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COMPUTATIONAL ANALYSIS OF A MODEL SCALE MODEL HELICOPTER ROTOR IN GROUND EFFECT

Mehmet Şahbaz[1], Nilay Sezer-Uzol[2], Dilek Funda Kurtuluş[3]
Middle East Technical University
Ankara, Turkey

ABSTRACT

In this study, a numerical investigation of ground effect of a helicopter rotor is investigated with Computational Fluid Dynamics method. For this purpose, a model scale 2 bladed helicopter rotor is chosen. An experimental study is referred for comparison and validity of CFD method.

INTRODUCTION

The ground effect is basically defined as a change in the performance of a helicopter rotor when operating near the ground. The downwash flow returns to the rotor due to the presence of the ground. This flow affects overall performance parameters of rotor such as rotor thrust and torque.

Recirculating flow from the ground reduces the inflow. Reduction in inflow leads to induced power reduction since induced power is directly connected with inflow. Hence, lower power need is available with the same thrust of the out-of-ground-effect (OGE) condition. Similarly, with the same power input, changing inflow leads to increasing thrust when ground proximity increases [Griffiths et al., 2005; Brown et al, 2004]. Due to the power consumption advantages, ground effect is beneficial and it supplies extra power for helicopters in order to facilitate climb performance or transition to forward flight.

The rotor downwash flow is complex. One issue about this complexity is, rotor blade encounters with variable flow velocity. Another issue is, interference of one blade vortex with rotating next blade. When ground lies under the rotor downwash, Flow complexity increases and nonlinearity occurs on inflow distribution. 60% of rotor power is induced power which is supplied by inflow. [Zhao et al.,2014]. Thus, it is vital to inspect the effect of ground in details, since the rotor performance is directly affected. The ground effect is observed on helicopters when the helicopter approaches to the landing pad, ship deck, or inclined hills etc.

[1] M. Sc Student, Aerospace Engineering, METU, Turkey, msahbaz@ae.metu.edu.tr
[2] Asst. Prof. Dr., Aerospace Engineering, METU, nuzol@metu.edu.tr
[3] Assoc. Prof. Dr., Aerospace Engineering, METU, dfunda@ae.metu.edu.tr

The initial studies about the ground effect for rotary wings are performed by Bennett and Cheesman and Hefner and Knight [Hefner and Knight, 1941; Bennett and Cheeseman, 1955].

Model scale helicopter experiments were carried out for ground effect studies [Leishman and Rauleder, 2012; Leishman and Rauleder, 2013; Leishman and Sydney, 2013; Leishman and Sydney, 2014; Lee, Leishman and Ramasamy,2008; Amiraux, Thomas and Baeder,2013]. The model scale or full scale whirl tower tests are also compared [Balch, Sacullo and Sheehy, 1983]. In addition, there exist a number of numerical simulations performed in literature [Baeder, Kalra, Lakshminarayan, 2010; Bensing, Kessler, Kramer, Kutz, 2010]. Additionally, the ground effect with inclined surfaces or partial ground effect are also investigated by Hayata et al. [Hayata, Iboshi, Itoga and Prasad,2002; Hayata, Iboshi, Itoga and Prasad,2003].

METHODOLOGY

Test Setup

A reference experimental test case [Şahbaz, Uzol and Kurtuluş, 2016] is used for the validation of the current CFD method. In this test campaign, different ground effect distances and different inclined ground plane angles were also tested. Figure 1 shows the ground effect experimental test setup in Aerospace Engineering Department of METU where the black plane could be inclined to test different plane angles. Table 1 presents different parameters and test performed during the experimental campaign.

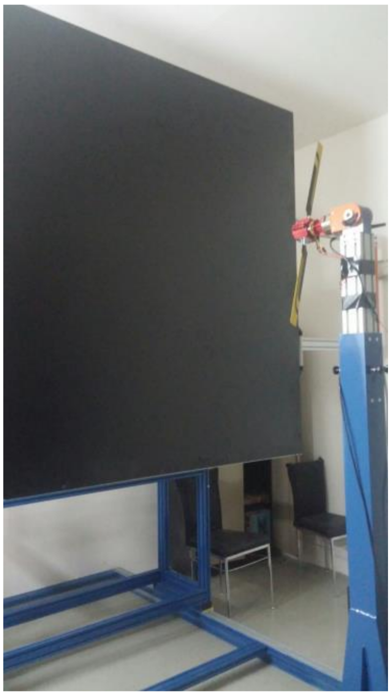

Figure 1: Ground Effect Test Setup [Şahbaz, Uzol and Kurtuluş, 2016]

Table 1: Test Matrix

RPM	2000, 2500, 3000	3 cases
Non – Dimensional Ground Distance (z/R)	0.25, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8,0.9,1, 1.2, 1.4, 1.6, 1.8, 2 2.5, 3	16 cases
Ground Inclination Angle(β)	0°, 5°, 10°, 15°,20°, 25°	6 cases
Number of Repetition Per Test Case		3
Total Number of Cases		864
Data Collection Frequency (Hz)		10000

The non- dimensional ground distance is simply the ratio of the distance between the tip Path Plane and ground (z) to the rotor radius (R). The ground inclination angle (β) is defined from the mid – section of the ground plate and rotor disk.

Computational Method

In the current study, CFD ++ Sowftware is used as a computational fluid dynamics (CFD) tool to investigate the rotor downwash in ground effect.

Surface Grid Generation: For CFD simulations, the surface mesh of rotor blade is generated with quadrateral elements. During the mesh generation process, the root cut-out section is ignored since it has no aerodynamic force contribution to the overall thrust. The zone with lifting capability is meshed. On the surface of tip region, additional refinement is done in order to capture tip vortex initiation accurately. Figure 2 shows the surface mesh over the rotor blade.

