Safety analysis of Rotors In Ground Effect

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The flowfields generated by rotors operating In Ground Effect (IGE) are complex and unsteady. Furthermore, the result of the interaction between the rotor wake and the ground plane is the transition of the rotor induced flow from vertical (downwash) to radial flow (outwash). This can be a source of risk for ground personnel, equipment and landscape due to the forces generated by high outflow velocities. Furthermore, in case of brownout or whiteout the flowfield can interact with a loose sediment bed, uplifting particles all around the aircraft. The prediction of the outwash is fundamental for the safety of IGE operations [1]. The downwash typically affects activities directly under the aircraft (like search and rescue operations), while the outwash impacts the surrounding environment like people, equipment and structures during landing and take-off. Rotor wakes IGE may affect also other aircraft operating nearby, different works tried to define 'safe zone' for wake encounters [2]. As already mentioned, brownout and whiteout may occur when a rotorcraft is operating in ground proximity and are due to the interaction of the rotor wake with particles of a loose sediment bed such as sand, snow etc. This interaction can eventually uplift particles from the ground into the air flow. When operating in desert areas or in snowy regions, the number of particles entrained can become extremely high creating a cloud around the rotorcraft. The main effect of this cloud of particles moving around the aircraft is on the pilot's visual environment. The rotorcraft structure and equipment can also be affected. The lack of pilot visibility defines brownout and whiteout as Degraded Visual Environment (DVE) conditions. In recent years, efforts have been made to help pilots in these situations, developing sensors and advanced cockpit displays. Dynamic rollover and collisions with objects are common accidents due to the low visibility [3]. Due to the complexity of these phenomena and the risks for safety that they may generate, rotor wakes IGE have been studied using different approaches, from full-scale aircraft tests [1], to small-scale isolated rotors [4]. In the first case, during experiments, it is possible to replicate the real operational conditions the aircraft may encounter in an operational scenario. In general, however, measurement techniques used in full-scale experiments, lack high resolution, and cannot provide a detailed view of the phenomena involved. On the other hand, small-scaled studies can be performed in a laboratory, within a controlled environment using high resolution measuring techniques, such as Particle Imagine Velocimetry (PIV). However, due to the limited size of the rotors, Reynolds number is lower with respect to the full-scale case, leading to some differences in the flowfield behaviour.

In the present work, computational fluid dynamics (CFD) is used to perform safety analysis of rotors operating IGE. Initially, experimental data of a micro-rotor, operating IGE at different heights above the ground, are compared with CFD results. The test case simulated was experimentally investigated at the University of Maryland by Lee et al. [4]. The flowfield data was obtained by 2D PIV, while the rotor performance was measured by a micro mass balance. Once the CFD analysis was complete, the outflows produced were used for safety analyses in terms of forces produced on ground personnel, properly scaled, using the PAXman model, and presence of particle. CFD validation has been performed for a small rotor with low Reynolds number and to obtain realistic full-scale scenarios, scaling factors have been applied to velocities using three different aircraft, categorized in terms of weight. Scaling factors take into account differences in terms of thrust and tip velocity, however, they cannot take into account effects of different Reynolds numbers between small-scale and full-scale. A common reference value for outflow velocities is the hover induced velocity λ_i, it can be computed as $\lambda_i = \sqrt{C_T/2}$. The scaling factor applied to velocities to take into account the difference of thrust coefficient between the small and full-scale, has been computed as: $\sqrt{C_T^{fs}/C_T^{ss}}$. The full-scale rotor is considered starting from the aircraft disk-loading to compute the proper full-scale aircraft thrust coefficient.

The PAXman model was originally developed for military personnel, and it is used to compute wind forces on people operating in proximity to the rotor. It is based on the projection of a crouching 6ft tall person immersed in the outwash.[1] To be comparable with the small rotor size, the PAXman height is scaled with the rotor radius for three different full-scale rotors. Their technical data are listed in table 1. According to [1] the caution zone starts when the force acting on the PAXman is more than 80 lbf (335 N), and the hazard zone is defined after 115 lbf (510 N). The distribution of the force over the body is calculated as: $f_{paxman} = \frac{1}{2}\rho_{air} V_{rad}^2 x$ where ρ_{air} is density of the air, V_{rad}

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is the radial velocity and x is the horizontal coordinate of the PAXman model. The total force is the integral of the distribution of the force over the height of the PAXman model: $F_{paxman} = \int_{h_{PAXman}} f_{paxman} dz$. Using this model it is possible to calculate the force distribution acting on a human body at a specific radial station.

