Contract # N00014-14-C-0020

Pilot-in-the-Loop CFD Method Development

Progress Report (CDRL A001)

Progress Report for Period: May 1, 2015 to July 20, 2015

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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 the period of this report, fully coupled simulations of the helicopter hovering over a ship deck and approaching to a ship deck were performed using loose coupling approaches with an actuator disk model. Results show the successful implementation of the actuator disk model with 1D Gaussian distribution and the changes in both helicopter flight dynamics and ship airwake flow characteristics when the simulation is fully coupled.

Simulation Results

Implementation of an Actuator Disk Model with 1D Gaussian distribution to the GENHEL-PSU helicopter simulation code has been completed and results of initial tests including the Gaussian sensitivity tests to determine the optimal values of Gaussian shape function parameters were presented in the precious report. In the previous report, fully coupled simulations of the helicopter hovering in an open domain w/o ship airwake were presented. In the scope of this progress report, additional simulations were performed for the same helicopter (a model of UH-60 utility helicopter) hovering over a ship deck and approaching to a ship deck and results. All calculations were performed using parallel computing with 128 CPUs on the COCOA4 cluster at Penn State.

Hover over a Ship Flight Deck

Simulations were performed with a helicopter hovering over the SFS2 flight deck with ship airwake effects. As described in the previous progress report, a similar procedure was applied as Case I (Phase I: 5 seconds of freeze, Phase II: 25 seconds in free-flight mode). The one-way coupled case was also performed with the ship airwake database approach.

Figure 1 and Figure 2 show the distribution of the streamlines released from horizontal and vertical line sources located above the superstructure of the ship. The interaction between the main rotor downwash and the ship airwake can be observed from the figures. In addition, trailing vortices generated by the main rotor are clearly visible.

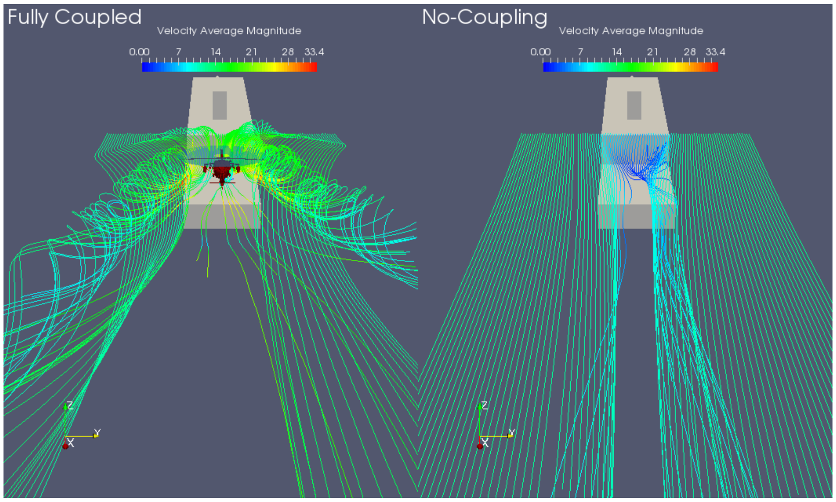

Figure 1 – Distribution of streamlines released from a horizontal line source above the superstructure of the ship.

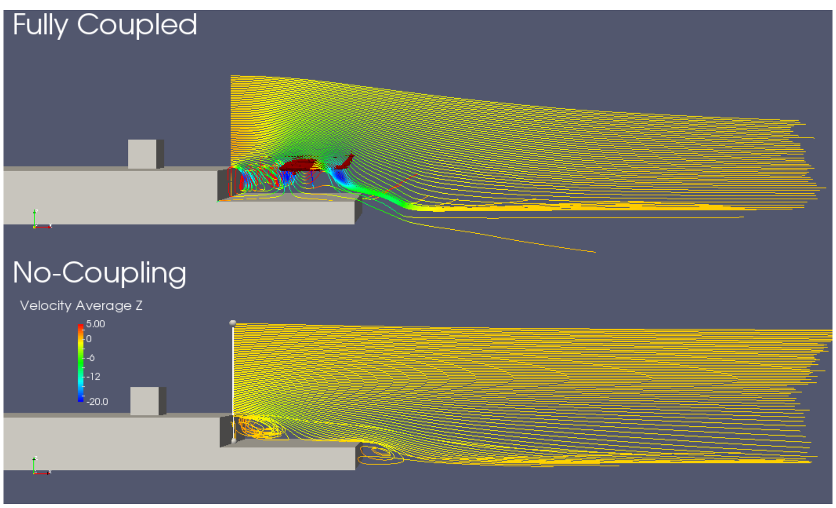

Figure 2 – Distribution of streamlines released from the a vertical line source above the superstructure of the ship

