Urban Air Mobility Noise Reduction Modeling
Project 49

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ASCENT

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Penn State

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Cost Share Partner(s): Continuum Dynamics, Inc; Blue Ridge Research and Consulting, LLC; Sikorsky, a Lockheed Martin Company; Supernal

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Objective:

- Develop a physics-based noise modeling system for future UAM aircraft with varied configurations
- Produce reference noise database for notional UAM configurations for hover, transition, cruise
- Identify configuration changes and operational strategies that minimize acoustic impacts

Project Benefits:

- Physics-based UAM noise predictions and reference noise database
- Better understanding of UAM noise characteristics
- Guide design of maneuvers with focus on noise, aircraft controllability, performance
- Development of semi-empirical models for rapid operational noise prediction

Research Approach:

- Build on success of PSU Noise Prediction System (PSU-NPS) developed in ASCENT Projects 6 & 38:
  - Couple flight simulation, aerodynamic modeling (CDI's CHARM), and PSU-WOPWOP
- Tailor approach to unique characteristics of UAM by modeling flight dynamics of distributed electric propulsion vehicles including multiple propellers and rotors with DEPSim
- Develop low noise UAM trim strategies

Major Accomplishments (to date):

- Dataset of measurements by Brooks, Pope & Marcolini (BPM) digitized for analysis
- Novel turbulent boundary layer trailing edge noise trends observed
- Background research on adapting Pegg helicopter noise model for Distributed Electric Propulsion (DEP) / multirotor aircraft

Future Work / Schedule:

- Retune constants of BPM semiempirical airfoil self-noise model based on angle of attack dependent scaling trends observed
- Understand trends in parameters tuned for Pegg model for distributed electric propulsion aircraft configurations

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Presentation Outline

- Introduction, Objectives, Approach, Outcomes
- PSU-WOPWOP broadband noise prediction
  - Enhancement of the Brooks, Pope and Marcolini trailing edge noise model
  - Rederivation and tuning of the Pegg broadband noise model
- Summary:
  - Accomplishments
  - Future work

Motivation

- Rapidly growing interest in the development and use of Urban Air Mobility (UAM) aircraft
- **Noise is widely recognized as one of the barriers to public acceptance of UAM operations**
- **UAM are a new category of aircraft, and their acoustic characteristics are not well understood: new important physics**
- **Information about UAM noise is needed to:**
  - Design quiet configurations
  - Understand how to operate UAM quietly
  - Inform the approach to noise certification
  - Understand the impact on communities

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Objectives

Near term:

- Develop a physics-based noise modeling system for future UAM aircraft with varied configurations
  - PSU Distributed Electric Propulsion Simulation (DEPSIM)
  - Continuum Dynamics, Inc's CHARM rotor analysis
  - PSU-WOPWOP noise prediction

Long term:

- Produce a database of noise predictions for notional UAM configurations across a wide range of operating modes: hover, transition, cruise
- Identify configuration changes and operational strategies that minimize acoustic impacts

Approach

- Build on success of helicopter PSU-NPS developed under ASCENT Projects 6 & 38
- Tailor approach to unique characteristics of UAM:
  - Use PSU Distributed Electric Propulsion Simulation (DEPSim) to model flight state of multiple propellers and rotors
  - Model **unsteady aerodynamic loading** using CDI's CHARM
  - Couple DEPSim with PSU-WOPWOP
  - Improve PSU-WOPWOP for better computational efficiency with large numbers of rotors or propellers
  - **Update and generalize broadband noise modeling capabilities of diverse fidelity**
- Develop low noise UAM trim strategies
  - Assess tradeoffs between noise, **safety** & performance
  - Evaluate practicality and “flyability” of non-unique trim strategies using Penn State flight simulation facilities

Outcomes and Practical Applications

Outcomes:

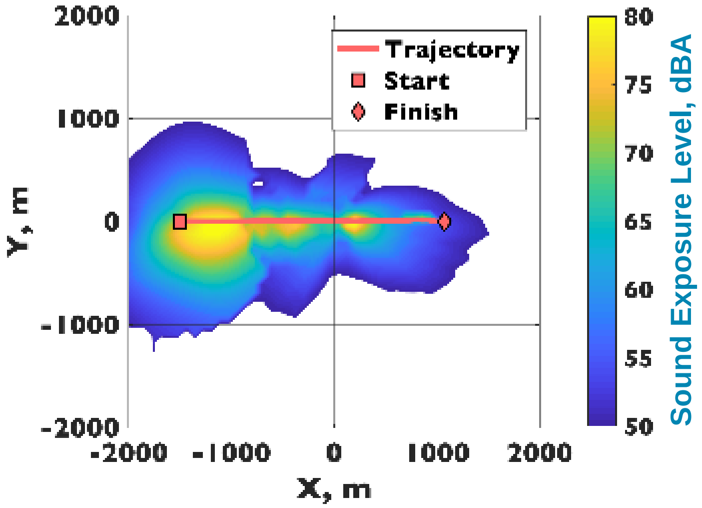
- Develop initial capability to predict UAM acoustics
- Improved understanding of UAM noise characteristics
  - Levels, directivity, spectral content
  - Variations between configurations
  - Variations between operating modes
- Identification of noise reduction opportunities
  - Low noise configurations
  - Noise abatement flight operations

