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Acoustic Analysis of Urban Air Mobility Quadrotor Aircraft

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ABSTRACT

This paper investigates the acoustics of a 1-passenger and a 6-passenger quadrotor Urban Air Mobility (UAM) aircraft designs in level flight based on a high-fidelity Computational Fluid Dynamics (CFD) approach. The CFD simulations are carried out using the HPCMP CREATETM-AV rotorcraft analysis and simulation tool Helios. The acoustic simulations are performed using the acoustic prediction tool PSU-WOPWOP. A total of three CFD models is simulated: 1-passenger isolated rotor configuration, 1-passenger full configuration, 6-passenger isolated rotor configuration. The noise comparison between the 1-passenger isolated rotor and full configurations shows that the vehicle fuselage can increase the A-weighted sound pressure level (SPL) up to 5 dB. An acoustic comparison between the 1-passenger and 6-passenger configurations suggests that the maximum difference in overall SPL between the two configuration is 14 dB. Furthermore, it is shown that the noise of 1-passenger and 6-passenger configurations is significantly lower than that of a four-bladed conventional helicopter in level flight. However, there is still a challenge to meet the community noise acceptance level so that further noise reduction is recommended. The community noise impact of UAM aircraft is also assessed and compared to background noise in different scenarios. The results show that the 1-passenger vehicle noise can be fully masked by the highway noise at an altitude greater or equal to 1,000 ft while the 6-passenger vehicle noise can only be partially covered by the ambient noise.

NOMENCLATURE

c	speed of sound in the undisturbed medium, m/s
C_{tip}	tip chord length, m [or ft]
$\vec{l}$	blade surface loading vector, N/m
l_r	$\vec{l} \cdot \hat{r}$, N/m
$\vec{M}$	local Mach number vector
M_r	$\vec{M} \cdot \hat{r}$
M_∞	freestream Mach number
R	rotor radius, m [or ft]
r_b/R	nondimensional radial position
$\hat{r}$	unit vector in the radiation direction
r	distance between $\vec{y}$ and $\vec{x}$, m
p'	total acoustic pressure, Pa
p'_L	loading noise acoustic pressure, Pa
p'_T	thickness noise acoustic pressure, Pa
q	q-criterion, $\frac{1}{2}(W_{ij} ^2 - S_{ij} ^2)$, 1/s ²
$\bar{q}$	non-scaled q-criterion, $q/(c_\infty/L_{ref})^2$
S_{ij}	strain-rate tensor, 1/s ²
t	observer time, s
t_{max}	maximum observer time, s
W_{ij}	spin-rate tensor, 1/s ²

$\vec{x}$	observer location, m
$\vec{y}$	acoustic source location, m
α	pitch attitude
θ_o	blade collective pitch, deg
β_o	blade coning angle, deg
β_{1c}	longitudinal flapping angle, deg
β_{1s}	lateral flapping angle, deg
μ	advance ratio
ρ_o	air density, kg/m ³
v	local fluid velocity on the blade surface, m/s
Ψ	rotor azimuth, deg
M_∞	freestream Mach number

Acronyms

CFD	Computational Fluid Dynamics
CSD	Computational Structural Dynamics
CCW	counterclockwise
CW	clockwise
eVTOL	electric vertical take-off and landing
SPL	sound pressure level, dB
OASPL	overall sound pressure level, dB
UAM	Urban Air Mobility
VTOL	vertical take-off and landing

Subscript

<i>ret</i>	at retarded time
<i>ref</i>	at the reference position
<i>far</i>	at the far-field position

Superscript

$^{\circ}$	rotor azimuth
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INTRODUCTION

Hybrid- and fully-electric vertical take-off and landing (VTOL) aircraft designs have become increasingly popular lately due to the emerging concept of Urban Air Mobility (UAM) (Ref. 1), or also known as the urban air taxi operations for air passenger and cargo transportation in urban and suburban areas. The two main purposes of UAM are to alleviate massive traffic congestion in metropolitan areas and efficiently interconnect suburban and urban areas through a green, safe, and affordable transportation system. Unlike conventional helicopter designs, most current UAM aircraft designs (Ref. 2) feature multi-rotors and a hybrid or fully electric propulsion system. Hence, the aerodynamic and acoustic characteristics of eVTOLs are expected to be drastically different from that of conventional helicopters. It is anticipated that the complex aerodynamic interactions of a multi-rotor UAM aircraft design can lead to significant broadband and blade-vortex interaction (BVI) noise, and therefore, low-noise emission is one of major UAM aircraft design challenges in addition to safety.

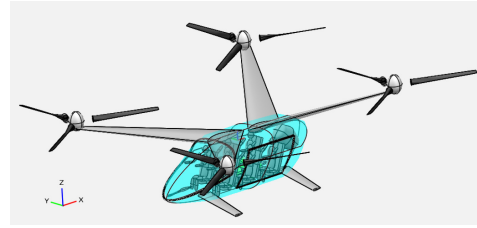
In support of the UAM technology development, there has been ongoing research to improve the current UAM aircraft designs. In 2018, Ventura Diaz et al. (Ref. 3) performed high-fidelity Computational Fluid Dynamics (CFD) simulations on a scaled rotary-wing VTOL model, which has a small nose fan and a pair of transformable tilt-wings with two rotors. Their simulation results showed significant rotor-to-wing and nose-fan-to-fuselage interactions. BVIs induced by the aerodynamic interactions between blade-tip vortices and rotor blade surfaces in close proximity were also identified when the tilt-wings are tilted 90 degrees in helicopter mode. Johnson et al. (Refs. 4,5) performed multidisciplinary analysis of several conceptual vehicles, ranging from one to fifteen passengers, based on the NASA's preliminary design and analysis code NDARC (Ref. 6) and the comprehensive rotorcraft analysis software CAMRAD II (Ref. 7). Two of the UAM vehicle designs are shown in Fig. 1. Their research suggested that both rotor-to-rotor and rotor-to-wing interactions could significantly impact vehicle vibration, acoustics, and power performance.

In 2019, Ventura Diaz et al. (Ref. 8) performed a high-fidelity Computational Fluid Dynamics (CFD) study on a NASA's side-by-side tiltrotor hybrid VTOL in support of UAM research development. Their results showed that the rotor airloads are sensitive to the percentage of rotor-to-rotor overlap, which is a key design parameter of the side-by-side rotor. The 15% rotor overlap case shows the best aerodynamic efficiency. They have also identified potential rotor-to-rotor BVI, which

is an important noise source of a side-by-side rotor with rotor overlap. Wachspress et al. (Ref. 9) analyzed the acoustics of eVTOL configurations based on the airloads obtained from the Comprehensive Hierarchical Aeromechanics Rotorcraft Model (CHARM) (Ref. 10), a comprehensive rotorcraft analysis tool. Their results showed that propeller-wing and rotor-duct interactions could lead to higher overall sound pressure level.



(a) A one-passenger quadrotor design with electric propulsion.



(b) A six-passenger quadrotor design with turboshaft propulsion.

Fig. 1: NASA's conceptual quadrotor VTOL designs (Refs. 4,5)

While most recent eVTOL research focuses on mission design requirements and aeromechanics design, little attention has been given to acoustic analysis. As mentioned earlier in this section, low-noise emission is an important design requirement and is directly related to the public perception of UAM aircraft noise. Most preliminary designs also only consider low-fidelity simulations based on rotorcraft comprehensive analysis tools due to the advantage of computational speed. However, low-fidelity simulation tools are incapable of providing detailed information regarding the acoustic sources and associated noise.

Therefore, the focus of this work is to investigate the acoustics of a one-passenger quadrotor and a six-passenger quadrotor UAM aircraft in cruise based on a first-principled and high-fidelity CFD approach. The acoustic sources of each vehicle is identified in the present work. The influence of both the fuselage model and vehicle size on rotor acoustics is also investigated. Furthermore, the UAM aircraft noise is compared against the noise of a conventional helicopter and ambient noise in urban and suburban areas.

METHODS

A one-passenger and a six-passenger quadrotor UAM aircraft designs (see Fig. 1) from NASA (Refs. 4,5) are analyzed in this paper. The fundamental properties of these two aircraft are shown in Table 1. The two rear rotors are 0.35 rotor radii

Table 1: Fundamental properties of the two conceptual designs.

Aircraft Properties	1-Passenger	6-Passenger
Rotor Radius	2.0 m (6.5 ft)	4.0 m (13.1 ft)
Tip Chord Length	0.12 m (0.38 ft)	0.21 m (0.7 ft)
Number of Rotors	4	4
Blades per Rotor	3	3
Nominal Rotor Speed	662 RPM	400 RPM
Nominal Rotor Tip Speed	137.2 m/s (450 ft/s)	167.6 m/s (550 ft/s)
Gross Weight	601 kg (1,325 lb)	2,934 kg (6,469 lb)
Payload	100 kg (220 lb)	544 kg (1,200 lb)
Propulsion Type	Electric	Electric or Turboshaft

(R) above the two front rotors in both one-passenger and six-passenger designs. The rotor blades of both designs are assumed rigid and modeled based on two modern airfoils: Boeing VR-12 and Sikorsky SSC-A09. VR-12 is used for $R < 85\%$ span; a linear interpolation of VR-12 and SSC-A09 is assumed between 85% and 95% span; SSC-A09 is used for $R > 95\%$ span. Both blade chord and twist distributions are assumed linear. A total of three CFD models are analyzed in the present work: a one-passenger configuration without the fuselage (isolated rotor case), a one-passenger full configuration with the fuselage (full configuration case), and a six-passenger configuration without the fuselage (isolated rotor case). Rotor hubs are included in all three models. Figure 2 shows the rotation of each rotor. Detailed mesh and numerical setups are described in the subsequent sections.

