Numerical Investigation of Propeller-Wing Interaction Noise with Scattering and Shielding

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Georgia Tech

Introduction

Installed propellers are significant noise sources in Urban Air Mobility (UAM) concepts.

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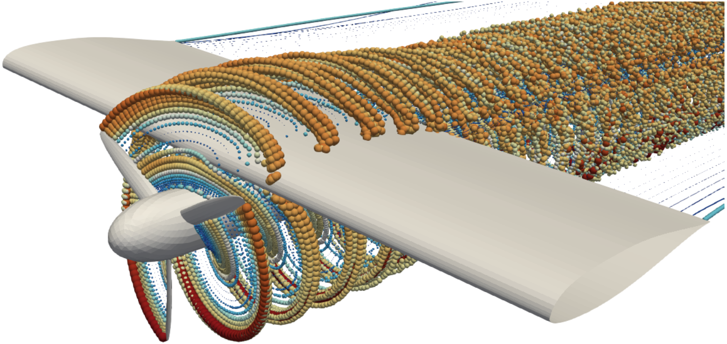
- Existing options are very computationally expensive, even for tonal noise.

Objective: develop an efficient prediction approach for installed propeller tonal noise with suitability for full-vehicle design and optimization tasks.

Interaction Mechanisms



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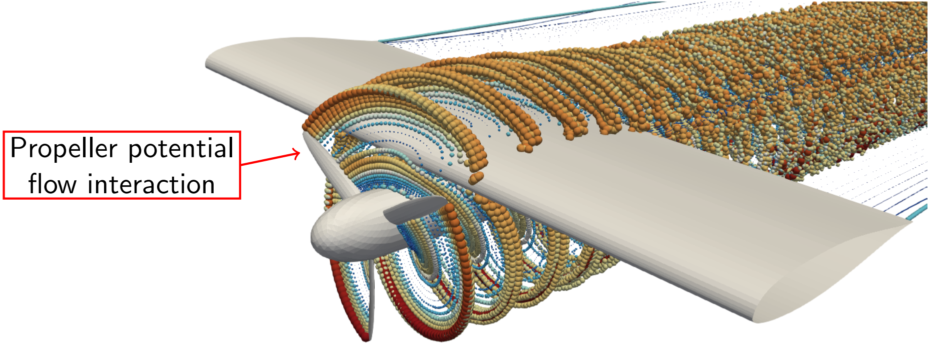

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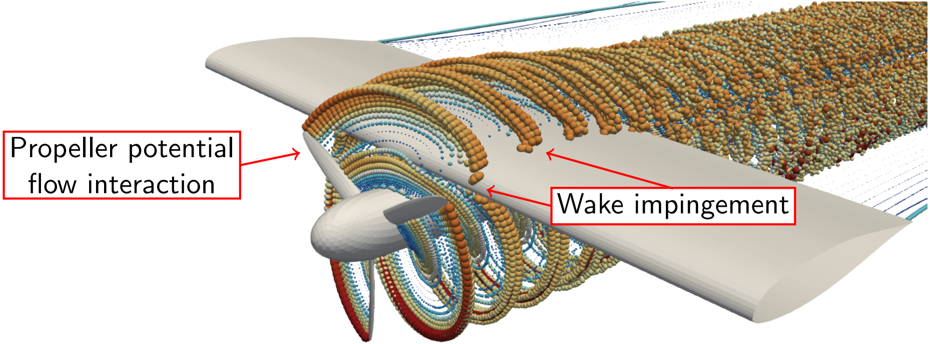

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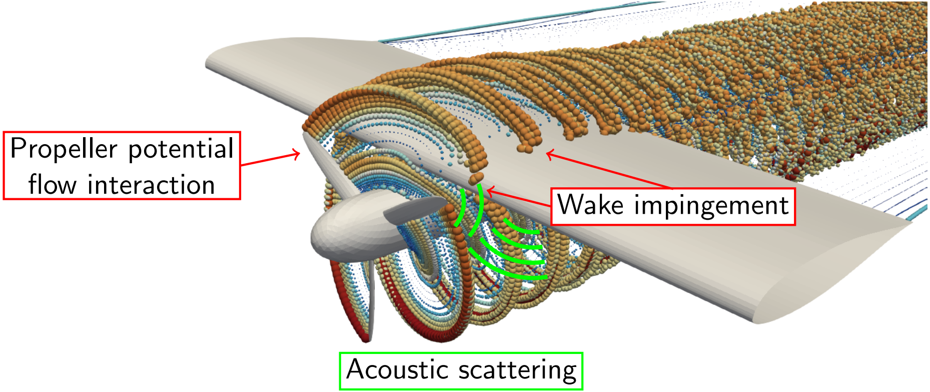

