Contract # N00014-14-C-0020

Pilot-in-the-Loop CFD Method Development

Progress Report (CDRL A001)

Progress Report for Period: November 1, 2014 to January 31, 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), 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.

2. Activities this period

During the period of this report, the loose and hybrid coupling integration of the CRUNCH flow solver and the GENHEL-PSU helicopter simulation code has been completed. An actuator disk model approach was implemented to the GENHEL-CRUNCH coupling interface, and initial simulations of the helicopter hovering in an open domain were performed using hybrid coupling and loose coupling approaches with the actuator disk model. It is expected that a loose actuator disk model coupling will provide significantly faster and more stable flow solutions over tightly coupled simulations.

Implementation of the Actuator Disk Model with Loose Coupling Approach

To resolve the full geometry of the helicopter blades in a CFD simulation is computationally too expensive. So, instead of resolving the geometry of a full helicopter blade, the actuator disk model (ADM) and the actuator line model (ALM) can be used as less expensive alternatives [1]. ALM represents the blades as a set of segments along with each blade axis and the ADM represents the entire rotor as permeable disc of equivalent area where forces from the blade are distributed on the circular disc. The distributed forces on the actuator disc or actuator line alter the local flow velocities through the disc and in general the entire flow field around the rotor disc [2]. ADM and ALM are two very popular approaches for rotor disk CFD simulations [3-5].

During the previous studies of this project, implementation of the ALM approach had been used, and the results were presented in the previous progress reports. It was seen that the ALM approach is easier to implement than resolving the full blade geometry (as is used for true tightly-coupled simulations) and results have enough accuracy for fully coupled flight dynamics simulations. However, the actuator line model approach still requires a form of tight coupling, in that the CFD and dynamic model must operate and exchange data at a high frame rate (only a few degrees of blade sweep per step at the maximum). This is computationally too expensive and real-time simulation is less feasible.

As mentioned above, the actuator disk model approach is another simpler way to model rotor blades in CFD calculations and it was shown that this assumption gives equivalent to the time averaged induced velocity of a rotor having finite number of blades [4]. Moreover this approach allows using the loose-coupling approach in the simulations. Loose coupling approach minimizes the data exchange frequency between rotor flight dynamics code (GENHEL-PSU) and the flow solver (CRUNCH CFD). It is also expected that loose coupling will result in more numerically stable CFD solutions, since a more evenly distributed set of smaller magnitude source terms are implemented in the flow solver. In the ALM approach, a smaller set of highly dynamic and higher magnitude source terms are introduced. So it is possible that the ADM method will also speed up computation, since the CFD solver iterations will converge more rapidly. It has been decided to implement an ADM with loose coupling approach in the current GENHEL-PSU simulations. However, the loose coupling methods are more complex to implement, since it requires storing and interpolation of blade load and blade velocity data over several blade steps. So much of this reporting period was devoted to development and debugging the code to implement this method.

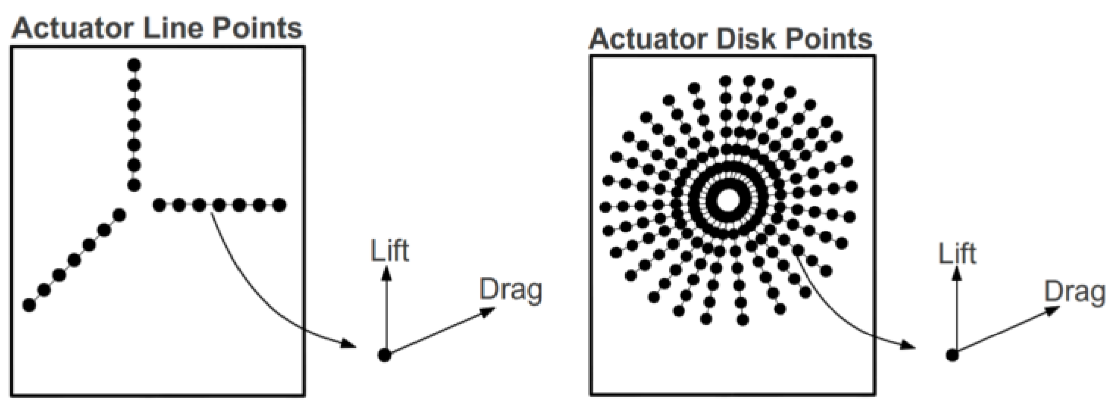


Figure 1 – A schematic of Actuator Line Model (ALM) and Actuator Disk Model(ADM)[1].