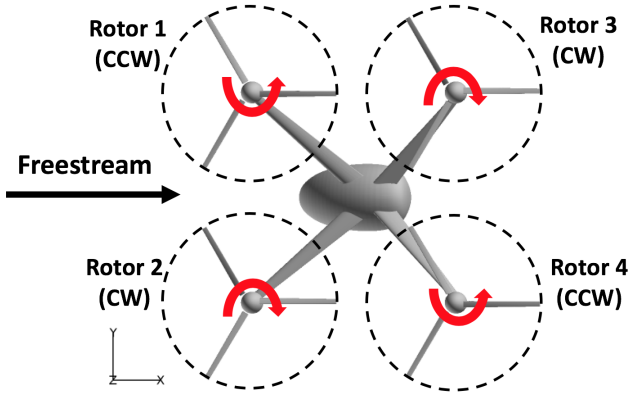
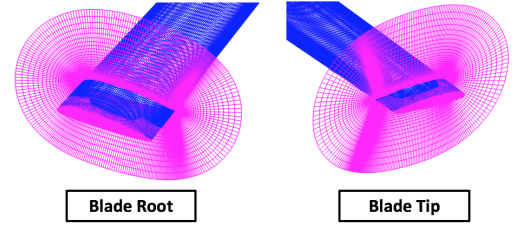


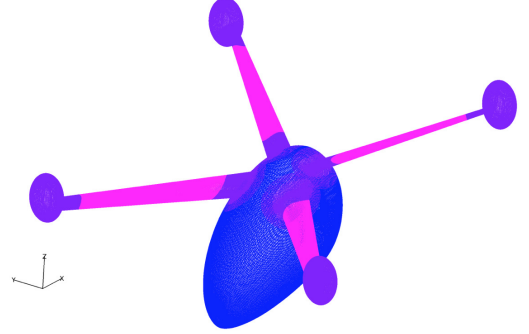
Fig. 2: Rotor setup.

CFD Grids and Boundary Conditions

A dual mesh paradigm, solving the near-body domain using structured overset grids and the off-body domain using adaptive Cartesian grids, is employed in present work. The near-body grids (see Fig. 3) are constructed using NASA's overset grid generation software Chimera Grid Tools (CGT) (Refs. 12, 13). An O-grid topology is applied to all near-body grids. Each rotor blade is composed of three components: main blade, blade root, and blade tip. The dimensions of the main blade are 239 (chordwise) $\times$ 171 (spanwise)



(a) Main blade surface and volume grids.

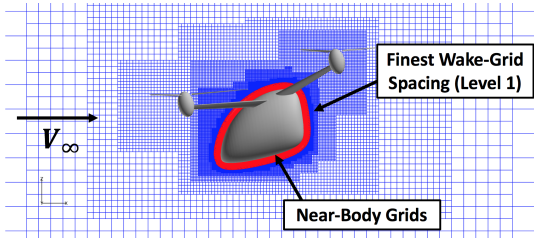


(b) Rotor hub and fuselage surface grids.

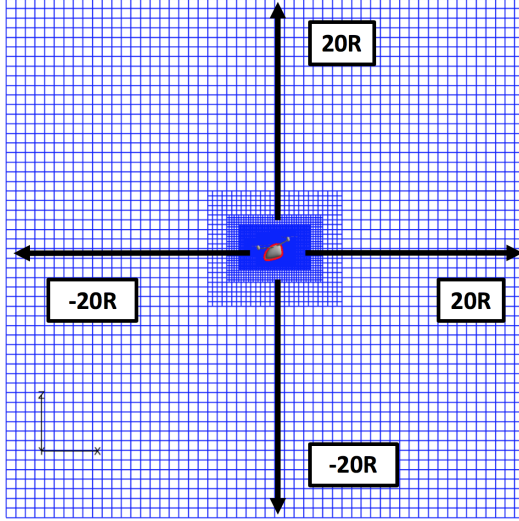
Fig. 3: Near-body grids.

$\times 65$ (normal) with leading and trailing edge spacings equal to $0.05\% C_{tip}$ and $0.02\% C_{tip}$ respectively, where C_{tip} is the tip chord length. The grid dimensions of the one-passenger and six-passenger designs are kept the same for comparison analysis. A wall spacing of 1×10^{-5} grid unit is used to match a dimensionless wall distance $y^+ = 1.0$. The end spacing of the near-body volume grids is set to $10\% C_{tip}$. A viscous adiabatic wall boundary condition is applied to the surface of near-body grids, and a periodic boundary condition is applied at the trailing blunt edge of the main-blade grids in the chordwise direction. Each rotor blade is composed of approximately 3.6 million grid points, and a total of 43.2 million grid points for 12 blades. The fuselage of the one-passenger full configuration is also meshed and shown in Fig. 3b. The structured fuselage grids have a sum of 8.3 million grid points. The total number of grid points of the 1-passenger full configuration is 51.5 million when combined with the fuselage.

The off-body Cartesian mesh as shown in Fig. 4 is gen-



(a) A zoomed-in view.



(b) An overview.

Fig. 4: Off-body mesh.

erated using the adaptive off-body Cartesian solver SAMCart (Ref. 14), the off-body solver of the CREATETM-AV software Helios (Ref. 15). Helios is a high-fidelity and multidisciplinary rotorcraft simulation software being developed under the U.S. Department of Defense (DoD) Computational Research and Engineering Acquisition Tools and Environments - Air Vehicles (CREATETM-AV) program and the U.S. Army. Helios has been recently used to simulate multi-rotor or coaxial rotor systems (Refs. 16–19). The off-body solver SAMCart is capable of resolving complex rotor wakes based on high-order numerical schemes and Adaptive Mesh Refinement (AMR). In this research, eight levels of AMR are used after the first rotor revolution in order to capture the detailed flow physics of rotor wakes. The off-body mesh boundary (see Fig. 4b) is 20 rotor radii away from the origin with the finest wake-grid or Level-1 spacing equal to 10% C_{tip} . Freestream boundary conditions with pressure set to the ambient pressure and velocity set to the vehicle forward velocity are applied at the outer boundaries. The off-body Cartesian mesh of the 1-passenger isolated rotor and full configuration cases has approximately 290 and 320 million grid points, respectively, after numerical convergence.

CFD Simulation Setup and Rotor Trim

NASA's structured and high-fidelity compressible flow solver OVERFLOW (Ref. 20), which is incorporated as a near-body flow solver available in Helios, is used for the near-body flow

simulation. The off-body adaptive Cartesian solver SAMCart is used for the off-body flow simulation. A fifth-order spatial scheme and a second-order temporal scheme are used for both near- and off-body simulations. A time step size of 0.25 degrees azimuth, which results in 1,440 time steps per rotor revolution, is used for time-accurate CFD simulations presented in this paper. 40 and 10 dual-time-stepping subiterations within each physical time step are used in the near-body and off-body simulations, respectively. The Spalart-Allmaras (SA) Reynolds-averaged Navier Stokes (RANS) turbulence model (Ref. 21) coupled with Detached Eddy Simulation (DES) (Ref. 22), which is capable of resolving large eddies away from the near-body boundary layer, is employed for turbulence modeling. Blade surface geometry and solution are extracted every 0.5 degrees azimuth or every two time steps for acoustic simulations. All simulations are performed using the Excalibur Cray XC40 high performance computer of the U.S. Army Research Laboratory (ARL) DoD Supercomputing Resource Center (DSRC). A total number of 640 processors is used, and each rotor revolution of the 1-passenger full configuration case takes approximately 16 hours.

The eVTOL trim outputs are provided by Johnson et al. (Refs. 4, 5), which are computed using NASA's rotorcraft design and analysis tool NDARC. Each rotor of both 1-passenger and 6-passenger configurations has a flapping hinge with fixed collective control, and the blade flapping motion is coupled with the blade pitching motion due to the δ_3 flap-pitch coupling (Ref. 11). The total lift force of the four rotors is trimmed to balance the vehicle weight. The force equilibrium in the x-direction is achieved by summing the rotor thrust and vehicle drag. The pitch attitude (α) of the 1-passenger and 6-passenger vehicles are trimmed to -8.49 and -6.14 degrees, respectively. The blade pitching and flapping motions are prescribed based on the blade collective pitch (θ_o), coning angle (β_o), longitudinal flapping angle (β_{1c}), and lateral flapping angle (β_{1s}), which are shown in Table 2 for both front and rear rotors.

Acoustic Simulation Setup

PSU-WOPWOP (Refs. 23, 24), an acoustic prediction tool being developed at the Pennsylvania State University that has very general capabilities and can accept input data of varying fidelities, is used for acoustic prediction. PSU-WOPWOP is a numerical implementation of Farassat's Formulation 1A (Ref. 25) of the Ffowcs Williams and Hawkings (FW-H) equation (Ref. 26). Farassat's Formulation 1A is calculated based on the impermeable surface strategy in the present work, and the quadrupole source term is neglected since the blade tip Mach number is subsonic (less or equal to 0.6). The equations of Farassat's Formulation 1A are:

$$p'(\vec{x}, t) = p'_T(\vec{x}, t) + p'_L(\vec{x}, t) \quad (1)$$

Table 2: Prescribed rotor motion.