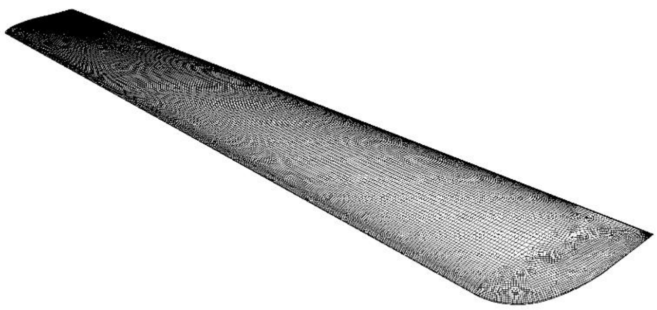

Figure 2: Surface Mesh of Rotor Blade

Volume Grid Generation: The volume mesh is composed of unstructured tetrahedral grids for farfield mesh and prismatic elements for the boundary layer mesh. Similar approach is observable in the work of Abras et al [Abras et al., 2015]. The volume grid generation could be divided into two parts: Grid of ground effect without inclination and grid of ground effect with inclination.

For cases without inclination, in order to achieve grid size saving, only one of the two blades is meshed. Figure 3 shows that, the interface boundary conditions are defined as “periodic” for the sake of the definition of the periodicity of rotational motion of blade. In the end, total thrust and torque are computed as the 2x of the solution due to the single blade simulation.

Periodic boundary condition is implemented in the similar work of Thomas et al. [Thomas et al. 2013].

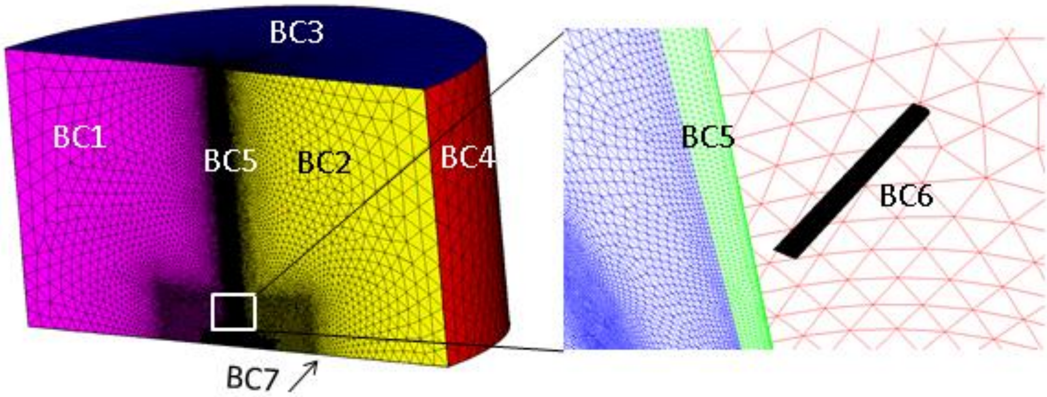

Figure 3: Boundary Conditions

BC1, BC2 = Periodic Boundary Conditions
BC3, BC4 = Farfield Boundary Conditions
BC5 = Slip Wall
BC6 = Blade, No Slip Wall
BC7= Ground, Slip Wall

For cases with inclination, it is impossible to define a periodicity due to the unsymmetry of the rotating flow. Hence, both of the blades are modelled and grid generation is performed due to that point:

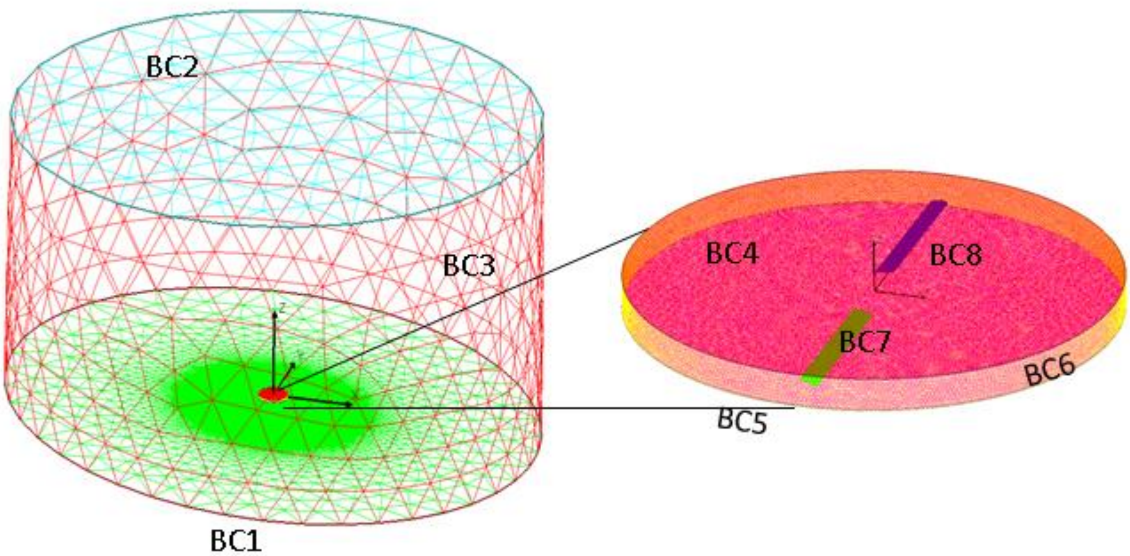

Figure 4: Boundary Conditions of Inclined Cases (5 degrees inclination)

BC1 = Inclined Ground (Slip Wall)
BC2, BC3 = Farfield
BC4, BC5,BC6 = Zonal Interfaces
BC7, BC8 = Blades (No Slip Wall)

As imposed on Figure 4, new boundary condition type is defined apart from periodic cases: zonal interfaces.

