Project 049 Urban Air Mobility Noise Reduction Modeling

The Pennsylvania State University, Continuum Dynamics, Inc.

Project Lead Investigator

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University Participants

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- P.I.: Kenneth S. Brentner, Professor of Aerospace Engineering
- FAA Award Number: 13-C-AJFE-PSU-049, Amendment No. 82
- Period of Performance: October 1, 2021 to September 30, 2022
- Tasks:
    12. Develop several additional notional Urban Air Mobility (UAM) and Electric Vertical Take-off and Landing (eVTOL) aircraft models for noise testing
    13. Continue validating the new flight simulation/noise prediction system
    14. Investigate test trim strategies for notional UAM/eVTOL vehicles
    15. Develop a database of noise predictions for UAM and eVTOL vehicles during the various stages of operation
    16. Begin investigation of low-noise flight operation development

Project Funding Level

The FAA provided $280,000 in funding. Continuum Dynamics, Inc. (point of contact: Dan Wachspress) provided $75,000 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. Penn State also provided $18,400 in equipment cost sharing, for a total of $93,400 cost sharing.

Investigation Team

- Kenneth S. Brentner, P.I., Penn State; acoustic prediction lead (Tasks 12–16)
- Eric Greenwood, co-P.I., Penn State; acoustics prediction/analysis (Tasks 13, 14, 16)
- Joseph F. Horn, co-P.I., Penn State; flight simulation lead (Tasks 12-15)
- Daniel A. Wachspress, co-P.I., Continuum Dynamics, Inc.; rotor loads, wake integration, and CHARM coupling (Tasks 12-14, 16)
- Ze Feng (Ted) Gan, Graduate Research Assistant, Penn State; developing PSU-WOPWOP noise prediction software and performing acoustic predictions (Tasks 13 and 15)
- Bhaskar Mukherjee, Graduate Research Assistant, Penn State; software coupling, establishing new aircraft models, developing simulations for new aircraft types, performing acoustic predictions, and developing flight abatement procedures (Tasks 12–16)

Project Overview

A wide variety of unconventional configurations for UAM and eVTOL aircraft, most with many electrically driven propellers and lifting rotors, have been proposed and are currently under development by companies worldwide. These novel configurations make up a new category of aircraft that will need to be certified, particularly for acceptable noise levels, given their urban operations. Furthermore, the noise of UAM and eVTOL vehicles is expected to be one of the factors determining community and passenger acceptance. Therefore, first-principles noise predictions of these aircraft will be important for providing the FAA with information independent from that provided by manufacturers, and before manufacturer flight test or certification noise data are available. For clarification, unmanned aerial systems (UAS, also known as drones), UAM, and eVTOL vehicles all share electric motors as the source of power to drive the rotors. In most cases, UAM are likely to use batteries, but the electrical power could come from fuel cells, gas generators, or other sources. Furthermore, although most UAS and UAM vehicles are likely to have VTOL capabilities, such capabilities are not a requirement. In this report, these UAM and eVTOL are used synonymously, whereas UAS are eVTOL drones.

In ASCENT Project 38, the helicopter noise prediction system initially developed in ASCENT Project 6 was successful in accurately predicting the noise of six helicopters (usually within sound exposure levels of 1–3 SELdBA), when the predictions were compared with results from an FAA/NASA rotorcraft noise abatement flight test performed in August and October of 2017. Sound exposure level contours from the flight test were compared with predictions for several flight procedures. The noise prediction system developed in Project 38 consisted of the PSUHeloSim flight dynamics simulation code coupled to the CHARM aeromechanics modeling software and the PSU-WOPWOP noise prediction code. This coupling with the flight simulation code was demonstrated to be important for noise prediction, which markedly improved when the simulation was modified to track the time-dependent aircraft position, velocity, and attitude flown in the individual run, rather than the nominal flight path.

To build upon the success of ASCENT Project 38, in ASCENT Project 49, we took an analogous approach of coupling a flight simulation code with CHARM and PSU-WOPWOP. The PSUHeloSim flight simulation component of the noise prediction system used in Project 38 was replaced with DEPSim, a flight simulation code designed for many electrically driven rotors and the unique control strategies to fly such vehicles effectively. Coupling of DEPSim with CHARM was performed in work outside ASCENT, but the DEPSim–CHARM coupling with PSU-WOPWOP was performed in this project.

