A NUMERICAL INVESTIGATION OF GROUND EFFECT ON ROTORCRAFT IN THE PRESENCE OF SIDE WALL

Cibin Joseph
Doctoral Student
Aerospace Engineering
Indian Institute of Technology
Chennai, India
cibinjoseph92@gmail.com

Ranjith Mohan
Assistant Professor
Aerospace Engineering
Indian Institute of Technology
Chennai, India
ranjith.m@iitm.ac.in

Abstract

Rotorcraft flying in close proximity to ground are known to generate a larger thrust due to the shed wake being obstructed by the ground. The effect has been well researched and empirical corrections are available in literature. However, studies on the influence of side walls on ground effect is still lacking. Such studies may be applied to full scale rotorcraft hovering near walls, skyscrapers and similar structures, rotor-based UAVs flying in a constrained space and in corrections for wall interference in wind tunnel testing. This work aims to study the influence of a side wall in the presence of ground effect on a lifting rotor using a CFD tool, RotCFD. Rotor thrust and torques were found to be largely unaffected by side wall interference. However, pitching and rolling moments of considerable magnitudes were observed. These appear to be a result of the asymmetry in the flowfield developed from wake recirculation and interference when the rotor is close to the wall and the ground.

NOTATION

A	Rotor disk area
CCW	Counterclockwise
C_T	Thrust Coefficient, $T/\rho A V_{TIP}^2$
C_Q	Torque Coefficient, $Q/(\rho A R V_{TIP}^2)$
C_{M_X}	x-Moment Coeff., $M_X/(\rho A R V_{TIP}^2)$
C_{M_Y}	y-Moment Coeff., $M_Y/(\rho A R V_{TIP}^2)$
IGE	In Ground Effect condition
OGE	Out of Ground Effect condition
R	Rotor radius
V	Velocity
V_h	Inflow velocity in OGE hover
V_{TIP}	Blade tip velocity
W	Wall distance from rotor tip
w	Non-dimensional wall distance, W/R
(X,Y,Z)	Rotor reference frame
H	Elevation from ground level
h	Non-dimensional elevation from ground, H/R

1 INTRODUCTION

Ground effect in rotorcraft occurs when the wake shed by the rotor is obstructed by the ground resulting in a rise in rotor thrust and reduction in inflow velocity across the rotor disk. Prominently affecting rotorcraft in hover, this phenomenon is also observed in forward flight. This aerodynamic interaction between the rotor and the ground has been studied exhaustively over the years and quantified by means of empirical corrections and thrust augmentation factors [1;2;3;4;5]. A few recent experiments using Particle Image Velocimetry(PIV) and pressure sensitive paint measurements aimed at determining the wake and rotor outwash characteristics [6;7;8;9] are noteworthy. However, studies detailing the effect of side walls on rotorcraft in ground effect are still lacking. A closely related development in recent literature is the rotor-obstacle interaction study using Laser Doppler Anemometry(LDA) and Stereoscopic Particle Image Velocimetry (SPIV) [10;11] that was conducted to observe the rotor wake interaction with a cubic obstacle and effects on rotor performance. There are empirical factors present to incorporate the interference of wind tunnel side walls on a rotor placed in the tunnel[12;13], however these are specific to certain wind tunnels/wind tunnel geometries and do not provide an insight into the effects of a combination of ground and a side wall on a hovering rotor.

A few cases where such a study has applications are- rotorcraft hovering close to ground near a building, rotorcraft taking off and landing on a ship deck where the island(the superstructure that houses the command centre) creates an obstruction to the wake, Unmanned Aerial Vehicles(UAVs) and Micro Aerial Vehicles(MAVs) flying through constrained spaces and in experiments on rotorcraft in wind tunnels with side-wall interference.

This paper is an attempt at understanding the influence of side-walls on a rotor hovering in ground effect using computational methods. The study utilizes the capabilities of a commercial software package, RotCFD that models the rotor as a distribution of momentum sources[14;15].

2 METHODOLOGY

Two sets of simulations were performed - a baseline ground effect case without the presence of a side-wall and another in the presence of side-wall. Details on the rotor model used, flow conditions prescribed and case studies performed are provided in this section.

2.1 Rotor Model

The rotor geometry was based on experiments conducted by Knight and Hefner[4;5] on a hovering rotor in ground effect. Of the several cases examined by them, a two-bladed rotor was used here at constant collective pitch. The rotor parameters used in the simulations are provided in Table 1. Blade root and tip surfaces were flat and polars corresponding to an airfoil with a sharp trailing edge was utilized for all blades.

In the plots illustrated in subsequent sections, the elevation H was measured from ground level and the side-wall distance W was measured from the rotor tip to the wall as depicted in Figure 1. For ease of description, in further sections, a positive moment about the X axis is considered a 'roll in' while a negative moment is considered a 'roll away' for the rotor. A positive moment about the Y axis is considered a 'pitch down' while a negative moment is considered a 'pitch up'.

