Rotorcraft Simulations with Coupled Flight Dynamics, Free Wake, and Acoustics

Umberto Saetti
uxs116@psu.edu
M.S. Candidate

Joseph F. Horn
joehorn@psu.edu
Professor

Kenneth S. Brentner
ksbrentner@psu.edu
Professor

Willca Villafana
wrv105@psu.edu
M.S. Candidate

Department of Aerospace Engineering
The Pennsylvania State University
University Park, PA, USA

Dan Wachspress
dan@continuum-dynamics.com
Senior Associate
Continuum Dynamics
Ewing Township, NJ, USA

ABSTRACT

This study presents the integration of a flight simulation code (PSUHeloSim), a high fidelity rotor aeromechanics model with free wake (CHARM Rotor Module), and an industry standard noise prediction tool (PSU-WOPWOP) into a comprehensive noise prediction system. The flight simulation uses an autonomous controller to follow a prescribed trajectory for both steady and maneuvering flight conditions. The aeromechanical model calculates blade loads and blade motion that couple to the vehicle flight dynamics with suitable resolution to allow high fidelity acoustics analysis (including prediction of blade-vortex interaction (BVI) noise). The blade loads and motion data is sent to PSU-WOPWOP in a post-processing step to predict external noise. The coupled analysis is being used to evaluate the influence of flight path on aircraft noise certification metrics like EPNL and SEL for various rotorcraft in work for the FAA. The software was used to analyze the acoustic properties of a blade planform similar to the "Blue Edge" rotor blades developed by DLR and Airbus Helicopters – predicting BVI noise reduction as compared to more conventional blade geometries on the same order as that reported for the "Blue Edge" rotor.

INTRODUCTION

The integration of rotorcraft simulation software with complex aeromechanical models can provide increased fidelity and functionality of the system as compared to any of the individual tools. Continued advancement in computational resources allows coupled codes to be executed efficiently and even in real-time. In 2006, the GENHEL-PSU simulation code was integrated with the CHARM free wake module and the coupled code was shown to provide improved fidelity in flight dynamics.[1] Real-time operation required limitations in the rotor wake geometry, but with use of parallel computing and the steady improvement in CPU performance these limitations can be relaxed. Coupling of GENHEL-PSU with Navier-Stokes CFD solutions has also been performed, with specific application to simulation of ship airwake interactions with the helicopter[2]. These simulations are still far slower than real-time, but scaling studies have shown that with massively parallel processing and reduced order CFD models, real-time simulation and CFD coupling might be possible in the near future.

GENHEL-PSU was also coupled with the acoustics prediction software PSU-WOPWOP.[3] This coupling was a serial "one-way" coupling in that GENHEL-PSU simulations first calculated the helicopter motion and blade loads and then PSU-WOPWOP used this information to predict the external acoustics. One-way coupled simulations were reasonable since the acoustics have no impact on aircraft dynamics. The simulations allowed predictions of rotorcraft noise in maneuvers, whereas historically such calculations were only performed in steady-state trimmed flight. The limited fidelity of the blade loads predicted by GENHEL-PSU meant that the acoustics prediction could not account for Blade-Vortex-Interaction (BVI) noise. However, subsequent work used a free-wake model to re-construct more detailed blade loads for the prediction of BVI[4]. The wake model was coupled "one-way" in that the flight dynamics simulation was based on a simple blade element rotor with finite-state inflow and was not affected by the free wake. The free wake was used to re-construct more detailed blade loads for use only in the acoustics prediction.

The prediction of noise in generalized maneuvering flight is relevant in that it can be used to determine flight procedures that minimize noise and impact on communities. This is of particular interest to the Federal Aviation Administration, who through the Aviation Sustainability Center of Excellence (ASCENT), is seeking to develop noise abatement procedures. Physics-based models are particularly useful for noise prediction when no measured data is available, such as for new rotorcraft designs and configurations. To achieve these goals, the noise prediction should be coupled with flight simulation codes that generate realistic trajectories and pilot control input histories for typical rotorcraft maneuvers. This could be done through either real-time piloted simulations or through batch simulations using an autonomous controller (that models a pilot compensation to track a desired trajectory). In addition, such simulations should be coupled with high fidelity aeromechanical models that provide suitable blade load and blade motion predictions for acoustics analysis (including BVI), and these aeromechanical models should be consistent with the total forces and moments acting on the rotorcraft during the flight simulation. In this study, we continue development of a comprehensive noise prediction system[5], that couples a flight simulation code (PSUHeloSim), a high fidelity rotor aeromechanics model with free wake (CHARM Rotor Module[6]), and an industry standard noise prediction tool (PSU-WOPWOP[7-9]). All of these tools are physics-based models that can be adapted to predict flight dynamics, rotor loads, and noise on a variety of rotorcraft configurations. In this paper, we present the coupling of these codes and preliminary results showing vehicle motion and noise prediction for steady flight conditions.

SIMULATION ARCHITECTURE

Helicopter Flight Dynamics Model

The flight dynamics simulations were performed using the PSUHeloSim code. This is a basic simulation tool developed at PSU to provide a generic rotorcraft flight dynamics model for research and education. PSUHeloSim is developed in the MATLAB/Simulink environment for ease of development and adaptation to different rotorcraft configurations. The simulation model is constructed in first order state space form $\dot{x} = f(x, u)$, which makes it well suited for numerical integration, trim, and linearization calculations. It includes the 6 DoF non-linear equations of motion of the fuselage, 2nd order rotor flapping dynamics, and a 3-state Pitt-Peters inflow model, resulting in a 21-state non-linear model. It uses a simple aerodynamic model of the fuselage and empennage based on given lift and drag properties. A static Bailey model is used for the tail rotor, and while the main rotor includes flapping dynamics, it uses linearized blade equations of motion and simplified analytic integrations of the aero lift and drag forces along the blade. The limitations in rotor model fidelity are not significant for the current application, as the simple rotor model is replaced with the high-fidelity CHARM (Comprehensive Hierarchical Aeromechanics Rotorcraft Model) rotor module in the final results. The simple rotor model is only used in the trim calculation for initializing the simulations and in the controller design process. A general schematic of the PSUHeloSim flight dynamics model (not including the controller described below) is shown in Figure 1.

The simulation is integrated with a non-linear dynamic inversion control law.[10] This control law has been developed for rotorcraft application on a number of research programs at PSU, and has recently been used for non-real-time simulations with complex aeromechanical models.[2] The controller achieves high precision closed-loop control of the simulated helicopter and tracks a commanded velocity vector and heading in NED frame. Note that an evolution of this controller, designed to follow a specific trajectory (*x*,*y*,*z* coordinates), will be used in future coupled simulations. Engineering simulations require a "pilot model" to regulate the helicopter (which may have unstable dynamics) and keep it on a specific flight path during maneuvers. The NLDI controller serves this purpose.

High-Fidelity Rotor Module

PSUHeloSim is integrated with a high-fidelity rotor module for fully-coupled or one-way-coupled simulations. The CHARM Rotor Module uses a Constant Vorticity Contour (CVC) full-span free-vortex wake model, combined with a vortex lattice, lifting surface blade model[11]. The module calculates blade motion including structural modes in the blade dynamics. This module runs as a separate code obtaining the state, state derivatives and controls from PSUHeloSim at each time step of the simulation and returning the forces, moments, and flapping coefficients of the rotor systems. In the one-way coupled mode, the blade loads are stored for use in acoustic prediction, but are not used by the PSUHeloSim flight dynamics model. In the fully-coupled mode, the forces and moments calculated by CHARM are used as inputs for the PSUHeloSim code. Thus in the fully coupled mode, CHARM acts as the main rotor module and/or tail rotor module of the simulation (it replaces the simple built-in rotor models in PSUHeloSim).

