Direct CFD Predictions of Low Frequency Sounds Generated by a Helicopter Main Rotor

Ben W. Sim  Mark A. Potsdam  Dave A. Conner  Michael E. Watts
UARC/AFDD  U.S. Army AFDD  U.S. Army AFDD/JRPO  Aeroacoustics Branch
Ames Research Center  Ames Research Center  Langley Research Center  NASA Langley Research Center
Moffett Field, CA  Moffett Field, CA  Hampton, VA  Hampton, VA
ben.w.sim@us.army.mil  mark.potsdam@us.army.mil  david.a.conner@nasa.gov  michael.e.watts@nasa.gov

ABSTRACT

The use of CFD to directly predict helicopter main rotor noise is shown to be quite promising as an alternative mean for low frequency source noise evaluation. Results using existing state-of-the-art grid structures and finite-difference schemes demonstrated that small perturbation pressures, associated with acoustics radiation, can be extracted with some degree of fidelity. Accuracy of the predictions are demonstrated via comparing to predictions from conventional acoustic analogy-based models, and with measurements obtained from wind tunnel and flight tests for the MD-902 helicopter at several operating conditions. Findings show that the direct CFD approach is quite successfully in yielding low frequency results due to thickness and steady loading noise mechanisms. Mid-to-high frequency contents, due to blade-vortex interactions, are not predicted due to CFD modeling and grid constraints.

NOTATION

\( \alpha \)  Shaft tilt (corrected) or tip-path-plane angle  
\( \text{BPF} \)  Blade passing frequency  
\( C_{T/\sigma} \)  Thrust coefficient to rotor solidity ratio  
\( M_{adv} \)  Advancing tip Mach number  
\( \mu \)  Advance ratio  
\( \Theta_b \)  Collective pitch angle, deg.  
\( \Theta_{\lambda} \)  Longitudinal cyclic pitch angle, deg.  
\( \Theta_{\kappa} \)  Lateral cyclic pitch angle, deg.  
\( \text{LFSPL} \)  Low frequency sound metric (1st-6th BPF), dB  
\( \text{MFSPL} \)  Mid frequency sound metric (> 6th BPF), dB  
\( \text{OASPL} \)  Overall sound metric (Full-bandwidth), dB

INTRODUCTION

Computational Fluid Dynamics (CFD) methods have demonstrated ample fidelity and precision in simulating the aeromechanics characteristics of helicopter rotors. Many on-going efforts\(^4\) have shown that, when coupled to Comprehensive Structural Dynamics (CSD) codes, the combined state-of-the-art CSD/CFD approach is capable of simulating realistic rotor trim solutions, performance, blade structural loads and blade airloads. Much of this success is attributed to CFD’s abilities in capturing volumetric flow details surrounding the rotor, such as effects due to the rotor wake, and those due to three-dimensional, unsteady transonic flows over blade surfaces.

In recent years, these CSD/CFD prediction codes have shown even greater improvements with the advent of faster and more powerful computing platforms. Better correlations of predictions to experiment are foremost attributed to an increase in number of grid points used in the computational domain - to the extent that complex rotor aerodynamics and flow details at smaller length scales of interests can now be resolved. In conjunction with efforts tasked to develop new, higher-order finite difference schemes that minimize numerical errors, these coupled-CSD/CFD methods are promising to be a powerful and useful tool for accurate numerical studies and, eventually, for designing future rotorcraft.

Success in predicting near body aerodynamics of helicopter rotors naturally leads to the question if realistic acoustics pressure perturbations from the rotor can be captured by CFD as well. General consensus\(^5\) dismiss the use of direct CFD numerical simulation for long range external acoustics due to the small acoustics perturbations often obscured by accruing numerical dissipation/dispersive errors resulting from the implementation of finite difference schemes. Parasitic waves associated with wave reflections from ill-defined boundary flow conditions may also distort results. In many cases, these errors can be of the same order of magnitude, or even greater, compared to the acoustics pressure perturbations themselves where solutions are required at great distances from the source. The computations are also prohibitively expensive and time-consuming due to the vast number of grid points necessary to cover the spatial extent and the acoustics bandwidth of the problem.