GENHEL works with a time step of 0.01 sec and each main rotor blade sweeps ~15.47 azimuth degrees in this time step. As mentioned before, in fully coupled solutions, blade positions and aero loads are transmitted to the CFD code; the CFD code then calculates a velocity field (including the induced velocities from the aircraft airloads) and sends these velocity values back to the helicopter simulation model. Moving rotor blades 15.47 azimuth degree per time step will also move the source terms, written on the CFD domain, through more than one grid cells within a time step and this can result in instability in CFD flow calculations. So a smaller azimuth degree increment per time step is needed for accurate CFD calculations. Using a “Multi Step Rotor” feature of GENHEL can decrease azimuth degree increment of each blade per time step. In this purpose, GENHEL was set to run with “Multi Rotor Step=5” which decreases the azimuth degree increment of each rotor blade per time step to 15.47/5=3.094 Ψ/dt. As mentioned before, in fully coupled simulations, GENHEL writes the blade segment loads and positions first and then CRUNCH returns back the induced velocity information to the GENHEL for the next blade segment loads and positions calculations. This approach requires GENHEL to use the previous value of induced velocities in time. But since the blades are flexible and freely moving along the rotor disk, usually the blades do not pass through the same azimuth degree. Using the value of the closest blade point can be a solution with a small error but this might lead inaccurate results on longer simulations. Although, using the interpolation techniques, this error can be minimized and the most accurate induced velocities at desired query points over the rotor disk can be found. This interpolation can be done on either CFD side or GENHEL side. We have decided to do the interpolation on GENHEL side to minimize the data exchange load.

Implementation of Interpolation Approach

The general approach of the actuator disk model is to use a cloud of point with fixed locations relative to the rotor disk center. Rotating a line of points over the entire disk with 3 azimuth degree increments creates a uniformly distributed cloud of data points. As described in the previous section, in this approach all the source terms will be interpolated onto these fixed cloud of data points (instead of applying source terms at the actual blade positions). The process of interpolation consists of a couple of steps. First GENHEL calculates the load terms for each blade segment. These loads are sent to the CRUNCH-GENHEL coupling interface subroutine and the blade segment loads are stored until 5 iterations (0.01sec) are completed. The same subroutine calculates the interpolated value of the nearest data points on the actuator disk point cloud based on the actual values of the blade segment loads, using a 3th order polynomial interpolation method. This process repeats until a quarter of revolution ($1/N_b$) is completed so GENHEL can write positions and the load terms of the entire disk. This information is passed to the CFD solver and the CFD solver returns back the induced velocity information of the entire disk at the same coordinate positions. Then GENHEL calculates the required induced values at the related azimuth degree for each blade by interpolating the nearest five data points on the actuator disk grid until the next quarter revolution is completed. The block diagram of the interpolation process can be seen in Figure 2.