Prescribed Angles	Front Rotors 1-passenger	Front Rotors 6-passenger	Rear Rotors 1-passenger	Rear Rotors 6-passenger
θ_o (deg)	9.19	7.67	10.43	8.38
β_o (deg)	1.78	2.39	1.98	2.48
β_{1c} (deg)	-5.45	-1.08	-6.19	-1.54
β_{1s} (deg)	-0.61	-3.95	-1.16	-4.25

$$4\pi p'_T(\vec{x}, t) = \int_{f=0} \left[\frac{\rho_\infty (\dot{v}_n + v_{\hat{n}})}{r|1 - M_r|^2} \right]_{ret} dS + \int_{f=0} \left[\frac{\rho_\infty v_n (r\dot{M}_r + c(M_r - M^2))}{r|1 - M_r|^3} \right]_{ret} dS \quad (2)$$

$$4\pi p'_L(\vec{x}, t) = \frac{1}{c_\infty} \int_{f=0} \left[\frac{\dot{l}_r}{r|1 - M_r|^2} \right]_{ret} dS + \int_{f=0} \left[\frac{l_r - l_M}{r^2|1 - M_r|^2} \right]_{ret} dS + \frac{1}{c_\infty} \int_{f=0} \left[\frac{l_r (r\dot{M}_r + c(M_r - M^2))}{r^2|1 - M_r|^3} \right]_{ret} dS \quad (3)$$

where p' is the total acoustic pressure; p'_T is the thickness noise acoustic pressure induced by blade motion; p'_L is the loading noise acoustic pressure generated by the aerodynamic forces — lift and drag — of the rotating blades; c and ρ_o are the speed of sound and fluid density in the undisturbed medium, respectively; r is the distance between the source position $\vec{y}$ and the observer position $\vec{x}$; v_n is the blade velocity in the surface normal direction; M_r is the Mach number of the blade surface in the radiation direction pointing toward the location of observer; l_r is the component of the blade surface loading in the radiation direction; $\dot{l}_r$ represents the change of blade surface loading with respect to the change of acoustic source time or retarded time. All of above quantities within the square brackets of the integrands in Farassat's Formulation 1A are evaluated at the retarded time, which is denoted by the subscript *ret*.

The magnitude of the acoustic pressure is heavily influenced by two key terms in Farassat's Formulation 1A: 1) Doppler amplification factor $1/|1 - M_r|$ and 2) abrupt change of airloads with respect to the retarded time $\dot{l}_r$. Since the maximum blade-tip Mach number and impulsive airloads associated with blade-vortex interactions (BVIs), which usually occur in the first quadrant, are located on the advancing side of the rotor disk, both $1/|1 - M_r|$ and $\dot{l}_r$ are expected to be high on the advancing side of the rotor disk. Therefore, the advancing side of each rotor disk becomes the dominant acoustic source region.

Microphone Positions

Eight out-of-plane microphones, which are positioned in a circular manner are used for acoustic analysis. These microphones are 10 rotor radii (40.0 m) of the 6-passenger vehicle away from the origin in both horizontal and vertical direction.

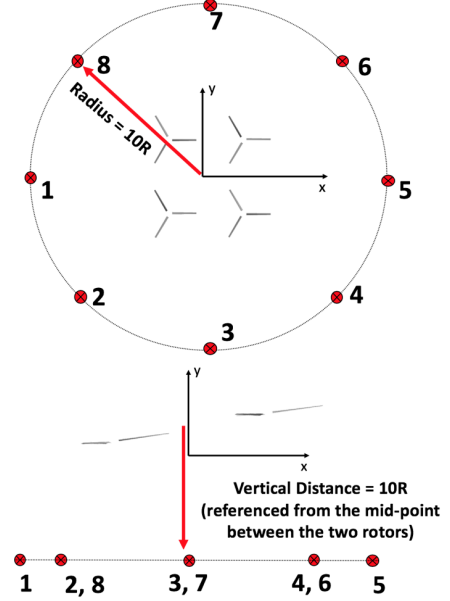


Fig. 5: Acoustic simulation setup (not drawn to scale).

The direct distance between each microphone and the origin is approximately 14 rotor radii (56.0 m) with an elevation angle equal to 45 degrees. A schematic representation of the eight microphones from the top and side views are shown in Fig. 5. The microphone positions in terms of the rotor radius (R) of the 6-passenger vehicle are shown in Table 3.

Table 3: Microphone locations.

Microphone Number	Position (x,y,z), in terms of R
1	(-10.0, 0.0, -10.0)
2	(-7.07, -7.07, -10.0)
3	(0.0, -10.0, -10.0)
4	(7.07, -7.07, -10.0)
5	(10.0, 0.0, -10.0)
6	(7.07, 7.07, -10.0)
7	(0.0, 10.0, -10.0)
8	(-7.07, 7.07, -10.0)

RESULTS

The 1-passenger and 6-passenger quadrotor UAM aircraft are analyzed in steady forward flight at a speed of 70 knots or 130 km/hr. The freestream Mach number M_∞ of both 1-passenger and 6-passenger simulation cases is 0.11. The 1-

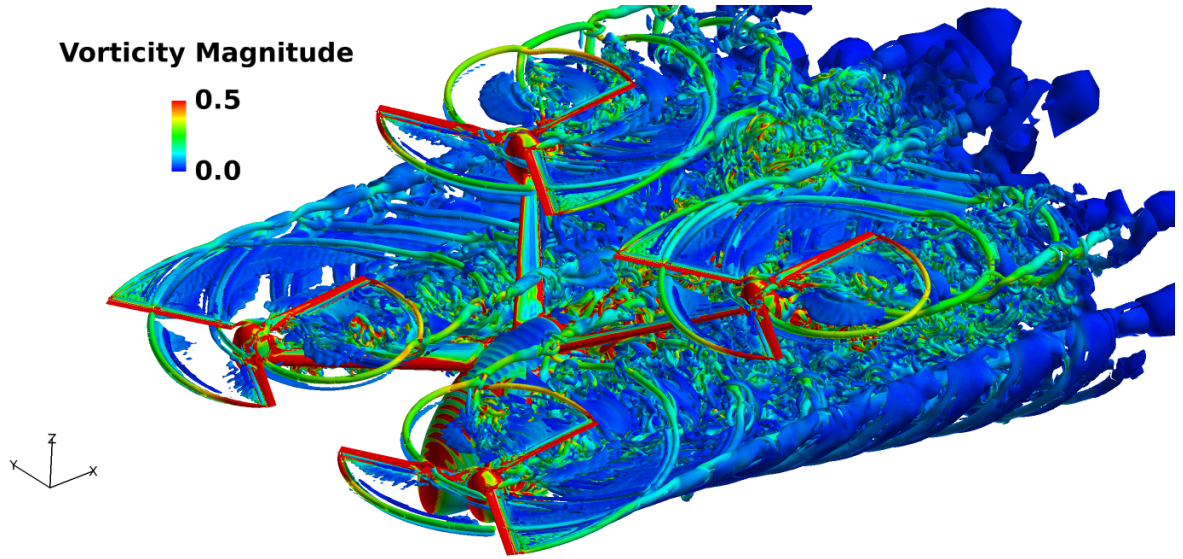


Fig. 6: An iso-surface of q -criterion colored by the vorticity magnitude for the 1-passenger quadrotor full vehicle .

passenger vehicle is designed to cruise at an attitude of 5,000 ft (1,524 m) (Ref. 4) while the 6-passenger vehicle is designed to cruise at a slightly higher attitude, which is at 6,000 ft (1,829 m) (Ref. 5). Each rotor of the two vehicles is assumed to operate at the nominal rotational speed, which is 662 PRM for the 1-passenger vehicle and 400 PRM for the 6-passenger vehicle. The advance ratios μ of 1-passenger and 6-passenger simulation cases are 0.26 and 0.21, respectively. The rotor forces and moments of each simulation case are converged after five rotor revolutions with the near-body unsteady subiteration residual of OVERFLOW drops at a maximum order of approximately 2.0. The off-body unsteady subiteration residual of SAMCart drops at a order of magnitude greater than 2.0 at each time step.

Acoustic Source Comparison Between the Three Models

The BVI strength of the 1-passenger isolated rotor configuration, 1-passenger full configuration, and 6-passenger isolated rotor configuration is compared. Jia and Lee (Ref. 29) have previously shown that the self-BVI events, which are defined as aerodynamic interactions between blade-tip vortices and the same rotor in close proximity, are the most dominant acoustic sources of both 1-passenger and 6-passenger quadrotor configurations. Figure 6 shows an iso-surface of a non-scaled q -criterion ($\bar{q} = 0.001$) of the 1-passenger full configuration colored by vorticity magnitude. The results showed that root-induced BVI, hub wake, and fuselage wake are also potential noise sources. In this subsection, the azimuthal (time) derivative of sectional normal force ($dF_z/d\Omega$), which is a key source term ($\dot{l}_r$) of the loading noise acoustic pressure equation of Farassat's Formulation 1A (Eq. (3)), is shown.