2.2 Flow Solver

The commercial software package RotCFD, used for simulations, is an Integrated Design Environment specific to rotors, capable of simulating a complete rotorcraft and aerodynamic interactions with other aircraft or bodies. Of the various modules provided by RotCFD, this research utilizes RotUNS, the fluid solver module that uses unstructured octree type meshing. The rotor is modelled as a distribution of momentum sources, the strengths of which are determined from flow-field properties, rotor geometry and aerodynamic characteristics of the blade cross-section[16;17;18;19]. The realizable $k-\varepsilon$ turbulence model was used for all simulations.

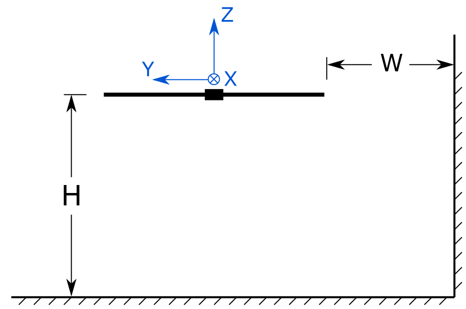


Fig. 1: Schematic of reference frame and distances

Parameter	Metric	English
No. of blades	2	
Airfoil	NACA 0012	
Rotational Velocity	960 rpm	
Direction of rotation	CCW when viewed from above	
Aspect Ratio	15	
Solidity	0.0427	
Collective pitch	8 deg	
Radius	0.7620 m	2.500 ft
Chord	0.0508 m	2.000 in
Flap hinge offset	0.0254 m	1.000 in
Root cutout radius	0.1270 m	5.000 in

Table 1: Rotor Characteristics

For simulating the ground and side-wall cases, the boundary of the domain was assigned a viscous wall boundary condition. The fluid properties were set to ambient conditions as shown in Table 2.

Convergence was ensured by monitoring thrust and torque coefficients alongside residuals of the fluid equations. On an average, the simulations required to be run to around 200 rotor revolutions for convergence with an azimuthal resolution of 5^o per timestep (iteration).

2.3 Grid System

Two sets of grids were used for simulating ground effect- *without* side-wall(baseline case) and *with* side-wall. Unstructured 3D grids with tetrahedral elements, generated using an in-built octree-type method[20] were used for all

Parameter	Metric	English
Tip Mach number	0.23	
Tip Reynolds number	2.78×10^5	
Static Density	1.28 kg/m^3	0.0025 $slug/ft^3$
Static Pressure	103351.5 bar	1.48×10^{-4} psi
Static Temperature	279.65 K	503.37^oR
Dynamic Viscosity	1.8×10^{-5} kg/ms	3.8×10^{-7} slug/fts

Table 2: Flow Properties

simulations. Grid refinement was provided at the rotor and in the region the wake impinges the ground. The domain extents chosen and a representative cross-section of the grids used are shown in Figures 2 and 3.

3 RESULTS AND DISCUSSION

3.1 Baseline Case - Ground Effect without Side-Walls

3.1.1 Thrust Augmentation

Conventionally, the thrust augmentation gained from operating rotorcraft within ground effect is illustrated using a plot of the rotor thrust normalized with the OGE thrust against the non-dimensional rotor elevation. It is easier to determine the boundaries of ground effect from such a plot[6]. Figure 4 illustrates thrust augmentation plotted alongside experimental results by Knight[5]. The results of the simulation were found to match within permissible limits even though a slight amount of scatter is present, likely due to the turbulent wake not being fully resolved.

3.1.2 Torque Variation

The obtained torque from RotCFD was also compared with experimental results in a similar manner to that described in the previous section and were found to match well as shown in Figure 5. The torque does not show considerable variation with a change in rotor elevation.

3.2 Ground Effect with Side wall

Ground effect cases were run for various combinations of elevations and side wall distances as illustrated in Table 3. Although all cases showed a convergence for rotor thrust and torque, some cases exhibited oscillations in rolling and pitching moments. The variations in magnitudes of these moments from the mean value were in extreme cases around 10% of the rotor torque in OGE. With frequencies two orders lower than the rotor rotational frequency, these appear to be a result of fluctuations in the wake rather than numerical issues since the residuals amply satisfied required convergence criteria. Similar oscillations were also observed in the cases without side wall but of negligibly small magnitudes (1% of rotor torque in OGE). In a few cases the oscillations also appear to damp out over a large time span. A focussed investigation is however required to establish a credible cause for this behaviour. In Table 3 cases that exhibited these oscillations in rotor moments are marked with 'O' and cases that were partially stopped or faced other technical issues are marked 'X'.

h \ w	0.250	0.375	0.500	0.625
0.375		O	X	O
0.500		O	O	X
0.625	O		X	
0.750				
1.000			X	

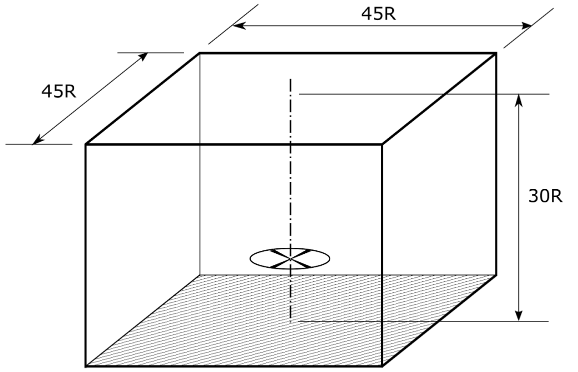
Table 3: Summary of side wall cases simulated

