Contract # N00014-14-C-0020

Pilot-in-the-Loop CFD Method Development

Progress Report (CDRL A001)

Progress Report for Period: October 21, 2016 to January 20, 2016

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Prepared under:

Contract Number N00014-14-C-0020
2012 Basic and Applied Research in Sea-Based Aviation
ONR #BAA12-SN-028
CDRL A001

Report Distribution per CDRLs for Contract No. N00014-14-C-0020

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Section I: Project Summary

1. Overview of Project

This project is performed under the Office of Naval Research program on Basic and Applied Research in Sea-Based Aviation (ONR BAA12-SN-0028). This project addresses the Sea Based Aviation (SBA) virtual dynamic interface (VDI) research topic area "Fast, high-fidelity physics-based simulation of coupled aerodynamics of moving ship and maneuvering rotorcraft". The work is a collaborative effort between Penn State, NAVAIR, and Combustion Research and Flow Technology (CRAFT Tech). This document presents progress at Penn State University.

All software supporting piloted simulations must run at real time speeds or faster. This requirement drives the number of equations that can be solved and in turn the fidelity of supporting physics based models. For real-time aircraft simulations, all aerodynamic related information for both the aircraft and the environment are incorporated into the simulation by way of lookup tables. This approach decouples the aerodynamics of the aircraft from the rest of its external environment. For example, ship airwake are calculated using CFD solutions without the presence of the helicopter main rotor. The gusts from the turbulent ship airwake are then re-played into the aircraft aerodynamic model via look-up tables. For up and away simulations, this approach works well. However, when an aircraft is flying very close to another body (i.e. a ship superstructure) significant aerodynamic coupling can exist. The main rotor of the helicopter distorts the flow around the ship possibly resulting significant differences in the disturbance on the helicopter. In such cases it is necessary to perform simultaneous calculations of both the Navier-Stokes equations and the aircraft equations of motion in order to achieve a high level of fidelity. This project will explore novel numerical modeling and computer hardware approaches with the goal of real time, fully coupled CFD for virtual dynamic interface modeling & simulation.

Penn State is supporting the project through integration of their GENHEL-PSU simulation model of a utility helicopter with CRAFT Tech's flow solvers. Penn State will provide their piloted simulation facility (the VLRCOE rotorcraft simulator) for preliminary demonstrations of pilot-in-the-loop simulations. Finally, Penn State will provide support for a final demonstration of the methods on the NAVAIR Manned Flight Simulator.

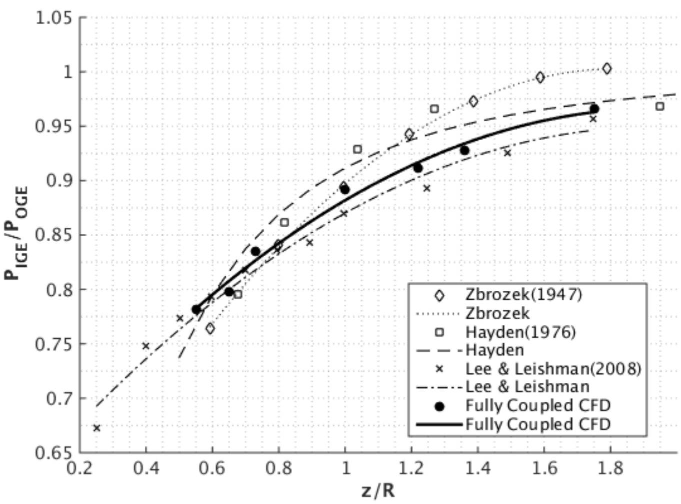
Activities this period

During this report period, we expanded our previous in-ground-effect (IGE) hover and acceleration cases to cover lower altitudes above ground level (AGL) and higher forward speeds, respectively. Hover IGE cases showed as high as 22% power reduction at z/R=0.55R and a similar trend in power reduction to the experimental data of Lee and Leishman [1]. The updated acceleration case showed a flow formation representative of recirculation and ground vortex.