In either mode, CHARM is able to produce loading files that are then used by PSU-WOPWOP to determine the aerodynamically induced noise. One can choose to couple the main rotor, the tail rotor or both. The acoustic prediction is able to operate with more than one rotor at a time. The only present limitation is that the loading output for acoustic prediction is limited to a single rotor revolution which is assumed to be periodic. This means that acoustic analysis can be performed just for steady or quasi-steady flight conditions. (It is planned to relax this limitation to enable fully coupled transient maneuver simulations.)

Noise Prediction Model

The noise prediction model used in this work, PSU-WOPWOP[7-9], is a numerical implementation of Farassat's Formulation 1A[11] of the Ffowcs Williams –Hawkings (FW-H) equation.[12] Formulation 1A is used to predict the discrete frequency noise prediction (thickness, loading, BVI, etc.) from first principles when provided with the aircraft and rotor blades position, motions, and blade loading. PSU-WOPWOP predicts the acoustic pressure time history for either stationary or moving observers and the code is also able to convert the output signals into acoustic spectra, such as 1/3rd octave bands and multiple types of noise metrics relevant to noise certification and community annoyance (PNL, PNLT, SEL, EPNL, and OASPL, etc.). The broadband noise is computed in PSU-WOPWOP by implementing an empirical prediction developed by Pegg[13] that predicts the broadband noise in 1/3rd octave bands. This is then combined with the discrete frequency noise for a total noise prediction. In a recent research effort, it has been demonstrated that a flight simulation coupled with

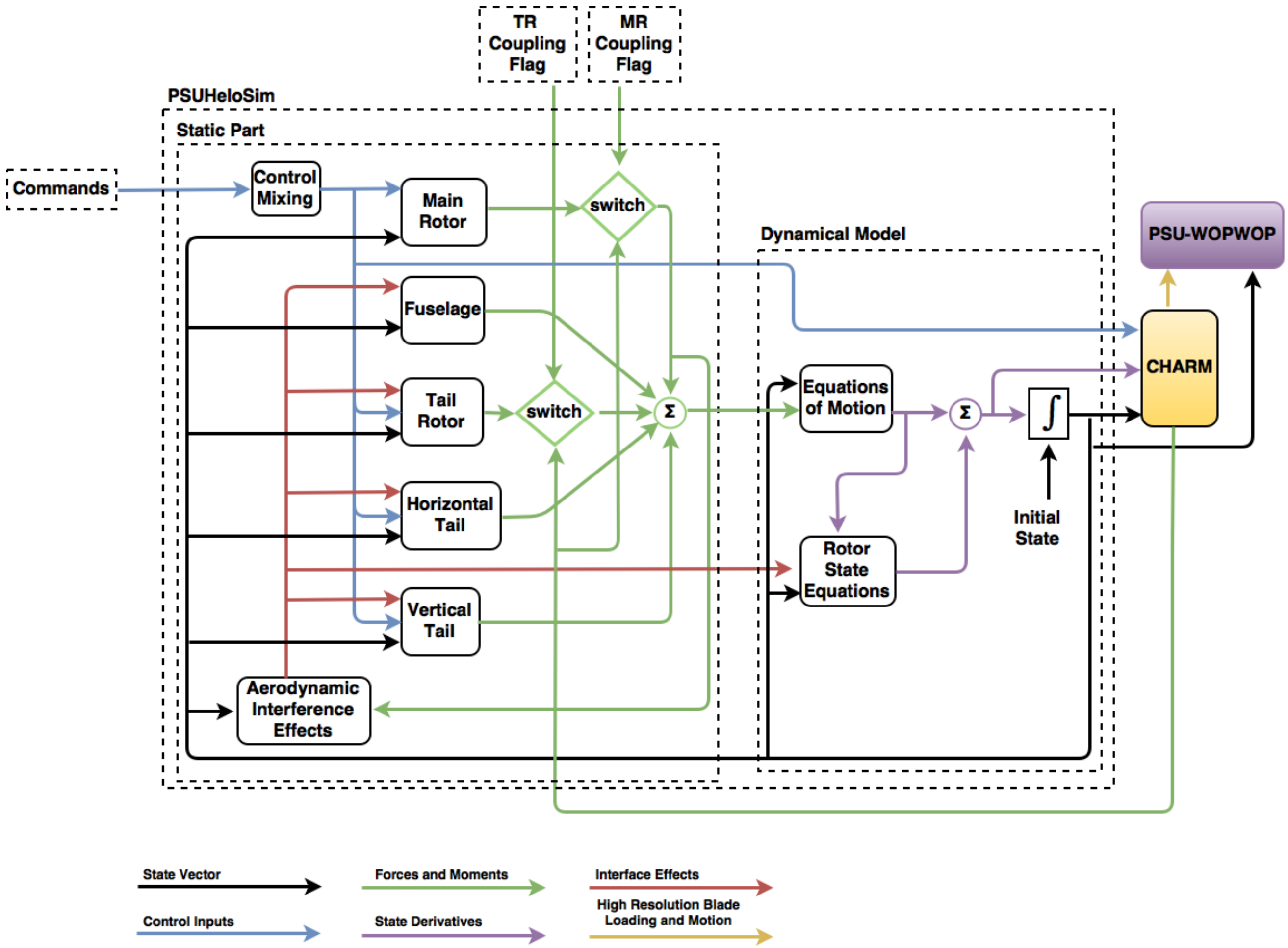


Figure 1. Schematic of the PSUHeloSim/CHARM/PSU-WOPWOP simulation model.

CHARM and PSU-WOPWOP can predict the noise in "real time". The system developed in this work is somewhat different, but it is still reasonably fast.

Schematic of the Simulation Process

The simulation process consists of three main steps: 1) solving trim for the prescribed flight condition, 2) running a PSUHeloSim /CHARM coupled simulation, and 3) performing an acoustic prediction with PSU-WOPWOP based on the results of the simulation. A Newton-Raphson based trimming algorithm is used to find an equilibrium condition for the state and the controls. Note that this trim solution is based only on the base PSUHeloSim model. Once trim is achieved, the trim state and control solution is used as initial conditions of the coupled simulation (both for PSUHeloSim and the CHARM rotor modules).

During the simulation, the time history of velocity and heading commands are fed to the dynamic inverse controller in the PSUHeloSim code. The controller calculates the control input based on the tracking error and feedforward signals as defined by the control law. The sim code updates the state, state derivatives, and swashplate inputs, which are then used as inputs for the CHARM rotor module. The resulting main rotor forces and moments calculated by CHARM are either saved as output (in one way coupled mode) or fed back into the simulation model in fully-coupled mode. When performing fully-coupled simulations, the full coupling is not initiated until three seconds of simulation have passed. This allows the free-wake model time to develop and initialize. After the simulation is completed, the PSU-WOPWOP acoustics analysis is performed using the aircraft state and loading files generated by CHARM. Figure 2 shows the flowchart of the simulation process.

