

Numerical Characterization of Acoustic Scattering in an Urban Air Mobility Configuration

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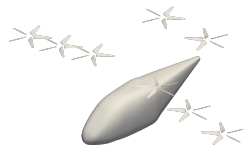
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Objective: investigate airframe scattering of both tonal and broadband noise for a full-size UAM concept vehicle.

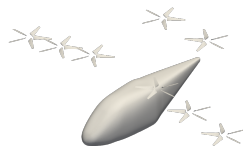
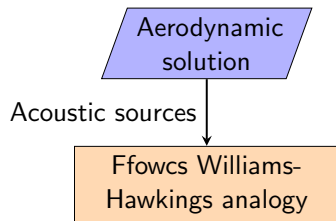
Noise Prediction with Acoustic Scattering

Aerodynamic
solution



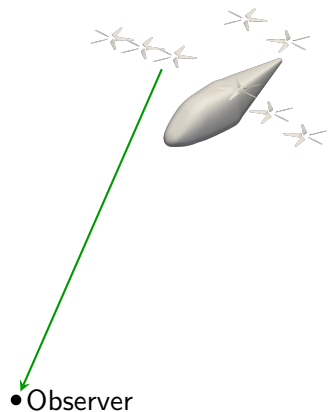
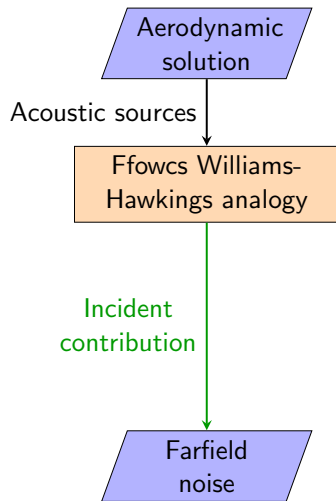
- Observer

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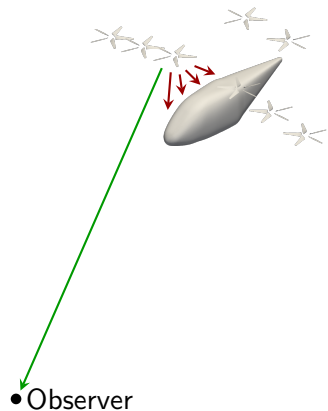
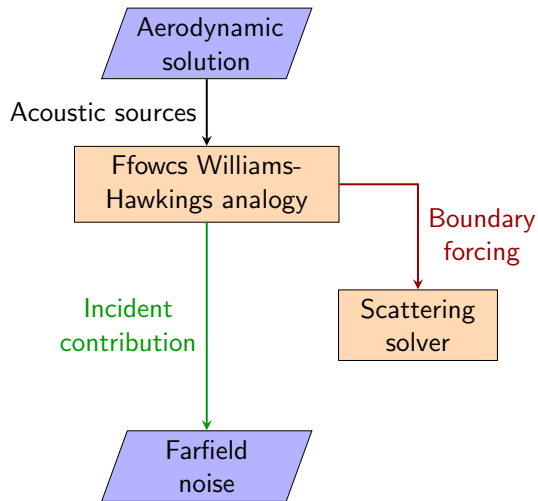


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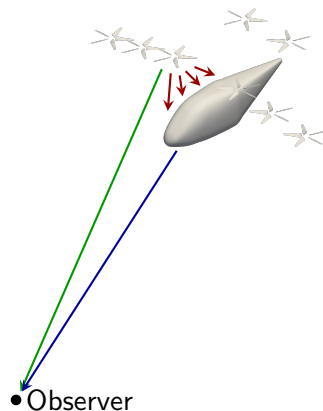
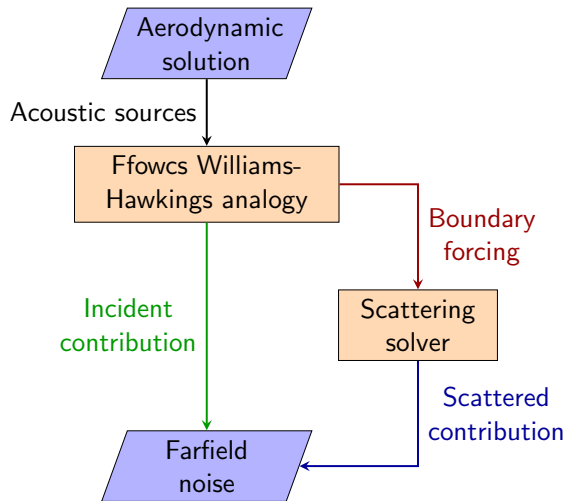
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Challenges for Broadband Noise Scattering

