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Aeroacoustic Analysis of a Side-by-Side Hybrid VTOL Aircraft

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ABSTRACT

This paper investigates the acoustics of a side-by-side Urban Air Mobility (UAM) aircraft with 0%, 5%, 15%, and 25% rotor overlaps in forward flight based on high-fidelity Computational Fluid Dynamics (CFD) simulations. The CFD and acoustics simulations are carried out using the HPCMP CREATE™-AV rotorcraft simulation and analysis tool Helios and the acoustic prediction tool PSU-WOPWOP. The influence of the finest wake-grid spacing size on acoustic prediction of the side-by-side rotor with 0% overlap is studied based on two wake-grid spacing cases: 5% C_{tip} and 10% C_{tip} . No significant difference in overall sound pressure level (OASPL) is found between the two cases. The effect of rotor overlap on rotor acoustics is also assessed, and it is shown that the 25% overlap case yields higher OASPL than the other overlap cases particularly due to stronger rotor-to-rotor blade-vortex interactions (BVIs). Furthermore, the noise of the side-by-side rotor with 0% and 25% overlaps is compared against similar-sized helicopter noise and various background noise levels. It is shown that the side-by-side rotor noise is comparable with the noise of a similar-sized four-bladed helicopter in cruise. The OASPL difference of the overhead case is less than 10 dB, which does not meet the guideline that the UAM noise should be 15 dB lower than similar-sized helicopter noise. The results also show that the side-by-side rotor noise could not be fully masked by the freeway background noise at an altitude of 1,500 ft. Thus, noise reduction technology should be developed to overcome the barrier of public acceptance of UAM noise.

NOMENCLATURE

c	speed of sound in the undisturbed medium, m/s
C_{tip}	tip chord length, m
F_z	blade sectional normal force, N/m
$\vec{l}$	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

V_∞	freestream velocity, m/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
θ_{1c}	blade lateral cyclic pitch, deg
θ_{1s}	blade longitudinal cyclic pitch, 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
Δ_{finest}	finest wake-grid spacing, m

Acronyms

BPF	blade passage frequency, Hz
CFD	Computational Fluid Dynamics
CSD	Computational Structural Dynamics
CCW	counterclockwise
CW	clockwise
VTOL	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

INTRODUCTION

The concept of Urban Air Mobility (UAM) (Ref. 1), which refers to urban on-demand air transportation by hybrid or fully electric vertical take-off and landing (VTOL) aircraft, has drawn significant interest from both the aviation and automobile industries worldwide in recent years. The ultimate goal of UAM is to provide affordable, environmental friendly, and safe air transportation in densely populated cities, which could lead to a reduction of urban traffic congestion and better interconnect suburban and urban regions. The application of UAM aircraft may also be extended to cargo transportation in urban and suburban communities (Ref. 2). Numerous developers, such as Joby Aviation, have revealed their prototypes and also shared their thoughts on UAM aircraft design (Refs. 3,4). Among the design criteria of UAM aircraft, low-noise emission is a key design requirement in addition to safety. As addressed at the third annual Vertical Flight Society eVTOL panel discussion (Ref. 5), the UAM aircraft noise, if exceeding background community noise, could be a major barrier to the public acceptance of UAM operations.

Unlike a conventional helicopter design, which only consists of a main rotor and a tail rotor, most UAM aircraft designs (Ref. 6) being built feature multi-rotors with small rotor radius, which results in lower rotor tip speed and noise. Some of the current UAM aircraft designs, such as the one shown in Fig. 1, also feature lifting wing surfaces in addition to a multi-rotor system that could lead to rotor-to-wing interactions. Thus, both aerodynamic and acoustic characteristics of UAM aircraft are expected to be different from that of conventional helicopters. It is anticipated that the complex aerodynamic interactions of a multi-rotor UAM aircraft could yield significant rotorcraft tonal and broadband noise.



Fig. 1. Joby’s five-passenger air taxi (Ref. 4).

In recent years, significant research has been carried out to improve the aeromechanics design of UAM aircraft. In 2018, Johnson et al. (Refs. 7,8) has performed a series of studies and designed several conceptual vehicles based on the NASA’s preliminary design and analysis code, NDARC (Ref. 9), and the comprehensive rotorcraft analysis software, CAMRAD

II (Ref. 10). Their research has suggested that both rotor-to-rotor and rotor-to-wing interactions could significantly impact vehicle vibration, acoustics, and power performance. For instance, blade-vortex interaction (BVI), which implies the aerodynamic interaction between blade-tip vortex and blade surface in close proximity, may become prevalent for a multi-rotor design.

In 2019, Ventura Diaz et al. (Refs. 11,12) have performed a series of high-fidelity computational studies for NASA’s six-passenger side-by-side hybrid VTOL configuration (see Fig. 2) based on a Computational Fluid Dynamics (CFD) and Computational Structural Dynamics (CSD) loose coupling approach. Their results showed that the rotor airloads are sensitive to the percentage of rotor-to-rotor overlap, which is a key design parameter for the side-by-side UAM aircraft. They found that the 15% overlap case yields the best effective lift-to-drag ratio with non-zero overlaps. However, the unsteady aerodynamic interactions between the two rotors in the overlap region are likely to increase the vehicle noise. In 2020, Sagaga and Lee (Ref. 13) have studied the aerodynamics of the same side-by-side rotor configuration in hover based on high-fidelity CFD simulations, and showed that the hover performance could be reduced with increasing rotor overlap. However, they have not performed aeroacoustic predictions for the side-by-side configuration.



Fig. 2. NASA’s six-passenger side-by-side conceptual design (Ref. 7).

Besides the aerodynamics research on NASA’s UAM vehicle designs, Jia and Lee (Refs. 14,15) have conducted high-fidelity aeroacoustic simulations for NASA’s one-passenger and six-passenger quadrotor UAM aircraft. They showed that BVI noise occurs in level-flight cruise condition for the one-passenger quadrotor aircraft, although the magnitude of the BVI noise is one order of magnitude smaller than conventional helicopter BVI noise. Their research results also demonstrated that the quadrotor noise in low-altitude operation could exceed various background noise (e.g., highway noise). Li and Lee (Refs. 16,17) have also investigated the broadband noise of NASA’s UAM aircraft designs for the first time to the best of authors’ knowledge. Their work showed that the high-frequency contents of UAM aircraft broadband noise, particularly the trailing-edge noise, could not be masked by various background noise. The amplitude of broadband noise was found to increase when multiple UAM vehicles operated simultaneously.

Moreover, Higgins et al. (Ref. 18) have performed aeroacoustic study of a propeller-driven tiltwing UAM aircraft based

on their in-house CFD solver. Their results showed significant rotor-to-fuselage and rotor-to-wing interactions, which lead to acoustic pressure wave oscillation on the fuselage and wing. Wachspress et al. (Ref. 19) have also analyzed the acoustics of existing UAM VTOL designs based on a mid-fidelity airloads analysis tool. Their results suggested that both propeller-wing and rotor-duct interactions could lead to significant higher overall sound pressure level when compared against their baseline models.

The aim of this work is to investigate the aeroacoustics of NASA's six-passenger side-by-side hybrid UAM vehicle (see Fig. 2) in steady forward flight based on a first-principled and high-fidelity CFD approach. First, the effect of the finest CFD wake-grid spacing size on acoustics prediction is investigated. Potential noise sources, such as blade-vortex interactions, are identified based on high-fidelity CFD results. The effect of rotor-to-rotor overlap percentage on noise strength and acoustic directivity is studied. The vehicle noise is also compared against the noise of a similar-sized four-bladed conventional helicopter and various background areas in order to assess the viability of low-altitude UAM operations in urban areas.

METHODS

The CFD model is developed based on NASA's six-passenger side-by-side hybrid VTOL vehicle design, which is shown in Fig. 2 (Ref. 7). Only the left (clockwise) and right (counter-clockwise) rotors are modeled for CFD simulations, and the vehicle fuselage is neglected. A 45 degrees phase shift is applied to the left rotor as shown in Fig. 3, a top view of the side-by-side rotor configuration without rotor-to-rotor overlap. A total of four rotor-to-rotor overlap cases – 0%, 5%, 15%, and 25% – are considered to investigate the effect of rotor overlap on the strength of aerodynamic interactions and associated acoustics. The overlap percentage is defined as the amount of rotor-to-rotor overlap distance in the spanwise direction that is nondimensionalized by the rotor radius (R). The rotor hub-to-rotor hub separation distances of the 0%, 5%, 15%, and 25% overlap cases are $2R$, $1.9R$, $1.7R$, and $1.5R$, respectively.

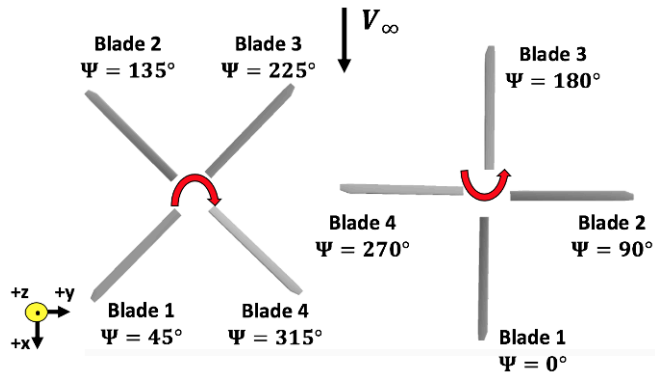


Fig. 3. The side-by-side rotor configuration without overlap.

The fundamental properties of this vehicle are shown in Table 1. Since the material properties of the conceptual designs

are not available, the rotor blades are assumed rigid. The rotor blades of the side-by-side rotor are modeled based on two modern airfoils: Boeing VR-12 and Sikorsky SSC-A09. VR-12 is used for $R < 85\%$ span; a linear interpolation between VR-12 and SSC-A09 is assumed from 85% to 95% span; SSC-A09 is used for $R > 95\%$ span. The blade chord is assumed constant at 0.217 m until $R = 94\%$ where blade taper occurs. The slope of the linear twist distribution is assumed -16 degrees, and the zero degrees twist occurs at 75% span. A 15 degree linear taper ratio is applied between $R = 94\%$ and the blade tip. Detailed CFD mesh and numerical setups are described in the subsequent sections.

Table 1. Basic properties of the two conceptual designs.