The goal of this project is to develop a noise prediction system with the initial capability to analyze the noise from UAM and eVTOL vehicles with unique configurations under any flight conditions. This project should enable the FAA, manufacturers, and related entities to investigate how this new class of vehicles—and their noise—might be integrated into the national airspace. Emphasis is placed on modeling the unique features of UAM and eVTOL configurations not commonly seen in conventional rotorcraft, such as rotors with variable rotation speed, and complex unsteady aerodynamic interactions between the many rotors and the airframe. Because UAM vehicles will probably have lower tip speeds to achieve acceptable noise levels, broadband noise is expected to become the dominant rotor noise source; accordingly, fast, accurate modeling of rotor broadband noise is a goal of this project. Another goal is to use the noise prediction system developed in this project to provide guidance on how to fly these vehicles in a quiet manner through flight operations. Because the analysis and computations are based on fundamental physics, noise abatement procedures for novel new vehicles can be developed.

Task 12 - Develop Several Additional Notional UAM/eVTOL Aircraft Models for Noise Testing

The Pennsylvania State University

Objective

The goal of this task is to develop notional aircraft models for understanding the acoustic characteristics of different UAM/eVTOL configurations. Required data from aircraft configurations must be extracted to enable flight simulation of maneuvers via the PSUDEPSim–CHARM–PSU-WOPWOP noise prediction system.

Research Approach

Table 1 summarizes the inputs required for any aircraft to be modeled in the noise prediction system. Barring the lack of available aircraft and rotor geometries, the primary hurdle remains the aircraft controller design in PSUDEPSim. Although most of the controller design is automated within PSUDEPSim, users must provide a trim schedule (initial guesses for state of control effectors that result in trimmed flight at various steady conditions) and the gains of the control mixers, which determine how the control effectors are actuated. For example, the structure of the control mixers determines whether the rotor thrust is controlled via the variation in angular velocity, collective pitch, or both.

Table 1. Parameters required by the PSUDEPSim–CHARM–PSU-WOPWOP noise prediction system.

Tool	Required input	Status	Challenges
PSUDEPsim	• Aircraft properties: weight, inertia, fuselage properties, rotor layout with respect to aircraft center of gravity • Gains for control mixers • Trim schedules or initial guess for controller to trim the aircraft in steady state	• Gains for control mixers and control inputs for trim schedules are currently being hand-tuned	• Information on existing commercial aircraft is lacking • Hand-tuning is extremely time-intensive, and more automated methods are required
CHARM	• Detailed rotor geometry: ○ Hub and tip radii ○ Chord and twist distribution ○ Airfoil polars	• A simple utility has been developed to obtain CHARM-friendly input files • A library of airfoil polars for common airfoils is being built • A utility has been developed to generate airfoil polars by using XFOIL for CHARM	• Openly available rotor geometries for eVTOL/UAM are limited • Estimation is difficult, because rotors tend to have complex twist and chord distribution
PSU-WOPWOP	Distribution of thickness across blade span	• This parameter can be estimated by using OpenVSP • A utility has been developed to convert OpenVSP blade geometry to the PSU-WOPWOP grid format required for thickness noise calculations	

Milestones

- Obtained input files for CHARM describing rotor geometry and airfoil polars (C-81)
- Obtained grid geometry required for calculation of thickness noise in PSU-WOPWOP
- Developed tools for determining parameters required in building flight controllers in PSUDEPSim

Major Accomplishments

- A utility code in FORTRAN has been written to obtain input files containing rotor geometry for CHARM.
- C-81 airfoil polars used by CHARM can be compiled for different airfoils by using XFOIL.
- An external tool has been developed that converts OpenVSP files to structured grids, which serve as input to PSU-WOPWOP for calculating thickness noise.
- A subsystem based on the CHARM Rotor Module has been developed that can simulate the aerodynamic response from rotors in any aircraft configuration, according to prescribed control inputs. The goal is to create procedures wherein a user commands the aircraft to perform certain maneuvers/actions that help determine the gains along the roll, pitch, and yaw axes of the aircraft that maintain required stability margins.
- Strategies for robust trim are being developed that will help generate accurate trim schedules required in PSUDEPSim.

Publications

None.

Outreach Efforts

None.

Awards
None.

Student Involvement
Bhaskar Mukherjee, a graduate assistant working on his PhD at Penn State, is integrating new aircraft into the PSUDEPSim–CHARM–PSU-WOPWOP noise prediction system.

Plans for Next Period
The Penn State Rotor Acoustics Group is acquiring more rotor and aircraft geometries through measurements of commercial drones. An immediate next step is to integrate the Tarot X-8 drone used in flight test measurements of noise in ASCENT Project 77. The design optimization capabilities of the CHARM standalone code are being explored to generate reasonable notional rotor designs for passenger-sized eVTOL aircraft.

Task 13 - Continue Validating the New Flight Simulation/Noise Prediction System
The Pennsylvania State University

Objective
One objective of this task is to validate time-varying broadband noise predictions by using full-scale flight test data, because the broadband noise model used by the noise prediction system—the Brooks, Pope, and Marcolini (BPM) model—is typically validated in the literature by using time-averaged noise measurements of small-model-scale wind tunnel tests.