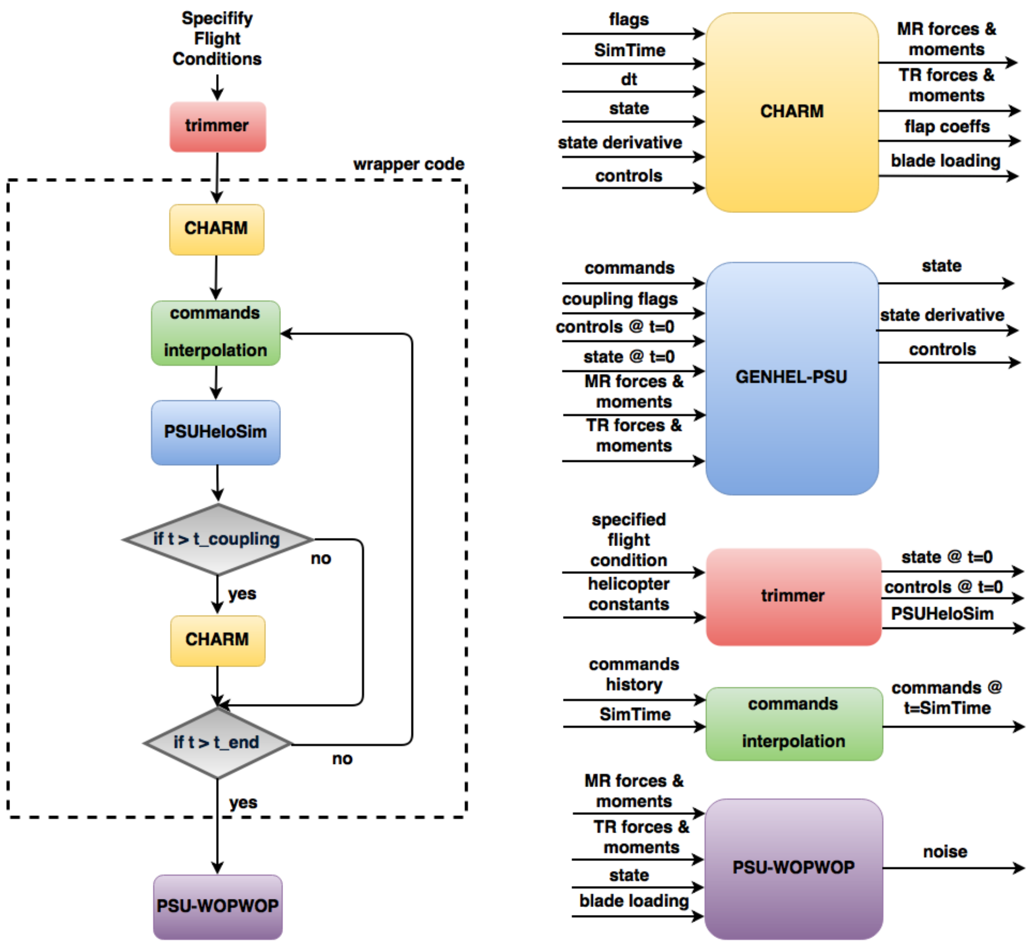


Figure 2. Flowchart of the simulation process.

SIMULATION RESULTS

Flight Simulation Results

The helicopter used for the current simulation results is a Bell 430; a summary of its characteristics is presented in Table 1.

A number of basic maneuvers were simulated using the standard PSUHeloSim model and the fully-coupled simulation with the CHARM rotor module. The simulations were used to verify that the fully-coupled simulations followed the expected behavior and that the NLDI controller can adequately stabilize and control the coupled model.

When using the one-way coupled simulation or the stand-alone PSUHeloSim model, the CHARM rotor module is not used in the flight dynamics solution. This means that the dynamic simulation involves just the base PSUHeloSim and the Dynamic Inversion based controller. The DI controller is designed around linearized models of the PSUHeloSim, which leads to very accurate tracking of controller commands. The trim solver is also based on the PSUHeloSim model and results in near perfect initialization. This is seen in the red results of Figure 3, which show the attitude response when the commanded trajectory simply holds a 100 kts level flight trim condition. It can be seen that there is no deviation from trim.

Mass and Inertia Properties	
W	$8700\ lbs$
I_{xx}	$3462\ slug\ ft^2$
I_{yy}	$15362\ slug\ ft^2$
I_{zz}	$12261\ slug\ ft^2$
I_{xz}	$300\ slug\ ft^2$
I_{β}	$398\ slug\ ft^2$
M_{β}	$37.9\ lbs\ ft$

Main Rotor	
Ω	$36.395\ rad/s$
R	$21\ ft$
θ_{tw}	$-7.7\ °$
N_b	4
c	$1.2\ ft$
e	$5\ \%$
M_b	$3.61\ slug$
Tail Rotor	
Ω	$197\ rad/s$
R	$3.442\ ft$
θ_{tw}	$0\ °$
N_b	2
c	$0.529\ ft$
δ_3	$45\ °$

Table 1. Bell 430 key characteristics.

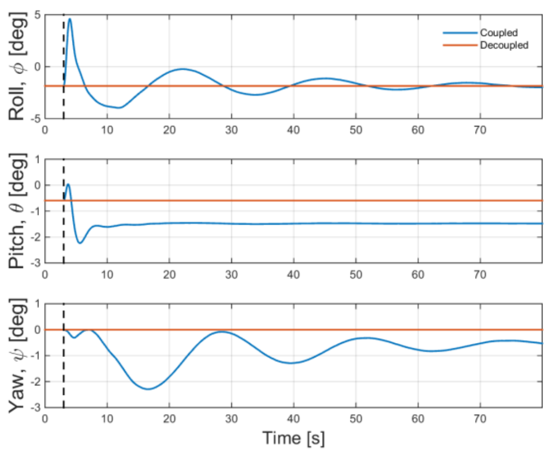
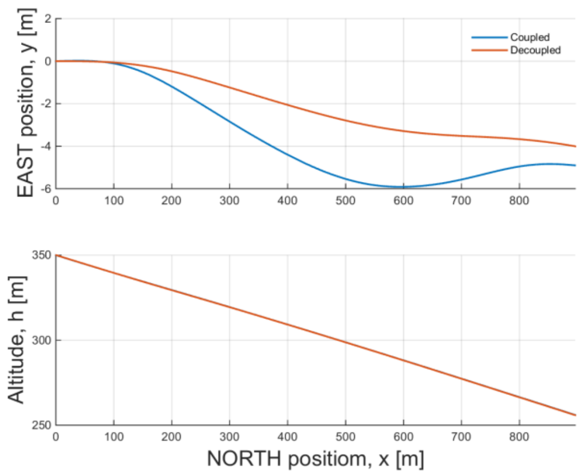


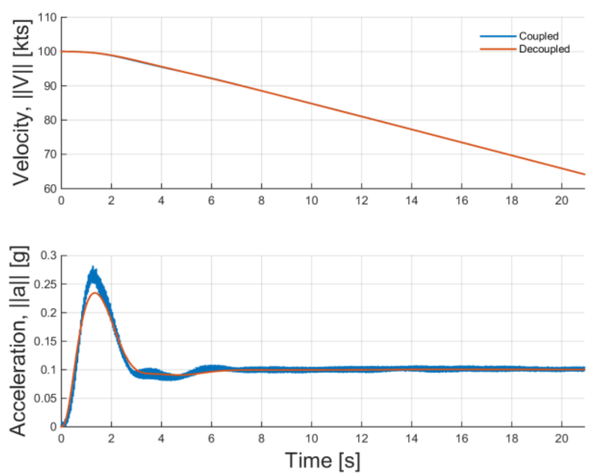
Figure 3. Coupling transient: dashed line marks the start of the coupling.

