

# Numerical Characterization of Acoustic Scattering in an Urban Air Mobility Configuration

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**This paper applies a time-domain numerical framework to investigate airframe scattering of both tonal and broadband noise for a full-size urban air mobility concept vehicle. The framework uses a stochastic approach to obtain time-domain realizations of broadband trailing edge noise, which are then scattered along with tonal noise using a time-domain boundary element method. Farfield noise predictions are presented including acoustic scattering from a simplified fuselage-only airframe geometry for both hover and cruise flight conditions. Significant variations are observed in the scattering effects between the tonal and broadband components and between the flight conditions. These variations are attributed to differences between the directivities and spatial structures of the rotor tonal and broadband noise components, as well as differences between the rotor positions and orientations in hover and cruise. Frequency-dependent scattering trends are also observed for the broadband component.**

## I. Introduction

Aerodynamically generated noise is an important consideration for the design and operation of vertical take-off and landing (VTOL) urban air mobility (UAM) configurations. Unlike traditional VTOL configurations, UAM concepts typically feature multiple distributed rotors and propellers, resulting in complicated aerodynamic and acoustic interactions. UAMs are specifically targeted for operation in congested urban environments, where low noise levels are necessary to mitigate adverse health impacts and improve public acceptability. It is therefore important to develop efficient numerical tools to enable consideration of vehicle noise in conceptual and preliminary design stages and to develop control and operation strategies that minimize adverse impacts.

Interactional effects in full-vehicle configurations include aerodynamic interactions that result in additional noise generation mechanisms, and acoustic interactions that affect the noise propagation from all sources, particularly scattering by vehicle surfaces. Acoustic scattering is not typically captured with widely used integral-based aeroacoustic analogy methods [1], and recent reviews of UAM noise research [2, 3] highlight the need for robust, integrated acoustic scattering approaches to account for the effect of vehicle surfaces on the propagation of aerodynamically generated noise. While several numerical methodologies for prediction of full-vehicle UAM noise sources have been developed and presented [4–7], acoustic scattering effects have mostly been neglected. Some recent works [8–10] have applied frequency-domain acoustic propagation methods to investigate scattering in multirotor UAM and drone configurations at a limited number of tonal harmonics, but scattering of both tonal and broadband noise has not been investigated.

Efficient scattering of broadband noise is limited by two main challenges. First, the dominant sources of broadband noise, such as turbulent boundary layer trailing edge noise and turbulence ingestion noise, are produced by stochastic fluctuations that can only be directly resolved with computationally expensive high-fidelity aerodynamic simulations [11]. For early design tasks, semi-analytical broadband noise modeling approaches [12–15] are often applied to obtain a statistical description of the broadband noise contributions based on information available from lower-fidelity aerodynamic analyses. Unfortunately, these modeling approaches typically discard information about the spatial structure of the acoustic field, including relative time delays at different observer locations that are necessary for scattering predictions. Second, many acoustic scattering methods are formulated in the frequency domain and therefore

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require a separate simulation at every frequency of interest. These approaches can become prohibitive for broadband noise scattering, where a large number of discrete frequencies would be required to represent the noise source [16, 17].

In this work, we apply a recently developed framework for broadband noise scattering [18] to investigate fuselage scattering from NASA’s six-passenger tiltwing UAM concept vehicle [19]. The framework consists of a stochastic broadband noise synthesis method to obtain time-resolved incident field realizations from existing semi-analytical noise source models coupled to a time-domain boundary element method [20] to scatter all frequencies together in a single computation. The tiltwing concept vehicle is publicly available and intended to be representative of industry UAM designs.

## II. Methodology

### A. Noise Source Modeling

For simplicity, we adopt an aerodynamic modeling approach based on isolated rotor blade element momentum theory (BEMT) predictions, neglecting aerodynamic interactions between rotors and with the airframe. The rotor blade loads and boundary layer properties are then used to obtain tonal and broadband noise sources. The BEMT solutions are computed using lookup tables generated with XFOIL [21]. The lift and drag coefficients are extrapolated post-stall using the method of Battisti et al. [22], while the boundary layer properties are obtained post-stall from the closest converged XFOIL solution. The BEMT implementation follows Ning’s formulation [23], and implements the Du-Selig [24] and Eggers [25] rotation corrections for lift and drag, respectively, along with Prandtl’s tip loss correction [26].

#### 1. Tonal Noise

The tonal thickness and loading noise contributions are obtained from the rotor blade geometry and steady blade loads via the Ffowcs Williams-Hawkings (FWH) acoustic analogy [27]. We use compact FWH formulations [28] to substantially reduce the computational cost. The compact approximation is based on both geometric and acoustic compactness of the source distribution. In this case, geometric compactness is satisfied because the blade chord is small compared to the propagation distances to the scattering surfaces and the farfield observers, while acoustic compactness is also satisfied because the blade chord is small compared to the acoustic wavelength at the blade passing frequency and its non-negligible harmonics. The acoustic field due to the tonal sources without scattering is obtained at the observer locations by applying the compact version of Farassat’s Formulation 1A (F1A) [29].

#### 2. Broadband Noise

Broadband turbulent boundary layer trailing edge noise is modeled with a time-domain synthesis approach [18] using the boundary layer properties at the trailing edge of each blade section. The method extends a class of semi-analytical broadband noise models based on aeroacoustic response functions to obtain time-domain realizations of blade self-noise. An aeroacoustic response function gives the linearized acoustic response of the two-dimensional airfoil section to hydrodynamic fluctuations that are responsible for noise generation. A modeled spectrum for the hydrodynamic disturbances, such as the wall pressure spectrum (WPS) for turbulent fluctuations at the trailing edge, is then used in combination with the aeroacoustic response function to obtain the spectrum of the radiated acoustic field. Models based on this approach were introduced by Amiet for leading edge noise [30] and trailing edge noise [31] using analytical aeroacoustic response functions for a semi-infinite flat plate. Amiet’s method has been extended to take into account leading edge backscattering effects and oblique disturbance modes [32], and similar methods have been introduced for other noise sources such as vortex shedding noise [13]. The approach can also be applied with numerical aeroacoustic response functions to more accurately reflect the radiation characteristics of realistic airfoil geometries [33].

While Amiet’s method is widely used for rotor trailing edge noise modeling [34], it only provides point-wise spectral information while discarding relative phase information that is necessary for scattering predictions. Although the sources are stochastic, the incident signals at different points are causally related to the same sources, and therefore the basic modeling approach must be extended to capture the relative time delay at each point on the scattering surface. Through time-domain realization and propagation of the modeled noise sources, we can naturally retain this causal information.

Trailing edge noise has previously been synthesized in the time domain using aeroacoustic response functions and WPS models for isolated airfoils [35] and propellers [36]. In both of these previous works, the fluctuating pressure distribution on the airfoil surface was realized in the time domain by discretizing the WPS into Fourier modes with

random phases and multiplying by the aeroacoustic response function. The resulting fluctuations were then propagated as unsteady loading noise using the full FWH analogy. The main limitation of this approach is the computational cost of the full FWH surface quadrature, which must adequately resolve all of the acoustic wavelengths. In our time-domain approach [18], we use geometrical approximations based on Amiet's method to perform chordwise and spanwise integrations over each blade element in closed form. The result is an observer-dependent effective loading that takes into account the acoustic non-compactness of the noise source and can be propagated with a compact FWH formulation at substantially reduced computational cost.

Let us consider a blade element with normal vector  $\hat{n}$ , chord  $c$ , and span  $d$ . For notational convenience, we let  $x$ ,  $y$ , and  $z$  denote Cartesian coordinates in the chordwise, spanwise, and normal directions, measured from the center of the trailing edge. For trailing edge noise, we suppose the turbulent boundary layer eddies can be decomposed into a continuum of sinusoidal gusts with chordwise and spanwise wavenumbers  $k_x$  and  $k_y$ , convection velocity  $U_c$ , and gust amplitude spectrum  $\hat{P}(k_x, k_y)$ . Under the assumption of geometric compactness, we obtain an effective loading source [18]:

$$L_{eff}(r_{obs}, t) = 2\hat{n} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \hat{P}(k_x, k_y) L_a(k_x, k_y, k_x(1 - \alpha_x)) D(k_y - k_x \alpha_y) \exp(ik_x U_c t) dk_x dk_y, \quad (1)$$

where  $r_{obs}$  denotes the observer position and the parameters  $\alpha_x$  and  $\alpha_y$  encode the dependence on the propagation direction:

$$(\alpha_x, \alpha_y, \alpha_z) = \frac{U_c}{c_0} \frac{r}{|r|(1 - M_r)}. \quad (2)$$

Here,  $M_r = (U \cdot r)/(c_0|r|)$  is the projection of the source Mach vector in the propagation direction,  $c_0$  is the speed of sound,  $r = r_{obs} - r_{src}$  is the propagation vector, and  $r_{src}$  denotes the reference position of the blade element (typically the center of the trailing edge). The functions  $L_a$  and  $D$  describe the acoustic weighting of the lift over the chord and span:

$$L_a(k_x, k_y, k_c) = \frac{1}{c} \int_{-c}^0 g(x, k_x, k_y) \exp(-ik_c x) dx, \quad (3)$$

$$D(k) = \text{sinc}\left(\frac{kd}{2}\right), \quad (4)$$

where  $g(x, k_x, k_y)$  is the aeroacoustic response function. In this work, we use the analytical aeroacoustic response function for a semi-infinite flat plate derived by Roger and Moreau [32], without the leading edge backscattering correction.

For sufficiently high blade aspect ratios, we approximate the integral over the spanwise wavenumbers to obtain the following simplified form:

$$L_{eff}(r_{obs}, t) = 2\hat{n} \int_{-\infty}^{\infty} \hat{P}(k_x, k_x \alpha_y) \sqrt{\frac{2\pi}{d}} L_a(k_x, k_x \alpha_y, k_x(1 - \alpha_x)) \exp(ik_x U_c t) dk_x. \quad (5)$$

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

$$L_{eff}(r_{obs}, t) \approx 2\hat{n} \sqrt{\frac{2\pi}{d}} \sum_{n=1}^N A_n L_a(n\Delta k_x, n\Delta k_x \alpha_y, n\Delta k_x(1 - \alpha_x)) \exp(in\Delta k_x U_c t), \quad (6)$$

$$A_n = \sqrt{\frac{1}{\pi} l_y(n\Delta k_x, n\Delta k_x \alpha_y) S_{qq}(n\Delta k_x U_c) \Delta k_x \exp(i\phi_n)}, \quad (7)$$

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 [32]:

$$l_y(k_x, k_y) = \frac{k_x/b_c}{k_y^2 + (k_x/b_c)^2}. \quad (8)$$

In this work, we use Rozenberg's WPS model [37], with a spanwise correlation length constant of  $b_c = 1.6$  and a convection velocity of  $U_c = 0.8U$ , where  $U$  is the freestream velocity relative to the airfoil section.