A visual representation of shedding vortices from the superstructure of SFS2 ship and trailing edge of the main rotor for both no-coupling and fully coupled cases can be seen on Figure 3. When the simulation is fully coupled, the impact of rotor downwash-ship airwake interaction changes the whole characteristics of the flow around flight ship deck. The flow around ship flight deck is much more turbulent when the simulation is fully coupled compared to the no-coupling case.

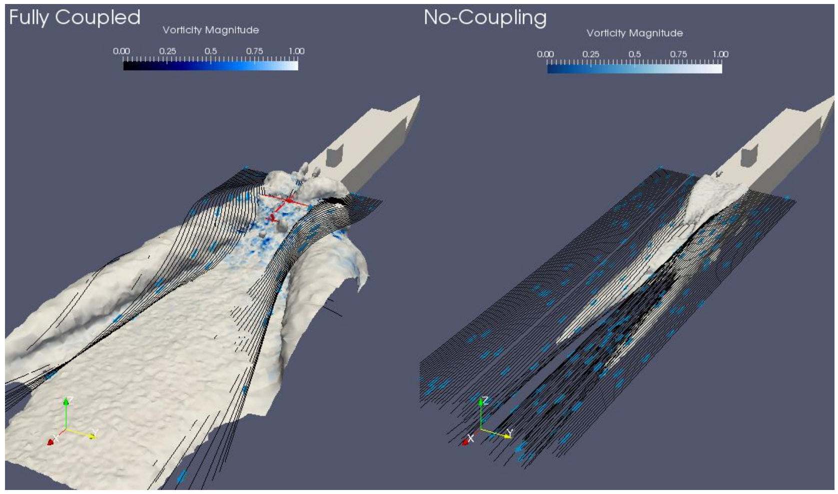

Figure 3 – Shedding vortices from ship superstructure

Figure 4 - Figure 6 show the time history change of the response in position, attitude and control inputs of the helicopter during hover for the no coupling (w/o airwake), one-way coupled (w/ airwake database) and fully coupled (simultaneous CFD solution of coupled airwake) cases.

It can be seen that the controller holds the helicopter within ±5 ft. range of the original position despite the effects of the ship airwake. The significant effect of the ship airwake can be observed from the attitudes and the pilot inputs. Note that the fully coupled solutions show the initial transient at 5 seconds as GENHEL-PSU enters free flight mode.

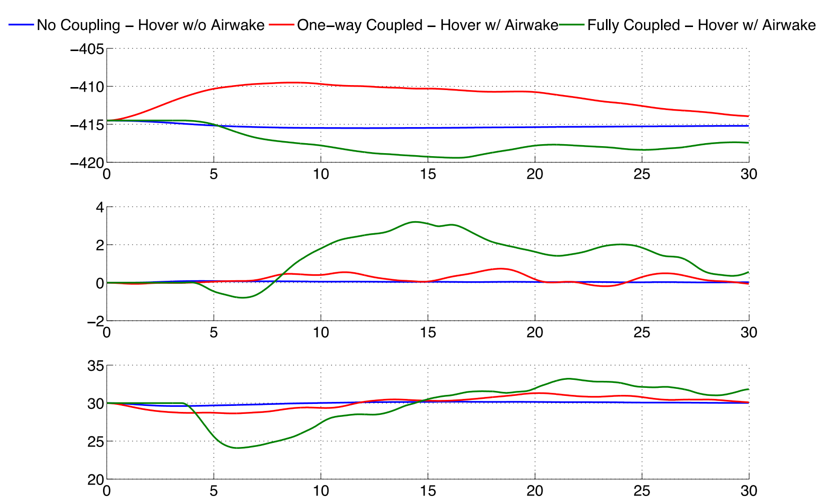

Figure 4 - Variations in position of the simulated helicopter hovering over the SFS2 flight deck.