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Efficient broadband noise source modeling:

- ▶ Direct prediction of broadband noise sources requires high-fidelity CFD (e.g., LES)
- ▶ Semi-empirical modeling approaches are efficient but lack spatial information needed for scattering predictions

Acoustic Scattering

Acoustic propagation problem: inhomogeneous convective wave equation with sound-hard boundary condition on scattering surface Γ .

$$\left(\frac{1}{c_0^2} \left(\frac{\partial}{\partial T} + U \cdot \nabla \right)^2 - \nabla^2 \right) p = S(X, T), \quad (1a)$$

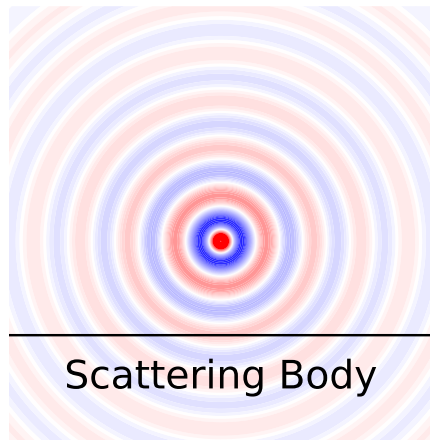
$$\text{BC}(p) = u \cdot N = 0 \text{ on } \Gamma. \quad (1b)$$

Incident Field

The acoustic analogy gives an incident field p_i does not automatically satisfy the BC:

$$\left(\frac{1}{c_0^2} \left(\frac{\partial}{\partial T} + U \cdot \nabla \right)^2 - \nabla^2 \right) p_i = S(X, T), \quad (2a)$$

$$\text{BC}(p_i) = -g \neq 0. \quad (2b)$$

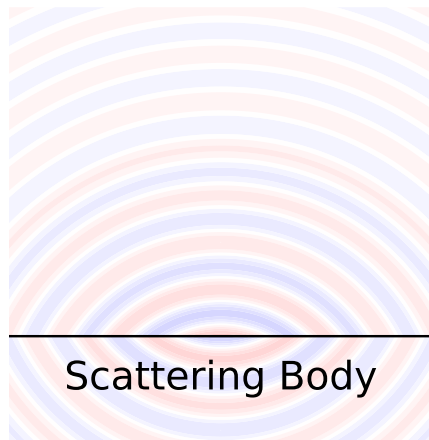


Scattered Field

Scattered field is the homogeneous solution of the convective wave equation satisfying an inhomogeneous boundary condition to cancel the residual from the incident field:

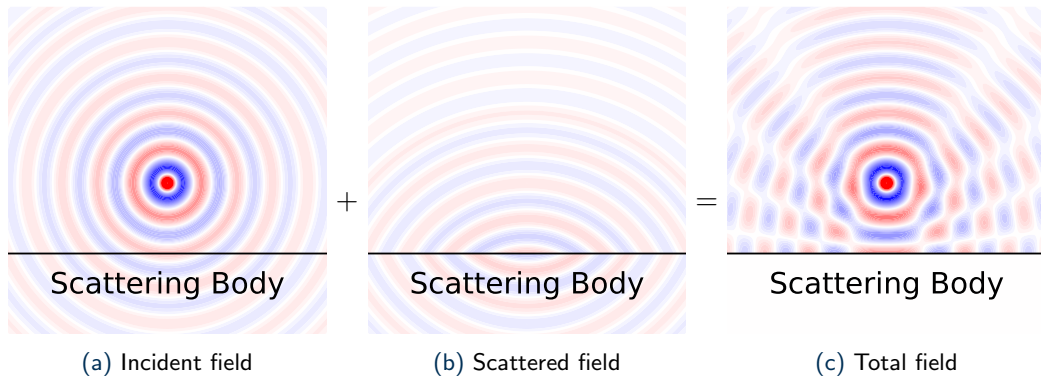
$$\left(\frac{1}{c_0^2} \left(\frac{\partial}{\partial T} + U \cdot \nabla \right)^2 - \nabla^2 \right) p_s = 0, \quad (3a)$$

$$\text{BC}(p_s) = g = -\text{BC}(p_i). \quad (3b)$$



Total Field

Total field ($p = p_i + p_s$) forced by the source distribution now satisfies the acoustic boundary condition:



Time-Domain Boundary Element Method (TDBEM)

Scattering solver: Galerkin TDBEM is used to compute the scattered field and enforce the acoustic boundary condition.

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- ▶ Analytical validation cases presented in previous work¹

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Tonal noise:

²Lopes, Journal of Aircraft, Vol. 54, No. 5, 2017, pp. 1649–1663.

