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. 120
- Period of Performance: August 23, 2024, to August 22, 2025
- Tasks:
  1. Predict and investigate turbulence interaction noise
  2. Compare predictions with flight tests
  3. Investigate time-varying broadband noise of multirotor aircraft
  4. Develop and investigate departure and arrival transition maneuvers
  5. Upgrade and document electric vertical take-off and landing (eVTOL) of noise prediction system

Project Funding Level

The project’s previous funding ended December 31, 2023, and was not renewed until August 2024, with the FAA providing $305,000 in funding. Blue Ridge Research and Consulting, LLC (BRRC) will provide $8,975 in-kind support to attend research and biannual meetings, and review software and documentation. Sikorsky, A Lockheed Martin Company, will provide $186,000 in-kind support to attend recuring meetings, provide aircraft configuration data, and acoustic flight measurements for verification and validation of the Penn State noise prediction system (PSU-NPS). Supernal will provide $121,000 in-kind support in the form of costs accrued to collect and extract datasets from a flying testbed Bell 407 as well as engineering hours. Continuum Dynamics, Inc. (point of contact: Dan Wachspress) will provide $225,000 of cost sharing in the form of a 1-year license for the CHARM™ rotorcraft comprehensive analysis software to the Federal Aviation Administration (FAA) for its designee and to industrial partners BBRC and Sikorsky. Total cost sharing: $540,975.00.

Investigation Team

The Pennsylvania State University

Kenneth S. Brentner (P.I.; acoustic prediction lead), Tasks 1-5
Eric Greenwood (co-P.I.; acoustics prediction/analysis), Tasks 1-5
Joseph F. Horn (co-P.I.; flight simulation lead), Tasks 2, 4, and 5
Bhaskar Mukherjee, PhD student (graduated August 2025), software coupling, establishing new aircraft models, developing simulations for new aircraft types, performing acoustic predictions, and developing flight abatement procedures), Tasks 1-5
Ze Feng (Ted) Gan, PhD student (graduated May 2025), investigation of broadband noise modulation, Task 3

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Continuum Dynamics, Inc.
Daniel A. Wachspress and Mrunali Botre (co-P.I.; rotor loads, wake integration, and CHARM coupling),
Tasks 1, 2, 4, and 5

Project Overview

A wide variety of unconventional configurations for urban air mobility (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 comprise a new category of aircraft that will require certification and show acceptable noise levels received by people on the ground during their urban operations. Unlike helicopters, eVTOL aircraft have limited flight test data and lack mature, empirically derived noise models developed from such data (e.g., the Pegg (1979) helicopter broadband noise model). Therefore, first-principles (methods based on universal laws of physics) noise predictions of these aircraft will be important to gain insight into the complex noise generation mechanisms, the acoustics and performance of the vehicle at different flight phases, and to inform developments of noise certification standards and noise modeling standards. In the absence of flight test data for multirotor UAM and eVTOL vehicles, noise measurements of unmanned aircraft systems (UAS) can be leveraged to provide insight into their noise characteristics. For example, ASCENT Project 077 has produced relevant datasets, since UAS measurements are often more practical to obtain because the aircraft are more accessible and can be built and tested locally. In this report, the terms UAM and eVTOL are used synonymously, whereas UASs are eVTOL drones.

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, rapid physics-based modeling of rotor broadband noise is a prominent goal of this project and motivates building upon prior validated noise-prediction capabilities. In ASCENT Project 038, the helicopter noise prediction system initially developed in ASCENT Project 006 was successful in accurately predicting the noise of helicopters (usually within sound exposure levels of 1 to 3 dBA), when the predictions were compared with results from an FAA/National Aeronautics and Space Administration (NASA) rotorcraft noise abatement flight test performed in August and October 2017. Sound exposure level contours from the flight test were compared with predictions for several flight procedures. The noise prediction system developed in ASCENT Project 038 consisted of the PSU HeloSim flight dynamics simulation code coupled to the CHARM aeromechanics modeling software and the PSU-WOPWOP noise prediction code. This combination 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 an individual run, rather than the nominal flight path.

To build upon the success of ASCENT Project 038 (focused on helicopter noise), ASCENT Project 049 employs an analogous approach of coupling a flight simulation code with CHARM and PSU-WOPWOP. The PSU HeloSim flight simulation component of the noise prediction system used in ASCENT Project 038 was replaced with PSU Distributed Electric Propulsion Simulator (DEPSim), a flight simulation code designed for many electrically driven rotors with unique control strategies to fly such vehicles effectively. Coupling of PSUDEPSim with CHARM was performed in work outside ASCENT, whereas PSUDEPSim–CHARM coupling with PSU-WOPWOP was performed in this project. The resulting noise prediction system has since been adopted in ASCENT Project 038, providing a common framework in which upgrades developed in either can project directly benefit the other.

The goal of this project is to develop a noise prediction system to analyze the noise from UAM and eVTOL vehicles with unique configurations under any flight conditions. 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. 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 vehicles can be developed.

Task 1 – Prediction and Investigation of Turbulent Interaction Noise

The Pennsylvania State University

Objective

Noise due to turbulent interactions in multirotor electric aircraft is an important contributor to high-frequency broadband noise, which strongly influences perceived annoyance. Key sources of turbulence include atmospheric boundary-layer and rotor wake/vortex-core interactions, which are especially relevant in hover (in and out of ground effect) and low-speed climb/descent. The objective of this task is to integrate PSU-MulTINoise (developed under ASCENT Project 049) into the noise prediction system. PSU-MulTINoise computes unsteady airloads on blade sections and lifting surfaces (e.g., wings) due to turbulence interactions and exports it to PSU-WOPWOP for noise prediction.

Research Approach

PSU-MulTINoise currently accepts turbulent intensity and length scale to characterize turbulence via the von Kármán spectrum (von Kármán, 1948) and calculates unsteady airloads generated on an airfoil. This spectrum can be used to characterize small-scale isotropic turbulence commonly observed in the atmosphere. A preliminary investigation on the impact of atmospheric turbulence on eVTOL aircraft noise is conducted. A new reference tiltrotor aircraft has also been developed to represent eVTOL aircraft designs such as the Joby Aviation® S4.

Milestones

- Developed a utility code that can generate a profile of atmospheric boundary layer and turbulent parameters dependent on local topography and weather conditions.
- Modeled a new tiltrotor reference aircraft (PSU Reference Aircraft 3 [PSU-RA3]) based on Joby Aviation S4.
- Investigated the Impact of atmospheric turbulence on a nominal transition maneuver.