Practical Applications:

- Low noise design tool for the UAM industry
- Data to support the development of certification procedures
- Initial set of representative UAM noise data for integration with FAA/DOT tools

NASA UAM Reference Vehicle

Lift + Cruise "Air-Taxi"



Broadband Noise Prediction

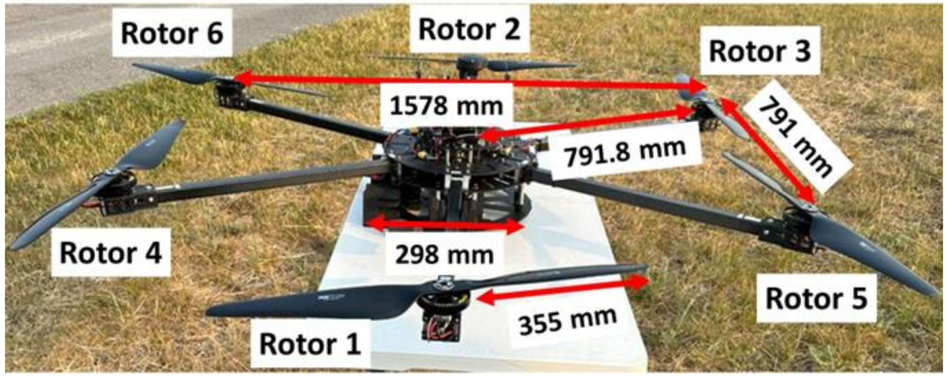
UAV Noise Prediction: Characteristics

Review

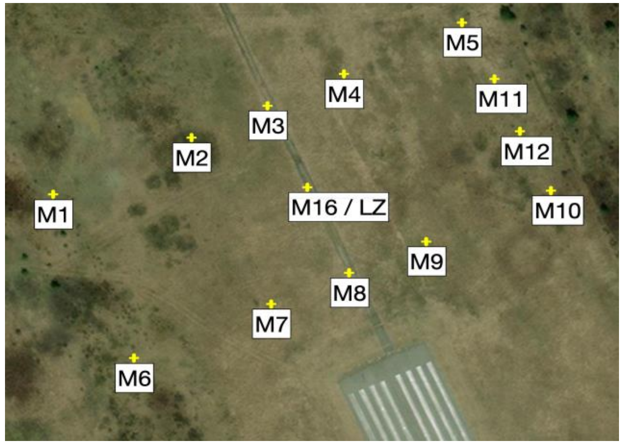
- Low-tip Mach number rotors: high-frequency broadband noise dominant (annoying to humans)
- Several sources of broadband noise: rotor-wake interactions, atmospheric turbulence, self-noise
- Contribution of sources dependent on flight conditions
  - UAV speed, angle of climb/descent, etc.
- Important low-altitude flight condition: hover
  - Expected during landing, takeoff, package drop etc.
  - High noise contribution with decreasing distance from humans on-ground
  - Self-noise expected to be dominant source of broadband noise (in *absence* of other contributions)

Uncrewed Aerial Vehicle (UAV) Noise Prediction

- Noise from small UAVs characterized by high-frequency broadband noise
  - Airfoil self-noise is dominant high-frequency (>1000 Hz) source in hover
  - BWI (blade-wake interaction) might also be present (usually around 500 – 1000 Hz)
- Broadband noise predictions using BPM model for UAV do not match well with outdoor data measured
- Reconfigurable hexacopter at PSU
  - Well instrumented: aircraft & rotor states measured (including RPM)
  - Large outdoor microphone array at Mid-State Regional Airport



Reconfigurable Hex



Microphone locations

BPM Self-Noise Model Review

- Equations in BPM are based on first-principles scaling functions

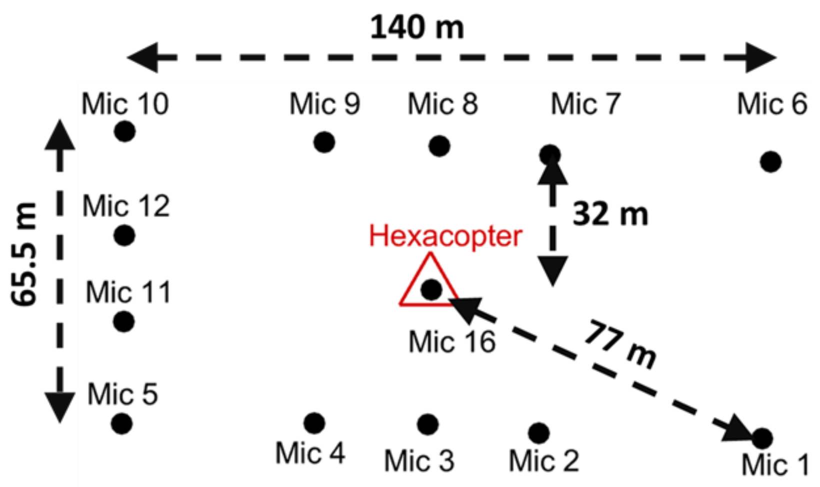
$$SPL_{TBLTE} = \boxed{10\log_{10}\left(\frac{\delta^* M^5 L\,\overline{D}_h}{r_e^2}\right)} + A(\delta^*, St)$$