For periodic cases (ground effect without inclination), Moving Reference Frame (MRF) method is implemented which enables rotational velocity to each cell in volume grid. This method is useful for rotary wing applications since rotating flow is a transient process, whereas, Moving Reference Frame method converts it to a steady state process and less computational effort is made.

When MRF method is applicated to a cases with inclined surfaces, problems arise since symmetry and periodicity of rotating flow spoil with ground inclination. To overcome this problem, the rotor blades are enclosed with a cylindirical domain composed of BC4, BC5 and BC6 as shown on Figure 4. Then rotation is defined to this domain only. Finally, satisfactory solutions are obtained.

The helicopter in hover condition creates a severe downwash flow either in the vicinity of the blades or downside from the rotor tip path plane. The tip vortices emerged from blade tip, affect the aerodynamics of the succeeding rotor blade which causes local inflow and angle of attack change. For this reason, it is significant that, rotor wake and tip vortices must be captured accurately in order to achieve a satisfactory rotor flow simulation. Hence, possible path of tip vortices must be refined during mesh generation.

For all cases, grid refinement study is done for the accurate visualization of the tip vortices. A tip vortex grid refinement study is done in the work of Kutz et al. [Kutz et al. , 2014]. In order to determine the possible tip vortex path, the path of tip vortices is generated by Kocureks' Method [Kocurek and Tangler, 1976] then, grid refinement at the wake region is established with respect to this path. Abras et al. [Abras et al., 2015] implement a grid refinement study in order to satisfy the wake vortex preservation. Blade tip vortex path is valid only for the region between the rotor and ground. On the ground, mesh refinement continues parallel to the ground with one rotor diameter distance from the end of the tip vortice path to the farfield. Additional mesh refinement is performed approximately 10 radius apart from the helicopter blade. Figure 5 shows the refinement zones for z/R=0.8 case enclosed with rectangles:

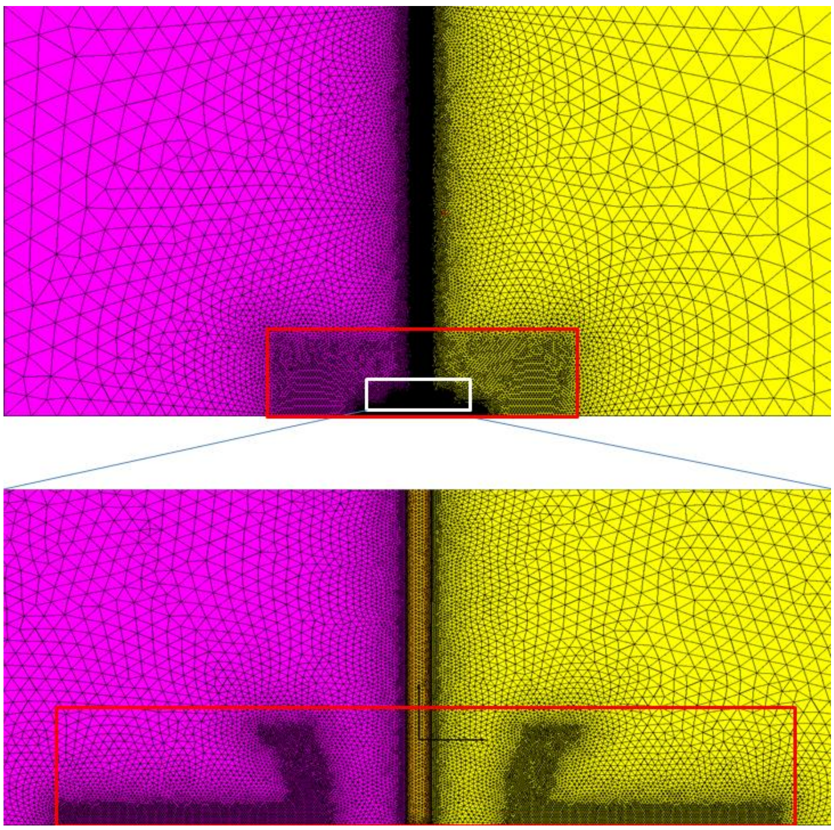

Figure 5: Grid refinement regions for tip vortex and downwash

The boundary layer solution on the ground is not applied since tip vortex and the ground boundary layer interaction are not the issues of this current work. Due to that point, no boundary layer grid is generated on the ground and ground is defined as “Slip Wall”. Slip Wall Boundary Condition approach is available in literature namely in the study of Filippone et al. and in the work of Tanabe et al. [Filippone and Mikkelsen, 2009;Tanabe et al., 2008]. In addition, the volume mesh without the ground wall boundary layer reduces the computational time [Doerffer et al. 2012].

Solution Parameters: The solution is obtained by using Finite Volume Method (FVM). Most of the rotary wing flow simulations implement NS equations as observed in the study of Kim et al. [Kim et al. 2014]. The vortex structure passed parallel to the ground must be fully resolved and this requires a full NS Equation solution, as discussed by Kang et al. [Kang et al., 1997]. The equation set is defined with compressible Preconditioning which is obtained from the work of Turkel [Turkel, 1999]. Preconditioning method is suitable for low speed flow regions and can improve convergence and accuracy [Kalra et al. 2010; Lakshminarayanan et al. , 2006]. Most valuable aspect of preconditioning is the reduction of the artifical dissipation which is the most encountered problem in rotary wing flow simulations after a certain iteration.