Power Reduction in Hover

Ground effect, the reduction in power of a helicopter as it flies in close proximity to the ground, is a well-known physical phenomenon. The rotor slipstream tends to rapidly expand as it approaches to the surface and this alters the slipstream velocity, the induced velocity in the rotor plane, and the power and thrust of the rotor [2]. Similar effects are seen in both hover and forward flight, but the power reduction benefits are strongest in the hovering flight state, and decrease as the aircraft accelerates into forward flight [3].

Figure 1 shows the main rotor power reduction for a helicopter hovering (constant thrust) in ground effect at different altitudes above a flat ground plane. The main rotor power required in ground effect was normalized by the main rotor power required for the same helicopter hovering out of ground effect. All of the fully coupled simulations have been performed using the same computational domain and Gaussian parameters which were calculated based on the guidelines presented in [4-6]. Fully coupled results are compared with experimental data developed by Zbrozek[7], Hayden[8] and Lee and Leishman[1]. The fully coupled simulation results show similar trends in power reduction to the data of Lee and Leishman, with as high as 22% power reduction at z/R= 0.55. The simulation trend differs from the classical ground effect model and data of Hayden, which shows a steeper drop off on power for lower altitude (z/R < 0.6), but shows more favorable comparison to the more recent experimental data of Leishman. The developed tool provides reasonable prediction of the power reduction due to proximity to the ground.



z/R	P_{IGE} / P_{OGE}
0.55	0.782
0.65	0.798
0.73	0.835
1.00	0.892
1.22	0.911
1.36	0.927
1.75	0.965

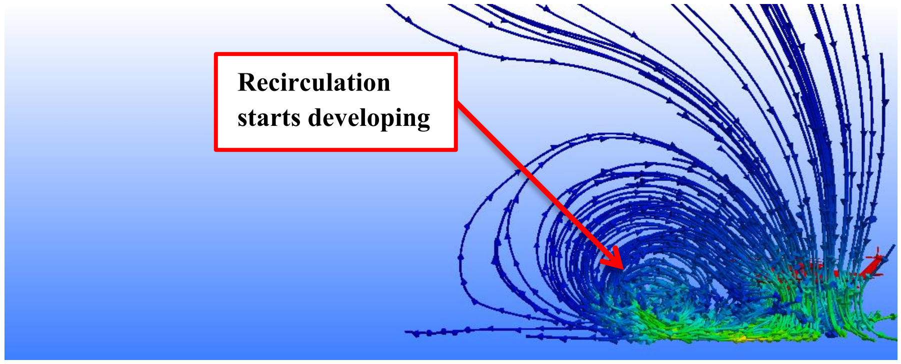
Figure 1 - Normalized main rotor power required for a helicopter hovering at different altitudes above ground.

It was seen that, the computational domain used in the CFD has a crucial effect on induced flow velocity predictions, as well as power and thrust predictions. Different mesh resolutions result in different thrust predictions. Gaussian parameters need to be tuned for each computational domain to have a consistent power prediction. If the same computational domain, with the same Gaussian distribution parameters are used, the developed tool successfully captures the impact of ground effect on the helicopter dynamics.

