Project 038 Rotorcraft Noise Abatement Procedure Development

The Pennsylvania State University, Continuum Dynamics, Inc.

Project Lead Investigator

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University Participants

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- PI: Kenneth S. Brentner, Professor of Aerospace Engineering
- FAA Award Number: 13-C_AJFE-PSU-038, Amendment No. 41
- Period of Performance: September 2018 to August 2019
- Task(s) (during this period):
    1. Continue evaluating flight test data to determine the effectiveness of noise abatement procedures
    2. Evaluate and refine noise abatement procedure development strategy
    3. Demonstrate the potential of refined noise abatement procedures

Project Funding Level

FAA: $150,000; In-Kind Matching (Continuum Dynamics, Inc.): $150,000

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 Comprehensive Hierarchical Aeromechanics Rotorcraft Model (CHARM) coupling.
- Mrunali Botre, Graduate Research Assistant, 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; involved in all tasks.

Project Overview

Rotorcraft noise consists of several components, including rotor noise, engine noise, gearbox and transmission noise, etc. 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 consists of multiple noise sources, including thickness noise and loading noise (typically combined as rotational noise), blade-vortex-interaction (BVI) noise, high-speed-impulsive (HSI) noise, and broadband noise. Each noise source has a 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 renders 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 (Ref. 19) 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, (i.e., 2-blade light, 4-blade light, 2-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 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.

The objective of this continuing project is to utilize computational and analytical modeling to develop noise abatement procedures for various helicopters in different phases of flight. The extension of this project also includes predictions aiming to analyze various flight procedures to determine their effectiveness in noise reduction. Comparisons of predictions and flight test data provide further validation of the noise prediction system and allow a deeper understanding of the impact of noise abatement procedures on noise directivity and amplitude. Emphasis is given to more complicated flight procedures (turns with deceleration or descending turns) and validation of the noise prediction system for these complex procedures. The predictions help to explain the details of the noise generated in various procedures, which will aid in the design of refined noise abatement flight procedures.

Task 11 - Continue Evaluating Flight Test Data to Determine the Effectiveness of Noise Abatement Procedures

The Pennsylvania State University

Objective(s)

The objective of this task is to provide continued assistance in the evaluation of flight test data and the effectiveness of various noise abatement procedures. Our goal is to understand the interactions among various noise sources, to determine which sources are predominantly changed by a given flight procedure, and to identify the governing mechanisms. Special emphasis was given to turns and more complicated procedures during the second half of this year.

Research Approach

The noise prediction system developed in ASCENT Projects 6 and 38 will be used and updated as necessary. The PSU-WOPWOP code will be used for noise prediction and will be coupled with a MATLAB flight simulator and CHARM to form a rotorcraft noise prediction system. The flight test data will be examined, and the measured and predicted results will be compared to help explain any significant but unexpected details of the noise measurements. This evaluation can also identify the primary and secondary noise sources involved in a given flight procedure and can clarify how the noise abatement was achieved (which can lead a generalized procedure for other helicopter categories, weights, etc.).

Milestone(s)

The milestones for this task include (a) analysis of noise predictions and flight data for straight flight profiles, (b) analysis of simulated and measured noise for level turns (without deceleration), and (c) analysis of noise from complex flight profiles (decelerating turns and descending turns). This task will examine various predicted noise sources and will investigate which sources are important in the flight test data (for several different microphones).