In the frequency domain, the contributions of individual blade elements are typically assumed to be uncorrelated and summed incoherently. With the time domain approach, the random Fourier coefficient phases are realized independently for each element and a final farfield spectrum is obtained by averaging over multiple realizations to approximate the effect of uncorrelated elements. Details of the derivation and validation of the time-domain broadband noise synthesis method are provided in [18].

## B. Acoustic Scattering

The incident acoustic pressure field  $p'_i$  computed with FWH does not account for the presence of the airframe during propagation and does not automatically satisfy the sound-hard boundary condition on the vehicle surfaces. We apply a time-domain boundary element method (TDBEM) [20] to calculate a scattered acoustic field  $p'_s$  that cancels the boundary residual from the incident field to obtain a total acoustic field  $p' = p'_i + p'_s$  that satisfies the boundary condition.

For low Mach numbers, we approximate the mean flow around the vehicle as a uniform freestream. This background flow approximation is selected for simplicity and to match the propagation approximations introduced by applying the solid surface FWH analogy without the volume terms. Under this background flow assumption, the propagation of the acoustic field satisfies a convected wave equation that can be exactly transformed to the standard rest medium wave equation by applying the Prandtl-Glauert-Lorentz (PGL) transformation [38]. The sound-hard boundary condition with the uniform background flow approximation requires zero energy flux through the boundary, which is equivalent to zero normal acoustic velocity in the transformed variables [38]. Consistent with the initial uniform background flow approximation, this boundary condition can be further approximated to zero normal pressure gradient [39]. The pressure gradient for the incident field can be obtained from the FWH analogy using the compact version of Lee's Formulation G1A [40].

Let  $\Omega \subset \mathbb{R}^3$  denote the interior of a bounded scattering body, and let  $\Gamma = \partial\Omega$  denote its boundary. We assume that the normal pressure gradient on  $\Gamma$  due to the incident field is known from the FWH computation:

$$\frac{\partial p'_i}{\partial n_x}(x, t) = -g(x, t), \quad (9)$$

where  $x \in \Gamma$  and  $t$  are the transformed space and time coordinates, and  $\frac{\partial}{\partial n_x}$  denotes the gradient in the normal direction at the point  $x$ . The TDBEM then calculates a scattered field  $p'_s(x, t)$  that satisfies the following initial-boundary value problem (formulated in the transformed space-time coordinates):

$$\frac{1}{c_0^2} \frac{\partial^2 p'_s}{\partial t^2} - \nabla^2 p'_s = 0, \quad x \in \mathbb{R}^3 \setminus \overline{\Omega}, t > 0, \quad (10a)$$

$$p'_s(x, 0) = 0, \quad x \in \mathbb{R}^3 \setminus \overline{\Omega}, \quad (10b)$$

$$\frac{\partial p'_s}{\partial n_x}(x, t) = g(x, t), \quad x \in \Gamma, t > 0. \quad (10c)$$

The TDBEM is based on full space-time Galerkin discretization of the first kind boundary integral formulation of (10):

$$g(x, t) = \int_0^t \int_{\Gamma} \frac{\partial^2 G}{\partial n_x \partial n_y} \psi(y, \tau) dy d\tau, \quad x \in \Gamma, t \in [0, T], \quad (11)$$

where  $\psi = [p_s]$  is the double layer potential, which corresponds to the jump in scattered pressure over the boundary, and  $G(x, y, t, \tau)$  is the free-space Green's function for (10a):

$$G(x, y, t, \tau) = \frac{\delta\left(t - \tau - \frac{|x-y|}{c_0}\right)}{4\pi|x-y|}. \quad (12)$$

Bamberger and Ha-Duong [41] obtain the energetic weak form of (11):

$$\int_0^T \int_{\Gamma} \int_{\Gamma} \frac{\partial^2 G}{\partial n_x \partial n_y} \psi(y, t - |x-y|) \dot{\eta}(x, t) dy dx dt = \int_0^T \int_{\Gamma} g(x, t) \dot{\eta}(x, t) dx dt, \quad (13)$$

for test functions  $\eta$  and the trial functions  $\psi$ . The TDBEM discretizes (13) with piecewise linear test and trial basis functions in space and time on a triangular surface mesh. Once the double layer potential is computed, the scattered field can be obtained from the representation formula:

$$p'_s(x, t) = \int_0^t \int_{\Gamma} \frac{\partial G(x, y, t, \tau)}{\partial n_y} \psi(y, \tau) dy d\tau. \quad (14)$$

Full formulation and implementation details are reported along with validation results in [20].

### III. UAM Concept Vehicle Configuration

The NASA tiltwing is a six-passenger concept vehicle design that was developed as part of a series of NASA UAM Reference Vehicles, in part to facilitate the development and demonstration of UAM noise analysis tools for conceptual design tasks [42]. The tiltwing has six rotors distributed along a tilting main wing and two tilting rotors installed on the empennage. All eight rotors are identical up to their rotation directions and provide equal lift during hover and equal thrust during cruise.

Sources of aerodynamic noise have not been comprehensively investigated in the tiltwing concept vehicle. A preliminary acoustic analysis was performed during the conceptual design for the isolated rotors using BEMT [19]. The isolated rotor noise was dominated by broadband trailing edge noise in hover and cruise, although the first tonal peak was also prominent in the hover condition. Subsequent high-fidelity aerodynamic modeling [43] identified significant rotor-wake-airframe interactions that could result in interactional noise sources, although the noise sources themselves were not characterized.

In this work, we consider a simplified airframe geometry consisting of the vehicle fuselage without the wings, empennage, nacelles, and landing gear. The vehicle geometry is obtained directly from the publicly available OpenVSP model. The scattering surface is discretized with 49748 faces and 24876 nodes to resolve frequencies up to 2.1 kHz in hover and 1.6 kHz in cruise with at least four points per wave in all directions. The effective frequency resolution in cruise is reduced compared to hover because the wavelengths in the upstream direction are decreased by the mean flow convection. We focus on the design hover and cruise flight conditions, which are summarized in Table 1. The placement of the scattering surface relative to the rotors is shown for both flight conditions in Figure 1.

**Table 1 Summary of flight conditions.**

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

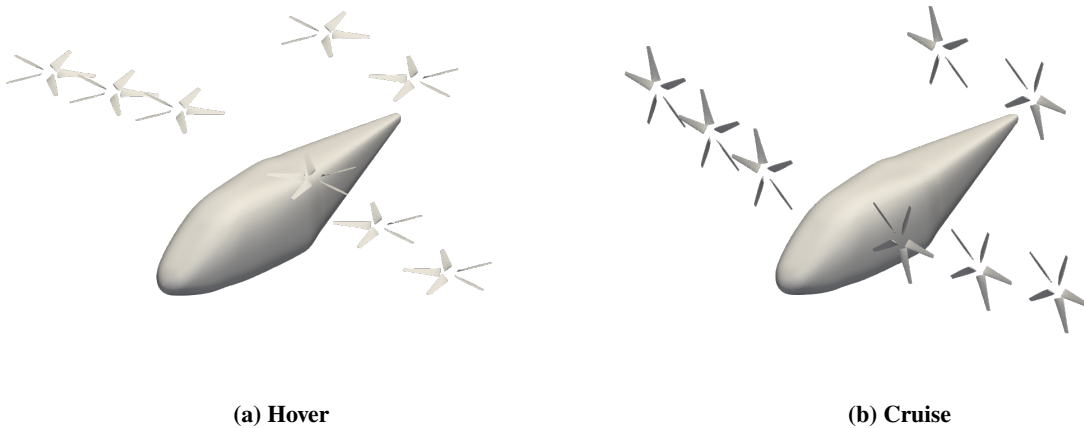


**Fig. 1 Simplified tiltwing geometry in hover and cruise conditions.**

## IV. Results

We now present farfield noise predictions for the tiltwing vehicle, taking into account fuselage scattering effects. The time-domain broadband trailing edge noise predictions are obtained by averaging over 10 independent stochastic realizations. The acoustic predictions are reported on a noise hemisphere with a radius of 30 m, centered on the aircraft design center of gravity.

### A. Full-Vehicle Noise

To assess the full-vehicle noise, we compute overall sound pressure levels (OASPL) with and without A-weighting. The OASPLs are band-limited to the resolved frequencies (2.1 kHz in hover and 1.6 kHz in cruise). The tonal contributions from the individual rotors are summed incoherently to represent an aircraft without phase synchronization, which reflects the control approach of many current industry concepts. The OASPL hemispheres are presented for the hover and cruise flight conditions in Figures 2 and 3, respectively. In the azimuthal direction,  $0^\circ$  corresponds to directly in front of the vehicle, while  $-90^\circ$  elevation corresponds to directly below the vehicle. Separate hemispheres are presented for the tonal and broadband components in addition to the total acoustic field.