In the fully-coupled case, the main rotor forces, moments calculated by the CHARM rotor module are fed back into the dynamic simulation, changing the nature of the nonlinear model. So when the coupling is turned on, after three seconds of simulation, the helicopter goes through a transient due to the differences of forces and moments between CHARM and the PSUHeloSim model. The controller is robust enough to restore the trim, causing the aircraft to converge to a steady state after a period of time. The new equilibrium is usually slightly different from the initial trim. This is partly due to differences in trim of the CHARM rotor and the simple rotor model in PSUHeloSim. In addition, a helicopter can trim with different combinations of roll attitude and sideslip angle. When trimming PSUHeloSim the yaw attitude / sideslip are set to zero, but after coupling is initiated the system settles into a slightly different steady state.

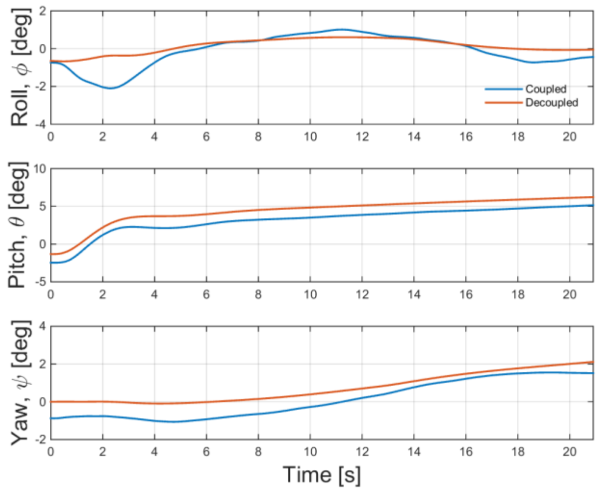
A decelerating descent maneuver was simulated with and without coupling. The results are shown in Figure 4. With coupling, the simulation is initially flown in steady 100 knot level flight for a period of time to allow the helicopter to return to trim after the transient at initialization. Figure 4 shows the response after the initial wait period. The maneuver consists of a 6° decelerated descent from 100 to 60 kts at 0.1 g of deceleration. Figure 4 compares responses of the “de-coupled” baseline PSUHeloSim and the fully coupled model with CHARM. In both cases, the vehicle response follows the command after the initial transient, and the responses are similar for both models. The velocity and altitude profiles are essentially identical, which is expected since these are tracked by the controller. There are slight differences in attitudes due to differences in the two rotor models. Note that there is some deviation of the lateral cross track (y-position), but the lateral drift is only about 4 ft after 900 ft down range motion.



a) Position



b) Absolute velocity and acceleration



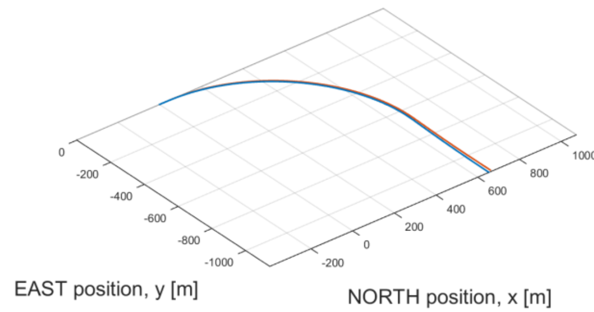
c) Attitude

Figure 4. Results from a 6° decelerated descent at 0.1 g of deceleration.

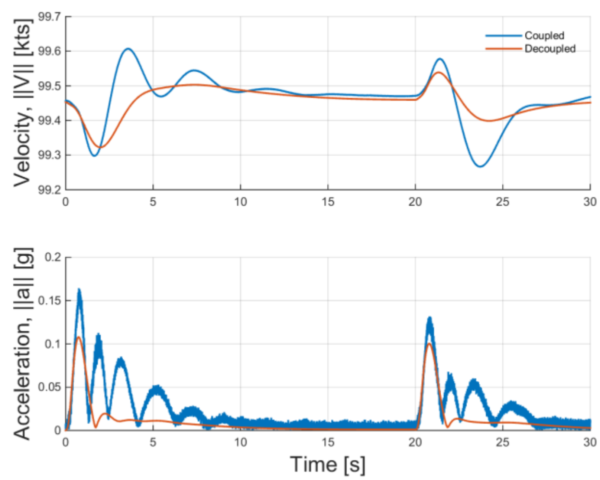
Figure 5 shows a 90° turn maneuver at 100 kts forward airspeed. Once again, time was allotted to allow the controller to stabilize the aircraft after the coupling transient. Once again we see very similar flight path with both the coupled and de-coupled PSUHeloSim. Note that the velocity fluctuations are quite small. The accelerations seen are largely in the lateral axis due to Dutch Roll oscillations. This mode appears to be less damped with the coupled model.

When simulating main rotor and tail rotor physics with the CHARM rotor module, the simulation time step is driven by the largest allowable tail rotor blade sweep per time step (since the tail rotor has a larger RPM). For example, 15° blade sweep per time step is usually considered the largest acceptable time step for blade element rotor simulations in flight dynamics. Consequently the main rotor (which turns slower) will have a smaller blade sweep.

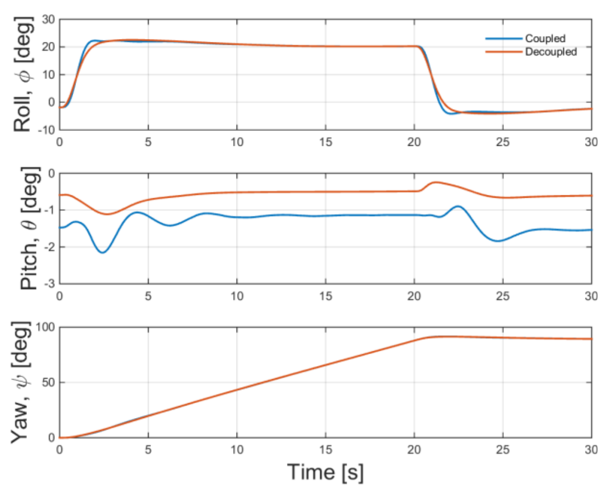
One of the unique features of this system is the ability to capture relevant physics for the acoustics. In particular, the free wake needs a sufficient number of elements for accurate blade loading, which in BVI conditions should be as fine as 1° azimuthal resolution. With such high temporal (azimuthal) and corresponding spatial resolution requirements, it is impossible to perform real-time analysis with the free wake and could take substantial computational power to be useful in the computation of realistic maneuvers – tens of hours on a single processor. Fortunately, this issue has been addressed in the CHARM rotor module through "reconstruction" of the rotor wake in post-processing. In this approach, a low resolution wake and larger time step is used in the flight simulation step, which is acceptable for flight dynamics modeling. Then, for the regions of the maneuver where acoustics are of interest, a higher resolution wake and blade loading is reconstructed in the CHARM rotor module[14]. These high resolution blade loads are then used by PSU-WOPWOP to predict BVI-dominated noise. In recent work, this method was used to perform real-time, BVI-noise predictions[15]. Currently reconstruction can only be applied to one rotor.



a) Trajectory



b) Absolute velocity and acceleration



c) Attitude

Figure 5. Results from a 90° turn at 100 knots.