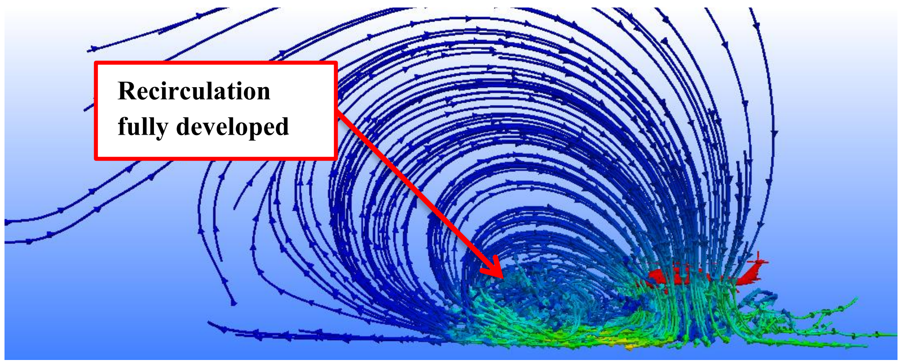
Acceleration at Near Ground Level

Fully coupled simulations were performed for a helicopter accelerating near the ground. This flight state can also be described as a transition from hover to forward flight. The helicopter starts free-flight in hover at z/R=1R and accelerates to 20 knots forward speed within 15 seconds with a constant acceleration. The NLDI controller controls the helicopter during free-flight and keeps the helicopter in the desired flight path.

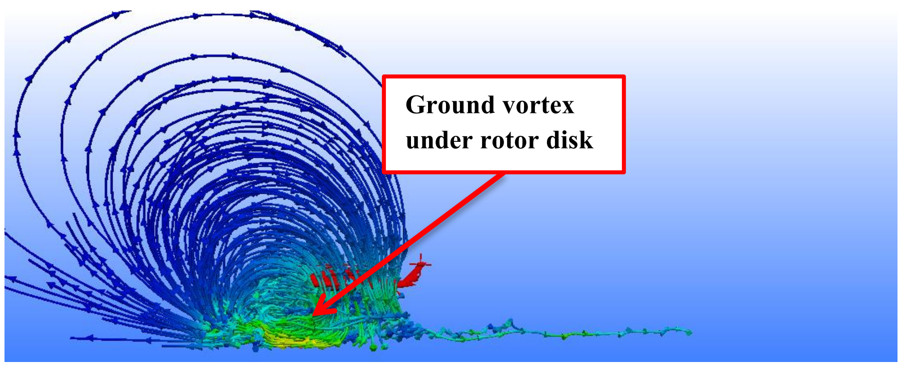
Figure 2 shows the streamlines around the helicopter at the 7.5th, 10th and 15th second of simulation. At these points, the helicopter flies with a forward speed V/v_h = 0.38, 0.51 and 0.8, respectively, where v_h is the theoretical induced velocity of the rotor in hover. A large outflow induced recirculation flow region outside ahead of the rotor tips can be observed at the beginning of the simulation from the figure. After a critical advanced ratio, this recirculation flow decreases in size and forms a flow pattern similar to the "ground vortex" under the rotor tip path plane.



a) $V/v_h = 0.38$



b) $V/v_h = 0.55$



c) $V/v_h = 0.8$

Figure 2 – Streamline distribution of rotor downwash of the simulated helicopter at different forward speeds, V/vh = 0.38, 0.55 and 0.8 respectively.

Figure 3-5 show the time history change of the response in position, attitude and control inputs of the helicopter for the fully coupled simulations of acceleration near the ground. Fully coupled simulations results have been compared with the no-coupling case. For the non-coupled simulations, the Pitt-Peters inflow model was used to predict the rotor induced inflow. It can be seen that when the simulation is fully coupled, there are fluctuations in the helicopter dynamics as a result of non-linear behavior of the rotor/terrain interactions. However these fluctuations are not as strong as we saw in the hover IGE cases. Helicopter shows slightly less pitch attitude (nose down) when the simulation is coupled. Moreover, when the simulation is coupled, at the beginning of the simulation helicopter requires less collective than the no-coupling case. However, after 7 to 8 seconds of the simulation when the forward speed (Figure 6) reaches $V/v_h \approx 0.4$, the helicopter needs higher collective compared to the no-coupling case. At this point, the recirculation flow formation starts to develop. The formation and the influence of recirculation flow is known to cause the rotor to experience a higher induced inflow than for hovering IGE [3], which increases power requirements slightly. Similar results have been obtained by Cheeseman and Bennett [9].

