Assessing Rotor Downwash and Surface Particle Mobilization on Titan for NASA's Dragonfly

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Introduction

NASA's New Frontiers mission, Dragonfly,[1,2] will use a rotorcraft lander to leap-frog across Titan's equatorial sand dunes. These flights involve repeated takeoff, landing, and hover maneuvers, keeping the vehicle close to the surface. Near the ground, rotor downwash interacts strongly with the terrain, altering thrust distribution and increasing wall shear stresses (WSS). This phenomenon, known as ground effect, can enhance lift by increasing pressure beneath the rotor but also generates complex, recirculating flows.

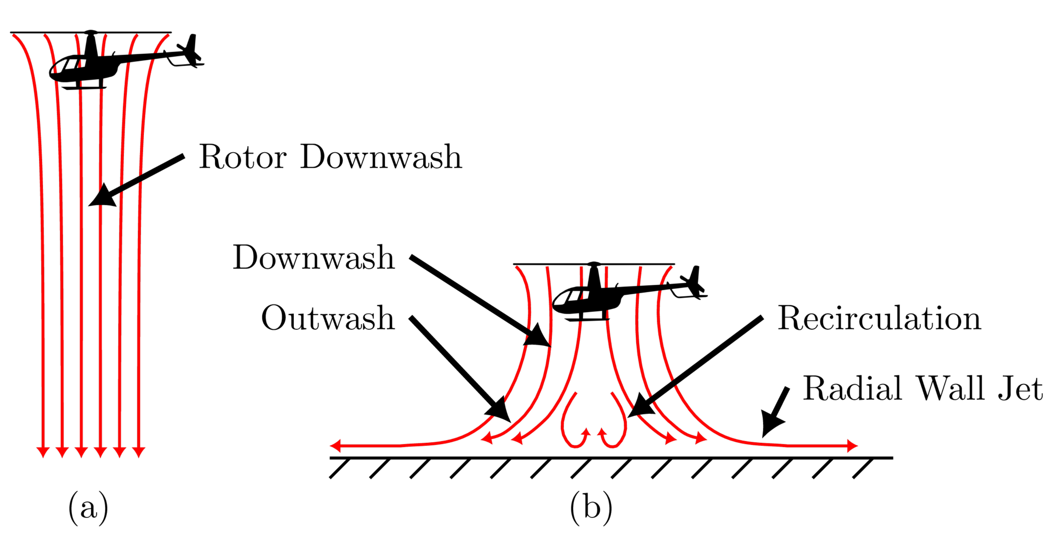

Figure 1. Rotor wake: (a) OGE; (b) IGE.

These complex flows can disturb loose material on Titan's terrain. Particle mobilization begins when wind exceeds a threshold, lowered by Titan's dense atmosphere and low gravity. Particles roll, hop, or lift into suspension, forming transient dust clouds that reduce sensor visibility and risk damage to exposed components[3].

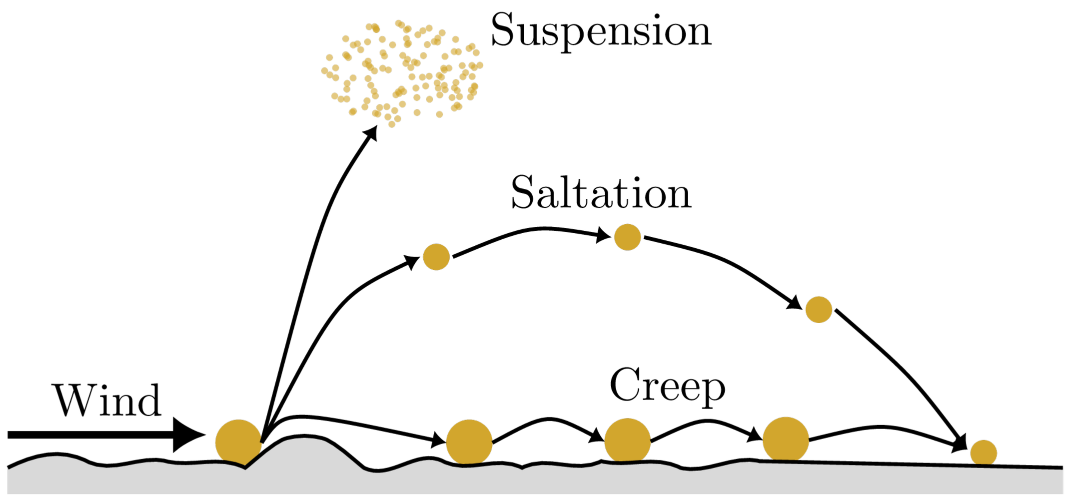

Figure 2. Modes of aeolian particle transport.