Rotor Radius	3.2 m (10.5 ft)
Tip Chord Length	0.13 m (0.43 ft)
Number of Rotors	2
Blades per Rotor	4
Nominal Rotor Speed	499.7 RPM
Nominal Rotor Tip Speed	189.5 m/s (621.7 ft/s)
Payload	544 kg (1,200 lb)
Gross Weight	1,792 kg (3,950 lb)

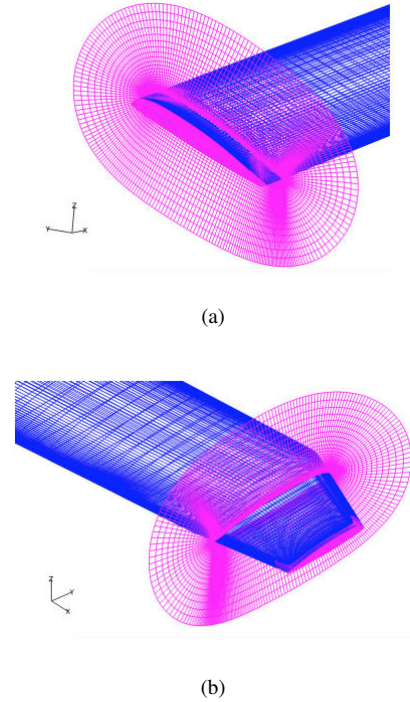


Fig. 4. The near-body grids of the blade. (a) at the blade root; (b) at the blade tip.

CFD Grids

A dual mesh paradigm, dividing the entire computational domain into near-body structured overset mesh and off-body adaptive Cartesian grid, is employed in the present work. The near-body grids are constructed using NASA's overset grid

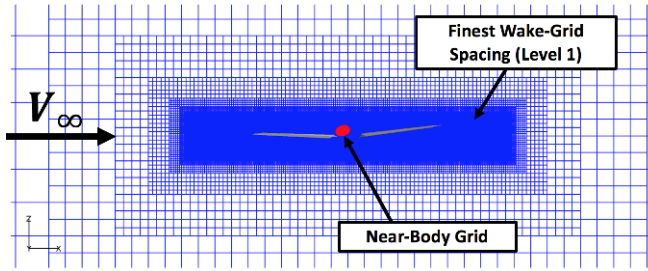


Fig. 5. The off-body mesh.

generation software Chimera Grid Tools (CGT) (Refs. 20,21). Figure 4 shows zoomed-in views of the blade overset mesh at the blade root and tip. An O-grid topology is applied to the near-body grids. Each rotor blade is composed of three components: main blade, blade root, and blade tip. The chordwise and spanwise dimensions of the main blade are 265 and 168, respectively. The leading and trailing edge spacings are set to $0.05\% C_{tip}$ and $0.02\% C_{tip}$, respectively, where C_{tip} is the tip chord length. In order to investigate the effect of the finest wake-grid spacing size (Δ_{finest}) of the off-body Cartesian mesh on rotor acoustics, two cases are considered: 1) $\Delta_{finest} = 5\% C_{tip}$; 2) $\Delta_{finest} = 10\% C_{tip}$. The number of grid points in the normal direction are set to 65 and 101 in the $5\% C_{tip}$ and $10\% C_{tip}$ cases, respectively, for the volume grid generation of the main blade. 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 match the finest wake-grid spacing or Level-1 spacing. In the $10\% C_{tip}$ case, each rotor blade is composed of approximately 2.9 million grid points, and a total of 23.2 million grid points for eight blades. The $5\% C_{tip}$ case yields 4.5 million grids per blade and 36 million grid points for eight blades.

The off-body Cartesian mesh is automatically generated by the adaptive off-body Cartesian solver SAMCart (Ref. 22), which is the off-body solver of the CFD solver CREATETM-AV Helios (Ref. 23). A short description of the software is included in the next subsection. The off-body solver SAMCart is capable of resolving complex rotor wakes based on high-order numerical schemes and Adaptive Mesh Refinement (AMR). Figure 5 shows a zoomed-in view of the off-body Cartesian mesh. In this research, nine and eight levels of AMR are used for the $5\% C_{tip}$ and $10\% C_{tip}$ cases, respectively, after the first rotor revolution in order to capture the detailed flow physics of rotor wakes. The off-body mesh boundary is 20 rotor radii away from the origin. The total number of off-body Cartesian grid points of the 5% and $10\% C_{tip}$ cases are approximately 642 million and 94 million grid points, respectively, at the initial time step.

CFD Simulation Setup

The unsteady CFD simulations are performed using the HPCMP CREATETM-AV Helios (Ref. 23) software suite, 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 utilizes a multi-module framework that allows a multi-solver approach and a dual-mesh paradigm. While the off-body Cartesian grids are solved by the off-body adaptive Cartesian solver SAMCart (Ref. 22), the near-body grids can be solved by various unstructured, structured, and strand near-body solvers: FUN3D (Ref. 24), kCFD (Ref. 25), NSU3D (Ref. 26), OVERFLOW (Refs. 27, 28), and mStrand (Ref. 29). Grid hole cutting, solution interpolation, and data transfer in both near- and off-body domains are controlled by the domain connectivity module PUNDIT (Ref. 30). Helios also encompasses a body dynamics module Melodi (Ref. 31), which enables dynamics modeling of a multi-body system in addition to fluid and structure coupling. Helios have recently been implemented to predict aerodynamics and acoustics of small drone, UAM vehicle, and compound helicopter (Refs. 14, 32, 33).

In this research, NASA's overset-structured and high-fidelity flow solver OVERFLOW (Refs. 27, 28) is used to simulate the near-body flow physics. The off-body adaptive Cartesian solver SAMCart (Ref. 22) is used to simulate the off-body flow domain. 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 each time-accurate CFD simulation. The dual-time-stepping subiterations used in the near-body calculation for the $\Delta_{finest} = 5\% C_{tip}$ and $10\% C_{tip}$ cases are 80 and 50, respectively. The subiterations used in the off-body calculation for the two cases are 30 and 10, respectively. The Spalart-Allmaras (SA) Reynolds-averaged Navier Stokes (RANS) turbulence model coupled with Detached Eddy Simulation (DES) is employed for turbulence modeling. Blade-surface geometric coordinates and flow solutions are extracted at every 0.5 degrees azimuth or every two time steps for acoustic simulations. The simulations are performed using the Centennial SGI-ICE-XA high performance computer of the U.S. Army Research Laboratory (ARL) DoD Supercomputing Resource Center (DSRC). A total number of 1,280 and 640 processors are used for the $\Delta_{finest} = 5\% C_{tip}$ and $10\% C_{tip}$ simulation cases, respectively. Each rotor revolution of the $5\% C_{tip}$ case takes approximately 28 hours, whereas the $10\% C_{tip}$ case consumes 15 hours per rotor revolution.

Prescribed Rotor Motion

The CFD simulations ran in the present work utilize the prescribed motion data provided by Ventura Diaz et al. (Ref. 11) based on a CFD/CSD loose coupling approach. The rotor coning angle (β_0), collective pitch (θ_0), lateral cyclic pitch (θ_{1c}), and longitudinal cyclic pitch (θ_{1s}) of both left (L) and right (R) rotors are shown in Table 2. A detailed description of their loose coupling approach can be found in their paper (Ref. 11). The total thrust of the two rotors is trimmed by the rotor collective to balance the vehicle weight. Each rotor is trimmed to have zero flapping by the rotor lateral and longitudinal cyclic

Table 2. Motion inputs of the left (L) and right (R) rotors (Ref. 11)

Overlap	0%		5%		15%		25%	
Rotor	L	R	L	R	L	R	L	R
β_0 [deg]	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1
θ_0 [deg]	9.2	9.5	9.1	9.4	9.1	9.4	9.2	9.3
$-\theta_{1s}$ [deg]	8.1	8.6	8.0	8.6	8.1	8.5	8.2	8.4
θ_{1c} [deg]	3.5	3.7	3.5	3.6	3.5	3.6	3.5	3.6

itches. The aircraft propulsive force is trimmed by the aircraft pitch attitude in order to balance the vehicle drag. The pitch attitudes (α) of the 0%, 5%, 15%, and 25% overlap cases are -2.52, -2.46, -2.44, and 2.46 degrees.

Acoustic Simulation Setup

PSU-WOPWOP (Refs. 34,35), an acoustic prediction tool being developed at the Pennsylvania State University, is used for acoustic predictions. PSU-WOPWOP is a numerical implementation of Farassat's Formulation 1A (Refs. 36,37) of the Ffowcs Williams and Hawkings (FW-H) equation (Ref. 38). Farassat's Formulation 1A is calculated based on the impermeable surface strategy in the present work, and the quadrupole source term is neglected. The equations of Farassat's Formulation 1A can be written:

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

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

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

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*.

It should also be noted that 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.

The acoustic simulations are performed on a hemispherical observer grid with a radius equal to $10R$. 50 grid points are used in the azimuthal direction and 20 grid points are used in the latitudinal direction. The observers are assumed to be attached to the center between the left and right rotors of the side-by-side vehicle for all acoustic simulations.

RESULTS

The side-by-side rotor with 0%, 5%, 15%, and 25% overlap are simulated in steady forward flight at a speed of 115 knots or 213 km/hr at an altitude of 5,000 ft. The freestream Mach number M_∞ is 0.17 and the advancing tip Mach number is 0.67 for each simulation case. Each rotor of the side-by-side vehicle design is assumed to operate at the nominal rotation speed, which is 499 RPM. The advance ratio of each rotor is 0.36. A total of six simulation cases are ran: 0% overlap with the finest wake grid spacing $\Delta_{finest} = 10\% C_{tip}$, 5% overlap with $\Delta_{finest} = 10\% C_{tip}$, 15% overlap with $\Delta_{finest} = 10\% C_{tip}$, 25% overlap with $\Delta_{finest} = 10\% C_{tip}$, 0% overlap with $\Delta_{finest} = 5\% C_{tip}$, and 25% overlap with $\Delta_{finest} = 5\% C_{tip}$. The rotor forces and moments of each CFD simulation case are converged after approximately five rotor revolution.

Effect of the Finest Wake-Grid Spacing on Aerodynamics and Acoustics

The effect of the finest wake-grid spacing Δ_{finest} on rotor aerodynamics and acoustics is evaluated for the 0% overlap case. Figure 6 shows a comparison of the iso-surfaces of a non-scaled q-criterion $\bar{q}$ colored by vorticity magnitude between the $\Delta_{finest} = 5\% C_{tip}$ and $\Delta_{finest} = 10\% C_{tip}$ cases of the 0% overlap configuration at the last simulation time step. Note that the freestream velocity (V_∞) points in the positive x-direction. Both the $\Delta_{finest} = 5\% C_{tip}$ and $\Delta_{finest} = 10\% C_{tip}$ cases predict similar flow patterns, except that the 5% C_{tip} case captures slightly finer wake turbulence and stronger tip vortex (shown in darker red color). Self blade-vortex interactions (BVIs), which imply the aerodynamic interactions between blade tip vortices and blade surfaces of the same rotor in close proximity, can be seen on the advancing side of both left (CW) and right (CCW) rotors.