A density based approach and perfect gas assumption with Sutherland Law is used for the solution algorithm of Navier Stokes Equations [Doerffer et al. 2012]

Implicit, Forward Euler Scheme is utilized since it is a stable method and provide better stability rather than explicit methods. Inviscid terms are computed by using 2nd order discretization polynomial scheme as available in the work of Doerffer et al. and in study of Kao et al. [Doerffer et al. , 2012;Kao et al. , 2013].The flux splitting method is applicated as Total Variation Diminishing (TVD) scheme. Due to its advantages, implicit schemes are available on some rotor simulations in literature like the work of Kao et al. [Kao et al., 2013] and the work of Bensing et al. [Bensing et al, 2012].

In order to increase the solution accuracy and convergence speed, multigrid method is utilized similar to the rotor simulation of Bensing et al. [Bensing et. al. 2012].

A fully turbulent, k-omega SST (Shear Stress Transport) turbulence model is selected in order to satisfy the $y+<1$ condition for boundary layer profile on the rotor blade. All simulations are done with isolated rotor. No interface effects of any other part of the test setup is added except ground surface. Turbulence model selection is based on similar literature studies [Kutz et al. 2014;Rodriguez, 2012;Kao et al. , 2013].

MRF (Moving Reference Frame) method is used where mesh is stationary. However, frame is moving with definition of rotational velocity to each cell of volume grid. MRF method is applicable to rotor simulations in literature [Pandey et al. 2011]. With MRF method, the cases requiring transient solution like rotary wing are able to solve with steady state simulations.

The hovering rotor flowfield coud be denoted as quasy-steady with respect to the blade motion and flowfield is periodic and symmetric when blade rotation is taken into account as described by Doerffer et al. [Doerffer et al. 2012]. For this reason, solution domain of ground effect with no inclination is established with periodic boundaries. The symmetry of downwash allows a periodic boundary condition implementation. For inclined surface cases, in order to satisfy the “quasi-steady” condition, only a cylinder enclosed the close proximity of rotor is created and rotation is defined to cells in this cylinder only. Hence, steady state solution ability is assigned. If rotation would be defined to entire domain for inclined cases, there wouldn’t have been a realistic solution since inclined surface spoils the symmetry and periodicity of the flow.

CFD cases were run at the High Performance Computer located in METUWIND Facilities, The HPC has 8 nodes. Each node has 64 cores.

RESULTS

The different inclined angles and ground distances are numerically investigated and results ar compared with experimental data.

Convergence

In order to investigate the accuracy of CFD solutions, convergence check is performed as can be seen from Figure 6.

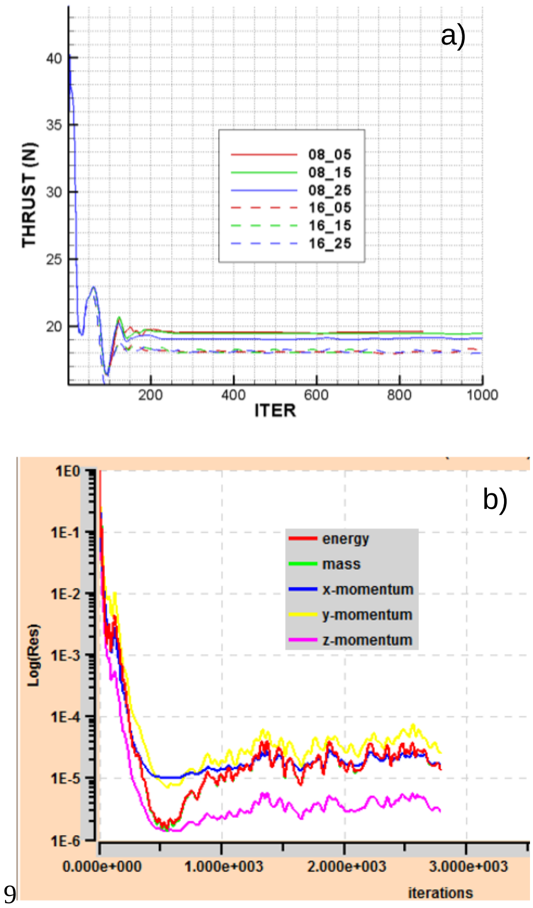

Figure 6: a) Convergence Rates of the thrust values for inclined cases b) Residuals and their Order of Magnitudes

As seen on Figure 6 a) and b), convergence rates are at satisfactory level. Thrust values converge in 1000 iterations however, most of the cases were run till 3000th step.

The residuals reach 4th or 5th order of magnitude which are apparent indicator for convergence.

Ground Effect Without Surface Inclination

Solutions are almost compatible with experimental results and literature studies occupied by flight test data, the approximation of Hayden and the calculations of Cheeseman and Bennett. This work includes extra information about the extreme ground effect cases where z/R value is between 0.25 and 0.5 which is denoted as “fuselage margin” by Leishman [Leishman, 2006].