- M, δ^*, L, r_e are the flow Mach number, boundary layer displacement thickness, airfoil span and distance from trailing edge to observer, St is the Strouhal number (fL/U)
- $A(\delta^*, St)$ is tuned with measured data
- $\overline{D}_h$ is normalized directivity function: Brooks et al. (1989) states directivity function by assuming acoustic compactness: chord/wavelength > 1
- Reasonable assumption for helicopter blades but not for UAV blades

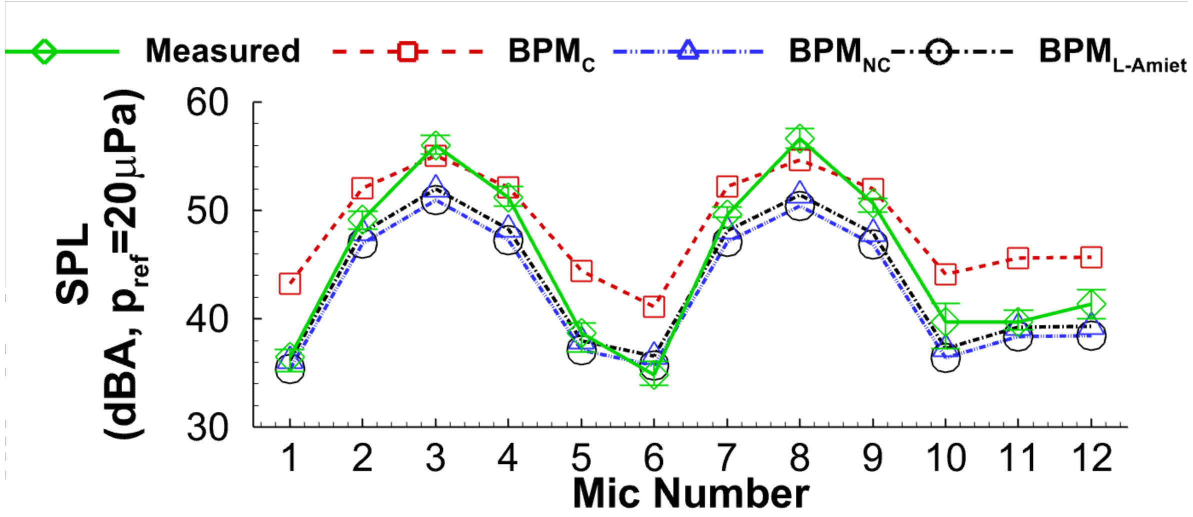
Acoustic Frequency (Hz)	Acoustic Wavelength (m)	Chord/Wavelength	
		PSU Hex rotor (chord ≈ 0.05 m)	UH-60 rotor (chord ≈ 0.53 m)
1000	0.343	0.14	1.54
2000	0.1715	0.29	3.09
3000	0.1143	0.43	4.63

Results: PSU Hexacopter Hover 40 ft (over Mic 16)

- BPM_C : Original BPM model with compact directivity function
- BPM_{NC} : Modified BPM model with non-compact directivity function
- $BPM_{L\text{-}Amiet}$: Modified BPM model with numerical directivity function (valid for all blades)
- Accounting for acoustic non-compactness improves predictions
  - TE noise model *should not overpredict* since other broadband noise sources are unaccounted for