Major Accomplishments

Task 1 of the ASCENT Project 049 Annual Report 2023–2024 described the integration of PSU-MulTINoise, a time-domain broadband noise prediction method based on Amiet's leading-edge noise theory (1975), into a quasi-steady implementation of PSU-NPS. This coupled framework was then used to conduct a preliminary investigation on noise generated by rotor blades interacting with the turbulence in low-altitude atmospheric boundary-layer (Mukherjee et al., 2025). Flight simulations of notional Airbus® AS350 helicopter and PSU-RA3 tiltrotor eVTOL aircraft indicated that not including the effects of atmospheric boundary-layer turbulence interaction led to an underprediction of noise levels. Surface roughness, an aerodynamic parameter representing the effective drag and turbulence generation caused by the ground, was found to be an important factor. Due to the low rotor tip-Mach number of PSU-RA3, atmospheric boundary-layer turbulence contributed more significantly to noise relative to AS350 helicopter.

A key limitation identified was the assumption of isotropic turbulence, i.e., the statistical properties of turbulent velocity fluctuations are identical in all directions. Prior work by Amiet et al. (1990) demonstrated that this assumption leads to overprediction of rotor broadband noise. In reality, turbulence approaching the rotor disk undergoes mean-flow contraction and streamline curvature, which stretch and tilt turbulent eddies. This process produces anisotropic turbulence, with the strongest stretching typically occurring along the rotor axis. The resulting deformation reduces the axial (upwash) velocity fluctuations, thereby reducing the unsteady lift on the blades and broadband noise levels. When anisotropy is neglected (i.e., turbulence is assumed isotropic at the rotor disk), these reduced upwash fluctuations are not captured, and the predicted noise can be overestimated by as much as 20 dB (Amiet et al., 1990). Consequently, it is essential that anisotropic turbulence effects be incorporated for accurate prediction of turbulence interaction noise.

This is carried out using rapid distortion theory (RDT), which assumes that turbulence does not significantly modify the mean flow and therefore behaves as a passive field that is convected by the mean motion. Under this approximation, eddies are stretched and reoriented by the mean-flow gradients, while viscous damping and nonlinear turbulence interactions are neglected. Amiet et al. (1990) began by assuming isotropic turbulence far upstream. As this turbulence is convected toward the rotor, the mean inflow accelerates and turns around the disk, producing strong contractions and curved streamlines. Amiet computed the resulting distortion using the deformation tensor of the mean flow, which quantifies how an infinitesimal fluid element is stretched, tilted, and reshaped as it moves from the upstream region to the rotor plane.

Here, the deformation tensor is obtained directly from CHARM's free-wake solution. CHARM allows users to extract the velocity field on an arbitrarily defined grid, enabling detailed characterization of the flow around the rotor. In this work, the flowfield is sampled on a structured three-dimensional grid that encloses the rotor and extends several rotor radii upstream, downstream, and laterally (refer to Figure 1). CHARM outputs the three velocity components at every grid point,

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which are then azimuthally averaged to represent the mean flow experienced by a fluid particle as it convects around the rotor.

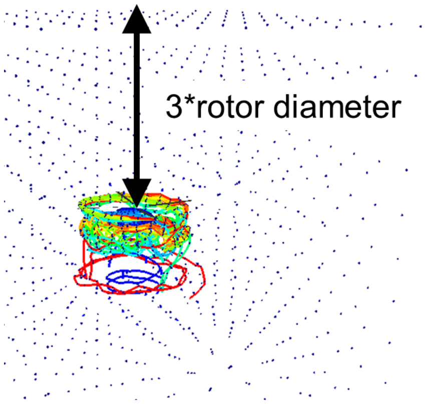
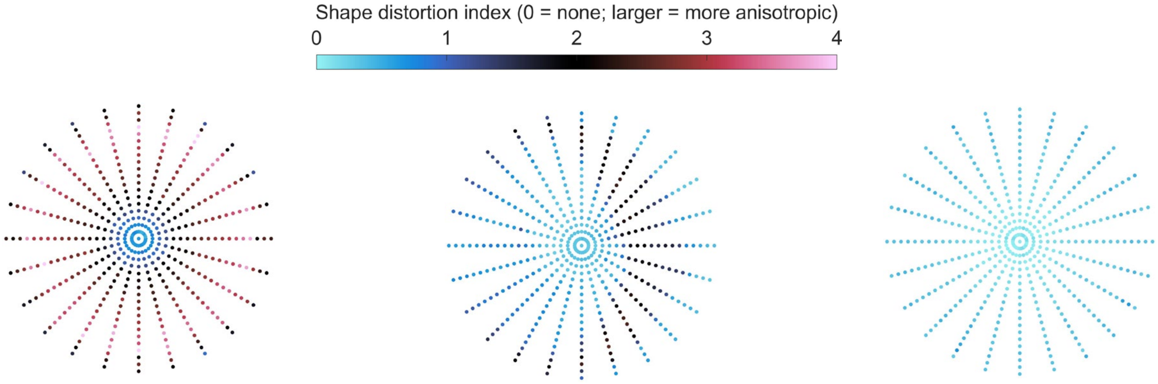


Figure 1. A grid of points measuring flow velocities around a hovering rotor in CHARM.

Following the procedure of Simonich et al. (1990), the deformation tensor is constructed by numerically tracing mean-flow streamlines backward in time from the rotor disk to a far-upstream reference region. Seed points are first placed across the rotor disk. For each seed point, a streamline is integrated backward through the CHARM-predicted mean flow to determine the upstream origin of that fluid element. By comparing the relative displacement of neighboring streamlines, i.e., how an initially orthogonal fluid element is stretched, tilted, and sheared during convection the local deformation tensor is computed.

Figure 2 shows the resulting shape distortion index for an isolated rotor operating in three conditions: hover, axial climb, and edgewise flight. This index measures how unevenly the turbulence is stretched by the mean flow. It is zero when the deformation is isotropic (equal in all directions) and increases as the flow becomes more anisotropic due to shear or directional stretching. Consistent with the findings of Amiet et al. (1990), hover exhibits the strongest deformation, followed by edgewise flight, while axial climb shows the weakest distortion of the incoming turbulence.



(a) Hover (b) Edgewise flight (c) Axial climb

Figure 2. Shape distortion index plotted for seed points on rotor disc.

Publications

None.

Outreach Efforts

None.