These short-comings are less pronounced for characterizing source noise properties close to the source. Stronger acoustic signals (at closer proximity to the source) tends to yield better “signal-to-noise ratio” - suggesting that it may be possible to yield realistic acoustic pressures directly from CFD. The challenges lie in satisfying the inherently large spectral bandwidth requirement and also addressing the large disparity between acoustic pressure perturbations and mean flow pressures. For plausible CFD
implementations, this stipulates a grid spacing constraint that
must be sufficiently small to represent the smallest
wavelength (i.e. highest frequency) of interest associated
with the source noise mechanism. Naturally, smaller grid
spacings and large spatial domains of interest (related to
observer locations) result in larger number of grid points that
render direct CFD methods to be sometimes impractical.

While there are some modeling constraints with this
approach, use of direct CFD method has been successfully
demonstrated before by Baeder\(^8\) in 1991. Euler-based CFD
simulations were then performed for a non-lifting, hovering
rotor at high tip Mach numbers known to produce strong
High Speed Impulsive (HSI) noise due to delocalized weak
shocks. Results illustrated the need to cluster grid points
along known directions of sound propagation to yield
satisfactory acoustics predictions that are in agreement with
measurements up to two radii away from the rotor hub. Grid
sensitivity studies also indicated the need for about 60,000
grid points to adequately capture the nonlinearities
associated with the delocalized shock front. This effort
clearly showed that acoustic predictions using CFD is
possible if the grids are adequately structured and sufficient
computational resources are available. The study, however,
did not extend to realistic flight conditions with a lifting
rotor operating at forward flight velocities and tip Mach
numbers representative of typical helicopter flight envelope.

As an extension to the effort by Baeder, this paper will
examine the ability of using CFD to directly predict
radiating acoustic pressure waves from a helicopter main
rotor (source noise) under more realistic circumstances.
Emphasis will be placed on noise predictions near in-plane
of the rotor that are of concern for military operations.
Fidelity of the predictions will be evaluated via comparing
results obtained from direct CFD methods to conventional
acoustics analogy-based methods for a MD-902 main rotor.
Measured acoustics data from wind tunnel and full-scale
flight testing will also be used when possible. With such a
wide range of source noise prediction models and source
noise measurements for comparisons, it is the goal of this
paper to:

- Determine the feasibility of direct CFD methods in
capturing the source noise of a helicopter main rotor in
steady-state forward flight lifting conditions. Note that
the cases in this paper are limited to Mach numbers
below delocalization, such that both the acoustic
thickness and loading components are significant in the
sound generation mechanism.
- Highlight the state-of-the-art using existing CFD
algorithms and grid structures, deemed appropriate for
accurate rotor aerodynamics modeling, directly for
acoustics predictions. Grid clustering efforts, though
known to generate better results, are not a focus of this
study.

**SOURCE NOISE PREDICTIONS**

The ensuing section provides a description of the
different source noise prediction methodologies used in the
paper. In particular, the procedures to extract acoustic
pressures directly from CFD results are highlighted and
compared to conventional acoustic analogy-based
methodologies. The pros-and-cons of each approach are
also discussed.

**Direct CFD Acoustics Predictions (DCAP)**

CFD calculations use the complex geometry Navier-
Stokes solver OVERFLOW 2.1ad\(^2\). Capabilities for loose
(delta) coupling have been added to the NASA release
version based on original developments under the DoD
CHSSI Portfolio, Collaborative Simulation and Testing
(CST-05)\(^10\). OVERFLOW computes solutions on structured,
overset grids using a near- and off-body discretization
paradigm (Fig. 1). The near-body grids surround the solid
surfaces and capture the viscous effects with highly
stretched curvilinear meshes. They extend out approximately
one chord from the rotor blade. Automatically generated
Cartesian off-body grids surround the near-body grids and
capture the wake. They extend out to the far field boundary,
placed at 5 rotor radii, with increasing spacing. There is a
factor of 2 spacing between successive off-body grid levels.
Time-accurate simulations of complex aircraft
configurations with aeroelastic bodies in relative motion can
be efficiently computed on parallel processors using the
overset methodology.

