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UCD-QuietFly: A New Program to Predict Multi-Rotor eVTOL Broadband Noise

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ABSTRACT

This paper investigates broadband noise of multi-rotor VTOL vehicles. Based on earlier single-rotor trailing-edge noise prediction method, a multi-rotor broadband noise prediction program is developed, where the multi-rotor coordinate transformation is included, and the amplitude modulation capability is introduced. Thereafter, the program is used to predict broadband noise from three VTOL conceptual designs and a vertiport conceptual design. It is found that VTOL vehicles' broadband noise is important in the high-frequency range, where community background noise is weak. For the same mission specifications, broadband noise is found to be higher for VTOL designs with more rotors. It is found that amplitude modulation of broadband noise on a single rotor is insignificant when the observer distance is larger than 4 rotor radii with an elevation angle of -45° . Multi-rotor vehicles have weaker amplitude modulations. Finally, noise contours from a vertiport design show the increase of broadband noise level when multiple VTOL vehicles are operated simultaneously.

NOTATION

c	chord length, m
c_o	speed of sound, m/s
C_f	skin friction coefficient
C_T	thrust coefficient
D	rotor diameter, m
D_ϕ	directivity term
dp/dx	pressure gradient, Pa/m
E^*	complex conjugate of a Fresnel integral
f	frequency, Hz
k_x	chordwise wavenumber
L	effective lift function
l_r	spanwise turbulence lengthscale, m
M	freestream Mach number
M_r	rotational Mach number
M_{β_p}	flapping motion matrix
M_t	rotor tilt motion matrix
M_{tip}	tip Mach number
M_θ	blade twist and collective pitch matrix
M_ϕ	azimuth motion matrix
N_B	number of blades per rotor
N_R	number of rotors
N_S	number of sections per blade
OASPL	overall sound pressure level, dB
R	rotor radius
R_o	observer-vehicle hub distance, m
R_s	observer-blade section distance, m

r	radial position of a blade section midspan, m
$SPL_{i(U/L)}$	blade section (upper or lower surface) sound pressure level, dB
SPL_{rotor}	rotor sound pressure level, dB
$SPL_{vehicle}$	vehicle sound pressure level, dB
S_{pp}	azimuthally averaged acoustic PSD
$\bar{S}_{pp}$	instantaneous acoustic PSD
t_r	rotor tilt, deg
t_v	vehicle tilt, deg
U_c	convective velocity, m/s
U_e	boundary layer edge velocity, m/s
U_∞	freestream velocity, m/s
u_τ	friction velocity, $(\tau_w/\rho)^{1/2}$
V_c	ascending speed, m/s
X, Y, Z	source local coordinate system
X_1, Y_1, Z_1	rotor coordinate system
X_2, Y_2, Z_2	observer global coordinate system
β_p	blade flap, deg
Δr	blade section span, m
δ	boundary layer thickness, m
δ^*	boundary layer displacement thickness, m
Ω	angular velocity, rad/s
τ	emission time, s
τ_w	wall shear stress, Pa
Θ	momentum thickness, m
θ	blade twist, deg

INTRODUCTION

Broadband noise from rotorcraft is characterized by its wide frequency range and high-frequency dominance. Historically, rotorcraft broadband noise has received less attention com-

pared to its discrete-frequency, or tonal, noise. However, as the concepts of Urban Air Mobility (UAM) have recently become more prominent, rotorcraft broadband noise has gained more interest due to its impact on urban residents. Specifically, Intaratap et al. (Ref. 1) demonstrated on a DJI Phantom drone that its broadband noise not only dominates the mid- to high-frequency noise spectrum, but the noise level is also significantly increased from the single-rotor to the multi-rotor configuration. Regarding the noise perception, Zawodny and Boyd (Ref. 2) showed the importance of high-frequency rotor broadband noise on the A-weighted sound pressure level (SPL).

Trailing-edge noise is a type of broadband noise that contributes significantly to mid and high-frequency noise. This noise is generated by the interaction between a turbulent boundary layer flow and a trailing-edge corner on an airfoil section or a flat plate. Trailing-edge noise models on an airfoil have been empirically and theoretically developed. A semi-empirical BPM model was developed by Brooks et al. (Ref. 3) and has been widely used to predict airfoil self-noise. Theoretically, Ffowcs Williams et al. (Ref. 4) provided a trailing-edge noise solution to the Lighthill (Ref. 5) acoustic analogy equation. Likewise, using the theory of Curle (Ref. 6), Amiet (Ref. 7) developed a theoretical model to predict trailing-edge noise on an airfoil. Using Amiet's model, Schlinker and Amiet (Ref. 8) predicted trailing-edge noise on helicopters, but some simplifications were made in their approach. For example, helicopter blades were modeled as flat plates; induced velocity on the rotor was not included; noise sources were located at the rotor hub. Using the rotating source formulation of Ffowcs Williams and Hawkins (Ref. 4), Kim and George (Ref. 9) predicted rotor trailing-edge noise with the loading function in Amiet's model (Ref. 7). In their method, however, each blade was modeled as a point source of a flat plate, and the angle of attack effect was neglected. Modeling rotor blades as actual airfoil sections, Blandeau and Joseph (Ref. 10) predicted propeller trailing-edge noise based on Amiet's model (Ref. 7), but the wall pressure spectrum model, Goody's model (Ref. 11), used in their approach was not accurate for airfoil adverse pressure gradient flows, and the noise source was modeled as a point source located at 75% of the blade radius. Li and Lee (Ref. 12) presented a new method to predict rotor trailing-edge broadband noise, which combines Blade Element Momentum Theory (BEMT), XOIL panel method (Ref. 14), Lee's wall pressure spectrum model (Refs. 15, 16), and Amiet's trailing-edge noise model (Ref. 7), and considers rotor blades' full motions. The rotorcraft aerodynamics is solved by the BEMT to obtain the local velocity and angle of attack along the blade span. For each blade section, the far-field noise is obtained from the Amiet trailing-edge noise model, which requires the coordinate transformations to include rotor blade motions. Although Zawodny et al. (Ref. 17) and Pettingill and Zawodyn (Ref. 18) have predicted broadband noise from small-scale rotors using the semi-empirical BPM model (Ref. 13), broadband noise from the passenger-size electric vertical takeoff and landing (eVTOL) vehicles has not been predicted, nor has the vehicle

designs been studied for their effects on the broadband noise.

Regarding the noise characteristics, Christian et al. (Ref. 19) used a synthesizing method with the BPM model to simulate the amplitude modulated broadband noise from a helicopter, which becomes more identifiable by its periodic features. However, the importance of such features has not been studied for the multi-rotor eVTOL vehicles. Regarding the VTOL designs, Johnson et al. (Ref. 20) made conceptual designs of single passenger quadrotor, six-passenger side-by-side helicopter, and fifteen-passenger tilt-wing and turbo-electric aircraft. Based on these designs, Silva et al. (Ref. 21) produced three new designs, quadcopter, side-by-side, and lift+cruise, with the same mission specifications of carrying six passengers. These conceptual designs are given in Fig. 1. However, the broadband noise has not been predicted on these designs.