3.2.1 Thrust Variation

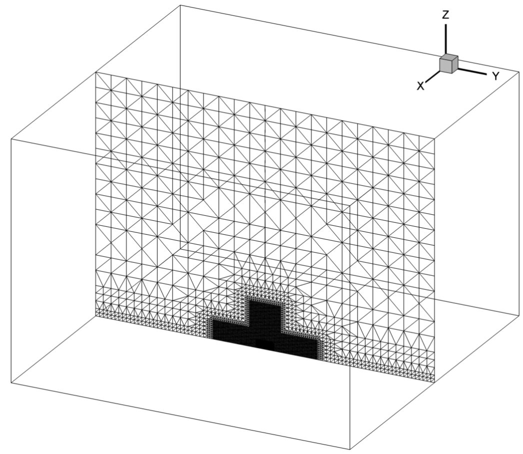
Figure 6a illustrates the variation in the thrust augmentation factor for the the rotor at various elevations with varying wall distances. Clearly, the thrust does not vary significantly with side wall distance. The effect of the ground on thrust remains unchanged even when the rotor is as close as 0.25R to the side wall.

3.2.2 Torque Variation

Shown in Figure 6b is the variation in torque of the rotor in ground effect with side wall distance. The torque, like thrust also appears to not be significantly affected by the side wall.

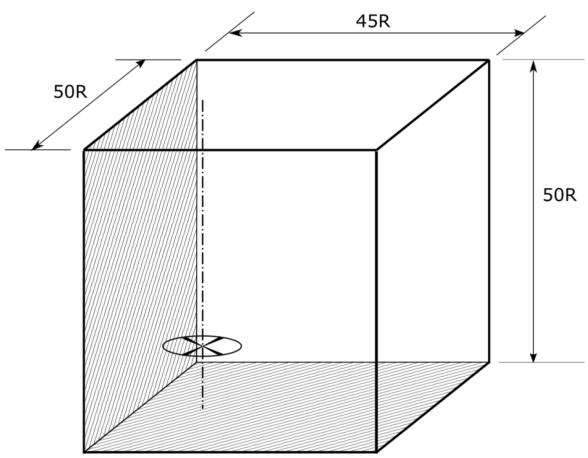


(a) Domain extents

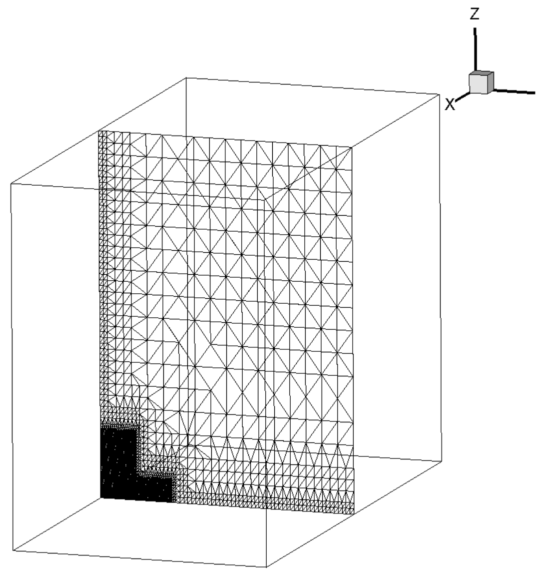


(b) Representative mesh

Fig. 2: Ground Effect: Domain extents and representative mesh



(a) Domain extents



(b) Representative mesh

Fig. 3: Ground Effect with side-wall: Domain extents and representative mesh

3.2.3 Rotor Moments and Inflow distribution

As described in Table 3 a few cases appeared to exhibit oscillations in rotor moments. In those cases, the plots presented here were computed using mean values of the moments.

Figure 7a shows the effect of the side wall distance on the rotor rolling moment (moment along x-axis) at various elevations while the rotor is in ground effect. A general trend for the rotor to roll away from the wall as the rotor moves closer to it, was observed. For a constant wall distance, the moment also appears to increase as the rotor elevation decreases and reaches a considerable magnitude of 30% of OGE rotor torque.

This behaviour was found to be consistent with the inflow distribution across the rotor. The rotor at two representative elevations are shown in Figure 8 with negative radius signifying the negative Y-direction. All velocities are normalized with inflow velocity computed from momentum

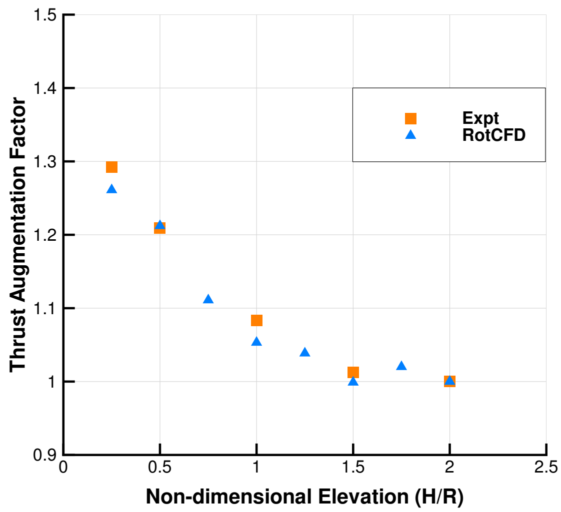


Fig. 4: Predicted thrust augmentation (IGE Thrust/OGE Thrust) due to ground effect from RotCFD compared with experiments by Knight[5]

