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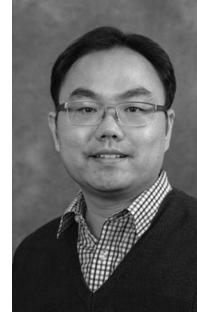
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High-Fidelity Computational Analysis on the Noise of a Side-by-Side Hybrid VTOL Aircraft



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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 CREATETM-AV rotorcraft simulation and analysis tool Helios and the acoustic prediction tool PSU-WOPWOP. First, the influence of the finest wake-grid spacing (Δ_{finest}) on the side-by-side rotor acoustics is studied. No significant difference in overall sound pressure level (OASPL) is found between the two wake-grid spacing cases: $\Delta_{\text{finest}} = 5\% C_{\text{tip}}$ and $10\% C_{\text{tip}}$. Physical noise sources, such as impulsive self blade–vortex interactions, rotor-to-rotor blade–vortex interactions, and separated flow and blade interactions, are investigated in details based on high-fidelity CFD simulation results and noise-integrand analyses. The effect of rotor overlap on rotor acoustics is also assessed. It is found that the maximum OASPL difference among the overlap cases is about 1 dB, but the radiation patterns are different for each overlap case. Furthermore, the noise of the side-by-side rotor with 0% and 25% overlaps is compared against the noise of a conventional helicopter and various background noises. The side-by-side rotor noise is comparable with the helicopter noise around 1000 Hz. The results also show that the side-by-side rotor noise could not be fully masked by the freeway background noise even at an altitude of 1500 ft and exceed Uber’s noise guideline of 62 dBA at 500 ft. Thus, noise reduction technology should be pursued to lower UAM aircraft noise, which is one of major technical barriers for UAM public acceptance.

Nomenclature

c_{∞}	speed of sound in the undisturbed medium, m/s
C_{tip}	tip chord length, m
d	observer distance, m
d/R	nondimensional observer distance
F_n	blade sectional normal force, N/m
$dF_n/d\Psi$	azimuthal derivative of F_n , N/(m-deg)
L_{ref}	grid unit reference length, m
$\vec{l}$	blade surface loading vector, N/m
l_r	$\vec{l} \cdot \hat{r}$, N/m
$\dot{l}_r$	change of blade surface loading with respect to the retarded time, N/(m-s)
$\vec{M}$	local Mach number vector
M_r	$\vec{M} \cdot \hat{r}$
M_{∞}	freestream Mach number
r	distance between $\vec{y}$ and $\vec{x}$, m

$\hat{r}$	unit vector of r in the radiation direction
R	rotor radius, m
q	q-criterion, $\frac{1}{2}(W_{ij} ^2 - S_{ij} ^2)$, $1/s^2$
$\bar{q}$	nondimensional q-criterion, $q/(c_{\infty}/L_{\text{ref}})^2$
S_{ij}	strain-rate tensor, $1/s^2$
t	observer time, s
t_{max}	maximum observer time, s
W_{ij}	spin-rate tensor, $1/s^2$
$\vec{x}$	observer location, m
$\vec{y}$	acoustic source location, m
α	vehicle pitch attitude, deg
Δ_{finest}	finest wake-grid spacing, m
θ_o	blade collective pitch, deg
θ_{1c}	blade lateral cyclic pitch, deg
θ_{1s}	blade longitudinal cyclic pitch, deg
β_o	blade coning angle, deg
μ	advance ratio
Ψ	rotor azimuth, deg

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Acronyms

BVI	blade–vortex interaction
CFD	computational fluid dynamics

CSD	computational structural dynamics
CW	clockwise rotation
CCW	counter-clockwise rotation
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 interests from the global rotorcraft community in recent years. The ultimate goal of UAM is to provide affordable, environment-friendly, and safe air transportation in densely populated cities, which could lead to a reduction of urban traffic congestions and better interconnect suburban and urban regions. The UAM aircraft also has the capability of transporting merchandise cargo in urban and suburban areas (Ref. 2). Numerous UAM aircraft developers, such as Joby Aviation, and Hyundai Motor Company, have revealed their prototypes and also shared their visions on UAM aircraft designs with the public (Refs. 3,4). Among various 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 could become a major barrier for the public acceptance of UAM operations if it exceeds background noise.

Unlike a conventional helicopter design, which only consists of a main rotor and a tail rotor, most UAM aircraft (Ref. 6) designs feature multiple rotors with a small rotor radius, which typically yield lower rotor tip speed and noise compared to a helicopter. Some of the current UAM aircraft designs also feature lifting wing surfaces in addition to a multirotor system, which may lead to significant rotor-to-wing aerodynamic interactions and noise. Thus, both aerodynamic and acoustic characteristics of UAM aircraft are expected to be different from that of a conventional helicopters, and the complex aerodynamic interactions of a multirotor UAM aircraft could generate significant rotorcraft tonal and broadband noise.

In recent years, some research studies have been carried out to investigate both aerodynamic and acoustic characteristics of multirotor UAM aircraft. In 2019, Ventura Diaz et al. (Refs. 7,8) performed a series of high-fidelity computational studies for NASA's six-passenger side-by-side hybrid VTOL configuration (see Fig. 1) based on a computational fluid dynamics (CFD) and computational structural dynamics (CSD) loose coupling approach. Their results showed that the rotor airloads of the side-by-side rotor 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 in cruise. 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. 9) 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 an increasing percentage of rotor overlap. In 2021, Sagaga and Lee (Ref. 10) performed acoustic predictions for the side-by-side rotor in hover and found that the configuration with 25% overlap yields the highest overall sound pressure level. However, neither Ventura Diaz et al. nor Sagaga and Lee have performed aeroacoustic predictions for the side-by-side configuration in forward flight.

