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Journal

JOURNAL OF THE AMERICAN HELICOPTER SOCIETY, 67(1)

ISSN

0002-8711

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Publication Date

2022

DOI

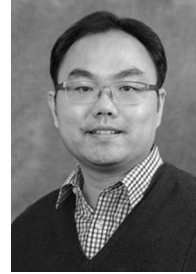
10.4050/JAHS.67.012009012009-1

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Computational Study on Noise of Urban Air Mobility Quadrotor Aircraft



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This paper investigates the acoustics of a one-passenger and a six-passenger quadrotor urban air mobility (UAM) aircraft in level flight based on a high-fidelity computational fluid dynamics (CFD) approach. The CFD simulations are carried out using the HPCMP CREATE™-AV multidisciplinary rotorcraft analysis and simulation tool Helios. The acoustic simulations are performed using the acoustic prediction tool PSU-WOPWOP. A total of three CFD models are simulated: a one-passenger isolated rotor configuration, a one-passenger full configuration with a fuselage, and a six-passenger isolated rotor configuration. The noise comparison between the one-passenger isolated rotor case and the full configuration case shows that the vehicle fuselage increases the A-weighted sound pressure level (SPL) up to 5 dB. The acoustic comparison between the one-passenger and the six-passenger isolated rotor configuration shows that the maximum overall SPL difference is up to 14 dB. Furthermore, it is shown that the noise of the six-passenger configuration is approximately 11 dB lower than that of a similar-sized conventional helicopter in an overhead scenario. The community noise impact of UAM aircraft is also assessed and compared to various background noise levels. The results show that the one-passenger quadrotor noise can be fully masked by freeway noise at an altitude greater than or equal to 1000 ft, while the six-passenger quadrotor noise can only be partially masked by freeway noise even at an altitude of 1000 ft.

Nomenclature

C_{tip}	tip chord length, m
$dF_n/d\Psi$	azimuthal derivative of F_n , N/(m-deg)
F_n	blade sectional normal force, N/m
M_∞	freestream Mach number
R	rotor radius, m
r_b	blade radial position, m
r_b/R	nondimensional blade radial position
q	q-criterion, $\frac{1}{2}(\ W_{ij}\ ^2 - \ S_{ij}\ ^2)$, $1/s^2$
$\bar{q}$	nondimensional 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, $1/s^2$
α	vehicle pitch attitude, deg
β_o	blade coning angle, deg
β_{1c}	longitudinal flapping angle, deg
β_{1s}	lateral flapping angle, deg
θ_o	blade collective pitch, deg
μ	advance ratio

Ψ

rotor azimuth, deg

Acronyms

BVI	blade—vortex interaction
BPF	blade-passage frequency, Hz
CCW	counterclockwise rotation
CFD	computational fluid dynamics
CSD	computational structural dynamics
CW	clockwise rotation
SPL	sound pressure level, dB
OASPL	overall sound pressure level, dB
UAM	Urban Air Mobility
VTOL	vertical take-off and landing

Subscript

ret	evaluated at the retarded time
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Superscript

°	degrees azimuth
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Presented at the Aeromechanics Advanced Vertical Flight Technical Meeting, San Jose, CA, January 21–23, 2020. Manuscript received December 2020; August 2021.

Introduction

Rotorcraft have always been an indispensable tool in both civil and military aviation due to its unique capability to take off and land vertically in addition to hover. In recent years, hybrid- and fully electric vertical take-off and landing (VTOL) aircraft designs have become increasingly popular due to the emerging concept of urban air mobility (UAM) (Ref. 1), or also known as urban air taxi operations for air passenger and cargo transportation in metropolitan areas. The two main purposes of UAM are to alleviate massive traffic congestions 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 multiple rotors and a hybrid or fully electric propulsion system. Hence, the aerodynamic and acoustic characteristics of UAM aircraft are expected to be significantly 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 tonal noise, and therefore, low-noise emission is one of the major UAM aircraft design challenges.

In support of the UAM technology development, the advocates of UAM from industry, government, and academia have performed ongoing research to investigate both aerodynamics and acoustics of multirotor UAM aircraft. In 2018, Johnson et al. (Refs. 3,4) performed research studies on aeromechanics of several conceptual UAM aircraft designs using NASA's preliminary design and analysis code NDARC (Ref. 5) and the comprehensive rotorcraft analysis software CAMRAD II (Ref. 6). Their research suggested that both rotor-to-rotor and rotor-to-wing interactions could significantly impact vehicle vibration, acoustics, and power performance. They anticipated that blade-vortex interaction (BVI) noise, which is due to the aerodynamic interaction between the tip vortex of a preceding blade and the blade surface of an aft blade in close proximity, could become an issue for a multirotor design.

In 2019, Ventura Diaz et al. (Refs. 7,8) investigated both aerodynamics and performance of NASA's six-passenger side-by-side rotor design with rotor overlaps based on a high-fidelity computational fluid dynamics (CFD) approach. Their results showed that the rotor airloads of the side-by-side rotor are sensitive to the percentage of rotor overlap, which is a key design parameter of the side-by-side rotor configuration. They found that the configuration with a 15% rotor overlap yielded the best aerodynamic efficiency. Their high-fidelity CFD results also captured potential rotor-to-rotor BVI, which is an important noise source of the side-by-side rotor with a rotor overlap due to the close aerodynamic interactions between the tip vortices of one rotor and the blade surface of another rotor. Sagaga and Lee (Ref. 9) also investigated the aerodynamic performance of the same side-by-side rotor configuration in hover based on high-fidelity CFD simulations, and they showed that the hover performance could be reduced with an increasing rotor overlap.

Jia and Lee (Ref. 10) analyzed the aerodynamically induced noise of the same side-by-side rotor configuration based on high-fidelity CFD simulations. They showed that rotor-to-rotor BVI is the most dominant acoustic source of the side-by-side rotor. Their acoustic predictions also showed that the noise level of the side-by-side rotor increases significantly with an increasing percentage of rotor overlap. Sagaga and Lee (Ref. 11) also utilized high-fidelity CFD simulations to study the acoustics of the side-by-side rotor in hover. They found that strong rotor-to-rotor BVIs occur at the entrance and exit of the overlap, and the BVI strength increases with larger overlap. Wachspress et al. (Ref. 12) analyzed the acoustics of UAM aircraft designs based on the airloads obtained from the Comprehensive Hierarchical Aeromechanics Rotorcraft Model (CHARM) (Ref. 13), a comprehensive rotorcraft analysis tool. Their results showed that propeller-wing and rotor-duct interac-

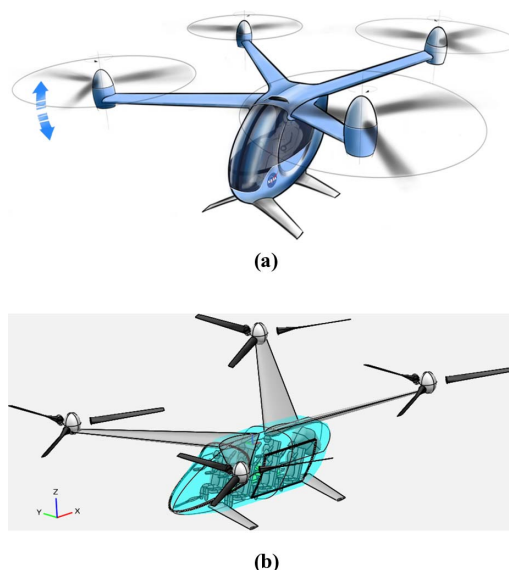


Fig. 1. NASA's conceptual quadrotor VTOL designs (Refs. 3, 4): (a) one-passenger configuration with electric propulsion; (b) six-passenger configuration with turboshaft propulsion.

tions could lead to a higher overall sound pressure level (SPL) than for their baseline cases without a wing and a duct.

Besides the research on tonal noise of UAM aircraft, Li and Lee (Ref. 14) have demonstrated the capability to predict broadband noise of NASA's six-passenger multirotor UAM VTOL designs using their in-house acoustic prediction tool UCD-QuietFly (Ref. 15). Their work showed that the high-frequency contents of UAM aircraft broadband noise, particularly the trailing-edge noise (Ref. 16), could not be completely masked by various background noise (e.g., freeway noise). They found that the amplitude of broadband noise could also increase if multiple UAM aircraft operate simultaneously.

Other than the acoustic research on large UAM aircraft, various parametric studies have been recently performed to investigate the noise characteristics of small-scaled multirotor drones that are capable of delivering small packages as part of UAM missions. Thai and Grace (Ref. 17) showed that the SPL of a quadrotor was significantly increased with an increasing rotor rotation rate based on high-fidelity CFD simulations. Yang et al. (Ref. 18) demonstrated that the rotor power of a small-scaled rotor was reduced at a lower rotor shaft angle, but the overall SPL was increased according to their in-door experiment. Lee and Lee (Ref. 19) analyzed the noise of a quadrotor configuration with various rotor-to-rotor separation distances based on a lifting surface method. They showed that the acoustic pressure was significantly increased with a decreasing rotor-to-rotor separation distance.

Although there have been active research studies on UAM aircraft and drone acoustics in recent years, the fundamental understanding of the noise impact of UAM aircraft, especially the quadrotor configurations, on the urban community is still limited. Therefore, the aim of this paper is to expand the current understanding of quadrotor UAM aircraft noise in steady forward flight based on first principles and a high-fidelity CFD approach. The two quadrotor models being analyzed in the present work are considered as shown in Fig. 1. Potential noise sources are identified for each quadrotor configuration based on high-fidelity CFD simulation results. The influence of a fuselage on both the acoustic source strength and the SPL is investigated. The effect of eVTOL size on aircraft noise is also studied based on the acoustic comparison between the one-passenger and six-passenger configurations. In order to assess the impact of UAM

Table 1. Basic properties of the two conceptual designs.