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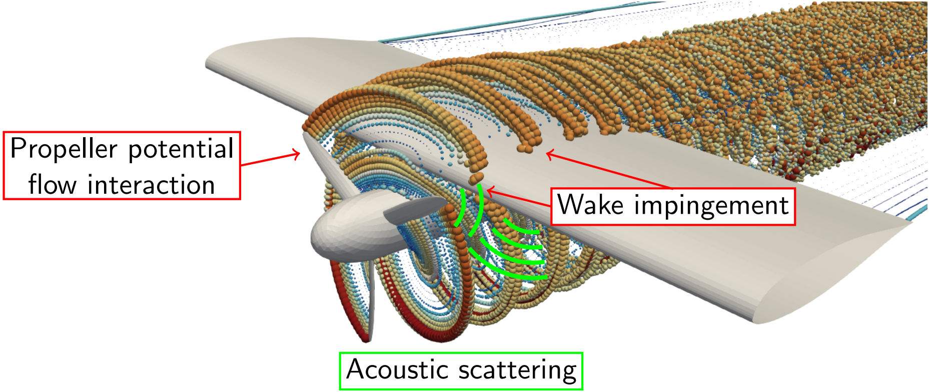

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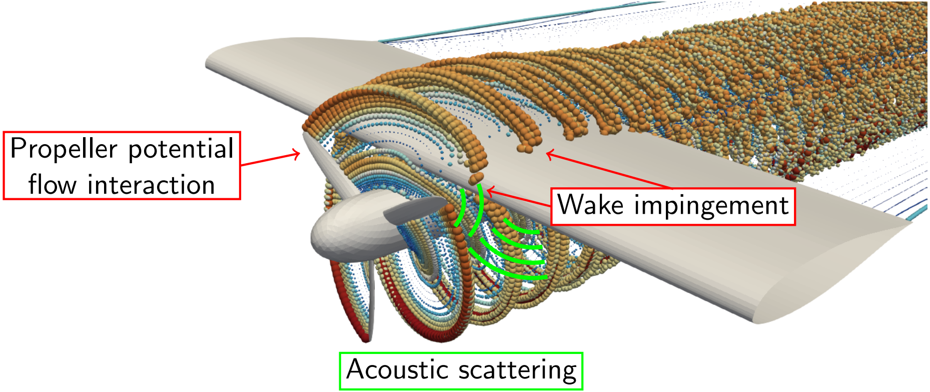

How can we efficiently capture each interaction mechanism in a numerical approach suitable for design optimization tasks?

Which mechanism(s) dominate the overall installation effect?

Numerical Approach

Aerodynamic solver: DUST[1]
3D panel-vortex particle method (VPM)

[1]Tugnoli et al., Aerospace Science and Technology 2021 Vol. 115.
[2]Farassat, NASA/TM-2007214853.
[3]Ghorbaniasl, Carley, and Lacor, AIAA Journal 2013 Vol. 51 No. 3.

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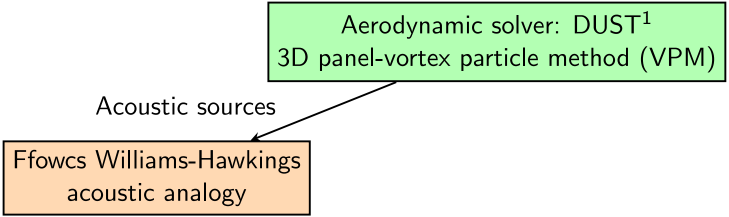

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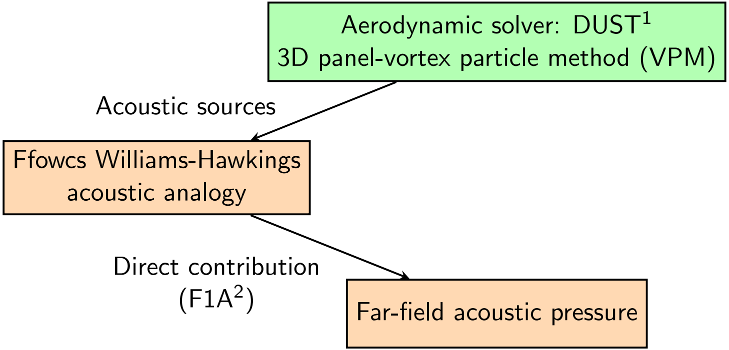