Figure 7 shows the comparisons of polar contours of the azimuthal derivative of sectional normal force ($dF_z/d\Psi$), which is a direct source term ($\dot{l}_r$) in the loading noise equation (3) of Farassat's Formulation 1A and an indicator of impulsive

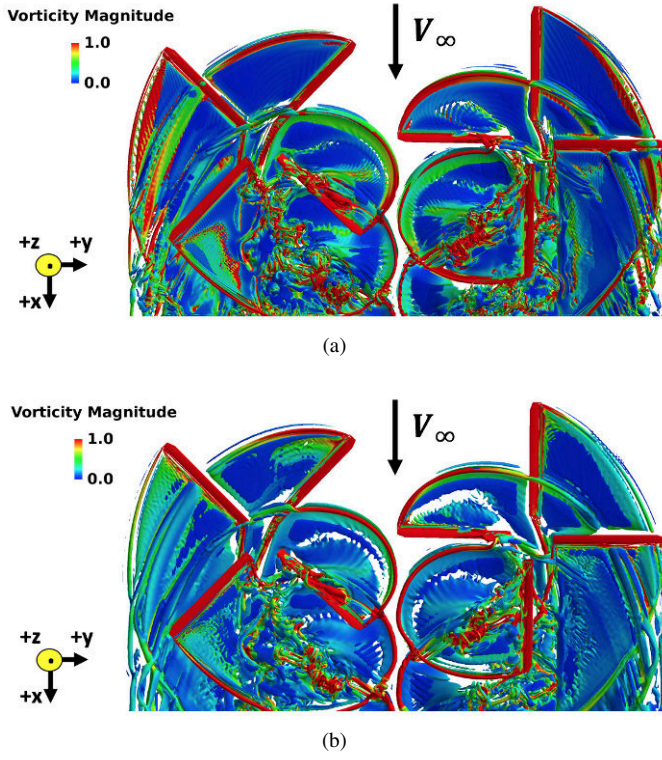


Fig. 6. Iso-surface of a non-scaled q -criterion $\bar{q}$ colored by the vorticity magnitude for the 0% overlap case from the top view. (a) $\Delta_{finest} = 5\% C_{tip}$; (b) $\Delta_{finest} = 10\% C_{tip}$.

aerodynamic interactions, between the $\Delta_{finest} = 5\% C_{tip}$ and $\Delta_{finest} = 10\% C_{tip}$ cases of one blade of the 0% overlap configuration over the last rotor revolution. These polar contours represent the rotor disks from the top view with freestream direction pointing from top to bottom. The left and right rotors show symmetrical distribution of $dF_z/d\Psi$. Both 5% and 10% C_{tip} cases predict: 1) the advancing-side self-BVI events in the first quadrant of each rotor at 50, 70, and 90 degrees azimuths; 2) a retreating-side self-BVI event in the fourth quadrant of each rotor at 300 degrees azimuth; 3) the separated flow and blade interaction near zero degrees azimuth. The separated flow and blade interaction occurs when the separated flow of the blade on the retreating side convects in the freestream direction while interacting with the blade at zero degrees azimuth. The 5% C_{tip} case, overall, captures slightly stronger self-BVI events (shown in slightly darker blue and red color) than the 10% C_{tip} .

A quantitative comparison of $dF_z/d\Psi$ between the 5% C_{tip} and 10% C_{tip} cases is also performed at 75% span of the right rotor (see Fig. 8), which rotates in the counterclockwise direction. Since the airloads distributions of the left and right rotors are symmetrical, only the right rotor results are presented here. The magnitude of the self-BVI positive peaks located at 50 and 70 degrees azimuths are similar in size between the two cases. Though the 5% C_{tip} shows a slightly stronger self-BVI peak at 300 degrees azimuth on the retreating side, the overall discrepancy between the two cases is not significant.

The acoustics results of both 5% C_{tip} and 10% C_{tip} cases of

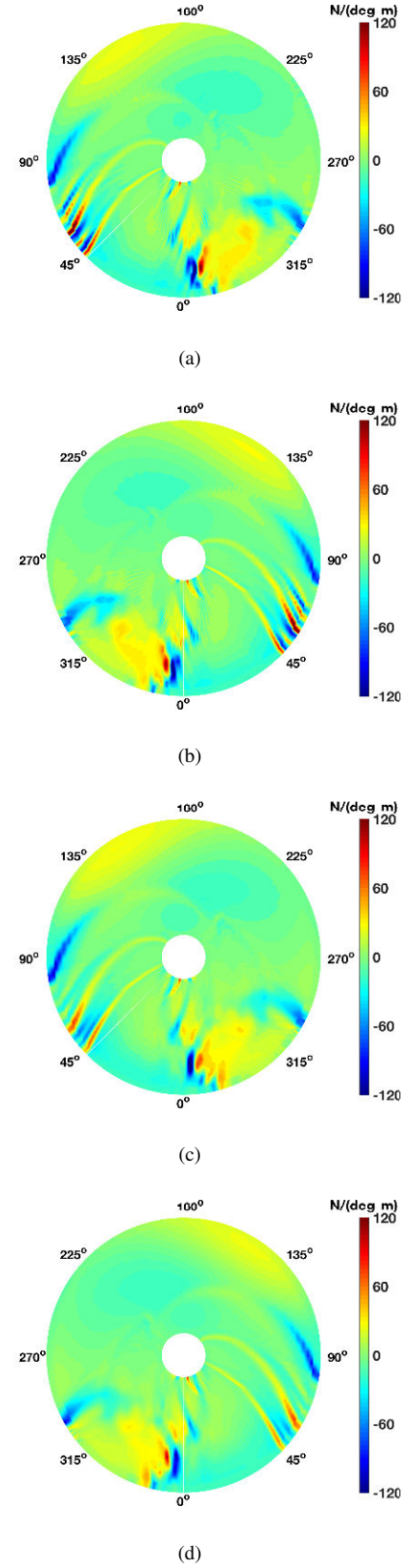


Fig. 7. Comparison of $dF_z/d\Psi$ of the 0% overlap configuration. (a) left rotor (5% C_{tip}) ; (b) right rotor (5% C_{tip}); left rotor (10% C_{tip}); (d) right rotor (10% C_{tip}).

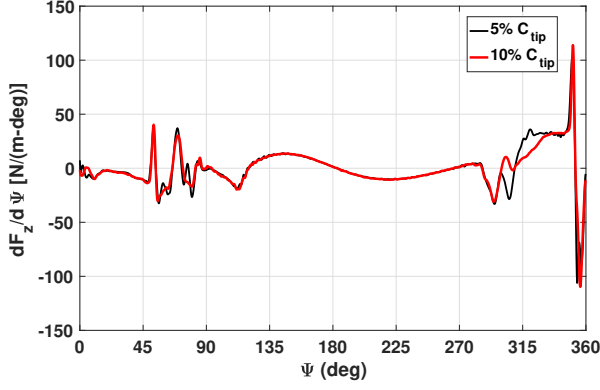


Fig. 8. Comparison of $dF_z/d\Psi$ of the right rotor (CCW) of the 0% overlap configuration at 75% span.

the 0% overlap configuration are simulated on a hemispherical grid with a rotor radius equal to $10R$, and an acoustic comparison between the two cases is performed as shown in Fig. 9. The contours shown in Fig. 9 represent the hemispherical-grid simulation results from the top view with the freestream direction pointing from top to bottom. No significant difference is found between the 5% C_{tip} and 10% C_{tip} cases.

Effect of Rotor Overlap on Acoustic Source Strength

Since a finest wake-grid spacing of 10% C_{tip} is expected not to affect the general trend of acoustics prediction for the four rotor overlap cases (0%, 5%, 15%, and 25%) while saving computational resources, $\Delta_{finest} = 10\% C_{tip}$ is implemented in CFD simulations to analyze the effect of rotor overlap on the acoustic source strength of the side-by-side rotor. Figure 10 shows a comparison of the iso-surfaces of a non-scaled q -criterion $\bar{q}$ colored by the vorticity magnitude between the 0%, 5%, 15%, and 25% rotor overlap cases at the last simulation time step. Self-BVI events can be seen on the advancing side of each rotor in all four cases. However, the 5%, 15%, and 25% cases introduce rotor-to-rotor BVI, which implies the aerodynamic interaction between the tip vortex of one rotor and the blade surface of another rotor in close proximity. The rotor-to-rotor BVI event of the 5% overlap case may not be clearly shown in Fig. 10(b), but it becomes more visible on the polar contours of the azimuthal derivative of sectional normal force, which will be discussed in the next paragraph.

Figures 11 and 12 show the comparisons of polar contours of the azimuthal derivative of sectional normal force ($dF_z/d\Psi$), which is a direct input to loading noise prediction, for both left and right rotors between the four overlap cases: 0%, 5%, 15%, and 25%. Again, the polar contours represent the rotor disks from the top view with the freestream direction pointing from top to bottom. These polar contours also represent the change of $dF_z/d\Psi$ of a single blade of the side-by-side rotor over the last rotor revolution. The self-BVI events can be seen at 50, 70, and 90 degrees azimuths in the first quadrant of both left and right rotors, and the strength of these aerodynamic interactions of the four overlap cases are approximately the same since the colors of these self-BVI footprints on the