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Broadband noise:

- ▶ Requires actual or modeled turbulent fluctuations (e.g., WPS)
- ▶ Not acoustically compact wrt. blade chord

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- ▶ Model spectrum: turbulent boundary layer wall pressure spectrum
- ▶ Geometrical approximations to perform propagation integral in closed form
- ▶ Limitation: provides point-wise spectral information while discarding phase information needed for scattering predictions

Time-Domain Broadband Noise Synthesis

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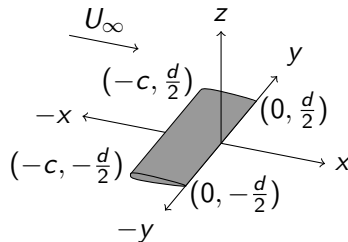
1. Synthesize stochastic fluctuations from aeroacoustic response function and model spectrum
2. Approximate chordwise and spanwise integrals to obtain effective loading that takes into account acoustic noncompactness
3. Propagate effective loading with compact FWH to obtain time-resolved field

Derivation: Trailing Edge Noise

Pressure jump over airfoil:

$$\Delta p(x, y, t) = 2 \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \hat{P}(k_x, k_y) g(x, k_x, k_y) \exp(-i(k_x(x - U_c t) + k_y y)) dk_x dk_y, \quad (4)$$

where $g(x, k_x, k_y)$ is the aeroacoustic response function and $\hat{P}(k_x, k_y)$ describes the turbulent boundary layer fluctuations.



Derivation: Trailing Edge Noise

FWH loading term: $L = \hat{n}\Delta p$

$$p'(r_{obs}, t) = \nabla \cdot \int_{-d/2}^{d/2} \int_{-c}^0 \left[\frac{\hat{n} \cdot \hat{r}}{4\pi|r|} \Delta p(x, y, \tau) \right]_{ret} dx dy, \quad (5)$$

where $r = r_{obs} - r_{src}$ and $\tau = t - |r|/c_0$.

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where $r = r_{obs} - r_{src}$ and $\tau = t - |r|/c_0$.

Direct propagation with full FWH is expensive - quadrature must resolve smallest wavelengths. We seek an approximation to (5):

$$p'(r_{obs}, t) = \nabla \cdot \left[\frac{\hat{n} \cdot r_{obs}}{4\pi|r_{obs}|} L_{eff}(r_{obs}, t - |r_{obs}|/c_0) \right]_{ret} cd. \quad (6)$$

Derivation: Trailing Edge Noise

If $|r| \gg c, d$, we introduce the following approximations:

$$\frac{\hat{n} \cdot \hat{r}}{|r|} \approx \frac{\hat{n} \cdot \hat{r}_{obs}}{|r_{obs}|}, \quad \tau(r_{obs}) \approx t - \frac{|r_{obs}|}{c_0} + \frac{1}{c_0} \frac{r_{obs}}{|r_{obs}|(1 - M_{r_{obs}})}.$$

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Then:

$$L_{eff}(r_{obs}, t) = 2\hat{n} \int_{-\infty}^{\infty} \hat{P}(k_x, k_x \alpha_y) \sqrt{\frac{2\pi}{d}} L_a(k_x, k_x \alpha_y, k_x(1 - \alpha_x)) \exp(ik_x U_c t) dk_x, \quad (7)$$

$$L_a(k_x, k_y, k_c) = \frac{1}{c} \int_{-c}^0 g(x, k_x, k_y) \exp(-ik_c x) dx, \quad (\alpha_x, \alpha_y, \alpha_z) = \frac{U_c}{c_0} \frac{r_{obs}}{|r_{obs}|(1 - M_{r_{obs}})}.$$

We now have an effective acoustically weighted loading source term that can be propagated with compact FWH.

Derivation: Trailing Edge Noise

The time-domain signals are synthesized by approximating the remaining chordwise wavenumber integral with a sum over discrete Fourier modes:

$$L_{eff}(r_{obs}, t) \approx 2\hat{n} \sqrt{\frac{2\pi}{d}} \sum_{n=1}^N A_n L_a(n\Delta k_x, n\Delta k_x \alpha_y, n\Delta k_x(1 - \alpha_x)) \exp(in\Delta k_x U_c t), \quad (8)$$

$$A_n = \sqrt{\frac{1}{\pi} l_y(n\Delta k_x, n\Delta k_x \alpha_y) S_{qq}(n\Delta k_x U_c) \Delta k_x \exp(i\phi_n)}, \quad (9)$$

where $\phi_n \sim \mathcal{U}(0, 2\pi)$ are random phases, $S_{qq}(\omega)$ is the wall pressure spectrum, and l_y is the spanwise correlation length.