More recently, Jia and Lee (Refs. 11, 12) conducted high-fidelity aeroacoustic simulations for NASA's one-passenger and six-passenger quadrotor UAM aircraft. They showed that blade-vortex interaction



Fig. 1. NASA's six-passenger side-by-side conceptual design [20].

(BVI) noise occurs in a level-flight cruise condition for the quadrotor aircraft, although the magnitude of the BVI noise is one order of magnitude smaller than conventional helicopter BVI noise. Their research also demonstrated that the quadrotor noise in low-altitude operation could exceed various background noises (e.g., highway noise, community noise, park noise, and rural noise), which may not be acceptable for quiet UAM operations. In addition to Jia and Lee's work on UAM noise, Li and Lee (Refs. 13, 14) investigated 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 trailing-edge noise (Ref. 15), could not be masked by various background noises. The amplitude of broadband noise was also found to increase with a large number of rotors.

Moreover, Alvarez et al. (Ref. 16) analyzed the acoustics of side-by-side rotors in hover based on an unsteady Reynolds-average Navier-Stokes (URANS) CFD solver and a midfidelity viscous vortex particle method solver. Their studies demonstrated that the A-weighted overall sound pressure level could increase up to 7 dBA when the amount of blade tip-to-tip clearance between the two side-by-side rotors is reduced. Smith et al. (Ref. 17) studied the acoustics of multicopters based on the Rensselaer Multicopter Analysis Code (RMAC) (Ref. 18) and the acoustics software PSU-WOPWOP. They demonstrated that the overall sound pressure level of a hexacopter could be reduced by 9.5 dB with an orthogonal phasing strategy. Wachspress et al. (Ref. 19) also analyzed the acoustics of existing UAM VTOL designs based on a midfidelity airloads analysis tool. Their results suggested that both propeller-wing and rotor-duct interactions could lead to significantly higher overall sound pressure level when compared against their baseline models.

The aim of this work is to investigate aeroacoustics of NASA's six-passenger side-by-side UAM aircraft design (see Fig. 1) in steady forward flight based on a first principles and high-fidelity CFD approach. First, the effect of the finest CFD wake-grid spacing on rotor acoustics is investigated. Second, physical noise sources, such as BVI, are identified based on high-fidelity CFD results. Third, the effect of the rotor-to-rotor overlap percentage on the strength of noise sources and far-field noise is studied. Lastly, the UAM aircraft noise level is compared against the noise level of a four-bladed conventional helicopter and various background noise levels in order to assess the viability of low-altitude UAM operations in urban areas.

Methods

In this research study, a simplified CFD model, without rotor hubs and aircraft fuselage, is developed based on NASA's six-passenger side-by-side UAM aircraft design, which is shown in Fig. 2 (Ref. 20). Figure 2 shows the side-by-side rotor configuration from the top view without rotor overlap. The left rotor rotates in the clockwise direction (CW), while the right rotor rotates in the counterclockwise direction (CCW). A 45-deg phase shift is applied to the left rotor in order to prevent rotor-to-rotor collisions in rotor overlap scenarios. A total of four rotor-to-rotor overlap cases of the side-by-side rotor—0%, 5%, 15%, and 25%—are considered in the present work in order to investigate the effect of rotor

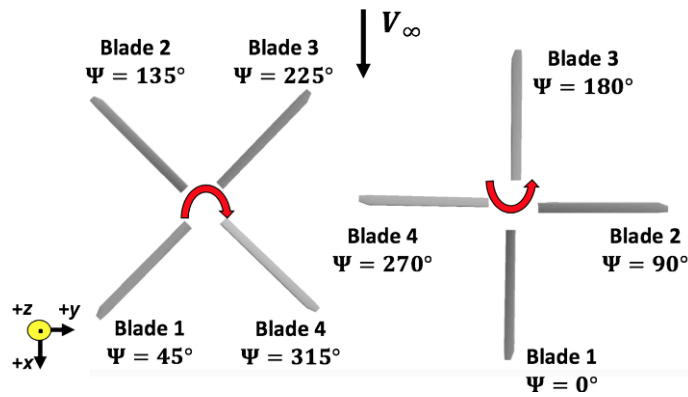


Fig. 2. The side-by-side rotor configuration without overlap.

Table 1. Basic properties of the side-by-side UAM aircraft.

Aircraft Properties	Descriptions
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)

overlap on the strength of aerodynamic interactions and the associated acoustics. The rotor overlap percentage is defined as the amount of a rotor-to-rotor overlap distance in the spanwise direction divided by the rotor radius (R). The rotor center-to-center separation distances of the 0%, 5%, 15%, and 25% overlap cases are $2R$, $1.9R$, $1.7R$, and $1.5R$, respectively.

The fundamental properties of the side-by-side UAM model (Ref. 20) 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 chord length of the blade is 0.217 m until $R = 94\%$ where a blade taper occurs. The slope of the linear twist distribution is assumed -16 deg, and the zero-deg twist occurs at 75% span. A 15-deg linear taper ratio is applied between $R = 94\%$ and the blade tip. Detailed CFD mesh and numerical setups are described in the subsequent sections.