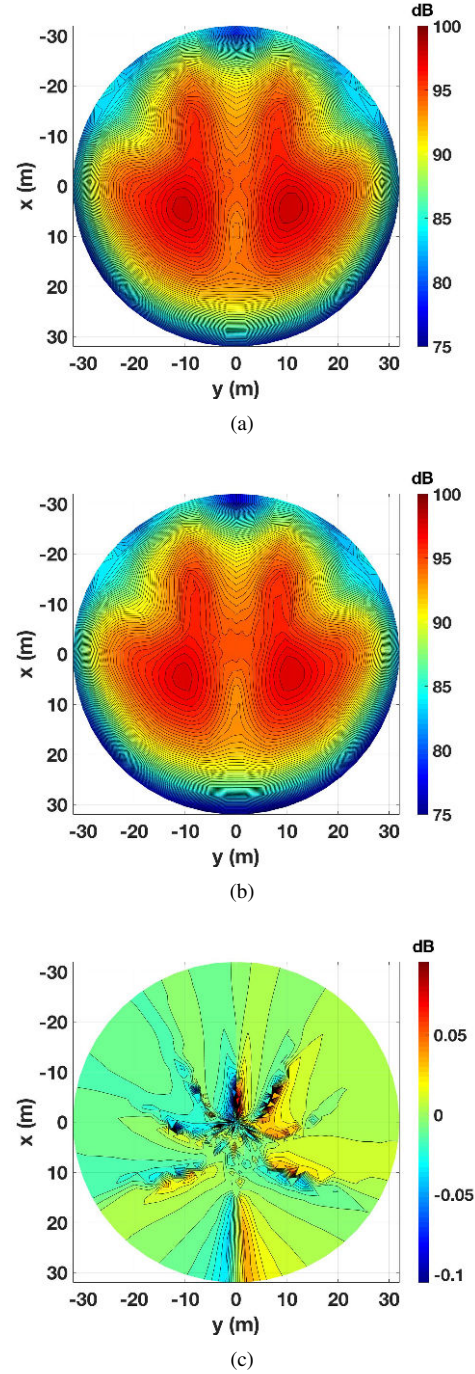
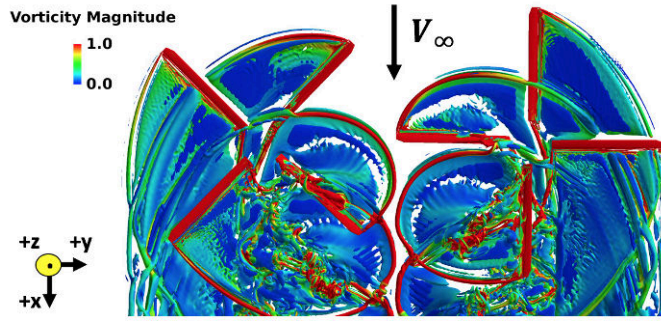
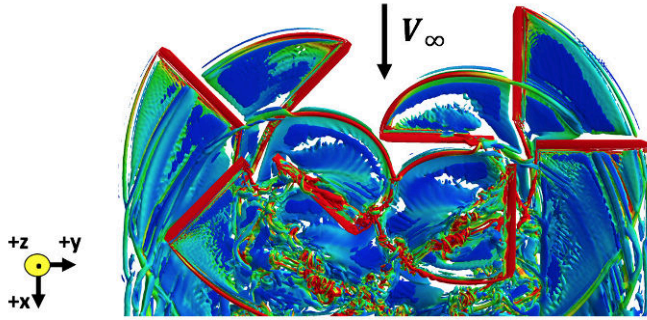


Fig. 9. Comparison of OASPL of the 0% overlap case. (a) 5% C_{tip} ; (b) 10% C_{tip} ; (c) 5% C_{tip} – 10% C_{tip} .

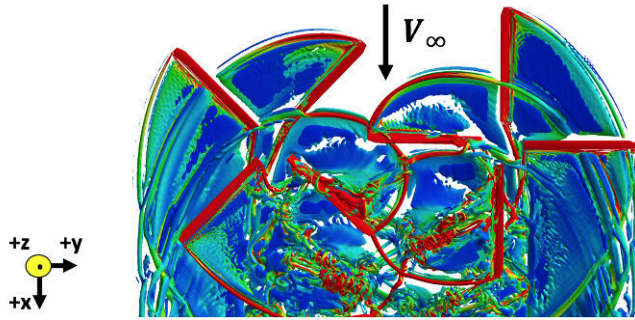
polar contours appear similar. Besides the self-BVI events, rotor-to-rotor BVI events are captured in the 5%, 15%, and 25% overlap cases, and these aerodynamic interactions were confirmed with the iso-surfaces of $\bar{q}$ in Fig. 10. The rotor-to-rotor BVI events are located at: 1) at 300 degrees azimuth of the 5% overlap case; 2) at 270 and 315 degrees azimuths of the 15% overlap case; 3) at 250 and 345 degrees azimuths of the 25% overlap case. The strength of these rotor-to-rotor BVI events is also significantly stronger than that of the self-BVI events since the rotor-to-rotor events are shown in darker



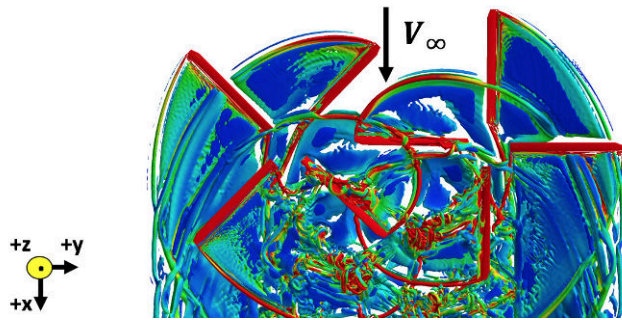
(a)



(b)

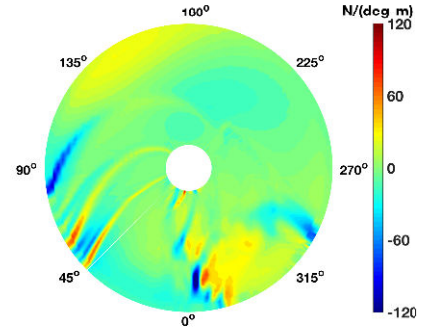


(c)

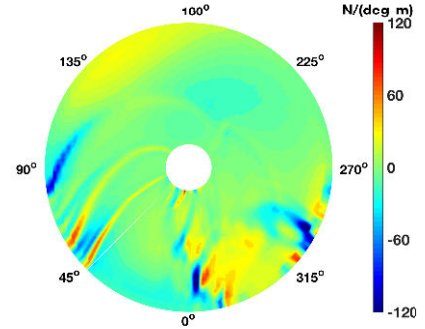


(d)

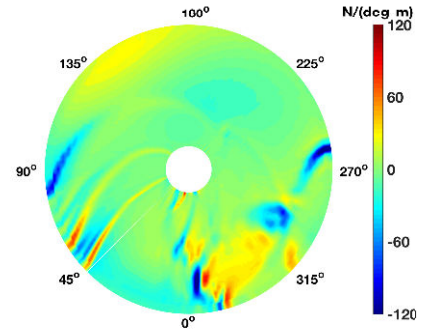
Fig. 10. Iso-surfaces of a non-scaled q -criterion $\bar{q}$ colored by the vorticity magnitude from the top view. (a) 0% overlap; (b) 5% overlap; (c) 15% overlap; (d) 25% overlap.



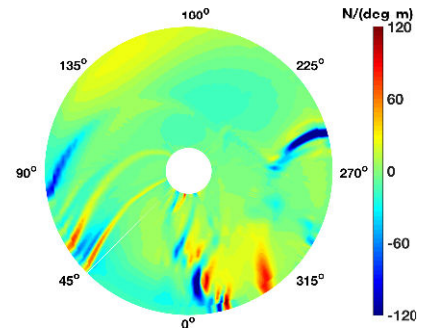
(a)



(b)



(c)



(d)

Fig. 11. Comparison of $dF_z/d\Psi$ of the left rotor (CW) of the 0% overlap configuration. (a) 0% overlap ; (b) 5% overlap; (c) 15% overlap; (d) 25% overlap.

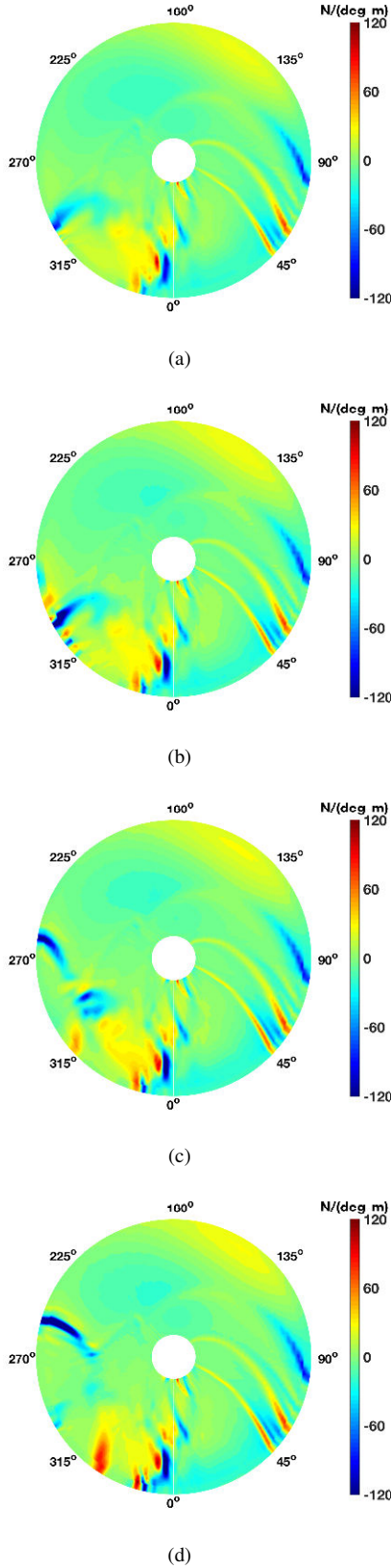


Fig. 12. Comparison of $dF_z/d\Psi$ of the right rotor (CCW) of the 0% overlap configuration. (a) 0% overlap ; (b) 5% overlap; (c) 15% overlap; (d) 25% overlap.

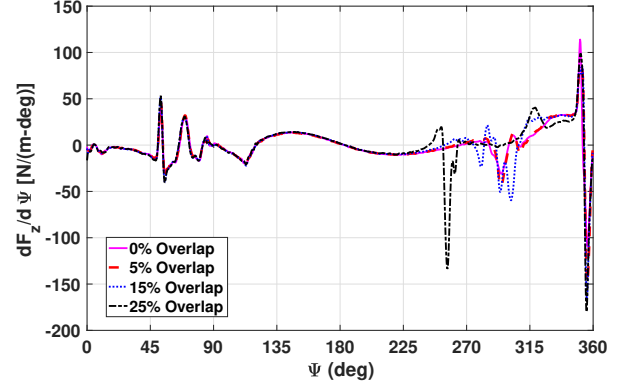


Fig. 13. Comparison of $dF_z/d\Psi$ of the right rotor (CCW) at 75% span.

red and blue colors. It is expected that these events are potential impulsive loading noise sources of the side-by-side rotor, which would contribute significantly to rotorcraft tonal noise at blade passage frequency (BPF) and higher harmonics. Additionally, the separated flow and blade interaction near zero degrees azimuth is observed among the four overlap cases. Large loading fluctuations near zero degrees azimuth are attributed to the convection of the separated flow on the blade at the retreating side and its interaction with the blade at zero degrees azimuth.