Configuration: NASA Tiltwing Reference Vehicle

NASA Tiltwing³: 6 passenger concept vehicle with six rotors on tilting main wing and two rotors on empennage.

³Whiteside et al., NASA/TM-20210017971

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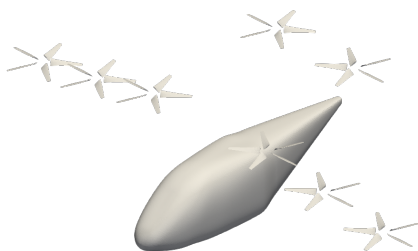
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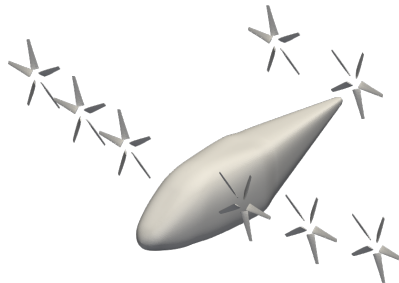
Flight condition	Velocity (m/s)	Rotor tip speed (m/s)	Rotor disk loading (N/m ²)
Hover	0.0	167.6	957.6
Cruise	79.7	91.4	92.0

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(a) Hover



(b) Cruise

Isolated Rotor Noise Verification

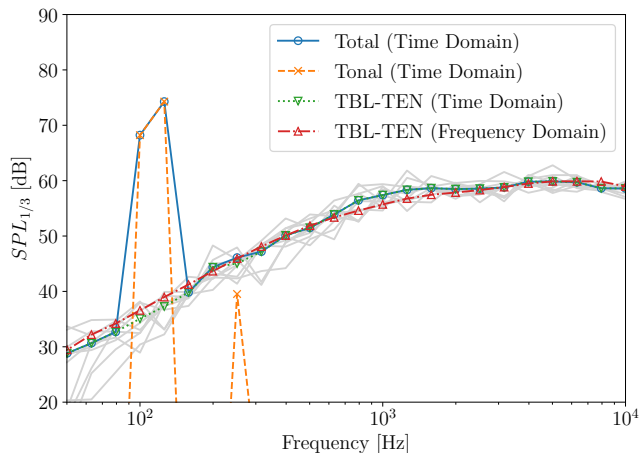
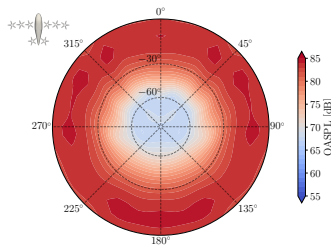


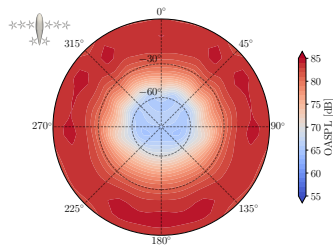
Figure: Tonal and trailing edge noise predictions in hover at 10 radii

Full-Vehicle Noise Predictions (Hover)

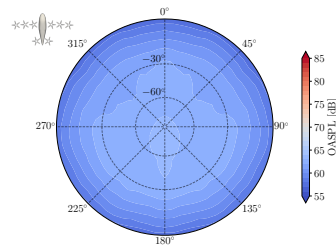
Unweighted overall sound pressure levels up to 2.1 kHz:



(a) Total



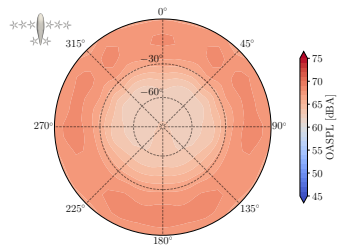
(b) Tonal



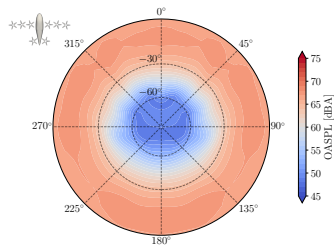
(c) Broadband

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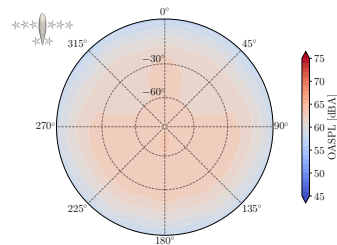
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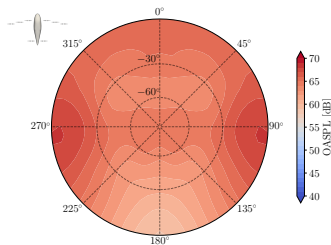
(b) Tonal



