Project 038 Rotorcraft Noise Abatement Procedure Development

The Pennsylvania State University, Continuum Dynamics, Inc.

Project Lead Investigator

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University Participants

The Pennsylvania State University (Penn State)

- PI: Kenneth S. Brentner, Professor of Aerospace Engineering
- FAA Award Number: 13-C_AJFE-PSU-038, Amendment No. 63
- Period of Performance: August 11, 2020 to August 10, 2021
- Task(s) (during this period):
    18. Compare the effectiveness of noise abatement procedures by helicopter class using 2017 and 2019 flight test data
    19. Analyze 2019 FAA/NASA acoustic flight test data
    20. Develop a method for coupling the noise prediction system with FAA noise prediction and analysis tools
    21. Continue efforts to develop noise abatement flight procedures for various helicopter classes
    22. Develop documentation and training materials for the noise prediction system

Project Funding Level

FAA Funding $150,000; Continuum Dynamics, Inc. (points of contact: Dan Wachspress and Mrunali Botre) will provide $150,000 of cost sharing in the form of a 1-year license for the Comprehensive Hierarchical Aeromechanics Rotorcraft Model (CHARM) rotorcraft comprehensive analysis software to Penn State and a second 1-year license to the FAA or its designee. Penn State will provide $21,787 as an academic year salary for the PI.

Investigation Team

- Kenneth S. Brentner, PI, The Pennsylvania State University; acoustic prediction lead on all tasks
- Joseph F. Horn, Co-PI, The Pennsylvania State University; flight simulation lead supporting all tasks
- Daniel A. Wachspress, Co-PI, Continuum Dynamics, Inc.; responsible for rotor loads, wake integration, and CHARM coupling
- Damaris Zachos and Lauren Weist, Graduate Research Assistants, The Pennsylvania State University; primarily responsible for establishing new aircraft models, developing simulations for new helicopter types, performing acoustic predictions, and developing flight abatement procedures; Damaris Zachos was involved in all tasks; Lauren Weist started working on this project near the end of the year.

Project Overview

Rotorcraft noise consists of several components, including rotor noise, engine noise, and gearbox and transmission noise. Rotor noise is typically the dominant component of rotorcraft noise to which the community is exposed upon takeoff and landing and along the flight path of the helicopter. Rotor noise arises from multiple noise sources, including thickness noise and loading noise (the combination of these two is known as rotational noise), blade–vortex interaction (BVI) noise, high-speed impulsive (HSI) noise, and broadband noise. Each noise source has its own unique directivity pattern around the helicopter. Furthermore, aerodynamic interactions among rotors, interactions between the airframe wake and a rotor, and unsteady time-dependent loading generated during maneuvers typically result in significant increases in loading noise. The combination of all potential rotor noise sources makes the prediction of rotorcraft noise highly complex, even though not all noise sources are present at any given time in the flight (e.g., BVI noise usually occurs during the descent, and HSI noise only occurs during high-speed forward flight).

In ASCENT Project 6, "Rotorcraft Noise Abatement Operating Conditions Modeling," the project team coupled a MATLAB-based flight simulation code with CHARM and PSU-WOPWOP to perform rotorcraft noise prediction. This noise prediction system was used to develop noise abatement procedures through computational and analytical modeling. Although this noise prediction system cannot predict engine noise or HSI noise, it was thoroughly validated via a comparison between predicted noise levels for a Bell 430 aircraft and flight test data (Snider et al., AHS Forum, 2013) for several observer positions and operating conditions.

In previous work for ASCENT Project 38, representative helicopters were recommended for noise abatement procedure development. These helicopters were selected to enable a determination of whether noise abatement procedures could be developed for various categories of helicopters (two-blade light, four-blade light, two-blade medium, etc.) or whether aircraft-specific design considerations would be required. Aircraft models were established for the following aircraft: Bell 430, Sikorsky S-76C+ and S-76D, Bell 407 and 206L, Airbus EC130 and AS350, and Robinson R66 and R44. Predictions were made before the 2017 FAA/NASA noise abatement flight test to provide guidance for the flight test. After the flight test, a comparison of L_A (A-weighted sound pressure level) time histories and sound exposure level (SEL) contour plots revealed a problem in the broadband noise prediction, which was subsequently corrected. Initial validation comparisons demonstrated that the simulations were within a few dBA of the flight test data; however, some discrepancies in the simulations (simplifications) remained, requiring a detailed examination. Work was also performed on the noise prediction system, including modifying PSU-WOPWOP to output plots of the maximum dBA, as plotted in the flight test. Further work was conducted to enhance the postprocessing of noise data to enable a direct comparison with flight test. Detailed analysis of the noise components and noise sources was performed for several of the helicopters in the 2017 FAA/NASA flight test.

The objective of this continuing project is to reduce the need for flight testing of each rotorcraft of interest for continued development of low-noise operating procedures. Current guidelines provided to pilots and operators in the Fly Neighborly guide are based on recommendations from manufacturers, but this guidance is not required and often not provided. Other methods for developing noise abatement procedures at the FAA and NASA are empirical, based on previous flight measurements of specific aircraft. The tasks described below will enable analyses of new flight procedures and noise analysis strategies through computations alone. This year's efforts included detailed analyses and investigation of the 2017 and 2019 FAA/NASA noise abatement flight tests, along with documentation and training materials for the FAA to use the tools more effectively.