Research Approach
Time-varying broadband noise predictions were compared with flight test noise measurements for a Bell 206 helicopter (Schmitz et al., 2007), for a variety of flight path angles (level and descending flight). This data set is well suited to studying time-varying noise, because the microphones are fixed to the aircraft, such that de-Dopplerization of noise signals is not required. This data set was readily available and well understood, because one of the project investigators (Prof. Eric Greenwood) was part of the joint NASA–Army–University of Maryland team that conducted the measurements. In contrast, flight test data of UAM aircraft are not easily accessible.

For computing the aerodynamic loading needed as input for noise predictions, the aircraft was trimmed by using the PSUHeloSim flight simulation code previously developed in ASCENT Project 38. Because no pilot control commands or flight disturbances inherent to flight test were modeled, the trim state was maintained. Therefore, these cases validate only the noise prediction, not the flight dynamics or controls, which differ between helicopters and UAM aircraft. Nonetheless, the validation is valuable, because time-varying broadband noise is not yet well understood, even for helicopters in steady flight conditions, and time-varying broadband noise predictions have not been well validated in the literature. Furthermore, aerodynamic interactions can still occur in trimmed flight: for helicopters, blade–vortex interaction (BVI) is known to occur in descent, and main rotor/tail rotor (MR/TR) interactions can occur even in level flight. Aerodynamic interactions important for helicopters represent more general aerodynamic interactions expected to be important for UAM aircraft noise. For example, BVI represents a rotor interacting with its own wake, and MR/TR interactions are a type of rotor–rotor interaction.

To validate the time-varying broadband noise, comparisons of modulation depth are made between the noise predictions and flight test measurements.

Milestones
The milestones reached for this task include validation of time-varying broadband noise with flight test noise measurements, including accurate prediction of noise modulation depths and trends.

Major Accomplishments
Spectrograms are shown in Figure 1 for a microphone fixed to the aircraft, below the main rotor advancing side. The Bell 206 helicopter is in steady level flight, with a forward flight speed of 60 knots. In the self-noise predictions, the dominant feature is the main rotor modulation peak in the observer time range $0.4 < t < 0.8$ main rotor blade passage periods. Although

the main rotor self-noise levels are higher than those of the tail rotor in the predictions, the tail rotor has a higher blade passage frequency; consequently, the tail rotor noise modulation remains visible when the main rotor noise levels are low (e.g., at t = 0.1 times the main rotor blade passage period).

Despite good prediction of discrete frequency noise with respect to the flight test noise measurements, broadband noise is significantly underpredicted. This underprediction is not a uniform level offset, because tail rotor broadband noise levels are particularly underpredicted. In the measurements, main and tail rotor broadband noise have similar levels; in contrast, in the predictions, tail rotor broadband noise levels are much lower than those of the main rotor. Despite these differences, the predictions do accurately capture the modulation trends and depths, thus helping validate the noise predictions.

These results also reveal aspects in which noise predictions could be improved. For example, significant aperiodicity in tail rotor broadband noise is observed between tail rotor blade passages in the measurements. However, these aperiodicities are not in the predictions, possibly because of MR/TR interactions that were not modeled.