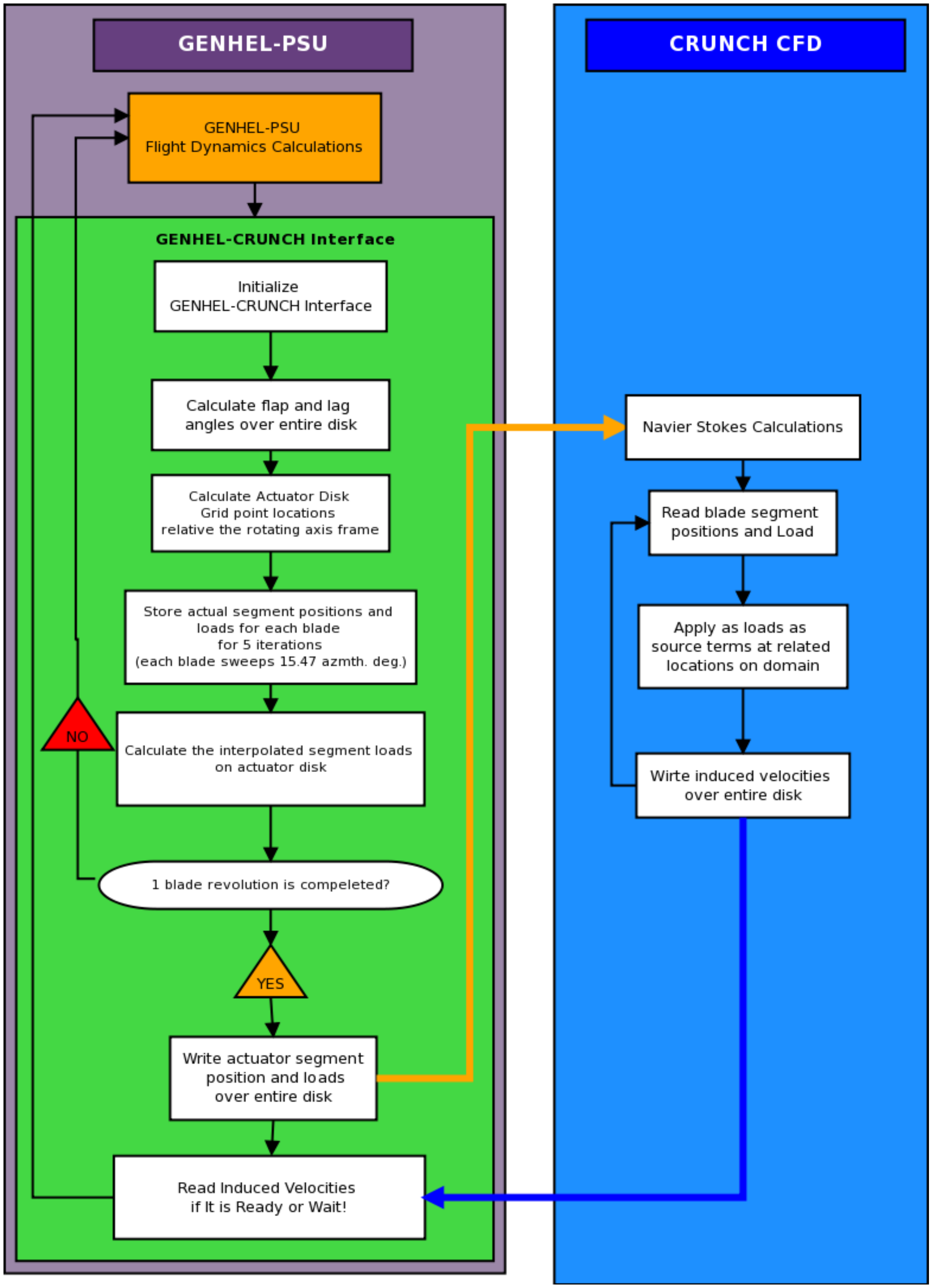


Figure 2 - GENHEL-CRUNCH Coupling Interface

Implementation of a Partial Actuator Disk Model with Hybrid Coupling

Hybrid coupling is a combination of tight and loose coupling approaches, and the partial actuator disk model can be seen as a combination of ALM and ADM approaches. In this approach, data is exchanged on every each time step as in tight coupling but this time blades are represented as a permeable disc of equivalent area where forces from the blades are distributed on the partial circular disc similar to the actuator disk model. Figure 3 shows a schematic of Partial Actuator Disk Model approach.

