diminished by both random “jitter” in the vortex location as well as increased dissipation due to the violent breakdown that is initiated by the three-dimensionalization of
the primary and secondary vortex. A full accounting of the turbulent kinetic energy budget is needed to ascertain the relative contributions to this trend, which is beyond the scope of the current limited data set. From Figure 8 it is also evident that the radial normal stresses are dominant over their shear stresses throughout the region by a factor of 2 to 3.

Finally, in regard to the stress magnitudes along the valley and streak regions (section AA and BB, respectively), Figure 8 indicates that the periodic component of both the normal and shear stresses should see higher magnitudes in the high-speed streak region (section BB) in comparison to the valley (section AA) due to the similarly elongated streaks of elevated stress in this region. The stochastic stress, on the other hand, maintains a comparable radial width across all of the azimuthal locations, keeping comparable contributions to the net stress when comparing the valley and the high-speed streak regions.

The above measurements can then be further distilled to their contributions to the time-averaged equations (Figure 9), which presents time-averaged sections of fence conditions, as well as time- and azimuthally-averaged data for both cases. The trends are muted relative to the ensemble-averaged results above, but maintain similar behavior. Specifically, the coherent stresses in the high-speed region (BB) are approximately 2 to 4 times what is observed in the valley (AA) over the range from $2.2 < r/R < 2.7$, after which they collapse to the azimuthal average values. For the normal stress, $\tilde{v}_r \tilde{v}_r$, the increase and decrease are roughly equal relative to the azimuthal average, while for the shear stress $\tilde{v}_r \tilde{v}_z$, the high-speed streak region remains similar to the azimuthal average, with the valley experiencing a significant decrease.

In comparing the fence, and no-fence conditions, the stochastic contributions to the stress are similar to each other, and the only significant differences result from variations in the periodic stresses (Figure 9). Examining the periodic stresses in more detail, the azimuthally-averaged periodic normal stress ($\tilde{v}_r \tilde{v}_r$) is elevated by roughly 50% within the region from $2.3 < r/R < 3.0$. This is a significant enough of an increase that even the reduced values in low-speed region (section AA) exceed the typical no-fence case magnitudes. In contrast to this, the peak of the wall-normal shear stress component, $\tilde{v}_r \tilde{v}_z$, is diminished in no-fence conditions, although a delay in the radial position of where the peak forms brings them to comparable values once $r/R > 2.3$.

### 3.3. Implications for sediment transport

For the mobilization and suspension of sediment into a turbulent boundary layer, the fluctuating stress components are typically the dominant contributors in comparison to pressure gradients and mean viscous shear stress. In the case of a coherent vortex within an impinging jet flow, it is perhaps of little surprise that the periodic stress components completely dominate over the stochastic components in the region of wall contact: the vortex is significantly larger and stronger than those that naturally formed in an unforced jet, and its coherence allow it to focus that energy in a highly localized and violent interaction at the walls surface. As seen in figure 8, the average of these stresses at their peak can be 10 to 20 times greater than the stochastic component. The non-linear nature of this interaction rapidly destroys the coherence of the vortex and increases the stochastic fluctuations, all while the total stress is continually decreasing as the system relaxes towards the state of an axisymmetric turbulent wall jet. In this context, the greatest mobilization of sediment would be expected to occur within this narrow region ($2 < r/R < 2.5$), initiating saltation of larger sizes that will settle back further downstream when the fluctuation levels are no longer sufficient to keep the particles mobilized, while finer grains will be rapidly dispersed and carrier further out into the flow. The anecdotal image shown in Figure 2 is consistent with this, showing an erosion pattern with a dominant ring-shaped scour pattern in this region, in addition to the small radial furrows.

For the conditions where a small bump is present on the surface of a mobile bed, the measurements indicate that the erosion of the sediment would likely preferentially enhance the
disturbance when under conditions close to sediment uplift threshold values: the significantly higher stresses formed in the high-speed streak region would continue to erode the particles at a higher rate on either side of the disturbance, while the reduced stress level immediately downstream of the disturbance would favor a reduced erosion rate, thus preserving a higher bed elevation. If one is well beyond the suspension threshold, then the erosion rate in both regions may be sufficiently rapid to preserve any significant azimuthal topography.

4. Conclusions

Detailed measurements of the vortex breakdown within a strongly forced impinging jet have been presented, with the goal of studying the effects of a small topographic disturbance on the breakdown and turbulence structure. Three-component velocity measurements acquired from a horizontal plane very close to the surface were analyzed using a triple-decomposition to examine the role of the coherent forced vortex in the presence of the radial fence. The results show a dramatic increase in the coherence of the three-dimensional looping exhibited by the secondary vortex, leading to a more organized and strongly perturbed mean flow. Specifically, a triple decomposition of the velocity fluctuations indicates a very intense periodic stress in the vicinity of the impingement site, followed by a significant decay. Conversely, the random component of the fluctuating stresses gradually increase to modest levels as the coherent contributions decrease, eventually becoming comparable to greater than the coherent stress. The fence produces a bifurcation in the flow through the perturbation of the secondary vortex, which in turn creates a high- and low-speed streak on either side of the fence. The subsequent dynamics leads to increased fluctuating stress in the high-speed region, and a dramatically lower stress in the low-speed region, favoring preferential erosion on either side of the topographic disturbance.

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