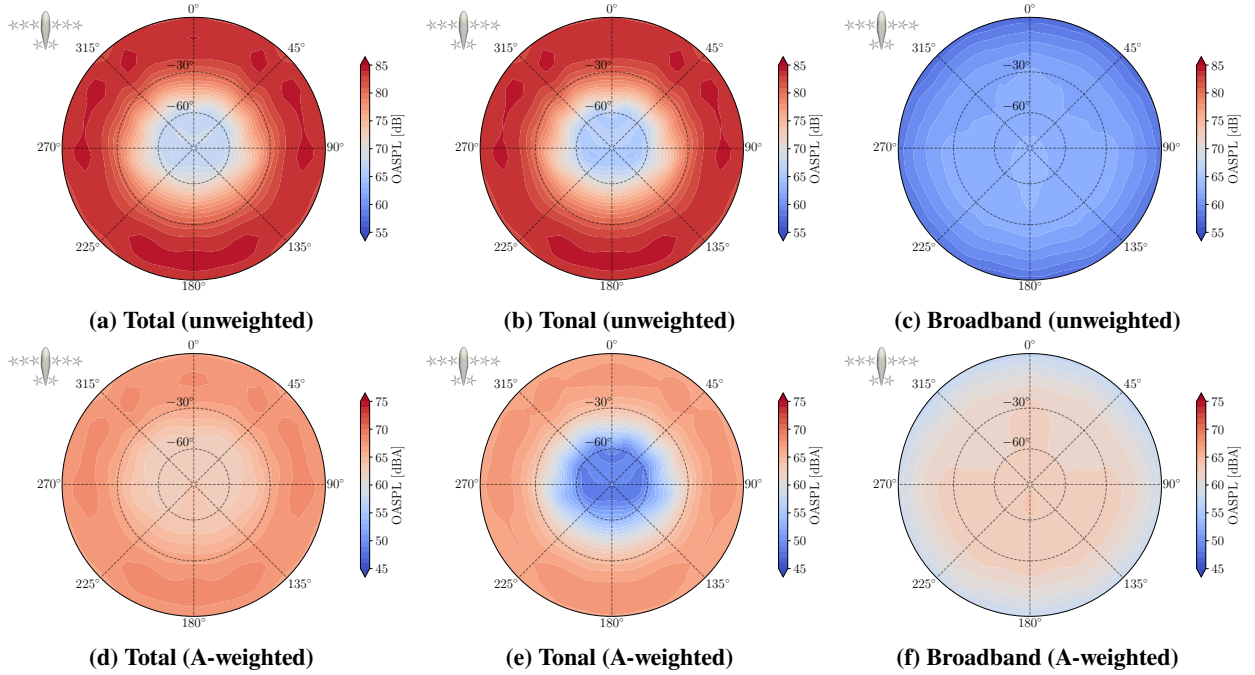


**Fig. 2 Comparison of unweighted (top) and A-weighted (bottom) OASPL hemispheres in hover by contribution (from left to right: total, tonal, broadband).**

In hover (Figure 2), the tonal noise is strongest at shallow elevation angles greater than  $-30^\circ$ , and dominates both the unweighted and weighted total OASPL hemispheres at these directivities. The broadband noise has a weakly axial directivity and is strongest below the vehicle. The A-weighting reduces the significance of the tonal contribution compared to the higher-frequency broadband, increasing the relative significance of the broadband component, which dominates the total OASPL for elevation angles below  $-45^\circ$ . Without the A-weighting, the tonal noise dominates the total OASPL everywhere except directly below the vehicle at steep elevation angles below  $-60^\circ$ . While the A-weighting affects the total OASPL directivity by emphasizing the broadband contribution, the directivities of the tonal and broadband components themselves are not substantially affected.

In cruise (Figure 3), the tonal contribution is strongest in the vehicle longitudinal plane and increases at shallow elevation angles around  $90^\circ$  and  $270^\circ$  azimuth on either side of the vehicle. The broadband contribution is more omnidirectional and increases slightly in the forward direction. In this flight condition, the rotor disk loading and resulting tonal contribution are substantially reduced, and the broadband contribution is therefore more significant in both the unweighted and A-weighted total OASPL hemispheres. The broadband contribution dominates the unweighted hemisphere everywhere except at shallow elevation angles around  $90^\circ$  and  $270^\circ$  azimuth, while the A-weighted total

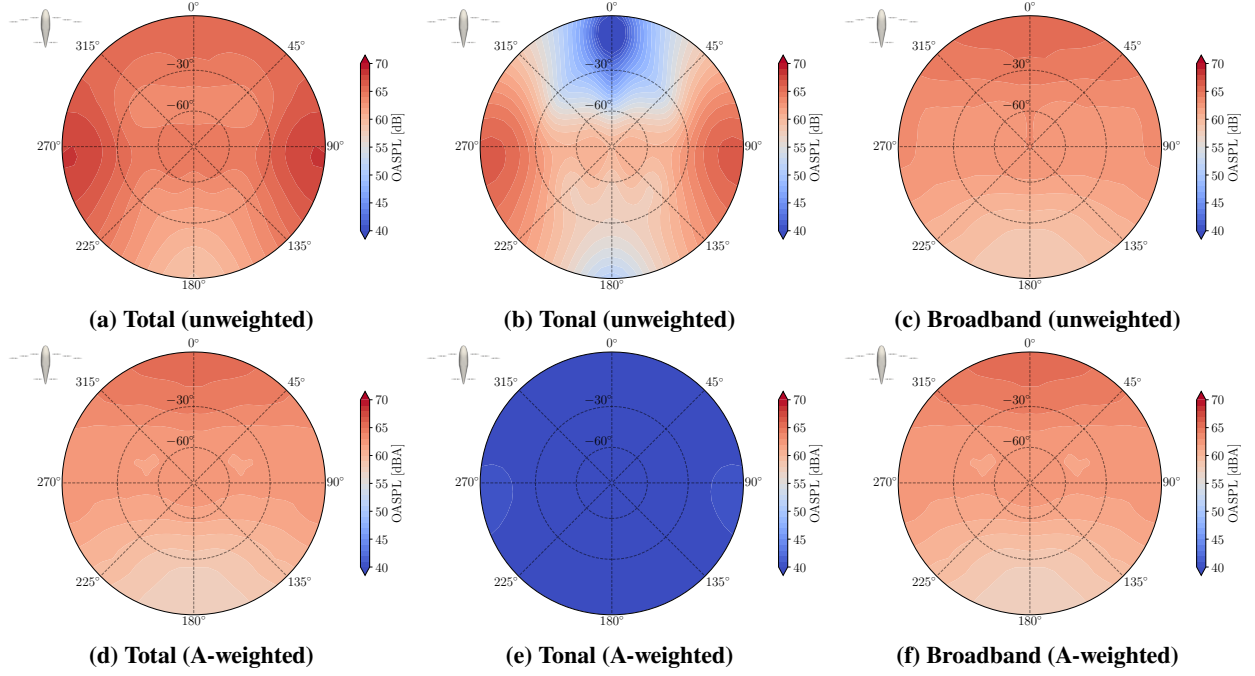


**Fig. 3 Comparison of unweighted (top) and A-weighted (bottom) OASPL hemispheres in cruise by contribution (from left to right: total, tonal, broadband).**

OASPL hemisphere is entirely dominated by the broadband contribution.

To examine the effect of fuselage scattering, we compute the difference between the OASPLs with and without the contribution from the scattered field:

$$\Delta\text{OASPL} = \text{OASPL} - \text{OASPL}_i, \quad (15)$$

where  $\text{OASPL}_i$  is the OASPL of the incident field only. Positive values therefore correspond to amplification due to acoustic scattering, while negative values correspond to reduction. These differences are reported with and without A-weighting for the hover and cruise conditions in Figures 4 and 5, respectively.

In hover (Figure 4), the tonal  $\Delta\text{OASPL}$  hemispheres show substantial amplification above 10 dB at elevation angles below  $-60^\circ$ . Above  $-60^\circ$ , some interference patterns are apparent, resulting in small amplifications and reductions within about 1-2 dB. In contrast, the broadband hemispheres show a much smaller scattering effect, with small reductions on each side of the vehicle at moderate to steep elevation angles and a small increase near the horizon. While the tonal and broadband scattering trends themselves are not significantly affected by the A-weighting, the effect on the overall scattering pattern is very significant. The overall unweighted scattering effect is dominated by the tonal component, showing significant amplification at steep elevation angles, while the A-weighting increases the influence of the broadband component and essentially masks the tonal scattering effect, resulting in only minor amplification and reduction patterns within 1 dB.

In cruise (Figure 5), the tonal  $\Delta\text{OASPL}$  hemispheres show strong amplification in the forward and aft directions, where the incident field is weak. Around the vehicle's longitudinal plane, the tonal  $\Delta\text{OASPL}$  shows moderate amplification at shallow elevation angles. At steep elevation angles, interference results in three longitudinal stripes where the amplification locally vanishes. The broadband component shows weak scattering effects, with small reductions to each side of the vehicle at shallow elevation angles and small amplifications behind and below the vehicle and along the forward horizon. The unweighted total  $\Delta\text{OASPL}$  hemisphere shows peak amplifications of up to 4 dB around  $135^\circ$  and  $225^\circ$  azimuth, while the A-weighted total  $\Delta\text{OASPL}$  hemisphere matches the broadband hemisphere and shows small amplifications and reductions within 1 dB.

Overall, large differences are observed in the scattering trends between the tonal and broadband components and between the two flight conditions, which are presumably related to differences between the directivities and spatial structures of the noise sources. These trends highlight the significance of the relative weighting of tonal and broadband noise components in a given acoustic metric for informing design decisions related to airframe scattering.

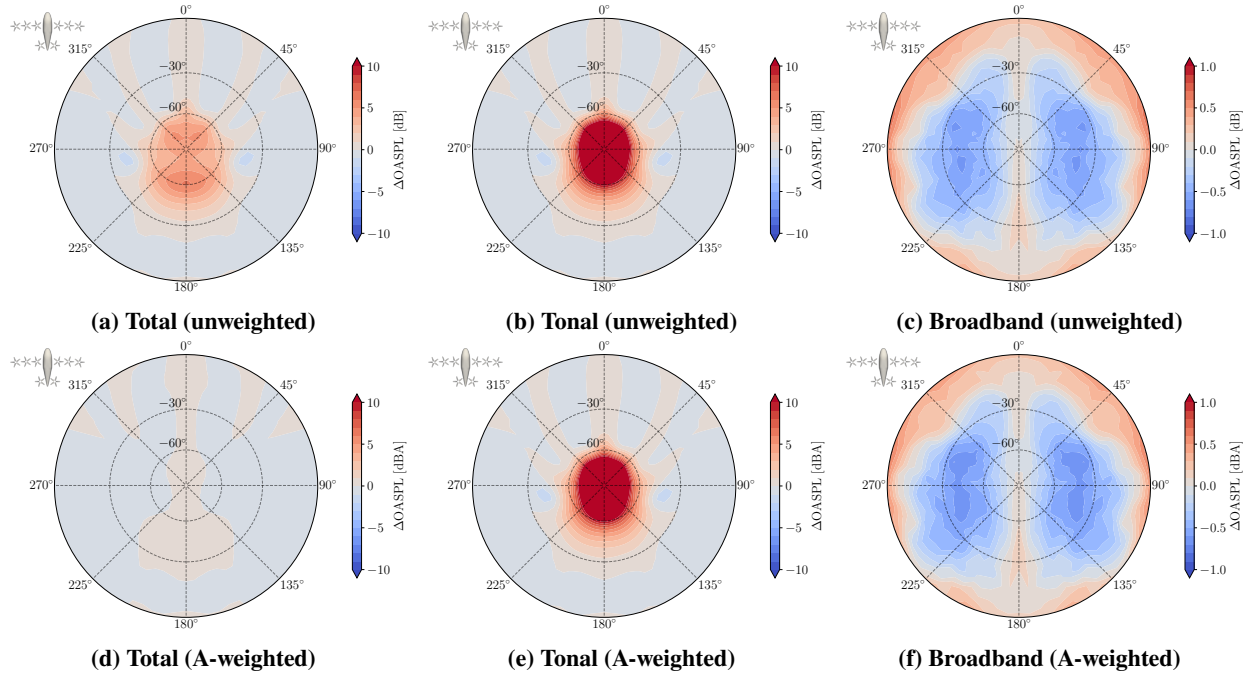


**Fig. 4** Difference between total and incident unweighted (top) and A-weighted (bottom) OASPL hemispheres in hover by contribution (from left to right: total, tonal, broadband).