Figure 8 shows a quantitative comparison of $dF_z/d\Omega$ at 75% span between the isolated rotor and full configuration cases. It can be seen that BVIs are located at $\Psi = 60^\circ, 90^\circ$, and 300° . No significant difference between the two cases is found at

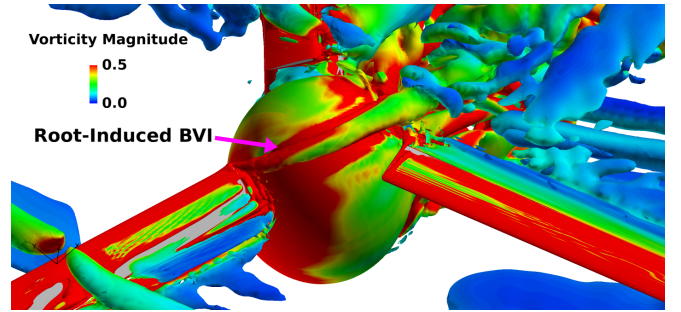


Fig. 7: A zoomed-in view of root-induced BVI.

the front rotors. However, the self-BVI event of the full configuration case at $\Psi = 60^\circ$ shows higher strength than that of the isolated rotor case probably due to the influence of fuselage blockage effect on rotor induced velocity and associated tip vortex trajectory. Note that the first BVI ($\Psi = 60^\circ$) of the rear rotors show higher strength than the first BVI of the front rotors in the isolated rotor case. This can be attributed to the difference in trim solutions between the front and rear rotors. Shown in Table 2, the collective pitch angle of the rear rotors is higher than that of the front rotors, which could result in higher tip vortex strength.

Figure 9 shows a quantitative comparison of $dF_z/d\Omega$ at 75% span between the 1-passenger and 6-passenger cases. The self-BVI event at $\Psi = 70^\circ$ and the self-BVI event at $\Psi = 270^\circ$ of the 6-passenger case show significantly higher peak values at the front rotors than that of the 1-passenger case. In the 6-passenger case, it was found that the different trim setting and the associated flow field result in a more direct impingement of tip vortex to the blade. It is anticipated that the 6-passenger configuration would yield significantly higher noise than the 1-passenger configuration.

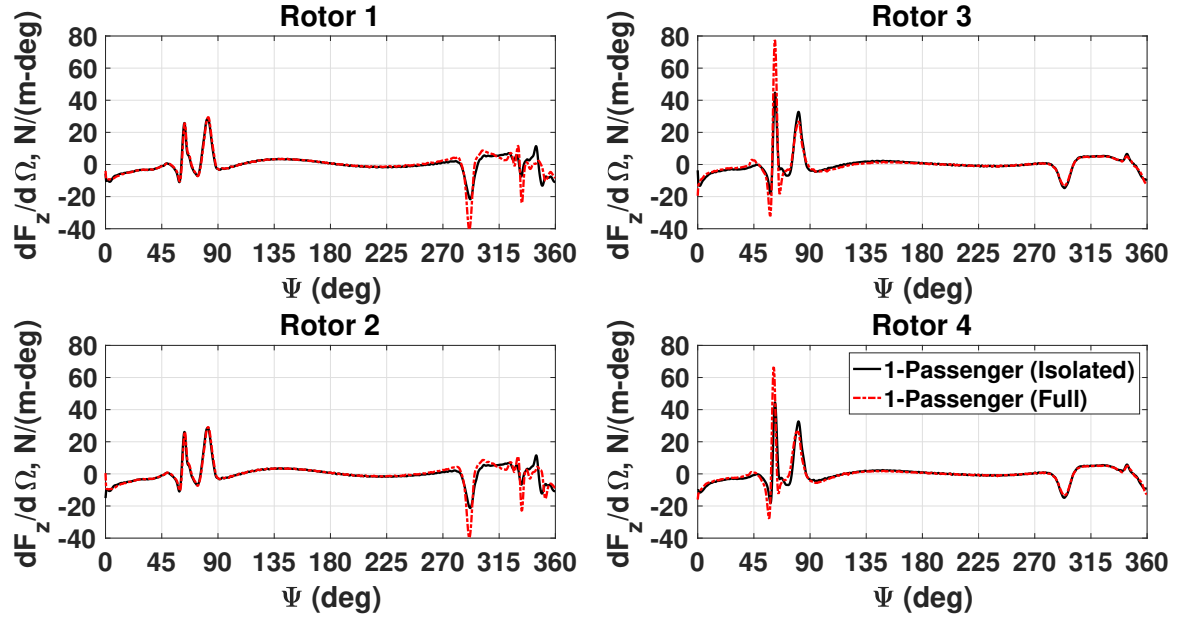


Fig. 8: A comparison of $dF_z/d\Omega$ at 75% span between the 1-passenger cases.

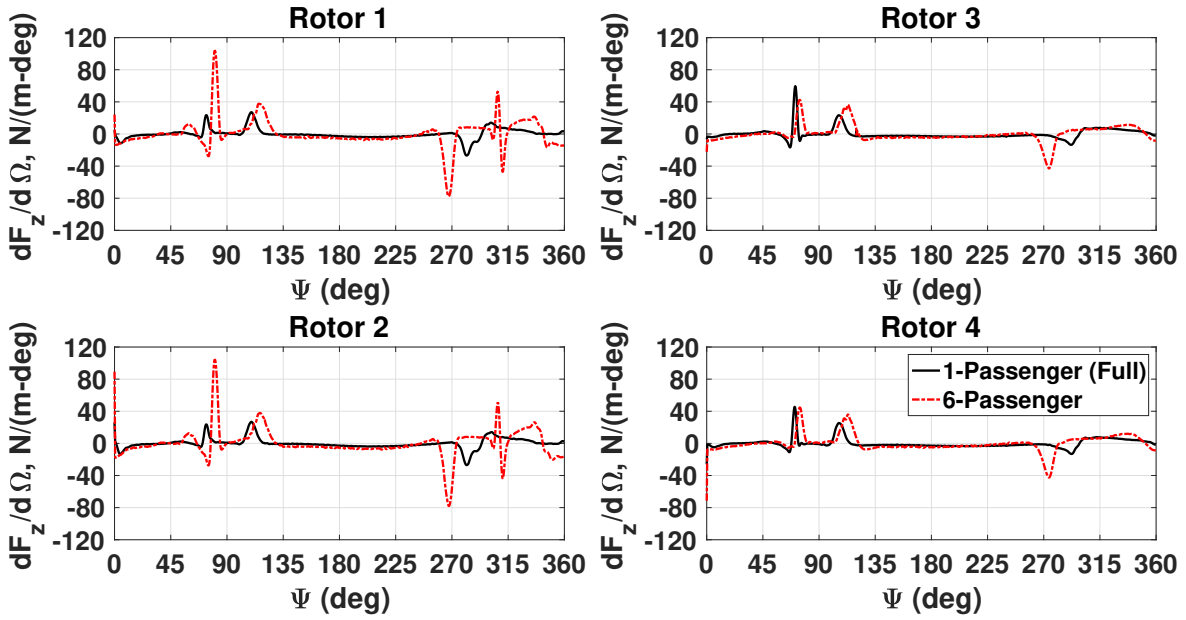


Fig. 9: A comparison of $dF_z/d\Omega$ at 75% span between the 1-passenger and 6-passenger cases.

Acoustic Comparison Between the 1-Passenger Isolated Rotor and Full Configurations

Both loading noise and overall sound pressure level (OASPL) between the 1-passenger isolated rotor and full configurations are compared in this subsection. Since the magnitude of thickness noise acoustic pressure is found to be much smaller than that of loading noise acoustic pressure (Ref. 29), only loading noise acoustic pressure is analyzed at the eight microphones (see Fig. 10). The positive and negative pressure peaks between the two cases are similar in magnitude at all microphone positions. Both cases display stronger broadband-noise like patterns at microphones 1, 2, and 8 due to a combination of root-induced BVI and blade wake impinging on the front surface of rotor hubs as shown in Fig (see Fig. 7).

Figure 11a shows a comparison of A-weighted sound pressure level (SPL), which accounts for the sound frequency range perceived by the human ear, between the isolated rotor and full configuration cases at the eight microphone positions. Both cases show higher A-weighted SPL at microphones 1, 2, and 8 as expected. The full-configuration case shows higher A-weighted SPL than the isolated rotor case at all microphones, especially at microphones 3, 4, 5, 6, and 7. These microphones are positioned on the sides and rear region of the vehicle. The largest difference between the two cases is approximately 5 dB at microphone 6. The OASPL of the two cases including the low-frequency SPL is also compared and shown in Fig. 11b. No significant difference is found between the two cases. It is interesting to find that the OASPL of the isolated rotor case is slightly higher (although hardly noticeable) than that of the full configuration case at microphones 2, 4, 5, 6, and 8, which might be due to the destructive interference among multiple surfaces in the full configuration case, especially at low frequencies. The full configuration noise, overall, is more important than the isolated rotor noise in the human-hearing frequency range (2,000 Hz to 20,000 Hz).

Acoustic Comparison Between the 1-Passenger and 6-Passenger Vehicles

Both loading noise and OASPL between the 1-passenger and 6-passenger vehicles are compared in this subsection. Since the rotation rates (Ω) of the two vehicles are not the same, the observer time (t) is nondimensionalized by the maximum observe time (t_{max}), which corresponds to one rotor revolution for each vehicle, as shown in Fig. 12. The 6-passenger isolated rotor case, overall, shows a higher positive and negative pressure peaks than the 1-passenger isolated rotor case primarily due to stronger BVI events. The maximum difference in acoustic pressure is found to be approximately 2 Pa at microphone 1.

Figure 13 shows the OASPL comparison between the two configurations, which is computed by integrating the entire domain of the acoustic sound pressure level spectrum. The 6-passenger case shows higher OASPL than the 1-passenger case as expected. The maximum difference is found to be approximately 14 dB at microphones 1.

Acoustic Decomposition of the 1-Passenger Full Configuration Model

The total noise of the 1-passenger full configuration model is decomposed into subcomponents — rotors, main fuselage, rotor hubs, and supporting arms — for a detailed acoustic analysis. Figure 14 shows the OASPL of each subcomponent at the eight microphone positions. The main rotors have shown the largest contribution to the OASPL of the full configuration. The main-rotor OASPL becomes higher than the full-configuration OASPL at microphone 6 due to the destructive interference of different noise sources in full configuration. The main-rotor OASPL is found to be slightly higher at microphones 4, 5, and 6 or in the rear region of the vehicle due to root-induced BVIs.