Task 18 - Compare the Effectiveness of Noise Abatement Procedures by Helicopter Class Using 2017 and 2019 Flight Test Data

The Pennsylvania State University

Objective(s)

In this task (Task 8.1 in the 2020–2021 proposal), helicopter models in the 2019 FAA/NASA flight test will continue to be analyzed. Several of the noise abatement procedures performed during the flight test will be simulated with the noise prediction system. Using both noise predictions and measured data, noise abatement procedures will be examined. The effectiveness of the procedures for the heavier helicopters in the 2019 test will be compared with that for the lighter helicopters in the 2017 test. The noise predictions will allow a deeper understanding of the noise sources and their relative importance to help explain differences in noise abatement procedures for helicopters of different weight classes and technology levels.

Research Approach

The noise prediction system developed in ASCENT Projects 6 and 38 was used and updated as necessary. The PSU-WOPWOP code was used for noise prediction and was coupled with the PSUHeloSim flight simulator and CHARM to form a rotorcraft noise prediction system. The flight test data were examined, and the measured and predicted results were compared to help explain any significant details in the noise measurements. This evaluation can also identify the primary and secondary noise sources involved in each flight procedure and can clarify how noise abatement was achieved (which can lead to generalized procedures for other helicopter categories, weights, etc.). After the prediction system is validated with 2019 flight test aircraft, a comparison between similar aircraft from the 2017 and 2019 flight tests will be developed. Identical maneuver cases will be developed for comparable aircraft, and various noise metrics will be evaluated for signs of significant differences in noise sources between heavier and lighter designs. The results of this study will provide guidance on the importance of aircraft weight in the development of noise abatement procedures and determine if separate procedures are necessary for aircraft in different weight classes.

In previous work performed as part of Project 38, M. Botre [Botre, Ph.D. dissertation, 2020] found that the Pegg broadband loading model overpredicts broadband noise for some helicopters and underpredicts broadband noise in other cases. The source of this over- and underprediction is not understood; however, the Pegg model is a simple empirical model, and changes in weight or other helicopter design features may be related to this discrepancy. In this work, we propose to determine whether it would be useful to include a simple shift in the Pegg broadband noise models, i.e., a scaling of the Pegg broadband noise prediction. To determine the scaling for each case, the measured flight test maximum dBA level is used at a single observer position to determine the necessary scale factor for each aircraft. Then, that Pegg scale factor is applied to plot the predicted ground contour results. Each aircraft has its own distinct scale factor. It would be beneficial to assess whether these unique scale factors follow any trends that could be used to improve Pegg broadband noise predictions.

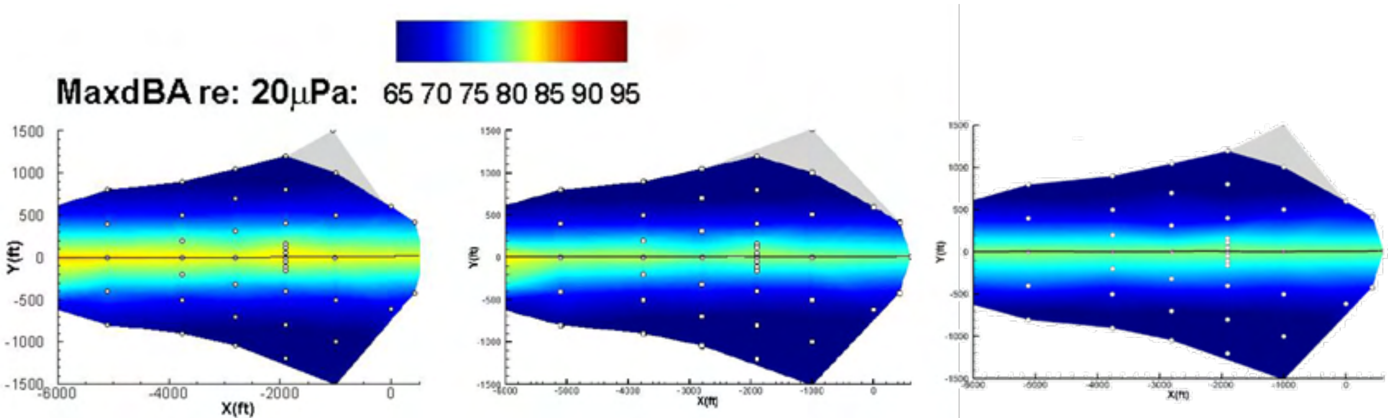
Milestone(s)

The milestones for this task include (a) using validated helicopter noise prediction models for aircraft from the 2019 and 2017 flight tests to simulate identical flight maneuvers for multiple aircraft and (b) evaluating noise prediction results for each noise source (thickness, loading, and broadband) to determine similarities between noises produced by aircraft in different weight classes. In this task, we will examine various predicted noise sources and will investigate which sources are important in simulated predictions (for several different observer locations). Dissimilarities between comparable aircraft with differences in weight will be used to determine the use of noise abatement procedures to reduce noise.