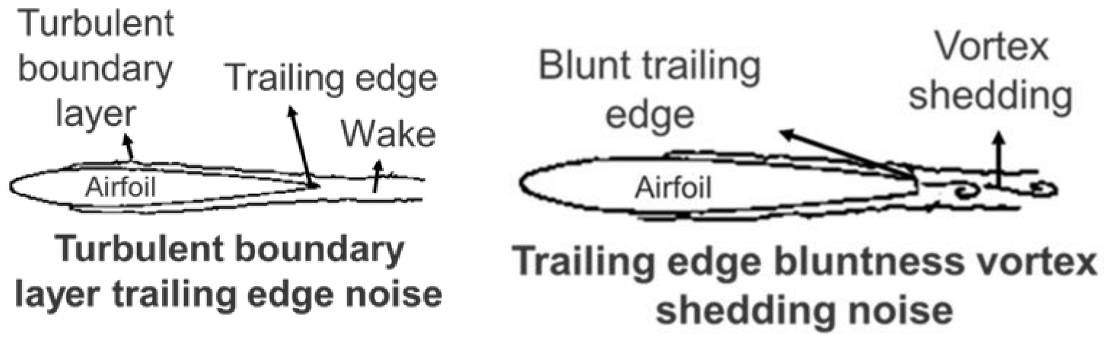
Mic grid layout *(Mukherjee 2025)*



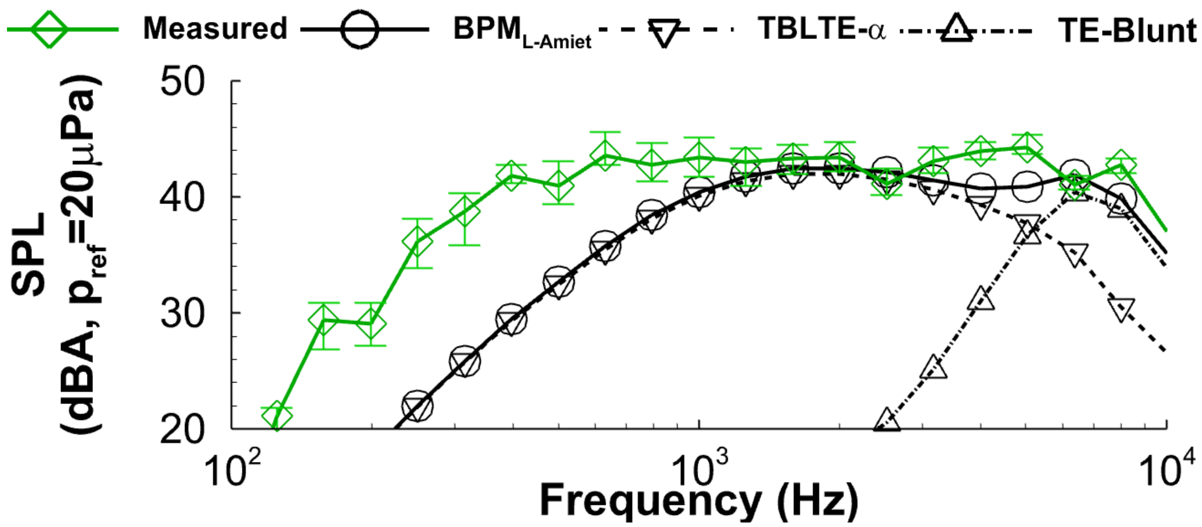
OASPL variation vs mics 1 - 12

Results: PSU Hexacopter Hover 40 ft (over Mic 16)

- Improvements in spectral match at several positions
- ≈ 1000 Hz peak is due to turbulent boundary layer trailing edge (TBLTE) noise
- ≈ 7000 Hz peak due to bluntness of trailing edge (TE-Blunt)



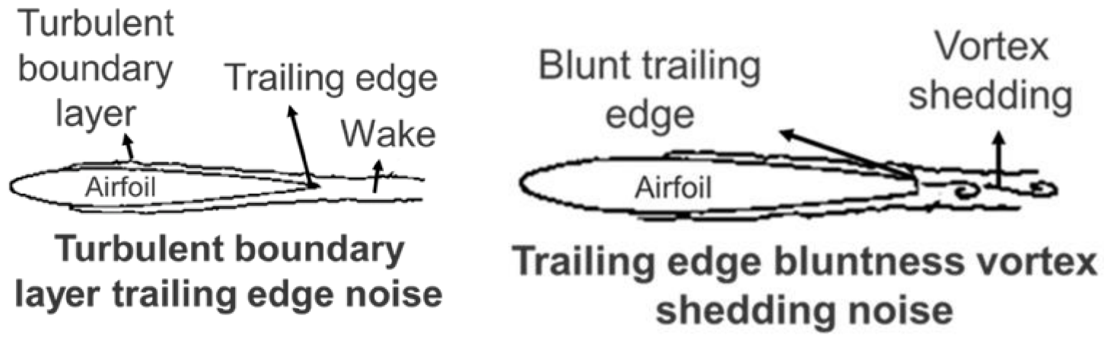
Airfoil self-noise mechanisms (adapted from Brooks et al. 1989)



Mic 3

Results: PSU Hexacopter Hover 40 ft (over Mic 16)

- Differences in some locations remain
- ≈ 1000 Hz peak missed by nearly 6 dBA
- TBLTE model needs further improvements



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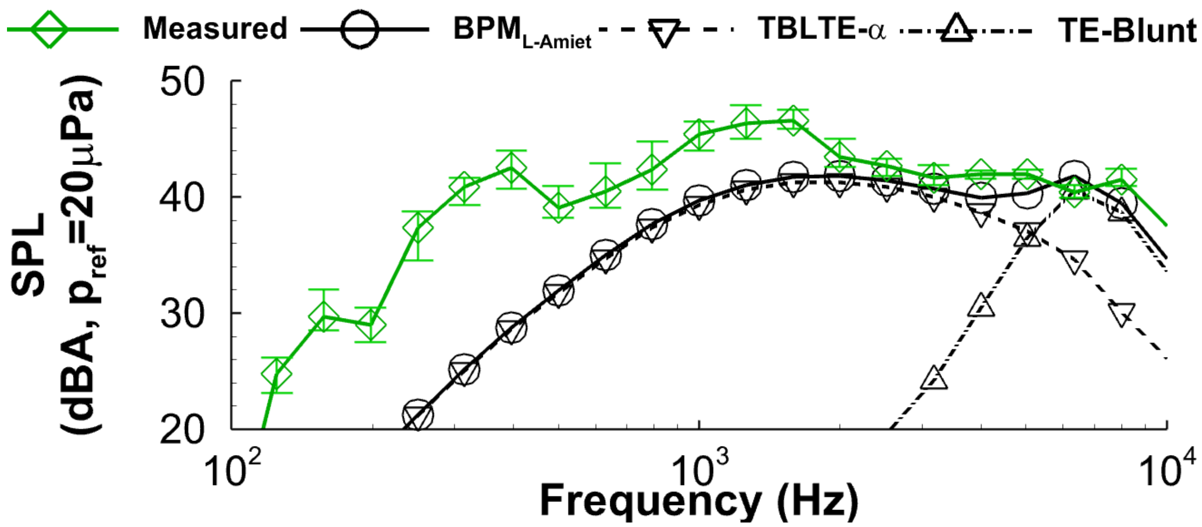