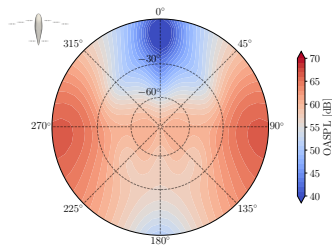
(c) Broadband

Full-Vehicle Noise Predictions (Cruise)

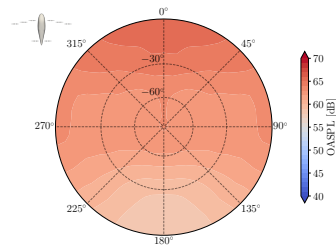
Unweighted overall sound pressure levels up to 1.6 kHz:



(a) Total



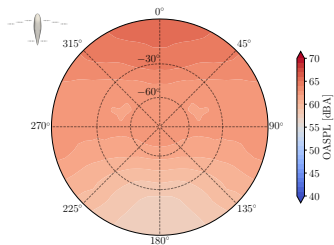
(b) Tonal



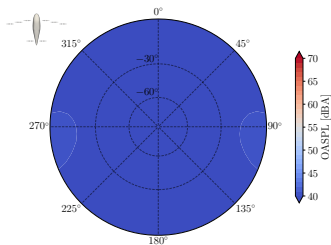
(c) Broadband

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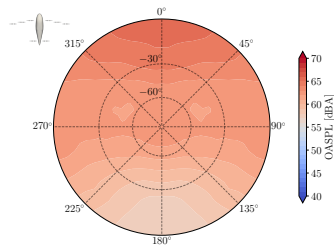
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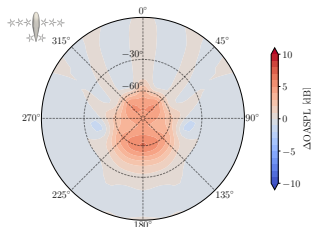


(c) Broadband

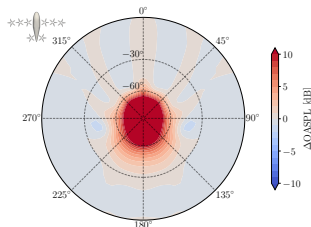
Scattering Effects (Hover)

Difference between unweighted OASPL with and without scattering:

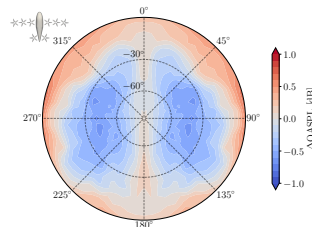
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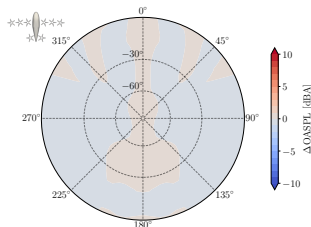


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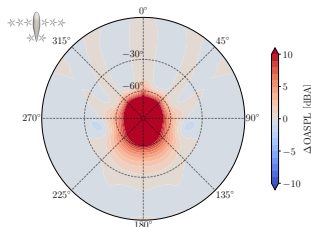
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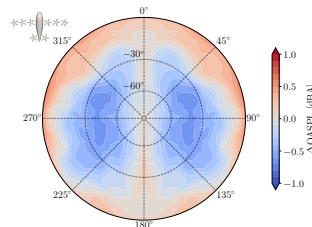
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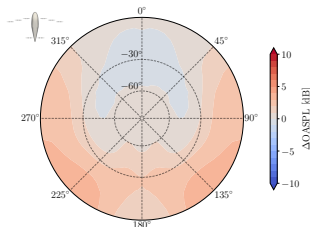


(c) Broadband

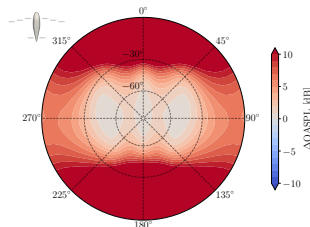
Scattering Effects (Cruise)

Difference between unweighted OASPL with and without scattering:

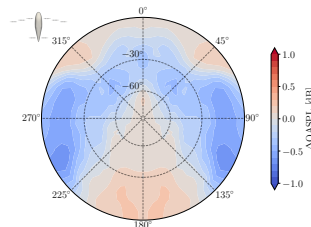
$$\Delta\text{OASPL} = \text{OASPL} - \text{OASPL}_i$$



(a) Total



(b) Tonal

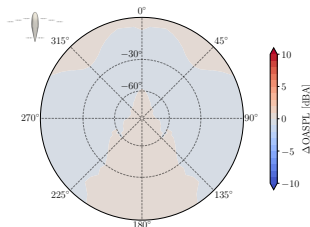


(c) Broadband

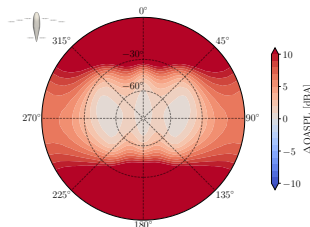
Scattering Effects (Cruise)