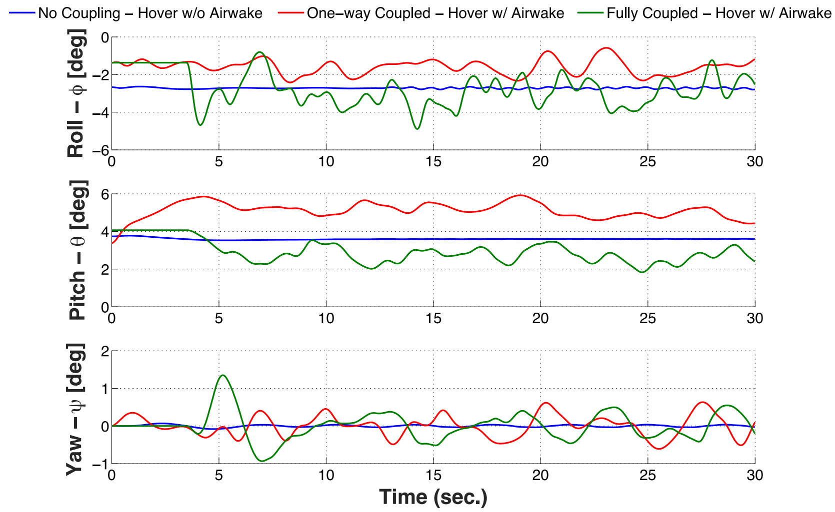

Figure 5 - Attitude response of the simulated helicopter hovering over the SFS2 flight deck.

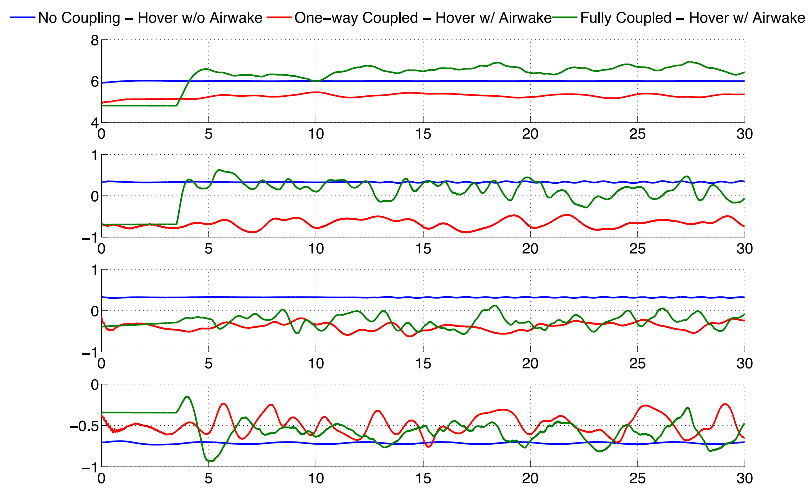

Figure 6 - Control responses of the simulated helicopter hovering over the SFS2 flight deck.

Approach to the Ship Flight Deck

The last fully coupled simulations were performed with a helicopter approaching the ship deck with ship airwake effects. Figure 7 shows the approach flight path of the helicopter during the simulation. A total of 40 seconds of simulation have been performed (Phase I: 5 seconds in freeze mode; Phase II: 35 seconds in free-flight mode). Fully coupled results have been compared with the no coupling and the one-way coupled cases. The same approach path has been used for all three cases.

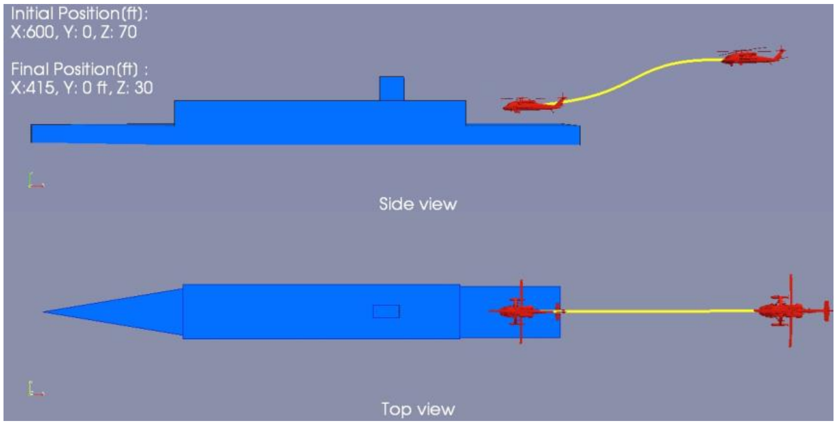

Figure 7 – Path used in ship approach simulations.