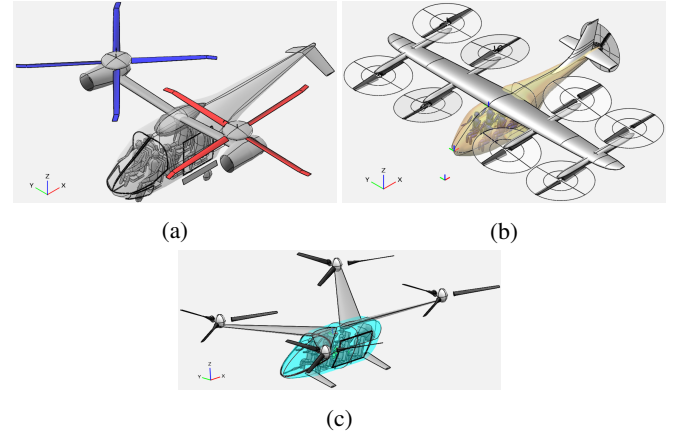


Fig. 1: NASA's six-passenger VTOL conceptual designs (Ref. 21): (a) side-by-side, (b) lift+cruise, and (c) quadcopter.

To investigate such topics, this paper will extend the authors' earlier work and develop a new computer program, UCD-QuietFly (Ref. 12), which has the capability of predicting broadband noise from multi-rotor vehicles. This program is used to predict broadband noise of the VTOL conceptual designs (Ref. 21) in Fig. 1; the importance of VTOL broadband noise is studied by comparing to the urban community noise measurements (Ref. 22). Furthermore, the significance of periodic features of VTOL broadband noise is studied at various observer locations. Finally, broadband noise of multiple operating VTOLs at one of Uber's considered vertiport design (Ref. 23) is predicted.

The specifications of the three conceptual designs are shown in Table 1. Silva et al. (Ref. 21) presented the electric and turbo-electric versions of each VTOL design, and in this paper the electric versions are studied.

METHOD AND FORMULATION

A. Multi-rotor Broadband Noise

In addition to a single-rotor prediction capability of UCD-QuietFly presented in Ref. 12, the multi-rotor broadband

Table 1: Parameters of UH-1B helicopter and six-passenger VTOL conceptual designs (Ref. 21).

Parameter	UH-1B	Quadrotor	Side-by-side	Lift+cruise
Rotor radius[ft]	22	13.1	14.9	5.0
Number of rotors	1	4	2	8
Blades per rotor	2	3	4	2
Tip speed[ft/s]	748.031	550	550	585
Rotor speed[RPM]	325	400	353	1117
Disk loading[lb/ft ²]	4.74	3.0	3.5	13.1
Solidity, thrust-weighted	0.0036	0.055	0.058	0.267
Airfoils	NACA0012	VR-12 ($r/R < 0.85$)/SSC-A09 ($r/R > 0.95$)		

noise prediction capability is included in this paper to investigate VTOL vehicles. In addition, the amplitude modulation capability is employed to study the time-dependent characteristics of the VTOL broadband noise.

UCD-QuietFly is a physics-based method that fluid-dynamically relates the far-field acoustics with the turbulent pressure fluctuations near the trailing edge through the theory of edge scattering (Ref. 6). Therefore, UCD-QuietFly not only predicts rotor broadband noise but also contains fundamental flow physics of the noise generation, which helps improve the physical understanding of noise generation and incorporate noise reduction techniques, such as trailing-edge serrations, into the model.

Besides the rotor trailing-edge noise, a capability of predicting the trailing-edge bluntness noise and the stall noise is added using the semi-empirical BPM model (Ref. 13). It is important to note that the separation noise described in the BPM model still physically describes trailing-edge noise at non-zero angles of attack. For airfoils that are not stalled, this effect is also captured in our trailing-edge prediction based on the Amiet model (Ref. 7); the BPM separation noise model is only used on the stalled blade sections, which rarely occur in normal conditions. These capabilities are intended to cover more noise sources belonging to rotor broadband noise, although trailing-edge noise is found to be the dominant source. However, the current UCD-QuietFly does not include a model for predicting turbulent wake/blade interaction broadband noise, which is more prominent at low frequencies during the onset. As for the amplitude modulation, the azimuthal averaging of the rotor trailing-edge noise is replaced by recording the narrow-band sound pressure level in the history of time steps. Since the blade sections have different positions with respect to the observer at an observer time, the retarded-time effect is also considered.

Using the Schwarzschild solution (Ref. 24), Amiet's power spectral density (PSD) $\bar{S}_{pp}$ (Ref. 7) at an observer location (X, Y, Z) with respect to each the two surfaces of an airfoil is written as

$$\bar{S}_{pp} = \frac{1}{32\pi^2} \left(\frac{\omega_d c Z}{c_o \epsilon^2} \right)^2 \Delta r |L|^2 l_r \Phi_{pp} \quad (1)$$

The overbar on S_{pp} means the acoustic power spectrum density from an airfoil section. In Eq. (1), $\epsilon^2 = X^2 +$

$\beta^2 (Y^2 + Z^2)$, $\beta^2 = 1 - M^2$, ω_d is the Doppler-shifted frequency, c is the chord length, c_o is the speed of sound, Δr is the blade sectional span, L is the loading term, l_r is the spanwise turbulence correction length, and Φ_{pp} is the wall pressure spectrum at 99% c near the trailing edge. The local coordinates used in Eq. (1) is shown in Fig. 2. On a rotor blade, the origin of the local coordinate of each section is located at its mid-span.

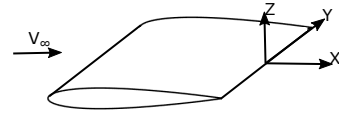


Fig. 2: Blade section local coordinate. (Ref. 12)

Figure 3 shows the coordinates of a blade section on a rotor relative to an observer. The coordinate transformation matrices were presented in the single rotor UCD-QuietFly method (Ref. 12) in Eqs. 2-3, where the tilt angle matrix M_t is modified to include multiple rotors on a vehicle. These matrices transform the rotor coordinate (X_1, Y_1, Z_1) at the rotor hub to the local coordinate (X, Y, Z) on a blade section.

