ABSTRACT

A fully-coupled simulation tool has been developed to analyze the rotorcraft/ship dynamic interface problem. An existing computational fluid dynamics code and a flight dynamics simulation model have been coupled for this purpose. The flight dynamics model provided the location and orientation of the helicopter and the main rotor as well as the blade loads while the computational fluid dynamics code provided local air velocities. Computations have been performed for a UH-60A hovering behind an aircraft hangar and approaching an LHA class ship. For the solutions the flowfield is assumed to be inviscid and atmospheric turbulence and boundary layer effects have been neglected. The results show that when the helicopter is operating in ground effect or close to solid structures, the interactions between the airwake and the rotor wake can invalidate the one-way coupled solutions.

INTRODUCTION

Shipboard launch and recovery operations of rotorcraft continue to be of significant concern to both military and civilian operators. The effects of unsteady airwake and deck motion can significantly increase pilot workload resulting in safety issues for ship-based rotorcraft. Over the last 15-20 years there has been a significant amount of work devoted to developing tools to analyze the dynamics of the helicopter, the ship, and the aerodynamic interactions between the two. Ultimately these tools are used in simulation models to help train pilots, define safe operating envelopes, and to develop better procedures for shipboard operations. The problem is extremely complex due to the complex flow fields over the ship coupled with the complex dynamics and aerodynamics of a rotorcraft. Previous studies have made a number of simplifying assumptions to make the problem more tractable. These assumptions include:

1) Neglecting the time-varying component of the ship airwake.
2) Assuming the ship airwake is frozen with respect to the ship, and not affected by ship motion.
3) Neglecting the effect of atmospheric turbulence and the atmospheric boundary layer.
4) Simplified representation of the effect of ship deck on the rotor wake (simplified ground effect).
5) Assuming some sort of one-way coupling in modeling interactions between ship / helicopter aerodynamics and dynamics.

There has been some significant progress in overcoming the first four assumptions, but the fully-coupled problem of helicopter / ship aerodynamics and flight dynamics has not been solved. Current tools rely heavily on one-way coupled simulations, in which the rotorcraft experiences disturbances due to a pre-calculated Computational Fluid Dynamics (CFD) ship airwake, but the ship airwake CFD solutions are unaffected by the downwash of the rotors [1]. This approach has been necessary to achieve real-time execution in flight simulators since the computational requirements of CFD make it unfeasible to perform real-time solutions [2]. However, the unsteady and nonlinear nature of both ship and rotor wakes invalidates superposition and thus the uncoupled solutions are somewhat questionable [3]. This situation becomes more severe when the aircraft has multiple rotors or there are more than one aircraft in the vicinity of the ship. A fully-coupled solution is necessary for correct understanding of the rotorcraft-ship dynamic interface problem. The fully-coupled solution can then be used to determine when simplified one-way coupled models give acceptable results and identify cases where they are invalid. Furthermore, the fully-coupled solution can be used as a baseline from which one can derive more accurate simplified models capable of running in real-time.
OBJECTIVE

This paper presents a method for calculating a coupled solution of the vehicle flight dynamics and the flowfield of the ship airwake and rotor downwash. An existing CFD code (PUMA2) capable of calculating ship airwakes [2] has been modified to include source terms that model the induced flow due to a lifting rotor. This code has been coupled to an existing flight dynamics simulation of a UH-60 helicopter (GENHEL) [4], which has been modified to incorporate external flow disturbances from CFD solutions [1]. The two codes run simultaneously, where the flight dynamics simulation calculates the location and orientation of the aircraft and the blade loading, while the CFD calculates the local air velocities on the main rotor and over the body of the aircraft. The CFD solutions effectively provide the flight dynamics simulation with both a ship airwake model as well as a dynamic inflow model with ground effect. The flight dynamics simulation provides the information on the strength and location of the source terms required to model the rotors in the CFD analysis. Since the simulations do not run in real-time, a pilot model has been used to simulate the desired trajectories [1], [5]. The ship motion could also be included in the analysis using moving boundary conditions, but this is beyond the scope of the current study.

FULLY-COUPLED SIMULATION PROCEDURE

Fully-coupled solutions have been achieved by running PUMA2 and GENHEL concurrently. This is somewhat complicated because PUMA2 requires a parallel computer, but GENHEL runs on a serial computer. During the solutions GENHEL provides location and orientation of the aircraft and rotors, and the loading on each blade. Using these blade loadings as source terms, PUMA2 computes the flow velocities at the desired locations; and thus provides an airwake and a dynamic inflow model for GENHEL. Communication between the codes is performed at each GENHEL time step which is 0.01 seconds. When a code finishes its computations it writes an output file and notifies the other code that it has finished its computations. When the other code reads this file it sets a check parameter to zero after reading the data. This is done to prevent the possibility of reading old data as if it were new.