CFD grids

A dual mesh paradigm, which divides the entire computational domain into a near-body structured overset mesh domain and an off-body adaptive Cartesian mesh domain, is employed in the present work. The near-body grids are constructed using NASA's overset grid generation software Chimera Grid Tools (Refs. 21, 22). Figures 3(a) and 3(b) show 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 grid points, 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 (Δ_{finest}) of the off-body Cartesian mesh on rotor acoustics, two simula-

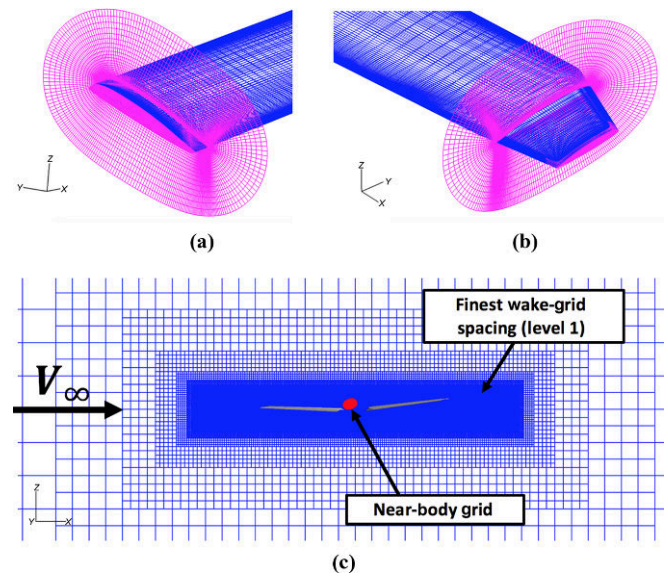


Fig. 3. CFD grids: (a) near-body grids at the blade root; (b) near-body grids at the blade tip; (c) off-body grids.

tion cases are considered: (1) $\Delta_{finest} = 5\% C_{tip}$; (2) $\Delta_{finest} = 10\% C_{tip}$. The number of grid points in the normal direction is 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 the Level-1 Cartesian 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 domain is automatically generated by the adaptive off-body Cartesian solver SAMCart (Refs. 23, 24), which is the off-body solver of the CFD solver CREATETM-AV Helios (Ref. 25). 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 3(c) shows a zoomed-in view of the off-body Cartesian mesh. In this research study, 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 is 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. 25) software suite, a high-fidelity, and multidisciplinary rotorcraft simulation tool 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 multimodule framework that allows a multisolver approach and a dual-mesh paradigm. While the off-body Cartesian grids can be solved by an off-body adaptive Cartesian solver named SAMCart (Ref. 26), the near-body grids can be solved by various unstructured, structured, and strand near-body solvers. Helios has recently been implemented to predict aerodynamics

Table 2. Motion inputs of the left (L) and right (R) rotors [7].

Overlap Rotor	0%		5%		15%		25%	
	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

Table 3. The simulation cases performed in this study.

Rotor Overlap Cases	0%	5%	15%	25%
$\Delta_{\text{finest}} = 5\% C_{\text{tip}}$	X			X
$\Delta_{\text{finest}} = 10\% C_{\text{tip}}$	X	X	X	X

and acoustics of small drones, UAM vehicles, and compound helicopters (Refs. 11, 27–30).

In this research, NASA's overset-structured and high-fidelity flow solver OVERFLOW (Refs. 31, 32) is used to simulate the near-body flow physics. The off-body adaptive Cartesian solver SAMCart (Ref. 26) 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 deg azimuth, which results in 1440 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 $\Delta_{\text{finest}} = 5\% C_{\text{tip}}$ and $10\% C_{\text{tip}}$ 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 Reynolds-averaged Navier–Stokes turbulence model coupled with Detached Eddy Simulation is employed for turbulence modeling. Blade surface geometric coordinates and flow solutions from the near-body surface grids are extracted at every 0.5 deg azimuth or every two time steps over the last rotor revolution 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 1280 and 640 processors are used for the $\Delta_{\text{finest}} = 5\% C_{\text{tip}}$ and $10\% C_{\text{tip}}$ simulation cases, respectively. Each rotor revolution of the $5\% C_{\text{tip}}$ case takes approximately 28 h, whereas the $10\% C_{\text{tip}}$ case consumes 15 h per rotor revolution.

Prescribed rotor motion

The rotor motions of the current work are simulated based on the trim outputs from the CFD/CSD loose coupling simulations performed by Ventura Diaz et al. (Ref. 7) at the same flight conditions. They used rigid blades, and the same assumption is used in the current paper. They trimmed the total thrust of the two rotors by the rotor collective to balance the vehicle weight. Each rotor is trimmed to have zero flapping by the rotor lateral and longitudinal cyclic pitches. The aircraft propulsive force is trimmed by the aircraft pitch attitude in order to balance the vehicle drag. 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 publication (Ref. 7). The pitch attitudes (α) of the 0%, 5%, 15%, and 25% overlap cases are -2.52 , -2.46 , -2.44 , and -2.46 deg, respectively.