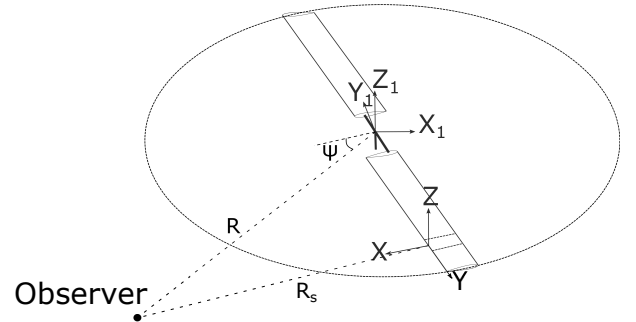


Fig. 3: Airfoil local and global coordinates for an observer. (Ref. 12)

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = M_\theta M_\phi \begin{bmatrix} M_t \begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix} + M_{\beta_p} \end{bmatrix} \quad (2)$$

$$\begin{aligned}
M_\theta &= \begin{bmatrix} \cos(\theta_0 + \theta) & 0 & \sin(\theta_0 + \theta) \\ 0 & 1 & 0 \\ -\sin(\theta_0 + \theta) & 0 & \cos(\theta_0 + \theta) \end{bmatrix} \\
M_\phi &= \begin{bmatrix} \sin \phi & -\cos \phi & 0 \\ \cos \phi & \sin \phi & 0 \\ 0 & 0 & 1 \end{bmatrix} \\
M_t &= \begin{bmatrix} \cos(t_v + t_r) & 0 & \sin(t_v + t_r) \\ 0 & 1 & 0 \\ -\sin(t_v + t_r) & 0 & \cos(t_v + t_r) \end{bmatrix} \\
M_{\beta_p} &= \begin{bmatrix} -r \sin \beta_p \cos \phi \\ -r \sin \beta_p \sin \phi \\ r \cos \beta_p \end{bmatrix}
\end{aligned} \tag{3}$$

This paper extends the rotor broadband noise prediction capability from a single rotor (Ref. 12) to multiple rotors on a vehicle. Equations 4-5 describe the coordinate transformations from the vehicle's global coordinate (X_2, Y_2, Z_2) with an origin at the vehicle hub to the rotor coordinate (X_1, Y_1, Z_1) with an origin at the rotor hub. Therefore, a user can conveniently input the global coordinate (X_2, Y_2, Z_2) relating a vehicle hub to an observer, and the program will perform the coordinate transformations internally to find the local coordinate (X, Y, Z) from Eqs. 2-5, which is necessary for the Amiet model (Ref. 7). The X_2Y_2 plane is parallel to the geographical ground shown in Fig. 4. Figure 5 shows the definitions of t_v and t_r , which were used in Eqs. 3 and 5. t_v is the vehicle tilt angle between the vehicle hub plane and the geographical ground and t_r is the rotor tilt angle between the rotor hub plane and the vehicle hub plane.

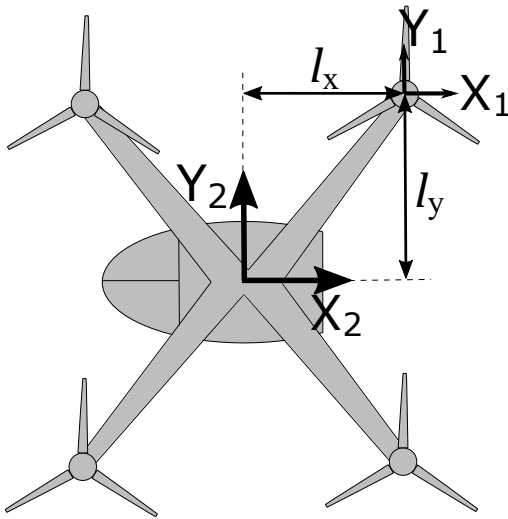


Fig. 4: The distance from rotor hub to vehicle hub is described by (l_x, l_y, l_z) , referred to the coordinate (X_2, Y_2, Z_2) .

$$\begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix} = M_{t_v} \begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \end{bmatrix} + M_{hub} \tag{4}$$

$$M_{t_v} = \begin{bmatrix} \cos t_v & 0 & \sin t_v \\ 0 & 1 & 0 \\ -\sin t_v & 0 & \cos t_v \end{bmatrix} \tag{5}$$

$$M_{hub} = \begin{bmatrix} l_x \\ l_y \\ l_z \end{bmatrix}.$$

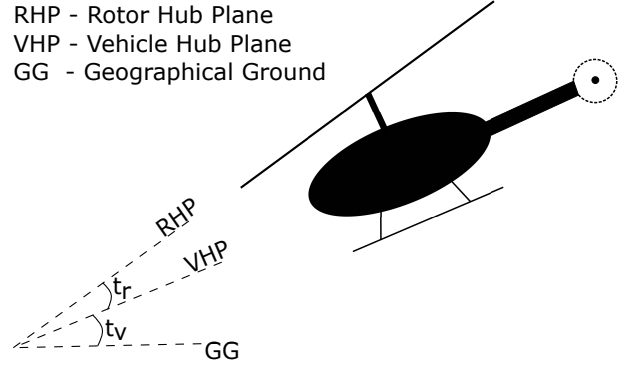


Fig. 5: Rotor hub plane, vehicle hub plane, and geographical ground.

The PSD of each section changes with the azimuth angle; hence, it is azimuthally averaged by

$$S_{pp} = \frac{N_B}{2\pi} \int_0^{2\pi} \left(\frac{\omega}{\omega_d} \right)^2 \bar{S}_{pp} d\phi, \tag{6}$$

in which the Doppler-shifted frequency ω_d at the observer is related to the source frequency ω using

$$\frac{\omega_d}{\omega} = \frac{1}{1 + M_r \left(\frac{X}{R_s} \right)}. \tag{7}$$

Note that $M_r = \Omega r / c_o$ is the rotational Mach number of the blade section. X has the direction pointing from leading edge to trailing edge shown in Fig. 3, and R_s is the distance between the blade section and an observer. Substituting Eq. (1) and Eq. (7) into Eq. (6) and expanding the terms gives the acoustic PSD generated from each blade section as

$$S_{pp} = \left(\frac{\omega}{c_o} \right)^2 c^2 \Delta r \left(\frac{1}{32\pi^2} \right) \frac{B}{2\pi} \int_0^{2\pi} D_\phi |L|^2 l_r \Phi_{pp} d\phi. \tag{8}$$

The directivity term is given as $D_\phi = (Z/\varepsilon^2)^2$, where ε is defined in Eq. (1). The local coordinate of Z and ε must be

found by taking the coordinate transformations in Eqs. (2) - (3) from the global coordinate. A detailed equation of the directivity term D_ϕ in terms of the global coordinate system (X_2, Y_2, Z_2) are provided in the Appendix.

The loading term L is given by Schlinker and Amiet (Ref. 8) as

$$|L| = \frac{1}{\Lambda} |e^{i2\Lambda} [1 - (1+i)E^*(2(\bar{K} + \bar{\mu}M + \bar{\gamma})) + e^{-i2\Lambda} \sqrt{\frac{K + \mu M + \gamma}{\mu x/\varepsilon + \gamma}} (1+i)E^*(2(\bar{\mu}x/\varepsilon + \bar{\gamma}))]| \quad (9)$$

where $\Lambda = \bar{k}_x - \bar{\mu}x/\varepsilon + \bar{\mu}M$, $K = \omega_d/U_c$, $\mu = \omega_d M/U\beta^2$, $\gamma^2 = (\mu/\varepsilon)^2(x^2 + \beta^2 z^2)$, and E^* represents the complex conjugate of a Fresnel integral. For rotorcraft, the turbulence convective velocity and spanwise turbulence length scale are defined as $U_c = 0.8U_\infty$ and $l_r = 1.6U_c/\omega$, respectively.