Figure 9 show that the controller successfully tracks the flight path and holds the helicopter position within ±5 ft. of the desired path. Figure 8 shows the vertical velocity distribution in the flow with the helicopter approaching the ship deck in the fully couple case.

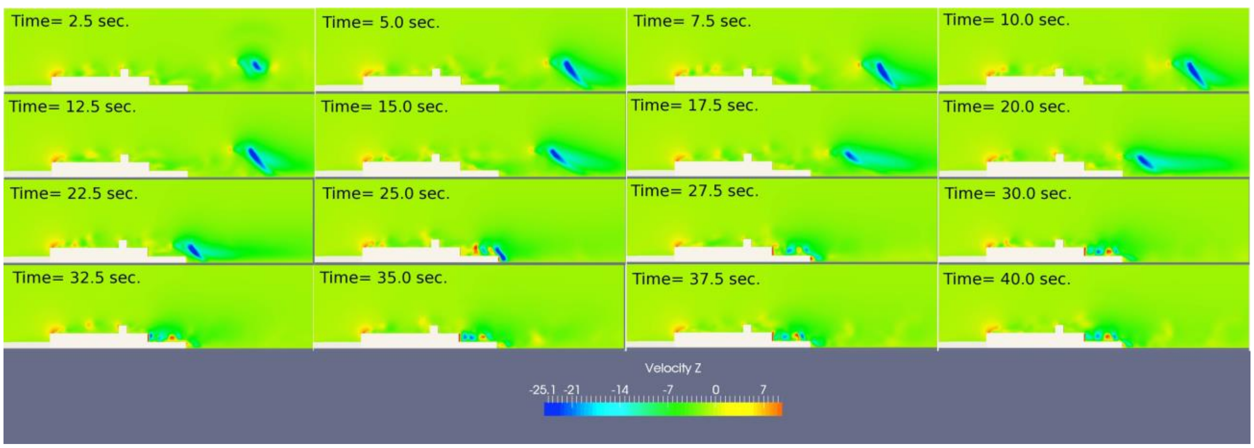

Figure 8 - Vertical velocity distributions with helicopter approaching the ship deck for the fully coupled case.

Figure 9 – 11 show the time history change of the response in position, attitude, pilot inputs and the thrust of the helicopter as it approaches the ship deck by following a specified path for the no-coupling, one-way and fully coupled cases. As it can be noted from Figure 10, after the 25th seconds of the simulation, there is a higher fluctuation on the roll dynamics of the helicopter compared to the first 25 seconds of the simulation. Additionally, a very similar fluctuation can also be observed on the thrust variation of the helicopter within the same time frame (Figure 12). After 25th second, helicopter starts flying over the ship flight deck and gets very close the superstructure of the ship. This behavior can be a result of both rotor-ground/wall interaction and flying within a close proximity of the vortical flow with a high internal energy shedding from the superstructure of the ship. A similar behavior had also been observed on the fully coupled simulations for a helicopter hovering in ground effect w/o ship airwake on (Hover IGE/OGE results were presented in the previous progress report). We will investigate this behavior in more detail in the scope of next progress report.