Acoustic simulation setup

PSU-WOPWOP (Refs. 33, 34), an acoustic prediction tool being developed at the Pennsylvania State University, is used for acoustic predic-

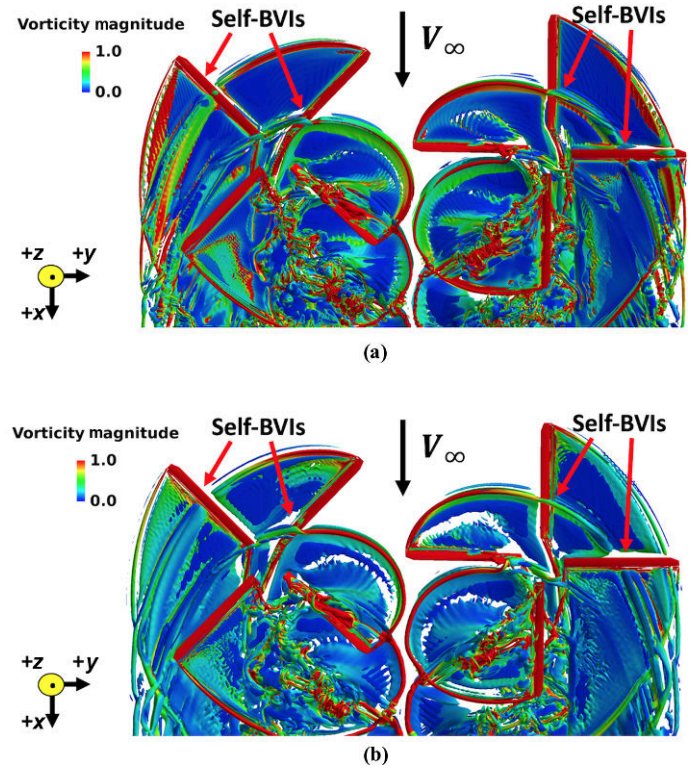


Fig. 4. Iso-surface of a nondimensional q -criterion, $\bar{q}$, colored by the vorticity magnitude for the 0% overlap cases from the top view: (a) the $\Delta_{\text{finest}} = 5\% C_{\text{tip}}$ case; (b) the $\Delta_{\text{finest}} = 10\% C_{\text{tip}}$ case.

tions. PSU-WOPWOP is a numerical implementation of Farassat Formulation 1A (Refs. 35, 36) of the Ffowcs Williams and Hawkins (FW-H) equation (Ref. 37). Farassat Formulation 1A is calculated based on an impermeable surface strategy in the present work, and the quadrupole source term is neglected.

The acoustic simulations in this work are performed on a hemispherical observer grid with a radius equal to $10R$. It will be shown later that this observer location is at an acoustic far-field distance. Fifty grid points are used in the azimuthal or circumferential direction, and 20 grid points are used in the latitudinal direction. The observers move along with the side-by-side rotor.

Results

The side-by-side rotor configurations with 0%, 5%, 15%, and 25% overlaps are simulated in steady forward flight at a speed of 115 kt or 213 km/h at the optimum cruise altitude of 5000 ft (Ref. 7). 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 rotational speed, which is 499 RPM. The advance ratio of each rotor is 0.36. The six simulation cases conducted in this work are marked with crosses in Table 3. The rotor forces and moments of each CFD simulation case converge after approximately five rotor revolutions.

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 4 shows a comparison of the iso-surfaces of a nondimensional q -criterion, $\bar{q}$,