Aircraft Properties	One-Passenger Design	Six-Passenger Design
Fuselage length	2.9 m (9.5 ft)	7.6 m (25.0 ft)
Fuselage height	2.0 m (6.5 ft)	1.6 m (5.1 ft)
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	Turboshaft

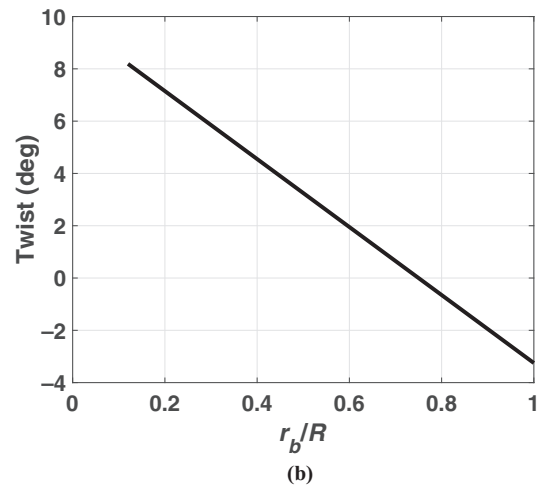
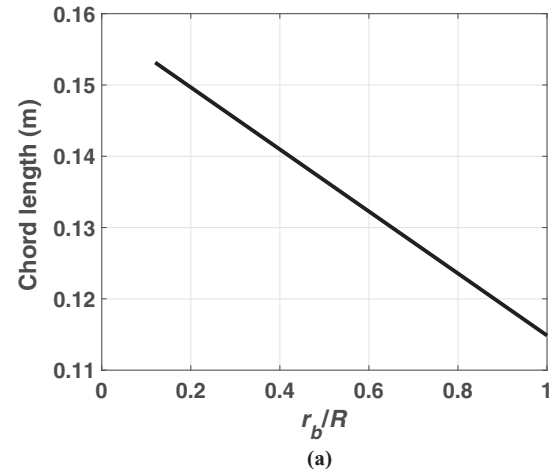
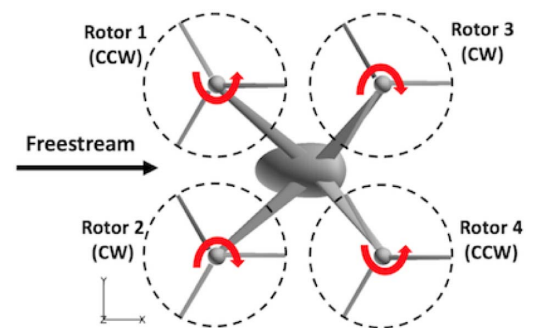
aircraft noise on the urban community, the noise levels of both the one-passenger and six-passenger configurations are compared against the noise level of a conventional helicopter and various background noise levels in urban and suburban areas.

Methods

Two of NASA's conceptual VTOL designs (Refs. 3, 4), a one-passenger quadrotor configuration (see Fig. 1(a)) and a six-passenger quadrotor configuration (see Fig. 1(b)), are analyzed in the present work. The fundamental properties of these two configurations are shown in Table 1. The two rear rotors are 0.35 rotor radii (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 spanwise locations less than 85% R ; a linear interpolation of VR-12 and SSC-A09 is assumed between 85% and 95% span; SSC-A09 is used for spanwise locations larger than 95% R . Linear blade chord and twist distributions as a function of nondimensional radial position (r_b/R) are shown in Fig. 2. A total of three CFD models are analyzed in the present work: a one-passenger isolated rotor configuration, a one-passenger full configuration with the fuselage, and a six-passenger isolated rotor configuration. Rotor hubs are included in all three models. Figure 3 shows the rotation of each rotor of the one-passenger full configuration model.

CFD grids and boundary conditions

A dual-mesh paradigm, which solves the near-body flow domain based on structured overset grids and the off-body flow domain based on adaptive Cartesian grids, is employed in the present work. The near-body surface and volume grids are constructed using NASA's overset grid generation software Chimera Grid Tools (Refs. 20, 21). Figure 4(a) shows the volume grids of a single rotor blade, and Fig. 4(b) shows the fuselage surface grids. 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) $\times$ 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 blade grid dimensions of both one-passenger and six-passenger configurations are chosen based on high-fidelity CFD simulations of single rotor research studies (Refs. 22–24) and are kept the same for comparison analyses. A wall spacing of 1×10^{-5} grid unit is set to match a dimensionless wall distance $y^+ = 1.0$. The near-body volume grids are extended one tip chord length away from the near-body surfaces with the end spacing of the volume grids equal to 10% C_{tip} .

**Fig. 2. Blade properties: (a) blade chord distribution; (b) blade twist distribution.****Fig. 3. Rotor setup.**

A viscous adiabatic wall boundary condition is applied to the surface of the near-body grids, and a periodic boundary condition is applied at the midpoint of the trailing blunt edge of the main-blade grids in the chordwise direction. This periodic boundary condition is required to close the loop for the overset mesh structure. Each rotor blade is composed of approximately 3.6 million grid points, and a total of 43.2 million grid points are used for 12 blades. The structured fuselage grid of the one-passenger full configuration, which accumulates a sum of 8.3 million grid points, is shown in Fig. 4(b). The total number of near-body grid points of the one-passenger full configuration is 51.5 million when combined with the fuselage.

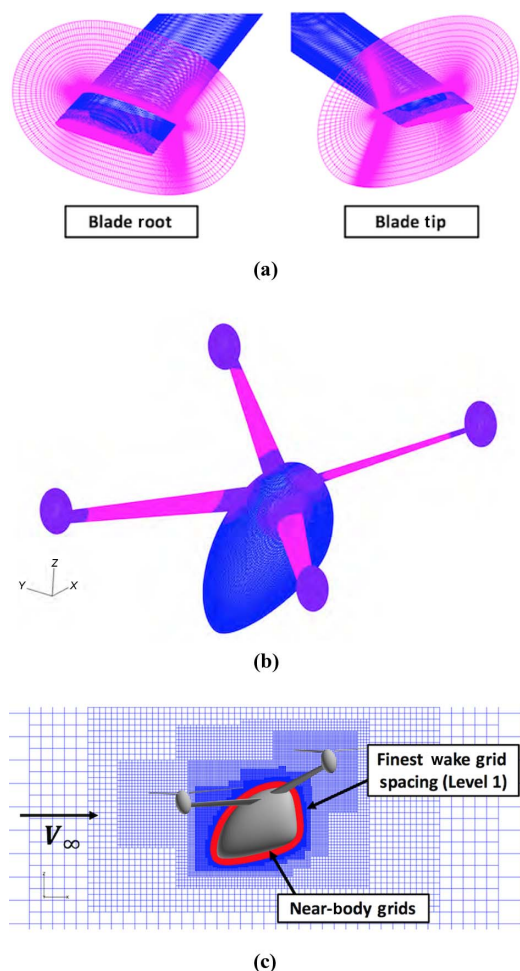


Fig. 4. CFD grids: (a) near-body blade volume grids; (b) near-body fuselage surface grids; (c) off-body Cartesian mesh.

The off-body Cartesian mesh as shown in Fig. 4(c) is generated using the adaptive off-body Cartesian solver SAMCart (Ref. 25), the off-body solver of the CREATETM-AV software Helios (Ref. 26). 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 applied to simulate multirotor and coaxial rotor systems (Refs. 27–30). The off-body solver SAMCart has been demonstrated to resolve complex rotor wakes based on high-order numerical schemes and adaptive mesh refinement (AMR) (Refs. 31,32). In the present work, eight levels of AMR are used after the first rotor revolution in order to capture the detailed flow physics of rotor wakes. The far-field boundaries of the off-body mesh are extended 20 rotor radii away from the origin in the x -, y -, and z -directions. The finest wake-grid or Level-1 spacing of the off-body mesh is set to 10% C_{tip} . Freestream boundary conditions with pressure equal to the ambient pressure and velocity equal to the forward flight velocity are applied at the far-field boundaries. The total number of Cartesian grid points of the one-passenger isolated rotor and full configuration cases is approximately 290 and 320 million, respectively, after the numerical convergence of CFD solutions. The total number of Cartesian grid points of the six-passenger isolated rotor case is approximately 260 million after numerical convergence.

CFD simulation setup and rotor trim

NASA's structured and high-fidelity compressible flow solver OVERFLOW (Ref. 33), which is incorporated as a near-body flow solver in Helios, is used for the near-body flow simulation. The off-body flow simulation is carried out using the off-body adaptive Cartesian solver SAMCart. 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 deg azimuth, which results in 1440 time steps per rotor revolution, is used for the time-accurate CFD simulations presented in this paper. Previous research studies (Refs. 22,32,34) also indicated that a time step size of 0.25 deg azimuth is capable of accurately predicting blade tip vortices. Forty and 10 dual-time-stepping subiterations within each physical time step are used for both near-body and off-body simulations, respectively. The Spalart–Allmaras (SA) Reynolds-averaged Navier–Stokes turbulence model (Ref. 35) coupled with detached eddy simulation (Ref. 36), which is capable of resolving large eddies away from the near-body boundary layer, is employed for turbulence modeling. In a recent research study, Thai et al. (Ref. 37) compared the fully turbulent SA model with five turbulence transition models for airloads predictions of a small quadrotor. Their results showed that the fully turbulent SA model gave the most accurate results for thrust while being the most efficient model. Since the accuracy of airloads predictions is directly correlated with the accuracy of tonal noise predictions, the SA model is anticipated to capture tonal noise components of the quadrotors analyzed in this paper. However, different turbulence models may affect the accuracy of broadband noise predictions, such as the A-weighted SPL results shown in Fig. 13(a) in Results. The effect of turbulence models on broadband noise predictions should be studied in the future given additional experimental data.

In order to perform acoustic simulations, blade surface geometry and flow quantities are extracted at every 0.5 deg azimuth or every two time steps over the last rotor revolution after numerical convergence. A total of six rotor revolutions are performed for each simulation case. All simulations were performed using the Excalibur Cray XC40 high-performance computer of the U.S. Army Research Laboratory, DoD Supercomputing Resource Center. A total number of 640 processors are used, and each rotor revolution of the one-passenger full configuration case takes approximately 16 h.

The rotor trim outputs are provided by Johnson et al. (Refs. 3,4), which are computed using NASA's rotorcraft design and analysis tool NDARC assuming a quasi-steady operating condition. Before the discussion of quadrotor trim, one should be aware that the collective and flapping motions of UAM aircraft would be significantly different from that of a conventional helicopter, such as the UH-60A helicopter analyzed by Yeo and Johnson (Ref. 38). Due to the polygon orientation of a quadrotor, it no longer requires longitudinal and lateral cyclic pitches to balance the vehicle forces and moments. It is also anticipated that a multirotor UAM aircraft with a small rotor radius would yield a higher magnitude of collective and flapping motions than that of a conventional helicopter.