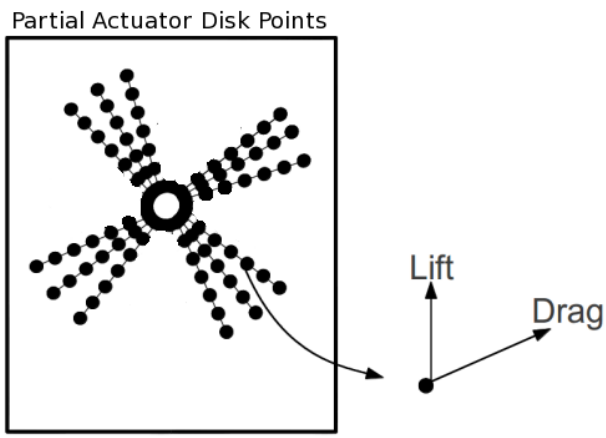


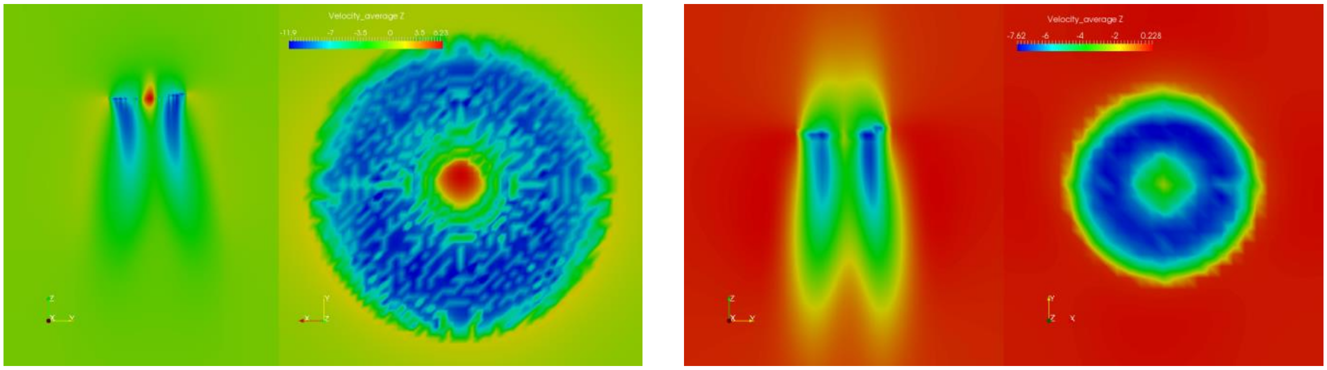
Figure 3 - A schematic of Partial Actuator Disk Model Approach

It is expected that, this approach could combine the advantages of the ALM approach with the advantages of the ADM and eliminate the disadvantages of both models.

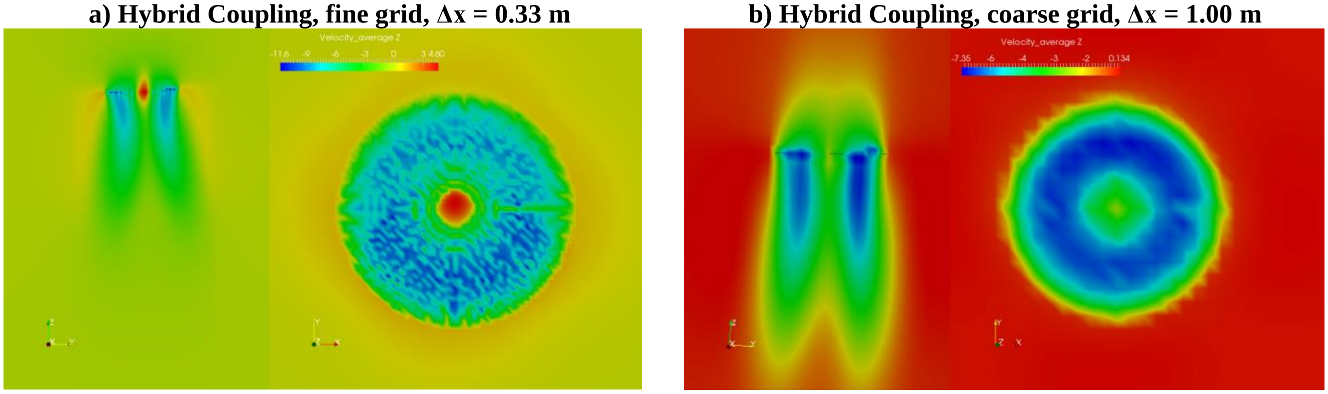
Initial Simulation Results

Hybrid-coupling and loose-coupling approaches have been implemented to GEHNEL-PSU and the initial tests have been performed with a helicopter hovers in an open domain case. It should be noted there has been relatively little work towards true optimization and large speed ups on the PSU side of the work (for example at this point we are still exchanging data using file IO). The idea is to resolve the methodology and then move towards large speed ups approaching real time. The current simulations are run much slower than real-time.

For the initial tests, the helicopter body was fixed at a point in space during the simulations and the helicopter rotor was allowed to run freely. The simulations were calculated using CRAFT Tech Navier Stokes flow solver and the COCOA4 supercomputer with 128 processors have been used to run the simulations. The tests using loose-coupling approach were needed approximately ~30 seconds per iteration. And the tests using hybrid-coupling approach were needed approximately ~60 seconds per iteration. The tests are also performed with two different grid refinement levels with $\Delta x = \Delta y = \Delta z =$ 0.33 m and 1.00 m. Using the finer and coarser grid refinement levels, one rotor blade is modeled with ~30 and ~10 grid cells, respectively.



a) Hybrid Coupling, fine grid, Δx = 0.33 m **b) Hybrid Coupling, coarse grid, Δx = 1.00 m**



c) Loose Coupling, fine grid, Δx = 0.33 m **d) Loose coupling, fine grid, Δx = 1.00 m**

Figure 4 – Time-averaged vertical velocity distributions on downwash and rotor disk plane for hybrid and loose coupling cases with fine and coarse grid refinement levels.