Major Accomplishments

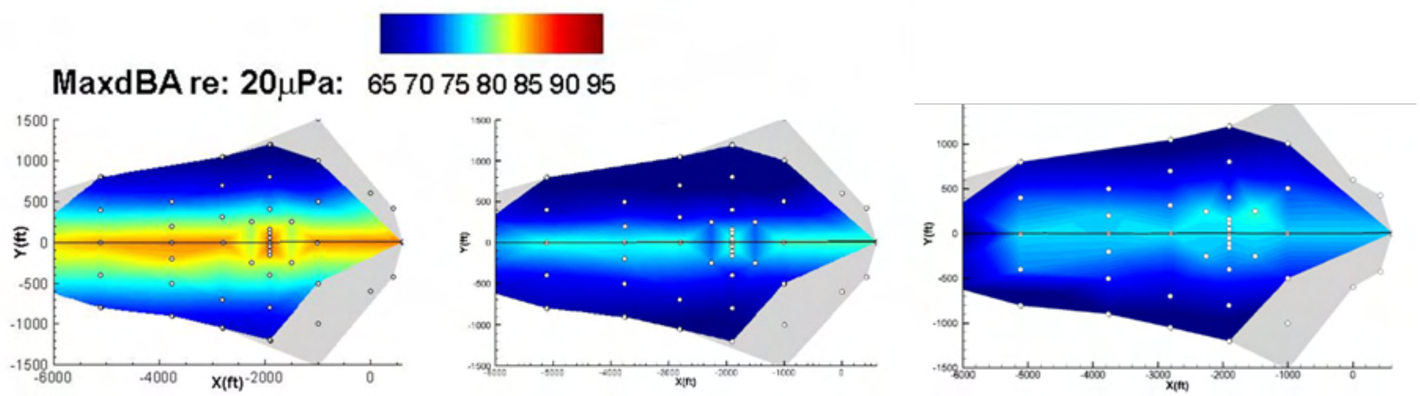
The required modeling parameters for the Bell 205 and Sikorsky S-76 helicopters were used to generate HeloSim flight path models that mimicked test trajectories from 2019 flight tests. These models have been validated against flight test data as part of Task 19 (8.2 in the 2020–2021 proposal). The S-76 model uses elements from S-76 models A–D because the needed parameters were not publicly available for S-76D. This “S-76” model was used to provide an initial view of the comparison between measured and predicted noise. The Bell 205 model was also validated using flight test data, and key parts of the noise predictions were assessed to determine areas for improvement in the prediction models. This work is also discussed in Task 19.

Models for aircraft flown during 2017 flight tests (Bell 206 and Bell 407) were updated during this past year to revalidate the models with system improvements made by Damaris Zachos. The system improvements (including Pegg broadband scaling) are described in more detail in Task 19. These efforts demonstrate the noise prediction system’s ability to predict maneuvering aircraft noise. Comparisons for these new models against 2017 flight test data are shown in Figures 1 and 2.



(a) Unscaled prediction (b) Scaled prediction. Pegg results scaled by -4 dB. (c) Flight Test

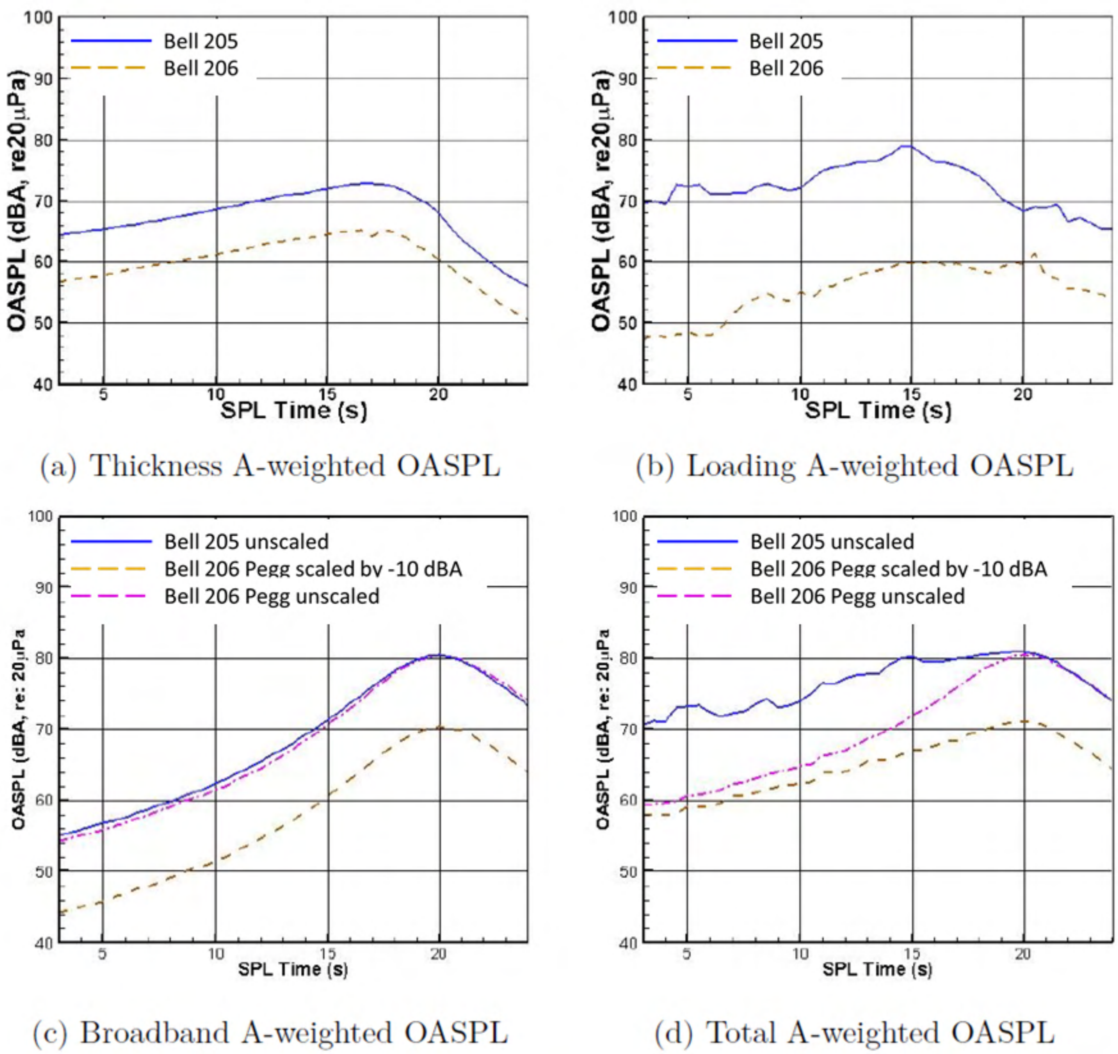
Figure 1. Comparison of maximum dBA results for the Bell 407 flying nominally at 80 knots in a level flight (run 283107) measured with the Amedee flight test grid.