The quadrotor aircraft analyzed in this paper are controlled using rotor collective at a constant rotation rate and a fixed aircraft pitch attitude. Note that each rotor is equipped with a flapping hinge which allows for pitch–flap coupling. The flapping hinges in both one-passenger and six-passenger configurations are located at 0.04% span. The total lift force of the four rotors is trimmed by the collective (θ_0) to balance the vehicle weight. The aircraft pitch attitude (α) of the one-passenger and six-passenger vehicles is trimmed to -8.49 and -6.14 deg, respectively, in order to provide the required forward thrust. The longitudinal flapping angles (β_{1c}) are trimmed to balance the vehicle pitching moment, while the lateral flapping angles (β_{1s}) are trimmed to balance the vehicle rolling

Table 2. Prescribed rotor motions

Rotor Angles	Front Rotors		Rear Rotors	
	One-Passenger	Six-Passenger	One-Passenger	Six-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

moment. The NDARC trim solutions of the quadrotor aircraft are given in Table 2.

Acoustic simulation setup

PSU-WOPWOP (Refs. 39,40), 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 predictions. PSU-WOPWOP numerically solves Farassat's Formulation 1A (Ref. 41) of the Ffowcs Williams and Hawkings equation (Ref. 42). In the present work, an impermeable surface strategy is implemented, and the quadrupole source term is neglected since the blade tip Mach number is subsonic (less than or equal to 0.6). The blade surface flow solutions of OVERFLOW are coupled with PSU-WOPWOP for noise prediction in the present work. Boyd (Ref. 43) validated the HART-II rotor noise based on the same coupling approach.

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 six-passenger vehicle away from the origin in both horizontal and vertical directions. The direct distance between each microphone and the origin is approximately 14 rotor radii (56.0 m) with an elevation angle equal to 45 deg. A schematic representation of the eight microphones from the top and side views is shown in Fig. 5.

Results

The one-passenger and six-passenger quadrotor UAM aircraft are analyzed in steady forward flight at a speed of 70 kt or 130 km/h. The freestream Mach number M_∞ of the one-passenger and six-passenger simulation cases is 0.11. The one-passenger vehicle is designed to cruise at an altitude of 5000 ft (1524 m) (Ref. 3), while the six-passenger vehicle is designed to cruise at a slightly higher altitude, which is at 6000 ft (1829 m) (Ref. 4). Each rotor of the two vehicles is assumed to operate at the nominal rotational speed, which is 662 PRM for the one-passenger model and 400 PRM for the six-passenger model. The advance ratios μ of one-passenger and six-passenger simulation cases are 0.26 and 0.21, respectively. The rotor forces and moments of each simulation case converge after five rotor revolutions, and the unsteady subiteration residuals of both near-body and off-body solvers drop an order of magnitude greater than 2.0 at each time step.

Acoustic source identification and source strength comparison

One-passenger isolated rotor configuration. Figure 6(b) shows an iso-surface of a nondimensional q-criterion ($\bar{q} = 0.001$) colored by vorticity magnitude for the one-passenger isolated rotor configuration. Self-BVI events, which are defined as aerodynamic interactions between blade-tip vortices and blade surfaces of the same rotor in close proximity, are visible on the advancing side of each rotor. According to Fig. 6(b), a zoomed-in view at rotor 2, the tip vortex pointed by the arrow directly impinges on the blade surface, which yields impulsive self-BVI. Note that self-BVI events are less likely to occur for a conventional helicopter

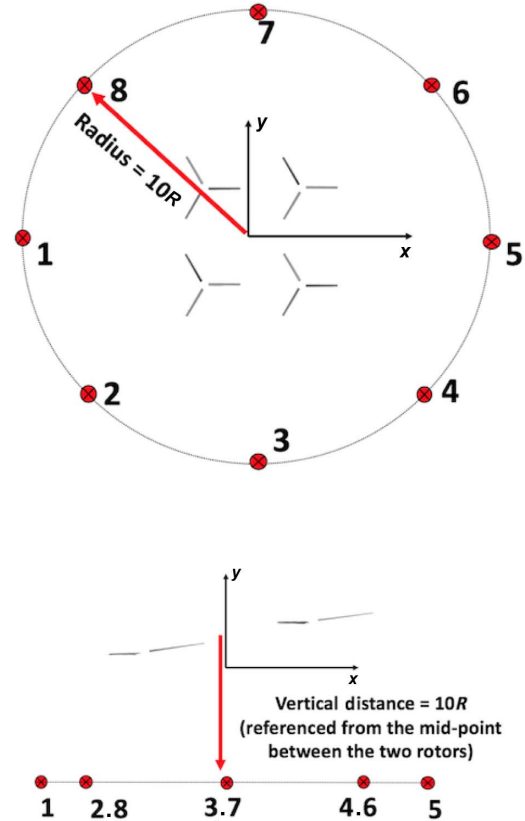


Fig. 5. Acoustic simulation setup (not drawn to scale): (a) top view; (b) side view.

on a cruise. It is anticipated that the induced velocity of an UAM aircraft rotor is lower than that of a conventional helicopter since the total lift force required to balance the vehicle weight is distributed among multiple rotors. Therefore, lower induced velocity could eventually lead to a lower wake convection rate in the vertical direction, and blade-tip vortices are more likely to interact with the blades of the same rotor.

A vorticity contour in Fig. 6(c) is also plotted from the side view in order to identify potential rotor-to-rotor BVI events between the front and rear rotors. Figure 6(c) shows the side view in the y -plane at the center position of rotor 2 (front rotor) and rotor 4 (rear rotor) with the freestream velocity pointing from left to right. Since the left (rotors 1 and 3) and right rotors (rotors 2 and 4) of the quadrotor design show symmetrical results, only the left rotors are shown in Fig. 6(c). Note that the front rotor is positioned $0.35R$ below the rear rotor. The trailing vortices of the front rotor convect in the downstream direction and below the rear rotor. No rotor-to-rotor BVI is found due to the vertical separation distance between the front and rear rotors. Although the one-passenger quadrotor design shown in the present work considers a vertical separation distance between the front and rear rotors in order to prevent rotor-to-rotor aerodynamic interactions, most UAM aircraft designs have placed the

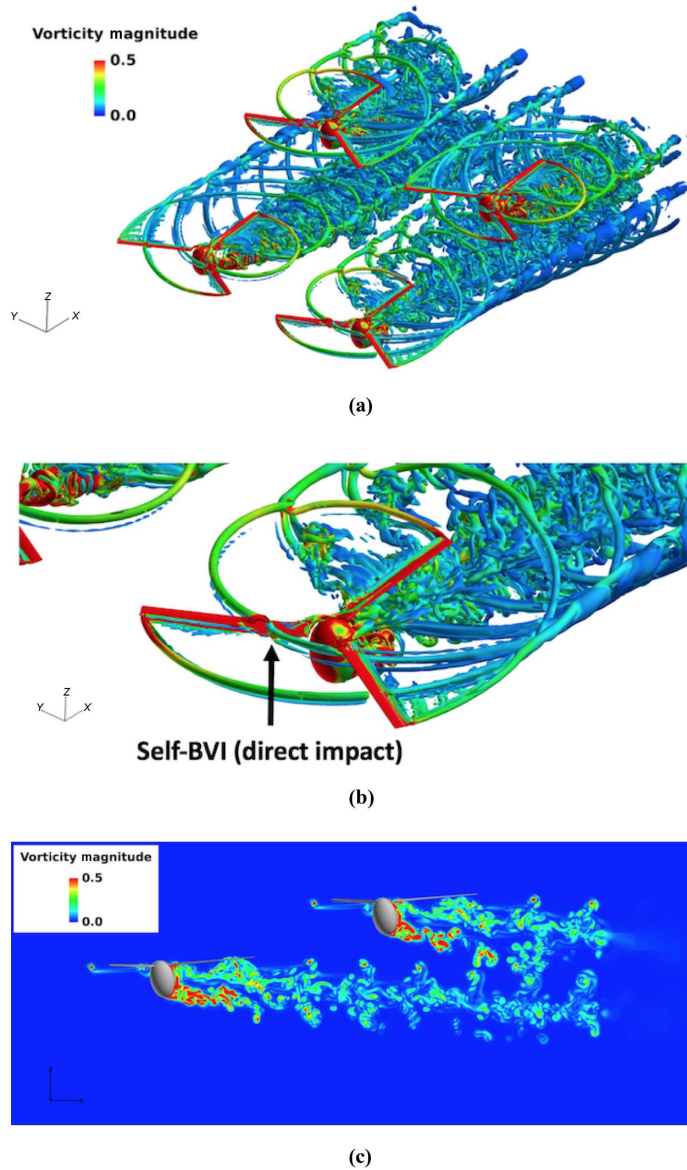


Fig. 6. The isosurface of q -criterion of the one-passenger isolated rotor configuration: (a) an isoparametric view; (b) a zoomed-in view at rotor 2; (c) the corresponding vorticity contour at the y -center of rotor 2.

front and rear rotors at the same height, which could lead to significant rotor-to-rotor interactions and noise.

The azimuthal derivative of sectional normal force ($dF_n/d\Psi$), which is a key source term of the loading noise acoustic pressure equation of Farassat's Formulation 1A (Ref. 41), is computed and shown in Fig. 7. These polar contours represent the change of $dF_n/d\Psi$ of one blade over the last rotor revolution. Self-BVI events are found on the advancing side of each rotor near $\Psi = 60^\circ$ and 90° (toward the blade tip) and are considered as the most dominant acoustic sources of the one-passenger quadrotor configuration. A self-BVI event near $\Psi = 300^\circ$ is also found on the retreating side of each rotor. Additionally, all four rotors show aerodynamic interactions between turbulent eddies coming from the rotor hubs and the rotor blades near $\Psi = 0^\circ$, but the strength of these interactions is weaker (highlighted in lighter blue colors) than that of the self-BVI events. A comparison of acoustic source strength between the

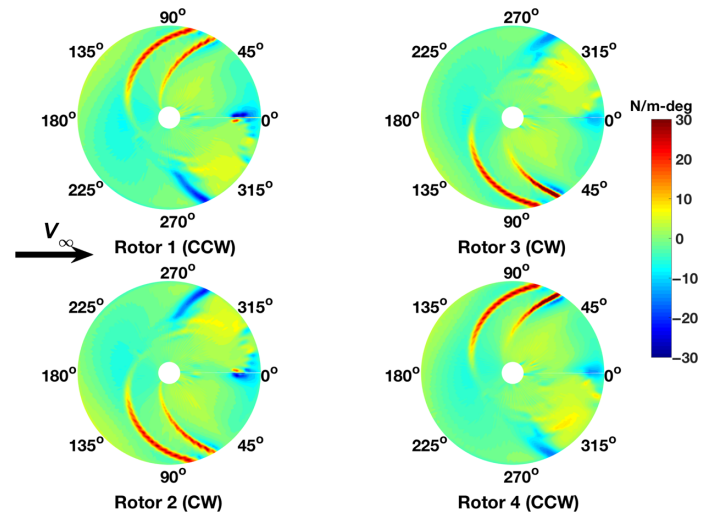


Fig. 7. The polar contours of $dF_n/d\Psi$ of the one-passenger isolated quadrotor configuration.

one-passenger isolated rotor and full configuration cases is illustrated in the next subsection.