The computational structural dynamics (CSD)
calculations use the CAMRAD II v4.6 (Johnson)
comprehensive rotorcraft analysis software, based on the
baseline DARPA Helicopter Quieting Program
MDART/SMART model input. The dual load path root
(pitchcase and flexbeam) and blade are modeled with 10
elements, along with a compliant pitch link. The flexbeam
has one axial degree-of-freedom. A harmonic analysis is
performed using 18 blade modes. CAMRAD II performs
both the CSD and rotor trim. Details of the structural
modeling are provided in Potsdam2.

CFD/CSD coupling between OVERFLOW and
CAMRADII is performed using a conventional (for
rotorcraft) loose coupling incremental “delta” formulation.1
Coupling is on a per revolution basis based on periodicity.
Motions (3 rotations and 3 translations of the airfoil
sections) and airloads (section normal force, chord force,
and pitching moment) are exchanged. Fully-automated
coupling is performed using shell scripting, file I/O, and
interface programs. Typically, 7 coupling iterations are used,
with 2/5 rev (2 blade passages for the 5-bladed rotor) between
each coupling.

The MD-902 main rotor is comprised of 5 blades and a
high fidelity hub. Each blade is composed of 3 grids (root
cap, blade, tip cap). Excluding tip caps, the main portions of
the blade are O-grid topology. The chordwise, spanwise, and normal dimensions are 221 x 248 x 59 for the main blade, with 21 points across the blunt trailing edge. The baseline grid contains 56.1 million points (67% off-body) in 62 grids. The finest Cartesian off-body level 1 (L1) grid has 8% mean chord wake spacing. It surrounds the rotor and captures the wake with dimensions ±1.1R in X and Y, and −0.14R, +0.20R in Z. There are 3.4 million points per blade. Solutions were run on 256 processors at 10.4 hours per rotor revolution on a Cray XT5.

The time-accurate calculations use a high order 6th-order central difference spatial discretization with added 6th-order scalar (near-body) and matrix (off-body) artificial dissipation, resulting in a nominally 5th-order scheme. A 7-point stencil is required, and the overset Cartesian meshes have triple fringing. A 2nd-order temporal backward difference scheme with iterative dual time stepping is used for time advancement along with a penta-diagonal left-hand side scheme. Fifteen (15) sub-iterations are used, typically resulting in 1.5 – 2.0 orders of magnitude reduction in the main blade grid residuals and considerably more (> 3.0) in the off-body grids. Quarter degree (0.25°) time steps are used (1440 steps per rotor revolution). The Spalart-Allmaras turbulence model is employed in the near-body grids. The off-body wake grids are inviscid.

Solutions are run from scratch for 3 rotor revolutions using previously computed CFD/CSD coupled motions. The last revolution is recorded for acoustics analysis. The flow field data is saved at 1-degree intervals. Saving the complete flow solution this frequently is very slow and inefficient. It generates a huge amount of data which must then be manually manipulated and stored. Instead, it is much more efficient to record the minimal amount of data needed. To this end the SPLITTM capability in OVERFLOW 2.1ad has been used. Data is stored on a Y plane at the microphone location (y = 0.63R) extracted from the off-body grids only. The pressure at the nearest point to the microphone in this 2D data subset is then extracted in a simple post-processing step to generate the pressure signal. In-plane data (z = 0) from the off-body meshes is saved for visualization purposes. Finally, surface data from the near-body grids is saved for on-surface non-compact noise predictions using WOPWOP. The grid and flow solution files for these three 2D datasets (y = −0.63R, z = 0, and solid surfaces) require 66 MB per time step, compared with 8.8 GB for the entire flow field. They represent less than 1% of the flow field data. Similarly, acoustic data surfaces, such as Pringles or tuna cans (Bain), for permeable surface FW-H analysis can be saved efficiently using the $ADSNML$ capability, which interpolates flow field data onto arbitrary user specified 2D grids. A severe limitation with ADS surfaces in OVERFLOW requires that these grids reside within the L1 domain. At this time, this generally precludes extracting hemisphere maps or ground plane acoustics data directly.

Other limitations include a bandwidth restriction on the acoustics data that is inherently governed by the grid spacing at the point of evaluation. The relatively coarse spacing (Fig. 1), away from the rotor, suggests it is unlikely that mid-to-high frequency contents, such as those due to blade-vortex interactions or high-speed impulsive noise, can be captured without grid refinement. The general rule-of-thumb is to approximate this upper frequency limit using at least five grid points per wavelength. For full-scale rotor studies, an off-body grid spacing on the order of 12 inches would yield a cut-off frequency of about 200 Hz — thus, preventing higher frequencies to be captured. It is also noted that this approach, unlike acoustic analogy-based methodologies, does not allow contributions from thickness and loading noise components to be evaluated separately.