(a) Unscaled prediction (b) Scaled prediction. Pegg results scaled by -10 dB. (c) Flight test

Figure 2. Comparison of maximum dBA results for the Bell 206 flying nominally at 94 knots in a level flight (run 278187) measured with the Amedee flight test grid.

With validated models for various aircraft of different weight classes, the helicopters were grouped into categories with similar design characteristics. The Bell 205 helicopter was compared against the Bell 206 because both of these aircraft have a main rotor and tail rotor with two blades each. The S-76 was compared against the lighter Bell 407 model because both aircraft utilize four-bladed main rotors (although the number of blades on the tail rotor of each aircraft is different). Comparing in this manner makes the comparisons between the differences in noise for each of these aircraft more isolated to the vehicle weight. The comparisons between the Bell 205 and Bell 206 aircraft are shown in Figure 3. The S-76 is compared with the Bell 407 in Figure 4.



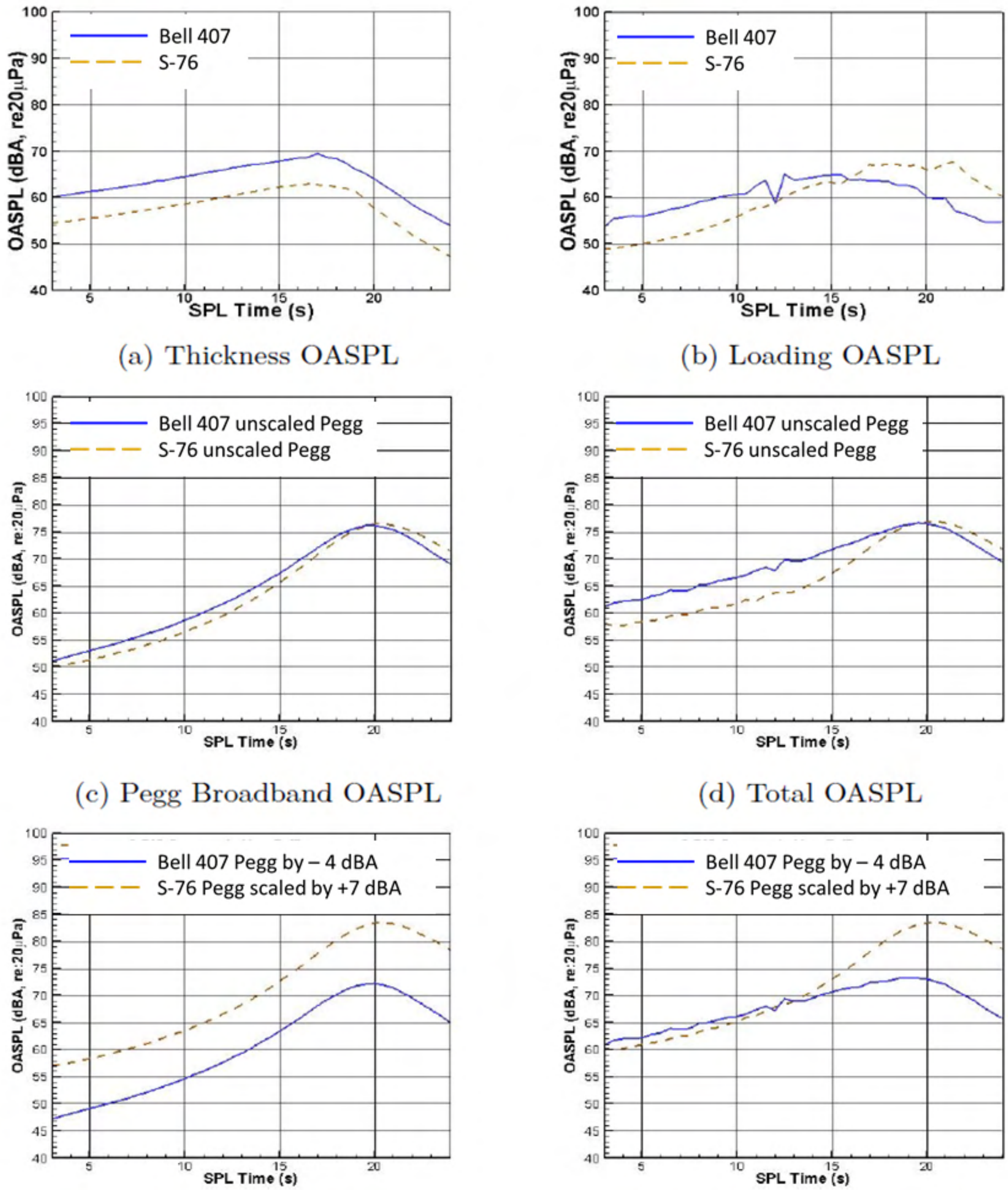
(a) Thickness A-weighted OASPL

(b) Loading A-weighted OASPL

(c) Broadband A-weighted OASPL

(d) Total A-weighted OASPL

Figure 3. A-weighted Overall sound pressure level (OAPSL) comparison results for the Bell 205 versus Bell 206 simulated at 80 knots in a level flight.



(a) Thickness OASPL

(b) Loading OASPL

(c) Pegg Broadband OASPL

(d) Total OASPL

(e) Pegg Broadband OASPL. Pegg scaled by 7 dB for S-76 and -4 dB for Bell 407

(f) Total OASPL. Pegg scaled by 7 dB for S-76 and -4 dB for Bell 407

Figure 4. A-weighted OASPL comparison of the Bell 407 versus S-76 simulated at 80 knots in a level flight.