Awards

None.

Student Involvement

Bhaskar Mukherjee, a graduate assistant who recently completed his PhD, worked on improving turbulence interaction broadband noise predictions in the PSU-NPS by incorporating turbulence distortion effects estimated using RDT.

References

Amiet, R. K. (1975). Acoustic radiation from an airfoil in a turbulent stream. *Journal of Sound and Vibration, 41*, 407–420.

Amiet, R. K., Simonich, J. C. & Schlinker, R. H. (1990). Rotor noise due to atmospheric turbulence ingestion. II – Aeroacoustic results. *Journal of Aircraft*, 27, 15–22.

Mukherjee, B., Ibnoukhaiber, S. & Brentner, K. (2025, January 5-9). *Impact of AAM Operations on Airport Noise* [Conference paper]. Transportation Research Board (TRB) 104th Annual Meeting, Washington, D.C.

Pegg, R. J. (1979). *A summary and evaluation of semi-empirical methods for the prediction of helicopter rotor noise.* National Aeronautics and Space Administration (NASA), NASA-TM-80200. https://ntrs.nasa.gov/api/citations/19800007615/downloads/19800007615.pdf

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Task 2 – Comparison Between Predictions and Flight Tests

The Pennsylvania State University

Objectives

This task is focused on comparing noise predictions with acoustic data measured in outdoor flight and anechoic chamber tests. The physics of eVTOL and UAS aircraft operations result in high-frequency broadband noise to be the dominant source. Time-averaged broadband noise predictions from the PSU-NPS are compared with experimental data. Differences between both are analyzed to identify methods for improving the prediction. In parallel, experimental data are analyzed to identify characteristics of time-varying broadband noise, with a focus on the impact of blade azimuth phase offsets between rotors during flight.

Research Approach

Noise from a reconfigurable hexacopter in hover was measured on a ground microphone array as part of ASCENT Project 077. Broadband noise predictions using the BPM self-noise model (Brooks et al., 1989) was compared with experimentally measured spectrum. Differences were analyzed, and improvements to the model were made along with its implementation in PSU-WOPWOP.

Simple prediction models for time-varying multirotor broadband noise were developed by supplementing analytical models with flight test and anechoic chamber measurements collected for ASCENT Project 077. These include measurements of the rotor azimuth phase and rotor rotation rates. Summation of the modulation of individual rotors represents the first step towards more formal prediction models. Summation of the broadband noise modulation of multiple rotors makes assumptions not previously validated in the literature, which are discussed and validated below.

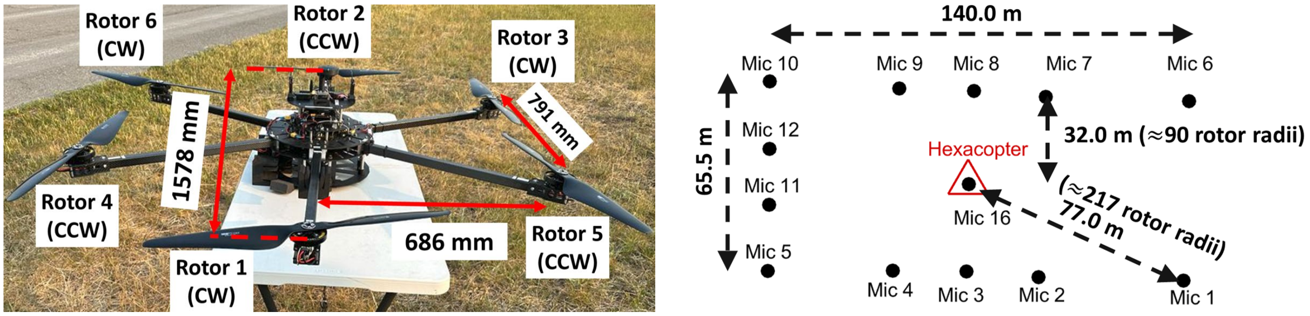
Milestones

- Modified the BPM model for smaller unmanned aerial vehicle (UAV)-sized blades that helps improve predictions.
- Developed analysis and prediction frameworks for characterizing multirotor broadband noise modulation, including characterizing the variability of noise with time and between repeated flights.

Major Accomplishments

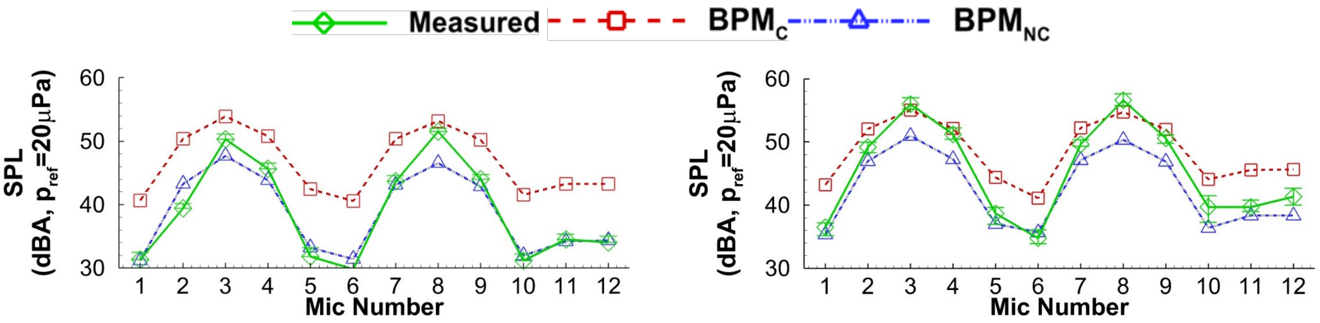
Mukherjee (2025) recently introduced a correction to the semi-empirical Brooks, Pope, and Marcolini (BPM) broadband airfoil self-noise prediction model (Brooks et al., 1989). This addressed an implicit assumption of acoustic compactness in the original formulation. Acoustic compactness is defined using the blade chord-to-wavelength (acoustic) ratio: when the ratio is greater than 1, the blade is considered acoustically compact; when it is less than 1, the blade is considered acoustically noncompact. While helicopter blades are generally acoustically compact, the much smaller rotors used on small Unmanned Aerial Systems (sUAS) are typically acoustically noncompact.