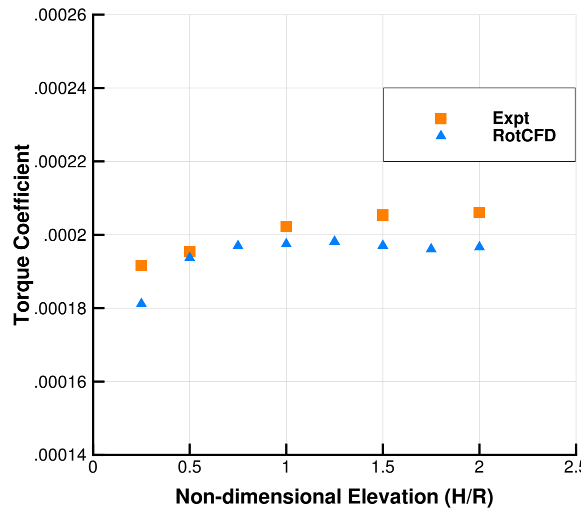


Fig. 5: Predicted torque coefficient of rotor in ground effect from RotCFD compared with experiments by Knight[5]

theory using the OGE thrust, as $R\Omega\sqrt{C_T/2}$. This is a popular way of normalization followed in literature[6;21;22] for aiding comparison of wake velocities with flight tests and other model tests.

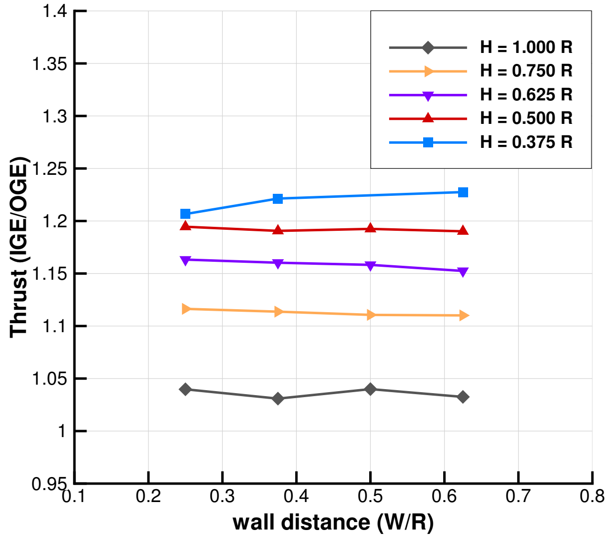
For the case H=0.500R in Figure 8a, the inflow distribution in the section farthest from the wall is steeper and has a slightly higher value near r=0.8R compared to the section closer to the wall. A larger induced velocity results in a lower value of computed lift resulting in a 'roll away' moment on the rotor. In a similar manner, for H=0.750R, at W=0.500R, the lift distribution near the wall has slightly higher magnitudes compared to the section farthest away as is seen from Figure 8b. This results in a larger lift in the farther region, leading to a 'roll in' moment. The major cause of this asymmetry in lift distribution is recirculation of the wake as the rotor nears the side wall and is described in later sections.

The variation in pitching moments at different elevations are shown in Figure 7b with varying wall distance. The general trend appears to be an increase in pitching down moment as the side wall distance decreases for a constant elevation. Contrary to the variation in rolling moment, there is a larger number of cases that transition from a pitching up moment to pitching down. These variations also appear to arise from an asymmetry in the inflow distribution along the X-axis. Two representative cases are shown in Figure 9. Similar to the rolling moment, a low inflow velocity is visible in the negative X-direction for cases having a pitch down moment.

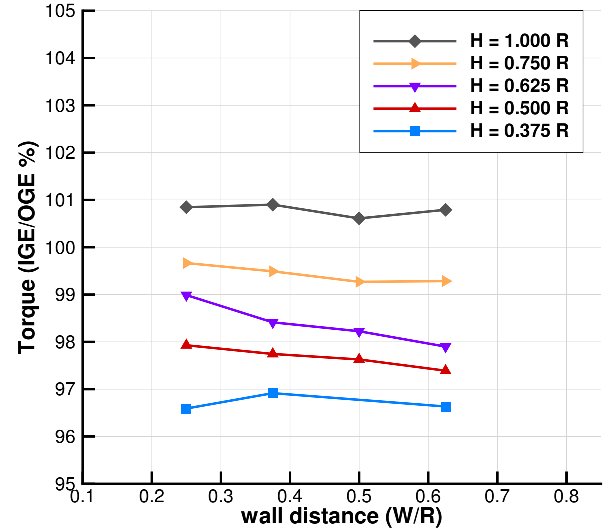
Although the resolution of the cases studied are low, evident in these plots is that the side wall appears to influence the rotor from around 0.5 R distance onwards in the form of rolling and pitching moments. Note that in the simulations conducted in this study, the rotor rotates in a counterclockwise direction only. The sense of the moments may also be influenced by the direction of rotation.