A detailed analysis of the difference in predicted noise for each noise source can be found in Damaris Zachos' master's thesis.

Publications
Zachos, D. R. (2022). Noise prediction for helicopter noise abatement and EVTOL design [M.S. thesis, The Pennsylvania State University]. Manuscript in preparation.

Outreach Efforts
None

Awards
None

Student Involvement
Damaris R. Zachos, a graduate assistant currently working toward her master's degree at Penn State, generated predictions for the Bell 407, Bell 206, Bell 205, and S-76. She also developed the simulated flight trajectories necessary to compare exactly identical flight maneuvers between aircraft.

Plans for Next Period
During the next period, simulated trajectories for the four aircraft studied during 2021 will be developed for maneuvering flight, including descent and turn trajectories. The broadband scaling method developed during this year will be evaluated to determine whether there is a better approach for predicting broadband noise for conventional helicopter designs. This effort might lead to a re-evaluation of the comparisons presented in this section.

Task 19 - Data Analysis of 2019 FAA/NASA Acoustic Flight Test Data
The Pennsylvania State University

Objective
The goal of this task (Task 8.2 in the 2020–2021 proposal) is to provide continued assistance in evaluating the 2019 FAA/NASA flight test data and assessing the effectiveness of various noise abatement procedures. This task will involve evaluating flight test data and examining and comparing measured and predicted results to help explain any significant unexpected differences in noise measurements. This evaluation can also identify which sources are the primary and secondary noise sources involved in a flight procedure and provide understanding about how the noise abatement was achieved (which can lead to generalized procedures for other helicopter categories, weights, etc.).

Research Approach
In this task, we will perform detailed noise predictions of noise abatement procedures executed in the 2017 and 2019 FAA/NASA flight tests (with an emphasis on the 2019 flight test) and will explain how noise abatement was achieved or why procedures did not work as expected. Specifically, the thickness, loading, and broadband noise from both the main and tail rotors will be predicted to determine which noise sources were increased or reduced. Variations in the flight procedure may also be predicted to help understand if the procedures applied in the flight test were optimal. This evaluation is expected to lead to better noise abatement procedures and perhaps even procedures tailored to particular helicopter models.

Milestone(s)
The milestones for this task include (a) replication of identical cases in PSU-WOPWOP, (b) comparison of noise predictions with flight test data to identify possible deficiencies in the noise prediction models, and (c) development of an improved model for Pegg broadband noise prediction.

Major Accomplishments
Flight test predictions for two of the aircraft flown during the 2019 flight test (Bell 205 and S-76D) have been generated. Predictions for various maneuvers (level flight, descents, and turns) were modeled, and prediction results were compared against flight test data. The discrepancy between noise levels noted during modeling of 2017 flight test aircraft was addressed via a scaling method for Pegg broadband noise prediction. By changing the peak level of the OASPL broadband

noise prediction, the maximum dBA value for various observers was adjusted to match flight test data (see Figure 5). In Figure 5, the difference in time when the peak occurs (flight test data vs. prediction) is thought to be a time shift when reading the data or plotting the prediction. The source of this discrepancy will be addressed in continuing work.

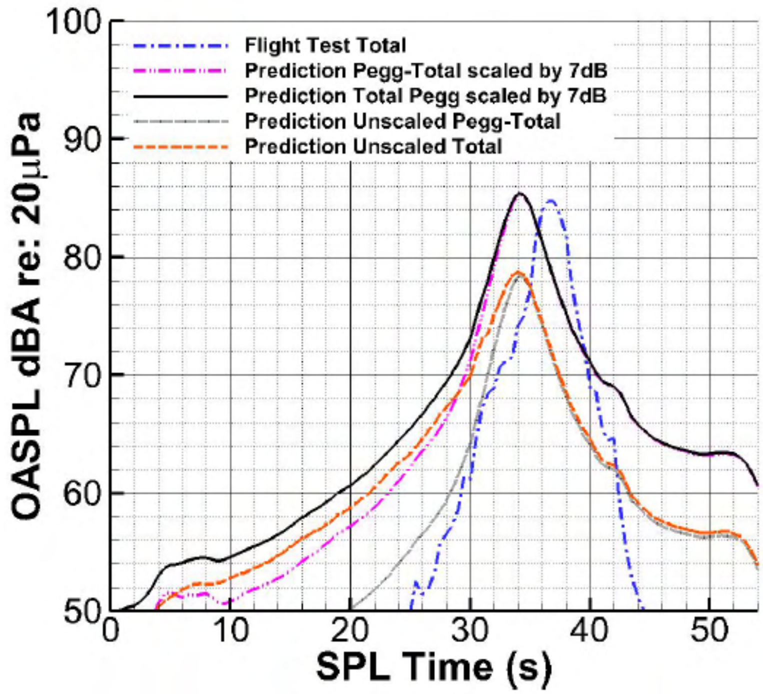
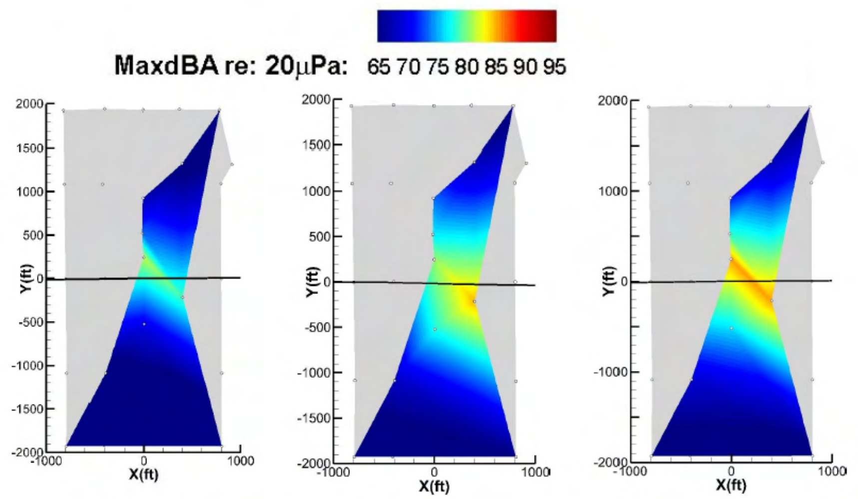


Figure 5. A-weighted OASPL noise breakdown. Flight Test Total refers to the measured flight test data for S-76D in a nominal 88-knot level flight (run 178301) at the Coyle Field, microphone location 26. The predictions are for the S-76 prediction model. Both scaled and unscaled broadband and total noise predictions are shown.