The remaining wall pressure spectrum Φ_{pp} is obtained by a recently developed empirical wall pressure spectrum model for non-zero gradient flows, Lee's model (Ref. 15), as

$$\frac{\Phi_{pp}(\omega)U_e}{\tau_w^2 \delta^*} = \frac{\max(a, (0.25\beta_c - 0.52)a)(\frac{\omega \delta^*}{U_e})^2}{[4.76(\frac{\omega \delta^*}{U_e})^{0.75} + d^*]^e + [8.8R_T^{-0.57}(\frac{\omega \delta^*}{U_e})]^{h^*}} \quad (10)$$

where $\beta_c = (\Theta/\tau_w)|dp/dx|$, $a = 2.28\Delta^2(6.13\Delta^{-0.75} + d)^e[4.2(\Pi/\Delta) + 1]$, $\Delta = \delta/\delta^*$, $\Pi = 0.8(\beta_c + 0.5)^{3/4}$, $e = 3.7 + 1.5\beta_c$, $d = 4.76(1.4/\Delta)^{0.75}[0.375e - 1]$, $R_T = (\delta/U_e)(v/u_\tau^2)$, $h^* = \min(3, (0.139 + 3.1043\beta_c)) + 7$, and if $(\beta_c < 0.5)$, $d^* = \max(1.0, 1.5d)$, otherwise $d^* = d$.

Finally, the far-field SPL for one side of the i^{th} section is calculated from the power spectral density S_{pp} as

$$\text{SPL}_{i(U/L)} = 10\log_{10} \left(\frac{2\pi S_{pp}}{(2 \times 10^{-5})^2} \right), \quad (11)$$

where U and L represent the upper and lower surfaces of an airfoil, respectively. The j^{th} rotor's total SPL is logarithmically summed to be

$$\text{SPL}_{\text{rotor},j} = 10\log_{10} \sum_{i=1}^{N_S} \left(10^{0.1\text{SPL}_{iU}} + 10^{0.1\text{SPL}_{iL}} \right), \quad (12)$$

where N_S is the total number of sections. Likewise, the total SPL of a vehicle with multiple rotors is given in Eq. (13), where N_R is the number of rotors.

$$\text{SPL}_{\text{vehicle}} = 10\log_{10} \sum_{j=1}^{N_R} \left(10^{0.1\text{SPL}_{\text{rotor},j}} \right) \quad (13)$$

B. Amplitude Modulation

Theoretically, the noise level is low when the blade is away from the observer and the level is high when the blade is close to the observer, so in a time duration, the noise level is fluctuating periodically, which is the logic of amplitude modulation. However, depending on its relative position to the observer, each section on a blade has the different corresponding observer time and noise level. Therefore, broadband noise from each blade section needs to be individually predicted. Figure 6 shows the blade sections as the noise sources, where τ is the noise emission time and $\tau + R_s/c_0$ is the observer time. The emission time is associated with the angular velocity Ω and azimuthal angle ϕ by

$$\tau = \frac{\phi}{\Omega} \quad (14)$$

For the calculation of amplitude modulation, the azimuthal averaging is removed and the broadband noise of each blade section is recorded in time history, so Eq. (8) becomes Eq. (15), where $S_{pp,\phi}$ is the acoustic power spectrum density of one blade section at an azimuth angle.

$$S_{pp,\phi} = \left(\frac{\omega}{c_0} \right)^2 c^2 \Delta r \left(\frac{1}{32\pi^2} \right) D_\phi |L|^2 l_r \Phi_{pp} \quad (15)$$

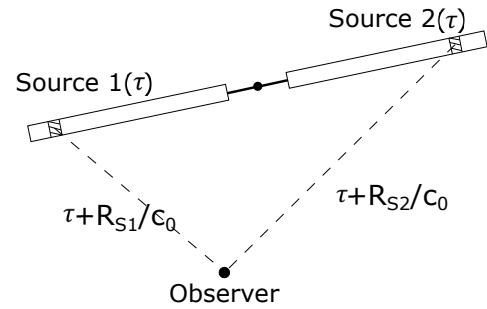


Fig. 6: Retarded effect and amplitude modulation on each blade section as a noise source.

In UCD-QuietFly, the observer time duration is a user's option, based on which the program generates a corresponding emission time. At every emission time step, the broadband noise from each blade section is calculated from Eq. (15), and based on the section's location its corresponding observer time is calculated. After the calculation of all sections and time steps, the total vehicle broadband noise as a function of time is interpolated and summed. As the output, the program generates the broadband noise sound pressure level as a function of both frequency and observer time.

RESULTS

This section presents the validation of UCD-QuietFly on broadband noise prediction on small-scale rotors. To investigate the importance of broadband noise for VTOL aircraft,

three 6-passenger VTOL vehicle designs (Ref. 21) are studied, and their broadband noise is compared to the noise measurements (Ref. 22) in urban areas. Regarding noise perception, the amplitude modulation of broadband noise is studied for single-rotor and multi-rotor configurations. Finally, the broadband noise contours from an urban vertiport are predicted.

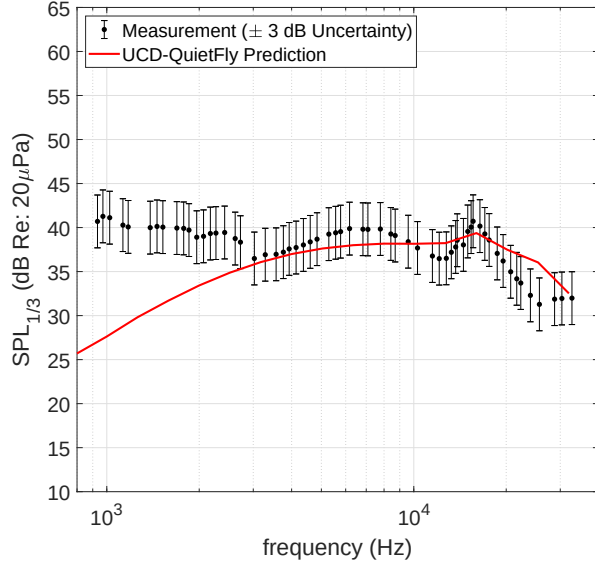


Fig. 7: APC rotor noise prediction against measurement (Ref. 17), $\Omega = 3600\text{RPM}$

Table 2: APC Slow Flyer 11X4.7 Rotor Parameters

Item	Value
Radius[m]	0.014
Number of blades	2
RPM	3600/4200/4800
Observer Distance[m]	1.095
Observer Elevation Angle[deg]	- 45
Airfoil	E63(hub)/ClarkY(tip)