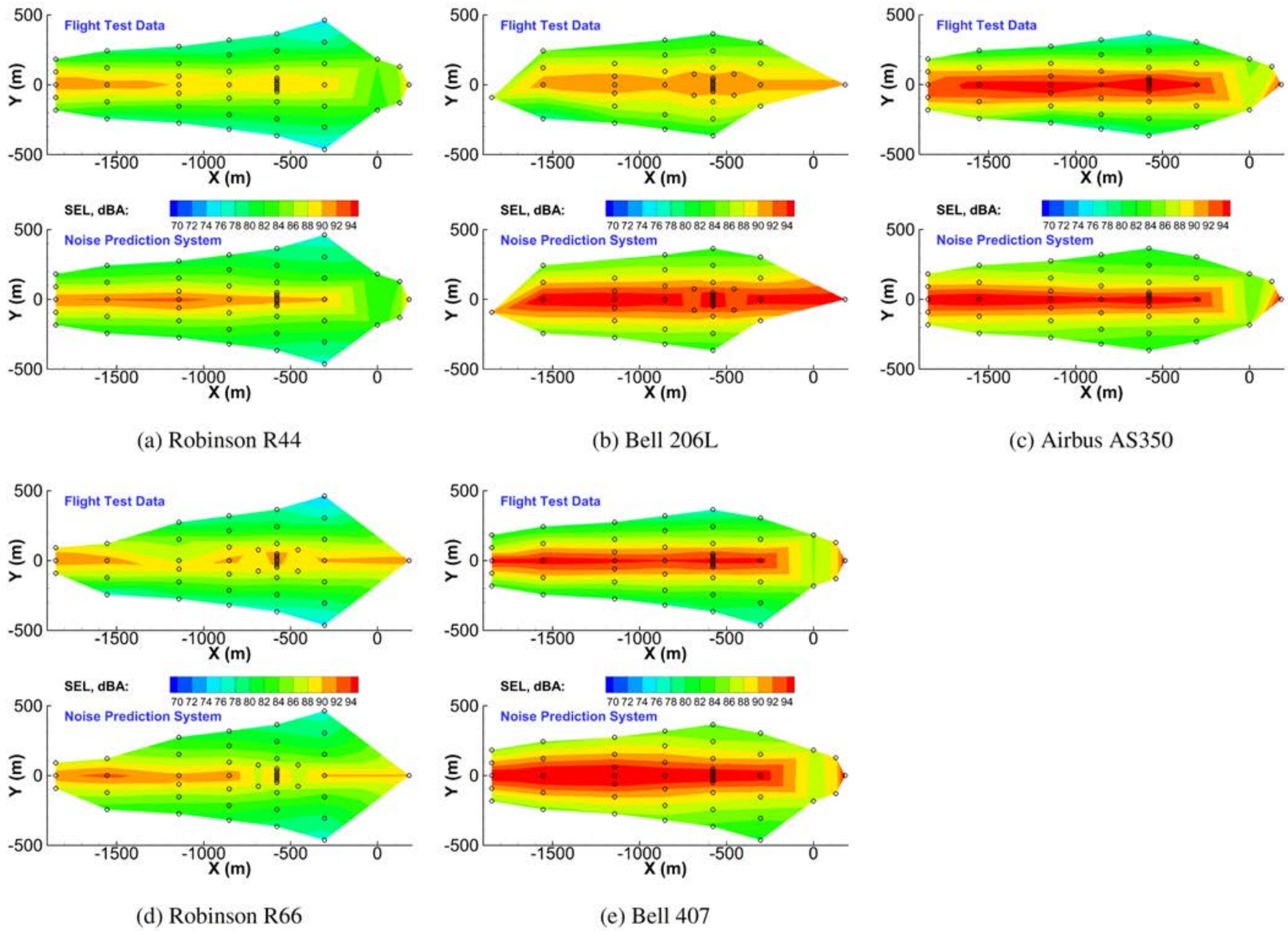


Figure 1. Total sound exposure level (SEL, dBA) for an 80-kts level flight. For each subfigure, top: flight test data; bottom: prediction.

Major Accomplishments

Noise predictions were made for five aircraft flown in the 2017 FAA/NASA noise abatement flight test. SEL contours from the simulations were compared to the flight test data. Straight flight conditions (level flight [shown in Figure 1] and 6° descent) were considered first. Individual noise components were considered (not shown here), and it was found that thickness noise is dominant as the helicopter approaches while loading and broadband noise is dominant overhead during the peak and after the helicopter passes. The main rotor is the primary source of low-frequency noise (OASPL) while the tail rotor is the primary contributor for L_A. The predicted SEL contours were slightly higher than the flight test data, except for Airbus AS350, because the thickness noise for a level flight was overpredicted. As determined in Task 12, it is important to match the small transients in the time-dependent aircraft position and attitude in the flight test to obtain the best agreement. Hence, the aircraft motion was included in the simulation, and the results were improved. For the straight cases, a comparison of the nominal flight path and attitude (both constants) with the actual flight variables resulted in a significantly better correlation, even though the changes were small.

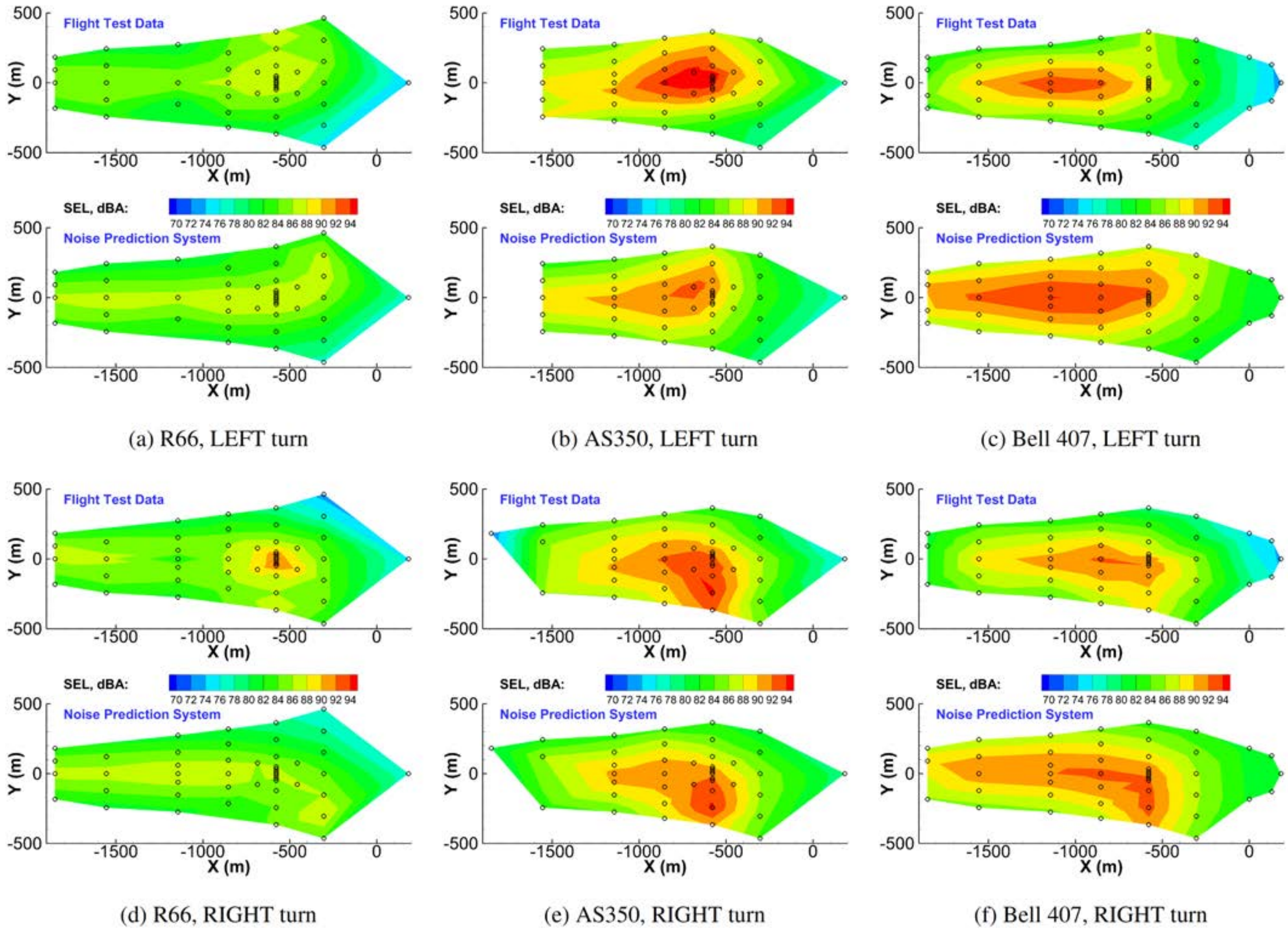
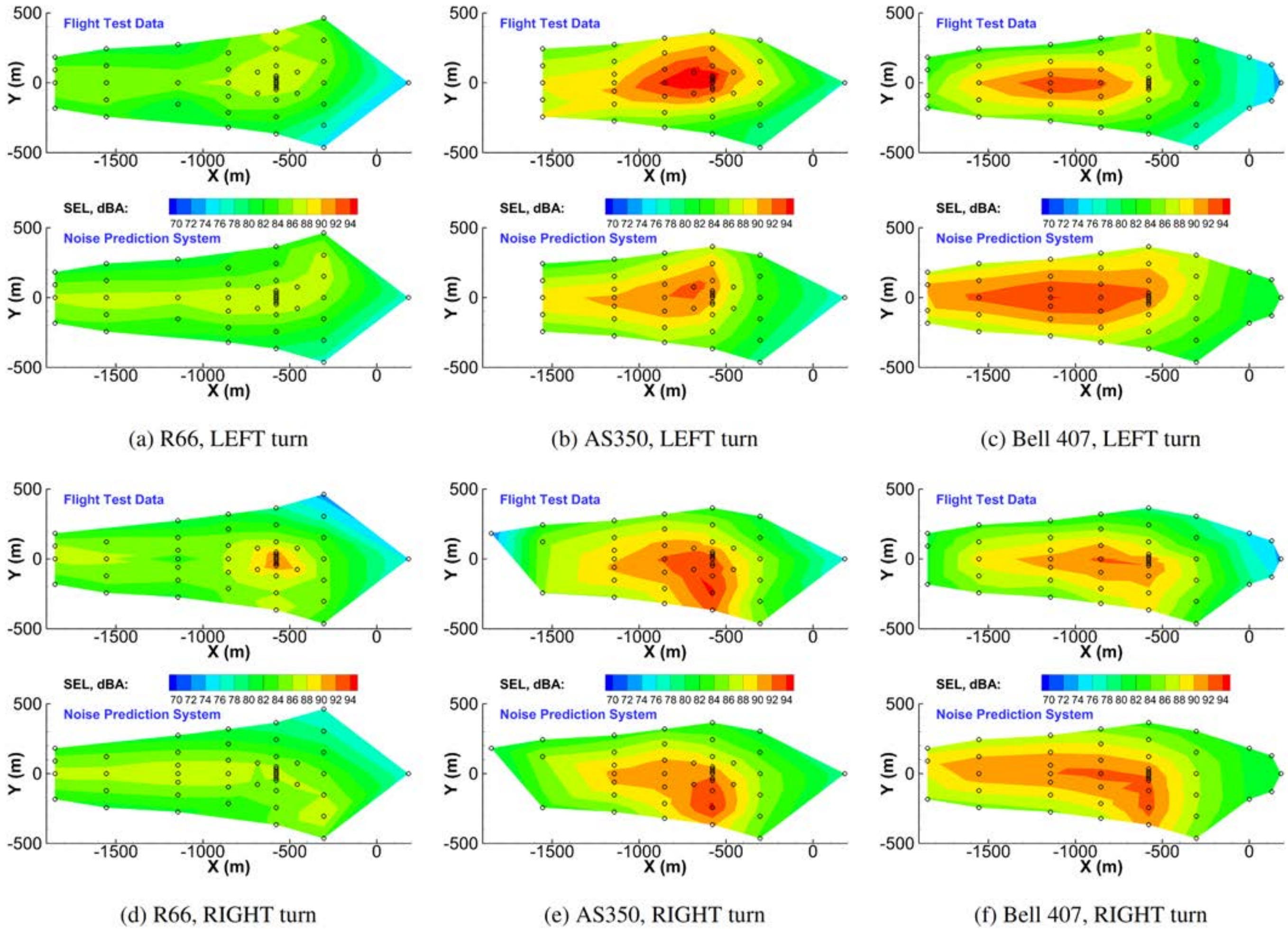