Figure 4 shows the time-averaged distributions of vertical velocities on both downwash and rotor disk planes for hybrid and loose coupling cases with fine and coarse mesh resolutions. Results show that we get a very similar flow distribution when the same grid resolution is used. For both hybrid and loose coupling approaches induced velocities reach to their maximum values of -11.7 m/s and -7.4 m/s when the fine and coarse mesh resolutions are used, respectively.

Figure 5 and Figure 7 show the distributions of vertical velocity on the rotor disk plane using the loose and hybrid-coupling approaches with different grid refinement levels at two different simulation times. Figure 5 show the flow development over the rotor disk plane at the beginning of the simulation, at t = 0.2 sec. The flow develops much slower when a coarser grid resolution is used. Also the difference between the tight and loose coupling cases with finer grid resolution can be seen from the results. It appears that when hybrid coupling is applied the blade skips some cells without applying a source term. However, when the flow is fully developed (Figure 5), the induced flow distribution is very similar for both loose and hybrid coupling cases when the grid resolutions are the same.

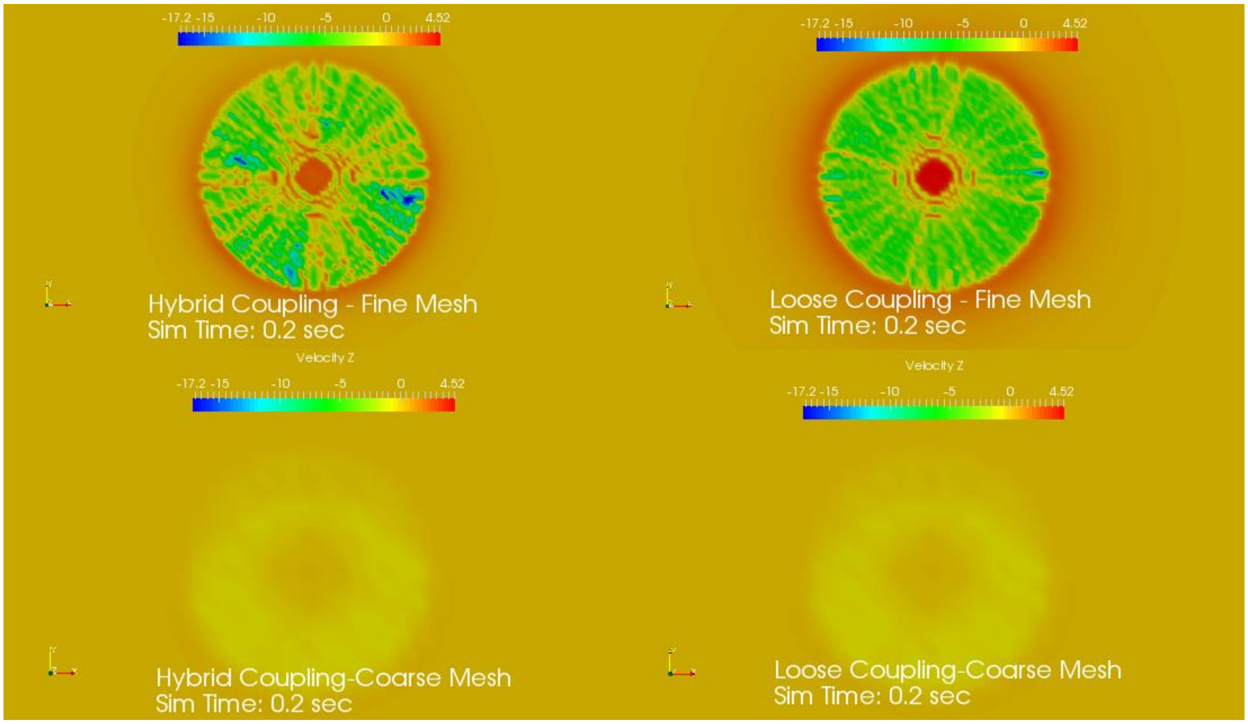


Figure 5 – Comparisons of vertical velocity developments over rotor disk plane using Hybrid and Loose Coupling approaches with fine/coarse mesh resolutions, at Simulation time: 0.2 sec