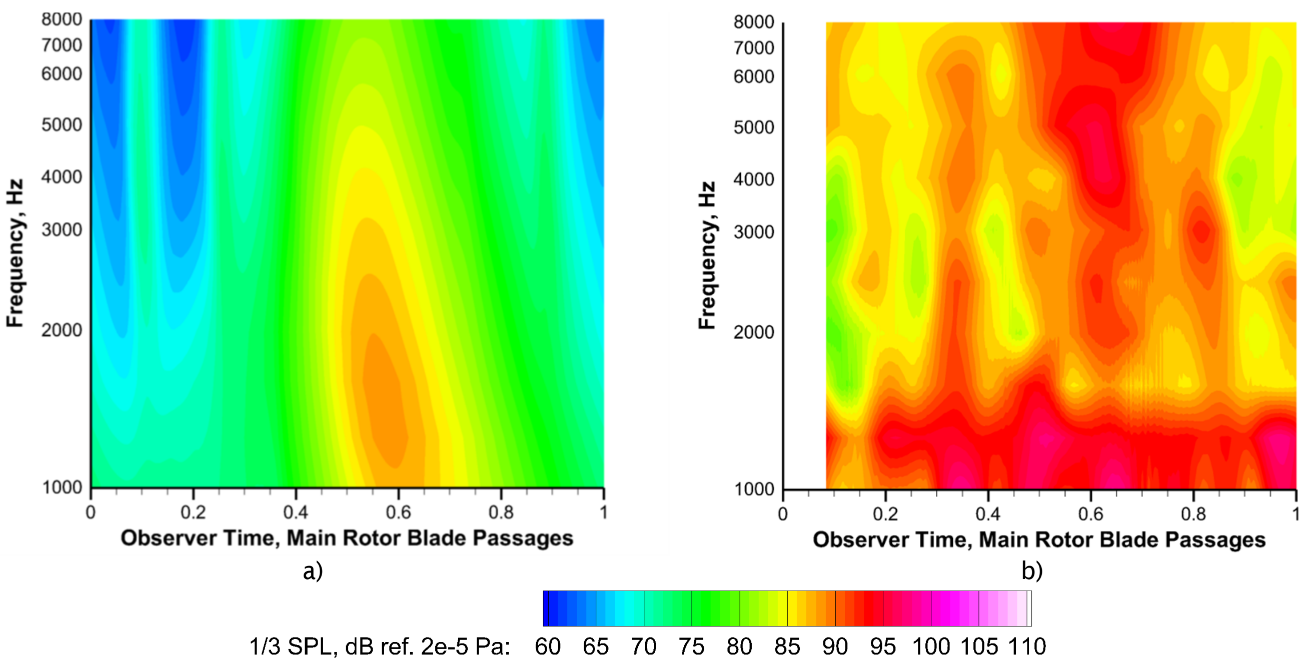

Figure 1. Spectrograms for 60-knot level forward flight. (a) Broadband self-noise predictions. (b) Flight test noise measurements.

The noise predictions in Figures 2 and 3 are shown for the same microphone as in Figure 1, but for a 60-knot, steady 7.5° descent flight condition. For this flight condition, BVI evidently occurs, as indicated by the discrete frequency noise peak seen in both the noise measurements and predictions (Figure 2). In the measurements, BVI adds broadband noise peaks at lower and higher frequencies, nearly in phase with the BVI peaks seen in the acoustic pressure time history. However, this finding is not seen in the broadband noise predictions (Figure 3), although the discrete frequency noise predictions accurately resolve the BVI peak fairly well.

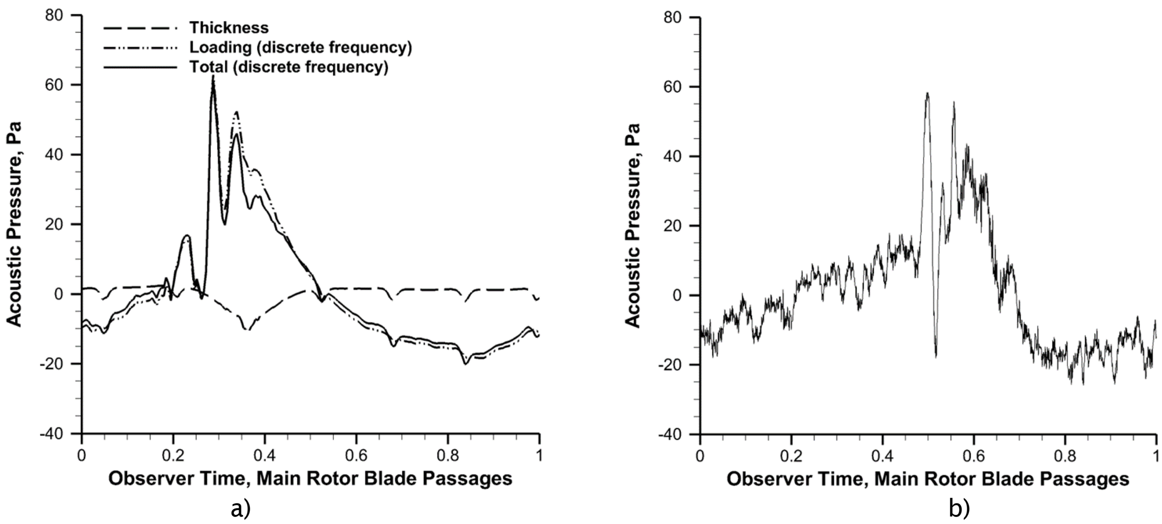

Figure 2. Acoustic pressure time histories for 60-knot, 7.5° descent. (a) Discrete frequency noise predictions. (b) Flight test noise measurements.