Figure 2. Total sound exposure level (SEL, dBA) for a level decelerating turn. The final roll angle is 25° for all turns. For each subfigure, top: flight test data; bottom: prediction.

Next, we considered level right and left turns (see Figure 2). For these maneuvers, it was discovered that the broadband noise was based only on the first timestep in the simulation, remaining constant throughout the turns. This phenomenon limited the accuracy of the predictions; thus, the PSU-WOPWOP code was modified to read in a time history of the input parameters for the Pegg loading model for each window time. This modification has been incorporated in all results shown in this report. It was observed that the SELs during level flight are normally higher than those during left and right level turns. This trend most likely occurs because the L_A peak has a shorter duration when the aircraft is turning. Thus, each microphone location will measure lower SEL levels.

Results for the most complex cases, i.e., decelerating or descending turns, are shown in Figures 3 and 4. These maneuvers are more complex and difficult, although not overwhelming, for the pilot to execute. Both decelerating turns and descending turns had generally higher SEL values compared with the level turn case. The lighter Robinson aircraft had lower noise levels due to their lower weight. Interestingly, although the flight test and simulations exhibited different SEL values, the agreements between the flight test and prediction data are roughly constant for all flight conditions and aircraft types.



(a) R66, LEFT turn

(b) AS350, LEFT turn

(c) Bell 407, LEFT turn

(d) R66, RIGHT turn

(e) AS350, RIGHT turn

(f) Bell 407, RIGHT turn

Figure 3. Total sound exposure level (SEL, dBA) for a level decelerating turn. The final roll angle is 35°, with a deceleration from 80 kts at 2 kts/s. For each subfigure, top: flight test data; bottom: prediction.