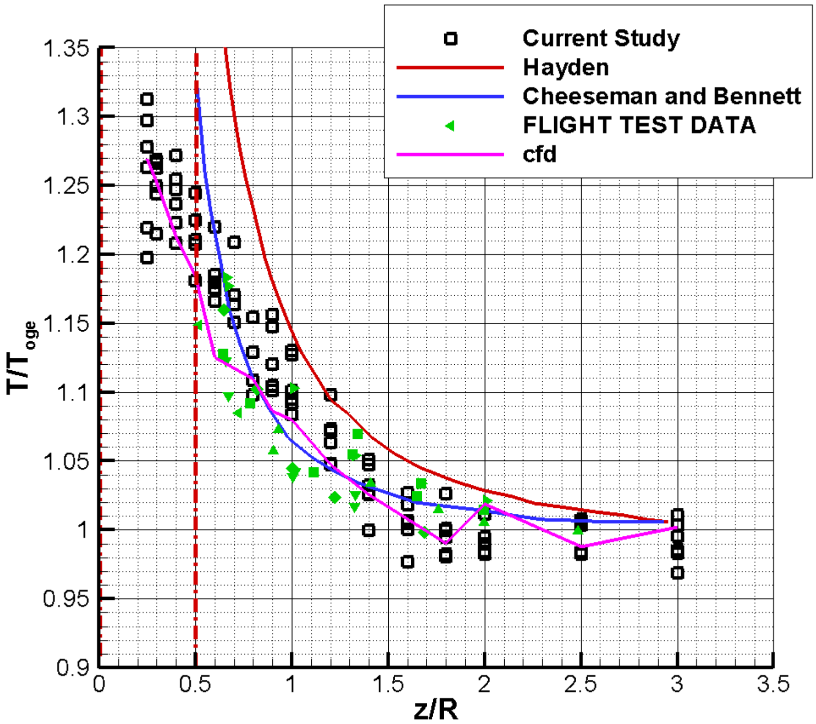

Figure 7: Non- dimensional thrust with respect to the ground proximity

When solutions are compared with literature studies [Bennett and Cheeseman, 1955; Hayden 1976] and current study [Şahbaz, Uzol and Kurtuluş, 2016] they are quite compatible, even for extreme ground proximities (z/R=0.25 – z/R = 0.5). For better comparison, all thrust values are non-dimensionalized with OGE thrust value since literature data are available with that way. It is inspected that between z/R=18 and z/R = 2, ground effect is decreasing and loses its effect over rotor performance which is declared by Leishman [Leishman 2006].

The non-dimensional thrust values between z/R = 0.5 and z/R = 1, are under estimated. It could be happened because rotor is simulated without hub in flow simulations (isolated rotor). Since blockage effect of rotor hub is not modelled which is contributor to thrust, thrust value may be obtained slightly low. This condition is encountered during the similar study of Kutz. et al. [Kutz et al. 2014].

Another point is tip vortex monitoring. Figure 8 depicts that, the tip vortices are accurately visualized in the defined wake region which is an indicator for the rotor CFD solution accuracy. Tip vortices are shown with the iso surfaces called Q criterion [Haller, 2005]. Q criterion is simply the second invariant of the velocity gradient tensor. The positive values of Q denotes the zones with high vorticity whereas negative values of Q denotes the the zone with high strain which are not the object of this study. Baeder et al. [Baeder et al. 2007] implies that, Q Criterion presentation is useful for vorticity dominated flowfields like rotor flows. For this reason, rotary wing Q Criterion applications are widespread as practiced by Kao et al. and Kalra et al. [Kao et al., 2013; Kalra et al., 2010].