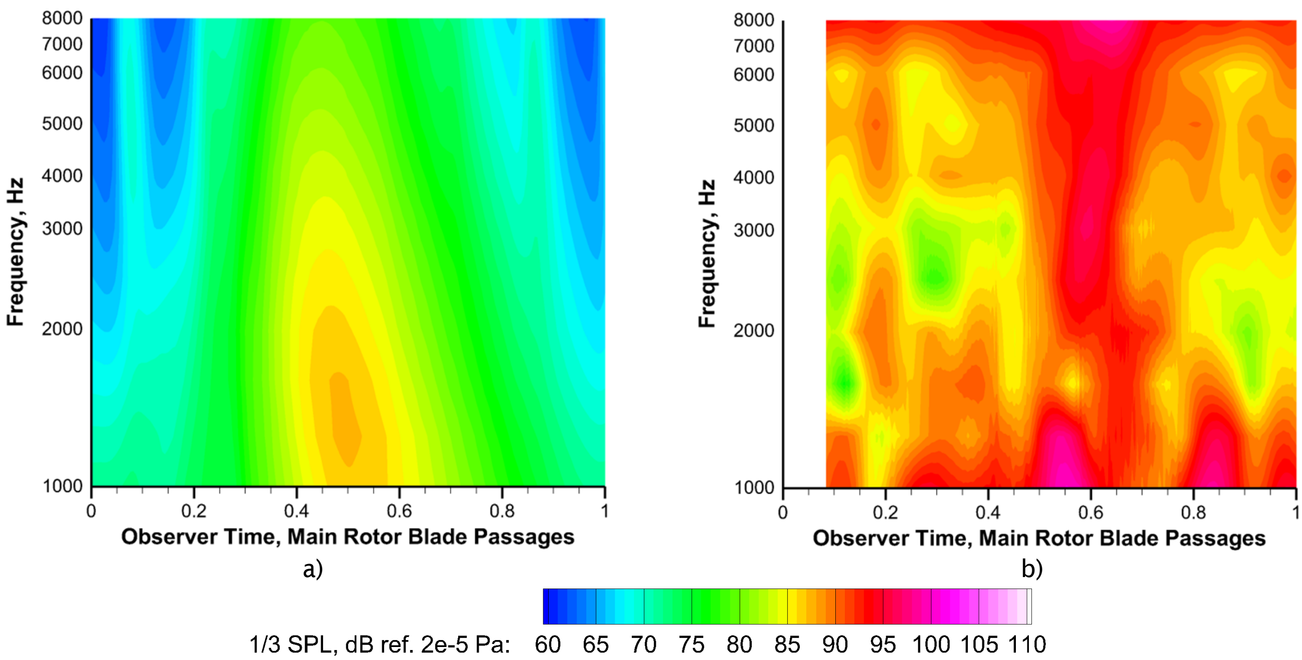

Figure 3. Spectrograms for 60-knot, 7.5° descent. (a) Broadband self-noise predictions. (b) Flight test noise measurements.

Publications

Published conference proceedings

Gan, Z.F.T., Brentner, K.S., Greenwood, E. (2022, June 14-17). *Time Variation of Helicopter Rotor Broadband Noise.* 28th AIAA/CEAS Aeroacoustics Conference, Southampton, UK.

Outreach Efforts

None.

Awards

None.

Student Involvement

Ze Feng (Ted) Gan, a graduate research assistant currently working toward his PhD degree at Penn State, performed validation of the time-varying broadband noise predictions for this task.

Plans for Next Period

The results shown above motivate refined modeling of possible sources of noise aperiodicity, particularly aerodynamic interactions. Noise caused by aerodynamic interactions will be thoroughly investigated, because it is expected to be important for the complex geometric configurations of UAM aircraft.

The underpredicted broadband noise levels previously shown suggest that modeling self-noise (broadband noise generated by turbulence that develops over the rotor blades) as the only broadband noise source may be insufficient. Therefore, we aim to model noise generated by aerodynamic interactions, such as ingestion of atmospheric or wake turbulence, in future work.

References

Schmitz, F. H., Greenwood, E., Sickenberger, R. D., Gopalan, G., Sim, B. W.-C., Conner, D. A., Moralez, E., and Decker, W. (2007). *Measurement and Characterization of Helicopter Noise in Steady-State and Maneuvering Flight.* American Helicopter Society 63rd Annual Forum & Technology Display.

Sargent, D. C. (2008) *In-Flight Array Measurements of Tail Rotor Harmonic Noise* [M. S. thesis, University of Maryland].

Task 14 - Investigate Test Trim Strategies for Notional UAM/eVTOL Vehicles

The Pennsylvania State University

Objective

The objective of this task is to explore various trim strategies for different notional UAM/eVTOL aircraft configurations. Several of these configurations tend to have more control effectors than are required for stable trimmed flight. The additional control effectors can be used to lower noise.

Research Approach

Figure 4 provides an overview of the mitigation strategies currently being explored. Notably, controller design strategies directly affect aircraft trim, particularly when additional control effectors are available. Thrust from rotors controlled via electric motors can be controlled by varying the angular velocity (variable revolutions per minute [RPM]) or collective pitch (variable pitch). These two methods of control can also be mixed to allow for more complex strategies. Aircraft trim strategies are diverse and highly correlated to the aircraft configuration being analyzed.