Nonetheless, the direct extraction from CFD results is deemed an attractive solution as it eliminates the need for a separate acoustics analysis in the computational chain. It is also deemed favorable for accounting any flow-field effects (quadrupole contributions off the blades) that may contain strong non-linearities caused by compressibility and flow separations.

**Acoustic Analogy, On-Surface (FWH)**

For comparison purposes, PSU-WOPWOP is used to generate acoustics predictions based on the classical acoustic analogy approach, first proposed by Lighthill, and subsequently adapted by Ffowcs-Williams/Hawkings and Farassat for moving bodies. This approach is typically executed at the end of the computational chain after blade geometry, blade motion and aerodynamic load information have been resolved. In this paper, blade geometry and CFD-predicted blade surface pressures (non-compact) are supplied to PSU-WOPWOP to enable “on-surface” acoustics predictions in the time domain — accounting for only the linear thickness noise source and “on-surface” loading noise source terms. Volumetric data, associated with “off-surface” flow-field features important for the nonlinear quadrupole source term, are not considered in this paper.
SOURCE NOISE MEASUREMENTS

Acoustic measurements will also be used in this paper to evaluate the fidelity of DCAP noise predictions. The bulk of which is obtained from the Boeing-SMART rotor test, completed in 2008. Selective test points from a full-scale MD-902 acoustics flight test conducted in 2007 are also used in subsequent discussions.

Boeing-SMART Rotor Test (WT)

This paper relies on results obtained from the joint DARPA/NASA/Army-funded program utilizing the Boeing’s Smart Material Actuated Rotor Technology (SMART) rotor, tested in the 40- by 80-Foot Wind Tunnel of the National Full- Scale Aerodynamic Complex (NFAC) at NASA Ames Research Center in 2008 (Fig. 2a), as a guide for prediction validation. The Boeing-SMART rotor is a 34-ft diameter, full-scale, bearingless, five-bladed main rotor modified from an existing MD-902 Explorer rotor system with active trailing-edge flaps. An array of microphones was strategically placed around the full-scale model to capture rotor noise. The general layout of microphone placement in the wind tunnel is illustrated in Figure 2b – with details of their location coordinates listed in Table 1. For present study, this paper will primarily focus on in-plane microphone M13 and on selective test conditions with the active trailing-edge flaps un-deployed. All results were obtained with the rotor trimmed to a target thrust and minimized flapping moments.

![Figure 2. Boeing-SMART rotor: a) installation in wind tunnel, b) microphone layout.](image)

### Table 1. Microphone positions

<table>
<thead>
<tr>
<th>Sensor Name</th>
<th>Cartesian</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>M01</td>
<td>-29.67</td>
<td>10.27</td>
</tr>
<tr>
<td>M04</td>
<td>-27.92</td>
<td>15.59</td>
</tr>
<tr>
<td>M05</td>
<td>-16.73</td>
<td>6.97</td>
</tr>
<tr>
<td>M06</td>
<td>-16.73</td>
<td>9.79</td>
</tr>
<tr>
<td>M07</td>
<td>-16.73</td>
<td>12.02</td>
</tr>
<tr>
<td>M08</td>
<td>-16.73</td>
<td>14.17</td>
</tr>
<tr>
<td>M09</td>
<td>-16.73</td>
<td>16.42</td>
</tr>
<tr>
<td>M10</td>
<td>-16.73</td>
<td>18.67</td>
</tr>
<tr>
<td>M11</td>
<td>-16.73</td>
<td>20.90</td>
</tr>
<tr>
<td>M12</td>
<td>-16.73</td>
<td>23.92</td>
</tr>
<tr>
<td>M13</td>
<td>-29.67</td>
<td>10.27</td>
</tr>
<tr>
<td>M15</td>
<td>-38.77</td>
<td>8.73</td>
</tr>
<tr>
<td>M14</td>
<td>-80.36</td>
<td>-0.33</td>
</tr>
</tbody>
</table>