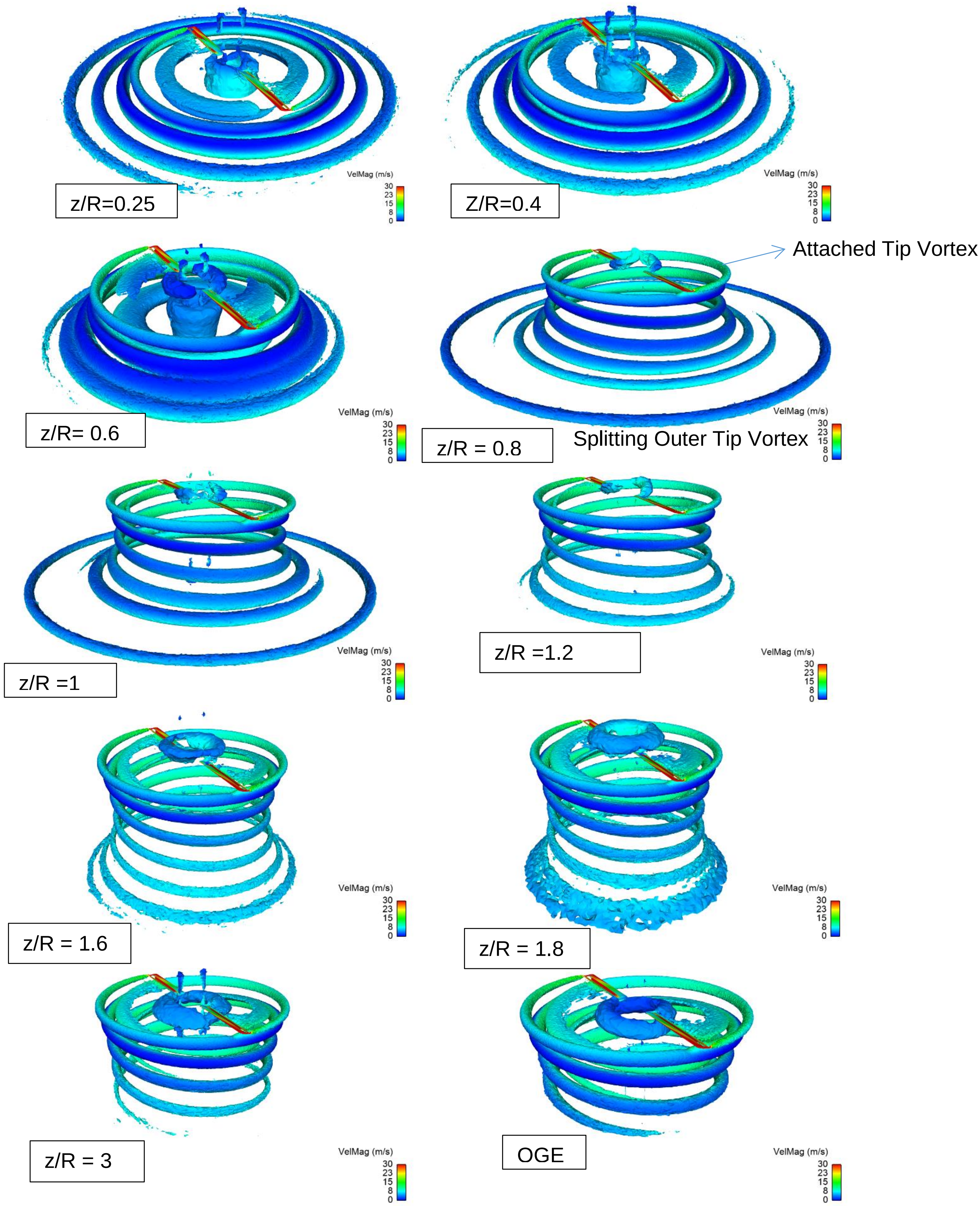

Figure 8: Q –Criterion Iso surfaces coloured with velocity magnitude, Q=2000

Figure 8 shows the tip vortex trajectories with changing ground proximities. It is definite that, tip vortex refinement in volume grid has a great role on tip vortex visualization in all cases.

As vortex path structures are investigated, a splitting outer tip vortex ring is observed during z/R= 0.8 and z/R=1. After z/R =1.2, no splitting vortex ring is observed since these vortices are quite weak compared to the attached vortices. If Q criterion value reduces below 2000, weak vortices will be visible for the higher z/R cases. From z/R=1.2 to z/R = 1.6, attached helical vortex path is quite observable. After z/R = 1.8, the effect of ground started to vanish which could be understood from quite weak lowermost vortices.

It is clear that, during the ground effect, a vortex path is not contracted. On the contrary, it expands by trigger of reduced inflow [Brown et al., 2004]. This expansion is started to reduce when z/R is 1.8 and higher which is another clue that, groud effect is started to demise after a certain proximity ratio. Approximately, after z/R = 2, no ground effect is observable as defined by Leishman [Leishman, 2006]. It is the first validated point of both test setup and CFD Method.

Ground Effect With Surface Inclination

In this part, in order to investistigare the insight of the effect of inclined ground over rotary wing flow, streamlines for z/R =0. 8 and z/R =1.6 with 3 different inclination angles (5°, 15°, 25°) are shown in Figure 8.

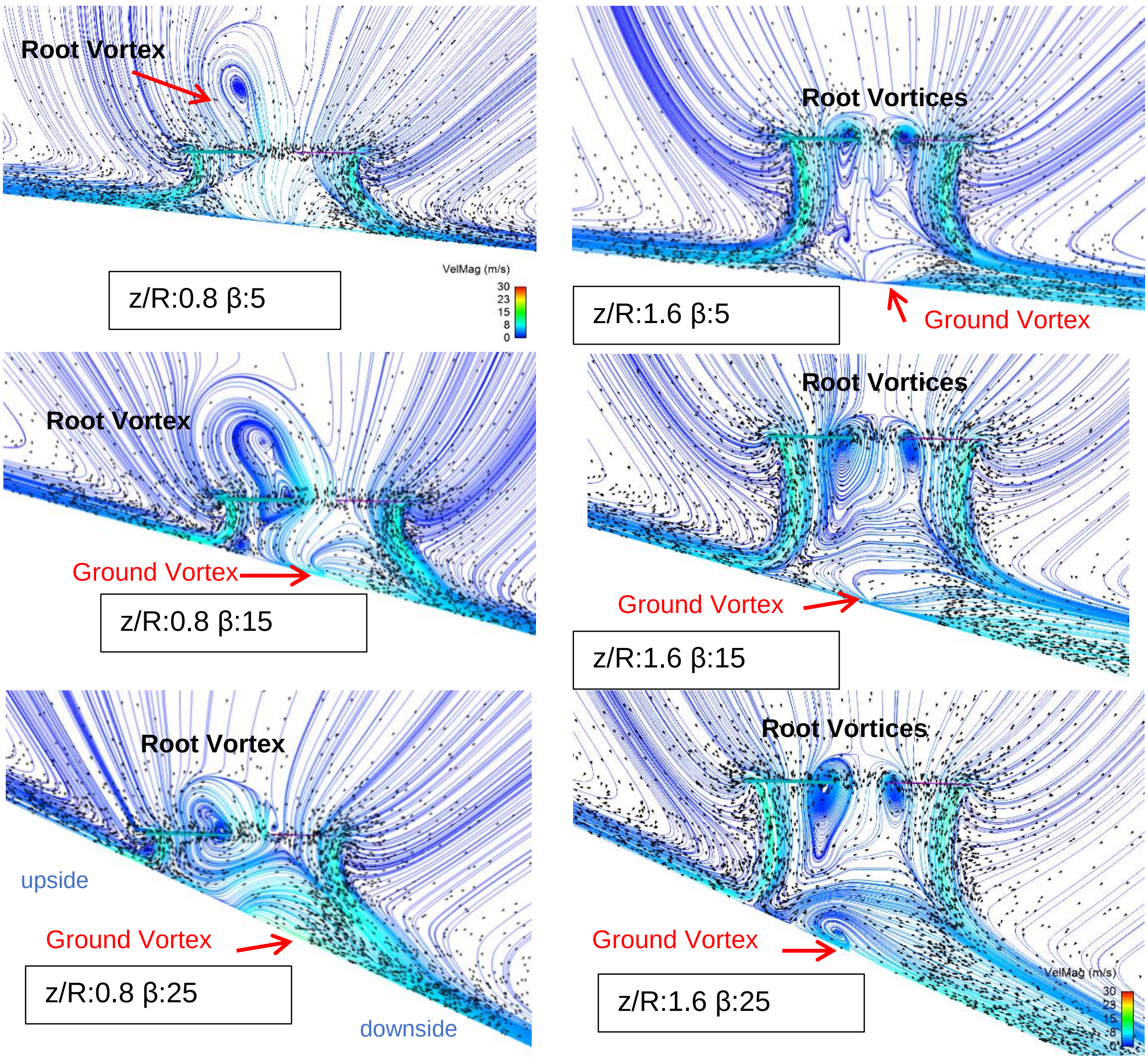

Figure 9: Streamlines of for z/R 0.8 and z/R =1.6 for different Beta (inclination angle) values

The ground inclination generates further complications on rotor downwash. The strong root vortex is seen on cases in Figure 9. Increasing inclination leads higher root vortex on closer side of the rotor to the ground (upside). In addition, a new ground vortex emerges from downside to the upside of the surface inclination. This ground vortex is in cooperation with the increasing root vortex and it is getting stronger with increasing inclination.