The rotor hubs are found to be second largest contributor to the total noise, especially at microphones 1, 2, and 8 or in the front region of the vehicle due to blade-wake and root-induced BVIs impinging on the frontal area of rotor hubs. The main fuselage contributes least total noise at all microphones. Figure 15 shows the comparison of one-third octave SPL spectrum between the subcomponents at microphones 1 and 5. The main rotor dominates the low-frequency range, which is from 100 Hz to 600 Hz, while the rotor hub dominates the high-frequency range or above 800 Hz.

Acoustic Comparison Against a Conventional Helicopter

It is expected that UAM aircraft noise with multi-rotors would be much quieter than helicopter noise, which is a definite requirement to operate UAM aircraft in urban or community areas. However, to the authors' best knowledge, no one has compared potential UAM aircraft noise with helicopter noise. Uber Technologies Inc. (Ref. 30), as one of the largest advocates of UAM, suggested that 15 dB lower than helicopter noise can be a guideline for UAM aircraft designs.

In this subsection, a comparison of UAM aircraft noise with helicopter noise is presented to better assess how quieter UAM aircraft could be compared to helicopter noise. The acoustics of the 1-passenger and 6-passenger configurations are compared against the noise of the conventional helicopter model Bell 430 in cruise. The fly test data analyzed by Snider et al. (Ref. 31) is used for the acoustic comparison. Table 4 shows a comparison of fundamental properties between the two UAM quadrotor aircraft and Bell 430. An overhead case, where the microphone is positioned 150 m directly below the vehicle, and a flyover case, where the microphone is positioned 150 m below and 457 m ahead of the vehicle, are considered for acoustic comparisons. Both the 1-passenger and 6-passenger configurations are simulated at a nominal cruise speed of 70 knots. The cruise speed of the Bell 430 is 124 knots during the flight test. The advancing tip Mach numbers are 0.52, 0.61, and 0.88 for the 1-passenger quadrotor, 6-passenger quadrotor, and Bell 430 helicopter, respectively, as shown in Table 4. It should be noted that due to a large discrepancy of the flight speed and advancing tip Mach number between the quadrotor and helicopter, the comparison is

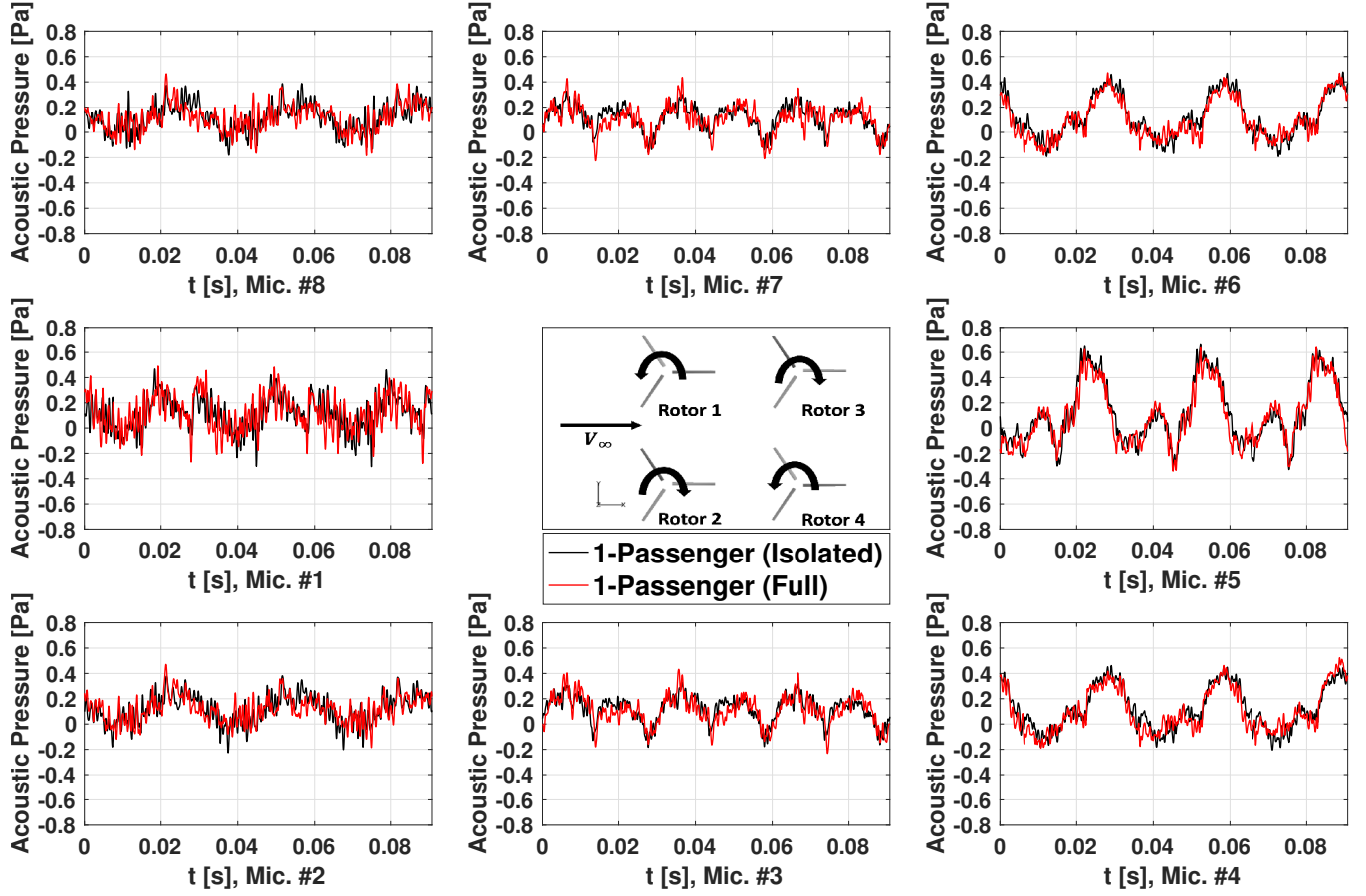


Fig. 10: Loading noise comparison between the 1-passenger isolated rotor and full configurations.

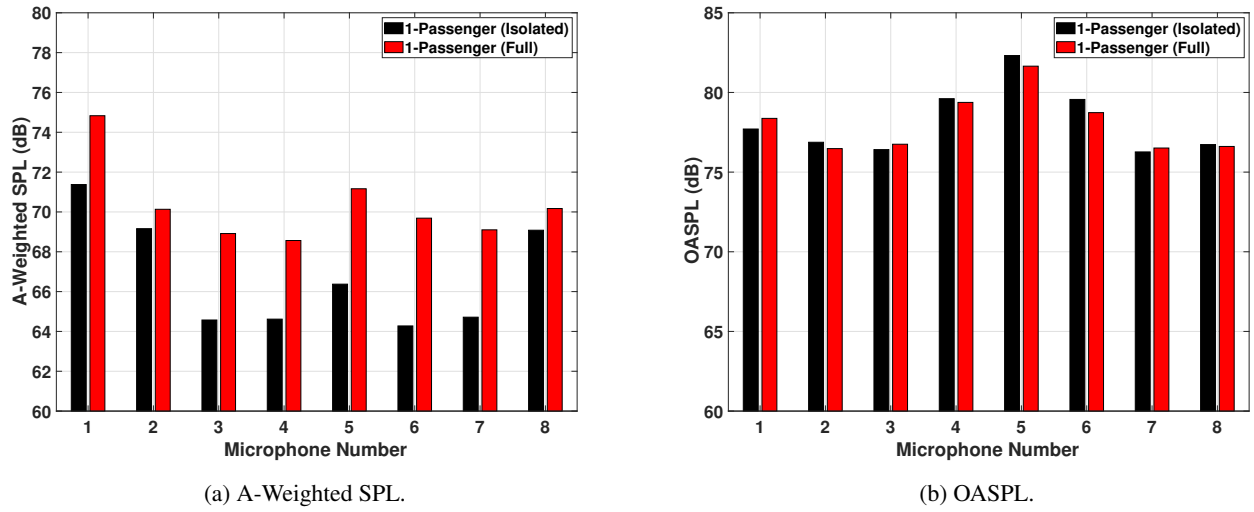


Fig. 11: Acoustic comparison between the 1-passenger isolated rotor and full configurations.