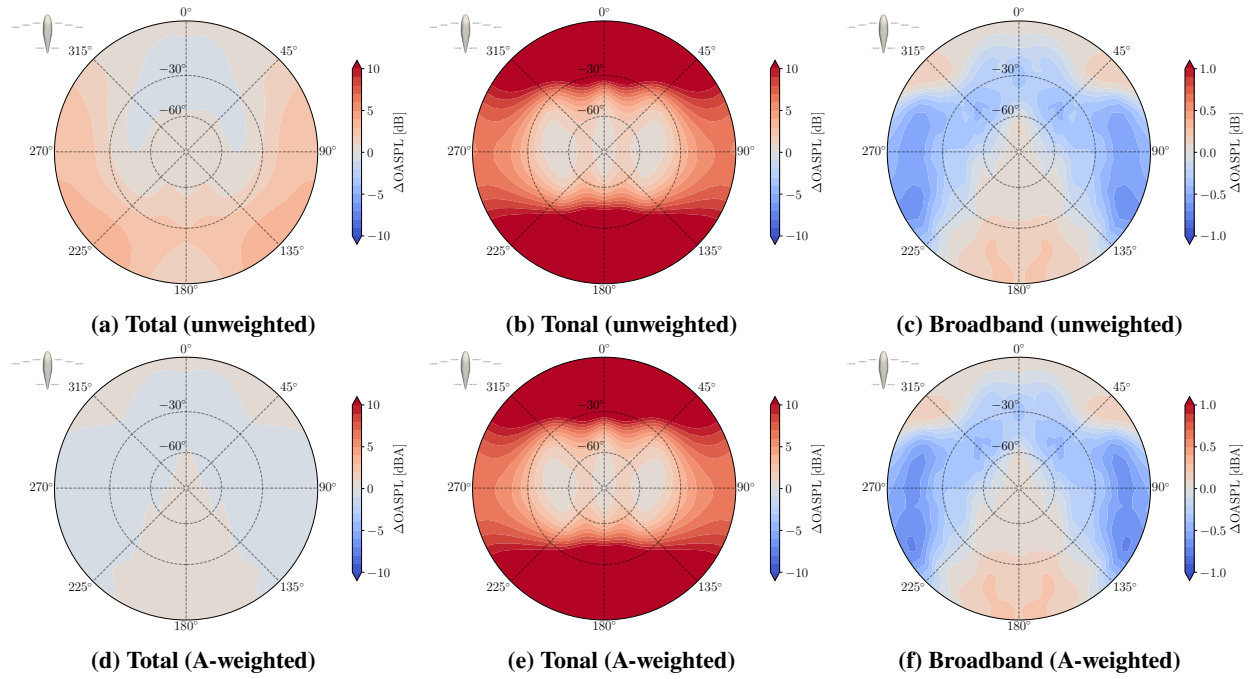


**Fig. 5** Difference between total and incident unweighted (top) and A-weighted (bottom) OASPL hemispheres in cruise by contribution (from left to right: total, tonal, broadband).

## B. Individual Rotor Contributions

To better understand the different scattering effects in the full-vehicle configuration, we examine the contributions from each rotor individually. The vehicle configuration is symmetric, so we select the four rotors on the starboard side. Because A-weighting does not appear to strongly affect the scattering trends in the separate tonal and broadband noise components, we focus on the unweighted OASPL predictions.

### 1. Tonal Noise

We present the tonal  $\Delta$ OASPL hemispheres in hover for each individual rotor (outboard wing, middle wing, inboard wing, empennage) in Figure 6. All four individual hemispheres show strong amplification above 10 dB near the rotor axis below approximately  $-60^\circ$  elevation, where the tonal incident field is weak. Around  $-60^\circ$ , each rotor shows an interference pattern with highly localized reductions that can exceed 10 dB. The interference pattern continues above  $-60^\circ$  as a group of weak radial stripes with small amplifications and reductions within 1-2 dB. The outboard and middle hemispheres appear to have a weak shielding region around  $250^\circ$  azimuth and above  $-30^\circ$ , which may correspond to the shadow of the fuselage. Similar shadows for the inboard and empennage rotors are potentially masked by the interference patterns. These weaker features on the individual hemispheres are masked by the other rotors (including by each rotor's pair on the port side), resulting in the simpler pattern in the combined tonal  $\Delta$ OASPL hemisphere in Figure 4. Overall, the four rotors have qualitatively similar scattering trends with notably little variation in amplification and reduction magnitudes even as the distances to the scattering body vary. This may be related to the in-plane directivity of the tonal noise and the position of the rotors. While the inboard and empennage rotor hubs are the closer to the fuselage, their rotor disk planes are located above the fuselage, which may reduce the magnitude of the incident field on the scattering surface.

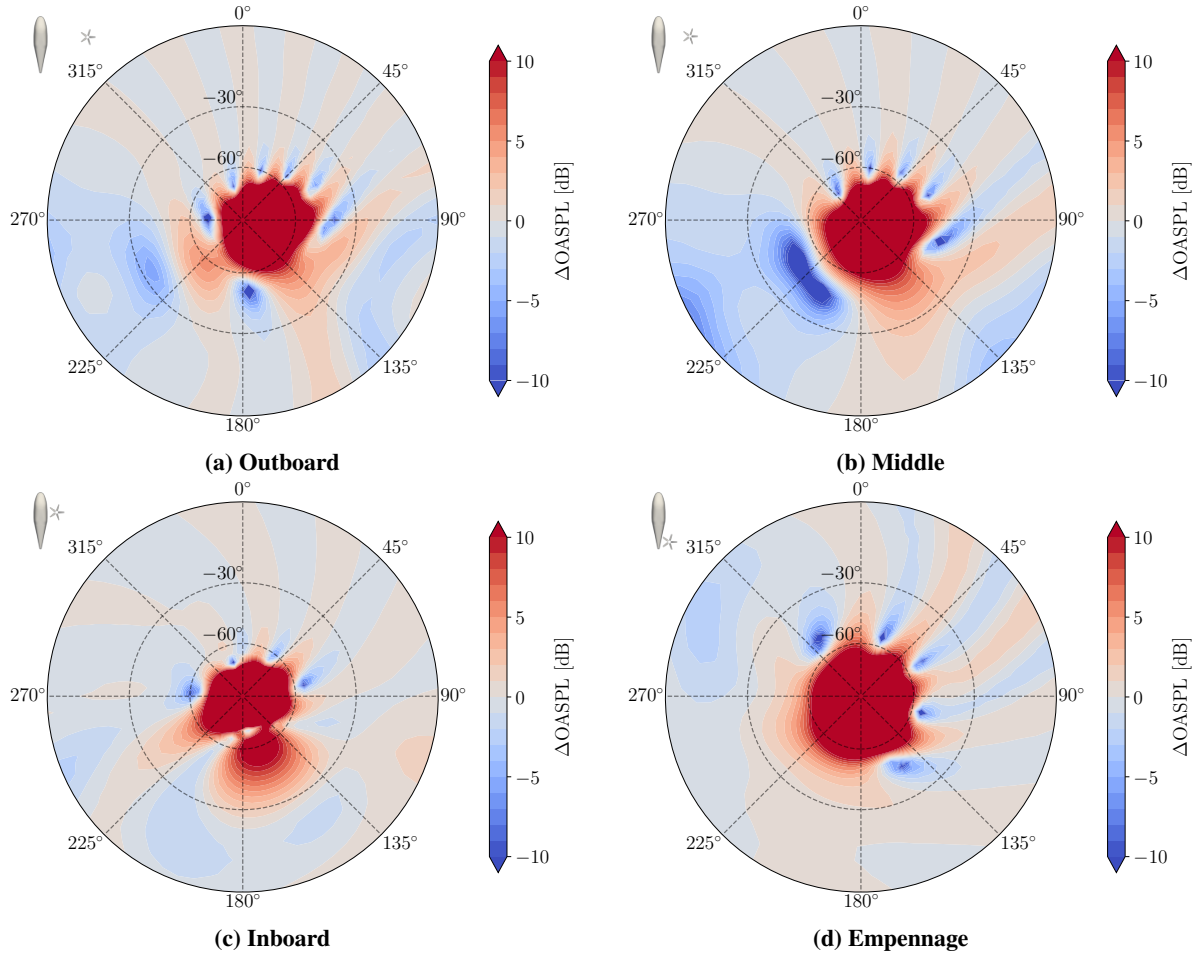


Fig. 6 Difference between total and incident tonal hemispheres in hover for individual rotors.

In cruise (Figure 7), all four rotors show longitudinal interference patterns, but the differences between the scattering trends are more significant than in hover. For the outboard and middle rotors, the interference stripes cover most of the hemisphere, with moderate amplifications and reductions mostly below 5 dB. These rotors also show two amplification regions above 10 dB near the rotor axis in front and behind the vehicle. The inboard and empennage rotors show much stronger interference stripes and amplification regions. The reductions exceed 10 dB and the stripes themselves are spaced more widely. The amplification region for the inboard rotor extends around the entire vehicle at shallow elevation angles, while the forward and aft amplification regions for the empennage rotor are much larger than for the outboard and middle rotors. These differences indicate a stronger scattering effect for the rotors located closer to the scattering body. Because the rotors are tilted forward in cruise, the rotor disk planes directly intersect the fuselage for all rotor locations, so the effect of rotor hub distance is more pronounced. The three longitudinal interference stripes located nearest to the centerline seem to mostly overlap across the different rotor contributions and appear weakly in the combined tonal  $\Delta$ OASPL hemisphere in Figure 5.