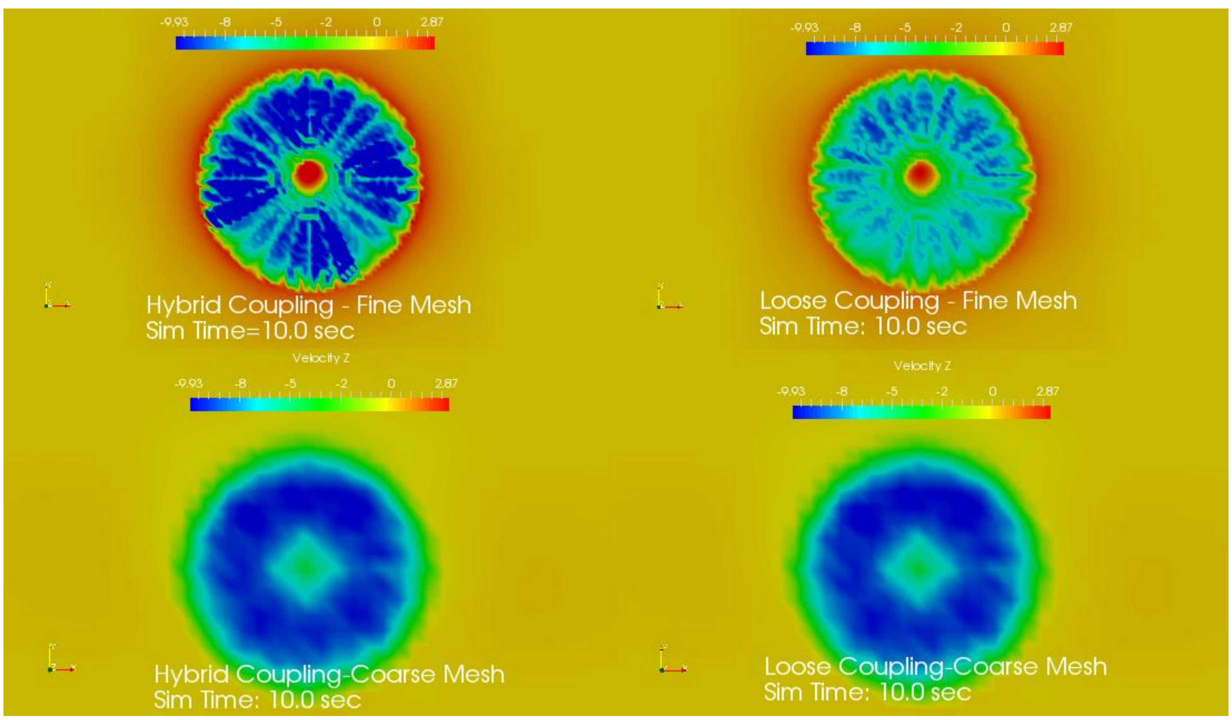


Figure 6 - Comparisons of vertical velocity development over rotor disk plane using Hybrid and Loose Coupling approaches with fine/coarse mesh resolutions, at Simulation time: 10.0 sec

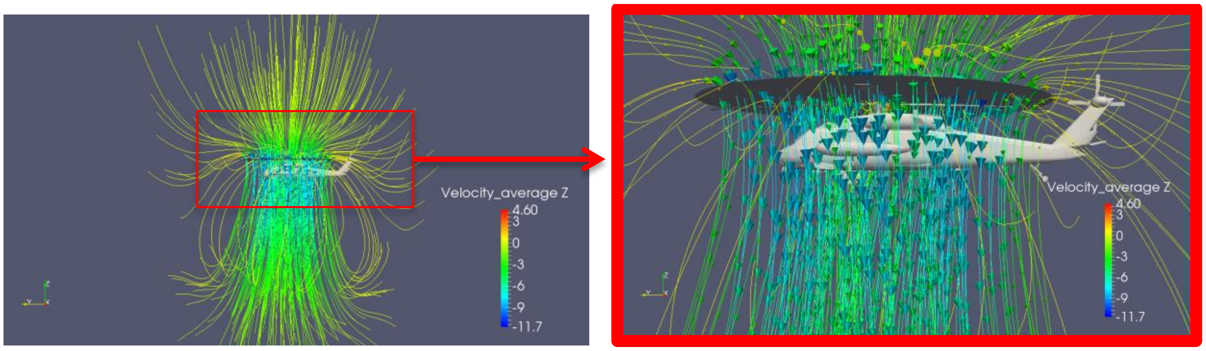


Figure 7 – A distribution of streamlines above, over and below rotor disk plane

Figure 7 - Figure 9 show the time-averaged streamline distributions of the flows above, over and below the rotor disk plane. The contraction on the induced flow can be clearly observed from Figure 7. Figure 8 show that the streamline distributions are very similar for both hybrid and loose coupling when the same grid refinement level is used. However the flow is more turbulent when a finer grid resolution is used. The finer grid resolution leaves some gaps between the blade segments as can be seen in Figure 4. This indicates that a more dense distribution of radial source terms will be in the ADM and ALM methods. I.e. the source term distribution should be at least as refined as the CFD mesh.