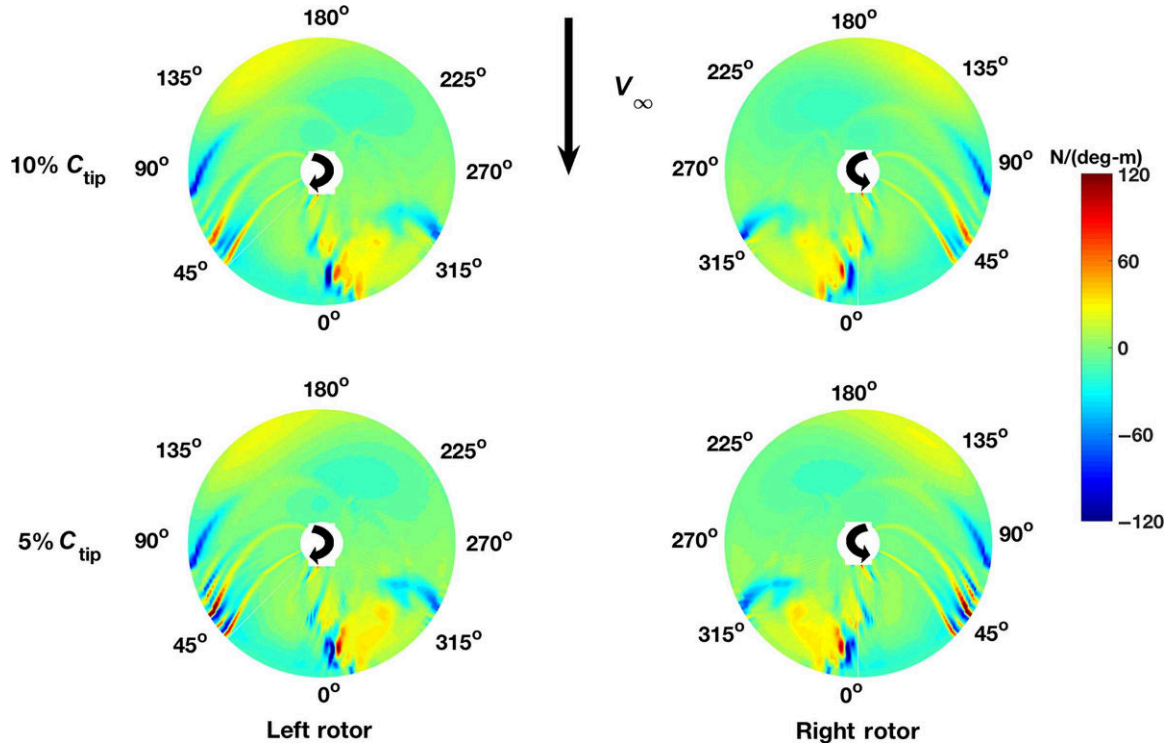


Fig. 5. Comparison of the polar contours of $dF_n/d\Psi$ between the $\Delta_{finest} = 5\% C_{tip}$ and $\Delta_{finest} = 10\% C_{tip}$ cases.

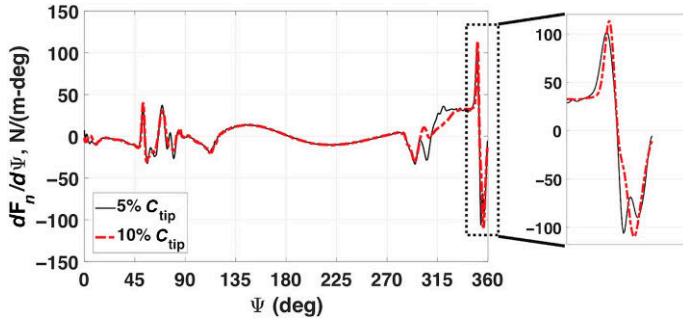


Fig. 6. Comparison of $dF_n/d\Psi$ on the right rotor (CCW) of the 0% overlap configuration at 75% span.

colored by the 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. In Fig. 4, the freestream velocity (V_∞) points in the positive x -direction. Both the 5% C_{tip} and 10% C_{tip} cases predict similar flow patterns, except that the 5% C_{tip} case captures slightly finer wake turbulences and stronger tip vortices (shown in darker red color). Self-BVIs, which imply the aerodynamic interactions between blade tip vortices and blade surfaces of the same rotor in close proximity, can be seen from both left (CW) and right (CCW) rotors in Fig. 4.

Figure 5 shows a comparison of polar contours of the azimuthal derivative of the sectional normal force ($dF_n/d\Psi$), which is a direct source term in the loading noise calculation of Farassat Formulation 1A and an indicator of impulsive aerodynamic interactions, between the 5% C_{tip} and 10% C_{tip} cases for one blade over the last rotor revolution. These polar contours represent the rotor disks from the top view with the freestream direction pointing from top to bottom. The left and right rotors show the symmetrical distributions of $dF_n/d\Psi$. Both the 5% and 10% C_{tip} cases predict (1) the advancing-side self-BVI events in the first quadrant of each rotor; (2) a retreating-side self-BVI event in the

fourth quadrant of each rotor around 300 deg azimuth; (3) the interaction between separated flows and a blade near zero deg azimuth. The last 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 deg 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 $dF_n/d\Psi$ between the 5% C_{tip} and 10% C_{tip} cases is also performed at 75% span on the right rotor (see Fig. 6), 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 deg azimuths are similar between the two cases. Though the 5% C_{tip} case shows a slightly stronger positive self-BVI peak at 300 deg azimuth on the retreating side of each rotor, the overall discrepancy between the two cases is not significant.

The overall sound pressure level (OASPLs) of the 5% C_{tip} and 10% C_{tip} cases for the 0% overlap configuration are simulated on a hemispherical grid with a radius equal to $10R$, and the OASPL comparison is shown in Fig. 7. The contours shown in Fig. 7 represent the hemispherical-grid simulation results from the top view with the freestream direction pointing from top to bottom. The maximum OASPL difference between the 5% C_{tip} and 10% C_{tip} cases is approximately 3 dB, and the noise directivity patterns are almost identical for the two cases. This comparison demonstrates that the 10% C_{tip} case shows the grid convergence solutions for acoustic predictions. Even though not shown in this paper, the 10% C_{tip} case provided the converged acoustic predictions for the 25% overlap case as well.

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 acoustic predictions while saving computational