The particle pick-up has been studied, using the Shao et al. [5] expression, which is based on Bangold model [6]. Following this approach, the friction velocity on the ground u^* have to be compared with a defined threshold, computed starting from the particle and fluid proprieties. The friction velocity on the ground has been computed using $u^* = \sqrt{\tau_w / \rho_{air}}$ (τ_w is the wall shear stress and ρ_{air} is the density of the fluid), while the threshold friction velocity (u_t^*) suggested by the model can be computed $u_t^* = \sqrt{A(\rho/\rho_{air} g d_p + \beta/\rho_{air} d_p)}$, where A and β are constant, ρ/ρ_{air} is the ration between the particle and the flow density, d_p is the particle diameter, and finally g is the acceleration of gravity. A particle can be considered uplifted if $u^* > u_t^*$. The uplift phenomenon has been investigated comparing results given by the different rotor heights above the ground. Once that the particles are uplifted, it is possible to seed properly the ground, and track the particles in the flowfield. Fig 2 shows the uplift results for the rotor at h/R=0.5, results show how the majority of particles is uplifted in proximity of the rotor, between 1R and 2R.

An in-house particle tracking tool has been developed for this work. The equation of motion for every particle is solved at every timestep. Particle tracking using realistic ballistics has been conducted, for hovering rotors at different heights above ground. The motion equation for the particles is Newton's 2nd law, considering aerodynamic and gravity forces: $m_p \mathbf{a}_p = 0.5 \rho_{air} S C_D (\mathbf{u}_f - \mathbf{u}_p) ||(\mathbf{u}_f - \mathbf{u}_p)|| - m_p \mathbf{g}$, where $\mathbf{a}_p$ and $\mathbf{u}_p$ are the acceleration and the velocity of particle, while m_p, S and C_D are particle proprieties (mass, frontal area and drag coefficient in turn), ρ_{air} is air density and finally, $\mathbf{g}$ is gravity constant. Fig 3 shows the particle positions, after a period of 100 revolutions, for two different scaling factors (heavy and light weight helicopters). Results show a common behaviour, with a branch of particles pushed away from the rotor, and another reingested by the rotor. A more detailed analysis, shows that the scaling factors have an influence on the final particles position, due to the different outflow strength. In general, heavy weight helicopters have a stronger outflow, which drives particles at higher values of h/R and r/R.

In general, results show that the distance criterion based on the PAXman forces, can be deducted by the outflow analysis. Outflow forces after a distance of 3R are low for the three helicopter cases considered. Furthermore, for the lightest helicopter, there is no risk due to the outflow forces for ground personnel. It is clear that the wake encounter criterion of 3D can be adopted for ground operation, if the presence of particles on the ground can be excluded. A more detailed analysis shows that the forces obtained for the medium and heavy aircraft are high enough to be dangerous for personnel and equipment in an area between 1R and 2R away from the rotor, but after 3R it is safer. Particle tracking results show that particles can reach large distances away the rotor, exceed the limit of 3D. In general, it seems that the FAA limit for wake encounters cannot guarantee safety in presence of particles on the ground. It is also clear that to define a particle free zone , it is necessary to take into account the rotor operating conditions due to the strongly influence of the disk loading and in general of the size of the aircraft on the particle paths. Particle paths are also strong influenced by the position of the rotor with respect to the ground.

CFD results demonstrate fairly good agreement with the experimental data in terms of rotor performance and flowfield, even with some differences in the outflow predictions for larger radial stations. The differences can be important if used to evaluate safety regions near the helicopter.

In this work, scaling factors are applied to a small-scale rotor to obtain full-scale PAXman forces and particle paths, however, the full physics of the brownout cannot be simulated in this way, due to the several factors. In general, the Reynolds number that is involved in the small and the full-scale scenario is dissimilar, leading to differences in the uplift phenomena and to a different evolution of the brownout cloud. This study can be a starting point for evaluating safe operational zones around a helicopter.

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Bibliography

[1] Silva, M., and Riser, R., "CH-47D tandem rotor outwash survey," *AHS 67th Annual Forum,Virginia Beach, Virginia, USA,*, 2011, p. 221.

[2] Garcia-Dorado, I., Aliaga, D. G., Bhalachandran, S., Schmid, P., and Niyogi, D., “Fast Weather Simulation for Inverse Procedural Design of 3D Urban Models,” *ACM Transactions on Graphics (TOG)*, Vol. 36, No. 2, 2017, p. 21.