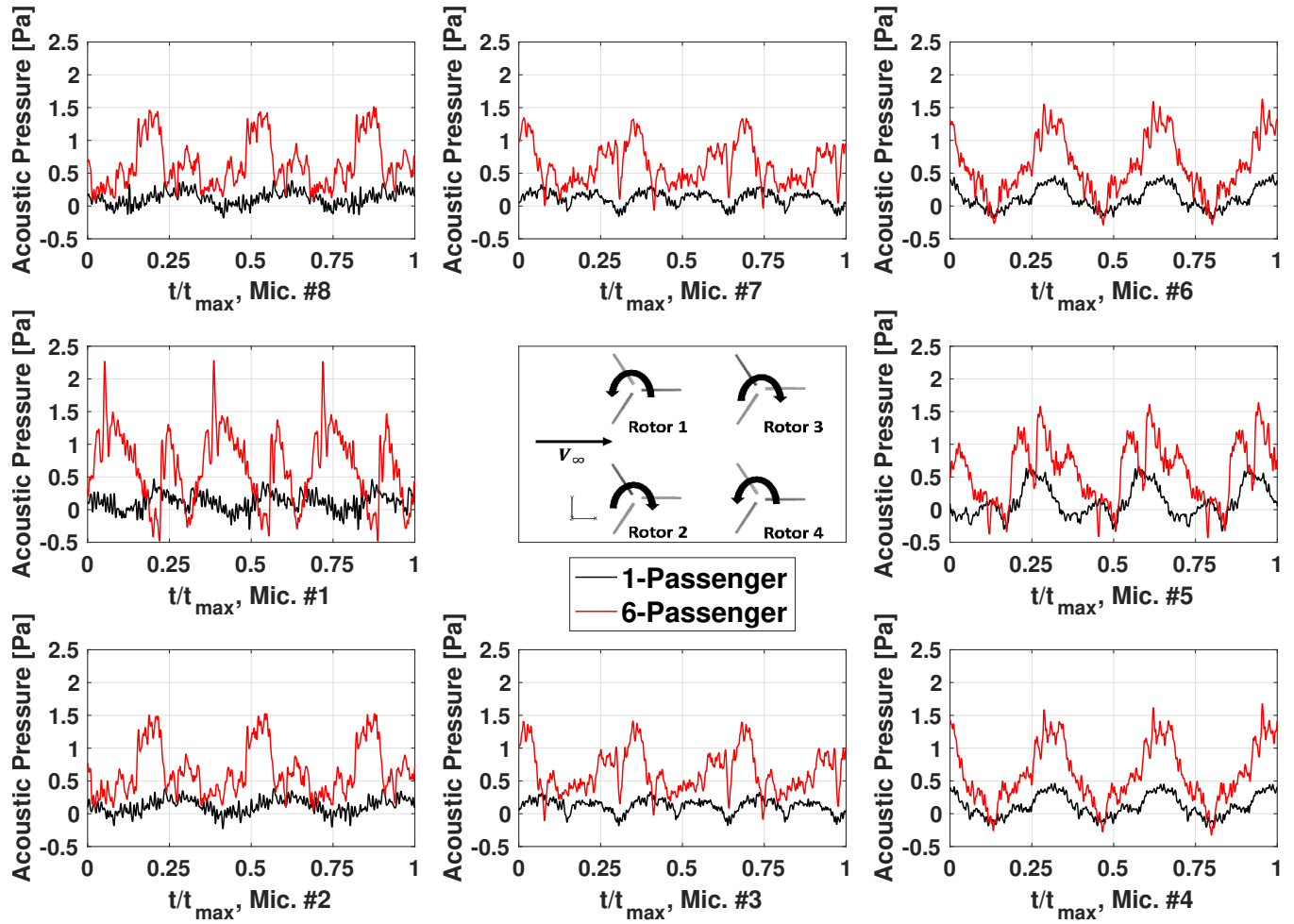


Fig. 12: Loading noise comparison between the 1-passenger and 6-passenger configurations.

Table 4: A comparison of physical properties.

Aircraft Properties	1-Passenger	6-Passenger	Bell 430
Rotor Radius	2.0 m	4.0 m	6.4 m
Number of Rotors	4	4	1
Blades per Rotor	3	3	4
Nominal Rotor Speed	662 RPM	400 RPM	349 RPM
Blade Passage Frequency	33.1 Hz	25.0 Hz	23.2 Hz
Freestream Velocity	70 knots	70 knots	124 knots
Hover Tip Mach Number	0.41	0.50	0.69
Advancing Tip Mach Number (Level Flight)	0.52	0.61	0.88
Payload	100 kg (220 lb)	544 kg (1,200 lb)	565 kg (1,247 lb)

Table 5: A comparison of OASPL.

OASPL	1-Passenger	6-Passenger	Bell 430
Overhead	50.9 dB	55.7 dB	75.3 dB
Flyover	56.6 dB	63.8 dB	77.2 dB

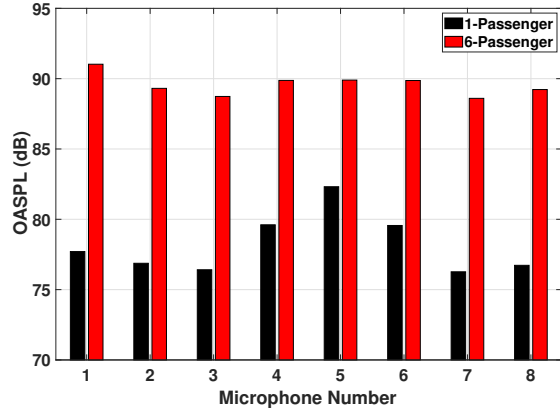


Fig. 13: OASPL comparison between the 1-passenger and 6-passenger configurations.

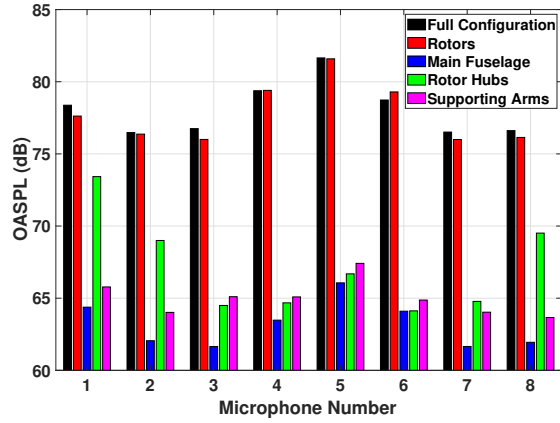
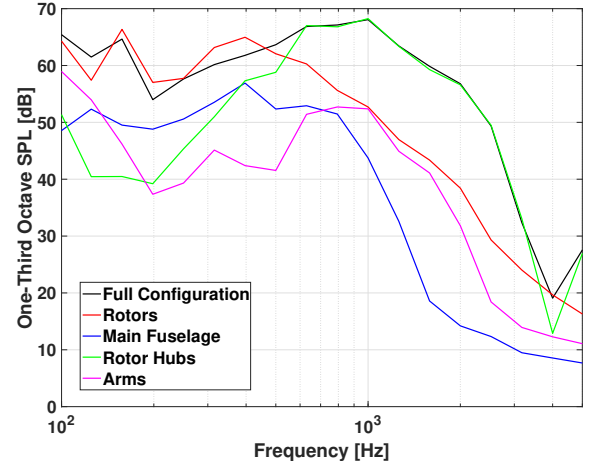


Fig. 14: OASPL decomposition of the 1-passenger full configuration.

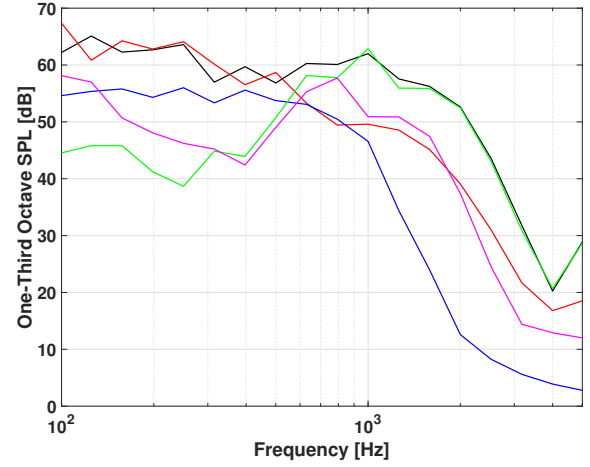
not entirely fair. At this time, no correction or compensation for the advancing tip Mach number was applied in the noise comparison.

Figure 16a presents the comparison of A-weighted SPL between the 1-passenger isolated rotor case, 6-passenger isolated rotor case, and Bell 430 at the one-third octave center frequencies ranging from 100 Hz to 5,000 Hz for the overhead scenario. The A-weighted SPL differences between the three cases are shown in Fig. 17a. The Bell 430, overall, shows much higher A-weighted SPL (> 10 dB), than both the 1-passenger and 6-passenger isolated rotor cases. Furthermore, the 6-passenger isolated rotor case shows higher A-weighted SPL than the 1-passenger full configuration at most one-third octave center frequencies, especially at lower frequencies.

A comparison between the three cases is also performed for the flyover scenario (see Fig. 16b and the corresponding SPL difference plot is shown in Fig. 17b). Again, the Bell 430 shows significantly higher SPL than the 1-passenger and 6-passenger cases. Note that the noise difference between quadrotor and helicopter becomes small (less than 10 dB for 6-passenger quadrotor) at 1,000 Hz where the human ear perception to noise annoyance is important.