Current work has focused on a generic eVTOL aircraft, which is a lift plus cruise configuration (Figure 5 and Table 2). This configuration has a wing that enables redundant control in the form of the operating angle of attack controlled via the pitch of the aircraft. Control of the wing lift provides control over total rotor thrust and consequently noise. Task 9 (last year) demonstrated the impact of this strategy on deterministic noise from generic eVTOL performing a level turn maneuver. However, considering the impact of trim strategies on time variation in broadband noise is also important.

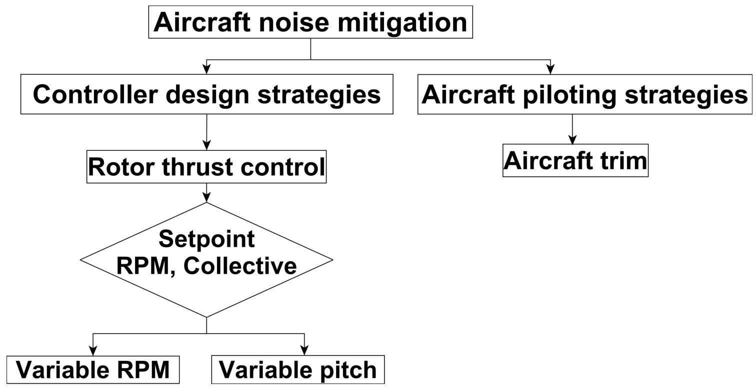

Figure 4. Overview of noise mitigation strategies.

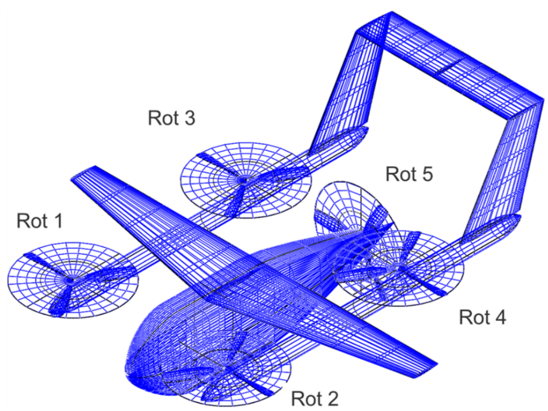

Figure 5. Generic eVTOL configuration.

Table 2. Properties of generic eVTOL aircraft.

Parameter	Generic eVTOL
Number of lift rotors	4
Number of pusher propellers	1
Gross weight	1,000 lb
Lift rotor radius	2.82 ft
Pusher prop radius	2.82 ft

Milestone

- Investigated the impact of variable RPM, variable pitch rotor thrust control strategies on broadband noise for generic eVTOL

Major Accomplishments

- Flight simulations of 10- and 50-knot level cruise were performed. The spectrogram of broadband noise for an observer in far field below the aircraft (Figure 6) revealed differences between variable pitch and variable RPM control schemes. The variable pitch scheme appeared to have higher peak noise levels in every modulation cycle, as a direct result of the lack of phase differences between rotors in the variable pitch scheme (Figure 7). This analysis opens new avenues of investigation of the effects of phase differences between rotors of an aircraft.
- Analysis of noise from turn maneuvers has revealed the effect of stall on broadband noise. The BPM model allows for separation of stall noise terms, thus helping isolate its importance. As shown in Figure 8, stall noise can add as much as 10 dBA to the total noise levels.

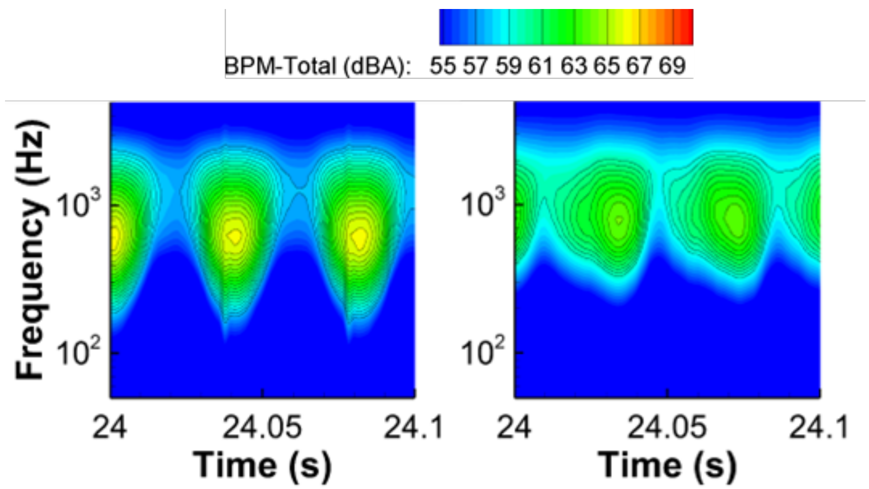

Figure 6. Spectrogram for 10-knot cruise at microphone in far field directly below the aircraft. Variable pitch (left); variable RPM (right).