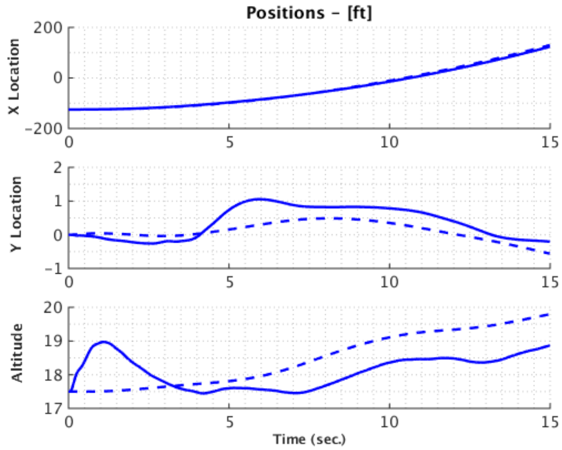


Figure 3. Variations in positions of the simulated helicopter accelerating IGE at z = 1R above ground.

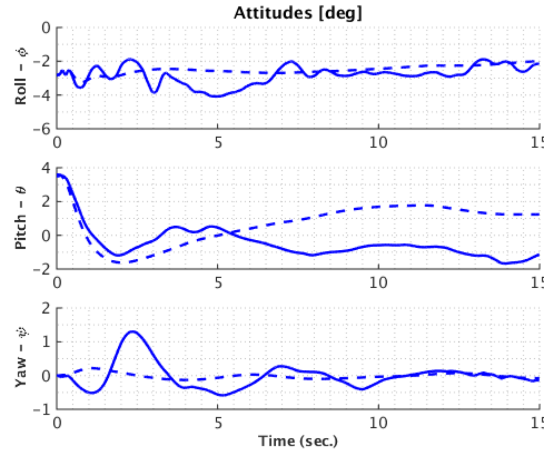


Figure 4. Variations in attitudes of the simulated helicopter accelerating IGE at z = 1R above ground.

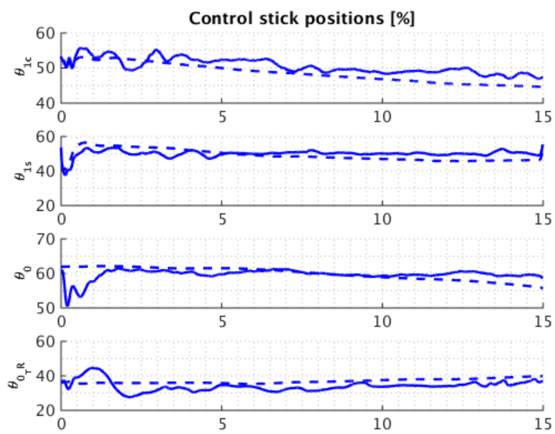


Figure 5. Variations in control response of the simulated helicopter accelerating IGE at z = 1R above ground.

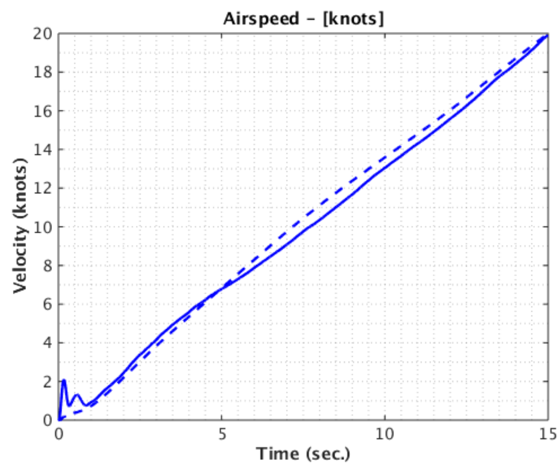


Figure 6. Variations in airspeed of the simulated helicopter accelerating IGE z=1R above ground.