(a) Microphone 1

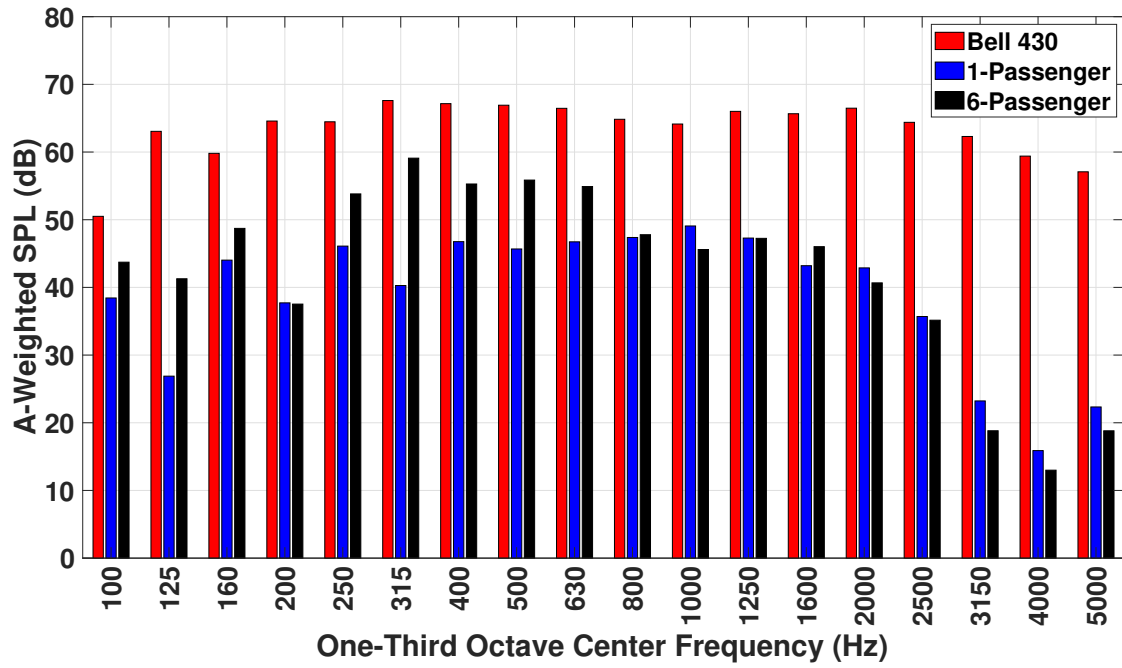


(b) Microphone 5.

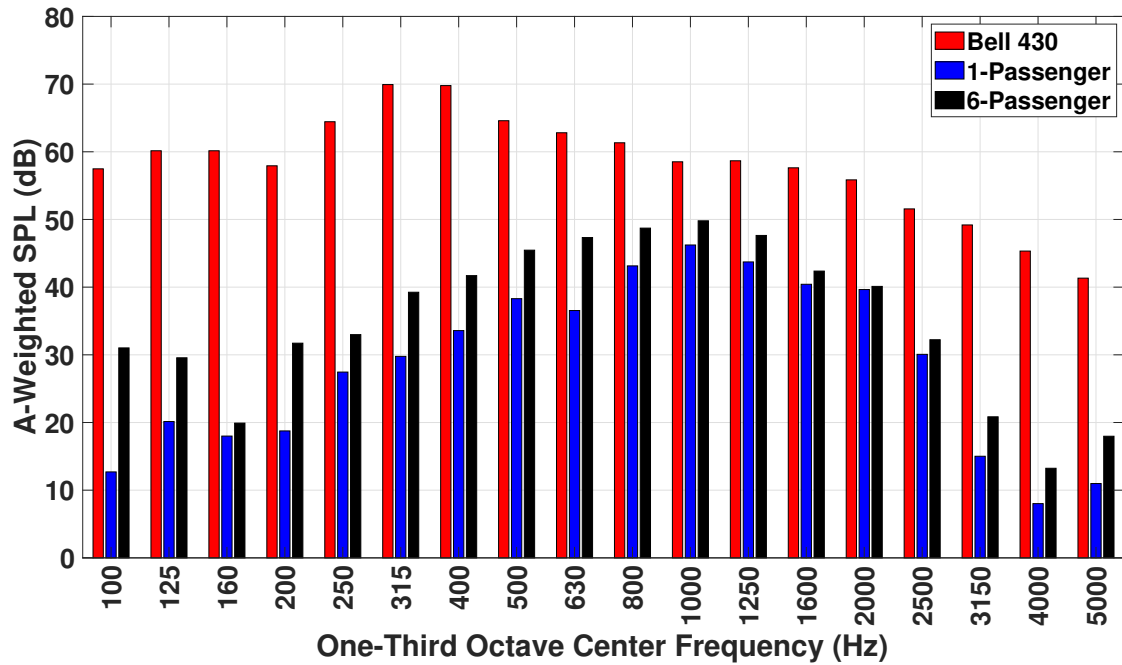
Fig. 15: Acoustic pressure spectrum of the decomposition analysis.

The large discrepancies in A-weighted SPL between the Bell 430 and UAM vehicles in both flyover and overhead scenarios can be attributed to several reasons. First and foremost, the Bell 430 operates at a higher advancing tip Mach number than both the 1-passenger and 6-passenger vehicles. Second, the Bell 430 incorporates a tail rotor, which contributes additional thickness and unsteady loading noise due to the aerodynamic interactions between the main rotor and the tail rotor and also the self tail rotor noise. Third, the broadband noise of UAM quadrotor vehicles could be under-predicted based on the present acoustic methodology particularly at high frequencies or greater than 1000 Hz. It should be noted that the maximum frequency is limited to 5000 Hz in order to eliminate the trailing-edge broadband noise, which is significant at frequencies higher than 5000 Hz (Refs. 32,33). Fourth, the rotor trim of the Bell 430 is expected to be significantly different than that of UAM quadrotor vehicles.

The OASPL, which is computed by integrating the A-weighted SPL from 100 Hz to 5,000 Hz, is shown in Table 5 for each simulation case. The differences in OASPL be-

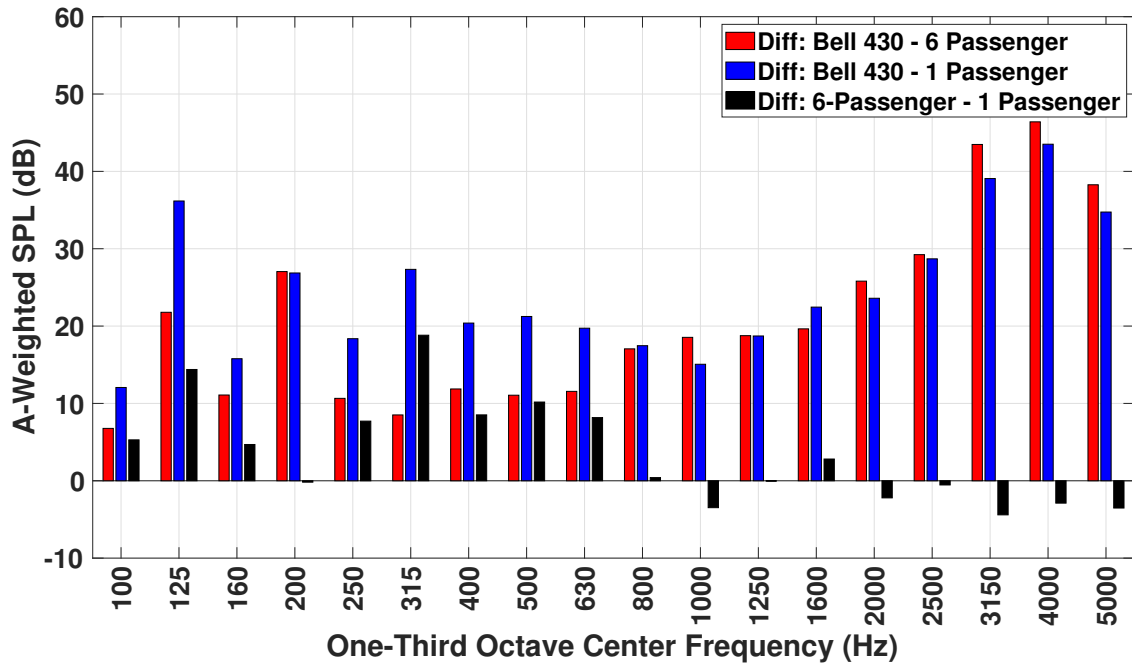


(a) Overheard case.

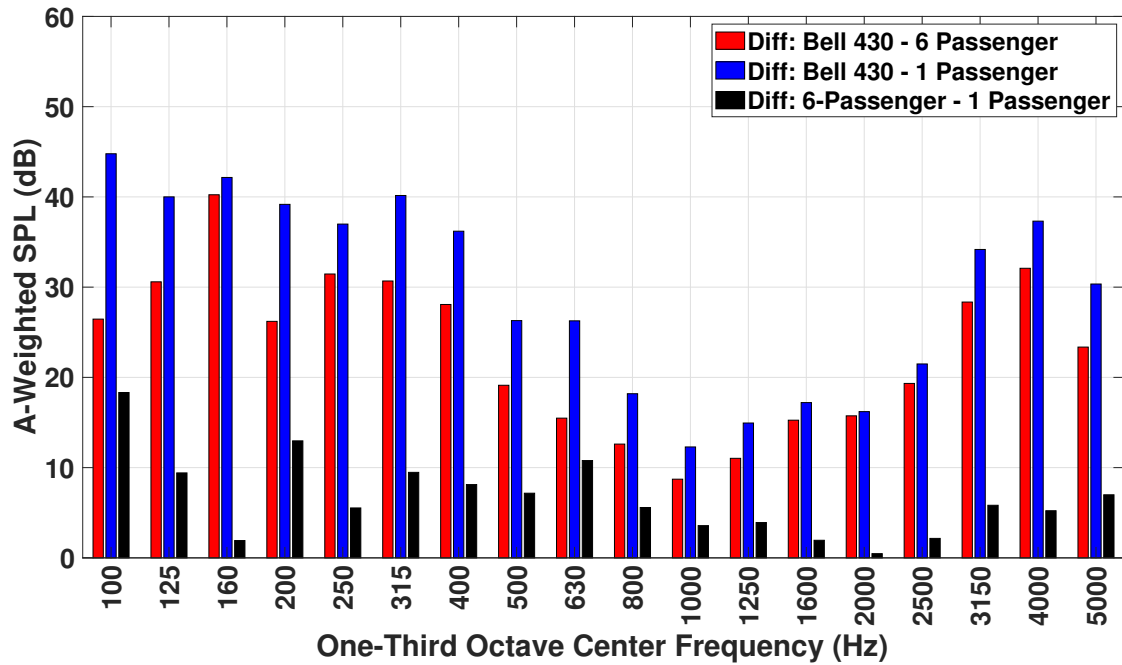


(b) Flyover case.