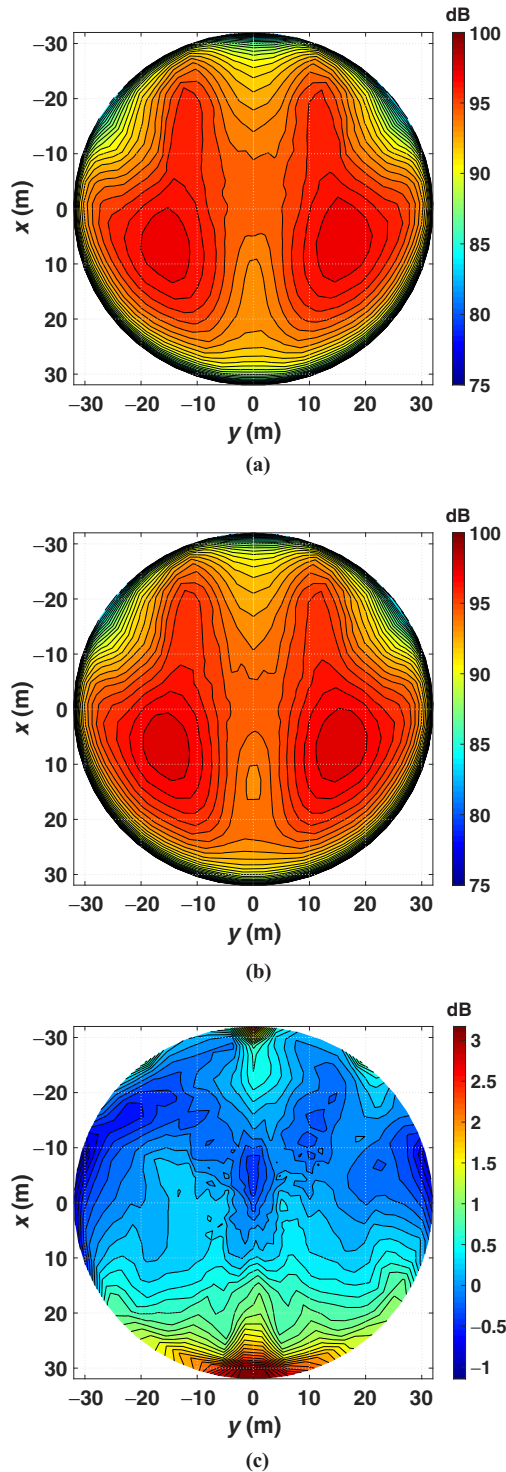


Fig. 7. OASPL comparison of the 0% overlap cases: (a) the 5% C_{tip} case; (b) the 10% C_{tip} case; (c) the difference between the two cases.

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 8 shows a comparison of the iso-surfaces of a nondimensional q-criterion, $\bar{q}$, colored by the vorticity magnitude for the four-rotor overlap cases at the last simulation time step. Self-BVI events can be seen from each rotor in the four overlap cases. However, the 5%, 15%, and 25% cases introduce rotor-to-rotor BVI events, which implies the aerodynamic interactions between the tip vortices of one rotor and

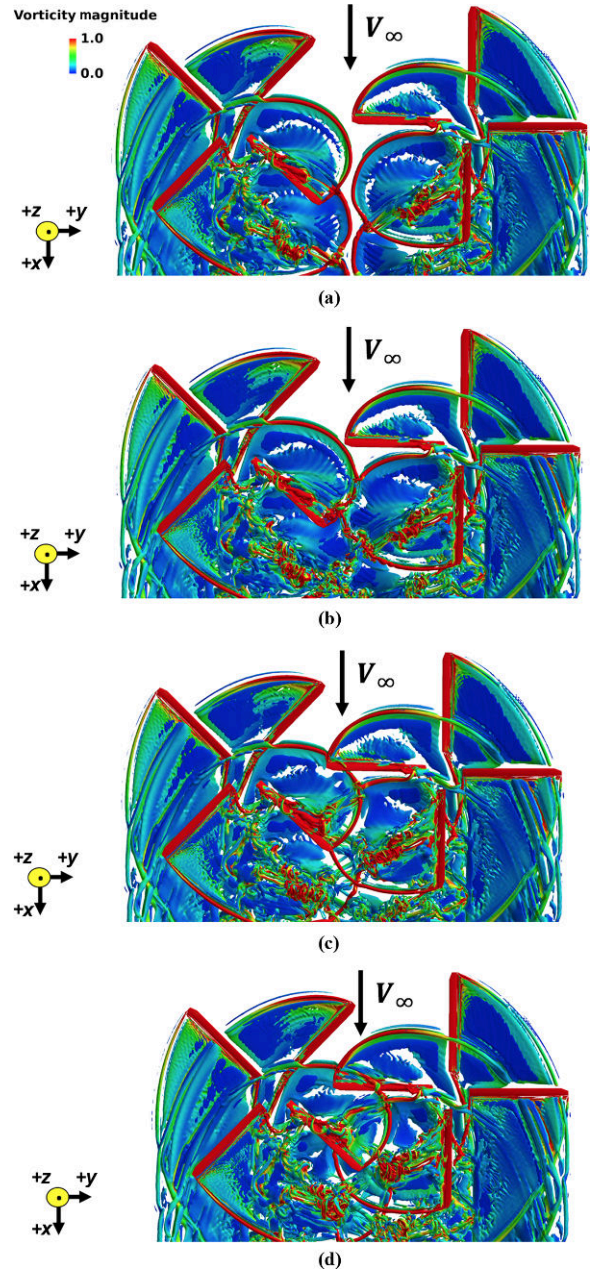


Fig. 8. Iso-surfaces of a nondimensional q-criterion, $\bar{q}$, colored by the vorticity magnitude from the top view for the four overlap cases: (a) 0% overlap; (b) 5% overlap; (c) 15% overlap; (d) 25% overlap.

the blade surfaces of another rotor in close proximity. The rotor-to-rotor BVI event of the 5% overlap case may not be clearly shown in Fig. 8(b), but it becomes visible on the polar contours of the azimuthal derivative of the sectional normal force, which will be discussed in the next paragraph.