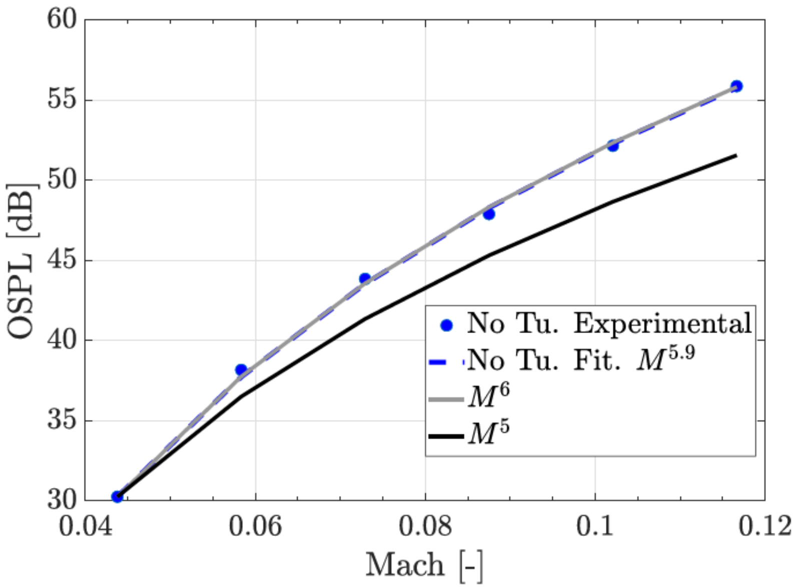
Mic 8

Modifying TBLTE Scaling Law

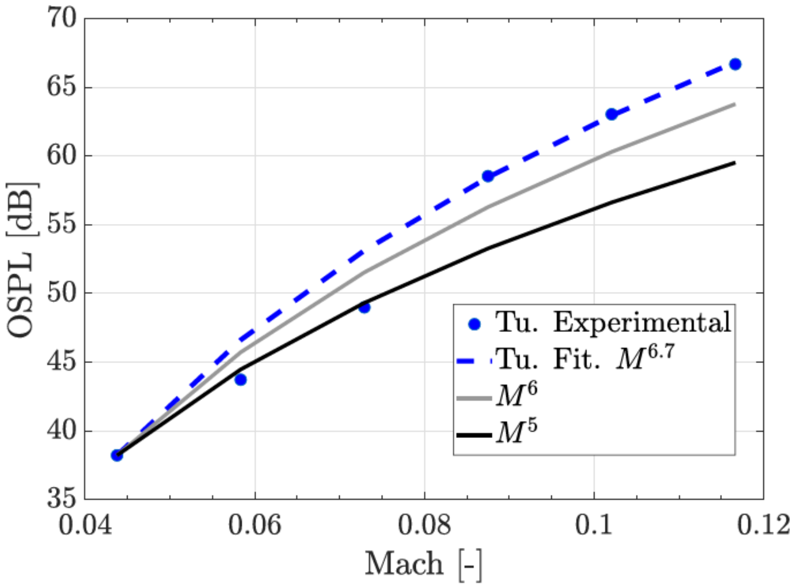
- Original M^5 law was analytically derived for flat plate with no external turbulence in flow

$$SPL_{TBLTE} = 10\log_{10}\left(\frac{\delta^* M^n L \, \overline{D}_h}{r_e^2}\right) + A(\delta^*, St)$$

- Santos et al. (2024) measured trends in noise from airfoil in wind tunnel with flow turbulence
  - $n = 6{,}7$ depending on turbulent intensity (Reynolds number = 3e+5, *angle of attack* = $0°$)