One-passenger full configuration. The one-passenger full configuration, which incorporates the aircraft fuselage, is also simulated in this work and compared against the one-passenger isolated rotor case. Figure 8(a) shows an isosurface of a nondimensional q -criterion ($\bar{q} = 0.001$) colored by vorticity magnitude, self-BVI events can be seen at the four rotor locations. According to the vorticity contour at the y -center of rotor 2 (see Fig. 8(b)), no significant rotor-to-rotor aerodynamic interactions are found between the front and rear rotors. Since there is a vertical separation distance of $0.35R$ between the front and rear rotors, less rotor-to-rotor interaction is expected. However, massive flow separations (see Fig. 8(c)) occur in the rear portion of the fuselage.

Figure 9 shows a quantitative comparison of $dF_n/d\Psi$ at 75% span between the isolated rotor and full configuration cases. The self-BVI events are located at $\Psi = 60^\circ$, 110° , and 300° in both simulation cases. No significant difference between the two cases is found at 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 likely due to the influence of fuselage blockage effect on rotor-induced velocity and associated tip vortex trajectory. Note that the first BVI of the rear rotors at $\Psi = 60^\circ$ shows 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. As 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.

Six-passenger isolated rotor configuration. The six-passenger isolated rotor configuration is also simulated and compared against the one-passenger isolated rotor configuration. Figure 10 shows a quantitative comparison of $dF_n/d\Psi$ at 75% span between the one-passenger full configuration and the six-passenger isolated rotor configuration. The self-BVI events at $\Psi = 70^\circ$ and 270° of the six-passenger case show significantly higher peak values at the front rotors (rotors 1 and 2) than that of the one-passenger case. In the six-passenger case, it was found that the different trim settings (see Table 2) and the associated flow field result in a more direct impingement of tip vortex to the blade. It is anticipated that the six-passenger configuration would yield significantly higher noise levels than for the one-passenger configuration.

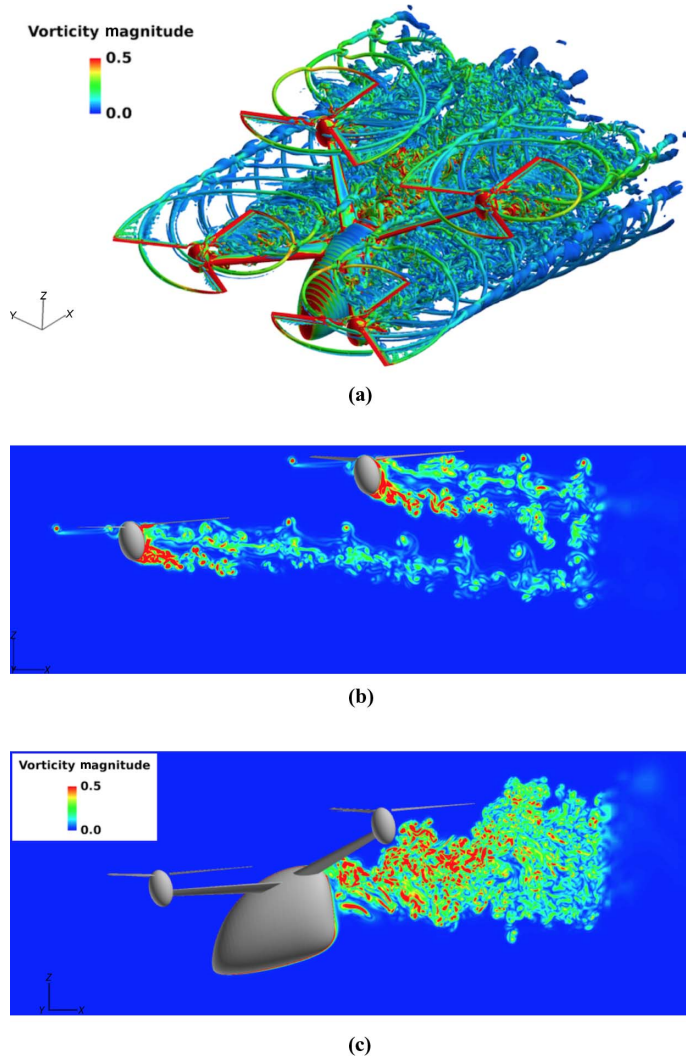


Fig. 8. The isosurface of q -criterion of the one-passenger full configuration: (a) an isoparametric view; (b) vorticity contour at the y -center of rotor 2; (c) vorticity contour at $y = 0$.

Acoustic comparison between the one-passenger isolated rotor and full configuration

Both loading noise and overall sound pressure levels (OASPLs) of the one-passenger isolated rotor at the eight chosen microphone locations are compared with that of the full configuration in this subsection. Note that only the rotor noise of the two configurations is compared. In the first place, a thickness and loading noise comparison for the six-passenger quadrotor configuration, which is expected to generate a higher thickness noise level than for the one-passenger case, is performed at the eight out-of-plane microphone positions and shown in Fig. 11. According to Fig. 11, the magnitude of the thickness noise acoustic pressure is found to be much smaller than that of the loading noise acoustic pressure, and, therefore, only loading noise acoustic pressure is analyzed in this paper and shown in Fig. 12. The positive and negative pressure peaks of the two one-passenger cases are similar in magnitude at all microphone positions.

Figure 13(a) shows a comparison of A-weighted SPL, which accounts for the sound frequency range (from 2000 Hz to 20,000 Hz) perceived by the human ear, between the isolated rotor and full configuration cases at the eight microphone positions. The reference sound pressure employed

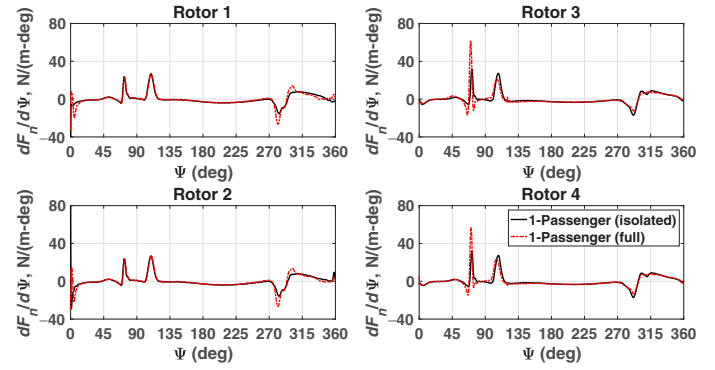


Fig. 9. A comparison of $dF_n/d\Psi$ at 75% span between the one-passenger isolated rotor and full configuration.

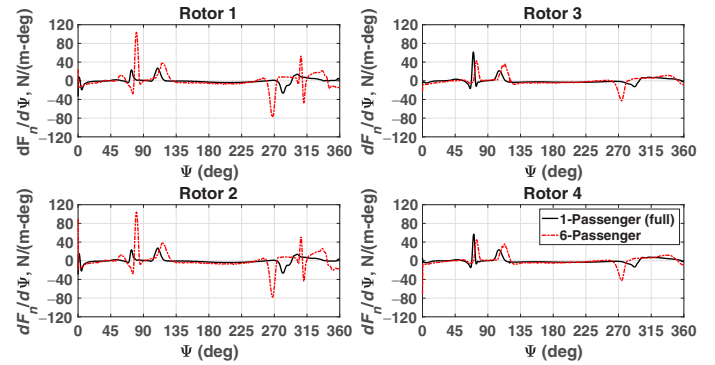


Fig. 10. A comparison of $dF_n/d\Psi$ at 75% span between the one-passenger and six-passenger cases.

in this research work is 2×10^{-5} Pa. In Fig. 13(a), the full configuration case shows higher A-weighted SPLs than the isolated rotor case at all microphone locations, especially at microphones 3–7. These microphones are positioned on the sides and in the rear region of the vehicle. Even though both microphones 4 and 6 are positioned symmetrically in the rear region, the difference between the isolated rotor and full configuration cases appears to be approximately 1.5 dB larger at microphone 6 than at microphone 4. This is likely due to slightly higher fluctuations of turbulence acting on the rotor 3 hub surface and supporting arm. However, this 1.5 dB difference is considered to be small.

To better explain the differences seen in A-weighted SPL (see Fig. 13(a)), a comparison of the acoustic pressure sound spectrum between the two cases is analyzed at microphone 6 and shown in Fig. 14. Since the SPL of the full configuration case has a greater magnitude than that of the isolated rotor case at frequencies above 2000 Hz, the full configuration case yields a higher A-weighted SPL than the isolated rotor case. The rotor hubs, arms, and fuselage, which are included in the full configuration model, are expected to be the major contributors to the A-weighted SPL differences between the two cases. Overall, the full configuration noise is more important than the isolated rotor noise in the human-hearing frequency range.