3.2.4 Wake Velocity Contours

Figure 10 shows the velocity vectors overlaid on normalized velocity contour plots for a rotor at an elevation of 0.500R and varying side wall distance. The wall is present to the left of the images. The impingement of the wake on the ground plane is clearly observable from the reddish regions to the right side near the ground plane, where the magnitude of velocity is almost twice that corresponding to OGE hover. By around 1.75R distance from the rotor hub, all velocity vectors appear parallel to the ground plane extending to a maximum height of around 0.2R on the right side. This is consistent with observations made from experiments[6] for ground effect simulations. On the left, the wake exhibits a strong recirculating nature for near wall conditions. Also observable in these plots is the asymmetry in the wake below the rotor, signified by the white regions. The velocity vectors also appear to change direction from right-to-left to left-to-right and then grow symmetric as the rotor moves away from the side wall. This may be attributed to the interference caused by the side wall. There is also a relatively large amount of upwash through the rotor hub which gets reingested into the blades nearer to the wall. Similar observations were made

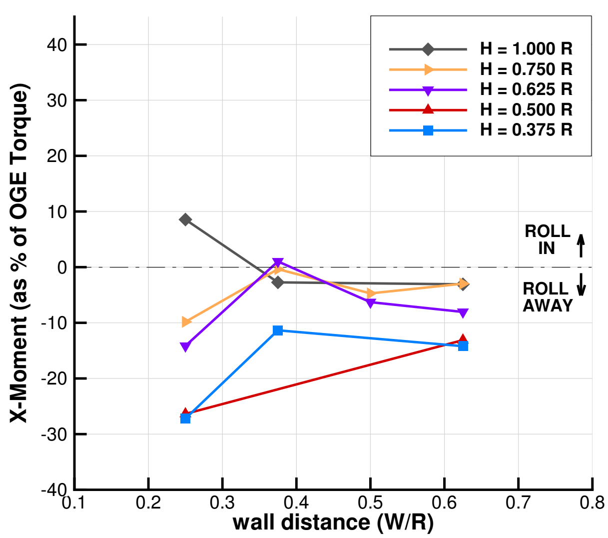


(a) Thrust variation

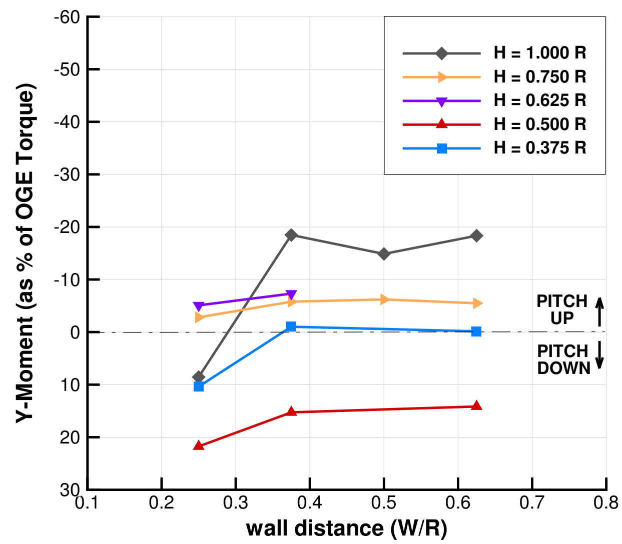


(b) Torque variation

Fig. 6: Variation in rotor thrust and torque in ground effect due to side wall at various elevations