The root vortex is stronger when ground proximity is higher. When z/R =0.8, due to the higher recirculation than the case of z/R = 1.6, an upper vortex emerges in the vicinity of the blade root. However, when z/R = 1.6, this upper vortex is not available since recirculation is lweak. In addition, inclination change at the higher proximity (z/R=0.8), creates higher downwash decay due to the stronger root and ground vortices.

The overall circulation from ground to rotor is generally observed on root regions. On tip regions, unlike the ground effect with no inclination cases, very low recirculation is observed. Instead, flow continues uphill or downhill which loses its contributory effect over rotor inflow hence, rotor performance.

Inclined surface creates abundant asymmetry on the rotor inflow where the risk of the loss of helicopter control may be emerged. This is actual when flowfields are inspected, the one half of the rotor has a normal downwash whereas other half of the rotor enters the vortex ring state which is critic phase for rotor flow and helicopter stability as explained by Leishman [Leishman, 2006].

CONCLUSION

Ground effect is the change in helicopter rotor performance during the ground presence below the rotor. The recirculating flow from ground to the blades, changes the inflow of the rotor hence, induced power changes which is advantageous that same thrust value is obtained with lower power consumption. This condition is validated with both test setup and CFD method. Accurate tip vortex iso-surfaces and thrust figure shows the validity of the solution procedure.

As ground is rotated, an asymmetric condition is imposed on the rotor flow, and this asymmetry removes the advantages of ground effect thus, flow field becomes more chaotic. This asymmetry is observable when rotor flow during inclined surface is investigated. The one half of the rotor struggles with vortex ring whereas other half is exposed to quite clean flow during the close distance to the ground. The asymmetry in rotor inflow is totally dangerous since it may spoil the overall stability of helicopter hence, catashtropic results may be inevitable. The fatality risk is higher than the out-of- ground-effect (OGE) condition. During the out of ground effect, pilot has a chance to regain the attitude and stability of aircraft due to the altitude and time advantages. Neverthless, during the in-ground-effect (IGE) condition, the distance is very close to the ground, and any corruption in flow like unsymmetric vortex, may create a sudden change in stability and helicopter may go down in a very short time on account of the close distance to the ground.

In this study, fuselage effect is not investigated. However, the occurrence region of the ground vortex is the possible location of any helicopter fuselage which increases the risk of fatality since recirculating flow may rotate the fuselage and this rotation may be a contribution to the overall stability corruption. For this reason, rotor and fuselage design must be resistive to any stability spoiling objects especially in ground effect with inclination. The unsymmetry in rotor flow and downwash must be taken into account during the stability analyses.

This study reveals a rough picture of rotor flow during the inclined surface scenarios. However, in order to investigate the details, transient analyses will be planned for specific cases. During the ground vortex formation, the reason of this phenomenon will be investigated with a ground boundary layer implementation.

For grid improvement, different mesh structures (hexcore, polyhedral) will be imposed in order to reduce the time spent for CFD analyses.

References

Abras J. N., Hariharan N. 2015 Comparison of CFD Hover Predictions on the S-76 Rotor. AIAA SciTech 5-9 January 2015 , Kissimmee ,Florida

Amiraux M., Baeder J.D., Thomas S., 2013*. GPU-accelerated FVM – RANS Hybrid Solver for Simulating Two-phase Flow beneath a Hovering Rotor*., AHS 2013.

Baeder J.,Duraisamy K., 2007 High Resolution Wake Capturing Methodology for Hovering Rotors Journal of the American Helicopter Society Vol.52 Number 2, 2007

Baeder J.D.,Kalra, T.S., Lakshminarayan, V. K., 2010.,*CFD Validation of Micro Hovering Rotor in Ground Effect.,.* Alfred Gessow Rotorcraft Center. University of Maryland, 66th Annual Forum and Technology Display of the American Helicopter Society International, Phoenix, Arizona, May 11–May 13, 2010

Balch D.T., Sacullo A., Sheehy T.W.,1983. ,*Experimental Study of Main Rotor/Tail Rotor/Airframe Interactions in Hover -Volume1*.,NASA Contractor Report 166485, June 1983.

Bennett, W.E. and Cheeseman, I.C. (1955) *The Effect of the Ground on a Helicopter Rotor in Forward Flight*, ARC R & M 3021.

Bensing F., Kessler M., Kramer E., Kutz B., 2010.,*CFD calculation of a helicopter rotor hovering in ground effect.,* STAB Conference, November 2010, Berlin.

Bensing F. , Embacher M., Hollands M., Kutz B., Kessler M., Kramer E. 2012, Numerical Simulation of Helicopter Wake Evolution, Performance and Trim, Institut für Aerodynamik und Gasdynamik, Universit¨at Stuttgart, Pfaffenwaldring 21, D-70569,Stuttgart, Germany

Brown R.E.,Whitehouse G.R., 2004. Modelling Rotor Wakes in Ground Effect. Journal of the American Helicopter Society 2004.