Note: hub-centered, 0 deg. shaft tilt

$X$ – positive towards aft of rotor, $Y$ – positive towards starboard, $Z$ – positive up

Acoustics data were acquired for 64 revolutions, at a rate of 2048 samples per revolution. The time records are subsequently averaged, on a per-rev basis, to isolate harmonic contents pertaining only to the rotation of the rotor. As reported in Ref. 18, these measurements contain reflections due to the presence of non-ideally treated wind tunnel walls. Also, it should be noted that these acoustic data were acquired in a configuration where the rotor and microphone were fixed at the same relative distance - similar to the setup in the prediction methodologies described above.

Eglin III Acoustics Flight Test (FT)

Acoustics data were also extracted from a MD-902 helicopter flight test, conducted at Eglin Air Force Base in 2007, for comparisons in this paper. The NOTAR-platform provides an excellent source of data for comparisons to main rotor-only wind tunnel test data and predictions. As described in Ref. 19, the flight test program utilized 19 ground-fixed microphones in a horseshoe-shaped array to create source noise hemispheres for various level and descent flight profiles. An extensive array of instrumentations, including a Differential Global Positioning System (DGPS) unit, a real-time pilot guidance and a tethered-weather balloon system, were used to monitor the vehicle’s flight track, performance state and atmospheric conditions.

To enable direct comparisons with the afore-mentioned wind tunnel/prediction data, segments of the measured flight test time history data (approximately five revolutions long) were extracted from a selected ground-fixed microphone that geometrically simulates the source-to-microphone directivity (emission angles) of the wind tunnel microphone M13 shown in Figure 2b. The data are subsequently de-
under-predicting negative main pulse acoustic obtained Results field. constitute the DCAP in Pascals. instantaneous the by perturbation level condition condition MDART, in use, L5 rotor described history flight rotor rotor source-to-microphone are adjusted arrival non-stationary condition MD-902 rotor, are, MDART, and MDART, in use, initial study. MDART condition simulates the MD-902 main rotor operating at a level flight of 124 knots (μ = 0.30). (See Table 2 for details of the rotor operating conditions.) All acoustics calculations are based on microphone M13 in the wind tunnel.

Figure 3 illustrates a snapshot (top view) of the perturbation pressure contours in the rotor plane predicted by DCAP obtained at an instant when microphone M13 sees the arrival of a strong acoustic wave-front. Contour levels are described in decibels (dB) using the absolute instantaneous perturbation pressures referenced to 2 x 10^-5 Pascals. Predictions were made with the microphone located in the L5 off-body grid that has a grid spacing of approximately one blade chord. These results show that DCAP can, not only capture the pressure fluctuations associated with the vortex-wake system and downwash near the rotor, but also pressure waves from the advancing side of the rotor that radiates forward. The latter essentially constitute the acoustics waves that propagate into the farfield.

Figure 4 illustrates the acoustic time histories over one rotor revolution for the MDART case at microphone M13. Results from direct CFD predictions (DCAP) and from PSU-WOPWOP (FWH) are compared against measurements obtained from the Boeing-SMART wind tunnel test (WT) and from the Eglin III acoustics flight test (FT). All of these acoustic time histories show five dominant peak negative pressure pulses per rotor revolution. Each of the negative pulse is attributed primarily to the thickness noise originating from each of the five blades on the MD-902 main rotor system. No impulsive blade-vortex interactions-like noise fluctuations are evident at this test condition.

Figure 5a shows a zoomed-in view of one of the peak negative pressure pulse. The Direct CFD method (DCAP) demonstrates that it is capable of capturing general features associated with the negative peak pressure pulse, albeit under-predicting the negative peak amplitude when compared to measurements. In comparison, predictions from the on-surface acoustic analogy method (FWH) is worse, with only half of the negative peak accounted for. Although not shown in this paper, this discrepancy is likely caused by the negligence of flow-field/compressibility effects off the tip of the rotor blade observed in Figure 3. Off-surface FWH implementations will likely facilitate better predictions.