Difference between A-weighted OASPL with and without scattering:

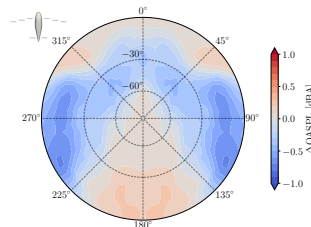
$$\Delta\text{OASPL} = \text{OASPL} - \text{OASPL}_i$$



(a) Total



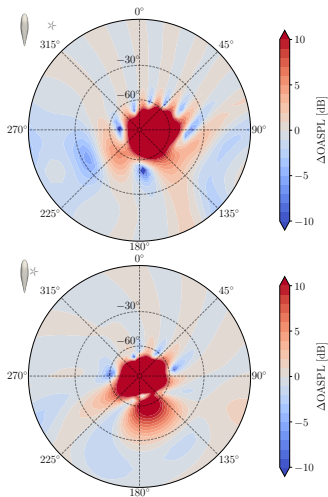
(b) Tonal



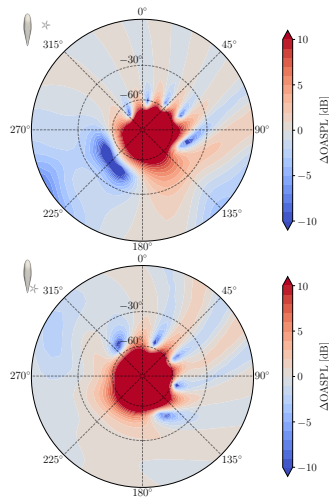
(c) Broadband

Individual Rotor Scattering Effects (Hover, Tonal Noise)

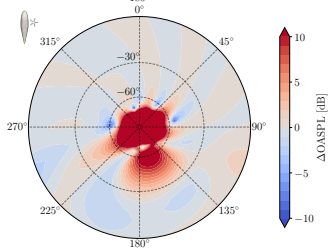
(a) Outboard



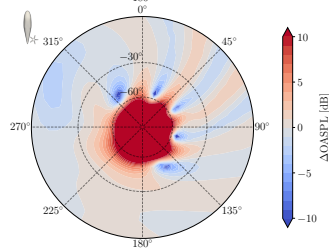
(b) Middle



(c) Inboard

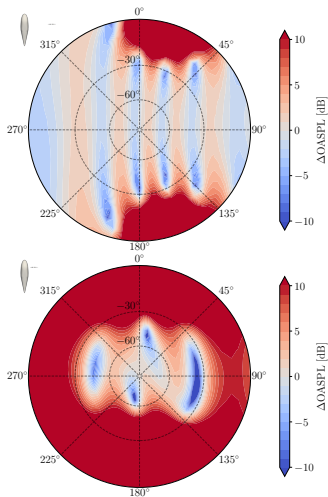


(d) Empennage

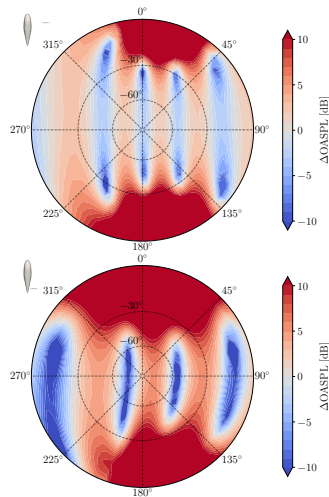


Individual Rotor Scattering Effects (Cruise, Tonal Noise)