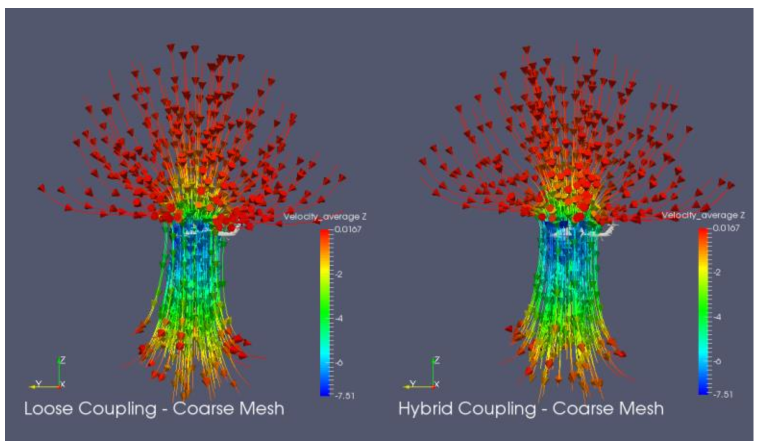


Figure 8 – Distributions of streamline using Hybrid and Loose coupling approaches with coarse mesh resolution.

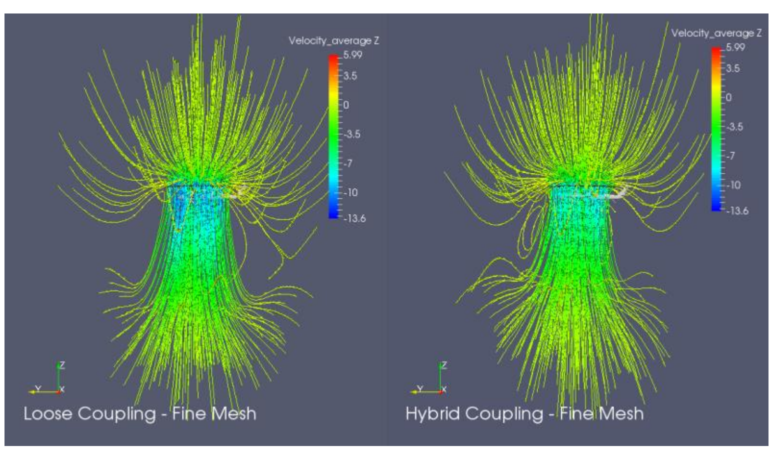


Figure 9 - Distributions of streamline using Hybrid and Loose coupling approaches with fine mesh resolution.