Figure 13 shows a quantitative comparison of $dF_z/d\Psi$ of the right rotor among the four overlap cases at 75% span. Since the left and right rotors show symmetrical distribution of $dF_z/d\Psi$, only the right rotor is analyzed here. The results, again, demonstrate that the magnitude of self-BVI events located at 50, 70, and 90 degrees azimuths are approximately the same, but a large discrepancy is shown in rotor-to-rotor BVI strength on the retreating side of each rotor. The 25% overlap case shows significantly higher rotor-to-rotor BVI peaks, which are located near 250 and 345 degrees azimuths, than the other three overlap cases. The rotor-to-rotor BVI events of the 25% overlap case is also found significantly stronger in magnitude than the self-BVI events of all four overlap cases. It is anticipated that the 25% overlap case would result in the highest sound pressure level. The relationship between the acoustic sources and the noise of the side-by-side rotor at a specific observer location is studied in the next subsection.

Effect of Rotor Overlap on Acoustics

After the identification of noise sources of the side-by-side rotor, the effect of rotor overlap on acoustics is analyzed and presented in this subsection. The acoustic simulations are performed on a hemispherical grid with a radius equal to 10R as mentioned under the subsection Acoustic Simulation Setup in Methods. Figure 14 shows the overall sound pressure level (OASPL) of each overlap case, and the color bar of the four overlap cases is kept the same for comparison purposes. These contours represent the hemispherical-grid simulation results from the top view, and the freestream direction points from top to bottom. According to the results, all four cases show

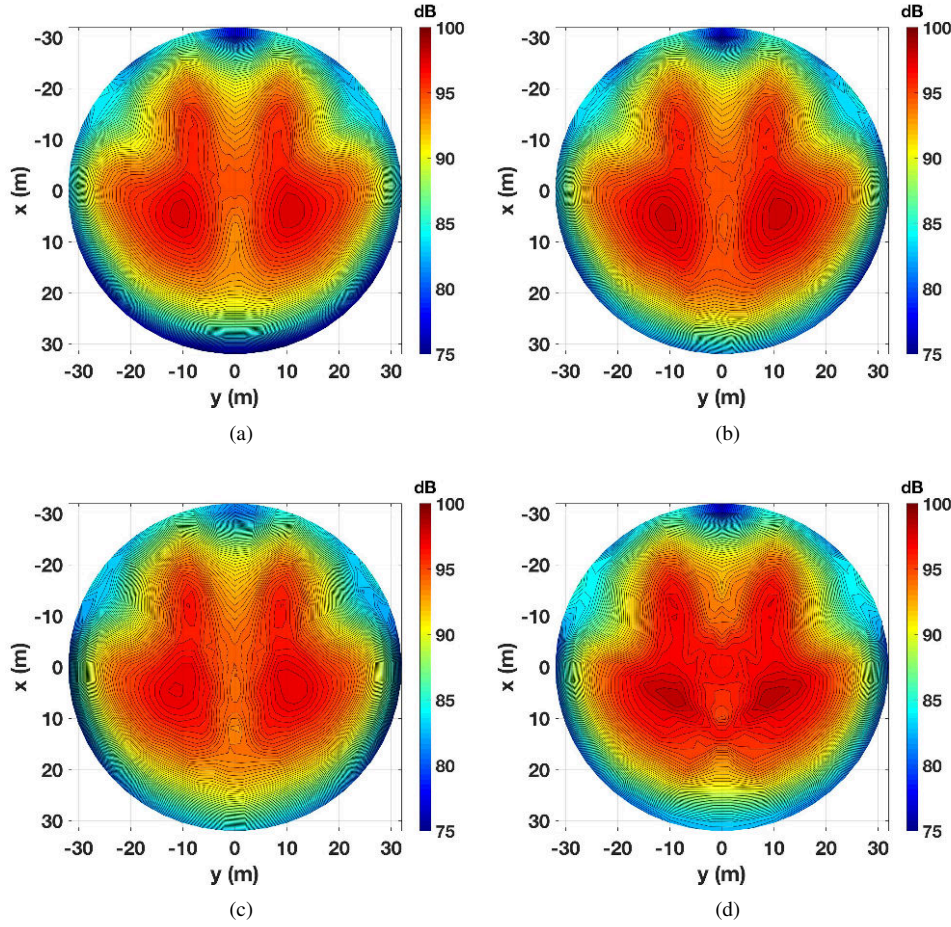


Fig. 14. Comparison of OASPL. (a) 0% overlap ; (b) 5% overlap; (c) 15% overlap; (d) 25% overlap.

similar radiation pattern with minor discrepancies. The rear region of the hemisphere shows a slight increase in OASPL as the rotor overlap percentage increases. This is due to the increasing strength of the rotor-to-rotor BVI and separated flow and blade interactions at a higher rotor overlap percentage. The relationship between the acoustic sources and the total noise is explored later in this subsection. The region below the side-by-side rotor (near $x = 0$ m and $y = \pm 10$ m) also shows an increase in OASPL due to stronger rotor-to-rotor interactions. A baseline comparison of OASPL with respect to the 0% overlap case is also performed and shown in Fig. 15. The 25% overlap case shows significantly larger discrepancies in OASPL than the other overlap cases. Figure 15 shows large bandwidth discrepancies are due to the increasing strength of acoustic sources and a minor difference in acoustic directivity since the noise source positions (e.g., the positions of rotor-to-rotor BVIs) of the four overlap cases are not the same as shown in Figs. 11 and 12. The acoustic results, overall, accord with the comparison of acoustic source strength among the four overlap cases as shown in the previous subsection.

A quantitative comparison of the total acoustic pressure as a function of observer time (t) among the four overlap cases is performed (see Fig. 16) at the microphone position $x = 5.5$ m, $y = -10.5$ m, and $z = -20.2$ m, where the maximum OASPL

occurs in the 25% overlap case based on the hemispherical results from Fig. 14. The 25% overlap case shows sharper periodic negative peaks than the other three cases (e.g., at $t = 0.1095$ sec in Fig. 16). In order to identify the acoustic source location where the negative peaks occur, the first integrand of the loading noise equation in Eq. 3, which represents the strength of noise source at a specific observer location after taking into account of the Doppler amplification factor $1/|1 - M_r|$, is calculated at each spanwise node of a single blade over the last rotor revolution. This approach is also taken by Kalki et al. (Ref. 39) to analyze the acoustic sources of a coaxial rotor. Recall that the magnitude of the Doppler amplification factor depends on both the blade tip Mach number and the radiation vector from the source position to the observer. The source strength also depends on the magnitude of $\dot{l}_r$, which is directly related to the magnitude of sudden change of airloads in the acoustic radiation direction. The same microphone position ($x = 5.5$ m, $y = -10.5$ m, and $z = -20.2$ m), which is used for the total acoustic pressure comparison, is chosen for the noise integrand analysis. The individual blade positions are also identified at a given observer time. For the noise integrand analysis, the observer time is chosen to be 0.1095 sec where one of the sharp periodic negative peaks of the four rotor overlap cases is observed in Fig. 16.

Table 3. A comparison of physical properties.

Aircraft Properties	Side-by-Side Rotor	Bell 430
Rotor Radius	3.2 m	6.4 m
Number of Rotors	2	1
Blades per Rotor	4	4
Nominal Rotor Speed	499 RPM	349 RPM
Blade Passage Frequency	33.3 Hz	23.2 Hz
Freestream Velocity	115 knots	124 knots
Hover Tip Mach Number	0.50	0.69
Advancing Tip Mach Number (Level Flight)	0.67	0.88
Payload	544 kg (1,200 lb)	565 kg (1,247 lb)

Table 4. A comparison of OASPL.

OASPL	0% Overlap	25% Overlap	Bell 430
Approach	57.6 dB	58.5 dB	75.0 dB
Overhead	69.1 dB	71.3 dB	76.8 dB

Figures 17 and 18 show the contours of the first integrand calculated results of the loading noise equation in Eq. 3 for both left and right rotors of the four overlap cases. The black dash lines represent the individual blade positions at the designated observer location and time. The key aerodynamic interactions that influence the total acoustic pressure the most at the given microphone position are: 1) the advancing-side self-BVI events at 90 degrees azimuth of both left and right rotors in all four overlap cases; 2) the rotor-to-rotor BVI events on the retreating side of each rotor in the 5% (at 315 degrees azimuth), 15% (at 270 and 315 degrees azimuths), and 25% overlap cases (at 250 and 345 degrees azimuths); 3) the separated flow and blade interaction near zero degrees azimuth of the left rotor of all four overlap cases. The magnitude of the acoustic sources is stronger on the left rotor than on the right rotor since the microphone is positioned closer toward the left rotor. The strength of the rotor-to-rotor BVI events of the 25% overlap case is significantly more impulsive than that of the other overlap cases.

At the designated observer time $t = 0.1095$ sec, blade 4 overlaps with the separated flow and blade interaction near zero degrees azimuth of the left rotor in each overlap case, which contributes to the negative pressure peaks at $t = 0.1095$ sec in Fig. 16. Note that the magnitude of separated flow and blade interaction is comparable with that of the retreating-side rotor-to-rotor BVI events in the 25% overlap case. In the 25% overlap case, the rotor-to-rotor BVI event, which occurs at 250 degrees azimuth on the left rotor (see Fig. 17(d)), completely overlap with blade 3 while blade 3 does not overlap with the rotor-to-rotor BVI events on the left rotor in the other overlap cases. This explains why the negative pressure peak of the 25% overlap case is particularly sharp at $t = 0.1095$ sec. It should also noted that blade 3 of the right rotor overlaps with the rotor-to-rotor BVI event near 315 degrees azimuth in both 5% and 15% overlap cases, which contribute to the negative pressure peaks of the two overlap cases. Blade 1 overlaps with the advancing-side self-BVI events at 90 degrees azimuth of

both left and right rotors in all overlap cases. These overlaps also contribute marginally to the negative pressure peaks in all overlap cases. The 25% overlap case, overall, shows significantly stronger acoustic sources than the other three overlap cases.