CFD METHODOLOGY

In this study viscous effects have been neglected and the Euler Equations were used to define the unsteady flowfield. The effect of the rotor was introduced into the solution using momentum sources which were added to the momentum and energy equations. Numerical solutions were obtained by modifying the in-house computational fluid dynamics code PUMA2, which is an unstructured finite volume code written in ANSI C++. PUMA2 was run in parallel using MPI [8].

Two approaches were used to obtain the magnitudes of the momentum sources. In the first approach, the sources were time-averaged for a single blade passage time and the magnitudes were obtained using blade element theory [9], [10]. This approach is similar to modeling the rotor as an actuator disk. In the second approach source magnitudes were computed using the blade loadings obtained from GENHEL. In both methods the effect of the rotor has been included to each computational cell as a force-per-unit volume term. The models do not require a well-defined rotor plane inside the computational mesh. Therefore, source terms can be easily moved inside the domain to simulate the rotor and/or the blade motion. These methods can also be used for more than one rotor simultaneously, thus allowing for multiple rotor analyses. PUMA2 has also been modified to include atmospheric boundary layer effects which may be important when the rotorcraft is in ground effect or in the vicinity of a ship.

The integral form of the Euler equations with the rotor force term can be written as follows:

\[
\frac{\partial}{\partial t} \int_{\Omega} \rho d\Omega + \int_{S} \rho \mathbf{V} \cdot \mathbf{n} dS = 0 \quad (1)
\]

\[
\frac{\partial}{\partial t} \int_{\Omega} \rho \mathbf{V} d\Omega + \int_{S} (\rho \mathbf{V} \mathbf{V}) \cdot \mathbf{n} dS = -\int_{S} \rho \mathbf{n} dS + \mathbf{T} \quad (2)
\]

\[
\frac{\partial}{\partial t} \int_{\Omega} \rho E d\Omega + \int_{S} (\rho H \mathbf{V}) \cdot \mathbf{n} dS = \mathbf{T} \cdot \mathbf{V} \quad (3)
\]

where \(\rho\) is the fluid density, \(\mathbf{V}\) is the flow velocity vector, \(p\) is the static pressure, \(E\) is the total energy per unit mass, \(H\) is the total enthalpy per unit mass, and \(\mathbf{T}\) is the force applied by the rotor.
The rotor force is defined as:

$$ T = \iiint \Omega \mathbf{f} \, d\Omega $$  \hspace{1cm} (4)

Here $\mathbf{f}$ is thrust per unit volume, which represents the effect of rotor thrust on each computational cell. In the first approach $\mathbf{f}$ is defined as:

$$ \mathbf{f} = \mathbf{f}_0(r, \psi) \exp\left[-k(z - z_0)^2\right] \quad r \leq R $$

$$ \mathbf{f} = 0 \quad r > R $$  \hspace{1cm} (5)

where $r$, $\psi$, $z$ are the radial, azimuthal and normal coordinates of the rotor-fixed coordinate system, $z_0$ is the rotor location, $k$ is a decay factor, and $R$ is the rotor radius. The vector $\mathbf{f}_0(r, \psi)$ is computed using a blade element theory, which was previously used to model the FANTAIL™ of the RAH-66 Comanche helicopter [9], [10].

For the second approach $\mathbf{f}$ is defined using the following relation:

$$ \mathbf{f} = \sum_{j=1}^{N_{\text{blades}}} \sum_{k=1}^{N_{\text{segment}}} \mathbf{F}_{jk} \frac{\Delta R_{jk}}{R} \exp\left(-k r^2\right) $$  \hspace{1cm} (6)

where $\mathbf{F}_{jk}$ is the force per unit length computed at a blade segment, $\Delta R_{jk}$ is a finite segment length, $k$ is a decay factor, $c$ is the constant chord length of the blades, and $r$ is the distance between blade segment and computational cell. In the above relation $N_{\text{blades}}$ and $N_{\text{segment}}$ stand for number of blades and number of blade segments respectively. In Eq. (6), $k$ is selected such that the effect of a blade segment on a computational cell drops to 1% when the cell is a chord length away from the segment.

**HELCOPTER FLIGHT DYNAMICS MODEL**

The flight dynamics model used in the solutions is based on the GENHEL model of the UH-60A Black Hawk helicopter [1]. The code has been modified to include a gust penetration model capable of simulating the ship airwake. An outer loop controller designed to simulate a human pilot model has also been developed so that the helicopter can follow prescribed trajectories [1], [5]. The details of these modifications to the flight dynamics model can be found in Ref. [1].