Goals:

1. Assess rotorcraft aerodynamic performance and unsteady load behavior IGE and OGE on Titan.
2. Quantify wall shear stress distributions and identify potential for particle mobilization and dust cloud formation.
3. Evaluate the effect of Dragonfly's opposing cant rotor configuration on mitigating ground effect interactions and reducing dust risks.

Methodology

Ground effect was evaluated by analyzing a normalized thrust $\left(\frac{T}{T_{h/D\to\infty}}\right)$ and normalized height h/D, where T is the rotor thrust, $T_{h/D\to\infty}$ is the rotor thrust far from the ground, h is the height of the rotor above the ground, and D is the rotor diameter.

Actuator disk and line models were employed to predict rotor wake structures in a full-vehicle configuration. These approaches enable a significantly lighter computational setup for descent case analyses. Isolated blade resolved simulations are being performed to validate these methods by comparing the resulting wall shear stress distributions on the ground.

Results: Ground Effect

Figure 4 below presents the ground effect trends for both rotor configurations across varying heights plotted alongside established correlations and experimental data.[4,5,6]

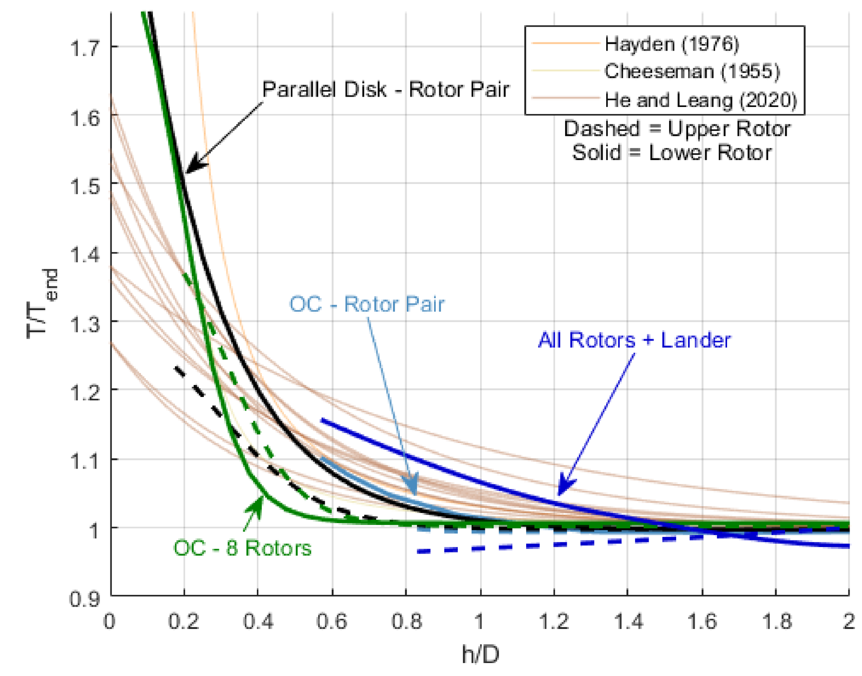

Figure 4. Ground effect comparisons for various configurations.

Key Observations:

1. General trends in the CFD agree with correlations and experiments.
2. The OC configuration demonstrates a reduction in ground effect interactions by $h/D = 0.7$.
3. The general trend of lower vs. upper rotor ground effect appears similar for the OC configuration (indicating the lower rotor out-performs the upper).