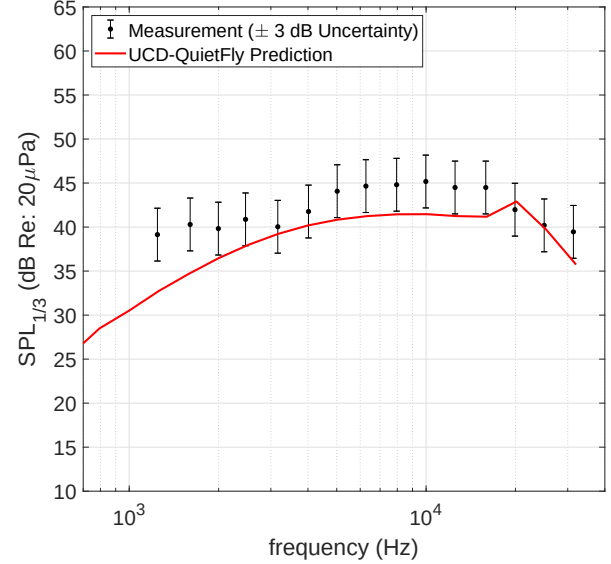


Fig. 8: APC rotor noise prediction against measurement (Ref. 17), $\Omega = 4200\text{RPM}$

A. Validation

Due to the lack of noise measurements of actual VTOL vehicles with multiple rotors, the validation of UCD-QuietFly is performed on a small-scale two-bladed single rotor while the validation of UCD-QuietFly on full-scale helicopters has been presented in Ref. 12. Table 2 shows the test conditions for a small-scale rotor, the APC Slower Flyer 11X4.7 rotor, where the predictions for three rotational speeds are presented in Figs. 7-9. In the measurement data, $\pm 3\text{dB}$ error bars were added for the reference of a comparison with predictions. The good comparisons of UCD-QuietFly and the measurements at various speeds demonstrate the validity of UCD-QuietFly's prediction on small-scale rotors. The predictions catch the noise spectrum from the mid- to high-frequency range, where rotor broadband noise is dominant; they also follow a trend of an increase in noise levels from low to high rotational speeds. A sharp peak in the predictions and measurements at high frequencies is attributed to the trailing-edge bluntness noise. It is expected that the predictions do not match the data at low frequencies at which other noise sources are important.

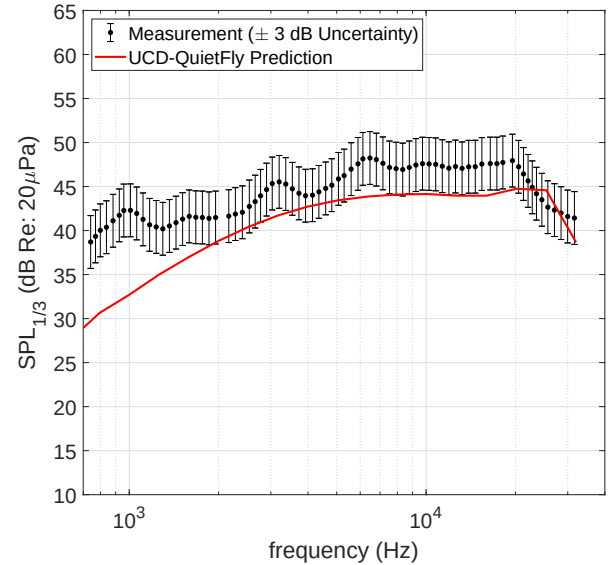


Fig. 9: APC rotor noise prediction against measurement (Ref. 17), $\Omega = 4800\text{RPM}$

B. VTOL Aircraft

Figures 10-12 shows the one-third octave band broadband noise predictions from UCD-QuietFly for the three different 6-passenger VTOL designs, quadcopter, side-by-side, and lift+cruise. The broadband noise from these three designs is compared to investigate the noise levels for the same mission specifications. Five different altitudes, from 50 ft to 1500 ft, were studied for the hover flight. In each figure, the community background noise measurements (Ref. 22) is attached for reference. For the quadrotor at the highest studied altitude of 1500 ft, the broadband noise is audible above 0.7 kHz in a rural area, above 1.1 kHz in a community park, above 1.2 kHz in a residential community, and above 1.6 kHz in a highway area. Compared to that at 1500 ft, as the quadrotor altitude is decreased, the noise level is increased by about 4 dB at 1000 ft, 10 dB at 500 ft, 15 dB at 250 ft, and 30 dB at 50 ft. At the typical altitude of a vertiport, 50 ft, quadcopter noise is not masked for a large frequency range (>0.4 kHz) even in the freeway environment. Note that broadband noise is predicted from one quadrotor, and a higher noise level is observed with multiple vehicles, which will be presented in the next section. Therefore, broadband noise of multi-rotor VTOL vehicles stands out in the mid- to high-frequency range, where community background noise is weak.

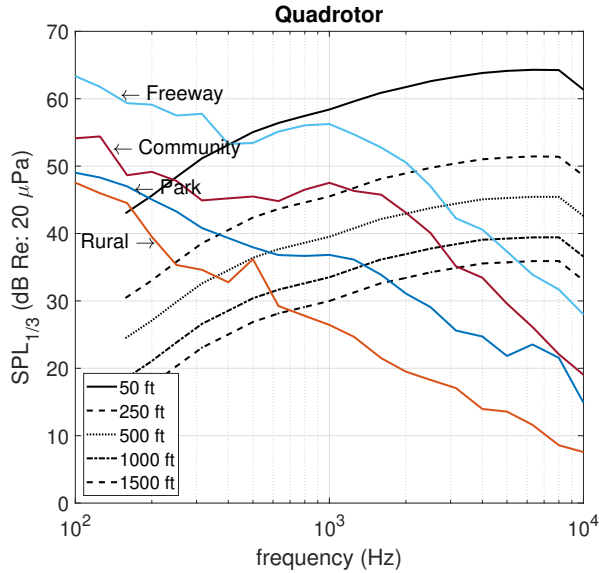


Fig. 10: Quadrotor VTOL broadband noise prediction from UCD-QuietFly compared to community background noise (Ref. 22)

Compared to the quadrotor design, the side-by-side VTOL generates slightly less broadband noise (2 dB) in the entire frequency range, but the high-frequency noise is important to human perception for its audibility in urban areas. Regarding the lift+cruise design, its high-frequency broadband noise remains the same importance as the quadrotor design while low- to mid-frequency broadband noise is increased.

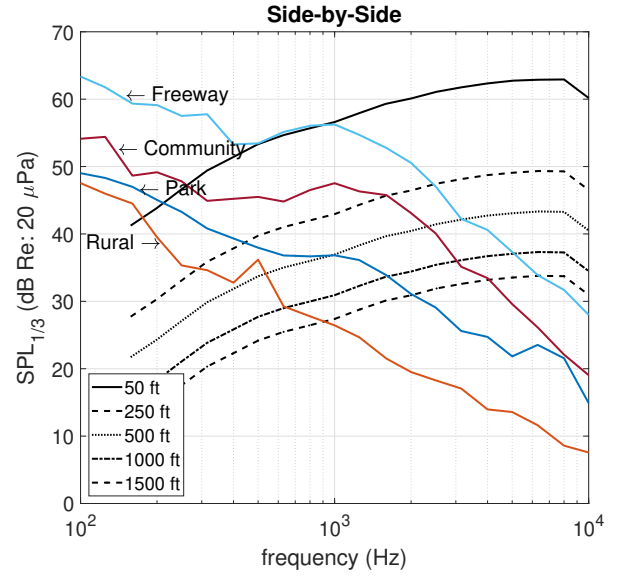


Fig. 11: Side-by-side VTOL broadband noise prediction from UCD-QuietFly compared to community background noise (Ref. 22)