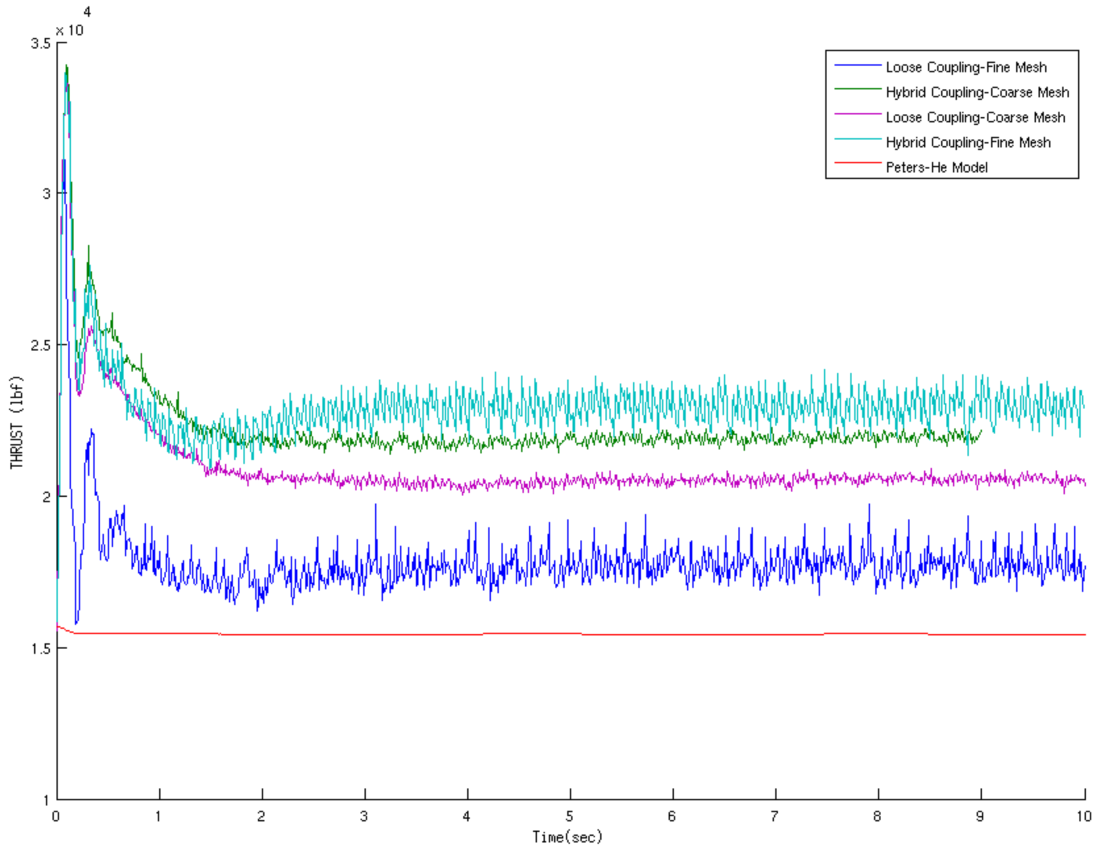


Figure 10 – The time-variation of calculated Thrust values based on the predicted induced velocity on rotor disk plane

Figure 10 shows comparison of the time-variation of calculated thrust values based on the predicted induced velocities on rotor disk plane by CFD and the Peters-He inflow model. Results show that the loose coupling with a finer grid refinement level calculates the highest induced velocity distribution over rotor disk plane so as the closest thrust values calculated by the Peter-He inflow model. It is well known that, rotor CFD calculations will be more accurate when the more detailed turbulence models are used and full rotor blade geometry is resolved. Also it is known that grid resolution is an important parameter on the CFD predictions. Results show that when ADM, ALM or partial-ADM approaches are applied; induced flow velocities over rotor disk plane are under-predicted. However it can be seen that, using loose coupling with finer grid refinement level, losses can be minimized and calculated thrust can get very close to the Peters-He inflow model predictions.

3. Significance of Results

The results show the successful implementation of hybrid and loose coupling approaches to the GENHEL-PSU. An interpolation method has been developed to interpolate the actual blade segment loads to an actuator rotor disk grid. The results will provide faster simulation speeds compared the tight coupling, which was implemented on the previous report. The validation tests of hybrid and loose coupling methods are still ongoing and the more detailed simulation results will be presented on the next progress report.

4. Plans and upcoming events for next reporting period

- Continue development of fully coupled simulations: Implementation of better spatial blending will be done for ALM, ADM, and hybrid approaches.
- A uniform radial grid formation will be used on the next simulations to see if the mapping of circular blade loads on the Cartesian structured grid is resulting in errors.
- Communication interface will be optimized for faster simulation process. We are currently using file IO.
- Discrepancies between inflow solutions from the coupled CFD and with traditional inflow models will be further investigated.
- We will look at some more forward flight and ship cases.

5. References

[1] Martinez, L., Leonardi, S., Churchfield, M., Moriarty, P., & Mart, L. a. (2012). A Comparison of Actuator Disk and Actuator Line Wind Turbine Models and Best Practices for Their Use. *50th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition*, 1-13 January.

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[5] Stepniewski, W.Z., and Keys, C.N., Rotary-Wing Aerodynamics Vol. 1, Basic Theories of Rotor Aerodynamics, Dover Publications Inc., Newyork, 1984, Chapter 4, pp. 154-159.

6. Transitions/Impact

No major transition activities during the reporting period.

7. Collaborations

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

8. Personnel supported

Principal investigator: Joseph F. Horn

Graduate Students: Ilker Oruc, PhD Student

9. Publications

An abstract with a title of “Coupled Flight Dynamics and CFD Simulations of the Helicopter / Ship Dynamic Interface” was accepted to the AHS Forum 71 “Simulation & Modeling” session.

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