Cooke, A.K. and Fitzpatrick, E.W.H., Helicopter Test and Evaluation, American Institute of Aeronautics and Astronautics Education Series, Reston, VA, 2002

Doerffer P. , Szulc O. 2008 Numerical Simulation of Model Helicopter Rotor in Hover, Institute of Fluid Flow Machinery PAS , Gdansk, Poland.

Filippone A. and Mikkelsen R. (2009) *Advances in CFD & Actuator Disk Models for Helicopter Aerodynamics*, ERF 2009

Griffiths D.A., Ananthan S., Leishman J.G. 2005. *Predictions of Rotor Performance in Ground Effect Using a Free-Vortex Wake Model.* Journal of the American Helicopter Society 2005.

Haller G., (2005) *An Objective Definition of a Vortex*, Journal of Fluid Mechanics vol. 525 pp 1 - 26

Hayata, Y.,Iboshi, N., Itoga, N., Prasad, J.V.R. ,2002.,*Ground Effect and Blade Flapping Motion of a Rotor Hovering above Finite Inclined Ground Plane*., Journal of the Japan Society for Aeronautical and Space Sciences

Hayata, Y.,Iboshi, N., Itoga, N., Prasad, J.V.R. ,2003.,*Hovering Performance of a Rotor in an Inclined and Partial Ground Effect*., Journal of the Japan Society for Aeronautical and Space Sciences, Volume 51, Issue 595, pp. 433-440, 2003

Hayden, J.S. (1976) *The Effect of the Ground on Helicopter Hovering Power Required*, 32th Annual National V/STOL Forum of the American Helicopter Soc., Washington DC, 10-12May 1976

Hefner R.A., Knight M.,1941., *Analysis of a Ground Effect on the Lifting Airscrew.,* Daniel Guggenheim School of Aeronautics , Georgia School of Technology, Washington December 1941.

Kalra S. T. ,V. K. Lakshminarayan, Baeder J. D. 2010, CFD Validation of Micro Hovering Rotor in Ground Effect, AHS 66th Annual Forum and Technology Display, Phoenix , Arizona 2010

Kao D.L., Ahmad J.U., Holst T.L., Allan B.G., 2013, Visualization and Analysis of Vortex Features in Helicopter Rotor Wakes. 51st AIAA Aerospace Sciences Meeting 07-10 January 2013, Grapevine ,Texas.

Kang N., Sun M., 1997 , Technical Note, Prediction of Flow Field of a Rotor in Ground Effect, Journal of American Helicopter Society, April 1997

Kim J., Sankar L.N., Marpu R., Egolf T.A.,Hariharan N.A Parametric Study of Planform Effects on Rotor Hover Performance Using a Hybrid Navier Stokes – Free Wake Methodology, European Rotorcraft Forum Southampton UK, 2014

Kocurek J. D. and Tangler J. L. (1976) *A Prescribed Wake Lifting Surface Hover Performance Analysis*, Journal of the American Helicopter Society , 14(4), pp. 20 – 32

Kutz B. M.,Günther T., Rumpf A.,Kuhn A. 2014 *Numerical Examination of a model Rotor in Brownout Conditions*. AHS 70th Annual Forum Montreal,Canada, 2014.

Lakshminarayanan V., Bush B., Duraisamy K., Baeder J. 2006 Computational Investigation of Micro Hovering Rotor Aerodynamics. 24th AIAA Applied Aerodynamics Conference San Francisco CA.

Layton D.M., Helicopter Performance , Matrix Publishers 1984.

Leishman, J.G. , 2006. *Principles of Helicopter Aerodynamics.,* Cambridge Aerospace Series

Leishman, J.G. ,Rauleder J.,2012. *Measurements of Organized Turbulence it the Dual-Phase Flow Below a Rotor*., Department of Aerospace Engineering., ERF 2012.

Leishman, J.G. ,Rauleder J.,2013. *Turbulence Modifications and Phase Couplingsin Ground Effect under Simulated Brownout Conditions*., Department of AEE University of Maryland, American Helicopter Society

Leishman, J.G. Sydney, A.,2013*. Measurements of Rotor/Airframe Interactions in Ground Effect Over a Sediment Bed.,* Department of AEE, American Helicopter Society

Leishman, J.G. Sydney, A.,2014., *Measurements of the Plume-Like Three Dimensionality of Rotor Induced Dust Fields.,* Department of Aerospace Engineering, American Helicopter Society

Pandey K. M.,Kumar G., Das D., Deka D., Surana A., Das H.J. CFD Analysis of an isolated main helicopter rotor for a hovering flight, ESTIJ, 2011

Rodriguez C. 2012 CFD Analysis on the Main Rotor Blade of a Scale Helicopter Model using Overset Meshing, KTH Stockholm, Sweden. 2012

Tanabe Y., Saito S., Ooyama N., Hiraoka K. 2008. Study of a Downwash Caused by a Hovering Rotor in Ground Effect.

Thomas S. , Amiraux M., Baeder J.D. 2013, GPU Accelerated FVM - RANS Hybrid Solver for Simulating two phase flow beneath a hovering rotor. AHS 2013

Turkel, Eli. 1999 *Preconditioning techniques in computational fluid dynamics*. *Annual Review of Fluid Mechanics* 31.1: 385-416.

Zhao J.,He C. 2014 *Physics – Based Modeling of Viscous Ground Effect for Rotorcraft Applications.* AHS Forum, Montreal, Canada May 20-22 2014.

Şahbaz M., Uzol N.S., Kurtuluş D.F., (2016) *Model Helikopter Döner Kanat Sistemi için Yer Etkisi Durumunda Performans ve Akış Araştırması*, 6th National Aerospace Conference, UHUK-2016-014, 28-30 September 2016, Kocaeli, Turkey