Acoustic Comparison Against Conventional Helicopter Noise

In order for UAM aircraft to operate quietly in urban areas without disturbing the local residential neighborhoods, it is anticipated that the noise level of UAM aircraft with multi-rotors is required be lower than that of a similar-sized conventional helicopter. Uber Technologies Inc., as one of the largest UAM promoter, specifically mentioned that UAM vehicle noise should be 15 dB lower than similar-sized helicopter noise at the same altitude and same flight operating condition (Ref. 40). Uber also sets the initial guideline that the A-weighted SPL of UAM aircraft at an altitude of 250 ft or 76 m should be less than 67 dB at the ground level (Ref. 41).

In this subsection, the A-weighted sound pressure level (SPL) of the side-by-side rotor with 0% and 25% overlap, which accounts for the sound frequency range most sensitive to human ears, is compared against that of a similar-sized conventional helicopter Bell 430. The acoustic results of the side-by-side rotor analyzed in this section are computed based on CFD simulations with the finest wake-grid spacing equal to 5% C_{tip} . The one-third band acoustic measurements of the Bell 430 are obtained from the technical paper written by Snider et al. (Ref. 42). Two acoustic simulation cases are considered for noise comparison: an approach or flyover case in which the microphone is positioned 150 m below and 457 m ahead of the vehicle and an overhead case in which the microphone is positioned 150 m below the vehicle.

Before the discussion of acoustic results, a comparison of physical properties between the side-by-side rotor and the Bell 430 is performed and shown in Table 3. It should be noted

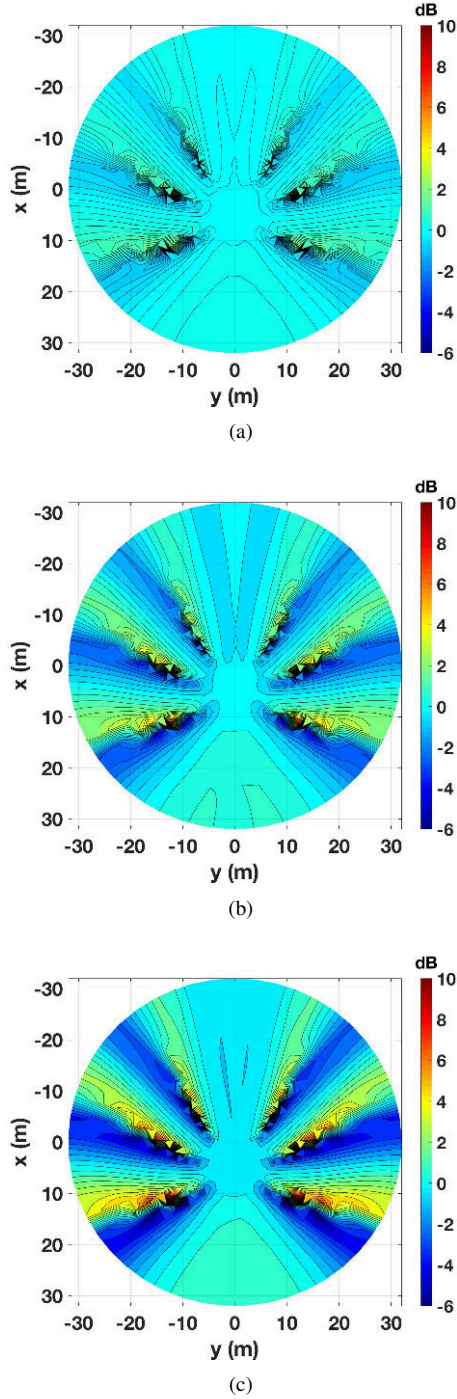


Fig. 15. Baseline comparison of OASPL with respect to the 0% overlap case. (a) 5% overlap subtracts 0% overlap ; (b) 15% overlap subtracts 0% overlap; (c) 25% overlap subtracts 0% overlap.

that the payloads of both vehicles are similar in magnitude, but the freestream velocities are differed by 9 knots. It is expected that the acoustic comparison would not be fair under two different freestream conditions. Therefore, a sixth-power scaling law (Ref. 43) as show in Eq. (4) is applied to the SPL calculation of the Bell 430 in order to offset the difference in freestream velocity between the two vehicles. SPL_2 refers the

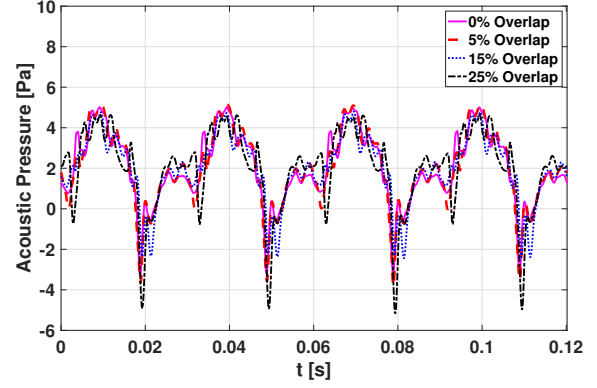


Fig. 16. Comparison of total acoustic pressure.

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 are taken; $M_{tip,1}$ refers to the new advancing tip Mach number after adjusting the Bell 430 freestream velocity to that of the side-by-side rotor.

$$SPL_1 = SPL_2 - 10 \log_{10} \left[\left(\frac{M_{tip,2}}{M_{tip,1}} \right)^6 \right] \quad (4)$$

Figure 19(a) presents the acoustic comparison of A-weighted SPL between the side-by-side rotor with 0% and 25% overlap and the Bell 430 at one-third octave band center frequencies ranging from 100 Hz to 5,000 Hz for the approach case. Higher frequencies beyond 5,000 Hz are not included since the broadband noise contribution becomes more dominant at high frequencies than tonal noise and our prediction does not include broadband noise (Ref. 17). The differences in A-weighted SPL between the three configurations at the one-third octave band center frequencies are illustrated in Fig. 19(b). The Bell 430, overall, shows significantly higher A-weighted SPL (> 10 dB), than both 0% and 25% overlap configurations of the side-by-side rotor. The minimum differences between the Bell-430 and the two overlap configurations of the side-by-side rotor are found to be < 5 dB at 1,000 Hz where the human ear perception to noise annoyance is important.

A comparison of OASPL, which is calculated by integrating the A-weighted SPL from 100 Hz to 5,000 Hz, for both approach and overhead cases is shown in Table 4. The OASPL of the Bell 430 is 17.4 dB and 16.5 dB higher than both 0% and 25% overlap configurations of the side-by-side rotor, respectively. No significant difference between the 0% and 25% overlap configurations is found. It should be noted that the Uber's initial guideline of 15 dB quieter than conventional helicopter noise is met for the approach case. As mentioned before, the acoustic calculations in the present work does not account for broadband noise at high frequencies, and therefore, the overall SPL of the side-by-side rotor could be under-predicted. Li and Lee (Refs. 16, 17) have shown that trailing-edge broadband noise becomes important and contributes sig-