The impact of this correction was demonstrated through comparisons between outdoor noise measurements of the PSU reconfigurable hexacopter (Figure 3a) collected using a ground microphone grid (Figure 3b) and broadband noise predictions generated using the BPM model. Figure 3c and Figure 3d present the A-weighted integrated sound pressure level (SPL) for microphones 1–12, plotted against measured noise for hover conditions at 20 and 40 ft, respectively. Two broadband prediction datasets are shown: the original BPM model assuming acoustic compactness (BPM_C) and the corrected model accounting for acoustic noncompactness (BPM_{NC}). The original BPM model with compact directivity (BPM_C) greatly overestimated the SPLs of the hexacopter hovering at 20 ft, with a median absolute deviation of 8.7 dBA for microphones 1 to 12. Using BPM_{NC} reduced the median absolute deviation to 1 dBA. At 40 ft, the overestimation by BPM_C decreased, yielding a median absolute deviation of approximately 2.8 dBA. Accounting for noncompactness (BPM_{NC}) reduced the deviation to 1.5 dBA.



(a) PSU Reconfigurable hexacopter flown for outdoor test

(b) Microphone grid layout



(c) Hexacopter in hover, 20 ft altitude: variation in measured and predicted SPL for microphones 1 – 12

(d) Hexacopter in hover, 40 ft altitude: variation in measured and predicted SPL for microphones 1 – 12

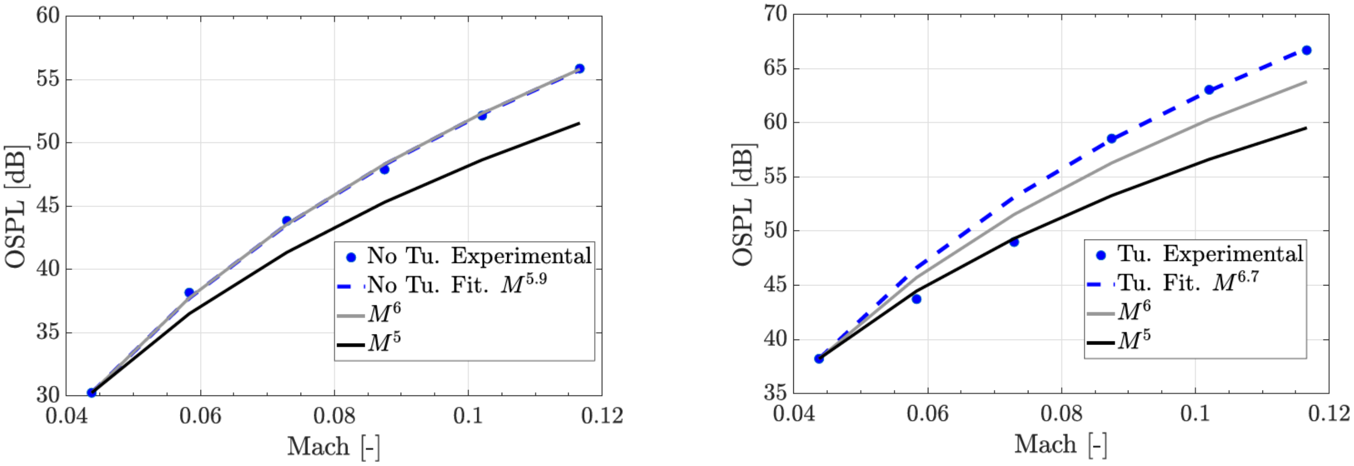
Figure 3. PSU hexacopter in hover, measured vs. noise prediction (Mukherjee, 2025). BPM: Brooks, Pope, and Marcolini, SPL: sound pressure level.

For all sources of self-noise, the BPM model scales the SPLs using two sets of terms: an analytical scaling function and additional functions tuned using measured flow and acoustic data. The analytical scaling equation was derived from an expression by Ffowcs Williams and Hall (1970) estimating the acoustic intensity (I) for an observer in the far-field as $I \approx \frac{M^5 \delta}{r_e^2}$. Here M, δ, r_e are the flow Mach number, boundary layer thickness, and distance from trailing edge to observer, respectively. Brooks et al. (1989) found that the predicted spectra agreed better when δ was replaced by the boundary layer displacement thickness δ^*, giving $I \approx \frac{M^5\,\delta^*}{r_e^2}$. Therefore, Equation 1 for predicting turbulent boundary layer trailing edge (TBL-TE) noise was written as follows:

$$\boldsymbol{SPL_{TBLTE} = 10\,log_{10}\left(\frac{\delta^* M^5 L\, \bar{D}_h}{r_e^2}\right) + A(\delta^*, St)} \qquad \text{(Eq. 1)}$$

Here L is the airfoil span, while $\bar{D}_h$ is the directivity function that was updated to improve sUAS broadband noise predictions. The function A is an empirical correction depending on the boundary layer displacement thickness and flow Strouhal number (St) that is used to match experimentally measured SPL_{TBLTE}.

Recent experimental data from Botero-Bolívar et al. (2024) provided additional insight into the scaling of trailing edge noise with Mach number (M). Noise measurements for a NACA 63018 airfoil have shown that the integrated overall sound pressure level (OASPL) can scale anywhere between M^6 and M^7 depending on the turbulence levels in flow around the airfoil. Figure 4a shows that in a non-turbulent inflow, trailing edge noise scales with M^6, whereas in a turbulent inflow (Figure 4b) the scaling increases to $M^{6.7}$.



(a) Non-turbulent inflow

(b) Turbulent inflow

Figure 4. Overall sound pressure level scaling of far-field trailing edge noise with inflow velocity for the NACA 63018, (Botero-Bolívar et al., 2024). OSPL: overall sound pressure level.

Similar trends can also be observed in the experimental acoustic data published by Brooks et al. (1989), which formed the basis for tuning the BPM model originally. In their extensive measurement campaign, noise from a NACA 0012 airfoil was recorded at angles of attack ranging from $0°$ to $20°$ and over Reynolds numbers between 1×10^5 and 6.3×10^5. Although Brooks et al. (1989) did not publish OASPL values directly, they reported one-third-octave spectra for nearly 104 flow conditions. These data were digitized from the original report and processed to estimate OASPL.

Figure 5 shows the resulting OASPL trends in the original dataset used for BPM model tuning. The angle of attack (AOA) appears to be the primary factor driving variations in the scaling exponent. At AOA = $0°$, noise scales approximately as $M^{4.3}$. As AOA increases, the exponent rises, reaching about $M^{7.6}$ at AOA = $19.8°$. This behavior is consistent with the increased turbulence intensity near the trailing edge at higher AOAs. Because these trends deviate significantly from the default M^5 scaling, they highlight the need to update the BPM model accordingly.