Fully Coupled - Acceleration IGE

No Coupling - Acceleration OGE

2. Significance of Results

The rotor/terrain interactions for a helicopter hovering above ground level and accelerating near ground have been investigated for a variety of altitudes AGL and forward flight speeds. The predictions of hover power reductions due to the ground effect compare well to the experimental data. Use of fully coupled flight dynamics and CFD simulations for a helicopter accelerating near ground appears to predict a flow formation similar to the recirculation and ground vortex flow regimes that develops during transition to the forward flight. This gives confidence in the tool's ability to predict rotor-ground interactions. However, comparisons to additional data would be helpful to validate this.

3. Plans and upcoming events for next reporting period

The collaboration between Penn State and CRAFT Tech is still continuing. We have recently, implemented the CRAFT CFD code to the Penn State VLRCROE Flight simulator and performed first PILCFD tests at Penn State using COCOA5 clusters. The initial tests were performed with 1.1 million grid cells using 640 processors and verified that the network configuration works well and we are able to perform PILCFD test using the actual flight simulator and Penn State computing systems. Initial tests showed slightly slower performance than real-time (3x slower than real-time). We will be investigating the performance of system and figure out potential speed up gains by optimizing the network connection and grid that we used for the simulation.

4. References

[1] Lee, T. E., Leishman, J. G. and Ramasamy, M., "Fluid dynamics of interacting blade tip vortices with a ground plane," American Helicopter Society 64th Annual Forum Proceedings, 2008.

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[5] Mikkelsen, R., "Actuator disc methods applied to wind turbines," Ph.D. thesis, Technical University of Denmark, 2003.

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[7] Zbrozek, J., "Ground Effect on the Lifting Rotor", ARC R&M 2347, July 1947.

[8] Hayden, J.S., "The Effect of the ground on Helicopter Hovering Power Required," American Helicopter Society 32nd Annual National V/STOL Forum, Washington, DC, May 1976.

[9] Cheeseman, I.C. and Bennett W.E., "The effect of the ground on a helicopter rotor in forward flight," British ARC R&M 3021, 1955.

5. Transitions/Impact

No major transition activities during the reporting period.

6. Collaborations

We had several tele-conference meetings with CRAFT Tech during this reporting period. We have discussed potential efficiency improvements on the coupling interface.

The work continues to involve close collaboration between PSU, CRAFT-Tech, and NAVAIR.

7. Personnel supported

Principal investigator: Joseph F. Horn

Graduate Students: Ilker Oruc, PhD Student

8. Publications

Oruc, I., Horn, J.F., Shipman, J., and Shenoy, R., "Coupled Flight Dynamics and CFD Simulations of the Rotorcraft/Terrain Interactions," AIAA Journal of Aircraft. (This journal paper is currently in the revision process. We were asked to clarify a couple of simulation results. We are hoping to submit the final version soon.)

Oruc, I., Shenoy, R., Shipman, J., and Horn, J.F., "Toward Real-time Fully Coupled Flight Simulations of the Helicopter/Ship Dynamic Interface," American Helicopter Society Forum 72, West Palm Beach, FL, May 2016.

Oruc, I., Horn, J.F., Shipman, J., and Shenoy, R., "Coupled Flight Dynamics and CFD Simulations of the Rotorcraft/Terrain Interactions," AIAA Modeling and Simulation Technologies Conference, AIAA SciTech, San Diego, CA, January 2016.

Oruc, I., Horn, J.F., Polsky, S., Shipman, J. and Erwin, J., "Coupled Flight Dynamics and CFD Simulations of the Helicopter/Ship Dynamic Interface", American Helicopter Society Forum 71, Virginia Beach, VA, May 2015.

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10. Acknowledgement/Disclaimer

This work was sponsored by the Office of Naval Research, ONR, under grant/contract number N00014-14-C-0020. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of the Office of Naval Research, or the U.S. government.