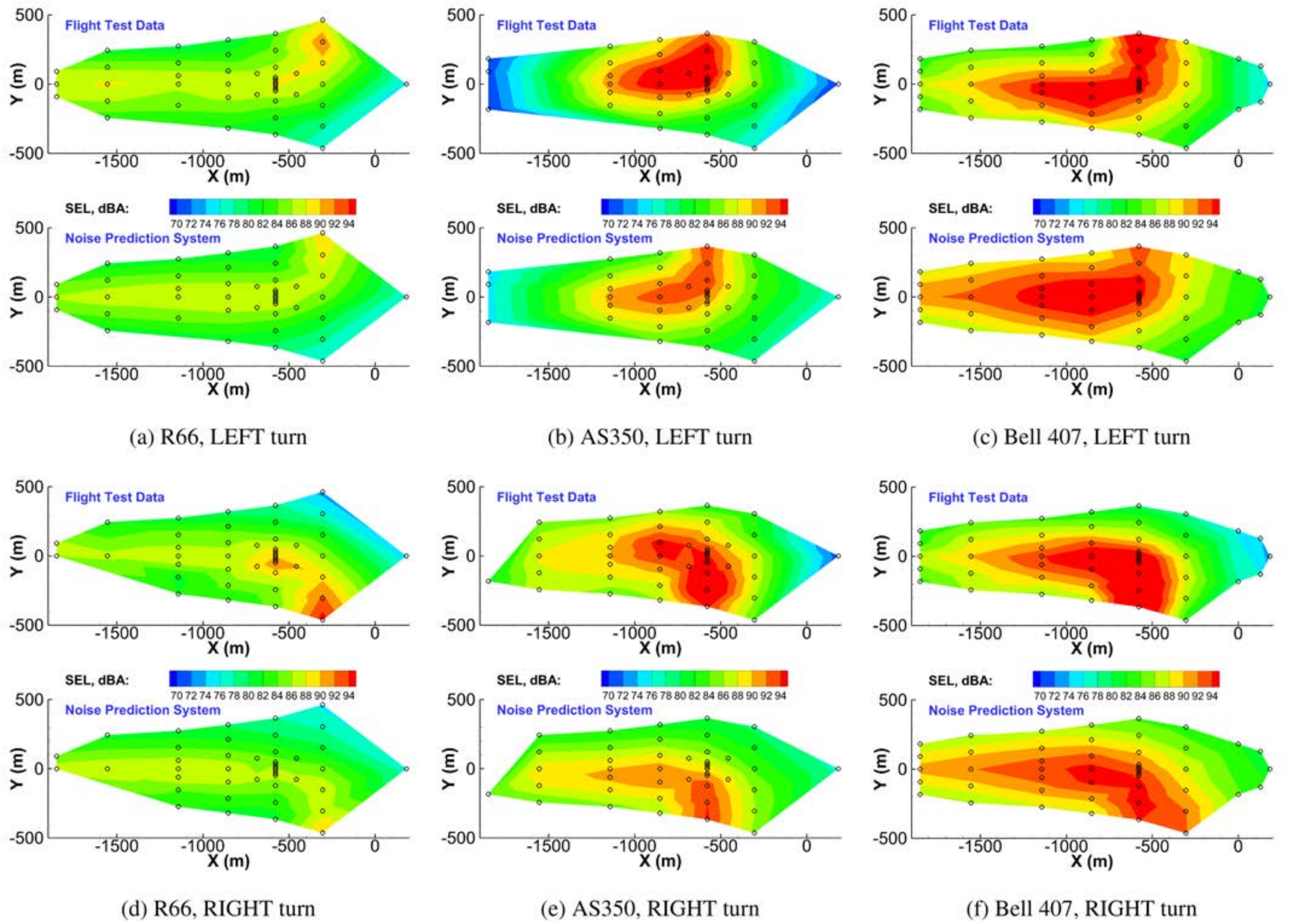


Figure 4. Total sound exposure level (SEL, dBA) for an 80-kts descending turn, with a flight path angle of 6° and a final roll angle of 35°. For each subfigure, top: flight test data; bottom: prediction.

Publications

Published conference proceedings

Botre, M., Brentner, K.S., Horn, J.F., & Wachspress, D.A. (2019). Developing a comprehensive noise prediction system for generating noise abatement procedures. 25th AIAA/CEAS Aeroacoustics Conference, Delft, The Netherlands, https://doi.org/10.2514/6.2019-2617

Botre, M., Brentner, K.S., Horn, J.F., & Wachspress, D.A. (2019). Validation of helicopter noise prediction system with flight data. VFS 75th Annual Forum, Philadelphia, PA.

Outreach Efforts

N/A

Awards

None.

Student Involvement

Mrunali Botre, a graduate assistant currently working toward her PhD at Penn State, performed the acoustic predictions and assisted in developing and implementing the broadband noise reflection capability in PSU-WOPWOP.

Plans for Next Period

During the next period, helicopter models representing the aircraft in the 2019 FAA/NASA flight test will be developed from publicly available sources. Several of the noise abatement procedures executed during the flight test will be simulated with the noise prediction system. Based on both the noise predictions and measured data, the noise abatement procedures will be analyzed. The effectiveness of these procedures for the heavier helicopters in the 2019 test will be compared to that for the lighter helicopters in the 2017 test, which will indicate the feasibility of classifying helicopter noise based on the helicopter size, type, and weight.

Task 12 - Evaluate and Refine Noise Abatement Procedure Development Strategy

The Pennsylvania State University

Objective

The objective of this task is to assess the development of noise abatement procedures and the data needed for this activity.

Research Approach

For this effort, the noise prediction system developed in ASCENT Projects 6 and 38 will be used to perform noise predictions and to process the acoustic pressure data from the 2017 FAA/NASA noise abatement flight test. This comparison will have two primary goals: (a) to determine the importance of tracking the helicopter position and attitude in a precise manner, which will also provide guidance on the execution of noise abatement procedures, and (b) to evaluate and verify the effectiveness of noise abatement flight procedures by evaluating both flight test data and simulated noise for various maneuvers and a range of helicopter types. Incidentally, it will also be important to determine whether the limited helicopter information that is currently available (i.e., incomplete data complemented by engineering judgement) is sufficient for obtaining an agreement with flight test data and for developing noise abatement procedures.

Milestone(s)

The milestones for this task are (1) analysis and validation of the predicted noise through a comparison with flight test data with different precision levels for tracking the flight test aircraft state as a function of time and (2) comparison of complex procedures to determine whether a given procedure results in noise abatement.

Major Accomplishments

Noise predictions were made for comparison with the 2017 FAA/NASA noise abatement flight test. In the evaluation of flight test data, it was discovered that the simulation must include aircraft position and attitude deviations from the nominal flight path (which was used in the initial predictions). When the simulation matched the aircraft position and attitude, it provided reasonable results. However, the results were not perfect, and the errors associated with deviations in the flight path and time-dependent aircraft attitude were not quantified. Thus, it was determined that the position and state of the aircraft must match the flight test data as closely as possible to validate the predictions.