**Figure 1** Flowchart of fully-coupled simulation
RESULTS

Preliminary CFD Results

Preliminary CFD results were obtained to validate PUMA2’s ability to generate correct thrust values. Here the rotor effects were modeled using the first approach described in the previous section. Numerical solutions were performed for a hovering 4-bladed rotor with a constant chord section and a constant chord distribution. The rotor had a rotation speed of 33 rad/s, radius of 7 m., and the pitch setting at 75% radius was 3 degrees. Table 1 shows the thrust prediction for this case and comparisons with a blade element theory prediction and wind tunnel measurements [11]. The current prediction is in very good agreement with the measurement and performed better than the other numerical method (Ref. [11]).

Of course, the magnitude of the forward speed affects the magnitude of the thrust generated by a rotor. Therefore, the presence of an atmospheric boundary layer can be very important when the rotor is close to the ground. In order to look into this, the rotor described above was analyzed in forward flight at a speed of 14 m/s at three different altitudes above the ground (h = 5, 15, and 25m). The atmospheric boundary layer was defined as described in Ref. [11] where the flow speed at 24 m above the ground was 14 m/s. Table 2 shows the thrust predictions obtained with and without the atmospheric boundary layer. This table clearly shows the effect of the ground and forward speed on the thrust generated.

Table 1 Thrust Prediction (Hovering Rotor, $\omega = 33$rad/s, $R = 7$m, $\theta_{75} = 3^\circ$)

<table>
<thead>
<tr>
<th></th>
<th>$C_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blade Element Theory Prediction (Ref.[11])</td>
<td>0.00387</td>
</tr>
<tr>
<td>Measurement (Ref.[11])</td>
<td>0.00367</td>
</tr>
<tr>
<td>PUMA2 Prediction</td>
<td>0.00368</td>
</tr>
</tbody>
</table>

Table 2 Thrust predictions in forward flight with and without the atmospheric boundary layer

<table>
<thead>
<tr>
<th>h</th>
<th>$C_T$ (w/ bl)</th>
<th>$C_T$ (w/o bl)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5m</td>
<td>0.004707</td>
<td>0.004847</td>
</tr>
<tr>
<td>15m</td>
<td>0.004306</td>
<td>0.004363</td>
</tr>
<tr>
<td>25m</td>
<td>0.004409</td>
<td>0.004354</td>
</tr>
</tbody>
</table>

The effect of the ground can be seen from Figures 2-4, which display the side views of pressure contours at different heights above the ground.
Results for Hover in Hangar Airwake

This section presents simulations of a UH-60A helicopter hovering in the wake of a large aircraft hangar structure. The airwake was produced by a 16-knot wind blowing over the hangar. A computational model of the hangar is shown in Figure 5. This hangar geometry was generated to mimic a 40 ft high aircraft hangar located at San Francisco International Airport, which was described in Ref [12]. The dimensions of the hangar were not known so they were estimated using Figure 23 of Ref. [12]. The coordinate system used in the solutions is an Earth-fixed coordinate system where the x-axis points North, the y-axis points East, and the z-axis points downwards. The wind blew from West to East (y-direction).

For the CFD solution an unstructured mesh composed of 1,350,926 tetrahedral cells was constructed using GridGen [13]. The unstructured mesh on the hangar surface and ground is displayed in Figure 6. The cells were clustered at approximately 100 ft away from the building where the helicopter typically hovers. Time accurate CFD computations were performed using a time step of 0.1 ms and the coupled codes were run on the High Performance Computing (HPC) Cluster of the College of Engineering of The Pennsylvania State University [14]. The HPC cluster is composed of a head node and 24 compute nodes with a Gigabit Ethernet Connectivity between the nodes. The head node has two Dual-Core 3.4GHz Processors with 8GB RAM and 1.2TB local disk space. Each compute node has two Dual-Core 3.4 GHz processors with 4 GB RAM and 40 GB local disk space.

Solutions were obtained for a UH-60A helicopter hovering 100 ft away from the hangar at an altitude of approximately 35 ft. Three cases were obtained for a real time of 20 seconds and compared with each other. Solutions were calculated for no airwake coupling, one-way coupling and two-way coupling. For the one-way coupled case, the unsteady hangar wake was obtained without the helicopter and then the transient velocity data was supplied to GENHEL as external disturbances. During the solution procedure atmospheric turbulence and boundary layer effects were neglected.