Figure 9 shows a comparison of polar contours of the azimuthal derivative of the sectional normal force ($dF_n/d\Psi$), which is an input to the loading noise prediction, on the right rotor for 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 represent the change of $dF_n/d\Psi$ of a single blade over the last rotor revolution. Since the left and right rotors show symmetric distributions of the sectional normal force, only the right rotor results are presented in Fig. 9. The self-BVI events can be seen in the first quadrant in each case, and the strength of these aerodynamic interactions

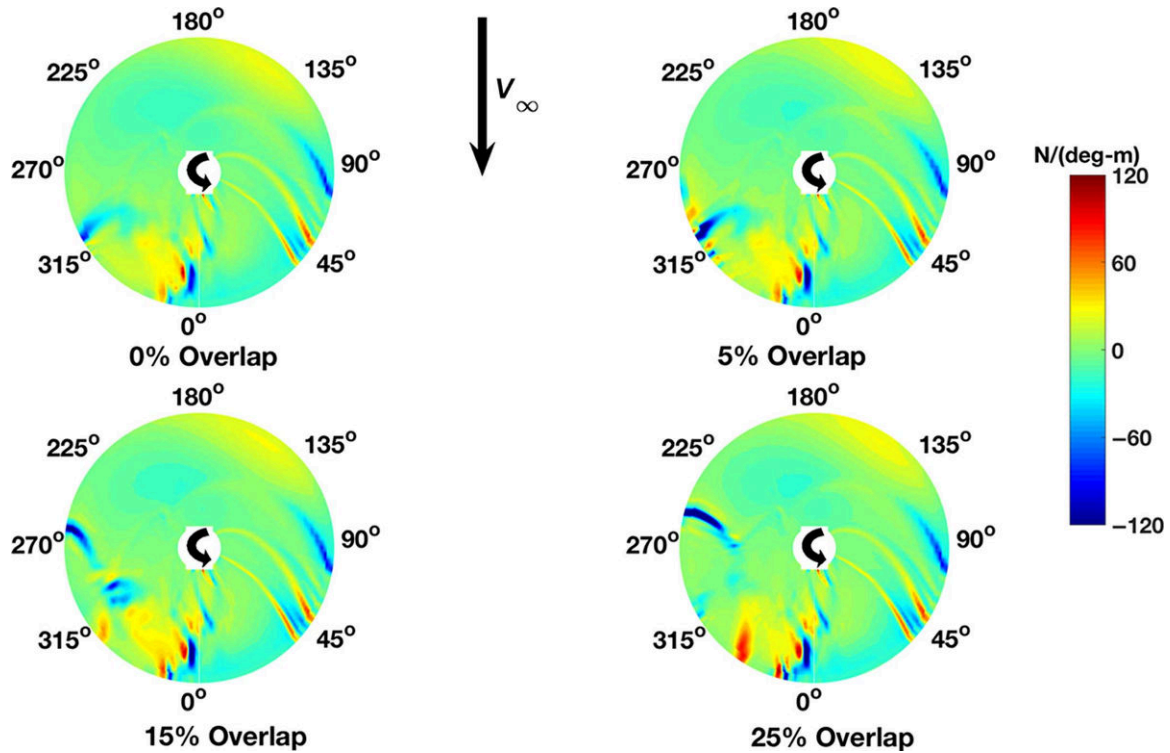


Fig. 9. Comparison of the polar contours of $dF_n/d\Psi$ on the right rotor for the four overlap cases.

is approximately the same since the colors of these self-BVI footprints on the polar contours appear similar. Besides the self-BVI events, rotor-to-rotor BVI events are found in the 5%, 15%, and 25% overlap cases, and these aerodynamic interactions are confirmed with the isosurfaces of $\bar{q}$ in Fig. 8. The rotor-to-rotor BVI events are located near the blade tip: (1) at around 300 deg azimuth in the 5% overlap case; (2) at around 270 and 315 deg azimuths in the 15% overlap case; (3) at around 250 and 345 deg azimuths in the 25% overlap case. The strength of these rotor-to-rotor BVI events is also stronger than that of the self-BVI events since the rotor-to-rotor events are shown in darker red and blue colors. It is expected that these events are loading noise sources of the side-by-side rotor, which would contribute to rotorcraft tonal noise at the blade passage frequency and its higher harmonics. Additionally, the separated flow and blade interactions near zero degrees azimuth are observed in each overlap case. As mentioned before, 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 10 shows a quantitative comparison of $dF_n/d\Psi$ on the right rotor among the four overlap cases at 75% span. Since the left and right rotors show symmetrical distribution of $dF_n/d\Psi$, only the right rotor is analyzed here. The results demonstrate that the magnitude of the self-BVI events located at 50, 70, and 90 deg azimuths are approximately the same, but a large discrepancy in BVI and separated flow and blade interactions are shown on the retreating side of the rotor. In particular, the peak magnitudes of the 25% overlap case are higher than that of the other three cases. The rotor-to-rotor BVI peak magnitude at 250 deg azimuth in the 25% overlap case is 3.2 times higher than the self-BVI peak at 300 deg azimuth magnitude in the 0% overlap case. The zoomed-in results from Fig. 10 show that the separated-flow-induced negative peak near 345 deg azimuth in the 25% overlap case is 64.2% higher in magnitude than that of the 0% overlap case. However, the separated-flow-induced positive peak near 345 deg azimuth in the 25% overlap case is 20.4%

lower in magnitude than that of the 0% overlap case. It is important to mention that these results represent the impulsive loading noise sources without considering the observer location. The far-field acoustic radiation results at a particular observer location could have different relative contributions from the impulsive loading noise sources after taking account of the acoustic radiation distance between the noise sources and the observer as well as the Doppler effect. The relationship between the acoustic source strength and the associated noise of the side-by-side rotor at a virtual observer location is studied in the next subsection.