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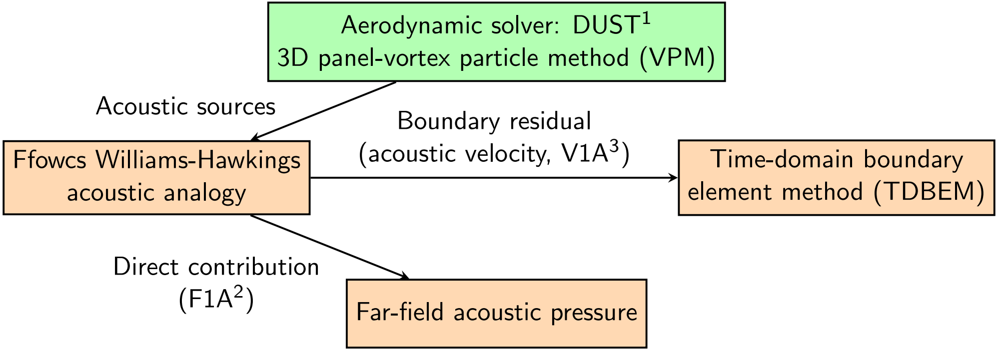

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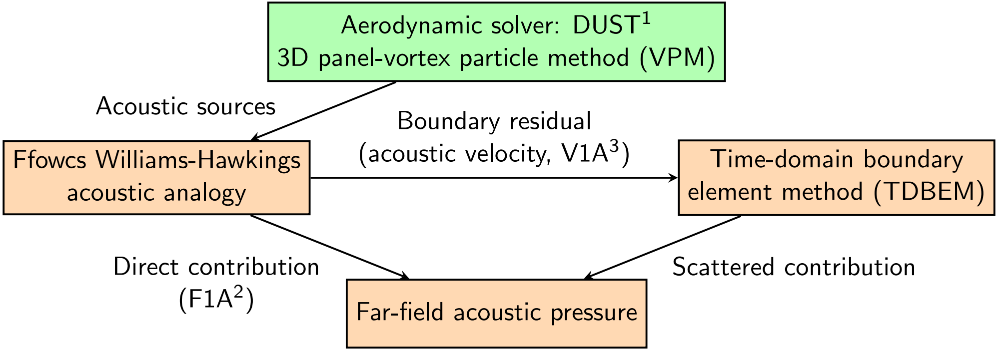

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$$\left(\frac{1}{c_0^2} \left(\frac{\partial}{\partial T} + U_i \frac{\partial}{\partial X_i} \right)^2 - \frac{\partial^2}{\partial X_i^2} \right) \phi = S(X, T) \tag{1a}$$

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$$u_i' N_i = \frac{\partial \phi}{\partial X_i} N_i = \frac{\partial \phi}{\partial N} = 0 \text{ on } \Gamma \tag{1b}$$

Direct contribution from acoustic analogy does not automatically satisfy (1b) unless aerodynamic solution fully resolves the acoustic field.

Time-Domain Boundary Element Method (TDBEM)

Galerkin TDBEM is used to include the effect of non-compact solid bodies on propagation by enforcing the acoustic boundary condition.

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- Natural coupling with time-domain aerodynamic solvers
- Useful numerical properties: quasi-best approximation and unconditional stability
- Analytical validation cases presented in previous work[4,5]

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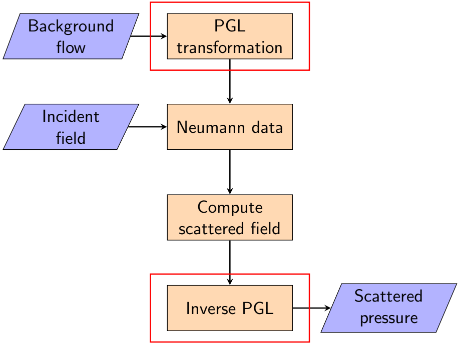
Background Flow