Figure 7 shows the time history of the helicopter position for these three cases. The no-coupling case shows almost no movement in any direction. The magnitude of the change in North-South position and altitude is nearly the same for the one-way and fully-coupled cases but the latter yielded a higher frequency response. Whereas in the East-West position the one-way coupled solution predicted almost no change until after 15 seconds. The biggest discrepancy between the two coupled cases occurred after 16 seconds where the one-way coupled case showed relatively large displacements compared to the fully-coupled case.

The attitude of the helicopter for the three cases is displayed in Figure 8. The oscillations for the fully-coupled case during the initial stages are partly due to discrepancies between the initial trim solution and the actual trim for the fully-coupled solution. There is also a 2-degree difference in the steady pitch attitude for the fully-coupled solution. The biggest differences were experienced in the yaw angle where the fully-coupled solution predicted a more oscillatory behavior.
The time histories of the cyclic and collective/pedal controls are shown in Figure 9 and Figure 10, respectively. As expected there is practically no control activity for the no-coupling case. The figures show differences in control activity between the one-way and fully-coupled solutions, especially at the collective and pedal controls. The discrepancy in the collective control is likely due to the different inflows the rotor faces for the one-way and fully-coupled cases.

Figure 11 displays velocity vectors plotted at different times on a vertical plane passing through the center of the hangar for one-way and fully-coupled solutions. The images on the left side are for the one-way coupled case while the images on the right side are for the other. It is evident from these images that the velocity fields for the two cases show considerable differences. The downwash generated by the rotor clearly affected the oncoming vortical flowfield which became more and more visible as the solution progressed.

Due to the ground the rotor induced a flowfield which went towards the building and then moved upwards when it reached the front face. This upward motion clearly prevented the formation of the vortex shedding from the building. This situation is clear at 8 and 12 seconds. This resulted in dramatic differences in the velocity field which became more severe after 16 seconds.

One-way coupled solutions provide the opportunity to perform real time flight dynamics simulations. But they carry a big assumption that the induced flow by the rotor does not affect the airwake through which the aircraft flies. But when the oncoming wind is mild and the aircraft in the vicinity of the ground or some other structure, the rotor wake can significantly affect the oncoming flow and one-way coupling solutions can be seriously in error.
In order to further analyze the effect of the ground and close proximity to the hangar, new solutions were obtained for a UH-60A hovering 50 ft away from the hangar and approximately 22 ft above the ground. Time histories of helicopter position and attitude for no-coupling, one-way coupled and fully-coupled cases are displayed in Figure 12 and Figure 13, respectively. Although there is not much difference in North-South and East-West positions, considerable differences are observed in the vertical position. Both roll and pitch attitudes predicted by the fully-coupled solution have somewhat more transient variation when the helicopter is 50 ft way from the building.

The real discrepancies between one-way and fully-coupled solutions occur for the control activities which are displayed in Figure 14 and Figure 15. It is clear from the figures that there is relatively more control activity in all the controls for the fully-coupled solution than those for the other solutions. This clearly indicates that the interaction between the rotor wake and the wake of the hangar is more severe for this case. To illustrate this situation, the velocity vectors in a vertical plane were plotted at different times for the one-way and fully-coupled solutions in Figure 16. The images clearly show that the induced flow generated by the rotor created an upwash on the front side of the hangar which blocked the wind blowing over the building.

**Figure 11** Velocity vectors for one-way (left) and fully- (right) coupled solutions on a vertical plane passing through the center of the hangar at different times. (100 ft)
Figure 12 Time history of the helicopter position (50 ft)

Figure 13 Time history of the helicopter attitude (50 ft)

Figure 14 Time history of the cyclic controls (50 ft)

Figure 15 Time history of collective/pedal controls (50 ft)
Helicopter/Ship dynamic Interface Results

This section presents the simulation of the approach of a UH-60A helicopter to a Landing Helicopter Assault (LHA) class ship. The computational geometry of the ship is displayed in Figure 17. The trajectory analyzed here is the last 24 seconds of the approach trajectory described in Ref. [1]. For the CFD solution, an unstructured mesh composed of 854,072 tetrahedral cells was used. This was the same mesh used for unsteady ship airwake predictions in Ref. [1] and [2]. The Earth-fixed coordinate system described previously was also used for the ship solutions. Here the ship’s bow is assumed to be pointing West. Computations were performed with a steady wind with a speed of 30 knots and a 30 degrees Wind-Over-Deck (WOD) angle. The helicopter approached landing spot 8 of the ship. The location of this spot has been described briefly in Ref. [1].