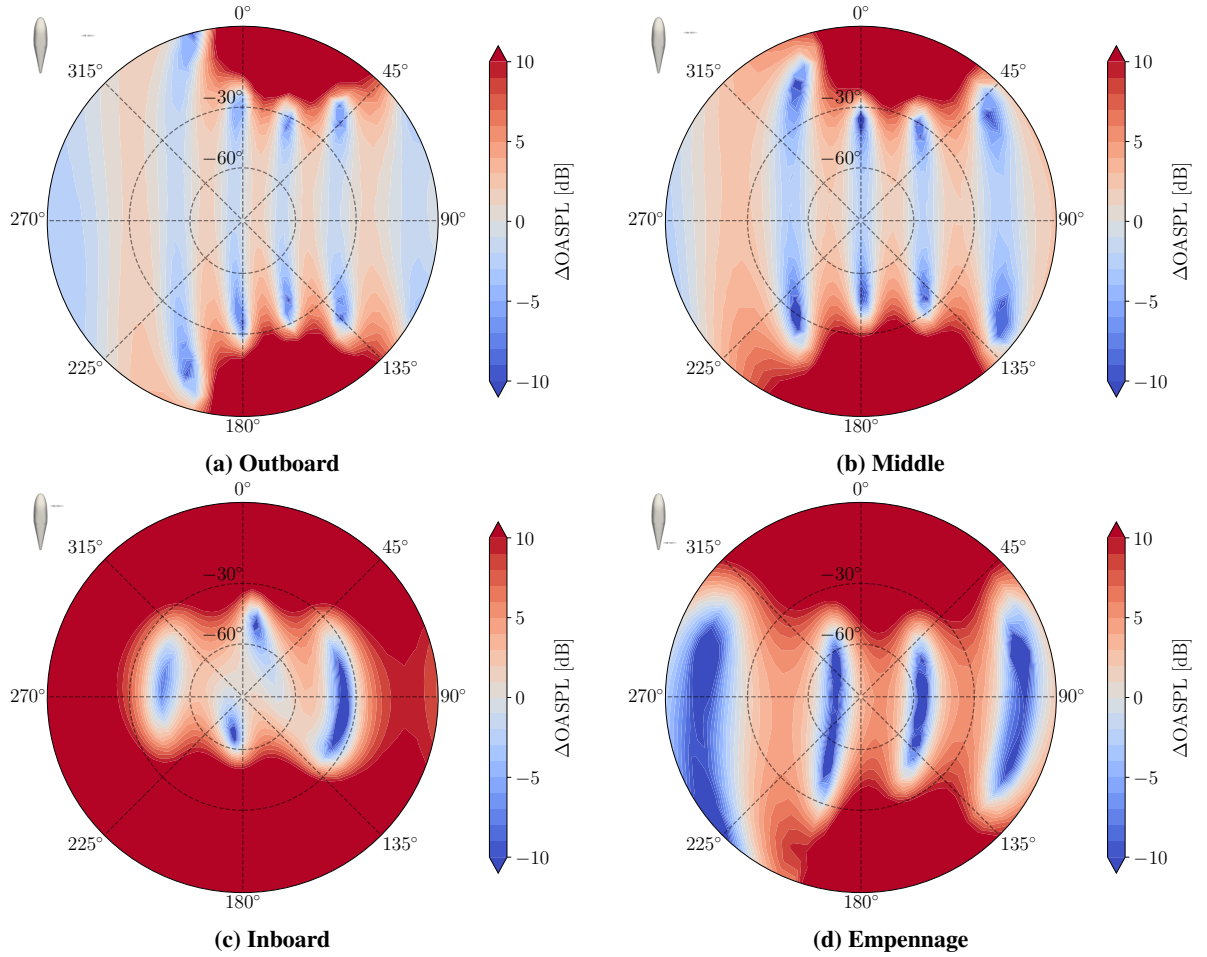


**Fig. 7 Difference between total and incident tonal hemispheres in cruise for individual rotors.**

To help explain some of the scattering trends, we examine the directivities of the scattered fields for each rotor in hover and cruise in Figures 8 and 9. In hover, the outboard and middle rotor scattered tonal noise magnitudes are highest around and behind the vehicle longitudinal plane. The peak magnitude is attained near the weak fuselage shadow regions around 240 – 250° azimuth. Although the peak magnitude is located on the opposite side of the rotor, the directivity is broader and the levels are high over most of the hemisphere on the rotor side. The inboard rotor induces a very different scattered field, with the peak amplitude attained around 180° azimuth and -40° elevation. The levels are high over most of the aft half of the hemisphere, and overall the radiation pattern is more symmetric than for the other wing-mounted rotors. The empennage rotor also induces a more symmetric scattered field, with higher magnitudes in the forward half of the hemisphere. Overall, the magnitudes of the scattered fields of the rotors are similar, with

more lateral directivities in the outboard and middle wing-mounted rotors compared to forward and aft directivities for the empennage and inboard rotors, respectively. Notably, the peak amplifications observed due to the inclusion of the scattered fields (Figure 6) do not coincide with the peak amplitudes of the scattered fields themselves (Figure 8).

In cruise, the difference in the scattered field magnitudes between the rotors is very pronounced. The outboard and middle rotor scattered tonal noise levels are similar, but the levels increase significantly for the inboard and empennage rotors, which are located closer to the fuselage. In particular, the increase between the middle and inboard rotors, which are similarly oriented relative to the fuselage, is approximately 30 dB. This rapid increase suggests a qualitative change in scattering when the fuselage is located in the immediate nearfield of the rotor, where the pressure gradients are strongly affected by the rotor geometry in addition to the wavelength. The hemispheres also show important differences in the scattered field directivities. For the outboard and middle rotors, the scattered field is primarily directed in the vehicle longitudinal plane, with slight increases at shallow elevation angles. The empennage rotor is similar, but the directivity is broader on the rotor side. For the inboard rotor, the directivity is primarily lateral, with the highest levels near 90° and 270° azimuth at shallow elevation angles and lower levels around the vehicle center plane and especially in the forward direction.