[3] D’Andrea, A., and Scorcelletti, F., “Enhanced numerical simulations of helicopter landing maneuvers in brownout conditions,” *American Helicopter Society International 66th Annual Forum Proceedings, Phoenix, AZ*, 2010.

[4] Lee, T. E., Leishman, J. G., and Ramasamy, M., “Fluid dynamics of interacting blade tip vortices with a ground plane,” *Journal of the American Helicopter Society*, Vol. 55, No. 2, 2010, pp. 22005–22005.

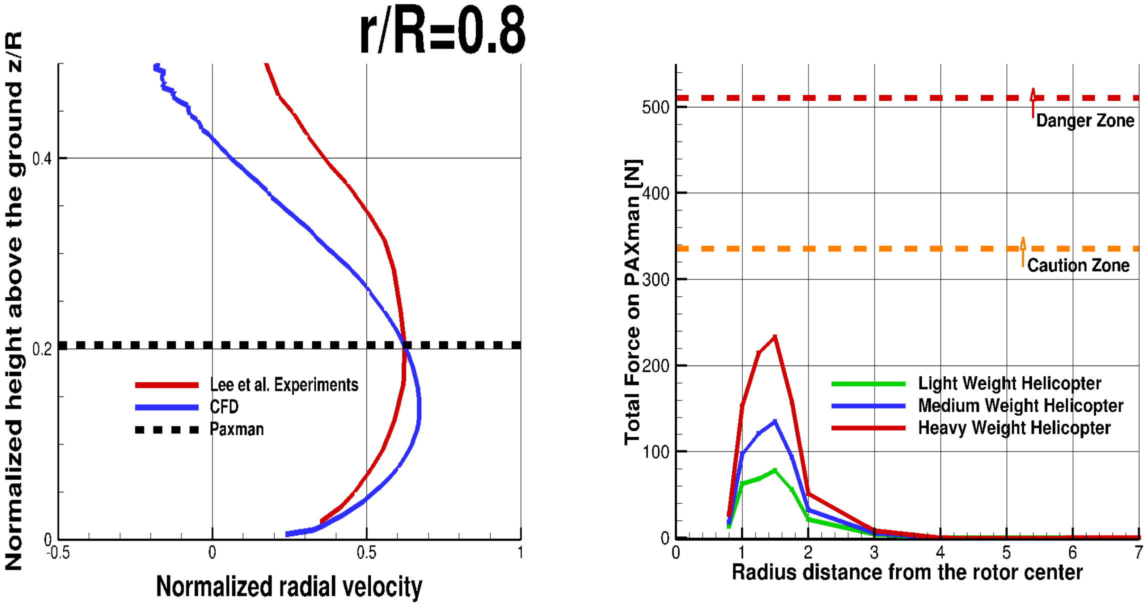
[5] Shao, Y., and Lu, H., “A simple expression for wind erosion threshold friction velocity,” *Journal of Geophysical Research: Atmospheres*, Vol. 105, No. D17, 2000, pp. 22437–22443.

[6] Bagnold, R., “The physics of blown sand and desert dunes. London: Methuen.” 1941.

[7] “Vertipedia,” `https://vertipedia.vtol.org/`, Accessed: 23-09-2019.

Category	Disk Loading (N/m^2)	V_{tip} (m/s)	C_T
Light	280	220	0.0094
Medium	420	220	0.0141
Heavy	560	220	0.0189