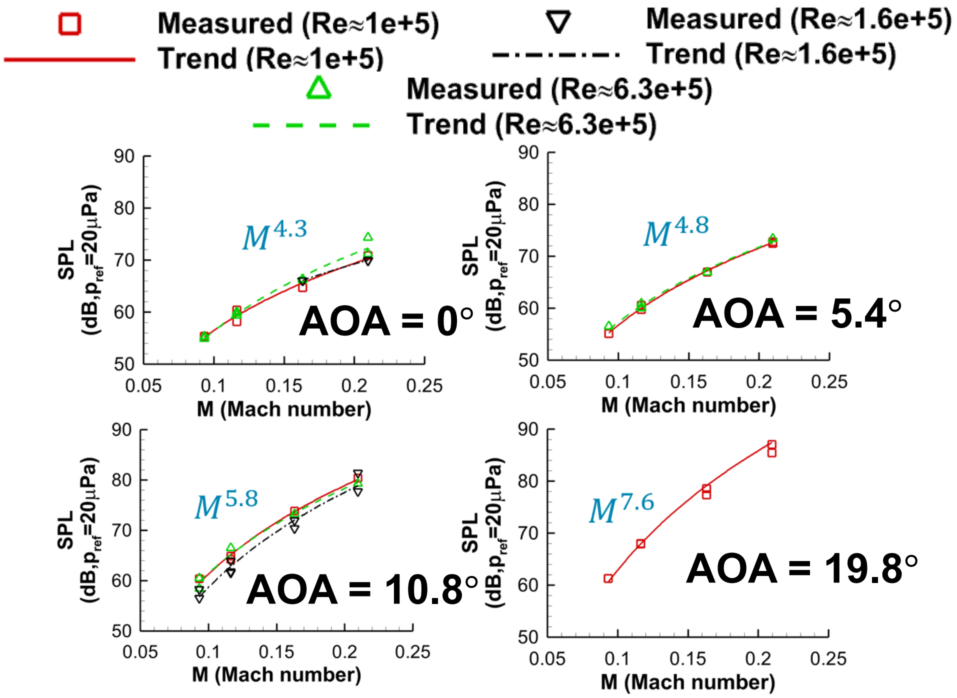


Figure 5. Scaling of far-field trailing-edge noise in data by Brooks et al. (1989). AOA: angle of attack, Re: Reynolds number.

Publications

Mukherjee, B. (2025). *Noise of Multirotor Electric Aircraft* [Doctoral dissertation, The Pennsylvania State University]. Penn State University Libraries, University Park, Pennsylvania.

Outreach Efforts

None.

Awards

None.

Student Involvement

Bhaskar Mukherjee, a graduate assistant who recently completed his PhD, worked on updating the semiempirical BPM broadband noise prediction model for improved prediction of high-frequency noise from small UAS and eVTOL aircraft.

References

Botero-Bolívar, L., dos Santos, F. L., Venner, C. H. & de Santana, L. D. (2024). Trailing-edge far-field noise and noise source characterization in high inflow turbulence conditions. *Journal of the Acoustical Society of America,155*, 803–816.

Brooks, T. F., Pope, D. S., & Marcolini, M. A. (1989). *Airfoil self-noise and prediction* (RP-1218). National Aeronautics and Space Administration. https://ntrs.nasa.gov/api/citations/19890016302/downloads/19890016302.pdf

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Mukherjee, B. (2025). *Noise of Multirotor Electric Aircraft* [Doctoral dissertation, The Pennsylvania State University]. Penn State University Libraries, University Park, Pennsylvania.

Task 3 – Investigate Time-Varying Broadband Noise of Multirotor Aircraft

The Pennsylvania State University

Objectives

One objective of this task is to determine the significance of time-varying multirotor broadband noise (multirotor broadband noise modulation) using flight test measurements. For clarity, time-varying broadband noise refers to the changes over time in noise levels across a wide range of frequencies, whereas broadband noise modulation refers to the cases where those level changes follow a periodic or quasiperiodic pattern at a particular modulation frequency (for example, once per blade passage or once per rotor revolution). With these definitions, this objective is motivated by anechoic chamber measurements taken for ASCENT Project 077 and analyzed in Task 2 of the *2023 Annual Report for ASCENT Project 049*, which found that the importance of time-varying multirotor broadband noise depends significantly on the blade azimuth phase offsets between rotors. This is contrary to predictions in the literature, which predict broadband noise to be fairly constant with time for many rotors, with the modulation depth decreasing as the number of rotors increases (Li & Lee, 2022).

Another objective of this task is to determine the significance and physical sources of broadband noise modulation at modulation frequencies not at the blade-passage frequency (BPF). Broadband noise modulation with the BPF was studied in Task 2 above, but other modulation frequencies were also observed in this work. Psychoacoustics studies of small multirotor UAS report significant noise modulation amplitudes at modulation frequencies much lower than the BPF; and the physical causes responsible for this modulation remain unclear (Gwak et al., 2020; Torija & Nicholls, 2022; Ramos-Romero et al., 2023).

One possible cause of low frequency modulation for multi-rotor aircraft with high BPFs is the presence of beating effects, or simply ‘beats’ for short. Beats arise when tones have closely spaced frequencies, resulting in modulation at a frequency equal to the difference of the tonal frequencies (Feynman et al., 2011). Although beats are typically studied as tones, one could hypothesize that there exists an analogous phenomenon for broadband noise modulation (i.e., for two amplitude-modulated, broadband noise signals with closely spaced modulation frequencies). However, this has not been studied in the literature.

Closely spaced BPFs are likely to arise in flight for aircraft with electric rotors with variable rotation speeds (for example, the flight controller may command slightly different rotor rotation speeds to trim the aircraft in hover or axial flight, to counteract the presence of atmospheric disturbances).

Research Approach

Flight test measurements of a hexacopter UAS collected for ASCENT Project 077 are analyzed using advanced signal processing methods such as envelope and cyclostationary analysis. Although these methods have not been widely applied to rotorcraft noise analysis, their fine time resolution enables deeper understanding and more precise and accurate quantification of multirotor broadband noise modulation, including the influence of variations in azimuthal phase.

Prediction models were developed by supplementing simple analytical and numerical models with anechoic chamber measurements collected for ASCENT Project 077. These include not only noise measurements, but also measurements of the time histories of rotor rotation rates.