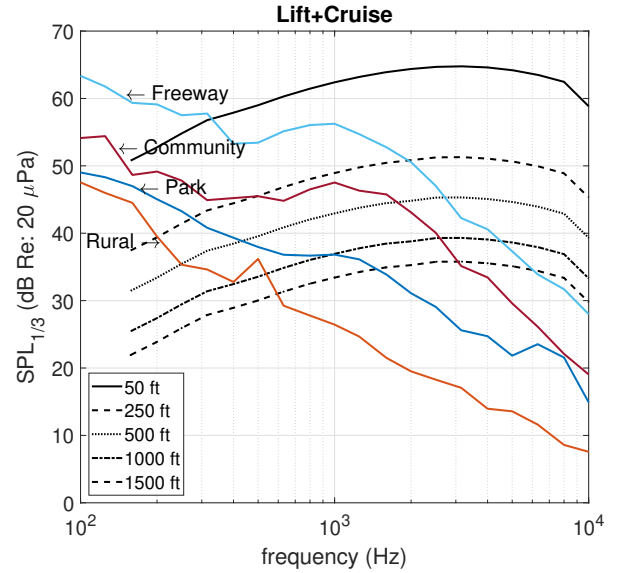


Fig. 12: Lift+cruise VTOL broadband noise prediction from UCD-QuietFly compared to community background noise (Ref. 22)

To make more direct comparisons, Figure 13 shows the community equivalent sound exposure level (L_{eq}) measured by Begault (Ref. 22) and the overall sound pressure level (OASPL) predicted from UCD-QuietFly for the three VTOL designs, where L_{eq} and OASPL are mathematically the same, since the broadband is statistically stationary or not time varying. In this paper, the OASPL is calculated in the frequency range from 0.1 kHz to 10 kHz. Comparing the overall sound pressure level, in the freeway environment, broadband noise from the VTOL vehicles are important at 50 ft altitude, or a vertiport's height. In the residential community, broadband

noise is important at an altitude of 250 ft. In the community park, broadband noise is important for the quadcopter vehicle at 1000 ft, the side-by-side vehicle at 500 ft, and the lift+cruise vehicle at 1000 ft. Finally, in the rural area, broadband noise is important for all vehicles at 1500 ft. However, OASPL represents the general importance, while the importance of high-frequency noise compared to all measured environments cannot be neglected as shown in Figs. 10-12. Although our research demonstrates the importance of high-frequency VTOL broadband noise, low-frequency VTOL noise can also be audible from other noise sources, such as blade-vortex-interaction noise (Refs. 25, 26).

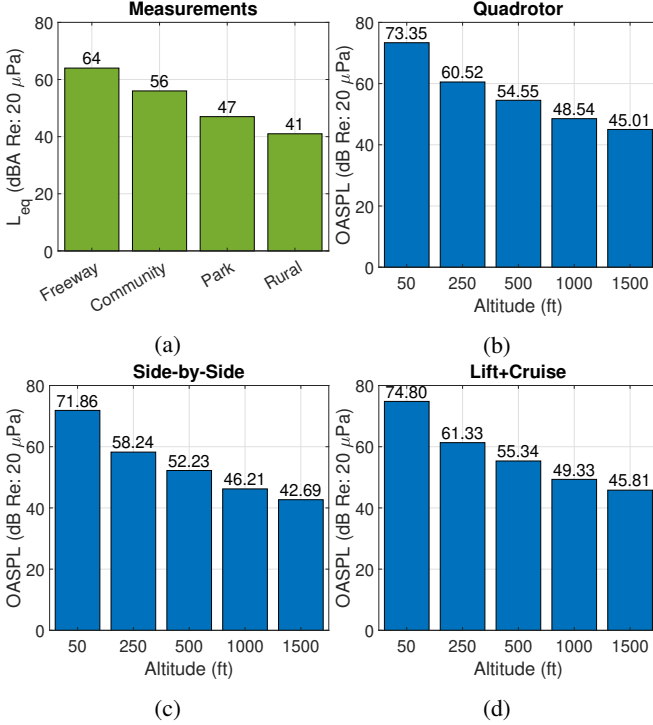


Fig. 13: Equivalent sound exposure level measurement and overall sound pressure level prediction for: (a) community background noise (Ref. 22), (b) quadrotor, (c) side-by-side, and (d) lift+cruise.

Comparing the broadband noise levels from the three VTOL designs, it was shown that the design with more rotors generate higher broadband noise in the same mission specifications. To further investigate the effect of the number of rotors on broadband noise, the number of rotors is varied with the lift+cruise VTOL being a base design, where the rotor tip speed and total swept area are kept the same. The one-third octave band sound pressure levels and flyover overall sound pressure levels from a various number of rotors are shown in Fig. 14. While the increasing number of rotors increases high-frequency broadband noise, low-frequency noise is decreased. This trend can be explained by the fact that reducing blade radius with multi-rotors results in decreasing low-frequency noise while maintaining the same high-frequency noise on a single rotor (Ref. 12). However, high-frequency noise in-

creases as added rotors generate more trailing-edge noise. In our case, since the tip speed and swept area of multi-rotors are kept constant, the blade radius of each rotor is reduced while the number of rotors is increased. As noise from multiple rotors with reduced blade radius is combined, the overall effect gives the increase in high-frequency noise and a decrease in low-frequency noise. At the 'overhead' position of 250 ft, the 10-rotor vehicle generates more broadband noise of about 2 dB than the 4-rotor vehicle.

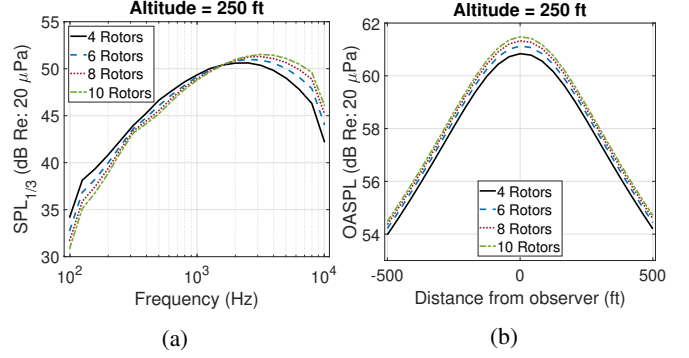


Fig. 14: Effect of number of rotors: (a) one-third octave band sound pressure level, and (b) overall sound pressure level on a fly path.

C. Amplitude Modulation

The amplitude modulation of VTOL aircraft broadband noise is investigated to find its importance for various observer distances and vehicle designs. On a 2-bladed single rotor, the broadband noise spectrum in time history is presented for various observer distances in Fig. 15, where elevation angle is fixed at -45° . The ending time is 1 second for the four cases, but the starting time is different due to the consideration of retarded time (observer starts receiving noise at a different time). Figure 15 shows that the broadband noise level periodically varies with time for the entire frequency range. As the observer distance is increased, the overall noise level is decreased while the amplitude modulation remains the same patterns. Due to the retarded time effects, the observers at different radial distances start to receive noise at different time, which explain the different starting time in Fig. 15. However, within the same time duration, the number of peaks appear remains unchanged for different observer radial distances. Such periodic variations are caused by the variation of source-to-observer distance as well as the Doppler effect; the blade moves away from the observer with decreasing noise and towards the observer with increasing noise. Therefore, the period of amplitude modulation is associated with the number of blades and the number of rotors.