Acoustic Results

Helicopter rotor noise consists of several noise sources including discrete frequency noise (thickness, loading, and blade-vortex-interaction (BVI) noise), broadband noise, and high-speed-impulsive (HSI) noise (HSI noise only occurs in high speed forward flight). Each of these noise sources has a unique directivity, as shown in Figure 6. Thickness noise is dominant in the plane of the rotor, so it is the primary noise heard as a distant helicopter approaches. Only the motion of the rotor blades and the aircraft, along with the geometry of the rotor blades, is needed to compute the thickness noise; hence, the flight simulation code is readily able to provide this information (at very low computational cost). High-speed impulsive noise has the same directivity as thickness noise, but it only occurs in high-speed flight (and will not be addressed here).

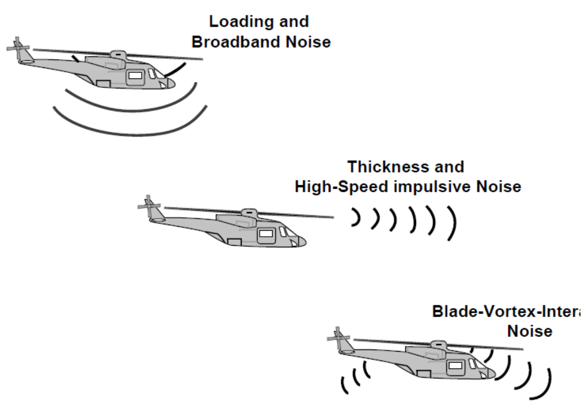


Figure 6. Typical direction of primary radiation for various rotor noise sources.

Loading noise is another important source of rotor noise, which is typically directed below the rotor – so loading noise is important as the aircraft is overhead. There are two important types of loading noise that are generally dealt with separately: BVI noise and broadband noise. BVI noise is the dominant noise source when it occurs. It has a very impulsive nature and originates from a nearly parallel close interaction between a blade and the tip vortex of a previous blade. BVI noise is highly directional and depends strongly on the vortex strength, miss distance, and interaction angle. This is the reason that a high-fidelity rotor and wake model are needed in this system to predict BVI noise accurately. Broadband noise is another type of loading noise that is a result of stochastic loading due to various airfoil self-noise sources, turbulence ingested into the rotor, or turbulence entrained by tip vortices (when they are not quite close enough to cause significant BVI noise). The empirical model derived by Pegg[13] are used in PSU-WOPWOP to predict the broadband noise and the input data is relatively easy to obtain from the flight simulation system.

Figure 7 shows the contribution to each of the noise components to the Overall Sound Pressure Level (OASPL) as function of the uprange/downrange distance for the Bell 430 helicopter flying at 100kts at an altitude of 150m. At $x = 0$, the helicopter is directly overhead. OASPL is not weighted by frequency and hence tends to reflect the large amplitude of the low frequency components of the rotor noise. Notice that as the aircraft approaches (negative distances) the thickness noise is the dominant source of noise. This is because the thickness noise directivity is in the plane of rotor; hence, the observer hears it first. The loading noise becomes begins takes over as the dominant noise source as the aircraft passes overhead and continues downrange (positive distances). The broadband noise makes only a contribution to OASPL, so it is not shown in the figure.

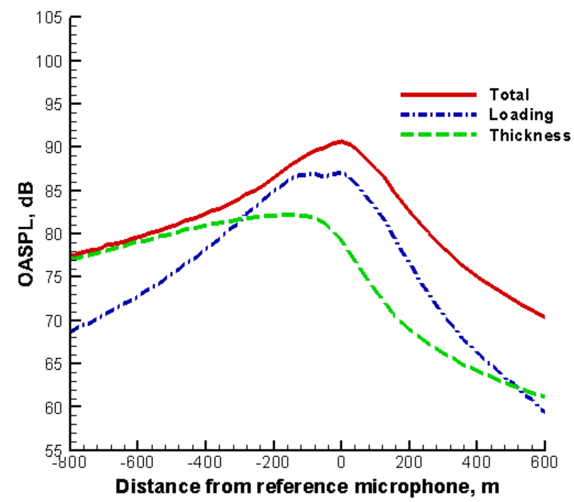


Figure 7. Noise components and their contribution to the OASPL predictions for a 100 kts flight case flown at 150 m altitude.

Figure 8 shows a similar plot of the noise components, but in this case the tone corrected, perceived noise level (PNLT) is plotted as a function of the uprange/downrange distance from the target observer location and the aircraft is directly overhead at $x = 0$. PNLT uses a frequency weighting that is intended to be representative of human annoyance; hence, higher frequencies are more important. The relative importance of the various noise sources is quite different in this case. The thickness noise is still the dominant noise as the aircraft is approaching (larger negative distances), but the broadband noise is significant as the aircraft approaches the overhead condition and dominant for all downrange positions (positive distances). The loading noise also increases overhead and downrange, but is always lower in this flight condition than broadband noise. This is because the loading noise in level flight has fairly low frequency content as this is a level flight condition. For level flight BVI noise is not expected, but if there had been BVI noise the loading noise levels would have been substantially higher.

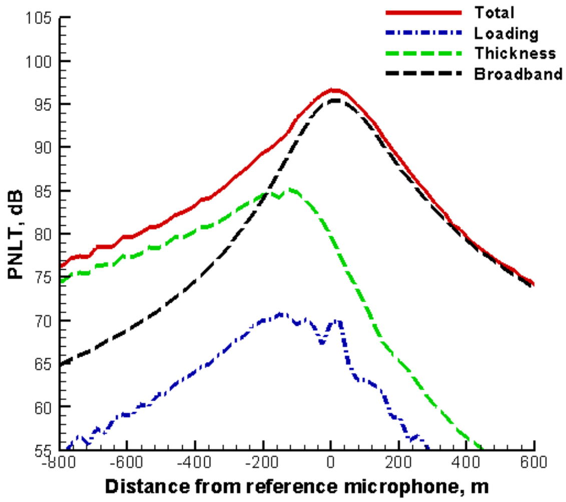


Figure 8. Noise components and their contribution to the PNLT predictions for a 100 kts flight case flown at 150 m altitude.