Similar trends are observed with acoustic time histories lowpass-filtered at 200 Hz (Fig. 5b). As discussed previously, this cut-off frequency is associated with DCAP’s bandwidth limitations using a grid spacing of 12.8 inches (approximately one blade chord) at microphone M13. In the frequency domain (Fig. 5c), this translates to the ability to account for only the harmonic contents at and below the 6th blade passing frequency (BPF) harmonic for the MD-902 rotor. Compared to wind tunnel results, predictions from DCAP in Figure 5c show much larger discrepancies at and beyond the 6th BPF harmonic. Low frequencies, below 6th BPF harmonic, are better predicted (to within 2 dB), with the exception of the 3rd BPF harmonic.

Also of interest to note is that while flight test time histories correlate quite well with wind tunnel measurement, there is a significant first BPF harmonic contribution in the flight test measurement not observed else where. In addition, it is unclear why the pulse width obtained from flight test is larger than those obtained in the wind tunnel. It is also indicated in the time histories that the wind tunnel data contains some spurious fluctuations not present in the flight test/predictions. These fluctuations have been determined to be due to wind tunnel wall reflections.

SENSITIVITY STUDIES

The MDART test condition is also used to examine effects of different CFD implementations to demonstrate their ability to capture small amplitude acoustic pressure waves.

Grid Spacings

Figure 6 shows the perturbation pressure contours for a case where the microphone M13 resides on a finer mesh. This is achieved in the CFD by extending the L1 grid forward to embody microphone M13. Doing so resulted in increasing the grid domain to 67.2 million total points and reducing the grid spacing at the microphone to about 0.8 inches (approximately one-tenth of the blade chord). Figure 6 shows that, although the refined grid results offered more details and smoother contours in the vicinity of the microphone, the overall patterns remain quite similar to the coarser grid solution shown in Figure 3.
Table 2. Rotor operating conditions for simulations and measurements

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Flight Conditions</th>
<th>Control Angles</th>
<th>Hub Forces</th>
<th>Hub Moments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>µ</td>
<td>M_{adv}</td>
<td>α</td>
<td>C_{p}</td>
</tr>
<tr>
<td>Units</td>
<td>deg.</td>
<td>deg.</td>
<td>deg.</td>
<td>deg.</td>
</tr>
<tr>
<td>WT³</td>
<td>0.300</td>
<td>0.806</td>
<td>-9.1</td>
<td>0.0804</td>
</tr>
<tr>
<td>FT²</td>
<td>0.294</td>
<td>0.785</td>
<td>-8.6</td>
<td>0.0795</td>
</tr>
<tr>
<td>DCAP³</td>
<td>0.300</td>
<td>0.806</td>
<td>-9.1</td>
<td>0.0804</td>
</tr>
<tr>
<td>FWH¹</td>
<td>Same as DCAP</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes:
1 Measured, Boeing-SMART Rotor test (FY 2008), Run 46, Point 94
3 CAMRAD/OVERFLOW-2 calculations trimmed to measured wind tunnel conditions and rotor thrust (min. hub moments)
4 Make use of OVERFLOW-2 predicted surface pressures at the same trim conditions as in DCAP

Figure 3. DCAP-predicted perturbation pressure contours for MDART case.
Figure 4. Predicted acoustic time histories for MDART case at microphone M13.

Figure 5. MDART case study: a) full-bandwidth time history, b) lowpass-filtered time history, c) frequency spectrum.
The effects on acoustics time histories are illustrated in Figure 7. Using the finer mesh (DCAP-L1) resulted in a slightly larger negative peak pressure compared to solutions obtained from the coarser grid (DCAP-L5). Overall, the effect seems to enhance the fidelity of direct CFD-based predictions to better correlate with wind tunnel measurement. Because of smaller grid spacing, the finer mesh solution is also able to capture sound levels at higher frequencies.

**Finite-Difference Scheme**

Results are also shown using a 3\textsuperscript{rd} order scheme in the CFD model, as compared to the 5\textsuperscript{th} order scheme discussed previously (Fig. 8a). Surprisingly, solutions obtained from the lower order scheme (DCAP-3\textsuperscript{rd}) show comparable predicted peak negative pressure as from the 5\textsuperscript{th} order scheme (DCAP-5\textsuperscript{th}). Some differences, off to the side of the negative pressure peak, are observed between the two solutions, but are not significant enough for considerations. The primary difference lies in the predicted frequency spectrum (Fig. 8c) where the lower order scheme is shown to be unable to capture the higher frequency content of the acoustics radiation.