0.08% turbulent intensity



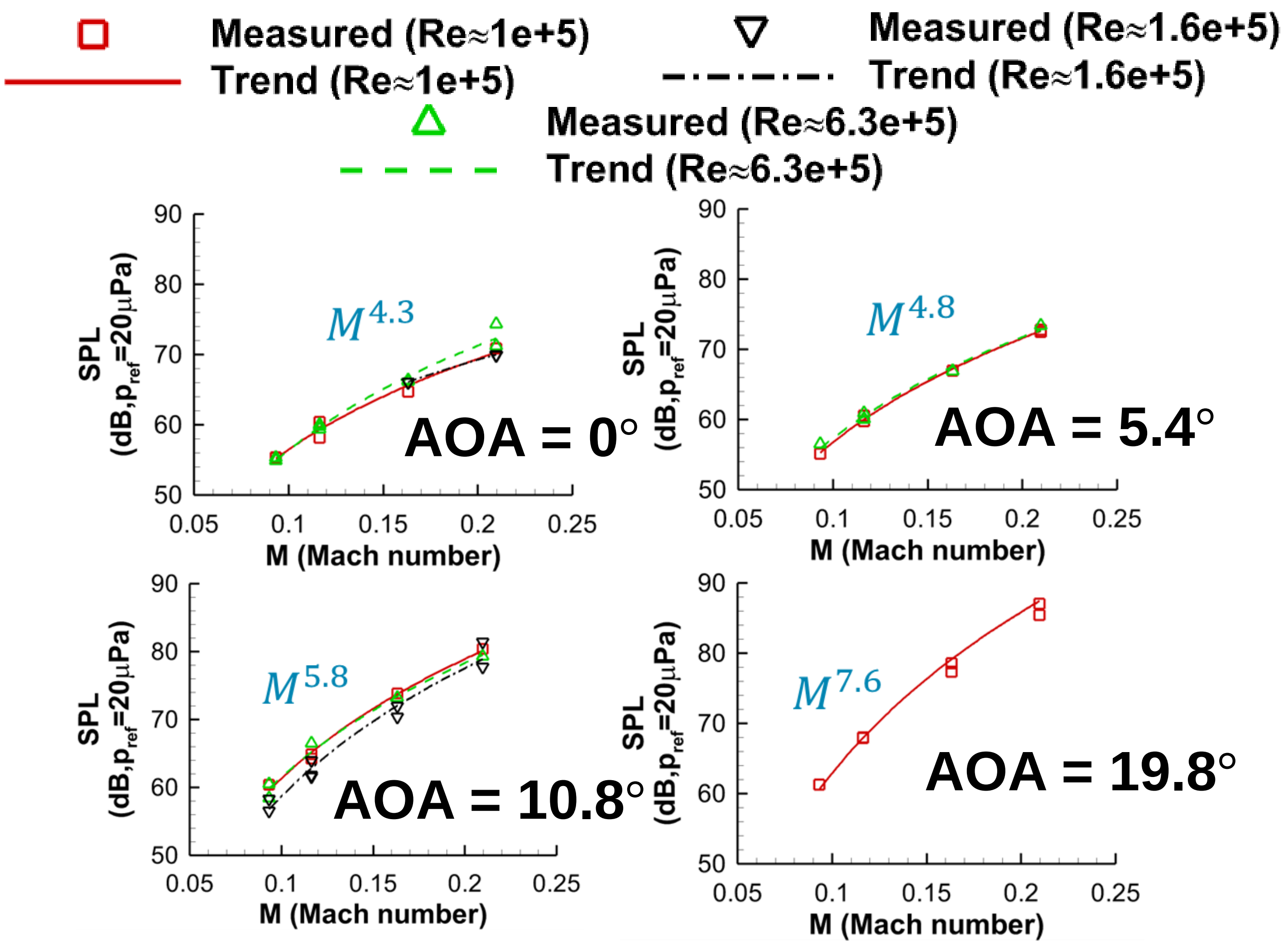
12.5% turbulent intensity

TBLTE Scaling in data by Brooks et al. (1989)

- Brooks et al. (1989) did ***not*** report any analysis of total sound pressure level (SPL)
- They provide experimental 3rd octave spectra for nearly **104** flow conditions
- Variation in flow Mach number, airfoil angle of attack (AOA), Reynolds number
- Data were digitized from the original report and processed to estimate total SPL

TBLTE Scaling in data by Brooks et al. (1989)

- Mach number (M^n) scaling estimated for different angle of attack (AOA) & Reynolds number (Re)
- For a given AOA, Re has little impact on M^n scaling
- Mach scaling exponent “n” increases with angle of attack
  - Turbulence in flow increases with angle of attack
- ***Should BPM model be recalibrated to account for this variation ?***



Pegg Broadband Noise Prediction Model

- Originally developed for predicting helicopter broadband noise (rotor-wake interaction and trailing edge noise)

$$\mathrm{SPL}_{1/3} = 20\log\left(\frac{V_T}{c_0}\right)^3 + 10\log_{10}\left[\frac{A_B}{r^2}\left(\cos^2(\theta_1) + 0.1\right)\right] + S_j + f(\bar{C}_L) + \mathbf{130}$$