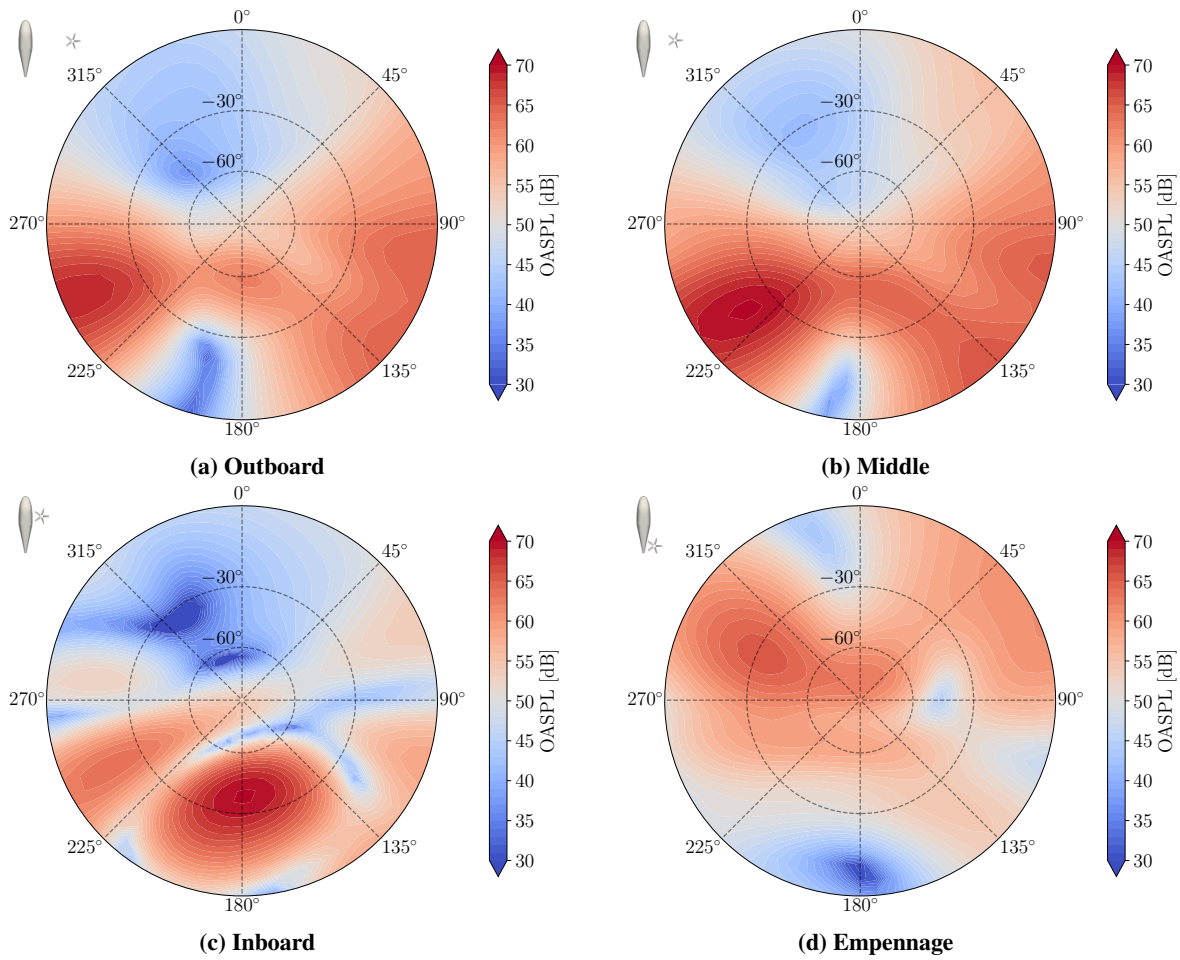


**Fig. 8 Scattered tonal noise hemispheres in hover for individual rotors.**

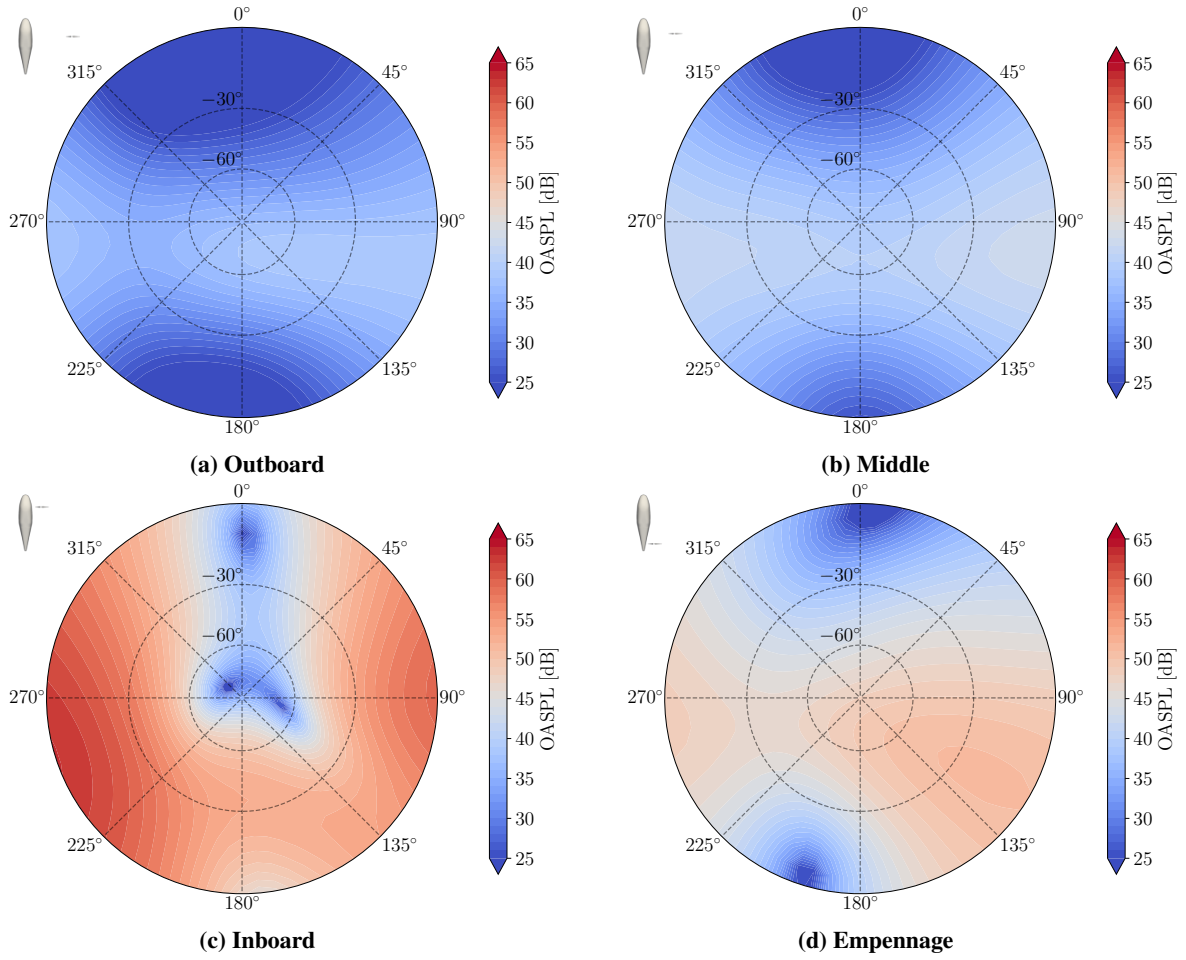


**Fig. 9 Scattered tonal noise hemispheres in cruise for individual rotors.**

## 2. Broadband Noise

The broadband  $\Delta$ OASPL hemispheres are shown for each rotor in hover in Figure 10. The main feature of these hemispheres is a prominent shadow zone due to shielding by the fuselage. This shadow zone is located between 220° and 300° azimuth at shallow elevation angles for the outboard and middle rotors and at steeper elevation angles for the inboard rotor. For the empennage rotor, the shadow zone appears farther forward from 230° to 350° azimuth. The peak magnitude of the reduction in each shadow zone is approximately 8-10 dB and is highest for the inboard rotor. Small areas of amplification within 1-2 dB are visible around 90° azimuth for the middle and inboard rotors, but otherwise the scattering effect is minimal outside of the shadow zone.

The broadband  $\Delta$ OASPL hemispheres are shown for each rotor in cruise in Figure 11. As with the hover condition, the main feature of these hemispheres is a strong shadow region due to the fuselage. The locations of the shadow regions are slightly shifted due to the changes in rotor position and orientation combined with the effect of the mean flow. Outside of the shadow region, small areas of amplification and reduction within 1-2 dB are visible, including near 135° azimuth and 0° elevation for the three wing-mounted rotors.

Overall, the broadband scattering patterns of individual rotors in both flight conditions are similar and are characterized by a strong shielding effect without significant amplification regions or interference patterns. Compared to the tonal noise component, the effect of the rotor orientation is relatively small because the broadband field is less strongly directed and lacks the spatial coherence that results in the tonal noise interference patterns. Although the peak reductions are significant, the shadow zones are mostly non-overlapping (especially with each rotor's pair on the port side) and their effects mostly cancel in the overall broadband  $\Delta$ OASPL hemispheres shown in Figures 4 and 5. However, each rotor individually has a strong shadow zone and a configuration that produced more overlap would likely result in a strong overall shielding effect.

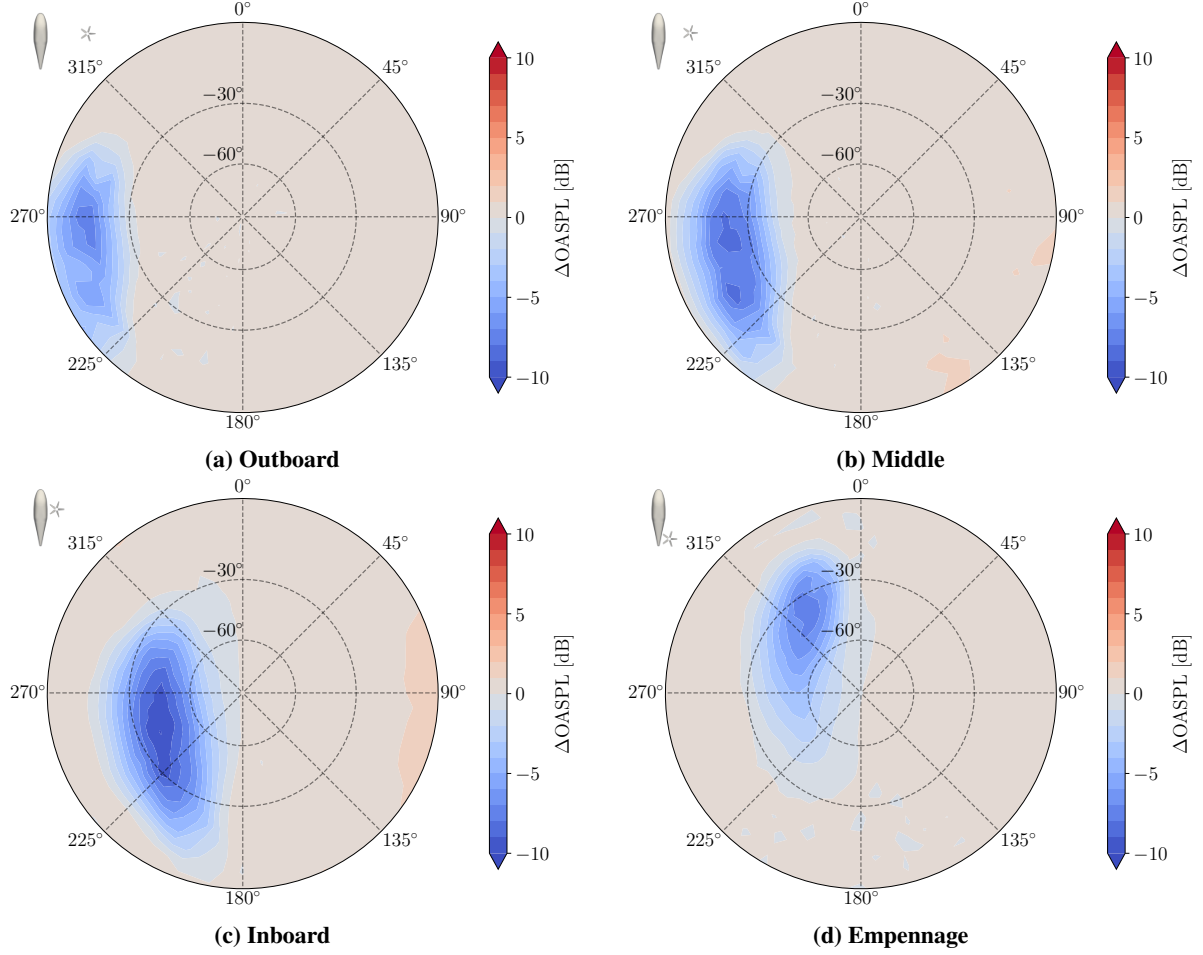


**Fig. 10** Difference between total and incident broadband hemispheres in hover for individual rotors.

To help explain the broadband scattering trends, we show the directivities of the scattered fields for each rotor in hover and cruise in Figures 12 and 13. In both hover and cruise, the scattered fields are strongest in the fuselage shadow regions, where they are contributing to destructive cancellation of the incident fields. Outside of the shadow regions, the scattered levels are low on the side of the hemisphere opposite the rotors. On the rotor side, the levels are more uniform, peaking at intermediate elevation angles. These levels are too low relative to the incident field to result in a significant scattering effect on this side of the hemisphere. Unlike the tonal scattered fields in hover, the magnitudes of the broadband scattered fields in both flight conditions increase noticeably with decreasing rotor distance from the scattering body, likely due to the more uniform directivity of the broadband noise component.

Finally, to explore potential frequency-dependent scattering trends, we compute the differences between total and incident broadband sound pressure levels (SPL) at selected one-third octave bands. Hemispheres are presented in Figure 14 in hover and cruise condition for the inboard wing rotor, which showed the strongest scattering effect in both flight conditions. In both flight conditions, the fuselage shadow zones become significantly stronger and sharper with increasing frequency. At the lower center frequencies of  $f_c = 315$  Hz and  $f_c = 630$  Hz, the shadow is still prominent but more diffuse, and there appears to be a weak annular pattern surrounding the shadow region. At the highest center frequency of  $f_c = 1250$  Hz, the edges of the shadow zones are relatively clean and the annular patterns are significantly reduced. This is the expected behavior in the high-frequency limit when the wavelength is very short compared to the dimensions of the scattering body.