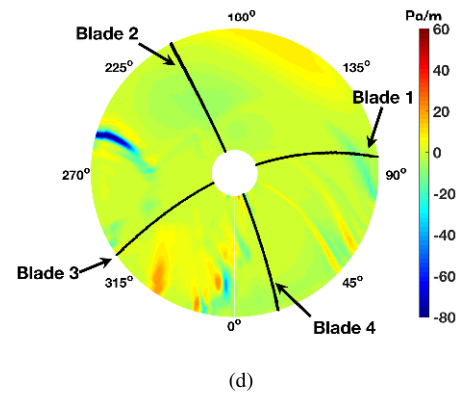
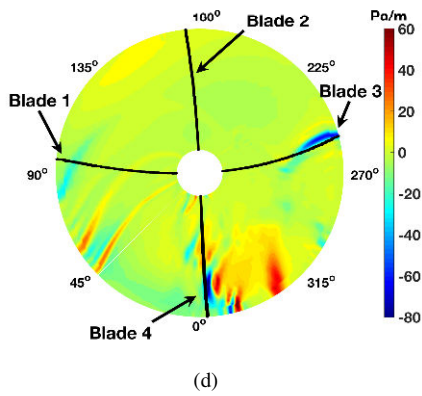
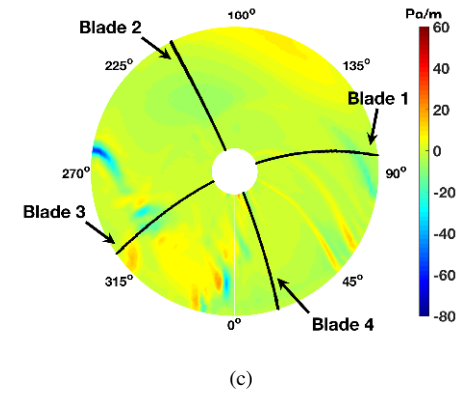
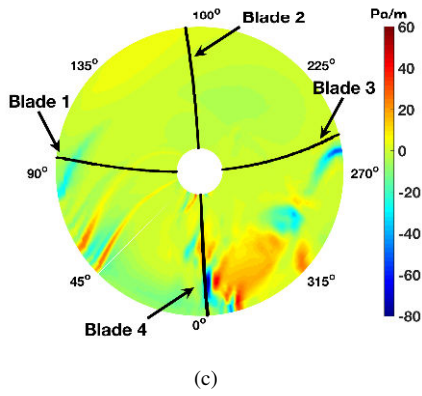
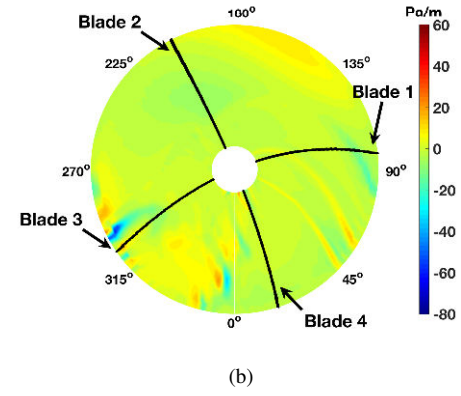
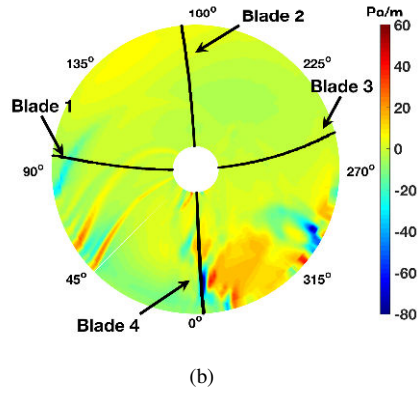
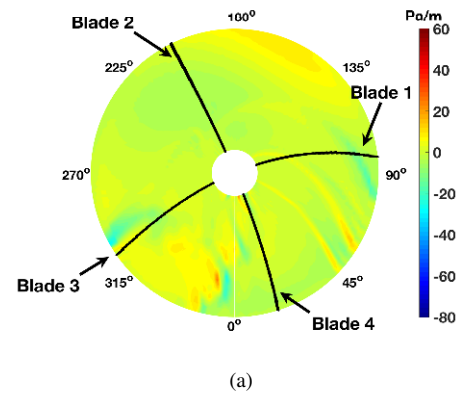
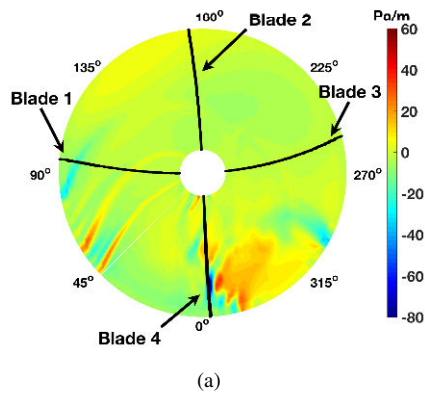
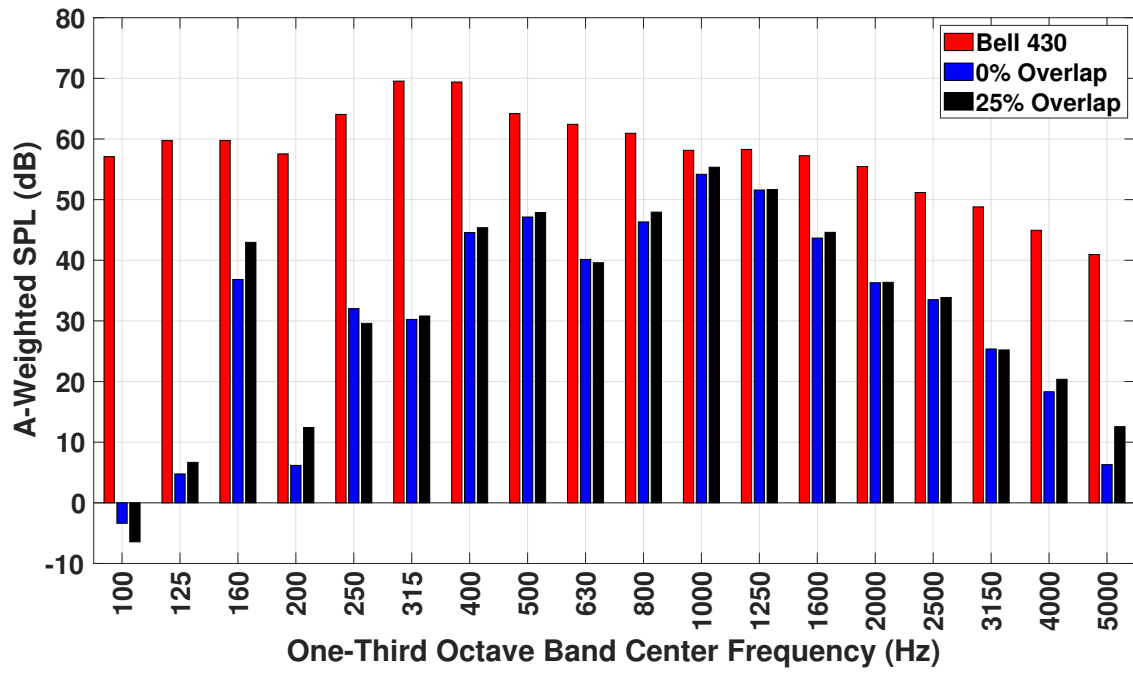
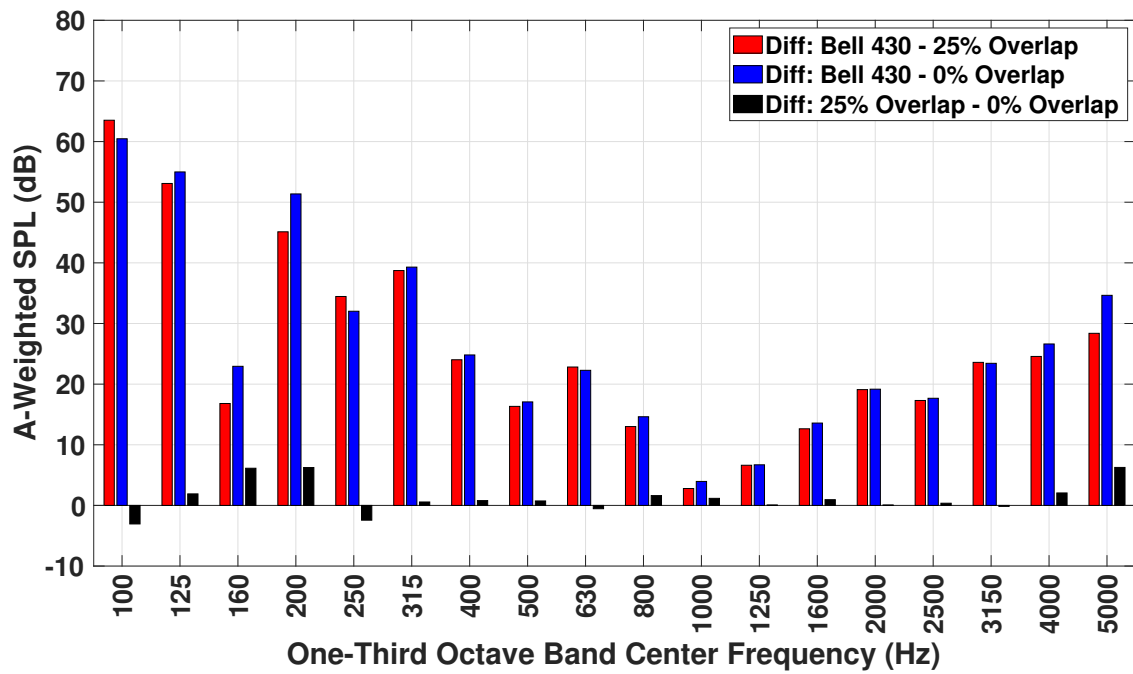


Fig. 17. Comparison of the noise integrand results for the left rotor (CW). (a) 0% overlap; (b) 5% overlap; (c) 15% overlap; (d) 25% overlap.

Fig. 18. Comparison of the noise integrand results for the right rotor (CCW). (a) 0% overlap; (b) 5% overlap; (c) 15% overlap; (d) 25% overlap.

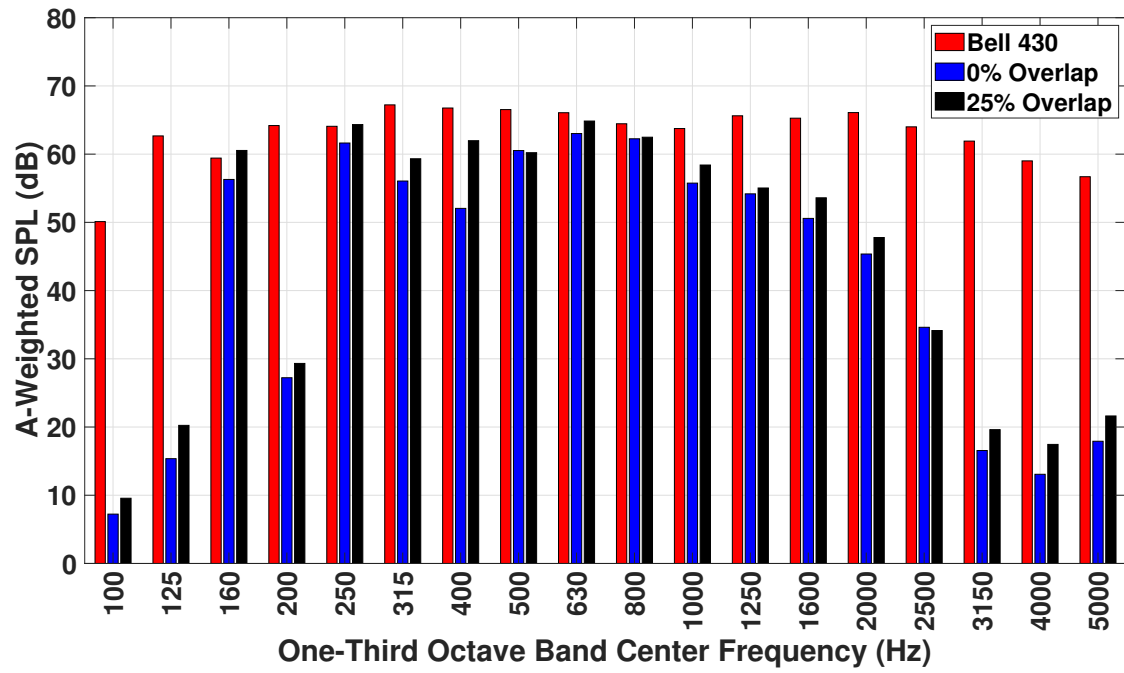


(a)

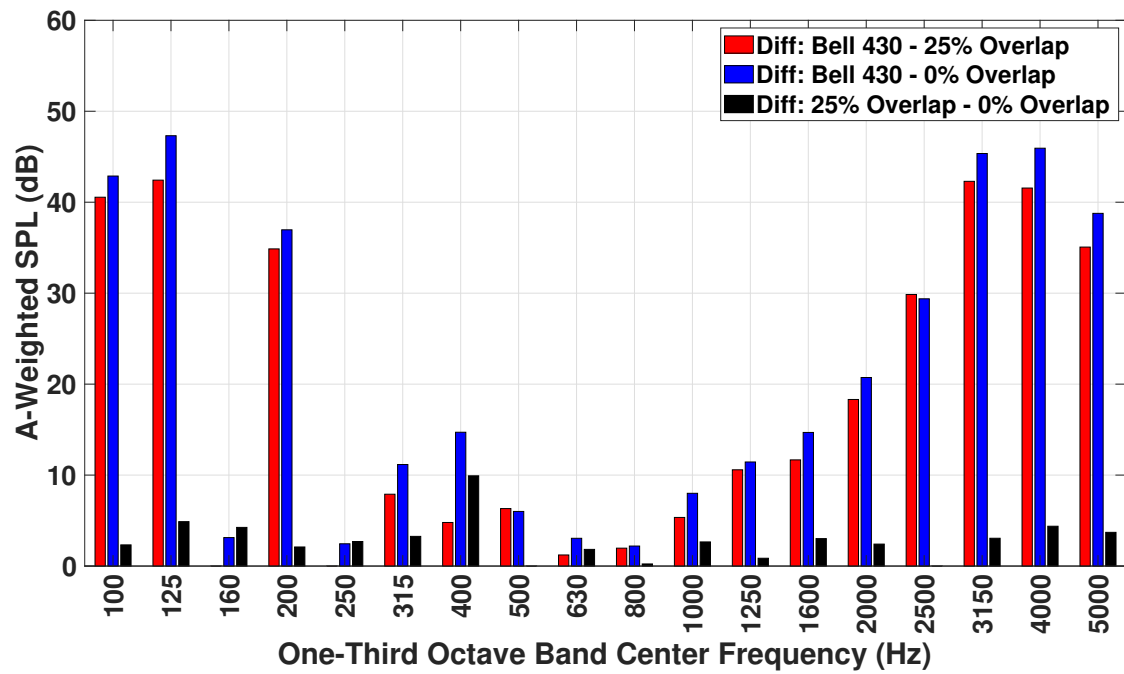


(b)

Fig. 19. Acoustic comparison of the approach case. (a) A-weighted SPL; (b) difference in A-weighted SPL.