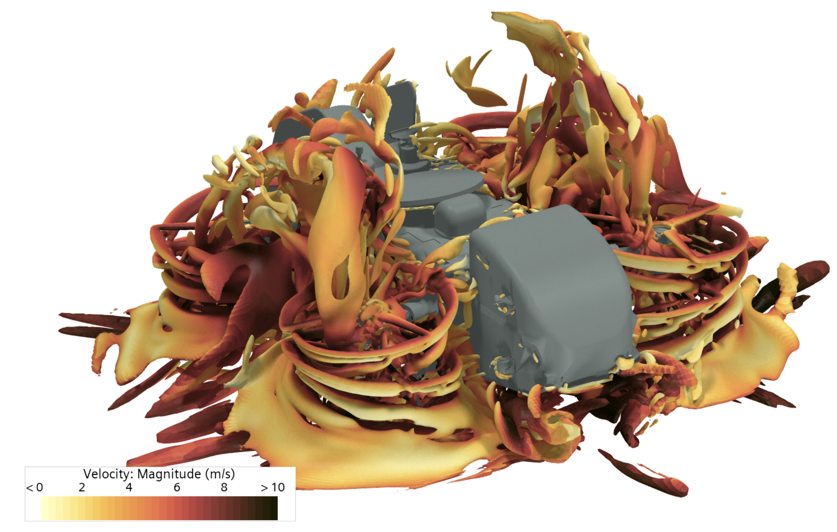

Figure 5. Isosurfaces of q-criterion colored by velocity magnitude.

Figure 5 highlights coherent vortices shed from each rotor and capture the interaction between the counter-rotating pairs.

Results: Dust Modeling

Figure 6 shows a preliminary dust transport model linking rotor downwash to dust cloud formation during takeoff and landing. The simulation reveals structured patterns of vertical linear upwellings and lateral spreading in the 8-rotor system. The contours provide early insight into where visibility degradation, optical contamination, or instrument interference might be severe.

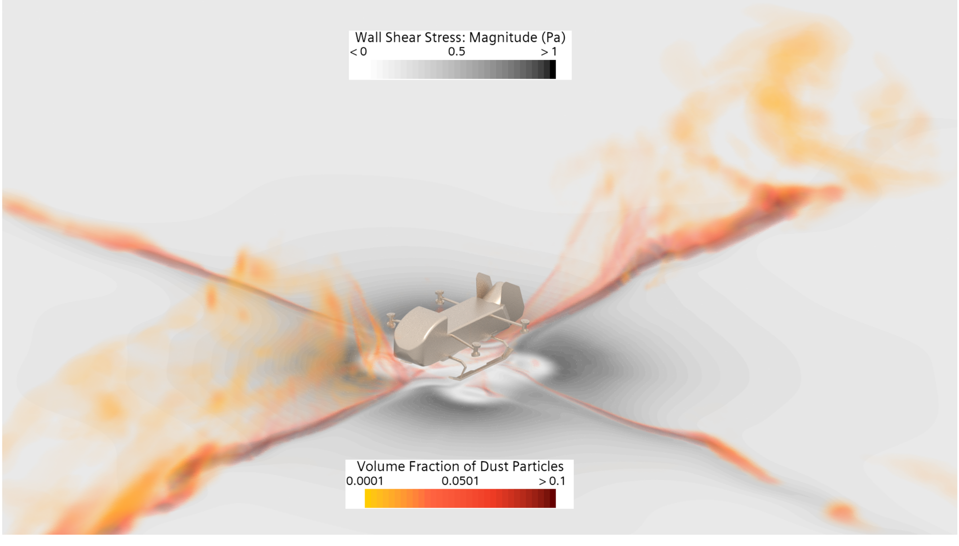

Figure 6. Modeled dust kickup (take-off/landing).

Key Observations:

1. Measurements can be taken along these linear paths during takeoff and landing.
2. Key regions for erosion concerns can be identified to inform material design.
3. Optimal sensor placement can be determined.

Results: Blade Resolved

Figures 7 and 8 show a preliminary blade resolved simulation of the isolated rotor hovering in ground-effect. These new set of simulations will enable the comparison of the wall shear stress induced on the ground with the virtual disk and actuator line models to verify its accuracy for full vehicle analysis.