In this task, to determine the sensitivity of the noise predictions to relatively small changes in flight path and attitude, we developed an improved flight controller that incorporated more information and that more closely matched the flight test data for each aircraft. Figure 5 shows the position and attitude time history for the two controllers in comparison to the flight test data. The conditions for Figure 5 correspond to a steady level flight, and the nominal flight condition (steady flight path) is shown for the original controller (left column). The original controller allows the aircraft to drift in the y-direction by approximately 50 ft over the 60-s flight period. The original controller also encountered difficulty in following the roll of the flight test. In contrast, the improved flight controller can track the flight test aircraft position and attitude much more closely. The roll angle still exhibits a slight deviation (right column of Figure 5), but the angle is tracked reasonably well over time. Although this example corresponds to steady level flight conditions, similar improvements were observed for more complex maneuvers.

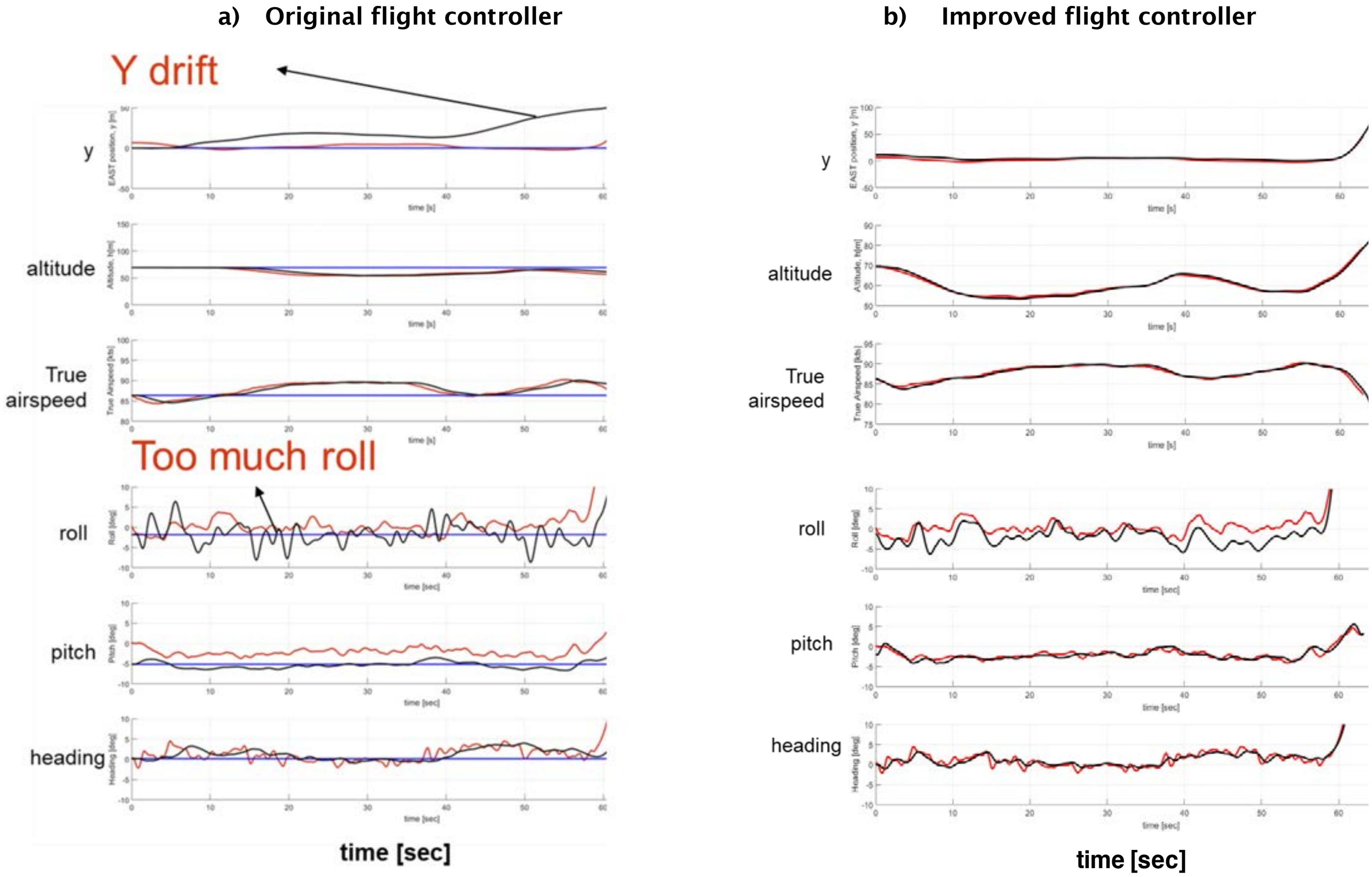
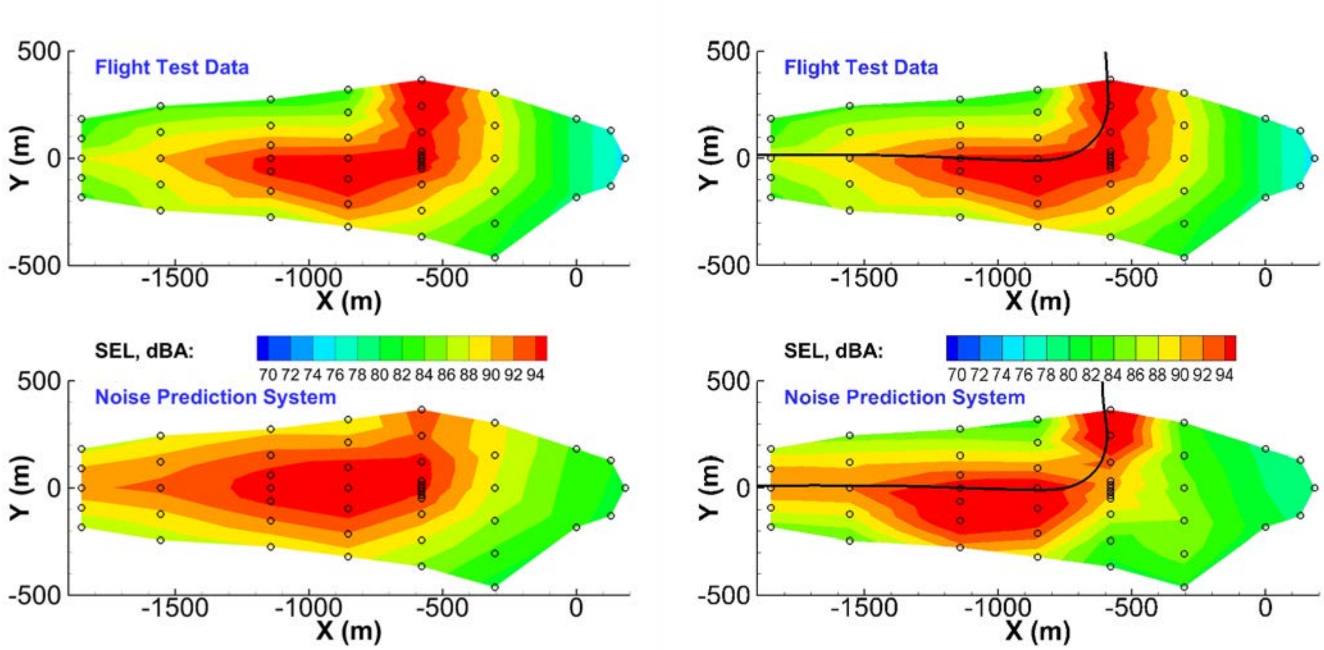