Approximate mean background flow with uniform free-stream and simplify to rest-medium via Prandtl-Glauert-Lorentz (PGL) transformation:

$$\frac{1}{c_0^2}\frac{D^2\phi}{DT^2} - \frac{\partial^2\phi}{\partial X_i^2} = S(X,T)$$

$$\Rightarrow \frac{\partial^2\bar{\phi}}{\partial t^2} - \frac{\partial^2\bar{\phi}}{\partial x_i^2} = s(x,t) \quad \text{(2a)}$$

$$\frac{\partial\phi}{\partial N} = 0 \text{ on } \Gamma \Rightarrow \frac{\partial\bar{\phi}}{\partial n} = 0 \text{ on } \Gamma \quad \text{(2b)}$$



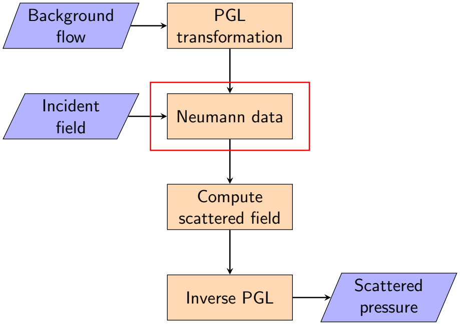
Incident Field

Evaluate residual from incident field:

$$\frac{\partial \bar{\phi}_i}{\partial n} = -g(x, t). \tag{3}$$

Scattered field must be a homogeneous solution satisfying a Neumann boundary condition to cancel the residual:

$$\frac{\partial \bar{\phi}_s}{\partial n} = g(x, t). \tag{4}$$



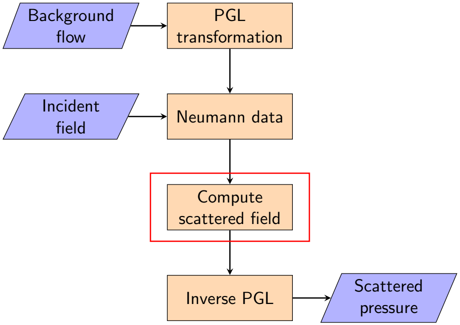
Scattered Field

We represent $\bar{\phi}_s$ with a surface distribution the double layer potential $\psi = [\bar{\phi}_s]$:

$$\bar{\phi}_s(x,t) = \int_0^t \int_\Gamma \frac{\partial G}{\partial n_y} \psi(y,\tau) dy d\tau, \qquad (5)$$

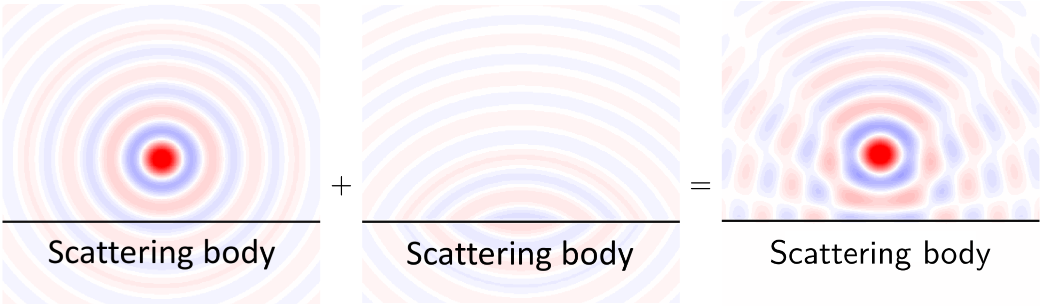
where $G(x,t;y,\tau) = \frac{\delta(t-\tau-|x-y|)}{4\pi|x-y|}$.
The first kind retarded potential boundary integral equation (RPBIE) relates g to the unknown layer potential:

$$g(x,t) = \int_0^t \int_\Gamma \frac{\partial^2 G}{\partial n_x \partial n_y} \psi(y,\tau) dy d\tau \qquad (6)$$



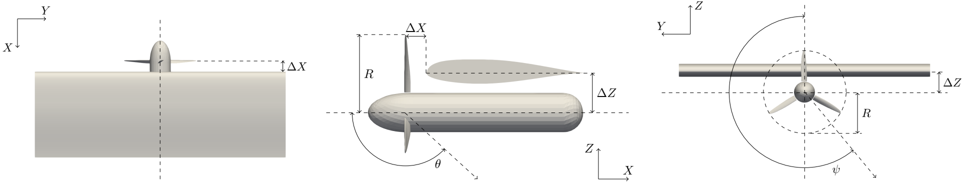
Total Field

Total field ($\bar{\phi} = \bar{\phi}_i + \bar{\phi}_s$) forced by the source distribution now satisfies the acoustic boundary condition:



(a) Incident field (b) Scattered field (c) Total field

Propeller-Wing Configuration

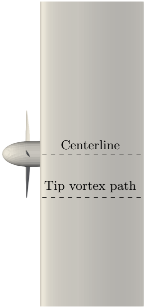


(a) Top view (b) Side view (c) Front view

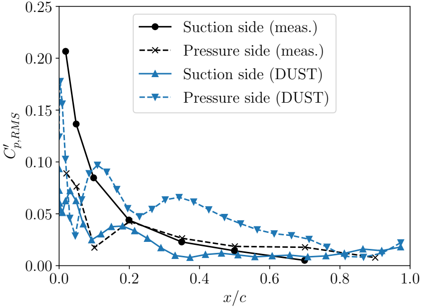
Propeller-wing geometry from Zawodny et al.[6], consisting of a three-bladed propeller installed on a nacelle below a rectangular wing. The wing leading edge is located at $(\Delta X, 0, \Delta Z)$ relative to the center of the propeller disk. The flyover observer array is located 3.5 m from the propeller axis at an azimuthal angle $\psi = 220°$.

[6] Zawodny, Boyd, and Nark, AIAA 2021-0714.

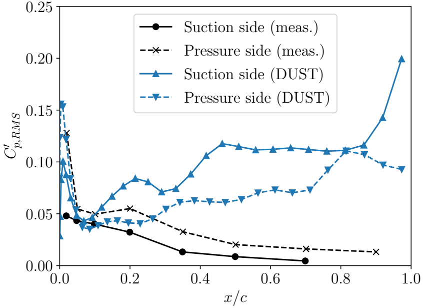
Aerodynamic Results: Unsteady Surface Pressure



$\frac{\Delta X}{R} = 0.25, \frac{\Delta Z}{R} = 0.5$



(a) Centerline



(b) Tip vortex path

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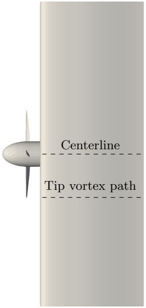

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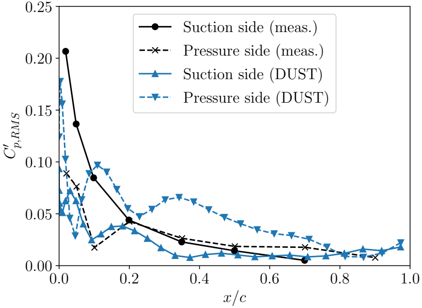

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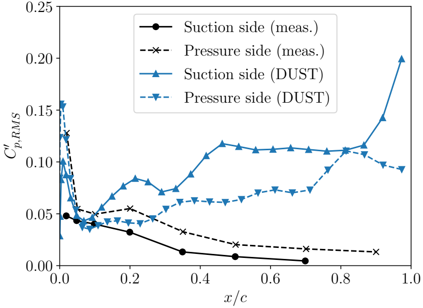
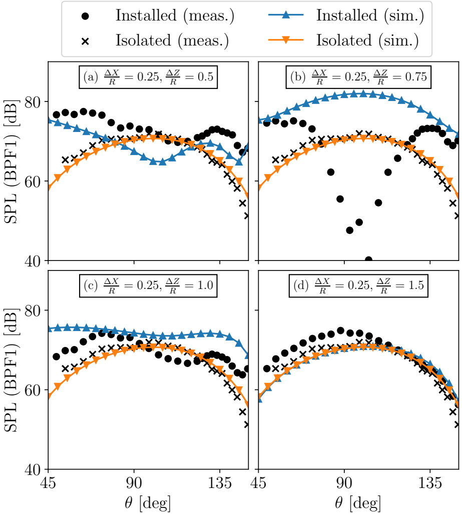
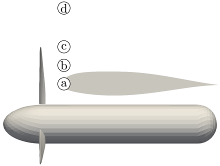


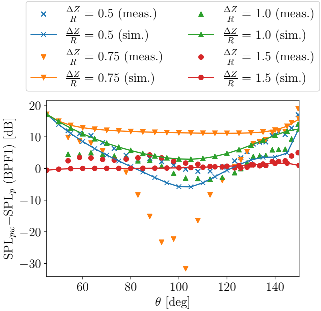
(b) Tip vortex path

Significant discrepancies are observed between simulation and experiment, especially at the tip vortex path.