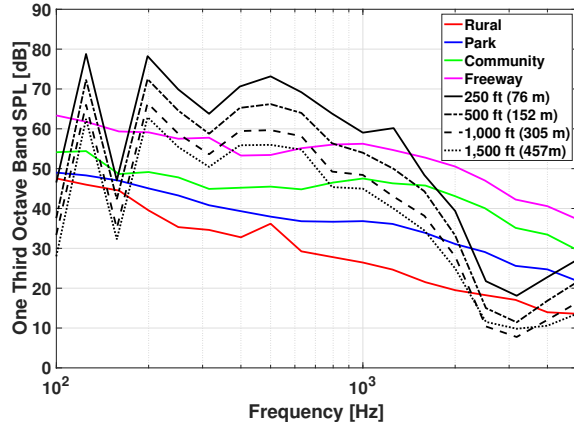


(a)

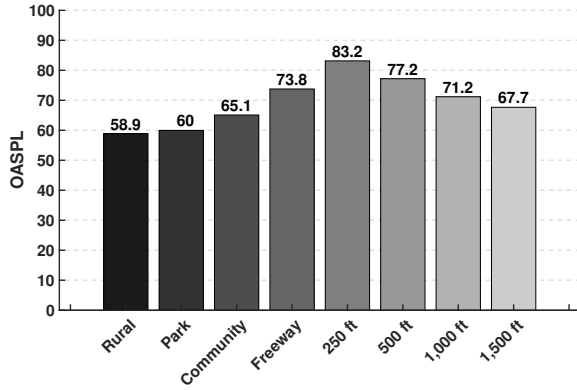


(b)

Fig. 20. Acoustic comparison of the overhead case. (a) A-weighted SPL; (b) difference in A-weighted SPL.



(a)

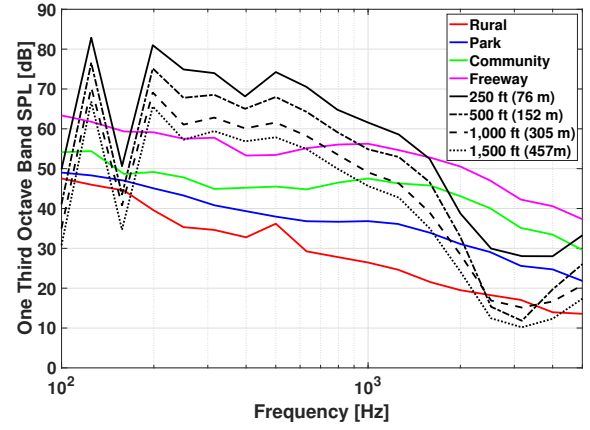


(b)

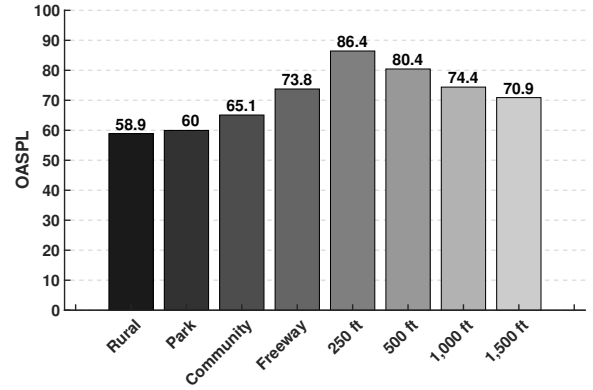
Fig. 21. Background noise comparison of the 0% overlap case. (a) one-third octave band SPL; (b) OASPL.

nificantly to overall SPL at high-frequencies. Moreover, the overall SPL of the side-by-side rotor configurations are approximately 60 dB at an altitude of 150 m from the ground. The noise level may become even higher at an altitude of 76 m, and Uber's restriction of 67 dB limit at ground level from an altitude of 76 m or 250 ft would be violated.

The acoustic comparison of A-weighted SPL is also performed for the overhead case and shown in Fig. 20. Unlike the approach case, the A-weighted SPL of Bell 430 is comparable (< 10 dB) with the A-weighted SPL of both 0% and 25% overlap configurations of the side-by-side rotor at most one-third octave band center frequencies below or equal to 1,000 Hz. The overall SPL between the Bell 430 and the two overlap configurations of the side-by-side rotor are 7.7 dB and 5.5 dB as shown in Table 4. The 25% overlap case shows slightly higher overall SPL than the side-by-side rotor. It becomes clear that Uber's UAM noise standards of 15 dB quieter than similar-sized helicopter noise and 67 dB limit at ground level are not met for the overhead case. The side-by-side rotor noise could become even larger if broadband noise is accounted in noise prediction.



(a)



(b)

Fig. 22. Background noise comparison of the 25% overlap case. (a) one-third band octave SPL; (b) OASPL.

Acoustic Comparison Against Various Background Noise

Besides the guideline that the UAM aircraft noise should be 15 dB quieter than similar-sized helicopter noise, there is also a general agreement that the UAM aircraft noise should not exceed background noise. In this subsection, the one-third octave band SPL of the side-by-side rotor with 0% and 25% overlap is calculated and compared against the rural, park, community, and freeway background noise measured by Begault (Ref. 44) in the San Francisco Bay Area, California. Note that UAM aircraft could fly in any of these zones. Again, the side-by-side rotor acoustic results are predicted based on the CFD simulations with the finest wake-grid spacing equal to 5% C_{tip} . The side-by-side rotor noise is simulated at the following distances below the vehicle: 250 ft (76 m), 500 ft (152 m), 1,000 ft (305 m), and 1,500 ft (457 m).

Figure 21 shows a comparison of the one-third octave band SPL and OASPL for the side-by-side configuration with 0% overlap. Though the vehicle OASPL is lower than freeway noise when operating at an altitude of 1,000 ft or above, the vehicle OASPL exceeds the rural, park, and community noise. The OASPL difference between the community and vehicle noise is more than 15 dB at 250 ft. More importantly, it is

also found that the vehicle noise partially exceeds the freeway noise even at an altitude of 1,000 ft or above around 500 Hz. The high-frequency contents at a frequency greater than 2,000 Hz are completely masked by the freeway and community noise. However, the current calculation, again, does not consider the broadband component of rotorcraft noise. It should also be aware that the UAM noise could become larger when multiple vehicles are operating simultaneously as demonstrated by Li and Lee (Ref. 17).

Similar trend is also observed in Fig. 22, which illustrates a background noise comparison for the 25% overlap configuration. The OASPL difference between the community and vehicle noise is approximately 20 dB at 250 ft. The vehicle OASPL exceeds the freeway noise at an altitude below 1,500 ft. Even at 1,500 ft, the vehicle noise partially exceeds the freeway noise according to the one-third octave band SPL spectrum shown in Fig. 22(a). These results highlight that noise reduction technology including noise abatement operational procedures should be developed for the public acceptance of UAM operations.

CONCLUSIONS

High-fidelity CFD simulations were carried out to study the acoustics of the side-by-side rotor with 0%, 5%, 15%, and 25% overlap in forward flight at a freestream velocity of 115 knots using CREATETM-AV Helios. The acoustic simulations were carried out using the acoustics prediction tool PSU-WOPWOP based on an impermeable surface approach and a hemispherical grid with a radius equal to 10R. The effect of wake-grid spacing on the acoustic prediction of the side-by-side rotor was studied. A detailed comparison of the acoustic source strength among the four overlap cases of the side-by-side rotor was performed. The relationship between the acoustic sources and the resulting noise was explored for each overlap case. A comparison between the side-by-side rotor noise, similar-sized helicopter noise, and various background noise was also performed to assess the impact of UAM vehicle noise on urban communities. The following conclusions were drawn based on the results presented and analyzed in this paper:

1. BVI events, particularly the rotor-to-rotor BVI events, are the most dominant noise sources of the side-by-side rotor with rotor-to-rotor overlap. The rotor-to-rotor BVI events are significantly stronger in magnitude than the self-BVI events for a larger overlap case.
2. A finest wake-grid spacing of 10% C_{tip} is good enough for the acoustics prediction of the side-by-side rotor in forward flight.
3. The noise level of the side-by-side rotor with 25% overlap is significantly higher than that of the 0%, 5%, and 15% cases primarily due to stronger rotor-to-rotor interactions.

4. The A-weighted SPL of the conventional helicopter Bell 430 in level flight is comparable with the noise of the side-by-side rotor configurations in the overhead case calculation, where the microphone is positioned 150 m below the vehicle. The OASPL difference between the Bell 430 and the side-by-side rotor with 0% overlap of the overhead case was less than 10 dB. The A-weighted SPL of the side-by-side rotor with 0% overlap was approximately 70 dB. The noise guidelines of 15 dB quieter than similar-sized helicopter noise and less than 67 dB A-weighted SPL on the ground from aircraft at 250 ft altitude are not met. Thus, noise reduction technologies should be pursued to enhance the public acceptance of UAM operations.
5. The noise of the side-by-side rotor with 0% rotor overlap could not be completely masked by the freeway noise even at an altitude of 1,500 ft or 457 m. The UAM noise impact is much more severe in other places considering their lower background noise levels. It should also be noted that the high-frequency broadband noise was not incorporated in the noise calculation of the present work, which implies that the noise level of the side-by-side could become higher. The noise level is also expected to increase when multiple vehicles operate simultaneously, and therefore, trajectory optimization with a goal to reduce the impact of UAM vehicle noise in urban areas should also be pursued.

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