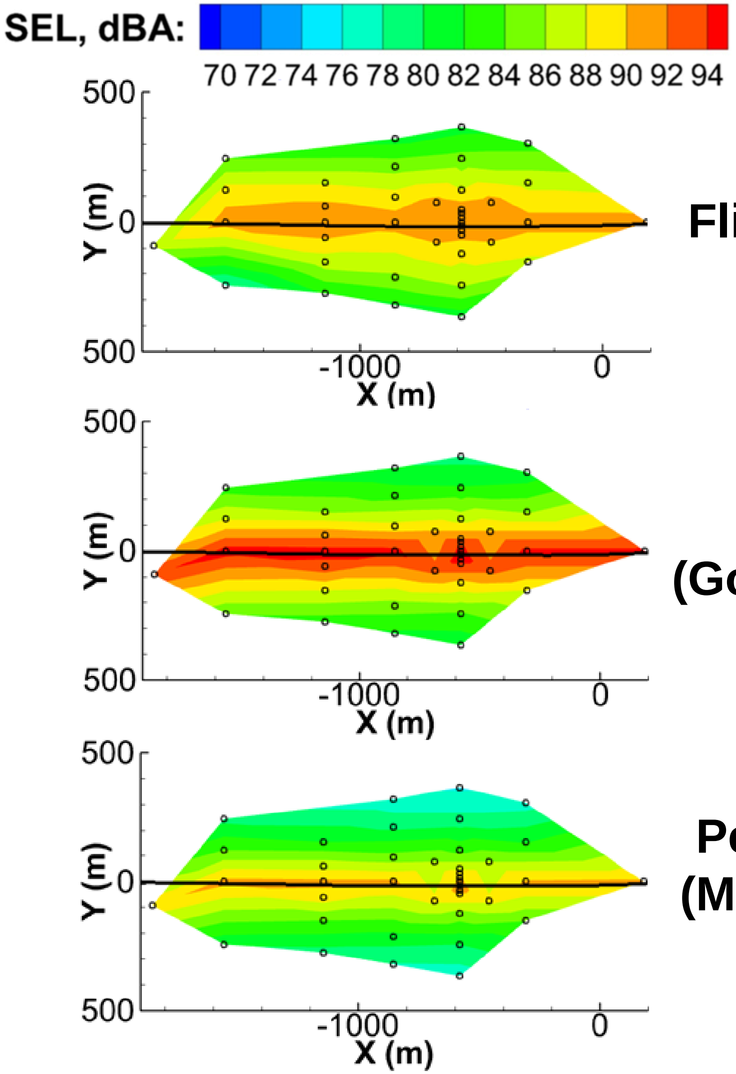
- Rederiving the Pegg model revealed the following expression:

$$\mathrm{SPL}_{1/3} = 20\log\left(\frac{V_T}{c_0}\right)^3 + 10\log_{10}\left[\frac{A_B}{r^2}\left(\cos^2(\theta) + 0.1\right)\right] + S_j + f(\bar{C}_L) + \mathbf{10log_{10}}\left[\frac{\mathbf{K r_K^2 c_0^6 10^{16.29}}}{\mathbf{\cos\theta_K}}\right]$$

- Parameter “K” is tuned based on noise measured at a microphone, distance $\boldsymbol{r_K}$ and polar angle $\boldsymbol{\theta_K}$
- **Advantage of Pegg model: Simple, details of rotor geometry and aerodynamics not required (unlike BPM model)**
  - **Can be used to develop more empirical models for tools such as AEDT**

Pegg Model: PSU-WOPWOP Correction

- Error in expression for the mean lift coefficient of the rotor $\bar{C}_L$
  - Expression by Goldman (2012): $\bar{C}_L = \frac{6T}{\rho A_B V_T^2}$
  - Pegg's expression: $\bar{C}_L = \frac{T}{\frac{1}{2}\rho V_{0.7}^2 A_B} = \frac{4.081T}{\rho A_B V_T^2}$
  - Not documented in original report
- Overprediction up to 13 dBA for heavily loaded rotor
- Simulation of Bell 206L in 80 knots level flyover



Flight test

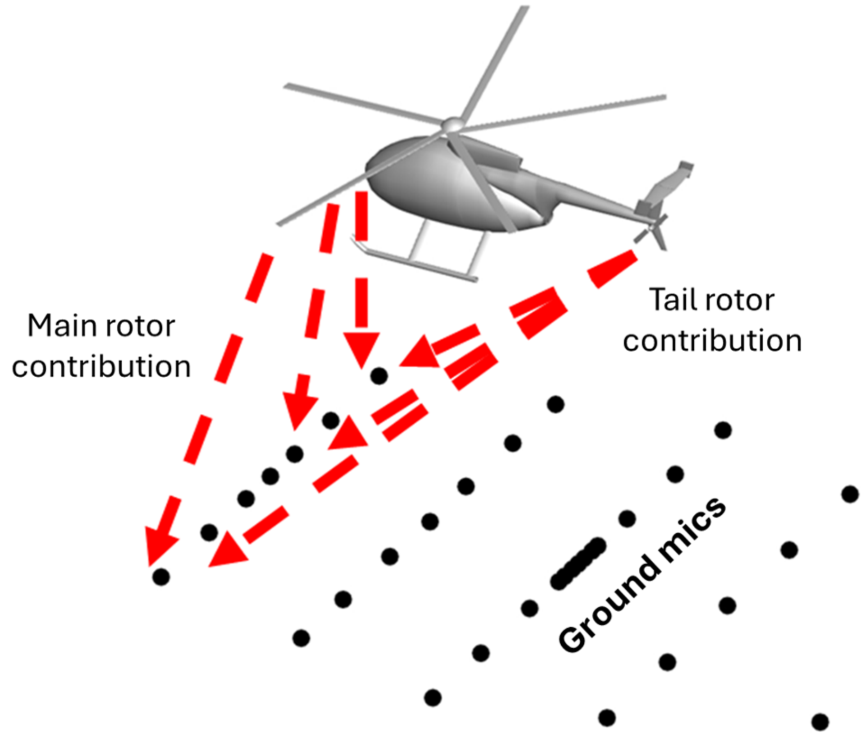
Pegg (Goldman 2012)

Pegg Corrected (Mukherjee 2025)