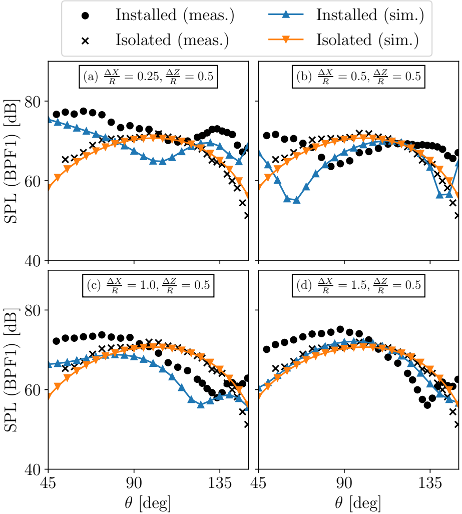
Acoustic Results: Vertical Wing Positions

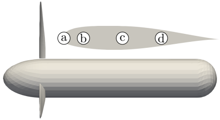


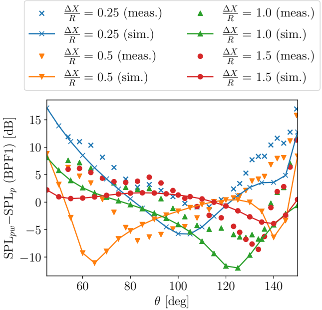




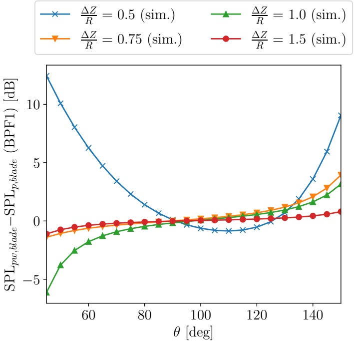
Acoustic Results: Horizontal Wing Positions



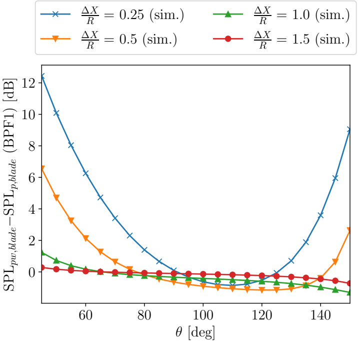




Propeller Potential Flow Interaction



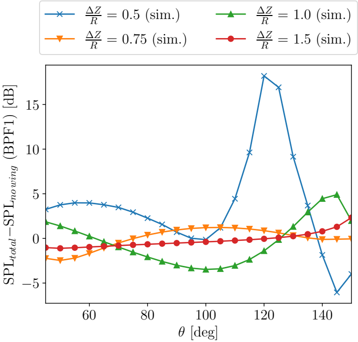
(a) Vertical position sweep



(b) Horizontal position sweep

Figures show the difference between installed and isolated blade contributions, indicative of the propeller potential interaction mechanism.

Wake Impingement



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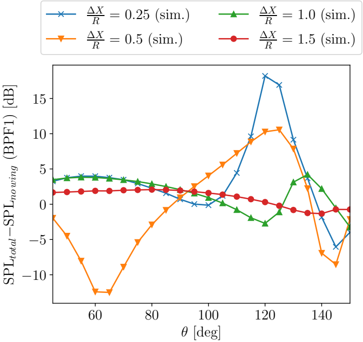
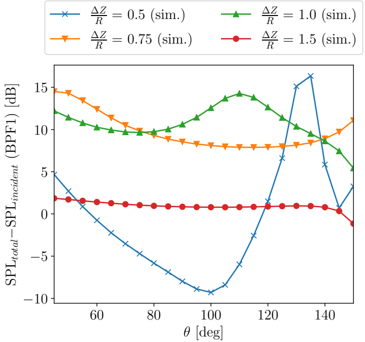


(b) Horizontal position sweep

Figures show the difference between installed directivities with and without the wing contribution, indicative of the wake impingement interaction mechanism.