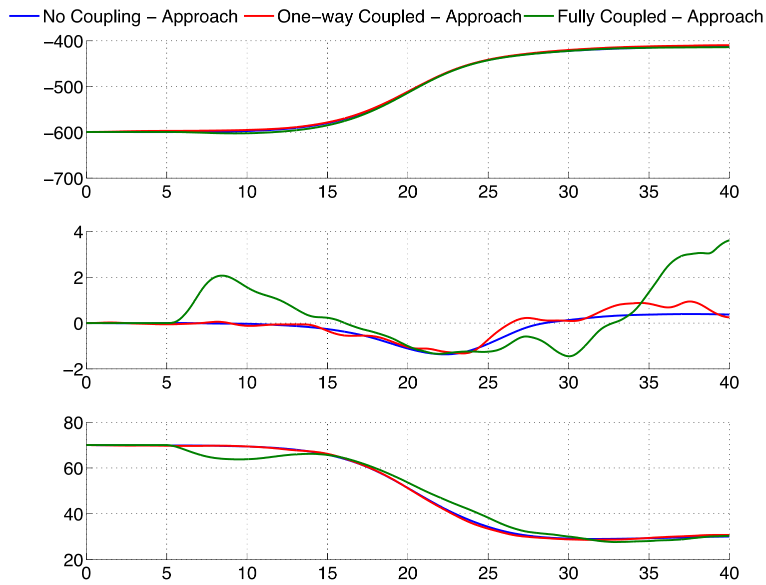

Figure 9 - Variations in position of the simulated helicopter approaching the ship.

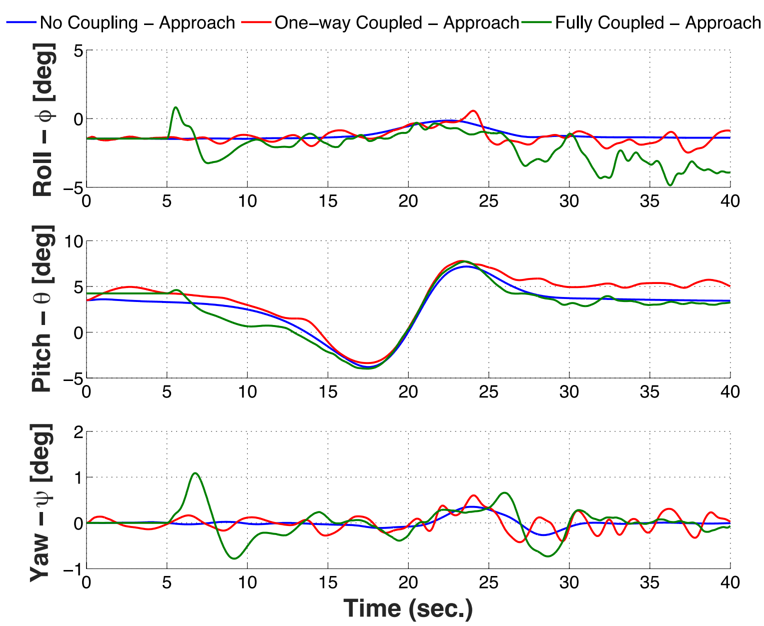

Figure 10 - Attitude response of the simulated helicopter approaching the ship.

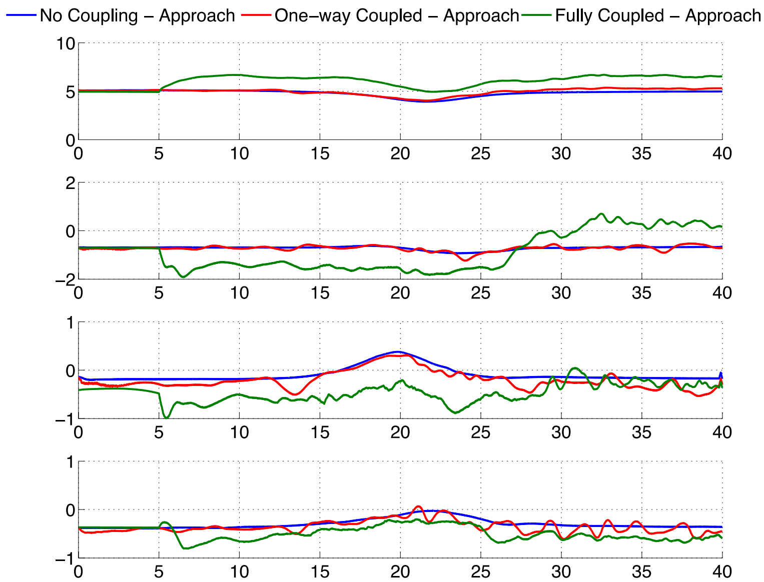

Figure 11 - Control response of the simulated helicopter approaching the ship.