Figure 5. Comparison of flight trajectory and attitude between the original and improved flight controllers for the Robinson R44 under 80-kts steady level flight conditions. —— flight test; —— steady flight path; —— simulated flight trajectory.

To demonstrate the improved noise prediction attained by the new flight controller, results for a descending left turn are shown in Figure 6 for the Bell 407 aircraft. For this complicated maneuver, the results for the improved flight controller show better agreement with the flight test data. Although the SEL contours for the improved controller do not exhibit a perfect agreement, the increased noise that occurs as the helicopter leaves the turn (rolls back to level flight) is captured by the improved controller (see the higher SEL levels as the flight path leaves the contour grid in the right figures). There is some discrepancy (overprediction) as the aircraft enters the turn, but overall, the SEL contours are improved by using the new flight controller. These examples were chosen to demonstrate that relatively small changes in the flight path and, more importantly, in the time-dependent aircraft attitude can be influential in the noise validation and the development of noise abatement flight procedures. Numerous other examples are documented in Mrunali Botre’s PhD dissertation.



a) Original flight controller b) Improved flight controller

Figure 6. Comparison of measured and predicted sound exposure level (SEL) contours from two flight controller models for a descending left turn of the Bell 407 aircraft. Top: flight test data; bottom: predicted SEL.

Publications

Published conference proceedings

Botre, M., Brentner, K.S., Horn, J.F., & Wachspress, D.A. (2019). Developing a comprehensive noise prediction system for generating noise abatement procedures. 25th AIAA/CEAS Aeroacoustics Conference, Delft, The Netherlands, https://doi.org/10.2514/6.2019-2617

Botre, M., Brentner, K.S., Horn, J.F., & Wachspress, D.A. (2019). Validation of helicopter noise prediction system with flight data. VFS 75th Annual Forum, Philadelphia, PA.

Outreach Efforts

N/A

Awards

None.

Student Involvement

Mrunali Botre, a graduate assistant currently working toward her PhD at Penn State, performed the acoustic predictions for this task. She also postprocessed the flight test data for the comparison.

Plans for Next Period

During the next period, we expect to begin working on the validation with and analysis of the 2019 FAA/NASA flight test data, which include results for four larger aircraft. This analysis will enable a comparison of noise abatement procedures for different "classes" of vehicles (different size and weight classes). The validation aspect of this task will compare various noise prediction models and their accuracy for the different sizes and weights included in the 2017 and 2019 flight tests. It is expected that some of the simpler models (i.e., Pegg's broadband noise model) may not perform as well for heavier, larger helicopters.

Task 13 - Demonstrate the Potential of Refined Noise Abatement Procedures

The Pennsylvania State University

Objective

The objective of this task is to demonstrate the potential of refined noise abatement procedures by simulating the flight procedures executed in the 2017 FAA/NASA acoustic flight test and ultimately comparing these procedures to new simulated procedures.

Research Approach

In this task, predictions of noise abatement procedures executed in the flight test will be simulated and compared to the optimal procedures developed under the new strategy. The process will be thoroughly documented (details are provided in Mrunali Botre's PhD dissertation, which is currently under review, and in the publication list for this task) and will provide the basis for future low-noise operational guideline development. Both linear flight profiles and turns will be considered, along with more complex procedures. These demonstrations will consider flight conditions both with and without BVI noise.

Milestone

The noise abatement flight procedures executed in the 2017 FAA/NASA flight tests will be compared to simulations, including future simulations of potentially improved noise abatement procedures. The first milestone will be a comparison between flight test data and the most refined predictions of simple and complex maneuvers for several aircraft.

Major Accomplishments

SEL noise contour predictions were made for five of the six aircraft in the 2017 flight test for linear (non-turning) flight procedures. Three of the six aircraft were simulated for level turns (Figure 7), decelerating turns (Figure 8), and descending turns (Figure 9). (Note: the most refined and updated figures, as of this report, are shown in this task.) The agreement was generally good, usually within 2 dBA. These conditions were analyzed in detail by examining the different noise components separately: thickness, loading, and broadband noise; main rotor and tail rotor noise (including the breakdown of noise components for each rotor). OASPL and L_A time histories were evaluated for several microphone locations. It was found that although the simulated SEL contours showed good agreement, discrepancies arose in the time history data. For example, the thickness noise was often overpredicted as the helicopter approached the observer, but this overprediction was still below the 10-dB down points included in the SEL calculation. Similarly, it was often found that the loading and broadband noise were overpredicted after the peak value in the time history. The main rotor is generally the dominant contributor to the OASPL, while the tail rotor is dominant in the L_A plots (as might be expected). Although there are only a limited number of flight procedures, many results were determined once the rotor noise components were analyzed separately. The details of these findings are documented in Mrunali Botre's PhD dissertation (currently under review).