Acoustic Scattering



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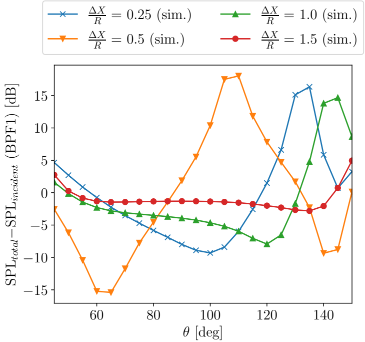
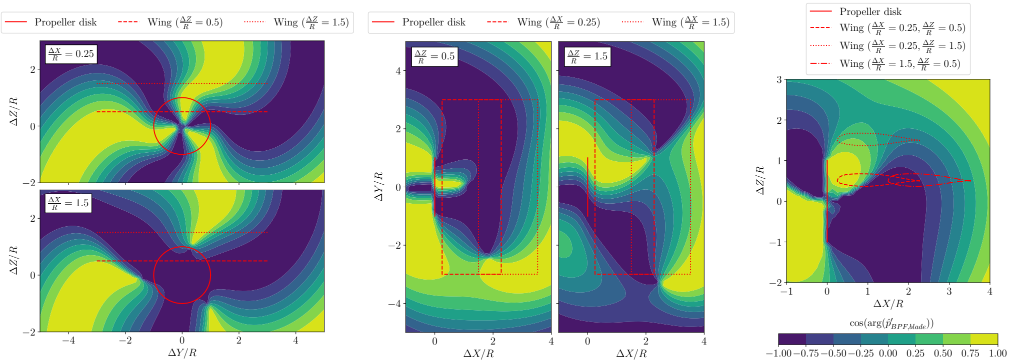


(b) Horizontal position sweep

Figures show the difference between installed directivities with and without the scattered contribution, corresponding to the scattering acoustic interaction mechanism.

Incident Acoustic Field



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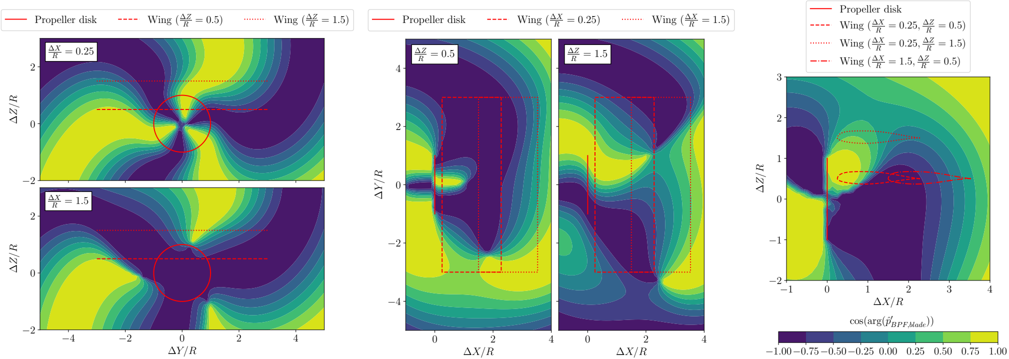

The wing chord is small compared to far-field length scale ($c \approx \lambda/6$) but large compared to near-field length scale ($c \approx 2R$).

Summary

- Panel-VPM and TDBEM approaches are coupled to efficiently model tonal propeller-wing interaction noise.
- Results show strong potential to capture interaction noise, although discrepancies remain for aspects of the unsteady aerodynamic and acoustic predictions.
- Breakdowns of acoustic contributions in the installed propeller configurations reveal significant effects from propeller potential interaction, wake impingement, and scattering mechanisms.
- The near-field spatial scaling of the propeller acoustic field with the propeller diameter strongly impacts the scattering effect from the wing.

Future Work

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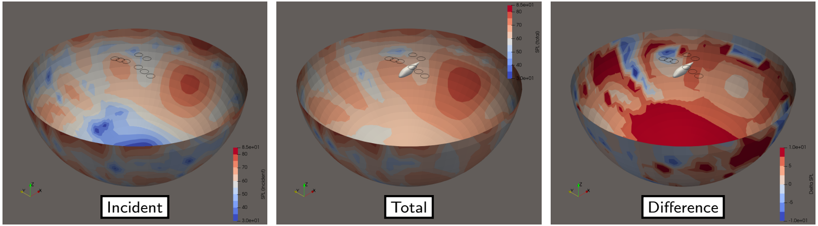
- Further validation against experimental data
- Full vehicle noise with scattering



Acknowledgments

The authors gratefully acknowledge Nikolas Zawodny at the NASA Langley Research Center for providing data and assistance to set up and benchmark the propeller-wing configuration.