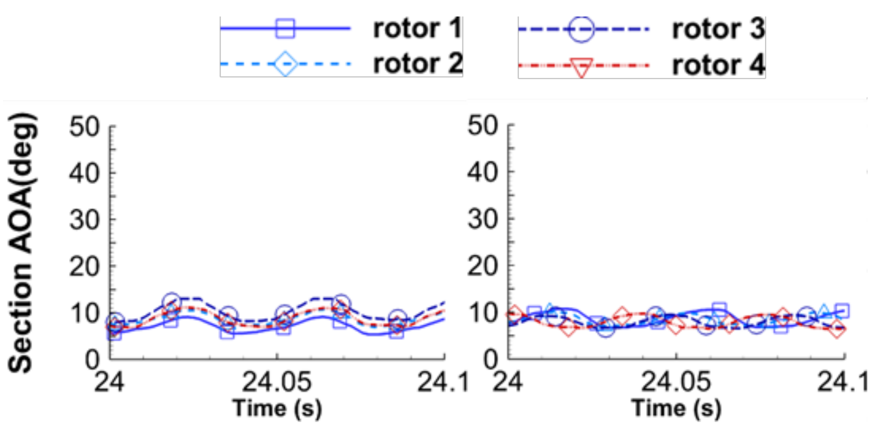

Figure 7. Variation in angle of attack at the rotor mid-section. Variable pitch (left); variable RPM (right).

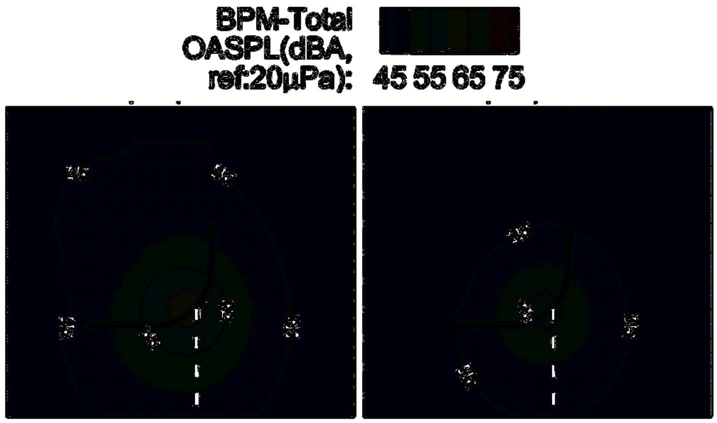

Figure 8. Broadband self-noise during a turn maneuver. Noise with stall (left); noise without stall (right).

Publications

Mukherjee, B., Brentner, K. S., Greenwood, E., Theron, J.-P., & Horn, J. F. (2022, May 10-12). *An Investigation of Piloting and Flight Control Strategies on Generic eVTOL Noise.* Vertical Flight Society's 78th Annual Forum & Technology Display, Fort Worth, TX. DOI: 10.4050/F-0078-2022-17441.

Outreach Efforts

None.

Awards

None.

Student Involvement

Bhaskar Mukherjee, a graduate assistant working on his PhD at Penn State, is investigating the impact of control schemes on eVTOL aircraft noise.

Plans for Next Period

On the basis of consistent findings from the controls and dynamics community, rotors in passenger sized eVTOL aircraft are poorly controlled via the variable RPM scheme. OEM manufacturers are highly likely to use a combination of variable pitch and variable RPM schemes. Future efforts will be directed to explore combinations of variable pitch and variable RPM further.

Task 15 - Develop a Database of Noise Predictions for UAM and eVTOL Vehicles During the Various Stages of Operation

The Pennsylvania State University

Objective

The objective of this task is to use the data generated in Tasks 13 and 14 to compile a database of vehicle models and noise predictions for various aircraft. This task will also develop and provide documentation of the "database," its contents, and how to add additional vehicle data to the database.

Research Approach

The approach to accomplishing this task is to use the noise prediction system developed in this project to make noise predictions for different aircraft under various flight conditions. Flight conditions can include flight speed, flight path angle (e.g., level vs. descending flight), maneuvers, etc. Ultimately, the initial database is envisioned to comprise a sequence of acoustic hemisphere data for each stage of a particular flight operation for an eVTOL aircraft. The format will allow the hemisphere data to be compatible with advanced air mobility (AAM) and potentially the Aviation Environmental Design Tool. In addition to the speed and flight path angle defined by the AAM hemisphere format, the data will be extended to include other flight state data unique to eVTOL configurations and additional acoustic data that may be required to calculate noise metrics in future versions of AAM.