Pegg Model: Retuning With FAA/NASA 2017 Flight Test Data

$$\mathrm{SPL}_{1/3} = 20\log\left(\frac{V_T}{c_0}\right)^3 + 10\log_{10}\left[\frac{A_B}{r^2}\left(\cos^2(\theta) + 0.1\right)\right] + S_j + f(\bar{C}_L) + \mathbf{10\log_{10}}\left[\frac{\mathbf{K r_K^2 c_0^6 10^{16.29}}}{\mathbf{\cos\theta_K}}\right]$$

- Several unknowns in the general equation need to be determined
  - K : constant that helps match the total SPL
  - S_j : spectral weights for octave bands
  - Pegg provides values for 13 octave bands: constant regardless of rotor geometry, flight condition
- Total unknowns for main & tail rotor: 13+13+1=27
  - Minimum of 3 mics required to obtain an answer
  - Additional mic data should be used to obtain more robust values that correct for limitations of analytical terms

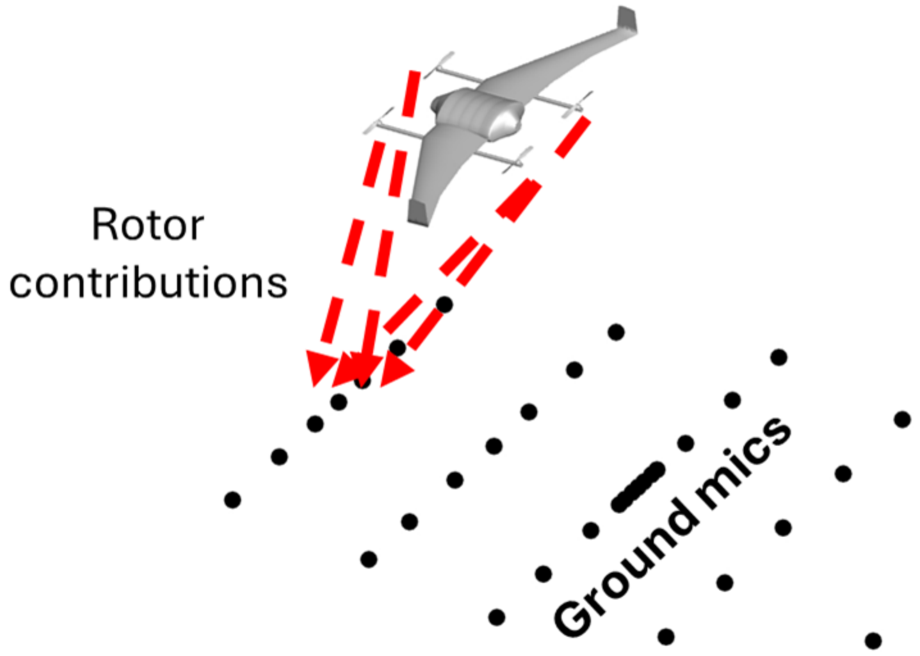


Pegg Model: Retuning With FAA/NASA 2017 Flight Test Data

$$SPL_{1/3} = 20\log\left(\frac{V_T}{c_0}\right)^3 + 10\log_{10}\left[\frac{A_B}{r^2}(\cos^2(\theta)+0.1)\right] + S_j + f(\bar{C}_L) + \mathbf{10log_{10}}\left[\frac{\mathbf{K r_K^2 c_0^6 10^{16.29}}}{\mathbf{\cos\theta_K}}\right]$$

- Several unknowns in the general equation need to be determined
  - K : constant that helps match the total SPL
  - S_j : spectral weights for octave bands
  - Pegg provides values for 13 octave bands: constant regardless of rotor geometry, flight condition

- Distributed Electric Propulsion (DEP) aircraft:
  - How many mics needed ?
  - Placement of mics ?



Summary

- ***Major Accomplishments:***
  - Including acoustic non-compact effects improves sound pressure level and spectral match
  - Turbulent boundary layer trailing edge noise underpredicted at some microphone locations
  - Large dataset published by Brooks et al. digitized for analysis
  - New scaling laws derived from data were found to depend upon angle of attack, but not flow Reynolds number
  - Calibration of Pegg model for multirotor aircraft
- ***Future Work:***
  - Recalibrate BPM model based on Mach scaling laws observed in data
  - Compare calibrated model with flight test data for PSU Hexacopter
  - Calibration of Pegg model for multirotor aircraft
    - Investigate robustness of tuned parameters using flight test data
    - Compare trends with helicopter broadband noise

References

1. Brooks, T. F., Pope, D. S., and Marcolini, M. A., “Airfoil Self-Noise and Prediction,” July 1989.
2. Botero-Bolívar, L., dos Santos, F. L., Venner, C. H. & de Santana, L. D. Trailing-edge far-field noise and noise source characterization in high inflow turbulence conditions. The Journal of the Acoustical Society of America 155, 803–816 (2024).
3. B. Mukherjee, “Noise Of Multirotor Electric Aircraft,” Doctor of Philosophy, The Pennsylvania State University, University Park, PA, USA, 2025. Available: https://etda.libraries.psu.edu/catalog/22433bxm437
4. B. A. Goldman, “Modifications to Psu-wopwop For Enhanced Noise Prediction Capabilities,” Master of Science, The Pennsylvania State University, University Park, PA, USA, 2012. [Online]. Available: https://etda.libraries.psu.edu/catalog/16434

Participants

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