![Figure 6. DCAP-predicted perturbation pressure contours with finer mesh.](image)
Figure 7. Grid dependence study: a) full-bandwidth time history, b) lowpass-filtered time history, c) frequency spectrum.

Figure 8. Finite-difference scheme sensitivity study: a) full-bandwidth time history, b) lowpass-filtered time history, c) frequency spectrum.
ADVANCE RATIO VARIATIONS

Robustness of the direct CFD method is highlighted in this section via evaluating the fidelity of DCAP predictions at for four different advance ratio conditions (Table 3). DCAP predictions are compared to acoustic analogy-based predictions, as well as measurements from wind tunnel, and flight test. First two conditions at lower advance ratios ($\mu = 0.165$ and $0.200$) pertain to strong BVI noise conditions during descent. As shown in Figure 9, distinct blade-vortex interaction fluctuations are present in the predicted airloads (normal force and chord force) and pitching moment at 87% span location. The $\mu = 0.250$ condition represents a shallower descent with less BVI-induced aerodynamics fluctuations. Finally, the $\mu = 0.300$ condition simulates a level flight condition at close to 123 knots. In all these cases, the rotor thrust was held approximately the same at a nominal $C_T/\sigma$ of approximately 0.075. All calculations are performed with the same overset grid (a grid spacing of 12.8 inches at microphone M13) and 5th order scheme.

Table 3. Rotor operating conditions for speed variation study.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Flight Conditions</th>
<th>Control Angles</th>
<th>Hub Forces</th>
<th>Hub Moments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Units</td>
<td>$\mu$</td>
<td>$M_{adv}$</td>
<td>$C_{T}/\sigma$</td>
<td>$\Theta_b$</td>
</tr>
<tr>
<td>$\mu \approx 0.165$</td>
<td>WT</td>
<td>0.164</td>
<td>0.721</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td>DCAP</td>
<td>0.164</td>
<td>0.721</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td>FW-H</td>
<td>Same as DCAP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu \approx 0.200$</td>
<td>WT</td>
<td>0.200</td>
<td>0.748</td>
<td>-2.6</td>
</tr>
<tr>
<td></td>
<td>DCAP</td>
<td>0.200</td>
<td>0.748</td>
<td>-2.6</td>
</tr>
<tr>
<td></td>
<td>FW-H</td>
<td>Same as DCAP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu \approx 0.250$</td>
<td>WT</td>
<td>0.250</td>
<td>0.779</td>
<td>-3.6</td>
</tr>
<tr>
<td></td>
<td>DCAP</td>
<td>0.250</td>
<td>0.779</td>
<td>-3.6</td>
</tr>
<tr>
<td></td>
<td>FW-H</td>
<td>Same as DCAP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu \approx 0.300$</td>
<td>WT</td>
<td>0.300</td>
<td>0.810</td>
<td>-8.8</td>
</tr>
<tr>
<td></td>
<td>FT</td>
<td>0.307</td>
<td>0.791</td>
<td>-9.3</td>
</tr>
<tr>
<td></td>
<td>DCAP</td>
<td>0.300</td>
<td>0.810</td>
<td>-8.8</td>
</tr>
<tr>
<td></td>
<td>FW-H</td>
<td>Same as DCAP</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1. CAMRADII/OVERFLOW-2 calculations trimmed to measured wind tunnel conditions and rotor thrust (min. hub moments)
2. Make use of OVERFLOW-2 surface pressures calculated at the same trim conditions as in DCAP
3. Measured, Boeing-SMART Rotor test (FY 2008), Run 46, Point 94

Figure 9. Predicted airloads and pitching moments at 87% span for the four different advance ratio conditions.
Figure 10 illustrates the CFD predicted perturbation pressure contours in the plane of the rotor for the different advance ratio conditions. Acoustic pressure wave-fronts generated by each of the blade can be seen to radiate forward from the advancing side of the rotor. As these wave-fronts arrive at microphone M13, Figure 10 illustrates that the perturbation pressures increase in strength with increasing advance ratios. Much of this is attributed to increased compressibility effects when a blade approaches the advancing side of the rotor near 90 degrees azimuth. It is also illustrated in Figure 10 that the flow-field off the blade tip, near the advancing side of the rotor, tends to become more prominent at higher advance ratios. This suggests that an off-surface approach is likely required to completely model the rotor acoustics at higher advance ratios.