Demonstration Calculation – Prediction of BVI Noise Reduction using the Blue Edge-like Blades

An important attribute of this work is that the coupled system can accurately predict the acoustic characteristics of dominant noise sources without reliance on test data. During approach and landing, blade-vortex interaction (BVI) noise is a dominant out-of-plane noise source responsible for much of the ground noise. In order to provide a tool for evaluating the impact of modifications to flight path and rotor design on ground noise exposure during landing, it is necessary to demonstrate that the model can accurately predict BVI noise for BVI-dominant flight conditions. The ability of the CHARM/WOPWOP and subsequently CHARM/PSU-WOPWOP solutions to predict main rotor BVI noise in these flight conditions for conventional rotors (and tiltrotors) was demonstrated in prior work.[14,15] In the current work, this demonstration was extended to an advanced blade design known to reduce BVI noise (Figure 9)[16], Airbus Helicopter's "Blue Edge" blade. The concept behind this design is described in Ref. 17 as:

> "With a standard blade, air coming off the end of the blade causes a vortex around the tip. Under certain flight conditions the advancing blade then hits the vortex of the preceding blade. This causes a sudden change in the relative angle of attack and thus a change in pressure on the surface of the blade. This BVI causes the slapping sound ubiquitous to helicopter operations. With Blue Edge technology, the blade tip is swept forward, then aft. This causes the advancing blade tip to hit the previous blade's vortex at an oblique angle, reducing the noise level by 3 to 4 EPNdB."[17]

Figure 9. Blue Edge blade concept from Eurocopter (now Airbus Helicopters).[16]

Calculations were performed to demonstrate the ability of the new analysis system to predict the reduction in BVI noise obtained using a Blue Edge-like planform. Three blade planforms were compared operating on a Bell 430 rotor/aircraft configuration: 1) conventional rectangular blades – nominally the current Bell 430 blade; 2) tapered blades, 3) Blue Edge-like planform with taper and forward/aft sweep. The planform characteristics of each of these three blade sets are provided in Table 2 below. Figure 10 compares the tapered and Blue Edge-like planforms. No optimization of the tapered and Blue Edge-like planforms was performed to minimize noise. The Blue Edge-like planform forward/aft sweep schedule is roughly comparable to photographs of the Airbus Blue Edge blade, capturing the key feature of reducing the "parallel" nature of the BVI.

Tip Speed	766.5 ft/sec
Rotor Cutout	10 %
Rotor Chord	1.2 ft - rectangular 1.8 to 1.0 ft linear taper - tapered and Blue Edge
Anhedral Tip	None
Swept tip	none - rectangular and tapered forward -12° at r/R=0.6 aft 34.4° at 0.85 (Blue Edge)
Root Airfoil	NACA 0012
Tip Airfoil	NACA 0012 - rectangular NACA 0009 - tapered and Blue Edge
Air Density	0.002378 slug/ft^3
Speed of Sound	1117 ft/s
Thrust Coefficient	0.000463
Hub Type	articulated
Lock Number	8

Table 2. Characteristics of the three blade planforms.

Figure 10. Tapered and Blue Edge-like planforms.

The flight condition studied was a descent at low speed (μ=0.15) with the rotor tilted back 6° relative to the flight path. The sound pressure level was determined in a plane one rotor radius beneath the rotor plane. The CHARM solution was performed with an azimuthal resolution of $\Delta\psi$=15° and then reconstructed to a resolution of $\Delta\psi$=1° using the method described in[14]. The blade aerodynamics and acoustic solution at 187 observer points was completed in 3 minutes on a single core of an off-the-shelf CPU.

Figure 11 shows predictions of both the overall sound pressure level (OASPL) and the BVI sound pressure level (BVISPL) (harmonics 6-40 in blade passage frequency) for this configuration. The magnitude and directionality predicted is characteristic of the results seen for BVI-noise dominated descent flight conditions. The analysis predicts that the taper reduces the peak BVISPL by roughly 2dB and the Blue Edge-like planform further reduces the peak BVISPL by another 3dB for a total reduction of peak BVISPL of 5dB, capturing the documented benefit of the Blue Edge planform.

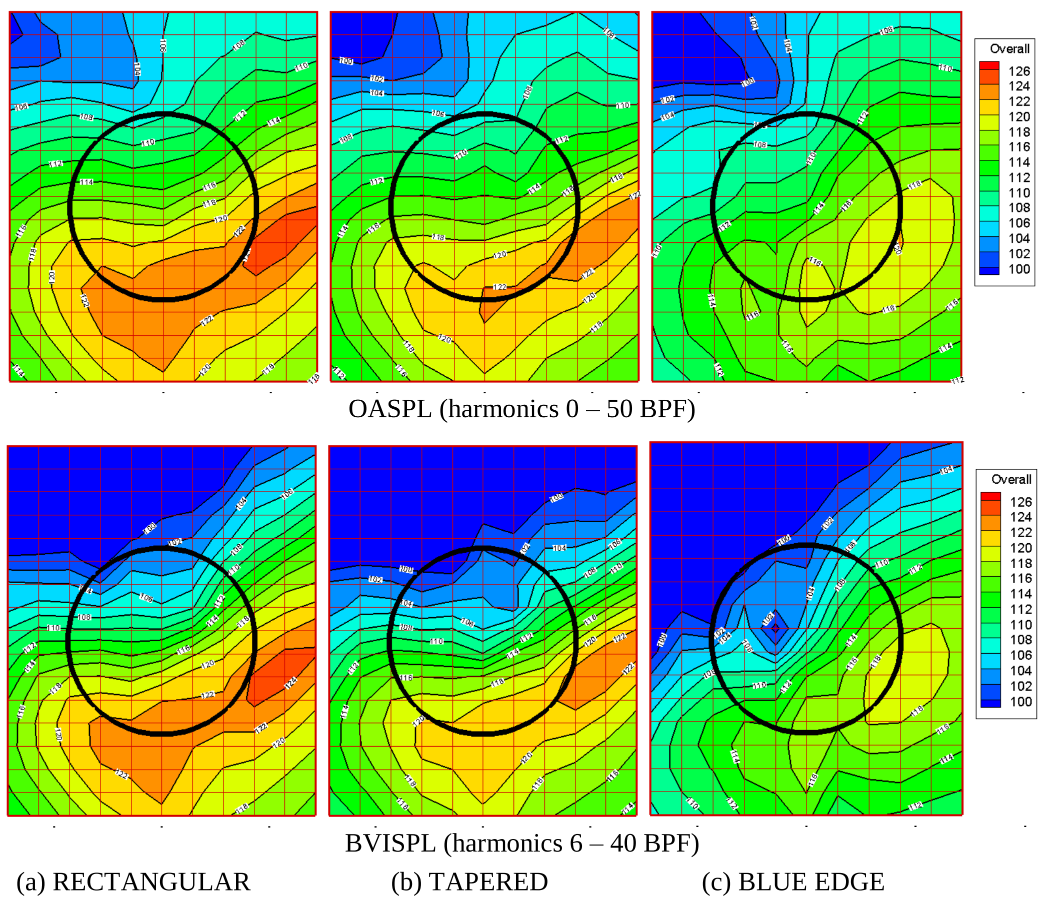


Figure 11. CHARM/PSU-WOPWOP main rotor OASPL and BVISPL predictions one rotor radius beneath the nominal Bell 430 rotor for the three blade geometries; α_s=6° (back), μ=0.15 and C_T=.00143. The black circle represents the rotor tip – advancing side on the right.

Figure 12 shows the advancing-side BVI for the Blue Edge planform compared with a rectangular blade as predicted by the CHARM code. Notice in the figure that the tip vortex (the red curved line) is nearly parallel to the entire length of the blade for the rectangular blade (left), while the shape of the Blue Edge planform (right) results in an interaction that occurs over a wider range of rotor azimuth angles; hence, it is a much less impulsive interaction.