The OASPLs of the isolated rotor and full configuration cases at the eight microphone locations are also compared and shown in Fig. 13(b). The maximum OASPL difference between the isolated rotor and full configuration cases is less than 1.0 dB, which is considerably small. Returning to Fig. 14, it can be seen that the SPLs between the two cases at the first (33.1 Hz) and second (66.2 Hz) blade-passage frequencies (BPFs) are approximately the same in magnitude. Note that the magnitude of the OASPL is predominately determined by the SPLs at the

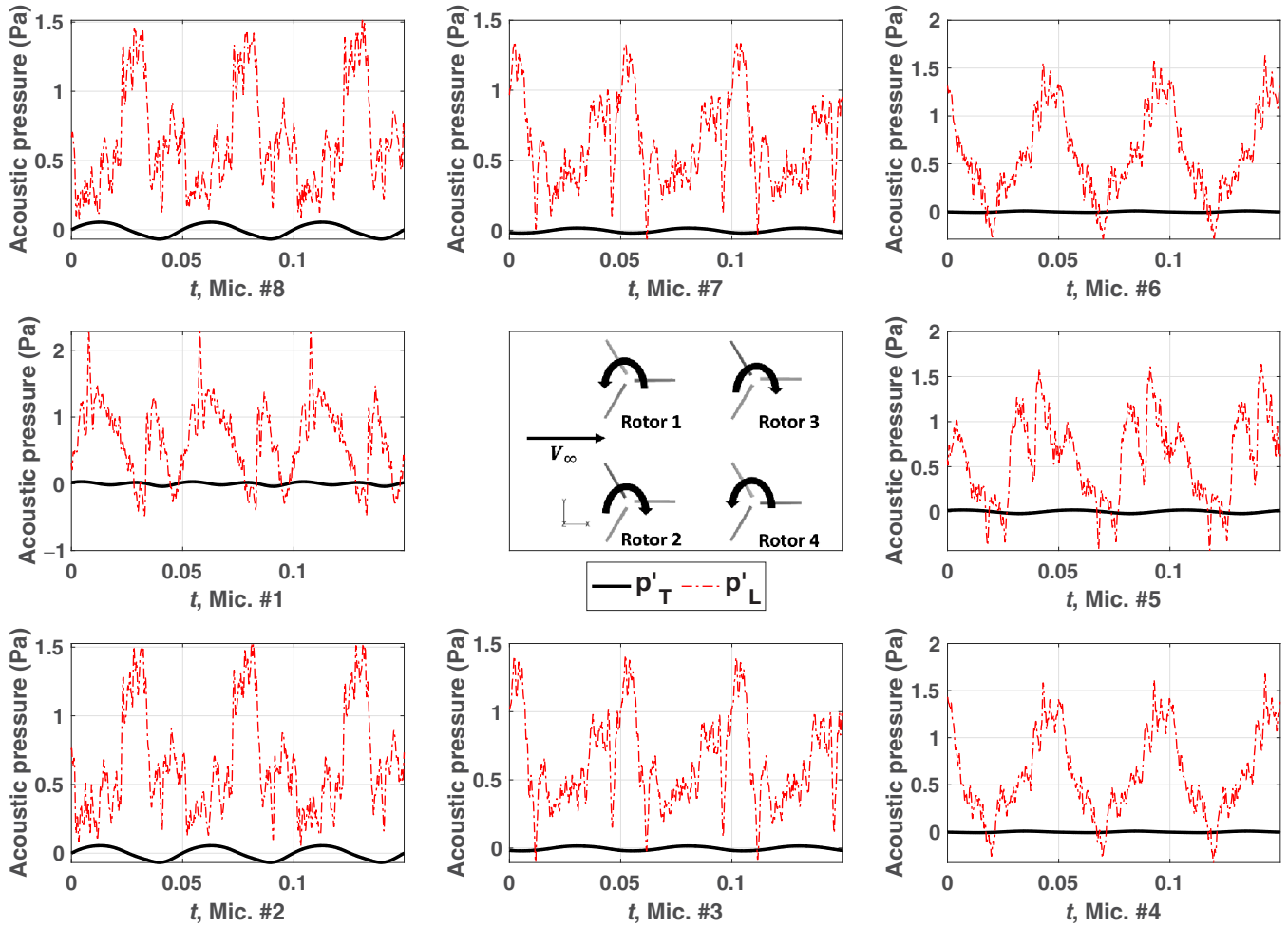


Fig. 11. Thickness (p'_T) and loading noise (p'_L) acoustic pressure comparison for the six-passenger quadrotor.

first few BPFs. Thus, no significant difference in nonweighted OASPL is found between the isolated rotor and full configuration 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. Figure 19(a) shows a comparison of the loading noise acoustic pressure between the isolated rotor and full configuration. The noise contributions from individual components of the full configuration including the individual rotors, main fuselage, rotor hubs, and supporting arms are also shown. A zoomed-in view of the acoustic pressure time history from $t = 0.024$ to 0.025 s is shown in the lower right corner of the figure. According to the zoomed-in view, the full configuration case presents lower acoustic pressure than for the isolated rotor case, which is due to the destructive interference among the subcomponents of the full configuration model. The sum of positive and negative pressure curves from the subcomponents ultimately leads to a pressure curve lower than that of the isolated rotor case.

Acoustic comparison between the one-passenger and six-passenger configurations

In order to investigate the effect of aircraft size on noise, both loading noise and OASPL between the one-passenger and six-passenger configurations are compared in this subsection. Since the rotation rates (Ω) of the two configurations are not the same, the observer time (t) is nondimensionalized by the maximum observed time ($t_{\max}$) over the last rotor

revolution as shown in Fig. 16. BVI-like pressure pulses are identified at microphone 1 in the six-passenger simulation case. The maximum difference in loading noise acoustic pressure is found to be approximately 2 Pa at microphone 1. The six-passenger isolated rotor case, overall, shows higher positive and negative pressure peaks than the one-passenger isolated rotor case likely due to stronger BVI events. Figure 17 shows the OASPL comparison between the two configurations, which is computed by integrating the entire domain of the acoustic SPL spectrum. The six-passenger case shows higher OASPL than the one-passenger case as expected. The maximum difference is found to be approximately 14 dB at microphone 1.

Acoustic decomposition of the one-passenger full configuration model

The total loading noise of the one-passenger full configuration model is decomposed into subcomponents: rotors, main fuselage, rotor hubs, and supporting arms. Figure 18 shows the OASPL of each subcomponent at the eight microphone positions. The OASPL of the main rotors is significantly higher than that of the other subcomponents at all microphone locations. To further investigate the contribution of each subcomponent to the OASPL of the full configuration model, a detailed SPL spectrum analysis is performed at microphone 1. Figure 19(a) shows a comparison of one-third octave SPL spectrum between the subcomponents at microphone 1. At this microphone location, the main rotors dominate the

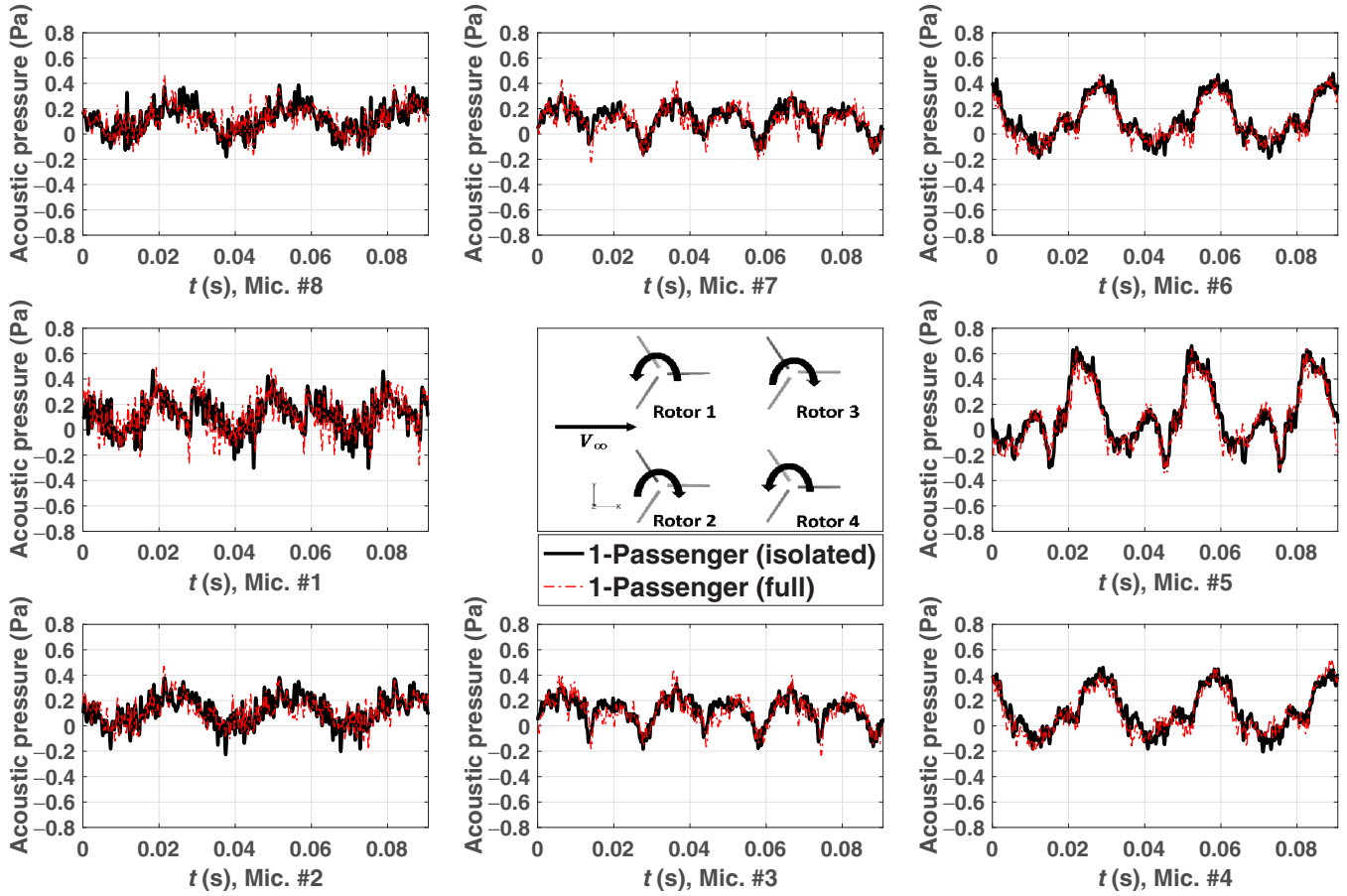


Fig. 12. Loading noise comparison between the one-passenger isolated rotor and full configuration.

low-frequency noise ranging from 100 to 600 Hz, which contributes the most to the logarithmic sum of the SPL spectrum. Figure 19(b), which represents a comparison of the SPL spectrum between the subcomponents from 100 to 500 Hz at microphone 1, also shows that the main rotors are the largest contributor to the OASPL of the full configuration likely due to the self-BVI events shown in Fig. 8(a). The largest SPL magnitude among the subcomponents is 72.3 dB at the first BPF or 33.1 Hz, which is induced by the main rotors.