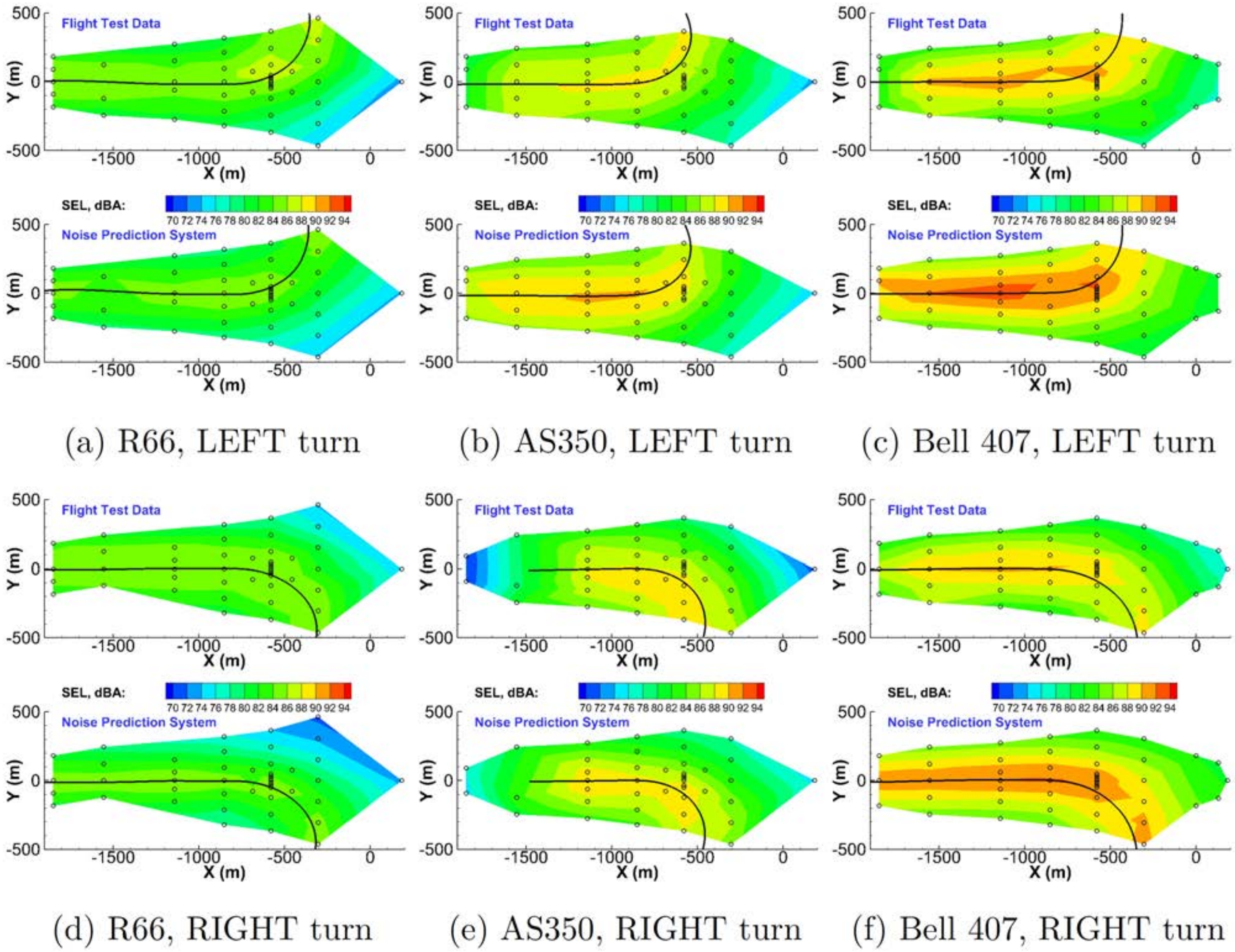
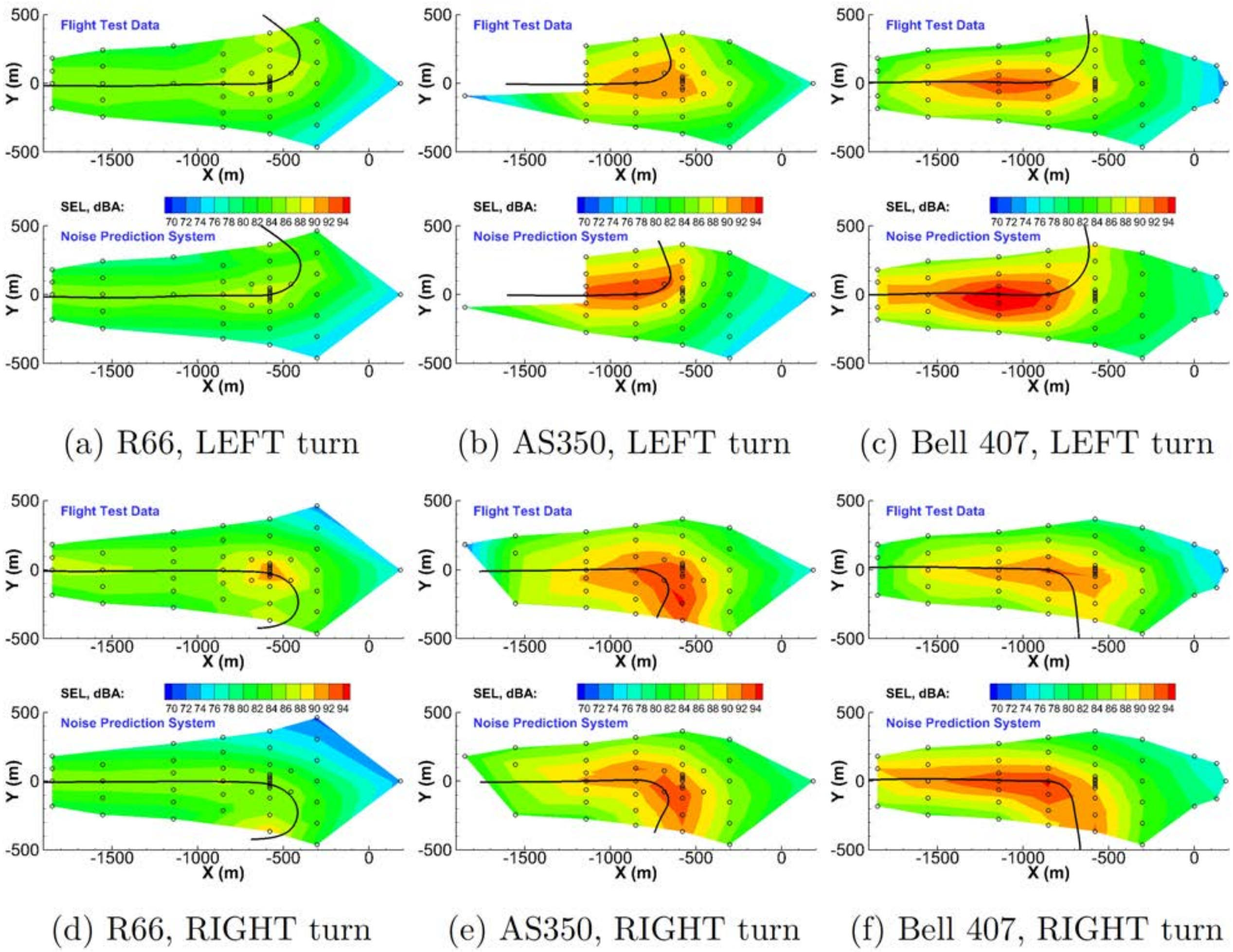


Figure 7. Total sound exposure level (SEL, dBA) for 80-kts level turns with a final roll angle of 25°. For each subfigure, top: flight test data; bottom: prediction.