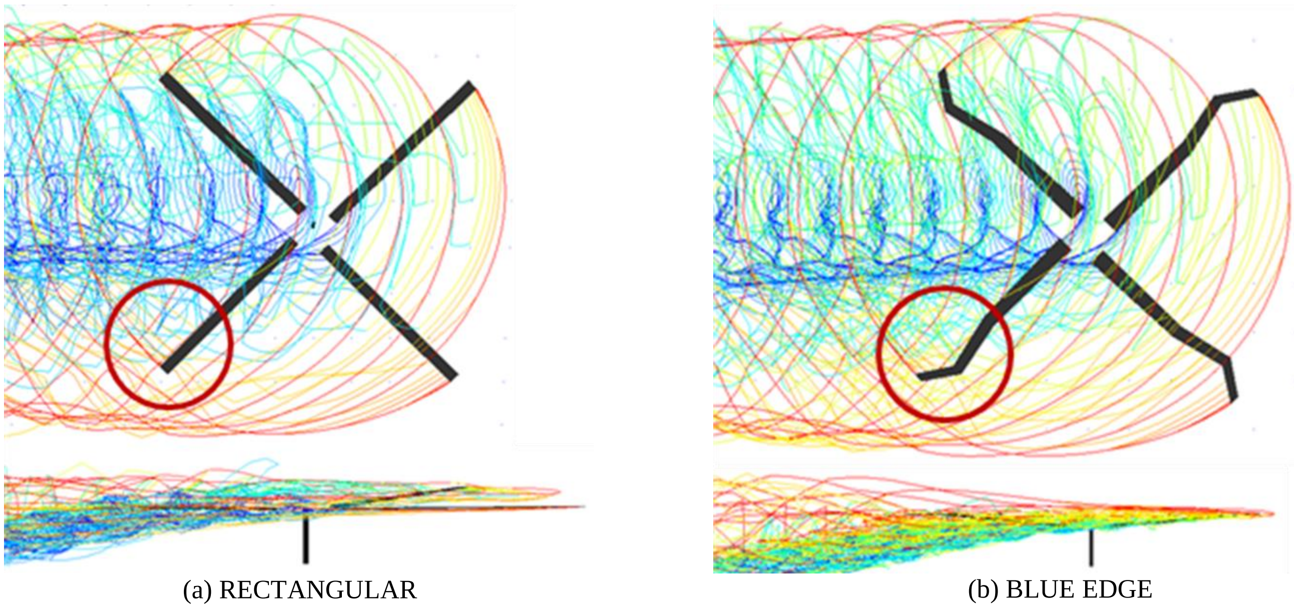


Figure 12. BVI event as predicted by CHARM for the baseline RECTANGULAR blade and the BLUE EDGE blade.

The measurement plane shown in Figure 11 reveals that the main rotor BVI noise is significantly reduced by the Blue Edge-like rotor planform, but a more typical noise prediction for a complete rotorcraft is made either on a hemisphere or a ground plane. To demonstrate the fully-coupled system this BVI noise was predicted for the full helicopter configuration. Here the aircraft flight condition is a forward speed of 68 kts and a 6° descent flight profile – providing the same main rotor operating condition as shown in Figures 11 and 12. Figure 13 shows the OASPL of the Bell 430 helicopter (with rectangular main rotor blades and the tail rotor included). Notice in the figure that the focused region of BVI noise is still clearly evident on the hemisphere surface.

Figure 14 shows the acoustic pressure time histories for each of the main rotor planforms at a point located on the hemisphere at an azimuth of 125° and down 45° from the main rotor tip-path plane (indicated by a small black dot in Figure 13). Notice in the figure, for each blade geometry there are 4 very narrow and high amplitude pressure spikes (or group of spikes). These are the BVI from each of the four blades on the main rotor. The thickness and loading noise of the main rotor also occur approximate the same time, so they are difficult to see. Comparison of the three different rotor blade geometries shows how the BVI acoustic pressure spikes amplitude is greatly reduced for the case of the Blue Edge-like rotor. The tapered blade also has a small reduction in BVI spike amplitude, primarily seen on the positive part of the pressure spike. The other features, i.e., the tail rotor noise, is essentially unchanged.

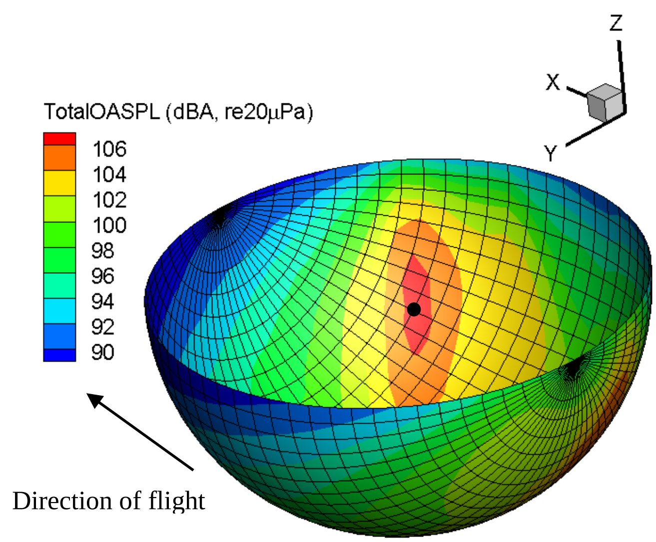
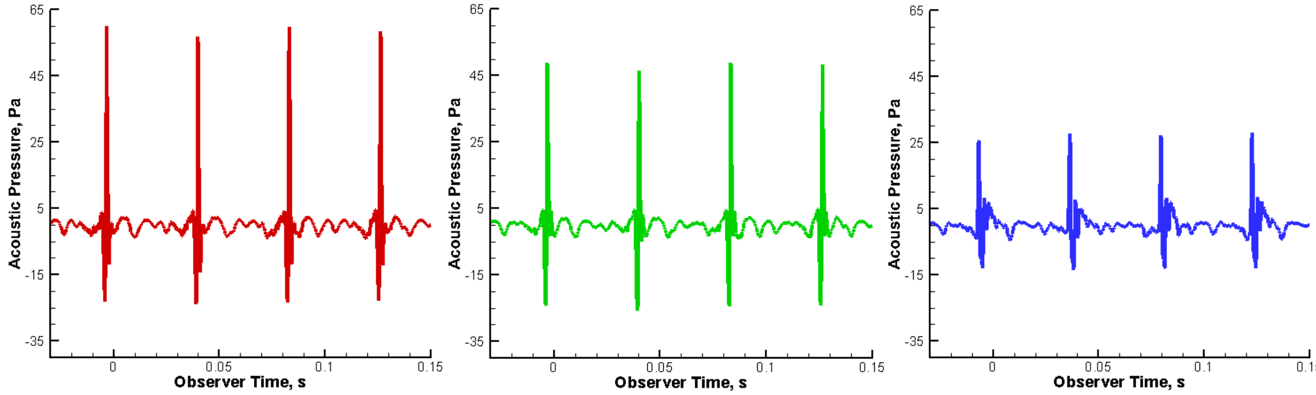


Figure 13. Contours of OASPL on a 30.48m radius hemisphere, centered at the Bell 430 c.g. location. The hemisphere follows the aircraft. OASPL contours shown are for the standard rectangular blades.