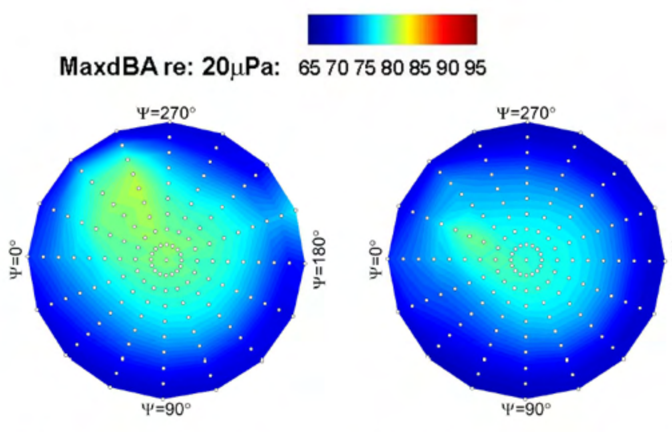
A single scaling value was found for the S-76 model. The Bell 205 model was not scaled because there were issues with the loading noise prediction that must be addressed first. Pegg scaling improved the correlation between the flight test maximum dBA ground noise contours and predicted ground noise contours during steady level flight (see Figure 6). Although this figure is not a good image to use for evaluating the noise generated by this aircraft, it does show how the use of Pegg scaling can improve the correlation between the peak flight test level and the maximum dBA predicted by the noise prediction system.



(a) Unscaled prediction (b) Flight test (c) Scaled prediction. Pegg results scaled by 7 dB.

Figure 6. Comparison of maximum dBA for a nominal 88-knot level flight (run 78301) measured on a flight test grid for measured S-76D versus modeled S-76 results. Note that the contours are skewed because there were too many inoperable microphones for this run.

Maneuvers, including descents and turns, were also modeled during 2021. These predictions provided initial insights into changes in noise for the Bell 205 and S-76D that are induced when the pitch of the aircraft changes during descent. Figure 7 shows the change in amplitude and directivity of the total S-76D noise generated during one of these descents. Because these results are predictions, the noise can be divided into components to determine whether the change in noise is caused by thickness, loading, or broadband noise. Descent cases for the Bell 205 were also modeled during this working period.



(a) 3 degree descent total noise prediction (b) 4.5 degree descent total noise prediction

Figure 7. Comparison of the total maximum dBA of descent cases for the S-76D over a hemisphere. The hemisphere has been distorted by using constant elevation spacing to better show the contours at the top edge of the hemisphere near an elevation angle of 0˚.

Left and right turn cases with multiple bank angles were also modeled with the noise prediction system. Both the Bell 205 and S-76 models yielded results regarding the changes in noise caused by these maneuvers. A normalization method was developed and implemented to remove the effects of distance from noise predictions to show peak noise levels in a ground noise contour as a turn was performed. Figure 8 shows the noise predictions for a Bell 205 performing various bank angle turns with this normalization method. Note that the transitions of entering or leaving the turn produced the highest noise levels in the predictions.