The OASPL comparison presented in Fig. 18 also indicates that the OASPL of the rotor hubs are at least 5 dB higher than that of the main fuselage and supporting arms at microphones 1, 2, and 8, which are positioned in the front region of the aircraft. According to the spectrum analysis shown in Fig. 19(a), the rotor hubs dominate the high-frequency range above 800 Hz, which yields an OASPL higher than that of the main fuselage and supporting arms. It should also be noted that the maximum SPL of both main fuselage and supporting arms never exceed the maximum SPL of the rotor hubs (approximately 68 dB) at 1000 Hz. Even though the main fuselage clearly shows higher SPLs at frequencies below 250 Hz in the SPL spectrum (see Fig. 19(b)), the SPL never exceeds 60 dB, which is far less than the SPL of the rotor hubs around 1000 Hz. The dominance of the rotor hub noise at high frequencies can be attributed to the blade wake and root-induced vortices impinging on the frontal area of each rotor hub as shown in Fig. 8.

Acoustic comparison against conventional helicopter noise

It is expected that the noise of UAM aircraft with multiple rotors is required to be much quieter than the noise of a similar-sized conventional

helicopter, which is a definite requirement to operate UAM aircraft in urban or community areas. Uber Technologies Inc. (Ref. 44), as one of the largest advocates of UAM, suggested that UAM aircraft should be 15 dB lower than a similar-sized helicopter at the same altitude and flight operating condition. Thus, it is important to assess how much quieter UAM aircraft could be compared to the noise of a similar-sized conventional helicopter.

In this subsection, the six-passenger quadrotor noise is compared against the noise of a similar-sized conventional helicopter model Bell 430 in level flight. The Bell 430 flight-test data analyzed by Snider et al. (Ref. 45) is used for the acoustic comparison. Two acoustic simulation cases are considered for noise comparison: an overhead case in which the microphone is positioned 150 m below the vehicle and an approaching or flyover case in which the microphone is positioned 150 m below and 457 m ahead of the vehicle.

Table 3 shows a comparison of fundamental properties and flight conditions between the six-passenger quadrotor aircraft and Bell 430. It should be noted that the payloads of the six-passenger quadrotor aircraft and Bell 430 are similar, but the freestream velocities of the two aircraft differ by 54 kt. It is expected that the acoustic comparison would not be fair under two different freestream conditions. Therefore, a sixth-power scaling law was developed by Aravamudan et al. (Ref. 46) for subsonic rotorcraft noise prediction as shown in Eq. (1) is applied to the SPL calculation of the Bell 430 in order to offset the difference in freestream velocity. SPL_2 refers to the original SPL level of the Bell 430 acoustic data; SPL_1 refers to the SPL level of the Bell 430 after the implementation of the scaling law; $M_{tip,2}$ refers to the original advancing tip Mach number of the Bell 430 when the acoustic measurements were

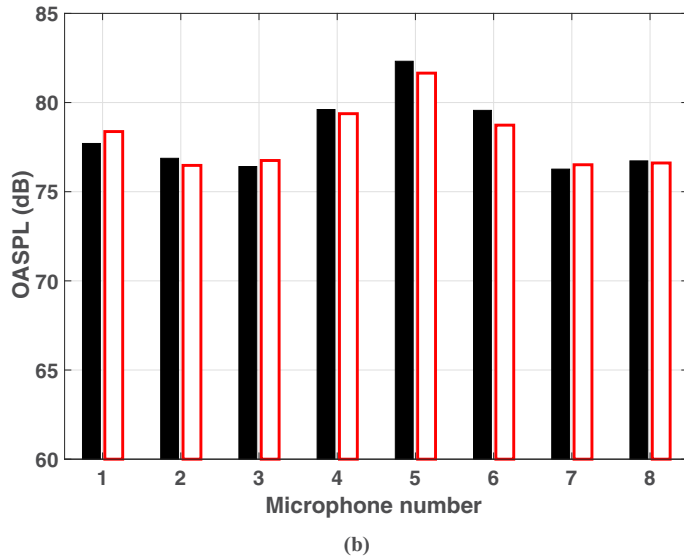
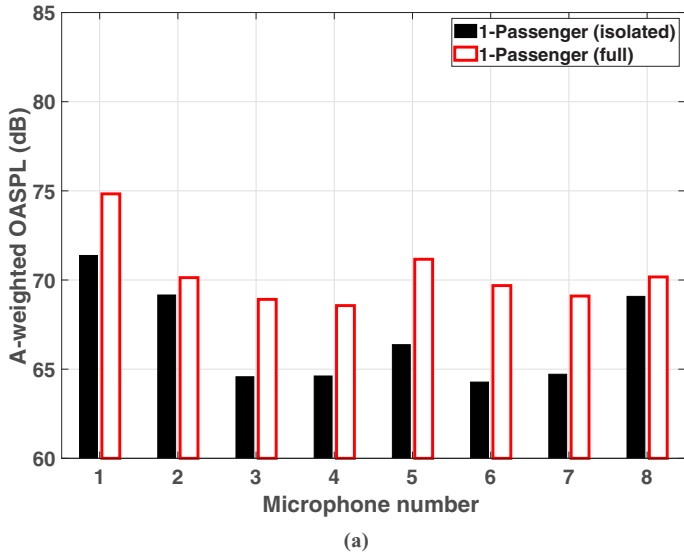


Fig. 13. Comparisons of A-weighted SPL and OASPL between the one-passenger isolated rotor and full configuration cases: (a) A-Weighted SPL; (b) OASPL.

taken; $M_{tip,1}$ refers to the Bell 430 advancing tip Mach number after reducing the freestream velocity from 124 to 70 kt.

$$SPL_1 = SPL_2 - 10 \log_{10} \left[\left(\frac{M_{tip,2}}{M_{tip,1}} \right)^6 \right] \quad (1)$$

Figure 20(a) shows the A-weighted SPL comparison between the six-passenger isolated rotor configuration and the Bell 430 at the one-third octave center frequencies from 100 to 5000 Hz for the overhead scenario. The A-weighted SPL difference between the two aircraft is computed by subtracting the six-passenger A-weighted SPL from the Bell 430 A-weighted SPL. The Bell 430, overall, shows higher A-weighted SPL (>10 dB) than the six-passenger isolated configuration at most one-third octave center frequencies, especially at frequencies above 640 Hz. The overall SPL is also computed for the two aircraft: the Bell 430 yields 74.7 dB, while the six-passenger configuration yields 63.8 dB. The overall SPL difference between the two cases is found to be 10.9 dB, which does not meet Uber's initial guideline of 15 dB quieter than similar-sized conventional helicopter noise.

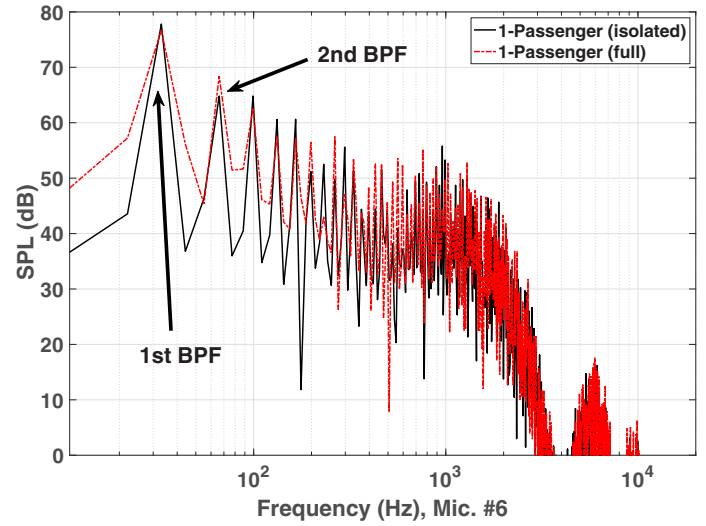


Fig. 14. Comparison of the SPL spectrum between the one-passenger isolated rotor and full configuration cases at microphone 6.

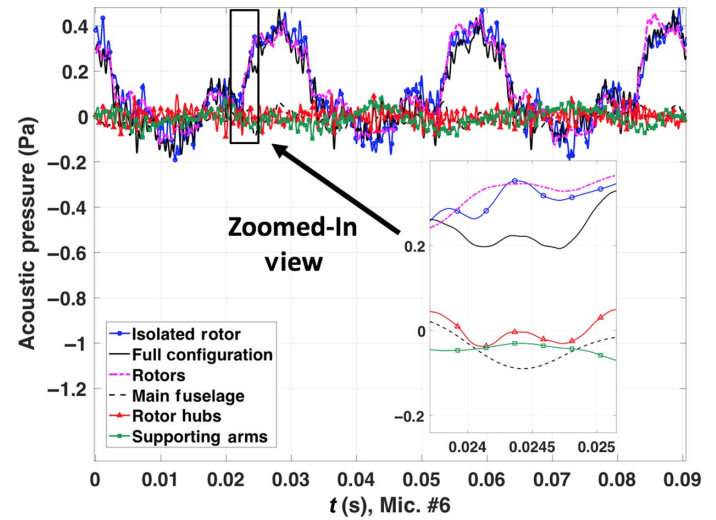


Fig. 15. Comparison of the loading noise acoustic pressure between the one-passenger isolated rotor and full configuration cases at microphone 6.

The A-weighted SPLs of the six-passenger configuration and the Bell 430 are also computed and compared for the approaching case and are shown in Fig. 20(b). Again, the Bell 430 shows significantly higher SPL (>10 dB) especially at frequencies lower than 1000 Hz, where tonal noise is expected to be dominant. The overall SPLs of the Bell 430 and the six-passenger configuration are found to be 72.9 and 55.7 dB, respectively, and the SPL difference between the two aircraft is 17.2 dB.