Milestones

- Determined that time-varying multirotor broadband noise is significant in flight.
- Determined the significance of beats of broadband noise modulation.
- Developed analysis and prediction frameworks for characterizing beats of broadband noise modulation.

Major Accomplishments

Gan’s work under ASCENT Project 049 is summarized in the doctoral dissertation *Time-Varying Noise of Electric Multirotor Aircraft* (2025). Using data measured in the Penn State anechoic chamber, Gan (2025) showed that the broadband SPL of a single rotor in hover rises and falls within each revolution modulating at the BPF. The primary contributor was found to be kinematic effects associated with rotation, including periodic changes in source–observer distance. This behavior is quantified using cyclostationary analysis, in which short-time broadband levels are computed over many overlapping windows and then ensemble-averaged while tracking blade azimuth.

Baars and Ragni (2024) investigated the same underlying phenomenon for an isolated benchmark rotor in the Delft[1] A-Tunnel over a range of advance ratios. Their analysis uses time–frequency methods (wavelet transform) to relate the BPF component to the envelope of the high-frequency broadband content. They also confirm that the broadband modulation depth does not impact its time-averaged spectrum. Extending their analysis, it is also reported that the magnitude and phase of time-varying broadband noise depend on operating condition, even at fixed rotor speed.

Publications

Gan, Z. F. (2025). *Time-Varying Noise of Electric Multirotor Aircraft* [Doctoral dissertation, The Pennsylvania State University]. Penn State University Libraries, University Park, Pennsylvania.

Outreach Efforts

None.

Awards

None.

Student Involvement

Ze Feng (Ted) Gan, a graduate assistant who recently completed his PhD, investigated time-varying broadband noise for this task.
Bhaskar Mukherjee, a graduate assistant who recently completed his PhD, worked on interpreting Ze Feng (Ted) Gan's results and connecting the findings to recent literature.

Plans for Next Period

- Study tonal beats and compare their importance to the significance of beats of broadband noise modulation.
- Validate the prediction approach outlined here using flight test measurements taken in ASCENT Project 077, including different maneuvers.

References

Baars, W. J. & Ragni, D. (2024). Low-Frequency Intensity Modulation of High-Frequency Rotor Noise. *AIAA Journal,* 62, 3374–3390. https://doi.org/10.2514/1.J063610

Task 4 – Develop and Investigate Departure and Arrival Transition Maneuvers

The Pennsylvania State University

Objective

The objective of this task is to design departure and arrival maneuvers aiming to balance the requirements of noise and performance for various eVTOL configurations.

Research Approach

Previous work in ASCENT Project 049 (see the 2023 Annual Report for ASCENT Project 049) analyzed a notional lift-plus-cruise aircraft departure transition maneuver using the Penn State noise prediction system. The analysis used multiple flight simulations to evaluate how different control strategies and trajectories affect aircraft performance and noise. However, the conclusions were limited by known deficiencies in the noise modeling, particularly the incomplete prediction of high-frequency broadband noise generated by aerodynamic interactions between rotor wakes and other components. These broadband sources are important during hover and low-speed flight, which define key portions of departure and arrival maneuvers at low altitude. Consequently, the transition-maneuver noise must be re-evaluated by developing and

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[1] Delft University of Technology

validating prediction models for these additional broadband noise sources while minimizing the associated increase in computational cost.

Milestones

Improve perpendicular Blade-Vortex Interaction (BVI) noise predictions.

Major Accomplishments

A recent experimental investigation of the generation of broadband noise from small rotors in hover and forward flight by Lößle et al. (2025) revealed several key insights into the dominant mechanisms. The results include acoustic source maps for three octave bands in the 1 kHz - 8 kHz range calculated using beamforming. Figure 6 marks the location of maximum sound emission in frequencies in the 1 kHz - 8 kHz range for the Aero-naut® CAM Carbon Light 16×6 rotor spinning at 3,000 and 4,000 rotations per minute (RPM) in hover. The position is at the trailing edge near the 80% span (x_B/R). This demonstrates the dominance of trailing edge noise in hover. Experimental flow visualizations have also revealed the presence of perpendicular blade vortex interaction from the tip vortex of a rotor in hover (Figure 7).

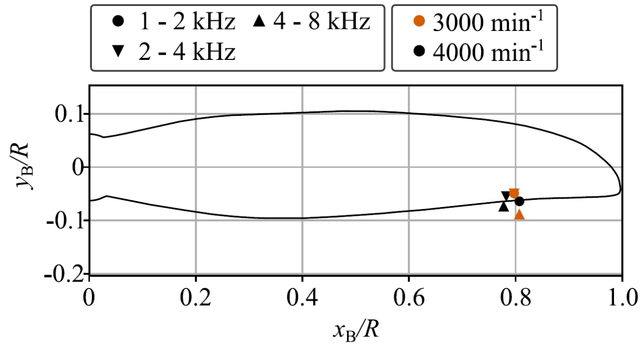

Figure 6. Position of the maximum sound emission on the rotor blade of the CAM Carbon Light 16 × 6 rotor in hover at rotational speeds 3,000 and 4,000 rotations per minute (RPM) (Lößle et al., 2025).

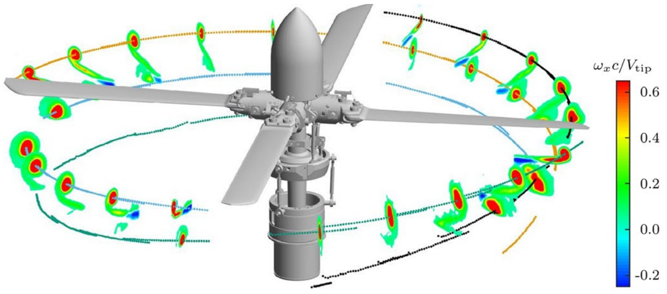

Figure 7. Rotor operating in hover: three-dimensional vortex locations with normalized vorticity contour (Brakumann et al., 2021).

At Penn State University, Zahirudin (2025) measured aerodynamic performance and acoustic data from a single 4-bladed rotor operating in hover at the Flow-Through Anechoic Chamber. The blade has a radius of 9 in. (0.23 m) with a linear distribution of twist and taper (further details can be found in Zahirudin et al. (2021). It is mounted on a shaft where a load cell measures the loads and moments generated, while the rotor speed was measured using a laser tachometer. Figure 8 shows the circular array of microphones installed to allow the measurement of noise at different elevation angles (θ_m) relative to the rotor plane.