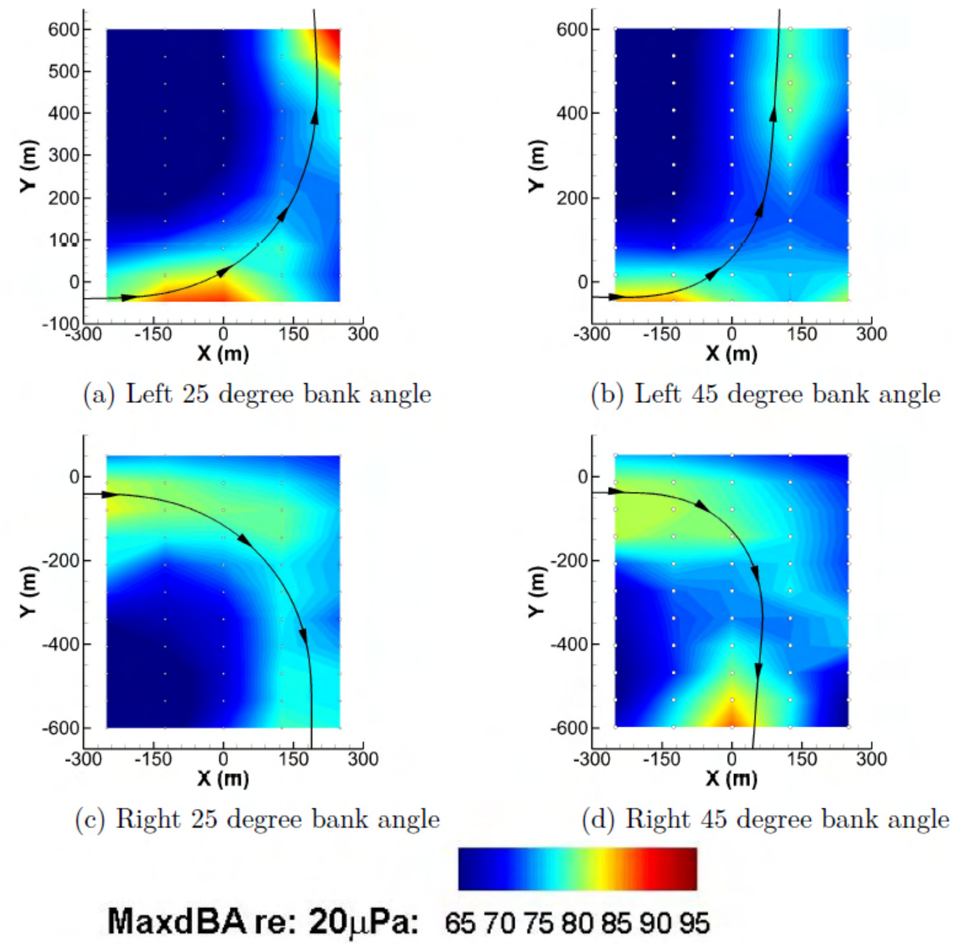


Figure 8. Comparison of maximum dBA ground noise contours for various turns and bank angles in the Bell 205.

Publications

Zachos, D. R. (2022). Noise prediction for helicopter noise abatement and EVTOL design [M.S. thesis, The Pennsylvania State University]. Manuscript in preparation.

Outreach Efforts

None

Awards

None

Student Involvement

Damaris R. Zachos, a graduate assistant at Penn State, postprocessed the flight test data for this task, added the capability to scale Pegg broadband noise predictions, implemented distance normalization to turning noise predictions, and generated and evaluated much of the processed flight test data to determine key noise aspects during various maneuvers.

Plans for Next Period

More maneuvering flight trajectories need to be modeled to better understand what happens to the noise of a helicopter as maneuvers are performed. Descents at different flight speeds and flight path angles must be modeled to determine an optimal descent rate for low-noise procedures. Additional runs are also needed for turns to evaluate the changes in noise induced at various flight speeds and flight path angles. The variability included in the 2019 flight test data must also be quantified to determine which noise abatement procedures can reliably be implemented by pilots.

Task 20 - Develop a Method for Coupling the Noise Prediction System with FAA Noise Prediction and Analysis Tools

The Pennsylvania State University

Objective

In this task (Task 8.3 in the 2020–2021 proposal), the goal is to increase the usability of the noise prediction system for the FAA and Volpe by creating tools to allow PSU-WOPWOP outputs in the Volpe Advanced Acoustic Model (AAM) format. The tool will be written in the Fortran language. This tool will then be included within PSU-WOPWOP in close collaboration with FAA/Volpe to ensure that the workflow and outputs are in the desired form for use with AAM.

Research Approach

The noise prediction system developed and validated in Projects 6 and 38 provides significantly more detailed noise and component analyses than is needed for routine noise assessment and abatement procedure analysis. However, the system has the unique capability to predict the noise from existing helicopter models for which noise measurements are not available in part or at all. Furthermore, notional aircraft or innovative changes to a helicopter can be analyzed because the noise prediction is a first-principles physical model. This capability could be more fully utilized if there were a more streamlined process to provide information in the correct format for FAA/Volpe tools, particularly AAM. It is anticipated that we will work closely with the Volpe Center to ensure that the correct format files are produced by the noise prediction system and that the process is efficient.

Milestone(s)

The milestones for this task are (a) creation of a tool external to PSU-WOPWOP in Fortran, (b) direct merging of the tool into PSU-WOPWOP, and (c) creation of documentation and training for the tool for use by FAA/Volpe.

Major Accomplishments

Initial coordination with Volpe was established, and Volpe provided AAM documentation to PSU to help develop the NetCFD file format used by AAM. PSU also obtained a site license for AAM so that testing can occur at PSU before the tool is sent to Volpe for testing. Finally, as part of another project, a tool was developed to convert PSU-WOPWOP output into AAM format, but this tool has not been well documented and is not ready for inclusion in PSU-WOPWOP.

Publications

None

Outreach Efforts

None

Awards

None

Student Involvement

Lauren Weist, a graduate assistant currently working toward her master's degree at Penn State, took over as the lead graduate researcher in 2021 and will develop a method for coupling the noise prediction system and the FAA/Volpe AAM tool.

Plans for Next Period

An existing tool written in the D coding language, developed as part of another project, will be updated. This step will guide the development of a Fortran language tool external to PSU-WOPWOP. Because the new code will be written in Fortran, once it is operational, it will be encapsulated in a Fortran module and incorporated in PSU-WOPWOP for ease of use within the noise prediction system. FAA/Volpe feedback will be sought to ensure that the most-needed features for Volpe are easy to use.

Task 21 - Continue Efforts to Develop Noise Abatement Flight Procedures for Various Helicopter Classes

The Pennsylvania State University

Objective

This task (Task 8.4 in the 2020–2021 proposal) will continue the development of noise abatement procedures. Based on the understanding developed by analyzing and predicting flight test noise procedures, potential new noise abatement strategies can be evaluated and demonstrated through simulations. The process will be documented and will provide a basis for future low-noise operational guidelines.

Research Approach

Following the validation of noise predictions with 2019 FAA/NASA flight test data (Task 18), the prediction system has been validated for multiple maneuvers. Using both predicted and experimental data, a flight path optimizer tool will be created to develop flight paths with the lowest noise. Optimal flight paths will be tested in the noise prediction system to verify that the noise is minimized. Predictions from these generated flight paths will yield new insight about noise abatement procedures for different size-class aircraft. Evaluations of noise results from these optimized flight paths will be compared against flight path recommendations from the Fly Neighborly guide to update the guidance as needed.