Figure 10. DCAP-predicted perturbation pressure contours at different advance ratios.
Figure 11. Predicted acoustic time histories for the different advance ratios at microphone M13.
c) $\mu = 0.250$

Figure 11 (continued). Predicted acoustic time histories for the different advance ratios at microphone M13.

d) $\mu = 0.300$
The corresponding acoustic time histories, at microphone M13, for the four advance ratio conditions are illustrated in Figure 11. For the lower advance ratio conditions ($\mu = 0.165$ and 0.200), DCAP predictions are unable to account for the high frequency, impulsive noise fluctuations due to constraints imposed by the grid spacing and finite-difference scheme. Large differences in the mid-frequency MFSPL metric, up to 20 dB, are observed between DCAP predictions and wind tunnel measurements.

Low frequency noise content are better captured by the direct CFD method. As shown in Figure 11b, the lowpass-filtered signals (< 200 Hz) from DCAP are in reasonable agreement compared to wind tunnel measurements. Overall, the DCAP results under-predicts the low frequency LFSPL metric by approximately 0.5 to 4.0 dB. These results demonstrate that the direct CFD method is not only capable of capturing thickness noise at higher advance ratios, but steady loading (in-plane) noise that dominates at lower advance ratios as well.

In contrast, the acoustic analogy-based predictions (FWH) appear to fair better for capturing high frequency noise contents. Impulsive noise fluctuations are predicted for the two lower advance ratio conditions with peak-to-peak amplitudes that are quite similar to wind tunnel measurements, albeit at different instances in time (blade azimuth). Low frequency noise contents are also well predicted at lower advance ratio conditions where steady loading noise mechanism dominates. At higher advance ratios, the acoustic analogy-based predictions become less accurate with upwards of 8.0 dB differences in LFSPL at $\mu = 0.300$. Increased discrepancies in the LFSPL metric with advance ratios suggest that it may be due to the negligence of the flow-field effects off the blade tip near the advancing side of the rotor.

CONCLUSIONS

The use of CFD to directly predict helicopter main rotor source noise is shown to be quite promising as an alternative mean for low frequency noise evaluation. Results using existing state-of-the-art grid structures and finite-difference schemes demonstrated that small perturbation pressures, associated with acoustics radiation, can be extracted with some degree of fidelity.

Assessment of the direct CFD method is performed via comparing predicted results to conventional acoustic analogy-based predictions and with measurements from wind tunnel and flight test data. Evaluation of in-plane noise radiation of the MD-902 main rotor at several advance ratio conditions yields the following results:

- Low frequency noise contents, below 6th blade-passing harmonics, are reasonably well-captured using the direct CFD method with a grid spacing of about 12 inches at the microphone. Results are in general agreements with wind tunnel and flight test data to within 4 dB.
- Mid-to-high frequency noise contents cannot be predicted by the direct CFD method due to grid spacing constraints. Large discrepancies of up to 20 dB, in the mid-frequencies, are found especially at conditions dominated by impulsive noise fluctuations associated with blade-vortex interactions.
- Conventional “on-surface” acoustic analogy approach is better at predicting the overall noise at lower advance ratios where loading noise and impulsive noise dominate. At higher advance ratios where thickness noise becomes more important, low frequency noise tends to be underpredicted. It is speculated that this discrepancy is due to the flow-field effects off the blade tips not accounted for in the “on-surface” modeling.

ACKNOWLEDGMENTS

The authors would like to acknowledge the following personnel, in no particular order, for their helpful discussions and efforts on validating the prediction models:

- Mr. Eric Greenwood, Dr. Doug Boyd and Dr. Leonard Lopes (NASA Langley)
- Mr. Charles Smith (Lockheed Martin)
- Dr. Shreyas Anathan, Prof. James Baeder (University of Maryland)
- Mr. Jeremy Bain (Georgia Institute of Technology)
- Dr. SeongKyu Lee and Prof. Ken Brentner (The Pennsylvania State University)
- Dr. Chris Hennes (Vortex Consulting, LLC)

REFERENCES