Fig. 16: A-weighted SPL of the 1-passenger, 6-passenger, and Bell 430 configurations.

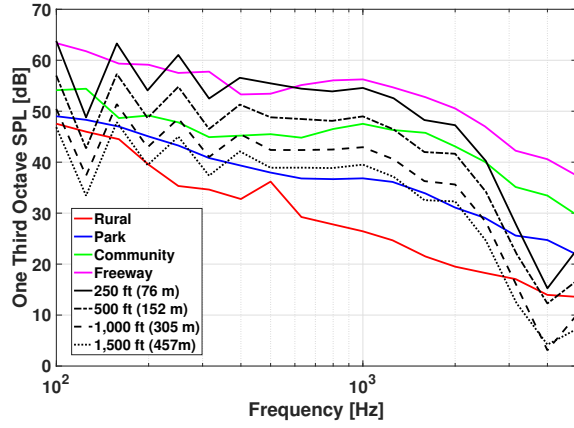


(a) Overhead case.

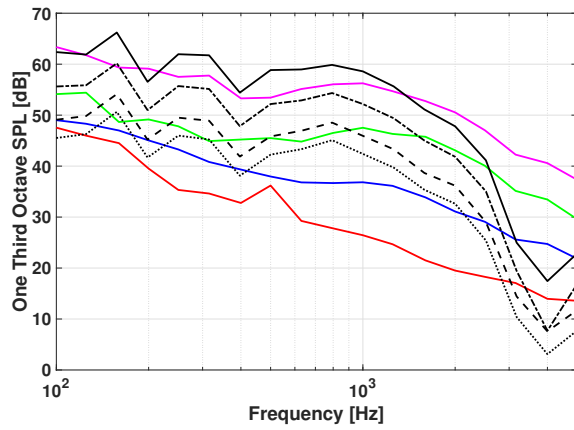


(b) Flyover case.

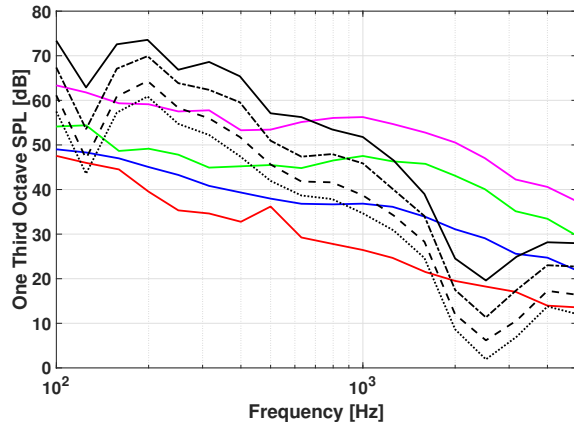
Fig. 17: A-weight SPL differences between the 1-passenger, 6-passenger, and Bell 430 configurations.



(a) 1-passenger isolated rotor case.



(b) 1-passenger full configuration case.



(c) 6-passenger isolated rotor case.

Fig. 18: A comparison between UAM vehicle noise and ambient noise.

tween the 6-passenger UAM vehicle and the Bell 430 are 13.4 dB and 19.6 dB for the flyover and overhead cases, respectively. The UAM vehicles with multi-rotors show a significant acoustic benefit than a conventional helicopter in level flight. However, Uber's initial guideline (Ref. 30) of 15 dB quieter than helicopter noise is not met for the flyover case. Considering a much higher advancing tip Mach number for the heli-

copter, the uncertainty of noise predictions and, the ignorance of other noise sources such as trailing-edge broadband noise, the risk of the excessive noise to the noise guideline would be higher. It is also worthwhile noting that numerous UAM aircraft will operate at the same time so that the noise impact would be much larger than a single vehicle comparison with helicopter. Overall, aircraft noise will be an important issue to UAM operation and noise reduction technology should be developed.

Acoustic Comparison Against the Community Background Noise

In addition to the comparison of UAM aircraft noise with helicopter noise, it is important to compare UAM aircraft noise with community background noise. There is a general agreement that UAM aircraft noise should not exceed the background noise to enhance the public acceptance of this new transportation method. The acoustics of the 1-passenger and 6-passenger UAM vehicles are compared against the background or ambient noise documented by Begault (Ref. 34). The ambient noise was recorded in rural, park, freeway, and community areas as a reference guide for UAM noise assessment. The maximum ambient noise occurs near highways while the rural area shows minimum noise. In the present work, the UAM vehicle noise was simulated at the following distances above the ground: 250 ft (76 m), 500 ft (152 m), 1,000 ft (305 m), and 1,500 ft (457 m). The microphones are positioned directly below the vehicle.

Figures 18 shows the comparisons in one-third octave SPL between the UAM vehicle noise and the ambient noise for the 1-passenger isolated rotor case, 1-passenger full configuration case, and 6-passenger isolated rotor case. For the 1-passenger isolated rotor case, the vehicle SPL exceeds the SPL in rural area from 200 Hz to 3,000 Hz at a maximum distance of 1,500 ft as shown in Fig. 18a. However, the UAM noise at a distance equal or greater than 500 ft could be masked by the freeway noise. It is anticipated that the 1-passenger flying at 5,000 ft altitude or the designed cruise altitude would not significantly affect the local community.

Similar trend can also be seen in the 1-passenger full configuration case (see Fig. 18b), except that the SPL from 100 Hz to 1,000 Hz is elevated by a maximum of 3 dB. Unlike the 1-passenger simulation cases, the UAM vehicle noise of the 6-passenger isolated rotor case shows higher SPL than the freeway noise (see Fig. 18c) even at a distance of 1,500 ft around 200 Hz. On the other hand, the SPL at a distance equal or greater than 1,000 ft could be masked by the freeway noise at a frequency above 300 Hz. It should be also noted that the high-frequency broadband noise components might not be well predicted in the present study, and therefore, the SPL could increase if a proper broadband noise prediction approach, such as the one developed by Li and Lee (Refs. 32, 33), is incorporated in the total noise calculation.

CONCLUSIONS

High-fidelity CFD simulations were performed for the acoustic analysis of a 1-passenger quadrotor UAM aircraft and a 6-passenger quadrotor VTOL aircraft in cruise at a speed of 70 knots. Acoustic simulations were carried out at eight microphone positions based on an impermeable FWH strategy. The acoustic source strength between the 1-passenger and 6-passenger configurations are compared based on CFD results. A detailed acoustic comparison between the 1-passenger isolated rotor, 1-passenger full configuration, and 6-passenger isolated rotor models was performed. The acoustics of both 1-passenger and 6-passenger quadrotor UAM aircraft were also compared against the noise of a conventional helicopter Bell 430 in level flight. A comparison between vehicle acoustics and ambient noise was performed to evaluate the impact of UAM vehicle noise on urban and suburban communities. The following conclusions were drawn based on the results presented in this paper:

1. It was found that BVI is a dominant noise source in the selected quadrotor UAM aircraft.
2. The eVTOL fuselage contributes additional noise with broadband noise characteristics to the total noise of the 1-passenger configuration. The maximum difference in A-weighted SPL, which accounts for the human-hearing frequency range, between the 1-passenger isolated rotor and full configurations is approximately 5 dB. However, the OASPL difference, which incorporates the low-frequency SPL, is insignificant between the two cases.
3. The main rotor is the largest contributor to the total noise of the 1-passenger quadrotor configuration, especially from the low- to mid-frequencies. The rotor hubs show significant impact on the total noise particularly at high-frequencies, and the rotor-hub noise is more likely to propagate in the front and rear directions. Rotor-hub noise could be reduced if the root section is tailored to reduce the root-induced BVI.
4. The 6-passenger quadrotor noise is significantly higher than the 1-passenger quadrotor noise. The maximum difference in OASPL between the two configurations is 14 dB. This noise difference would be affected not only by the size itself, but also by the rotor trim setting, which significantly changes the BVI strength. This indicates a potential to reduce BVI noise by changing the trim setting.
5. The noise of the conventional helicopter Bell 430 in level flight is significantly higher than both 1-passenger and 6-passenger quadrotor configurations. It should be noted that this comparison may not be fair since the advancing tip Mach number of the helicopter is much higher than that of the quadrotor aircraft. The OASPL difference in either the flyover or overhead scenario is greater than 10 dB between the 6-passenger quadrotor configuration and

the Bell 430. However, a goal of 15 dB quieter than helicopter noise for UAM aircraft would be challenging even with a large discrepancy of the advancing tip Mach number. In particular, the noise difference becomes smaller at frequencies where the human ear perception is sensitive. Noise reduction technology should be developed to enhance the public acceptance of UAM operations.

6. The noise of the 1-passenger quadrotor configuration can be completely masked by the highway noise at a distance greater or equal to 1,000 ft (305 m). On the other hand, 6-passenger quadrotor noise can be covered by the highway noise at a frequency above 300 Hz and altitude of 1,000 ft or above. It should be noted that high-frequency broadband noise was not completely considered in this analysis. Both 1-passenger and 6-passenger quadrotor noise during low-altitude operations could be a potential concern to both urban and suburban communities. It should be noted that this analysis is based on a single aircraft. In reality, multiple UAM aircraft will fly at the same time so that there is higher chance for UAM operation to exceed the ambient noise.

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