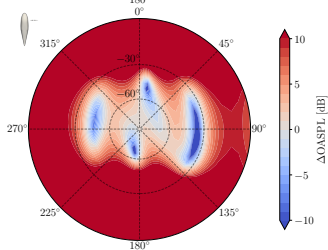
(a) Outboard



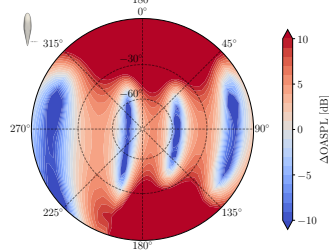
(b) Middle



(c) Inboard

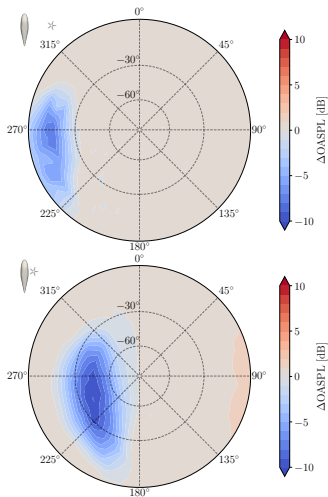


(d) Empennage

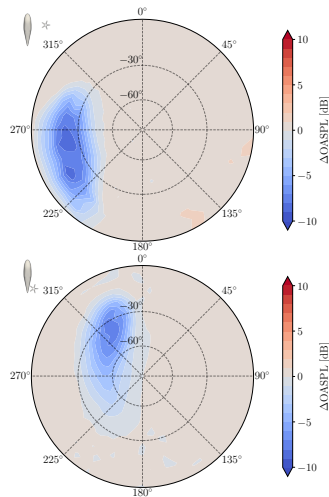


Individual Rotor Scattering Effects (Hover, Broadband Noise)

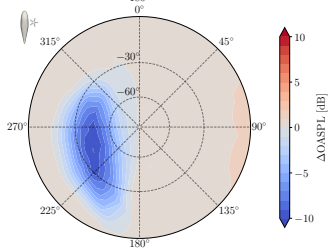
(a) Outboard



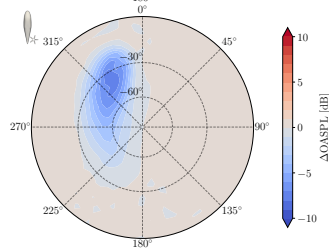
(b) Middle



(c) Inboard

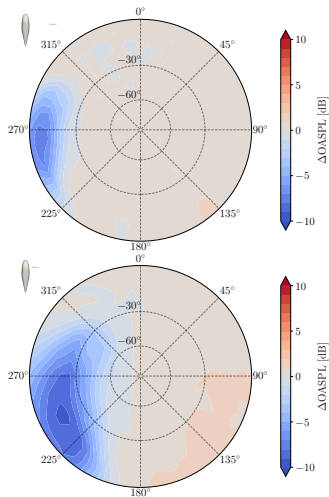


(d) Empennage

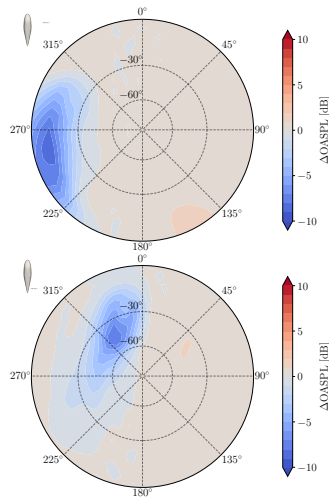


Individual Rotor Scattering Effects (Cruise, Broadband Noise)

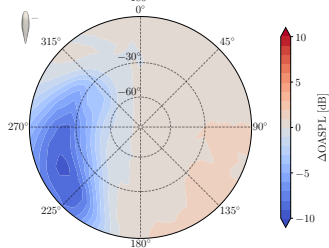
(a) Outboard



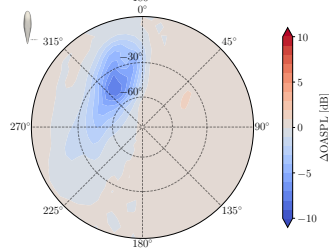
(b) Middle



(c) Inboard

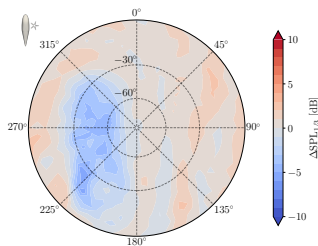


(d) Empennage

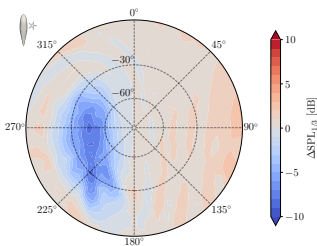


Frequency-Dependent Trends (Hover)

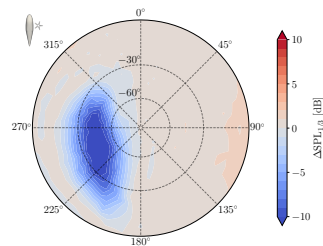
Selected 1/3 octave band sound pressure levels:



(a) $f_c = 315$ Hz



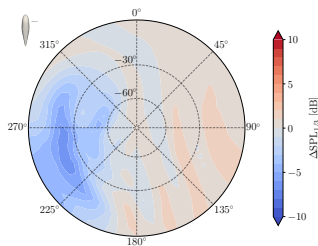
(b) $f_c = 630$ Hz



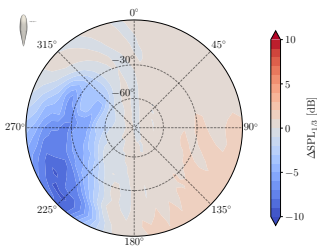
(c) $f_c = 1250$ Hz

Frequency-Dependent Trends (Cruise)