The discrepancies in A-weighted SPL between the Bell 430 and six-passenger configuration can be attributed to several reasons even with the same tip Mach number condition. First, the broadband noise of the six-passenger UAM aircraft at frequencies above 1000 Hz could be underpredicted based on the present acoustic methodology. For instance, our current method could not capture trailing-edge broadband noise at frequencies above 5000 Hz, but Li and Lee (Refs. 14, 15) showed that trailing edge broadband noise is an important noise source of the UAM aircraft. Second, the rotor trim of the Bell 430 is expected to be significantly different from that of the UAM aircraft. Third, the Bell 430

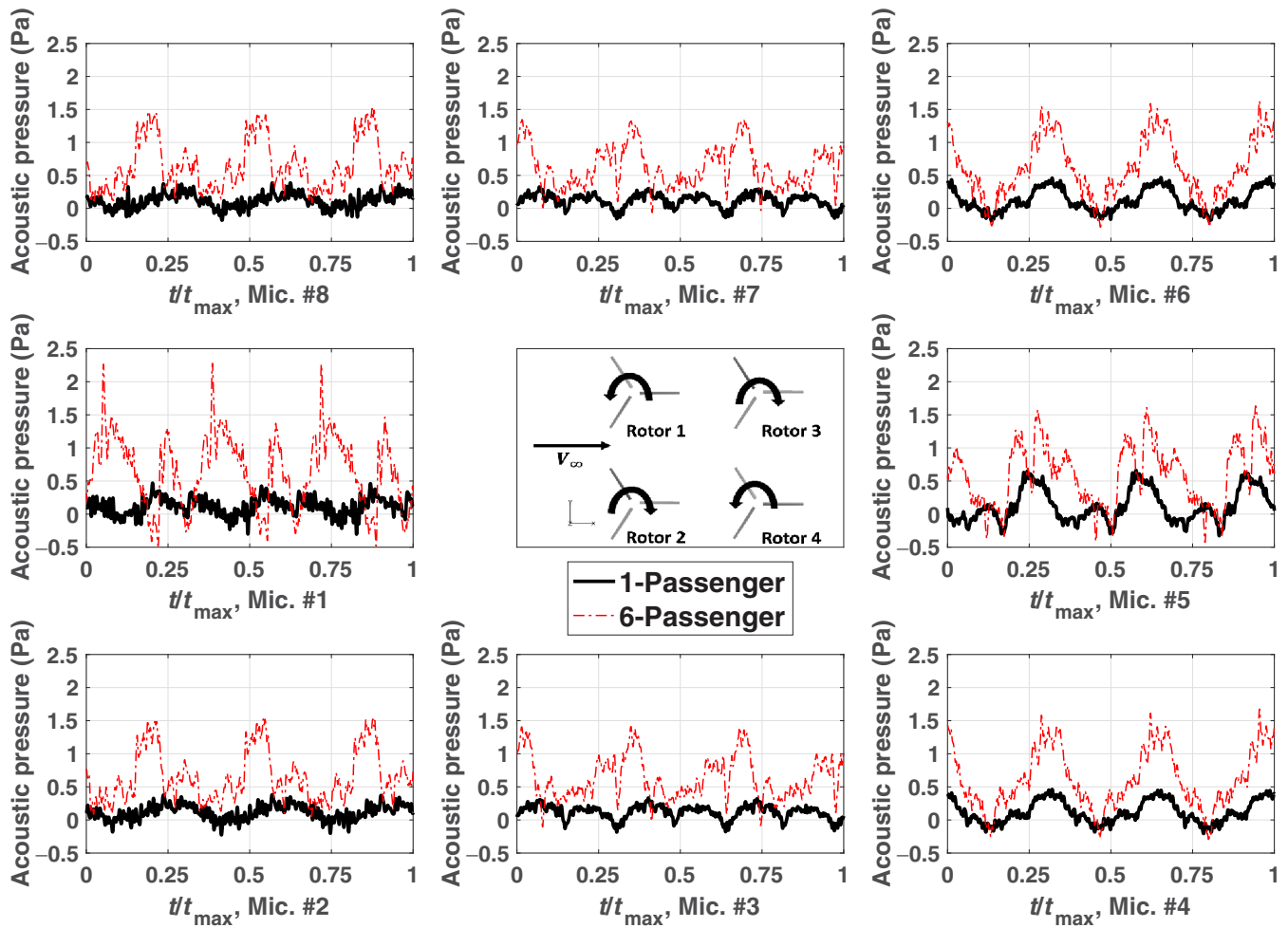


Fig. 16. Loading noise comparison between the one-passenger and six-passenger configurations.

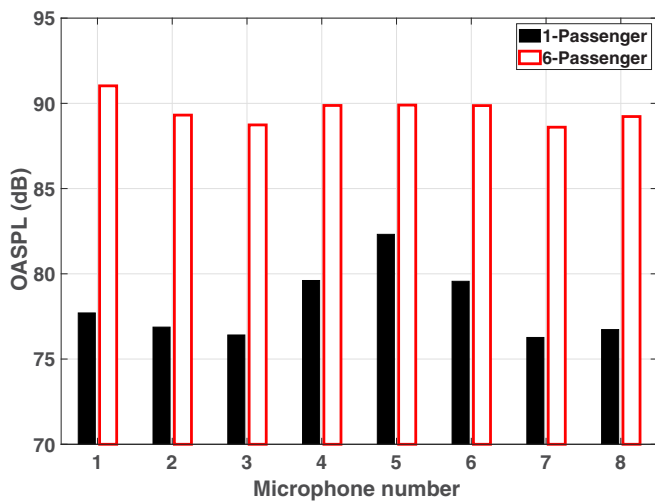


Fig. 17. OASPL comparison between the one-passenger and six-passenger configurations.

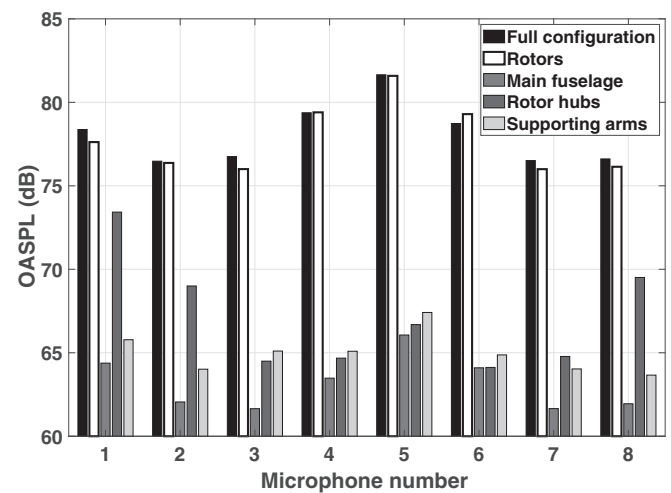


Fig. 18. OASPL decomposition of the one-passenger full configuration.

model incorporates a tail rotor as an antitorque device, which contributes additional thickness and unsteady loading noise due to the aerodynamic interactions between the main rotor and the tail rotor as well as self-tail rotor noise.

Considering the uncertainty of noise prediction and the ignorance of other noise sources such as trailing-edge broadband noise, the risk of excessive noise to the noise guideline would be higher. It is also worthwhile noting that multiple UAM aircraft will operate simultaneously so that the

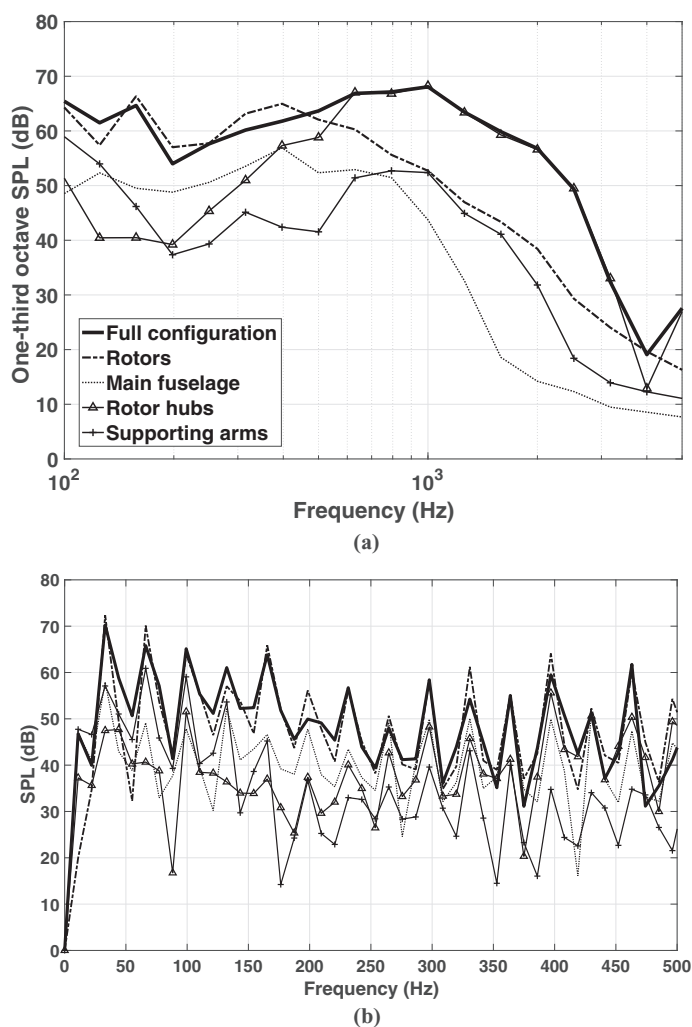


Fig. 19. Acoustic pressure spectrum comparison of the one-passenger full configuration model at microphone 1: (a) one-third octave SPL; (b) SPL.

Table 3. A comparison of physical properties.