To confirm these trends, we plot one-third octave band SPL spectra of the inboard rotor broadband noise at observer locations in the shadow zones at  $270^\circ$  azimuth and  $-45^\circ$  and  $-25^\circ$  elevation angles for hover and cruise, respectively (Figure 15). In both shadow zones, the incident and scattered fields have nearly identical magnitudes at all frequencies with more complete cancellation achieved at higher frequencies, resulting in an increasing shielding effect.

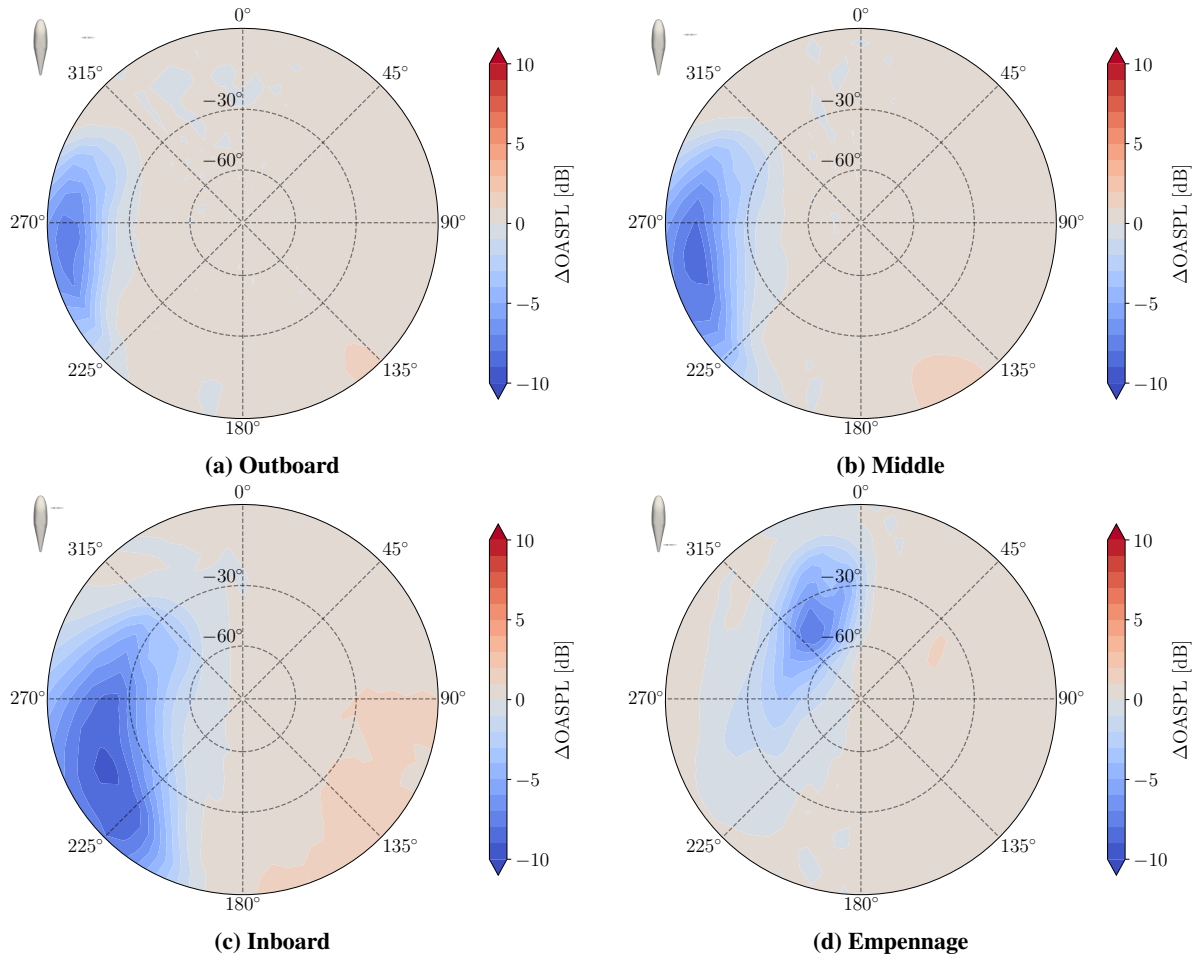


**Fig. 11** Difference between total and incident broadband hemispheres in cruise for individual rotors.

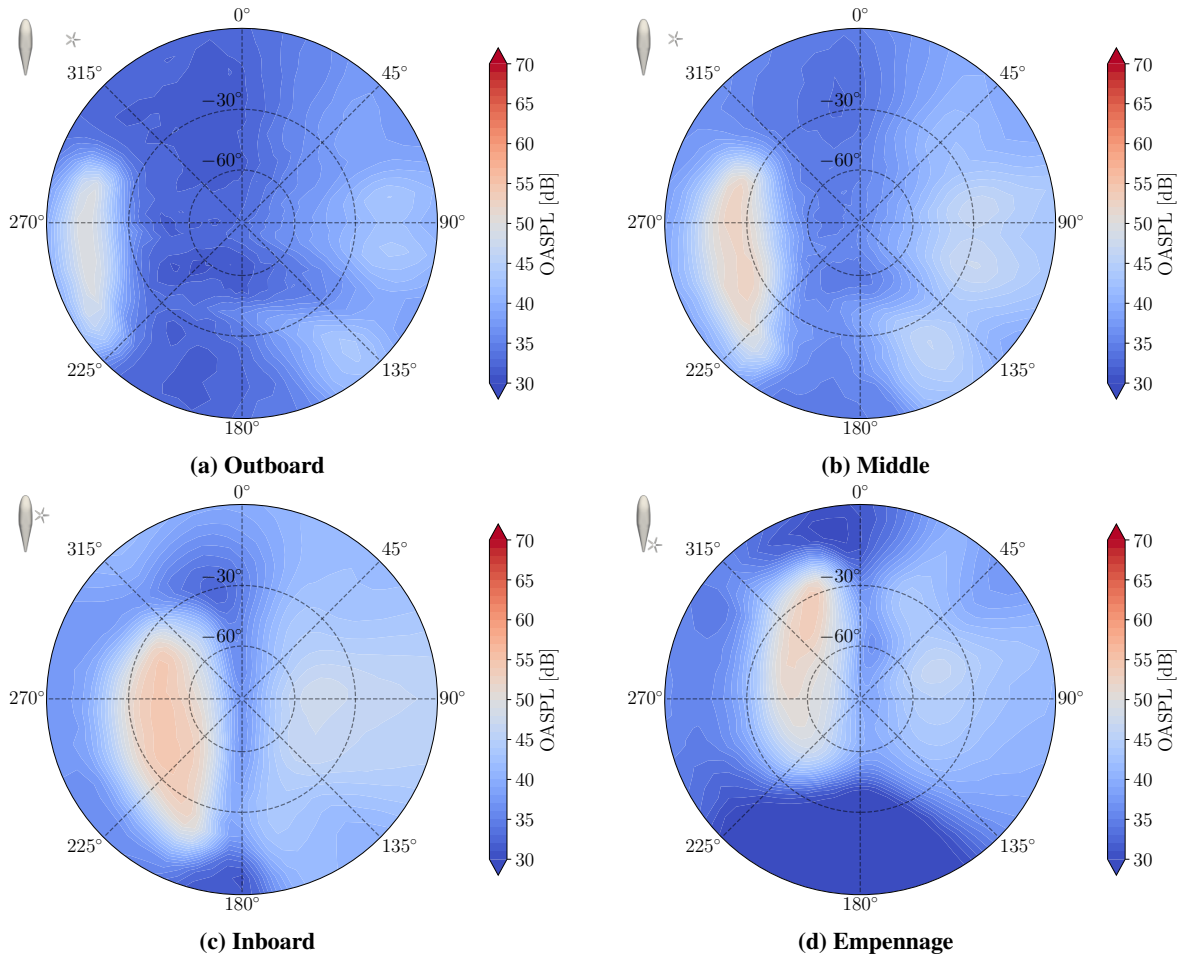


**Fig. 12 Scattered broadband noise hemispheres in hover for individual rotors.**

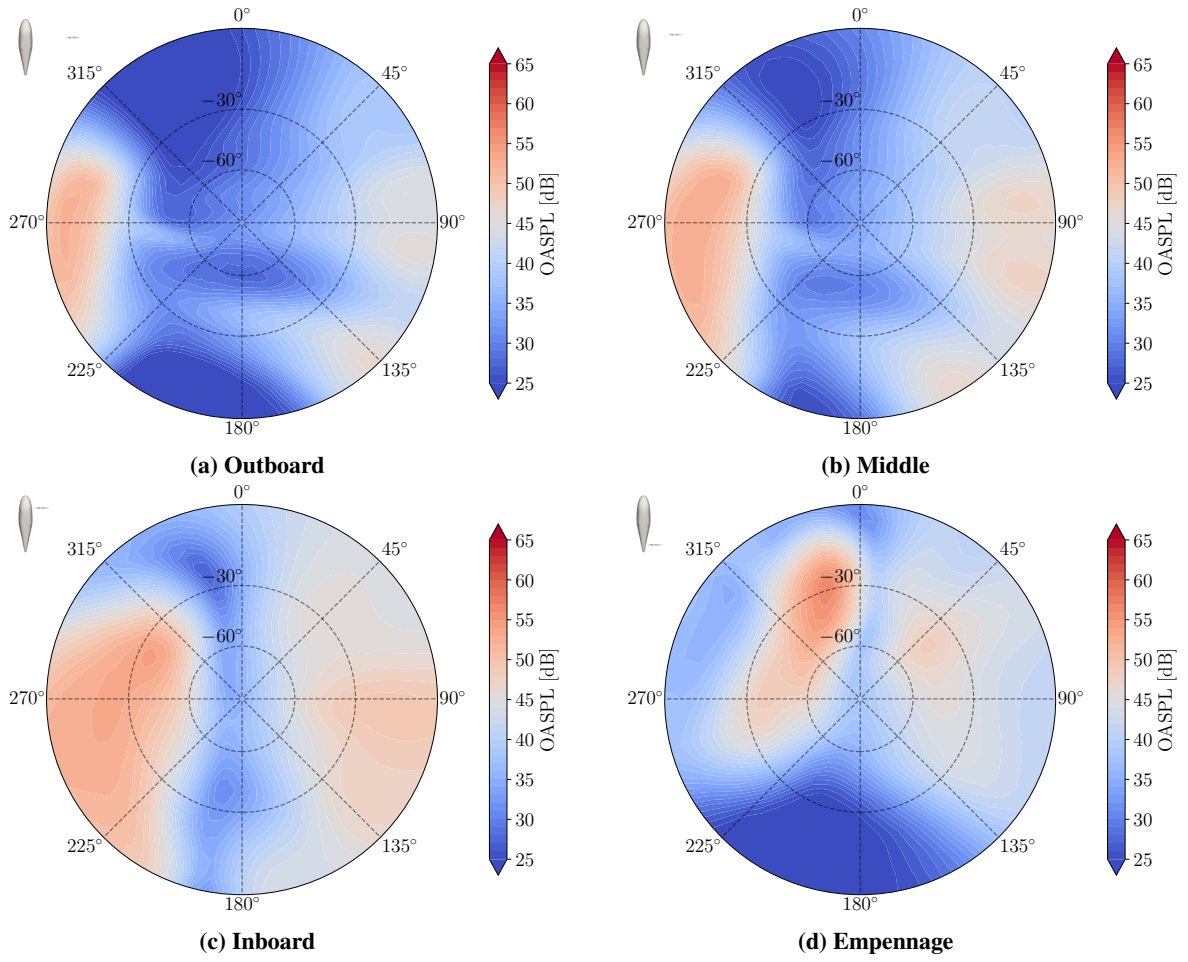


**Fig. 13 Scattered broadband noise hemispheres in cruise for individual rotors.**

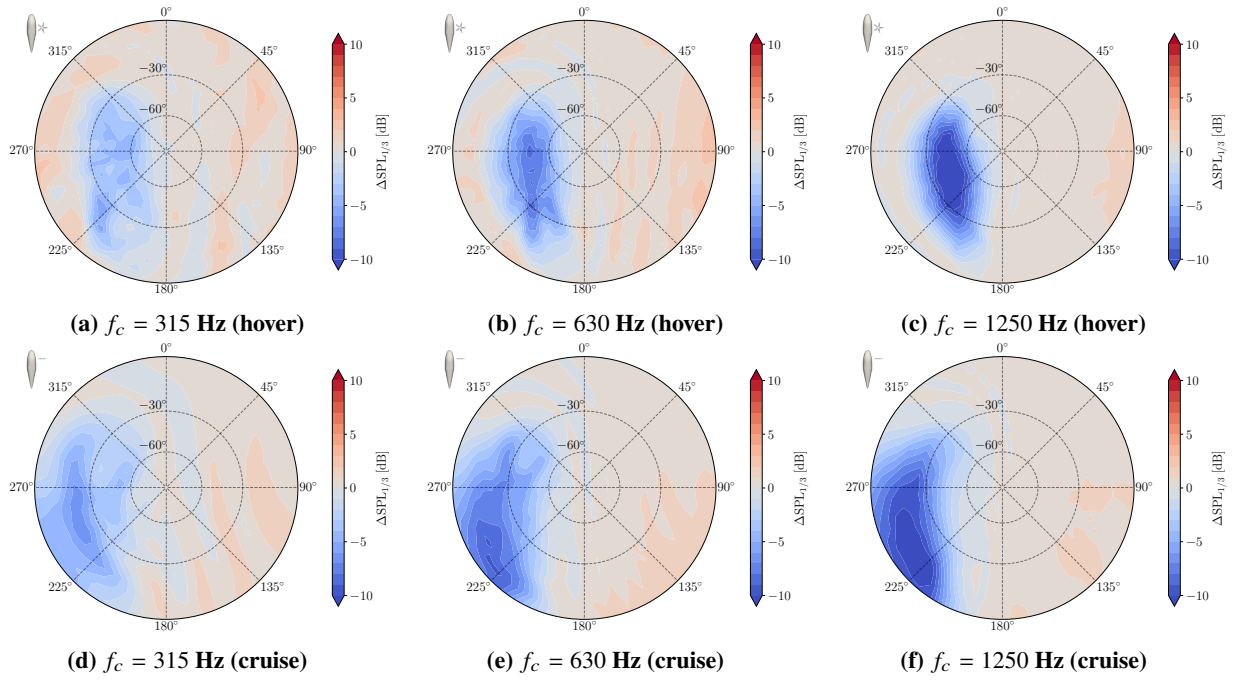


**Fig. 14** Difference between total and incident one-third octave band SPL broadband noise hemispheres for the inboard rotor in hover (top) and cruise (bottom) at selected center frequencies (from left to right:  $f_c = 315$  Hz,  $f_c = 630$  Hz,  $f_c = 1250$  Hz).

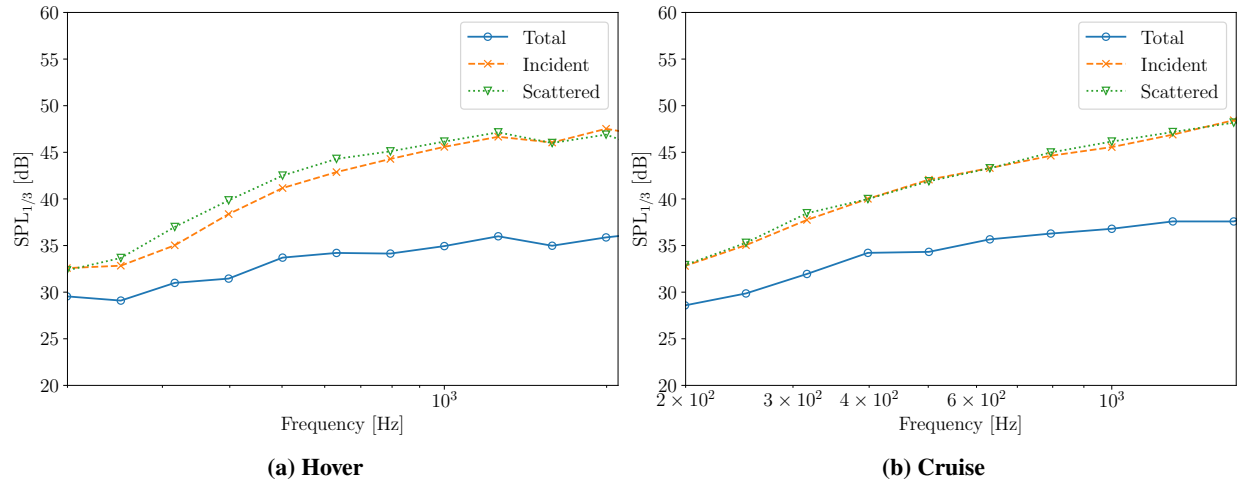


**Fig. 15** Broadband noise one-third octave band spectra in the shadow region for the inboard rotor in hover (left) and cruise (right).

## V. Conclusions and Future Work

In this work, we apply a time-domain boundary element method to investigate acoustic scattering of tonal and broadband rotor noise for the NASA tiltwing UAM concept vehicle. As the focus is on the acoustic scattering effects, the noise source representation is simplified and neglects aerodynamic interactions. The tonal noise is calculated using isolated rotor loading data computed with BEMT, while broadband trailing edge noise is included by synthesizing a stochastic unsteady loading distribution in the time domain and propagating it with FWH. The resulting scattered field can then be computed for all frequencies in a single simulation.

Farfield noise predictions with fuselage scattering are reported for hover and cruise flight conditions for frequencies up to 2 kHz. Full-vehicle overall sound pressure levels (OASPL) are presented with and without A-weighting for the total noise and for the tonal and broadband components individually. We assess the scattering effect by computing the differences between the OASPL hemispheres with and without the scattered field. The scattering trends differ strongly between the tonal and broadband noise components and between the flight conditions. In hover, the fuselage scattering results in significant tonal noise amplification below the vehicle where the incident field is small, while the broadband scattering effect is weak. In cruise, the fuselage scattering effect results in strong tonal noise amplification in the forward and aft directions and weak broadband noise reduction on each side of the vehicle. The relative strength of the unweighted and A-weighted contributions from each noise source determines the total scattering effect in each flight condition. The significant differences between the scattering trends of the tonal and broadband noise contributions emphasizes the potential sensitivity of design analyses to the weighting that a given acoustic metric applies to the respective contributions.