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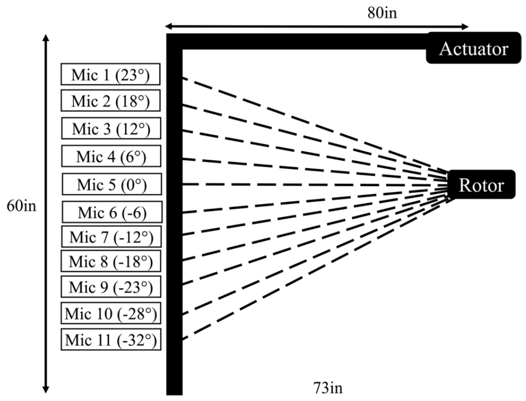
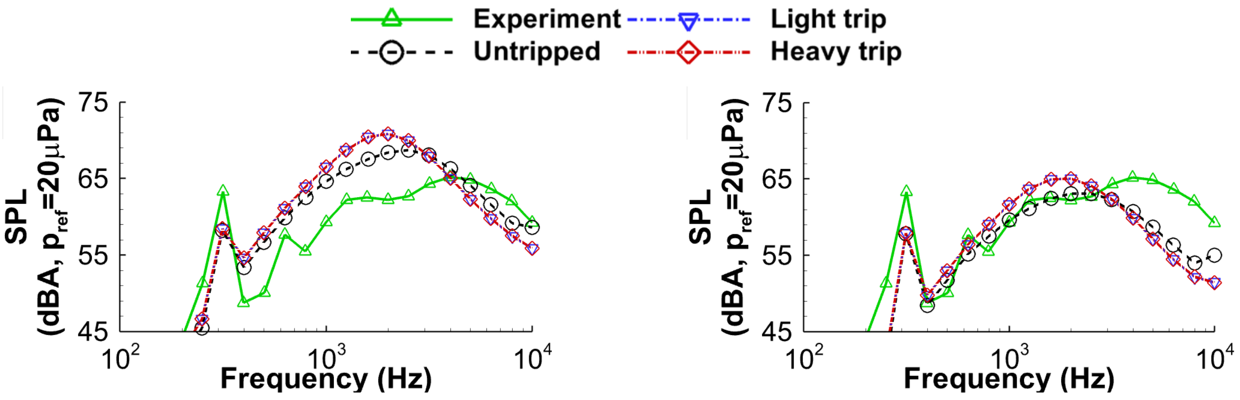


Figure 8. Microphone elevation angles (R. Zahirudin et al., 2021).

Noise during hover was investigated for the 4-bladed rotor operating around a speed of 4,500 RPM (470 rad/s), generating a thrust of 11.15 lbf ($C_T = 0.02126$). Rotor aerodynamics was simulated using the free-wake code CHARM, where the code trimmed the pitch to match the experimentally measured thrust. The resulting airloads were exported to PSU-WOPWOP, and noise predictions were compared with measurement at microphone 8 ($\theta_m = -18°$). Deterministic thickness and loading were calculated using the blade geometry and unsteady airloads calculated in CHARM, while broadband noise was calculated using the semi-empirical BPM self-noise prediction model developed by Brooks et al. (1989).

As discussed in Task 2, PSU-WOPWOP was updated by Mukherjee (2025) to correct the effects of acoustic compactness on noise predicted by the BPM model. This correction was found to be important in improving the prediction of rotors typically used in sUASs. Input parameters for the BPM model include the section angle of attack (obtained from CHARM), flow velocity (estimated kinematically in PSU-WOPWOP). A key modeling choice is the boundary layer state: untripped, light trip, and heavy trip. The BPM model does not internally determine the appropriate condition, so it must be specified based on the local flow physics. The CHARM solution indicates that the maximum Reynolds number across the blade sections is 1.5×10^5, which is consistent with predominantly laminar flow (untripped). Figure 9 plots the one-third-octave spectra measured at microphone 8 along with predictions for all three boundary layer trip conditions.



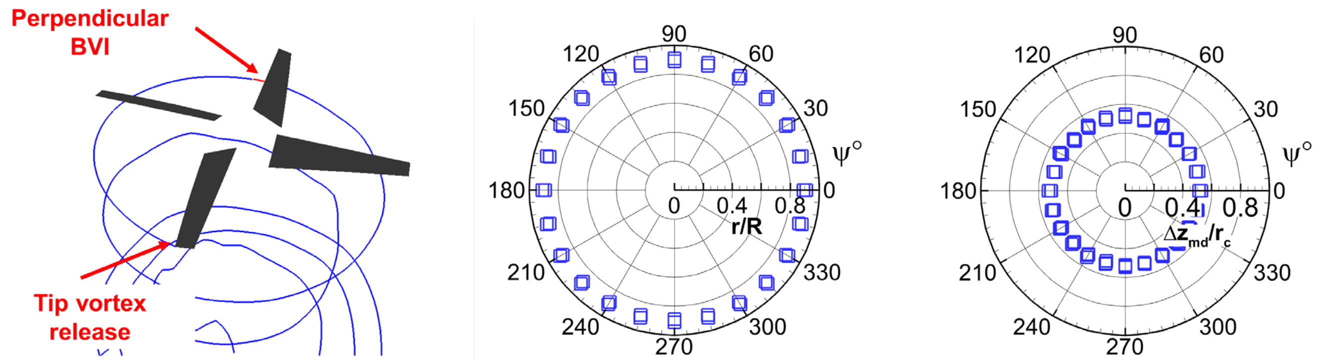
(a) BPM$_C$

(b) BPM$_{NC}$

Figure 9. Measured noise and prediction at mic 8: single 4-bladed rotor in hover (Ω = 470 rad/s, C_T = 0.02126). BPM: Brooks, Pope, and Marcolini, SPL: sound pressure level. Subscripts: C – compact, NC - noncompact

The predictions seem to underpredict the first tonal peak at ≈ 315 Hz by about 4 dBA, and the cause of this discrepancy is currently unknown. Using the compact (original) directivity function BPM$_C$, Figure 9a shows that the broadband noise is overpredicted by 6 – 8 dBA. This is removed in Figure 9b, when the noncompact formulation BPM_{NC} is used. As expected, untripped boundary-layer case performs best overall, matching the measured spectrum between 400 Hz and 2,500 Hz to within 1 dBA. Despite the significantly improved predictions obtained with BPM_{NC}, a pronounced peak near 4,000 Hz remains underpredicted by 5 – 6 dBA. This peak is suspected to be associated with trailing-edge noise generated by perpendicular BVI.