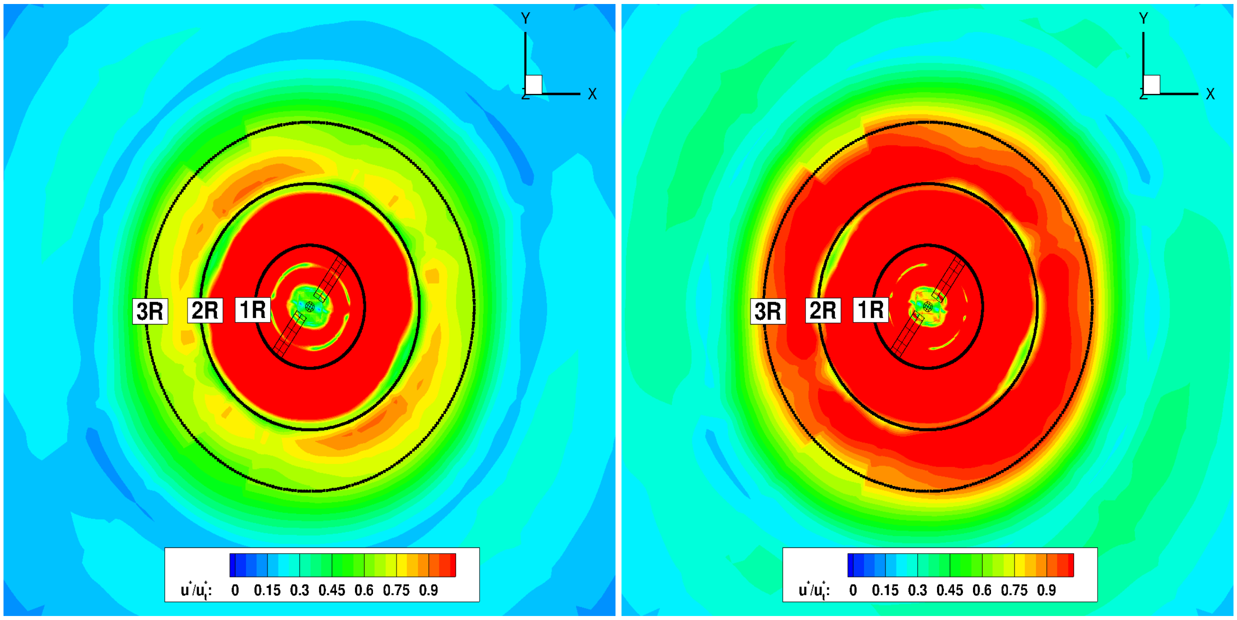
Table 1 Helicopters technical data [7]



(a) V_{rad}/v_i at r/R=0.8

(b) Total radial force F_{PAXman} for the three helicopters

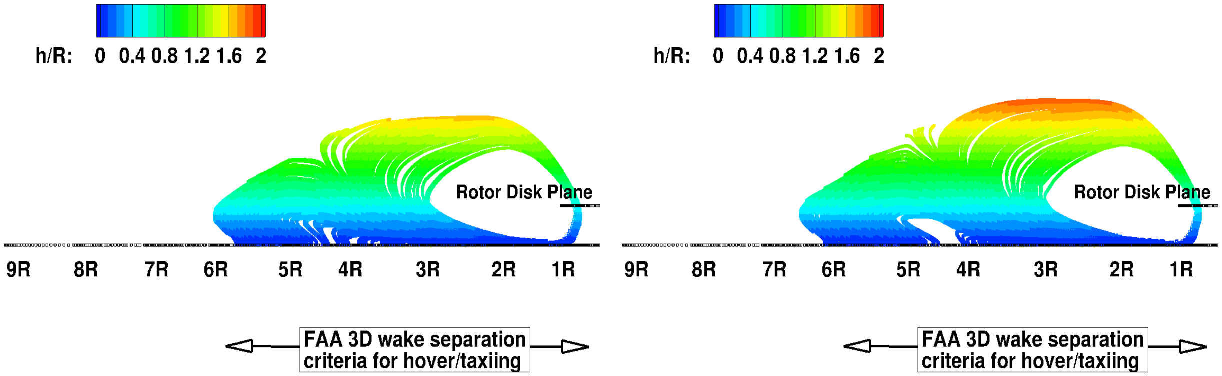
Fig. 1 Experimental and CFD time-averaged outflow velocity profiles and PAXman model forces calculated using the employed micro-rotor, scaled to V_{tip} m/s. The micro rotor rotor was operating at $\theta_{75} = 12deg$, $Re_{tip} = 35000$, $M_{tip} = 0.08$, $h/R = 0.5$ and $C_T = 0.035$.



(a) Uplift for h/R=0.5, Light scale helicopter

(b) Uplift for h/R=0.5, Heavy scale helicopter

Fig. 2 Uplift results for rotor at different heights above the ground and different scaling factors. The rotor was operating $\theta_{75} = 12deg$, $Re_{tip} = 35000$ and $M_{tip} = 0.08$. Particle properties: $\rho_p = 2650\ kg/m^3$ and $d_p = 9\mu m$



(a) Particle paths for h/R=0.5, Light scale helicopter

(b) Particle paths for h/R=0.5, Heavy scale helicopter

Fig. 3 Particle paths for rotor at different heights above the ground and different scaling factors. The rotor was operating $\theta_{75} = 12deg$, $Re_{tip} = 35000$ and $M_{tip} = 0.08$. Particle properties: $\rho_p = 2650\ kg/m^3$ and $d_p = 9\mu m$