(a) RECTANGULAR (b) TAPERED (c) BLUE EDGE

Figure 14. Acoustic pressure time history at azimuth angle $\psi = 125$, elevation angle $\theta = -45°$ below the rotor plane, and radius of 30.48m from the helicopter c.g. (i.e., the location of the black dot in Figure 13).

The noise comparisons shown in this section demonstrate the utility of the flight simulation, high-fidelity wake, noise prediction system that has been developed here. Furthermore, design changes to reduce BVI noise – one of the more challenging components of the noise to predict – show the expected noise reduction trends.

CONCLUSIONS

A simulation tool has been developed that couples: 1) A flight dynamics simulation with closed loop control (PSUHeloSim), 2) A high-fidelity aeromechanics model of the rotor with a free wake (CHARM rotor module), and 3) an industry-standard noise prediction code (PSU-WOPWOP). Both uncoupled and fully coupled simulations were first tested for some basic maneuvers, and the results showed that the rotorcraft (with controller) was able to fly the prescribed trajectory when using the CHARM rotor module for rotor force and moment calculations, and that the control and attitude response was reasonable. Coupling with PSU-WOPWOP acoustics analysis was then tested, with a focus in this paper on a BVI-dominated descent condition. Then three different blade geometries were evaluated on the Bell 430 helicopter, including a Blue Edge-like blade planform that is expected to provide significant BVI noise reduction. The acoustic analysis predicted the expected noise reductions with approximately the same level of noise reduction as reported by Airbus Helicopters.

Some specific conclusions from this effort:

1. It has been demonstrated that the integrated simulation was capable of predicting realistic maneuvers when coupling the CHARM rotor module and PSUHeloSim simulation. It is crucial that the simulation include a robust flight controller, to handle the transients and change in aeromechanics upon coupling with the higher fidelity main rotor and tail rotor models.
2. The time step and wake resolution requirements for accurate acoustic predictions of the main rotor and tail rotor would be much slower than real-time execution, but the use of wake reconstruction to get higher resolution of the blade loading in post-processing (especially in BVI dominated conditions) was found to be a critical tool for improving efficiency of the tool and approaches real-time prediction speeds while still providing highly accurate, high-fidelity blade loading for noise prediction.
3. The use of the CHARM rotor module significantly enhances the fidelity level of the simulation, by adding free wake and nonlinear dynamics of flexible blades (as opposed to 3-state inflow, and a rotor disk model with linearized flapping dynamics). While this level of fidelity is not necessarily required for flight simulation, the CHARM rotor module captures higher resolution blade loading needed for acoustics calculations. One of the motivations for full coupling (feedback of CHARM rotor forces to the vehicle dynamics) is to ensure consistency of the rotor force output with the flight trajectory flown.
4. The CHARM rotor module successfully captured the behavior of the "Blue Edge" blade in terms of blade vortex interaction thus underlining its strength in comparison to other more classic blade geometries. This case also demonstrates the predictive capability of the entire system.
5. The coupling of the simulation and CHARM rotor module results in a coupling transient. The transient is a simulation artifact and not relevant to the physics of interest. Some additional processing time is required to allow the controller to stabilize and re-trim the aircraft before performing the maneuver of interest. We are currently working to reduce this transient to improve efficiency of the tool.

ACKNOWLEDGEMENTS

This work was funded by the U. S. Federal Aviation Administration (FAA) Office of Environment and Energy as a part of ASCENT Project 6 under FAA

Award Number: 13-C_AJFE-PSU-006. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the FAA or other ASCENT Sponsors.

REFERENCES

1. Horn, J.F., Bridges, D.O., Wachspress, D.A, and Rani, S.L., "Implementation of a Free-Vortex Wake Model in Real-Time Simulation of Rotorcraft," AIAA *Journal of Computing, Information, and Communications*, Vol. 3, (3), March 2006.
2. Oruc, I., Horn, J.F., Polsky, S., Shipman, J. and Erwin, J., "Coupled Flight Dynamics and CFD Simulations of Helicopter/Ship Dynamic Interface," American Helicopter Society 71st Annual Forum Proceedings, Virginia Beach, VA, May 2015.
3. Brentner, K.S., Lopes, L.V., Chen, H.N., and Horn, J.F., "Near Real-Time Simulation of Rotorcraft Acoustics and Flight Dynamics," *AIAA Journal of Aircraft*, Vol. 42, (2), March-April 2005, pp. 347-355.
4. Chen, H.N., Brentner, K.S., Lopes, L.V., and Horn, J.F., "An Initial Analysis of Transient Noise in Rotorcraft Maneuver Flight." *International Journal of Aeroacoustics*, Vol. 5, (2), April 2006.
5. Li, Y., Brentner, K. S., Wachspress, D. A., Horn, J. F., Saetti, U., and Sharma, K., "Tools for Development and Analysis of Rotorcraft Noise Abatement", American Helicopter Society International, Inc. Sustainability 2015, Montréal, Québec, Canada, September 22-24, 2015.
6. Wachspress, D. A., Quackenbush, T. R., & Boschitsch, A. H. (2003, May). First-principles free-vortex wake analysis for helicopters and tiltrotors. In Annual Forum Proceedings – American Helicopter Society (Vol. 59, No. 2, pp. 1763-1786).
7. Brès, G. A., Brentner, K. S., Perez, G., and Jones, H. E., "Maneuvering rotorcraft noise prediction," *Journal of Sound and Vibration*, 275(3-5):719-738, August 2004.
8. Brès, G. A., "Modeling the noise of arbitrary maneuvering rotorcraft: Analysis and implementation of the PSU-WOPWOP noise prediction code," M.S. thesis, Department of Aerospace Engineering, The Pennsylvania State University, June 2002.
9. Perez, G., "Investigation of the influence of maneuver on rotorcraft noise," M.S. thesis, Department of Aerospace Engineering, The Pennsylvania State University, June, 2002.
10. Enns, D., Bugajski, D., Hendrick, R., & Stein, G. (1994). Dynamic inversion: an evolving methodology for flight control design. *International Journal of Control*, 59(1), 71-91.
11. Farassat, F. and Succi, G. P., "The Prediction of Helicopter Discrete Frequency Noise," *Vertica*, 7(4):309–320, 1983.
12. Ffowcs Williams, J.E., Hawkings, D.L., "Sound generated by turbulence and surfaces in arbitrary motion," *Philos. Trans. R. Soc.* A 1969; 264(1151):321-42.
13. Pegg, R.J., "A Summary and Evaluation of Semi-Empirical Methods for the Prediction of Helicopter Rotor Noise," NASA Technical Memorandum 80200, December 1979
14. Wachspress, D.A. and T.R. Quackenbush (2001). "BVI Noise Prediction using a Comprehensive Rotorcraft Analysis," American Helicopter Society 57th Annual Forum, Washington, D.C., May
15. Wachspress, D.A., K.S. Brentner, and J.A. Page (2005). "Real-Time Noise Prediction of V/STOL Aircraft in Maneuvering Flight," CDI Report No. 05-14 under NASA Contract NNL05AB01P, July.
16. Paur, J. *Eurocopter Moves One Step Closer To 'Whisper Mode'*. 2010 Feb 25, 2010 [accessed 3/4/2016]; Available from: http://www.wired.com/2010/02/eurocopter-moves-one-step-closer-to-whisper-mode/
17. Nelms, D. (2015). "New Eco-Friendly Bluecopter Unveiled," Vertiflite **61**(5): pp. 26-28.