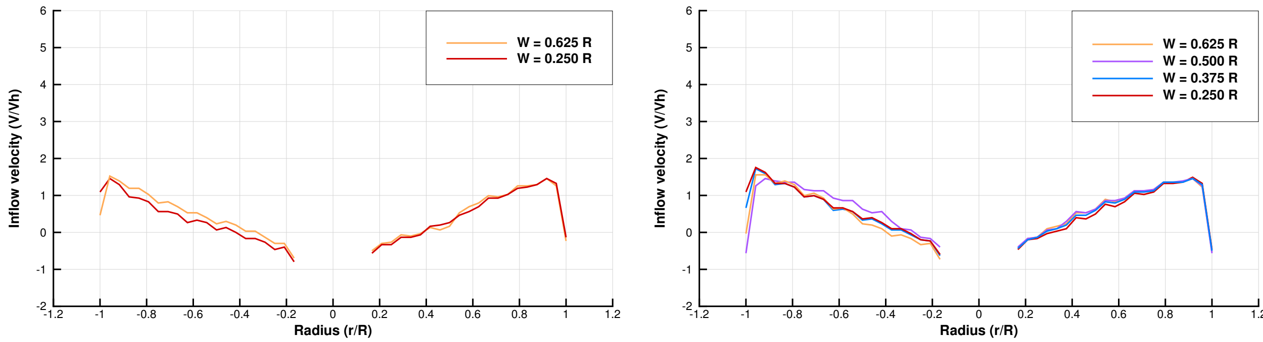


(a) Rolling moment variation



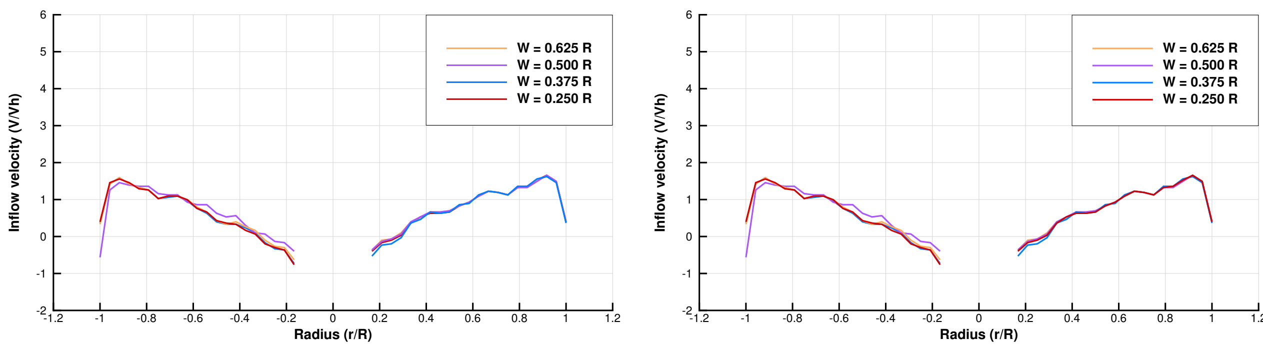
(b) Pitching moment variation

Fig. 7: Variation in rotor rolling and pitching moments in ground effect due to side wall at various elevations



(a) H = 0.500R (b) H = 0.750R

Fig. 8: Rotor inflow distribution along Y-axis for varying side wall distances



(a) H = 0.750R (b) H = 1.000R

Fig. 9: Rotor inflow distribution along X-axis for varying side wall distances

for other elevations also, another of which is provided in Figure 11

4 CONCLUSIONS

A lifting rotor in ground effect was simulated at various side wall distances to observe the influence of the side wall on rotor performance and shed wake characteristics. From this work conducted, the following can be concluded:

1. For a lifting rotor in ground effect at constant collective pitch and elevation, the rotor thrust and torque appear to not be influenced by side wall interferences even at distances as close as 0.25R.

2. The expected recirculation in the flowfield when the rotor nears the side wall was observed along with regions of stagnation where the velocities drop to negligible amounts.

3. Rotor pitching and rolling moments appeared to be most influenced by side wall interference during ground effect with magnitudes ranging between 10-30% of the OGE rotor torque.

4. The rotor experienced a moment that tends to roll it away from the side wall. As for the pitching moment, the tendency is for a pitch up (in the currently chosen coordinate frame). Both moments appear to increase in magnitude as the rotor nears the side wall.

5 ACKNOWLEDGMENTS

The authors would like to acknowledge Sukra Helitek, Inc. for providing academic licenses to the Aerospace Engineering Department at Indian Institute of Technology, Madras for the above work performed on RotCFD.

References

[1] Betz, A., "The Ground Effect on Lifting Propellers," NACA Technical Memorandum 836, 1937.

[2] Cheeseman, I. and Bennett, W., "The Effect of the Ground on a Helicopter Rotor in Forward Flight," Aeronautical Research Council Reports and Memoranda 3021, 1955.

[3] Light, J., "Tip Vortex Geometry of a Hovering Helicopter Rotor in Ground Effect," 45th Annual Forum of the American Helicopter Society, Boston, Massachusetts, USA, 1989.

[4] Knight, M. and Hefner, R. A., "Static Thrust Analysis of the Lifting Airscrew," NACA Technical Notes 626, 1937.

[5] Knight, M. and Hefner, R. A., "Analysis of Ground Effect on the Lifting Airscrew," NACA Technical Notes 835, 1941.

[6] Tanner, P. E., Overmeyer, A. D., and Bartram, S. M., "Experimental Investigation of Rotorcraft Outwash in Ground Effect," 71st Annual Forum of The American Helicopter Society, Virginia Beach, Virginia, USA, May 2015.

[7] Nathan, N. D. and Green, R. B., "Measurements of a rotor flow in Ground Effect and Visualization of the Brownout Phenomenon," 64th Annual Forum of The American Helicopter Society, Montreal, Quebec, Canada, May 2008.

[8] Nathan, N. D. and Green, R. B., "Flow Visualisation of the helicopter brown-out phenomenon," *The Aeronautical Journal*, Vol. 113, (1145), July 2009.

[9] Nathan, N. D. and Green, R. B., "Wind Tunnel Investigation of Flow Around a Rotor in Ground Effect," AHS Specialists Conference on Aeromechanics, San Francisco, USA, January 2010.

[10] Gibertini, G., Clavel, C., Grassi, D., Parolini, C., Zagaglia, D., and Zanotti, A., "An Experimental Setup for the Study of Helicopter and Building Aerodynamic Interaction," 40th European Rotorcraft Forum, South Hampton, United Kingdom, September 2014.

[11] Zagaglia, D., Gibertini, G., Giuni, M., and Green, R., "Experiments on the Helicopter-Obstacle Aerodynamic Interference in Absence of External Wind," 42nd European Rotorcraft Forum, Lile, France, September 2017.