Milestones

The milestones reached for this task include the following:

- Prediction of time-varying broadband noise for level and descending flight
- Prediction of aircraft response to external gusts

Major Accomplishments

- The noise generated at different flight conditions (e.g., flight path angles) studied for helicopters under Task 2 provides insight into the future development of a noise database for UAM and eVTOL aircraft. Particular insight has been gained for time-varying broadband noise, as studied in Task 13, which has not been extensively studied in the literature for helicopters in steady flight conditions, let alone UAM and eVTOL aircraft in maneuvering flight. Work described in this report under Task 13 contributes to this task by studying the time-varying broadband noise of a Bell 206 in nominally steady level flight and 7.5° descent.
- The generic eVTOL aircraft has been used to investigate several maneuvers, including level cruise, steady turns, and level acceleration. Every maneuver was analyzed with the rotors controlled by either the variable RPM or the variable pitch scheme. An overview of maneuvers executed is listed in Table 3.
- Updates to the PSUDEPSim–CHARM–PSU-WOPWOP noise prediction system have enabled prediction of noise with the aircraft experiencing external gusts. A new utility has been written that enables generation of 3D grids that allow the creation of gust profiles that can vary with respect to time. Currently, step gust profiles are used in maneuvers.

Table 3. Current library of maneuvers successfully executed with generic eVTOL aircraft (Fig. 5).

Type of maneuver	Flight speed (knots)	Notes	Rotor thrust control scheme
Level cruise	10, 20, 30, 40, 50, 60	None	Variable pitch, variable RPM
Level turn	50	None	Variable pitch, variable RPM
Level acceleration	10	Accelerate to 50 knots at 0.025*g* acceleration	Variable pitch, variable RPM
External step gust	10	30 ft/s gust along the principal axes of the aircraft	Variable pitch, variable RPM

Publications

Published conference proceedings

Gan, Z.F.T., Brentner, K.S., Greenwood, E. (2022, June 14-17). *Time Variation of Helicopter Rotor Broadband Noise*. 28th AIAA/CEAS Aeroacoustics Conference, Southampton, UK.

Mukherjee, B., Brentner, K. S., Greenwood, E., Theron, J.-P., & Horn, J. F. (2022, May 10-12). *An Investigation of Piloting and Flight Control Strategies on Generic eVTOL Noise.* Vertical Flight Society's 78th Annual Forum & Technology Display, Fort Worth, TX. DOI: 10.4050/F-0078-2022-17441.

Outreach Efforts

None.

Awards

None.

Student Involvement

Ze Feng (Ted) Gan, a graduate research assistant currently working toward his PhD degree at PSU, performed time-varying broadband noise predictions for level and descending flight for this task.

Bhaskar Mukherjee, a graduate assistant working on his PhD at Penn State, is creating a database of noise predictions of eVTOL/UAM aircraft.

Plans for Next Period

- Flight test data are available for other descent angles (3˚, 6˚, 9˚, and 12˚), for which noise predictions will be made for this task and validated for Task 13.
- With the recent release of PSUDEPSim v2, the current library of noise predictions is expected to be substantially expanded to include climb and descent maneuvers.

Task 16 - Begin Investigation of Low-Noise Flight Operation Development

The Pennsylvania State University

Objective

The objective of this task is to amalgamate the findings of Tasks 13 and 14 to develop low-noise flight operational procedures.

Research Approach

Current findings from Tasks 13 and 14 have indicated that broadband noise is more dominant than deterministic noise for rotors operating at low tip Mach numbers. Stall has been shown to be a potentially significant contributor to noise. Other acoustic phenomena such as BVI, blade–wake interaction (BWI), and turbulence ingestion noise must be included in developing low-noise flight operations.

Milestones

- Developed flight control strategies that avoid blade stall
- Identified flight regimes that will result in strong BVI and BWI noise

Major Accomplishments

Preliminary changes have been made to PSUDEPSim to accommodate changes in rotor setpoint. The setpoint includes the rotor collective pitch when thrust is actuated by the variable RPM scheme, and the rotor RPM when thrust is actuated by the variable pitch scheme.

Publications

None.

Outreach Efforts

None.

Awards

None.

Student Involvement

Bhaskar Mukherjee, a graduate assistant working on his PhD at Penn State, is identifying strategies to develop low-noise flight operation strategies for eVTOL/UAM aircraft.

Plans for Next Period

Current noise prediction capabilities must be extended to include BVI, BWI, and turbulence ingestion noise. Understanding these aspects will aid in identifying further low-noise operation strategies.