The simulation was performed for 24 seconds of real time. The time step used for the CFD solution was 0.1 ms, which required 10,000 iterations for a 1 sec. simulation. Figure 18 shows the time history of the helicopter position obtained with no-coupling, one-way coupled and fully-coupled solutions. The no-coupling results do not contain a ship-airwake. The North-South position predictions by the one-way and fully-coupled solutions follow a similar pattern while there are some discrepancies at the East-West position especially between 5 and 10 seconds. However, significant differences are observed at altitude where there is nearly a 90 degree phase difference between one-way and fully-coupled results during the first 15 seconds.

The attitude predictions for the helicopter are displayed in Figure 19. Here there are considerable discrepancies between one-way and fully-coupled solutions for the roll and pitch attitudes.

More visible disagreements between one-way and fully-coupled solutions are observed in the control actions which are displayed in Figure 20 and Figure 21. For the longitudinal cyclic, the one-way case qualitatively follows the no-coupling case while the fully-coupled solution is completely different. The differences are also evident for the...
collective controls where there is a nearly 90-degree phase difference between one-way and fully-coupled solutions during the first 8 seconds. The pedal controls also differ substantially.

As mentioned before, the discrepancies between the one-way and fully-coupled solutions arise because of the effect of the rotor wake on the ship airwake. The more severe this interaction becomes, the more discrepancies should be expected. In order to visualize this effect, velocity fields are plotted at different times for the one-way and fully-coupled cases. Figure 22 shows downwash velocity contours on a vertical plane passing through the landing spot 8 of the ship plotted at different times for one-way and fully-coupled solutions. The presence of the rotor clearly changed the vertical velocity distribution. The effect of the rotor wake was felt heavily between 8 and 12 seconds but this effect seems to diminish as time went on. Compared to hangar solutions the wind speed was higher in this case and there were no vertical structures in the vicinity of the helicopter. Therefore, the effect of the rotor wake on the ship airwake was relatively low when compared to that of the hangar wake.

![Figure 18 Time history of helicopter position](image1)

![Figure 19 Time history of helicopter attitude](image2)

![Figure 20 Time history of the cyclic controls](image3)

![Figure 21 Time history of the collective/pedal controls](image4)
Figure 22 Downwash velocity contours for one-way (left) and fully- (right) coupled solutions on a vertical plane passing through the landing spot 8 at different times.
CONCLUSIONS

A fully-coupled helicopter/ship dynamic interface tool has been developed by coupling an existing time-accurate CFD code (PUMA2) and a flight dynamics simulation model (GENHEL). For this purpose, PUMA2, which is capable of computing flowfields around complex ship geometries [2], has been modified to include source terms that model the induced flow due to a lifting rotor. These source terms introduce the effects of the rotor into the flowfield as a force per unit volume term. This method does not require a well defined rotor plane or individual blade geometries inside the computational mesh. Therefore, the modeled rotors and blades can be easily moved inside the domain as long as the local mesh is fine enough to resolve the important flow features. Two different approaches were employed to compute the magnitudes of the source terms. In the first approach rotor effects were time-averaged over a single blade passage time and the source magnitudes were computed using blade element theory [9], [10]. This was similar to modeling the rotor as an actuator disk. This first approach was only used to test the effectiveness of PUMA2 in computing rotor thrust. Results obtained for a hovering rotor were in good agreement with the wind tunnel data [11]. In the second approach source magnitudes were computed using the blade loads obtained from GENHEL. This approach has the ability to incorporate blade motions such as flapping and lead-lag; thus has been employed for the fully-coupled simulations.

Computations were performed for a UH-60A hovering behind an aircraft hangar and the same helicopter approaching an LHA-class ship. The fully-coupled solutions were compared to no-coupling solutions where there was no airwake and one-way coupled solutions where the rotor wake did not affect the oncoming velocity field.

The hangar results were obtained for a steady wind of 16 knots flowing over the building with the helicopter hovering 100 ft and 50 ft away from it. The results clearly show that when the helicopter is operating close to the solid structures the rotor wake can significantly affect the oncoming airwake. The situation becomes more severe when the aircraft moves closer to the ground and hangar. Because of these nonlinear interactions, the one-way coupled solution may be seriously in error for such cases.

The rotorcraft/ship dynamic interface simulation was performed by repeating the last 24 seconds of the approach trajectory described in Ref [1]. Solutions were obtained for a steady wind of 30 knots with 30 degrees of WOD angle. The results were compared to the no-coupling and one-way coupled cases. Despite the discrepancies observed in the control actions the interaction between the rotor wake and the ship airwake was not as severe as the one observed for the hangar problem.

REFERENCES