To further investigate the effects the number of blades and number of rotors on the broadband noise amplitude modulation, broadband noise in the time history is predicted for the three VTOL designs in Fig. 16. The side-by-side, quadrotor, and lift+cruise VTOLs have 2, 4, and 8 rotors, and 8, 12, and

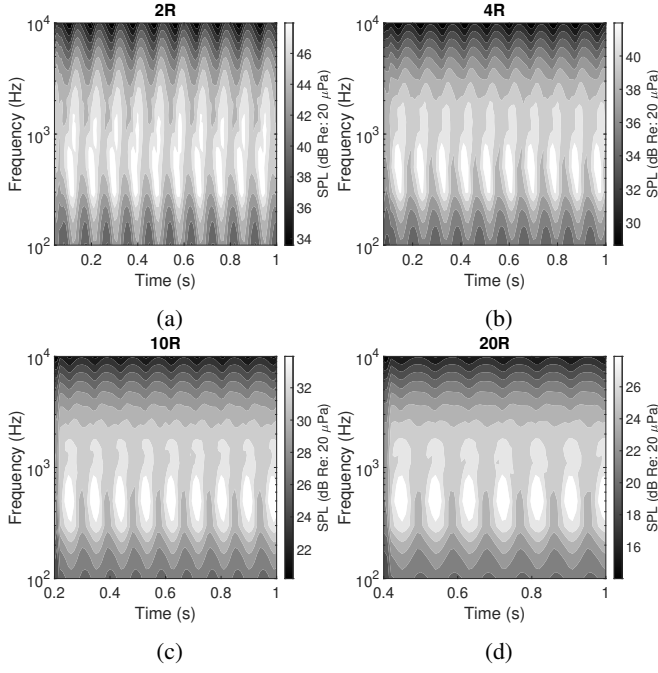


Fig. 15: Broadband noise spectrum of a UH-1B helicopter in time history for observer distances: (a) 2R, (b) 4R, (c) 10R, and (d) 20R.

16 blades in total. The observer is located at 44 ft (R_0) and -45° elevation angle from the vehicle hub. As the number of blades increases, the modulation period and the peak-to-peak amplitude are both reduced.

Figure 17 shows the OASPL peak-to-peak amplitudes and time history of OASPL of a single rotor at various observer distance. It is found that increasing an observer distance reduces the amplitude while the period remains the same. To explain this observation, as the observer-hub distance is increased, the difference between the observer-source 1 distance and the observer-source 2 distance in Fig. 6 becomes relatively smaller compared to the source-observer distance. For a fixed observer-hub distance (R_0), figure 18 shows the OASPL peak-to-peak amplitudes and time history of OASPL for different vehicle configurations, which include the UH-1B helicopter and the three VTOL designs. It is demonstrated that the multi-rotor designs have much smaller OASPL peak-to-peak amplitudes than the single rotor. Within a time duration of 0.2 seconds, the single rotor has 2 periods, the side-by-side VTOL has 6 periods, the quadrotor VTOL has 7 periods, and the lift+cruise VTOL has 9 periods, although they are not clearly shown in Fig. 18(b). Therefore, increasing the number of blades increases the number of amplitude modulations, which is similar to the blade passing frequency of tonal noise being increased with the number of blades. Since the observer location is kept at 44 ft, however, a rotor blade with a smaller radius with multiple rotors has a smaller difference between the largest and smallest source-to-observer distances as the blade rotates away and towards the observer, so the peak-to-peak amplitude is smaller. Therefore, more blades result in more noise peaks but smaller amplitudes of the modulation. Dif-

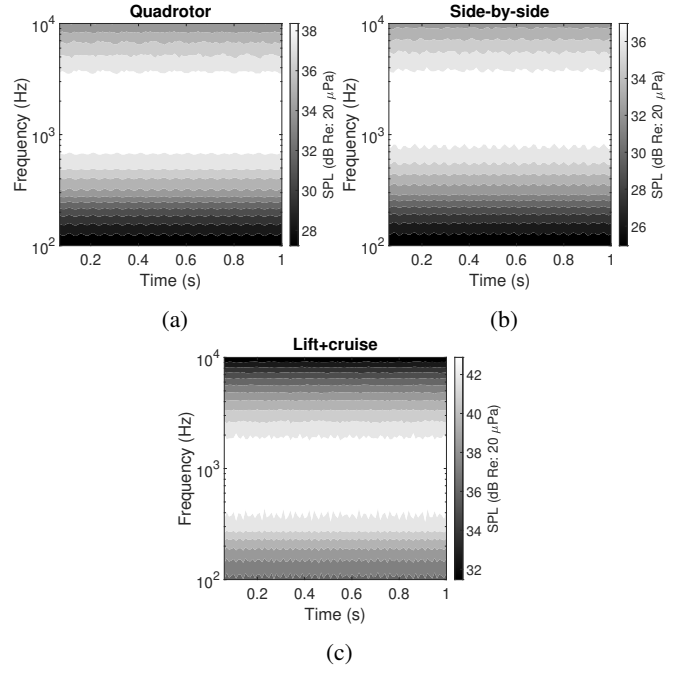


Fig. 16: Broadband noise spectrum of multi-rotor vehicles in time history: (a) quadcopter, (b) side-by-side, and (c) lift+cruise.

ferent from the simple periodic amplitude modulations for the single rotor, the multi-rotors have the irregular peaks, since their amplitude modulations are combined from multiple periodic modulations of each rotor with phase differences. In conclusion, the amplitude modulation of rotorcraft broadband noise becomes weak when the source-to-observer distance is large; in our case, the peak-to-peak amplitude of OASPL is less than 1 dB when an observer is 4 rotor radii from the vehicle. For a fixed observer location, the amplitude modulation is less important for a larger number of blades. Thus, one acoustic advantage of VTOL designs with more rotors and more blades is that they have less annoying broadband noise characteristics associated with amplitude modulation.

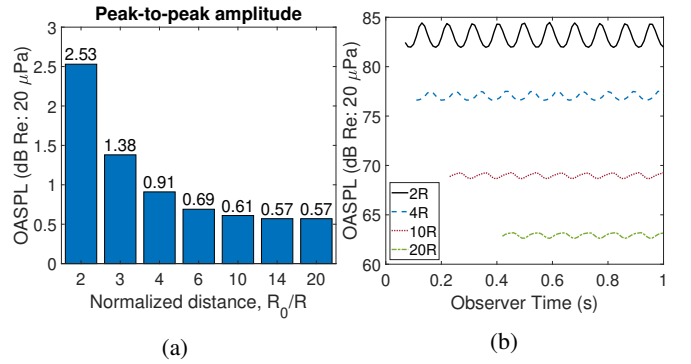


Fig. 17: Predicted UH-1B helicopter amplitude modulation: (a) peak-to-peak amplitude vs. observer distance, and (b) OASPL in time history for different observer distances.