[12] William, T., Young, W. H., and Mantay, W. R., "A Wind-Tunnel Investigation Of Parameters Affecting Helicopter Directional Control at Low Speeds in Ground Effect," NTRS D-7694, November 1974.

[13] Glauert, H., "Wind Tunnel Interference on Wings, Bodies and Airscrews," Aeronautical Research Committee Reports and Memoranda 1566, 1933.

[14] "Software Opens Computational Fluid Dynamics to the Uninitiated," *NASA Spinoff*, February 2017, pp. 62–63.

[15] Novak, L. A., Guntupalli, K., and Rajagopalan, R. G., "RotCFD : Advancements in Rotorcraft Modeling and Simulation," 4th Asian/Australian Rotorcraft Forum, Bangalore, India, November 2015.

[16] Rajagopalan, R. G. and Mathur, S., "Three Dimensional Analysis of a Rotor in Forward Flight," *Journal of the American Helicopter Society*, May 1991.

[17] Rajagopalan, R. G., Baskaran, V., Hollingsworth, A., Lestari, D., A. Garrick, Solis, E., and Hagerty, B., "RotCFD - A Tool for Aerodynamic Interference of Rotors: Validation and Capabilities," Future Vertical Lift Aircraft Design Conference, January 2012.

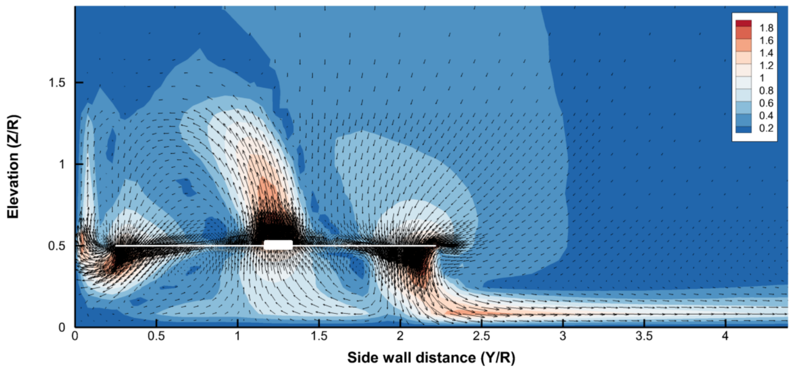
[18] Mark, A. and Strawn, R. C., 58th Annual Forum of The American Helicopter Society.

[19] Guntupalli, K. and Rajagopalan, R. G., "Momentum Source Model for Discrete Blades," International Powered Lift Conference, American Helicopter Society, 2010.

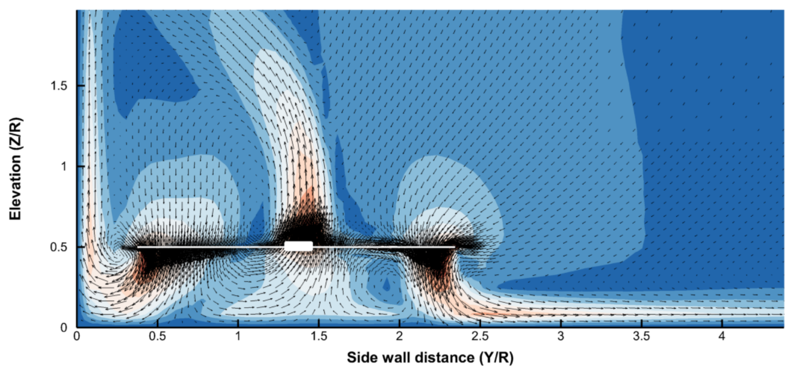
[20] Ochs, S. S., "An Adaptively-Refined Quadtree Grid Method for Incompressible Flows," *PhS Thesis*, 1998.

[21] Lee, T., Leishman, J., , and Ramasamy, M., "Fluid Dynamics of Interacting Blade Tip Vortices with a Ground Plane," 64th Annual Forum of the American Helicopter Society, April 2008.

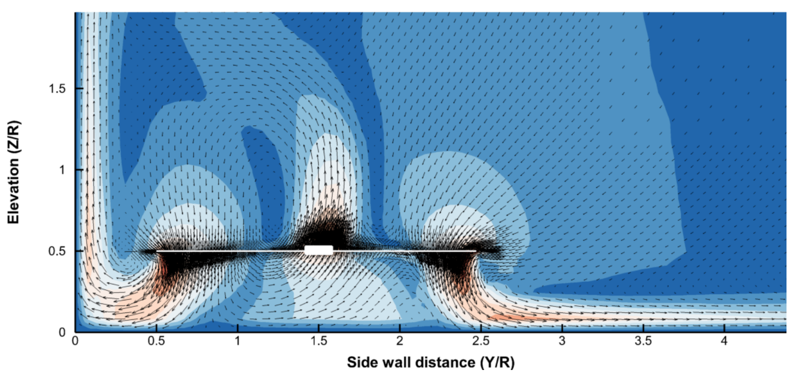
[22] Tanabe, Y., Saito, S., Ooyama, N., and Hiraoka, K., "Investigation of the Downwash Induced by Rotary Wings in Ground Effect," *International Journal of Aeronautical and Space Sciences*, Vol. 10, (1), May 2009, pp. 20–29.