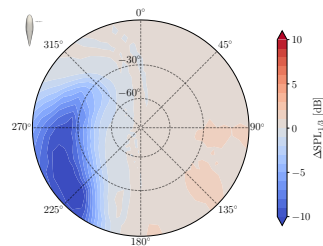
Selected 1/3 octave band sound pressure levels:



(a) $f_c = 315$ Hz



(b) $f_c = 630$ Hz



(c) $f_c = 1250$ Hz

Summary

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- ▶ Tonal scattering trends show strong interference effects that are sensitive to rotor placement and orientation
- ▶ Broadband scattering trends are characterized by strong shielding for individual rotors that are mostly masked in the full configuration
- ▶ Total scattering effect depends on the relative emphasis on tonal or broadband contributions

Future Work

- ▶ Include additional scattering surfaces: wings, empennage, nacelles, landing gear

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- ▶ Effects of rotor synchrophasing on acoustic scattering
- ▶ Higher frequencies and additional broadband noise sources

Acknowledgments

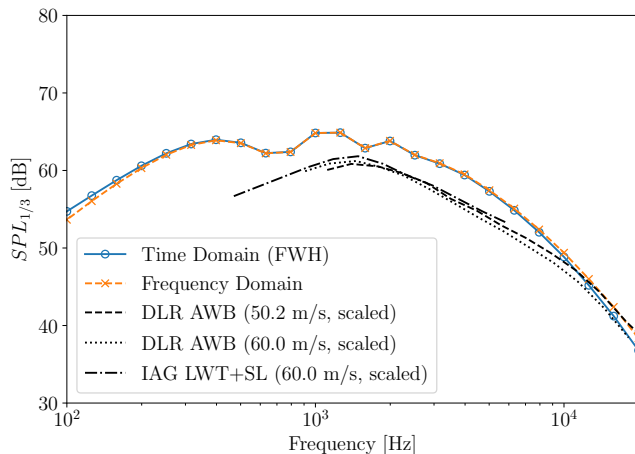
This research used computational resources from DeltaAI at the University of Illinois Urbana-Champaign's National Center for Supercomputing Applications through allocation ENG250008 from the Advanced Cyberinfrastructure Coordination Ecosystem: Services & Support (ACCESS) program, which is supported by U.S. National Science Foundation grants #2138259, #2138286, #2138307, #2137603, and #2138296.

Validation: Airfoil Trailing Edge Noise

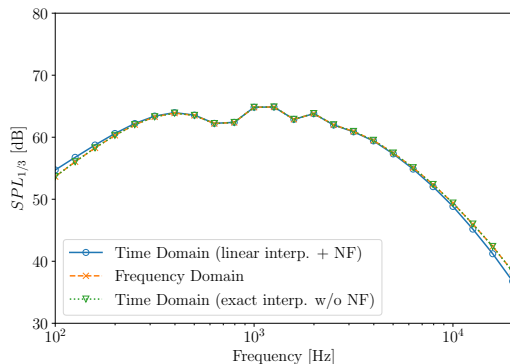
BANC-II Case 1:

- ▶ NACA0012 airfoil: 0.4 m chord, 1 m span
- ▶ Operating condition:
 $U_\infty = 56$ m/s, 0° AoA

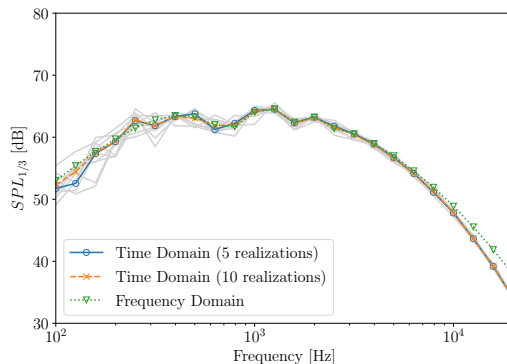
Comparison: proposed time-domain synthesis approach vs. Amiet's frequency-domain solution.



Validation: Airfoil Trailing Edge Noise



(a) Effect of observer time interpolation method and inclusion of nearfield terms



(b) Effect of averaging over independent realizations ($N = 40$ elements)

Validation: Airfoil Trailing Edge Noise

Simple scattering problem:

- ▶ Large scattering plate below airfoil
- ▶ Comparison with method of images (MOI) solution for infinite plane
- ▶ MOI provides a useful reference despite differences in scattering geometry