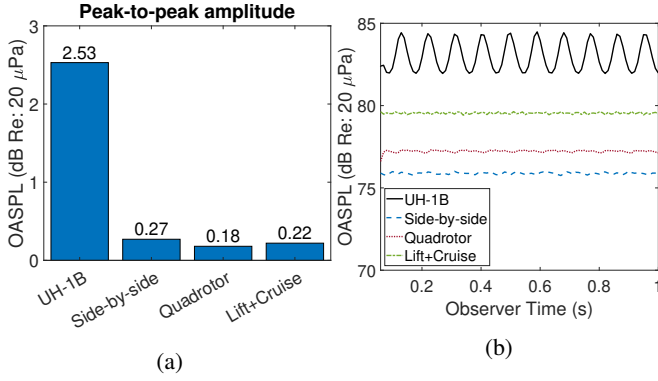


Fig. 18: Predicted amplitude modulations of different vehicle designs: (a) peak-to-peak amplitudes for four designs, and (b) OASPL in time history for four designs.

D. Vertiport

Built in urban areas for vehicles to vertically take-off and landing, vertiports are relevant to the communities' noise perception for their vicinities of residential areas. The Gannett Fleming vertiport (Ref. 23) is investigated for the generation of broadband noise from multiple VTOL designs. Four VTOL vehicles are operated simultaneously at the four final approach and takeoff areas (FATO) (Ref. 27) at the altitude of 40 ft, and the overall sound pressure levels are predicted for a map of observer locations on the ground, where the noise scattering effects from the vertiport building are neglected. The noise predictions for quadcopter, side-by-side, and lift+cruise VTOLs are shown in Fig. 19, respectively. The lift-cruise design has higher broadband noise than the quadrotor design, and the side-by-side design has the lowest broadband noise. This result is consistent with an earlier finding that more blades generate a higher amplitude of broadband noise. Directly below the FATOs are the four local noise maxima, with each vehicle accounting for each noise maximum.

CONCLUSIONS

A new computational program, referred to as UCD-QuietFly, has been developed to predict broadband noise from multi-rotor VTOL aircraft, which extended the single rotor trailing-noise prediction (Ref. 12) by adding the coordinate transformations from single to multiple rotors. The capability of broadband noise amplitude modulation was implemented to study the noise characteristics. UCD-QuietFly was validated against measured noise levels for a small-scale rotor. Key findings are concluded as follows:

1. Broadband noise of VTOL vehicles is important in the high-frequency range, where community background noise is weak. Comparing to the noise measurements shows that mid- to high-frequency broadband noise of VTOL aircraft is not masked in urban community environments, and future investigation on broadband noise reduction is recommended for UAM VTOLs.

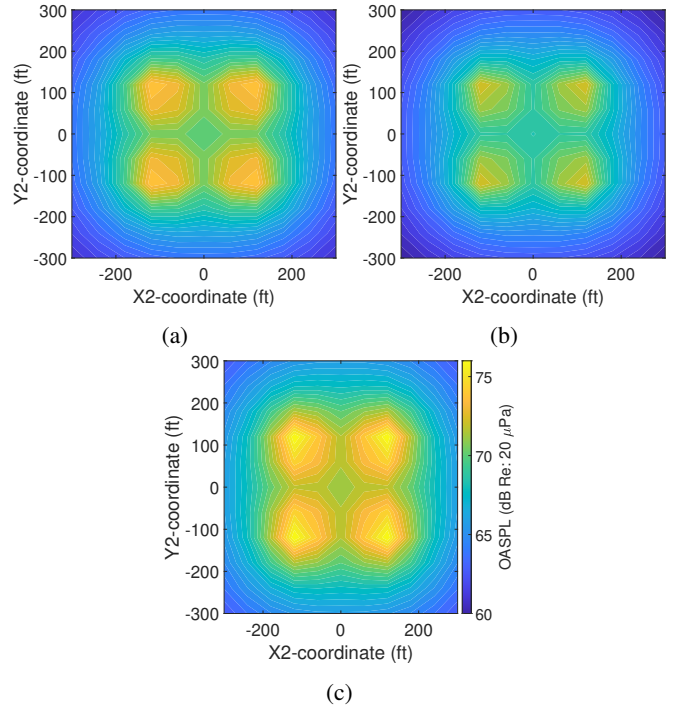


Fig. 19: Predicted broadband noise OASPL from the 4-FATO Gannett Fleming (Ref. 23) vertiport: (a) quadcopter, (b) side-by-side, and (c) lift+cruise.

2. For the same mission specifications, broadband noise of the quadrotor design is slightly higher than that of the side-by-side design, and the lift-cruise design has considerable broadband noise increase compared to the other two designs.
3. Amplitude modulation of broadband noise on a single rotor is weak when the observer distance is larger than 4 rotor radii with an elevation angle of -45° . Increasing the number of blades increases the number of amplitude modulations. Multi-rotor vehicles have weaker amplitude modulations, since the blade radius is decreased compared to the single rotors with the same swept area, which is a benefit of choosing multi-rotor designs.
4. Noise contours from a vertiport design demonstrate the increase in broadband noise level when multiple VTOL vehicles are operated simultaneously.

ACKNOWLEDGEMENTS

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APPENDIX

The expanded form of the directivity term D_ϕ is shown in Eq. (a-1), which is obtained by performing the coordinate trans-

formations in Eq. (2)-(5).

$$D_\phi = A_1 / \{ [\sin(\theta_0 + \theta) \cdot A_3 - \cos(\theta_0 + \theta) \cdot \cos\beta_p \cdot A_4 + \cos(\theta_0 + \theta) \sin\beta_p \cdot A_2]^2 + A_1 + [\sin\beta_p \cdot A_4 + \cos\beta_p \cdot A_2]^2 \}^2 \quad (\text{a-1})$$

A_1, A_2, A_3 and A_4 in Eq. (a-1) are shown as follows for clarity.

$$A_1 = [\cos(\theta_0 + \theta) \cdot A_3 + \sin(\theta_0 + \theta) \cos\beta_p \cdot A_4 - \sin(\theta_0 + \theta) \sin\beta_p \cdot A_2]^2 \quad (\text{a-2})$$

$$A_2 = \cos(t_r + t_v) [\cos t_v(l_x + X_2) + \sin t_v(l_z + Z_2)] + \sin(t_r + t_v) [\cos t_v(l_z + Z_2) - \sin t_v(l_x + X_2)] - r \cos \phi \sin \beta_p \quad (\text{a-3})$$

$$A_3 = \cos(t_r + t_v) [\cos t_v(l_z + Z_2) - \sin t_v(l_x + X_2)] - \sin(t_r + t_v) (\cos t_v(l_x + X_2) + \sin t_v(l_z + Z_2)) + r \cos \beta_p \quad (\text{a-4})$$

$$A_4 = l_y + Y_2 - r \sin \beta_p \sin \phi \quad (\text{a-5})$$

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