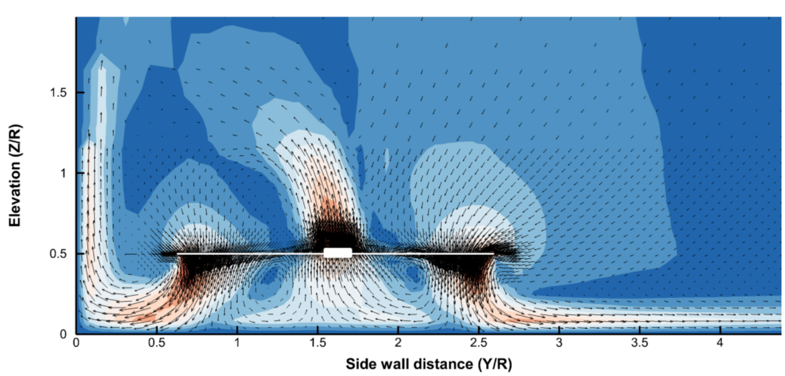
(a) W = 0.250R



(b) W = 0.375R

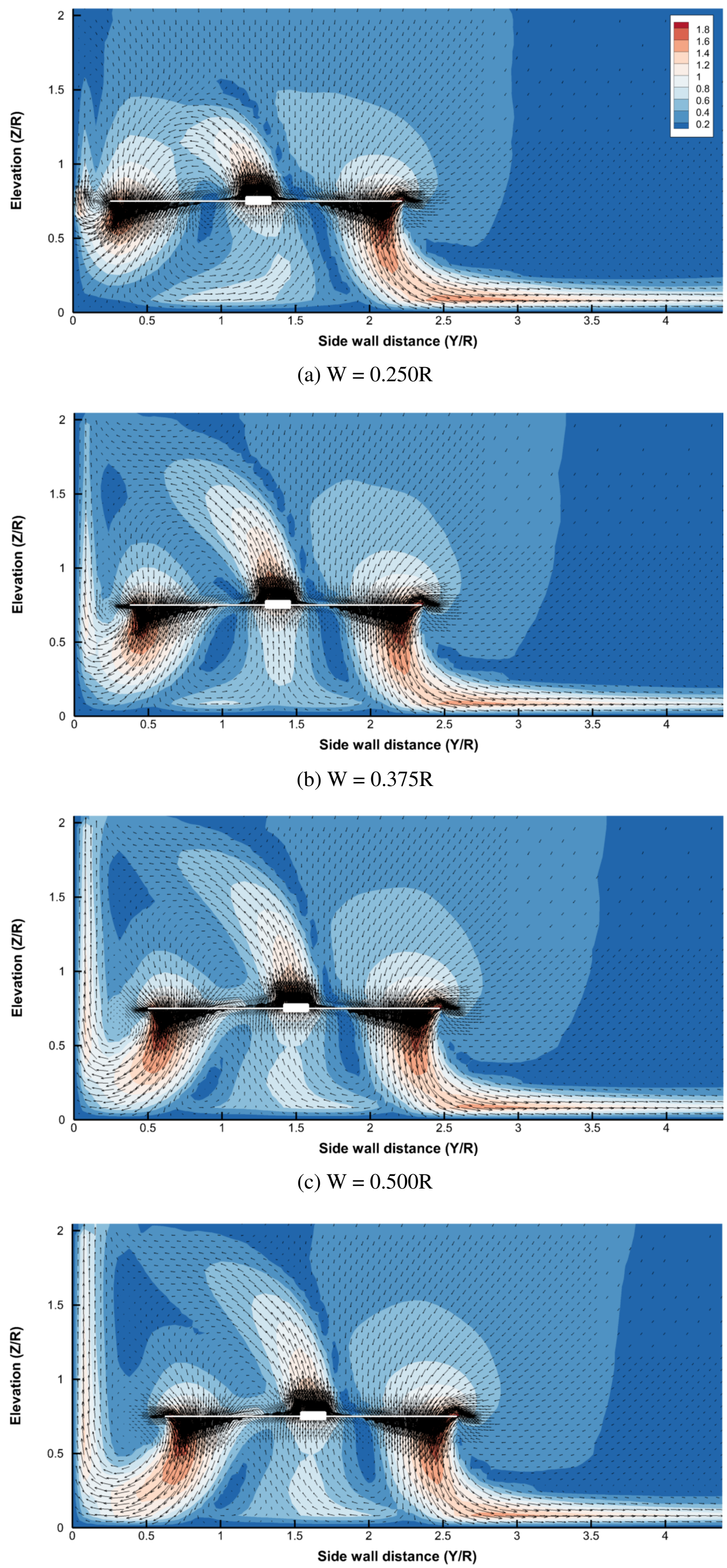


(c) W = 0.500R



(d) W = 0.625R

Fig. 10: Velocity vectors plotted on velocity contours (V/V_h) for Z=0.500R and varying side wall distance (wall on the left)



(a) W = 0.250R

(b) W = 0.375R

(c) W = 0.500R

(d) W = 0.625R

Fig. 11: Velocity vectors plotted on velocity contours (V/V_h) for Z=0.750R and varying side wall distance (wall on the left)