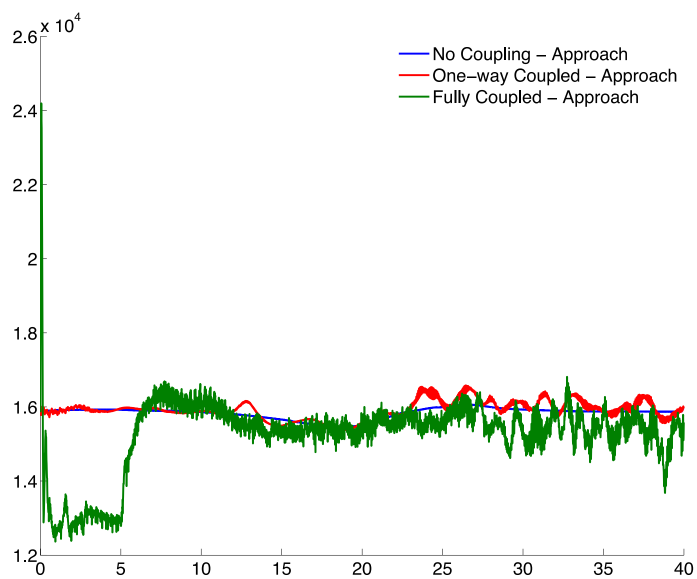

Figure 12 – Variations in thrust of the simulated helicopter approaching the ship.

Computational Performance

As noted earlier, all simulations were performed on the COCOA4 cluster at Penn State. At this point, relatively little effort has been devoted towards improving computational efficiency of the simulations by Penn State. No special optimization was performed on the computing hardware or software. For example, data exchange between the GENHEL-PSU simulation and the CRUNCH CFD® solver is performed using file IO. More efficient methods of data exchange will be required in the future.

For the hover simulations in the open-domain, fully coupled simulations required approximately 15 seconds of wall clock time per time step, where one time step is 0.01 seconds. For the cases with the SFS2 grid, fully coupled simulations required 35 seconds/time step. In both cases 128 CPUs were used in the parallel computations. These represent simulations that are slower than real-time by factors of 1500 and 3500 respectively.

2. Significance of Results

The results successfully show the change of both helicopter flight dynamics and ship airwake flow characteristics when the simulation is fully coupled. On the approach to ship flight deck case, we have observed the impact of both rotor/ground interaction and increased ship airwake disturbances on the rotorcraft dynamics when the rotorcraft flies over the flight deck. However, at this point the simulations are still far from real-time. Much of the future efforts will be devoted to increasing efficiency and computational speed.

3. Plans and upcoming events for next reporting period

- The flight dynamics behavior of the helicopter in IGE condition will be investigated in more detail. In order to verify the CFD predictions, predicted outwash flows will be compared with recently published measurement data.
- The effects of tail rotor thrust will be added to the coupled simulations.
- We have started working on a new communication interface between the CFD solver and simulation model that is optimized for a faster coupled simulation process. The “Multiple Program Multiple Data” approach has been selected for the new communication interface via the Message Passing Interface (MPI) communication protocol, which is commonly used for operating two independent programs simultaneously in high performance computing applications. In this approach, typically one node is picked to be the manager (Manager/Worker strategy) which runs one program that farms out data to all the other nodes which all run a second program. Those other nodes then return their results directly to the manager. Efforts towards implementation of this approach are still ongoing, but nearly completed at the end of this quarter.
- We have a meeting planned with CRAFT Tech in August 2015 to work towards a real-time demo of fully coupled simulations. PSU will port the coupled GENHEL-PSU code and X-Plane graphics interface to CRAFT Tech. CRAFT Tech will couple this code with their more efficient structured grid solvers and implement on their computing cluster. Communcations will use MPI as discussed above. We hope to achieve a real-time (or at least near real-time) demo of pilot-in-the-loop simulations with fully coupled CFD and a simple ship structure shape within next quarter.

4. References

No reference.

5. Transitions/Impact

No major transition activities during the reporting period.

6. Collaborations

Penn State has collaborated with CRAFT Tech and conducted regular discussion with them.

7. Personnel supported

Principal investigator: Joseph F. Horn

Graduate Students: Ilker Oruc, PhD Student

8. Publications

The paper "Coupled Flight Dynamics and CFD Simulations of the Helicopter / Ship Dynamic Interface" presented at AHS Forum 71 in the Simulation & Modeling session on May 7, 2015 at Virginia Beach, VA. The final paper has been published in the proceedings.

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