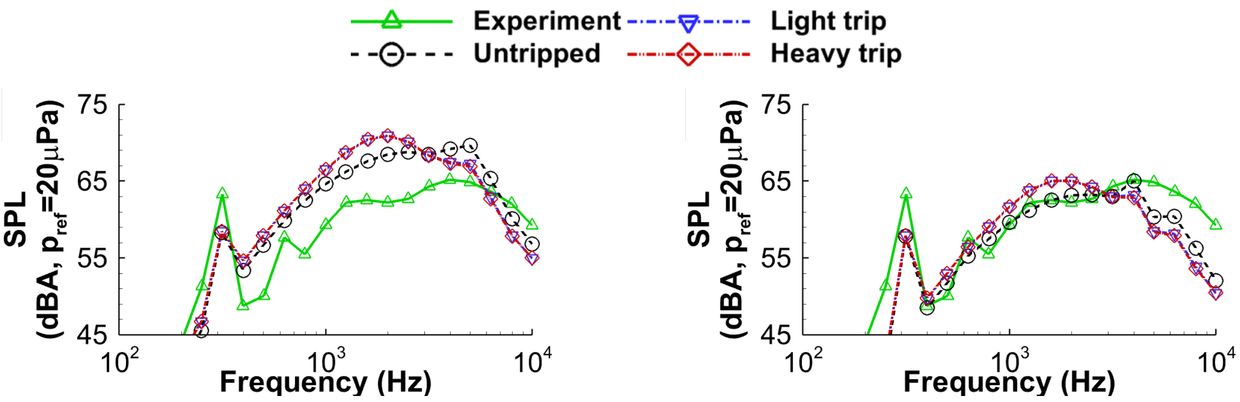
Further insight is obtained by analyzing CHARM's free-wake solution. Wake visualization (Figure 10a) reveals the presence of perpendicular BVI clustered near the non-dimensional radial position $r/R \approx 0.89$ (Figure 10b), with r denoting the radial distance from the center of the hub and R the rotor tip radius. Figure 10c plots the ratio of the vortex miss distance Δz_{md} to the vortex core radius r_c. Values less than 1 indicate that the vortex interacts with the blade. In this case, $\Delta z_{md}/r\_c \approx 0.5$, implying that the center of the vortex core passes through the blade plane, i.e., a strong perpendicular BVI event.



(a) CHARM wake visualization (b) Wake interaction locations across one revolution (c) Miss distance ratio ($\Delta z_{md}/r_c$)

Figure 10. Perpendicular blade-vortex interaction (BVI): Single 4-bladed rotor in hover (Ω = 470 rad/s, C_T = 0.02126).

Since the peak in the measured data near 4,000 Hz is hypothesized to be a result of perpendicular BVI, an ad-hoc model was developed that leveraged the BPM airfoil self-noise model to represent the trailing edge noise generated by perpendicular BVI while retaining a low computational cost. Among the model's various self-noise sources, the trailing edge bluntness vortex shedding noise appeared most suitable to represent the vortex shedding resulting from perpendicular BVI. Knowing the location of perpendicular BVI interaction (Figure 10b), bluntness vortex shedding noise from these blade sections were calculated using the maximum thickness of the section as an input to the model. This resulted in the predictions now capturing a second peak around 4,000 Hz as observed in Figure 11. While the compact formulation BPM_{C} still overpredicts significantly, BPM_{NC} prediction now accurately captures the 4,000 Hz peak.



(a) $\mathrm{BPM}_{\mathrm{C}}$ (b) $\mathrm{BPM}_{\mathrm{NC}}$

Figure 11. Measured noise and ad hoc prediction at mic 8: single 4-bladed rotor in hover (Ω = 470 rad/s, $C_T = 0.02126$). BPM: Brooks, Pope, and Marcolini, SPL: sound pressure level. Subscripts: C – compact, NC - noncompact

Publications

None.

Outreach Efforts

None.

Awards

None.

Student Involvement

Bhaskar Mukherjee, a graduate assistant who recently completed his PhD, worked on developing new approaches to modeling perpendicular BVI noise using the BPM self-noise model.

Plans for Next Period

- Compare noise measurements at other microphones against predictions to further validate the correction in the BPM model for acoustic noncompactness and ad hoc model proposed to capture trailing edge noise from perpendicular BVI.
- Revisit hover noise measurements for the PSU hexacopter (Task 2, Figure 3a) to validate predictions from the ad-hoc model for perpendicular BVI.

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Task 5 – Upgrade and Document eVTOL Noise Prediction System

The Pennsylvania State University

Objective

The objective of this task is to document the eVTOL noise prediction system and its components, including example cases, such that new users can easily learn to use this tool. Work in this task is being coordinated with Task 5 (ASCENT Project 038) as the two projects converge on using the same noise prediction system for helicopters and eVTOL aircraft.

Research Approach

In addition to documentation describing how to use the noise prediction system, example cases are provided to highlight new prediction capabilities and file formats. These example cases also serve as validation cases to ensure that the system is operating as expected. Example cases are automatically validated according to a regression testing procedure (checksuite).

Milestones

- Documented new prediction capabilities for time-varying broadband noise, as summarized in Task 3 above.
- Updated the existing PSU-WOPWOP user manual to include instructions on how to predict time-varying broadband noise.
- Provided example cases and updated the checksuite to automatically validate the file formats of these new time-varying noise results.

Major Accomplishments

The PSU-WOPWOP manual has been updated to document the implementation of corrections to the BPM broadband self-noise prediction model developed under Task 2. Digitization of the experimental data published by Brooks et al. (1989) is expected to allow development of new cases for the checksuite that can be used to automatically validate future development of PSU-WOPWOP code and maintain code correctness.

Publications

None.

Outreach Efforts

None.

Awards

None.

Student Involvement

Bhaskar Mukherjee, a graduate assistant who recently completed his PhD, worked on upgrading the noise prediction system by improving broadband noise prediction methods developed under Task 1 and 2 of this project.

Plans for Next Period

Updates to broadband noise prediction models developed in ASCENT Project 049 need to be merged with the code package of PSU-NPS developed and documented as part of Task 5, ASCENT Project 038. Predictions from the models developed here will also be compared against flight test data measured for helicopters that are being analyzed in ASCENT Project 038. The long-term goal is to have a universal system that can predict helicopter and multirotor electric aircraft noise accurately.

References

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