Aircraft Properties	Six-Passenger	Bell 430
Rotor radius	4.0 m	6.4 m
Number of rotors	4	1
Blades per rotor	3	4
Nominal rotor speed	400 RPM	349 RPM
Blade passage frequency	25.0 Hz	23.2 Hz
Freestream velocity	70 kt	124 kt
Hover tip Mach number	0.50	0.69
Advancing tip Mach number	0.61	0.88
Payload	544 kg (1,200 lb)	565 kg (1,247 lb)

noise impact would be larger than a single-vehicle comparison with a conventional helicopter. Thus, 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 conventional helicopter noise, the UAM aircraft noise is compared against various background noise (e.g., freeway noise). There is a general agreement

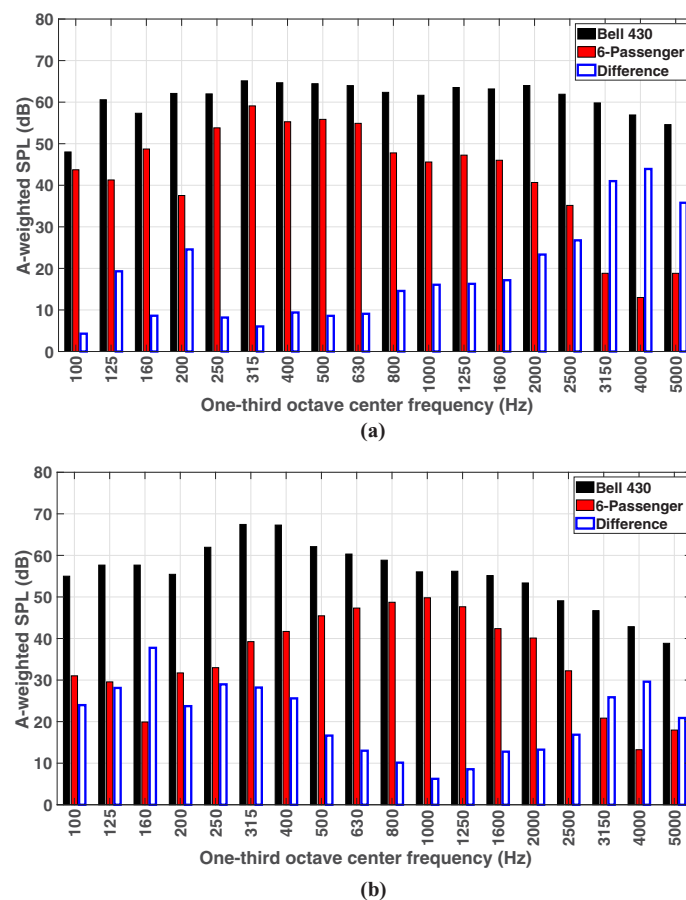


Fig. 20. A-weighted SPL comparison between the Bell 430 and the six-passenger configuration: (a) overhead case; (b) approaching case.

that UAM aircraft noise should not exceed the background noise in order to enhance the public acceptance of this new transportation method. In this section, the noise levels of the one-passenger and six-passenger UAM aircraft are compared against various background noise levels measured and documented by Begault (Ref. 47) in the San Francisco Bay Area. Begault recorded the background noise levels in rural, park, freeway, and community areas as a reference guide for UAM noise assessment.

In the present work, the UAM vehicle noise is simulated at 250 ft (76 m), 500 ft (152 m), 1000 ft (305 m), and 1500 ft (457 m) from the ground level. The microphones are positioned directly below the vehicle. Figure 21 shows the one-third octave SPL comparisons between the UAM aircraft noise and various background noise for the one-passenger isolated rotor, one-passenger full configuration, and six-passenger isolated rotor cases. Based on Fig. 21(a), the one-passenger isolated rotor case shows that the vehicle SPL exceeds the rural area SPL from 200 to 3000 Hz even at a maximum altitude of 1500 ft from the ground. The vehicle SPL also partially exceeds the park SPL from 200 to 2000 Hz at the maximum altitude. However, the aircraft noise at an altitude equal to or greater than 500 ft from the ground could be masked by the freeway noise. The aircraft noise could also be masked by the community noise level when operating at an altitude greater than 1000 ft. It is anticipated that the noise impact of the one-passenger quadrotor aircraft on urban communities could be reduced by operating the aircraft at the designed cruise altitude or 1500 ft from the ground level.

A similar trend is seen in the one-passenger full configuration case except that the SPLs of the four altitude cases are elevated by a maximum of 3 dB from 100 to 1000 Hz according to Fig. 21(b). The

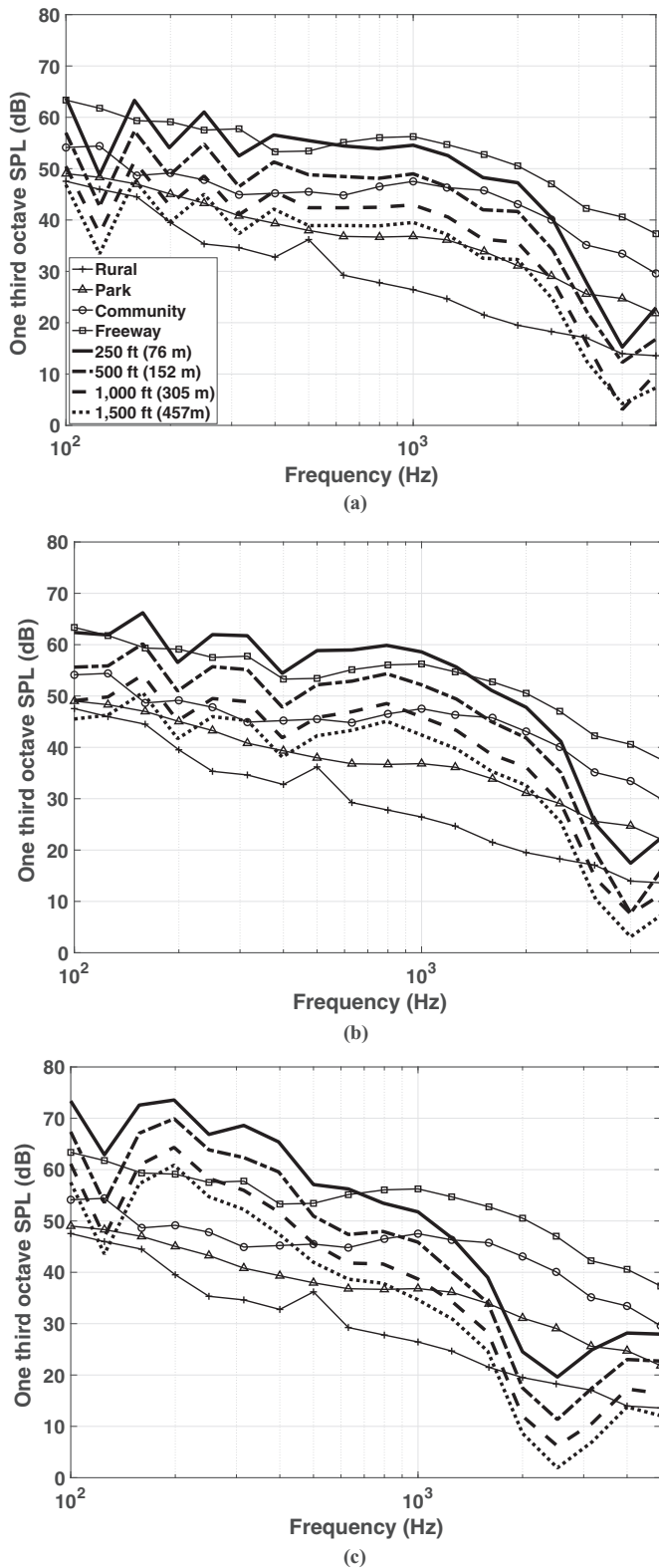


Fig. 21. A comparison of UAM vehicle noise and various background noise: (a) one-passenger isolated rotor case; (b) one-passenger full configuration case; (c) six-passenger isolated rotor case.

aircraft noise could still be masked by the freeway noise at an altitude of 500 ft or above. Unlike the one-passenger isolated and full configuration simulation cases, the noise of the six-passenger isolated

rotor case shows significantly higher SPL than the freeway noise (see Fig. 21(c)) at an altitude of 500 ft or below. Noise slightly exceeds the freeway SPL at 1000 ft by approximately 1 dB at 200 Hz. It should also be noted that high-frequency broadband noise components, such as trailing-edge noise, might not be captured in the present study. Li and Lee (Refs. 14, 15) have shown that trailing-edge broadband noise becomes important and contributes significantly to overall SPL at high frequencies. Therefore, the quadrotor SPL could further increase if a proper broadband noise prediction approach, such as the one developed by Li and Lee (Refs. 14, 15), is incorporated in the total noise calculation.

Conclusions

The acoustic characteristics of a one-passenger and a six-passenger quadrotor UAM aircraft in steady forward flight were analyzed based on a high-fidelity CFD approach. The CFD simulations were performed using the high-fidelity and multidisciplinary rotorcraft simulation tool Helios. The acoustic simulations were carried out using the noise prediction tool PSU-WOPWOP at eight out-of-plane microphone positions based on an impermeable surface methodology. A detailed acoustic comparison between the one-passenger isolated rotor, one-passenger full configuration, and six-passenger isolated rotor cases was performed. The noise of the one-passenger and six-passenger quadrotor UAM aircraft was also compared against the noise of a similar-sized conventional helicopter Bell 430 in level flight. The impact of UAM aircraft noise on urban communities was also assessed in this research study. The following conclusions were drawn based on the results presented in this paper:

- 1) The self-BVI events are the dominant noise sources of the one-passenger and six-passenger quadrotor UAM aircraft in forward flight.
- 2) The UAM aircraft fuselage contributes additional noise with broadband noise characteristics to the total loading noise of the one-passenger full configuration model.
- 3) The main rotor is the largest contributor to the total loading noise of the one-passenger quadrotor full configuration, especially from 100 to 600 Hz. The rotor hubs show a significant impact on the total loading noise particularly at high frequencies (above 800 Hz).
- 4) The noise comparison study between the one-passenger and six-passenger quadrotor demonstrated that the UAM aircraft noise can be significantly increased with an increasing payload.
- 5) The noise level of the Bell 430 is 10.9 and 17.4 dB higher than that of the six-passenger quadrotor in the overhead and approaching scenarios, respectively. The noise difference would become even smaller if a high-frequency broadband noise prediction model is incorporated in acoustic predictions, and therefore, a goal of 15 dB quieter than similar-sized helicopter noise for UAM aircraft would become more challenging.
- 6) As demonstrated by the assessment of UAM aircraft noise impact on urban communities, low altitude operations at 250 ft or below could lead to potential noise concerns. It should also be noted that the present acoustic analysis is based on a single aircraft. In reality, multiple UAM aircraft will operate simultaneously so that there is a higher chance for the UAM operation to exceed various background noise. Therefore, noise reduction technology should be developed to enhance the public acceptance of UAM operations.

Acknowledgments

The authors would like to sincerely thank Roger Strawn from the U.S. Army Capabilities Development Command Aviation and Missile Center (CCDC AvMC) | Technology Development Directorate (TDD-A) for providing the DoD High-Performance Computing resources and summer internship for the first author; Mark Potsdam, Jain Rohit, and Beatrice Roget from TDD for their insightful advice and assistance; Wayne

Johnson and Christopher Silva from NASA Ames for providing the UAM models. This research has been partially supported by the Hellman Fellowship award of the second author.

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