To better understand the scattering trends, we present the contributions from each rotor separately. In hover, the tonal scattering patterns are qualitatively similar for all rotors, with significant amplification beneath the vehicle and a radial interference pattern at shallower elevation angles. The amplification regions of different rotors substantially overlap while the interference patterns mostly cancel, resulting in the smoother full-vehicle scattering pattern. The amplification regions occur because the incident fields are very weak near the rotor axes and do not coincide with the peak amplitude of the scattered fields. No significant change in the magnitude of the scattering effect is observed for the rotors located closer to the fuselage, likely because those rotors are elevated above the vehicle in hover and their rotor disk planes do not directly intersect the fuselage. In cruise, the tonal scattering patterns are characterized by longitudinal interference patterns with regions of strong amplification in the forward and aft directions where the incident field is weak. Unlike for the hover condition, the rotors located closer to the fuselage show much stronger scattering effects because the rotor disk planes intersect the fuselage for all rotor positions.

The broadband scattering trends are significantly different, especially in hover, likely due to differences in the directivity and spatial structure of the broadband field. In both conditions, the primary scattering effect is a strong reduction in the direct shadow of the fuselage. While the shadow zones of individual rotors are significant, they mostly do not overlap and are effectively canceled out for the full-vehicle configuration. A configuration with greater overlap between the shadow zones of each rotor would likely see a significant shielding effect. An analysis of the scattering effect at one-third octave bands for the inboard wing-mounted rotor shows a frequency-dependent trend in the strength and sharpness of the shadow region.

Overall, this work presents an initial characterization of fuselage scattering effects for tonal noise and low- to mid-frequency broadband trailing edge noise in a full-size UAM concept vehicle. The results highlight significant differences between the scattering effects for the different noise components and in different flight conditions. Future work will investigate additional scattering effects from airframe surfaces that were neglected in the present investigation, including the wing, empennage, and nacelles. Additionally, we plan to consider higher frequencies and additional broadband noise sources in subsequent studies.

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