Milestone(s)

The milestones for this task are (a) creation of a noise-optimized flight trajectory generator, (b) evaluation of noise metrics for fully simulated flight test cases, and (c) recommendation of noise abatement flight maneuvers for aircraft.

Major Accomplishments

The flight path generation code created in August 2020 set the groundwork for a noise-optimized trajectory generator, which will be used to determine optimal noise abatement maneuvers. Preliminary work, which will incorporate the ability to turn in this command generation code, was continued in 2021. This code was used in 2021 to generate a simulated 80-knot level flight trajectory for several aircraft from 2017 and 2019 flight tests (see Figure 9). Preliminary tests have been performed using this tool to evaluate predicted noise from a simulated descent flight path, which is the next step for the maneuvering noise prediction tool.

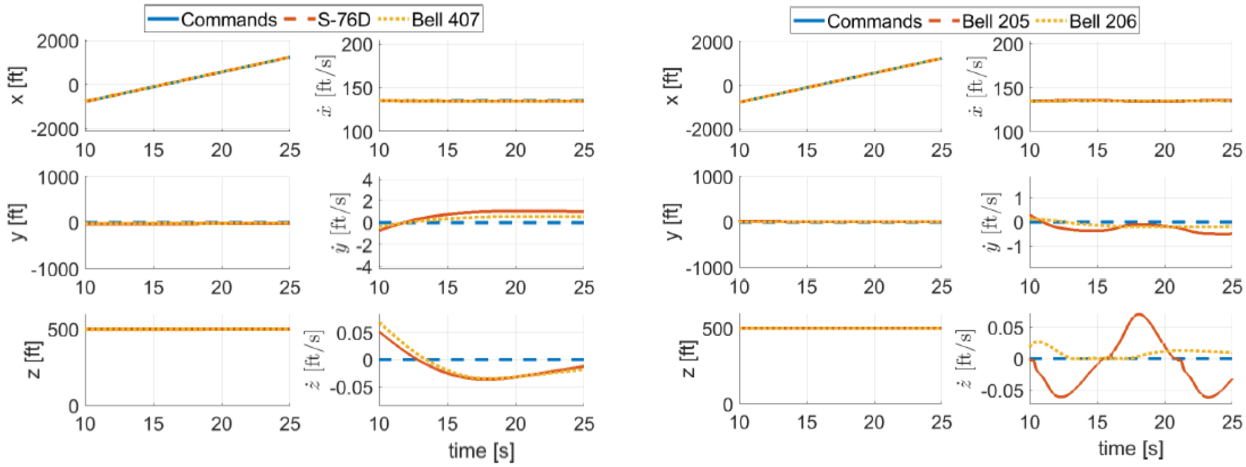


Figure 9. Results for an 80-knot simulated trajectory for S-76, Bell 407, Bell 205, and Bell 206.

Publications
None

Outreach Efforts
None

Awards
None

Student Involvement
Damaris R. Zachos, a graduate assistant at Penn State, used the tool to simulate level flight procedures and started the evaluation of noise prediction for aircraft using the descent flight path planning code.

Plans for Next Period
Further development of the waypoint trajectory generator will be needed to perform more complicated maneuvers and to add the capability to optimize the flight path based on noise results. An in-depth analysis of the changes in noise sources during each point in a maneuver is also required to determine which sound sources may be causing high noise levels. This information should be included in an optimizer tool for determining low-noise flight maneuvers. Evaluations of the effects of pilot commands on generated noise may also be assessed.

Task 22 - Develop Documentation and Training Materials for the Noise Prediction System

The Pennsylvania State University

Objective

In this task (Task 8.5 in the 2020–2021 proposal), we will develop documentation and collect other available information for applying the noise prediction system. Sample test cases will be developed for use in a training course. This material could be taught in a small class setting (perhaps at Volpe) or used as self-study materials by FAA, Volpe, or other designated persons.

Research Approach

As we work to use the noise prediction system to evaluate simulated helicopter noise, we will create documentation about the program's use, significant debugging issues, and necessary knowledge for use. Training documentation in both written and presentation form will be created to better enable a new user to start using the necessary programs.

Milestone(s)

The milestones for this task are (a) documentation of the steps necessary to use the noise prediction system, (b) identification and documentation of common mistakes made when using the noise prediction system, and (c) a description of acoustic knowledge that will help users understand the results provided by the system.

Major Accomplishments

A guide for helping new students at Penn State on the use of the PSU noise prediction system was written, which documents the steps necessary to install and use PSUHeloSim, CHARM, and PSU-WOPWOP at Penn State. The information contained within was tested when the new graduate assistant for Project 38, Lauren Weist, was introduced to the project. Any omissions in information during the installation and first use of the program were identified and added to the guide.

New debugging and common mistakes were documented while generating many of the noise prediction models necessary to progress on Tasks 18, 19, and 21. These issues were documented, and resolutions were recorded. A first attempt at the basic principles summary for effectively operating these tools was included in Damaris Zachos' master's thesis. As more prediction models are generated, the documentation will be updated and refined.

Publications

Zachos, D. R. (2022). Noise prediction for helicopter noise abatement and EVTOL design [M.S. thesis, The Pennsylvania State University]. Manuscript in preparation.

Outreach Efforts

None

Awards

None

Student Involvement

Damaris R. Zachos, a graduate assistant at Penn State, created a "Getting Started" guide for Penn State users and conducted the training for Lauren Weist based on this guide. Zachos also wrote a summary of the necessary helicopter aero-acoustics knowledge necessary for correct use of these modeling tools.

Plans for Next Period

As more users request access to the noise prediction system, Penn State will provide training and consultation when necessary. New errors and issues will be documented and resolved as more companies and users begin to use the tools.