(a) R66, LEFT turn (b) AS350, LEFT turn (c) Bell 407, LEFT turn

(d) R66, RIGHT turn (e) AS350, RIGHT turn (f) Bell 407, RIGHT turn

Figure 8. Total sound exposure level (SEL, dBA) for level decelerating turns, with a final roll angle of 35° and deceleration from 80 kts at 2 kts/s. For each subfigure, top: flight test data; bottom: prediction.

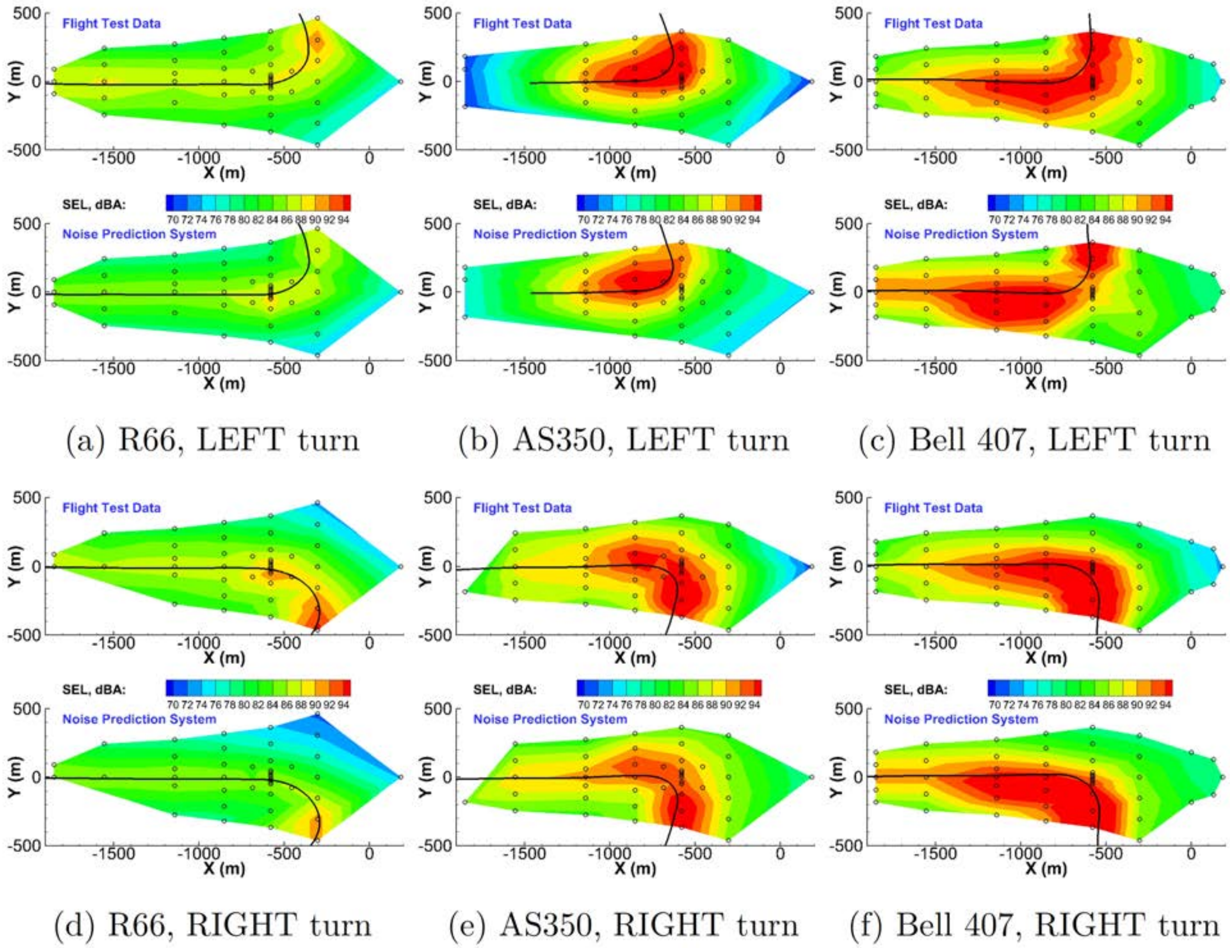


Figure 9. Total sound exposure level (SEL, dBA) for 80-kts descending turn with a flight path descent angle of 6° and a final roll angle of 35°. For each subfigure, top: flight test data; bottom: prediction.

Publications

Published conference proceedings

Botre, M., Brentner, K.S., Horn, J.F., & Wachspress, D.A. (2019). Developing a comprehensive noise prediction system for generating noise abatement procedures. 25th AIAA/CEAS Aeroacoustics Conference, Delft, The Netherlands, https://doi.org/10.2514/6.2019-2617

Botre, M., Brentner, K.S., Horn, J.F., & Wachspress, D.A. (2019). Validation of helicopter noise prediction system with flight data. VFS 75th Annual Forum, Philadelphia, PA.

Outreach Efforts

N/A

Awards

None.

Student Involvement
Mrunali Botre, a graduate assistant currently working toward her PhD at Penn State, performed the acoustic predictions and worked with Volpe to provide the needed predictions and any explanations regarding the results.

Plans for Next Period
More attention will be given to the noise abatement procedures executed in the 2017 and 2019 flight tests. Evaluations of the procedures and the generated noise (compared to a baseline procedure) will be aided by the availability of noise components in the simulations. This step will provide information regarding which noise sources, rotors, and frequency ranges are important.