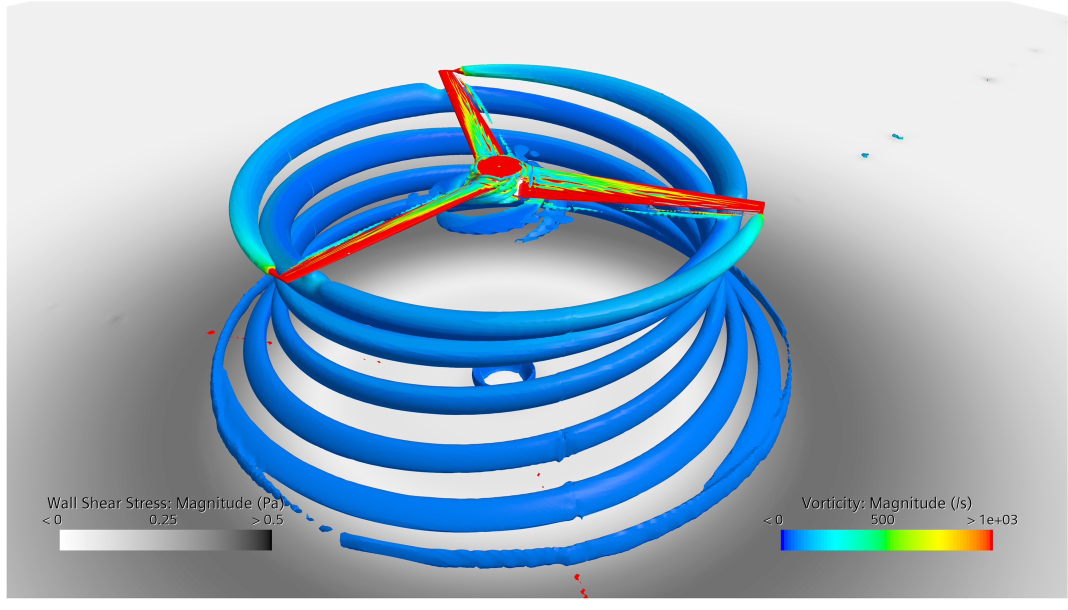

Figure 7. Q-criterion and wall shear stress of a single rotor hovering at 700 RPM with ground clearance of 0.7 m.

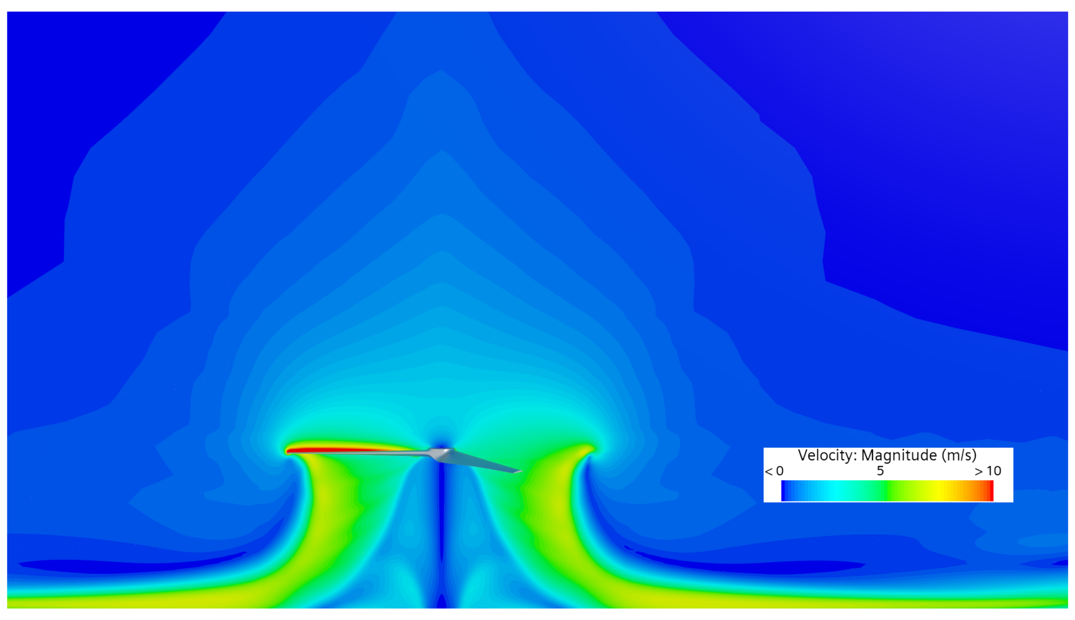

Figure 8. Averaged Velocity Contour of a single rotor hovering at 700 RPM with ground clearance of 0.7 m.

Key Observations:

1. Initial results indicate that the induced wall shear stress on the ground agrees well with predictions from the virtual blade model; however, deviations may arise when a canted rotor pair configuration is introduced.
2. Blade resolved simulations reveal a strong flow impingement that spreads laterally. As the rotor descends, this intensified ground interaction amplifies wall shear stress on the ground, significantly impacting particle mobilization.

Conclusion

CFD simulations reveal that Dragonfly's rotor downwash in ground effect enhances lift but increases unsteady loads and dust mobilization. The OC configuration delays ground effect interactions and reduces shear stress. Future work will refine dust models and enhance rotor-fuselage interaction simulations for Titan's conditions.

References

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