Effect of rotor overlap on acoustics

After identifying the physical noise sources of the side-by-side rotor, the effect of rotor overlap on rotor acoustics is analyzed and presented in this subsection. The acoustic simulations are performed on a hemispherical grid with a radius equal to $10R$. We have first verified that this

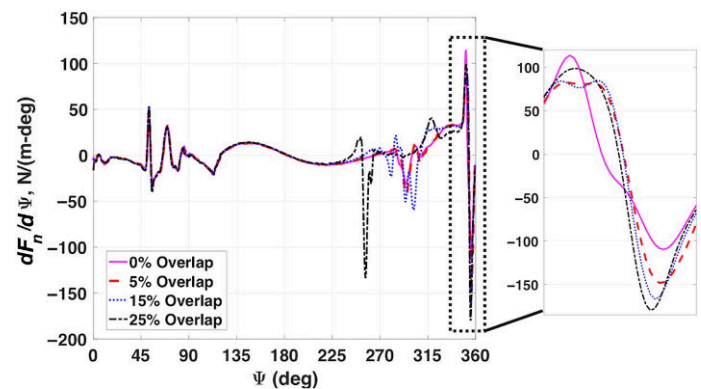


Fig. 10. Comparison of $dF_n/d\Psi$ on the right rotor (CCW) for the four overlap cases at 75% span.

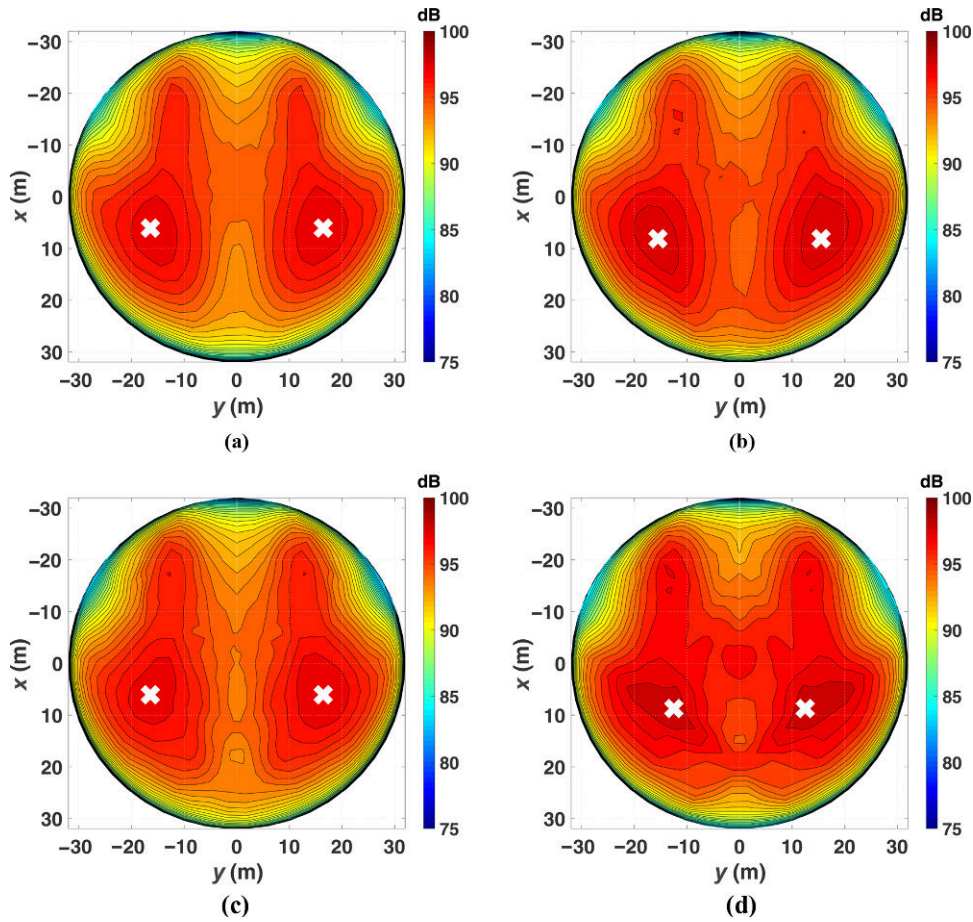


Fig. 12. OASPL comparison for the four overlap cases: (a) 0% overlap ; (b) 5% overlap; (c) 15% overlap; (d) 25% overlap. The white marks represent the maximum noise positions for each overlap case.

observer distance is located in the acoustic far-field. Figure 11 shows the OASPL as a function of normalized observer distances (d/R) below the center of the aircraft for the 0% overlap case with $\Delta_{\text{finest}} = 10\% C_{\text{tip}}$. The near-field ($1/r^2$ pressure decay or 12 dB noise reduction with doubling distance) and far-field ($1/r$ pressure decay or 6 dB noise reduction) trend

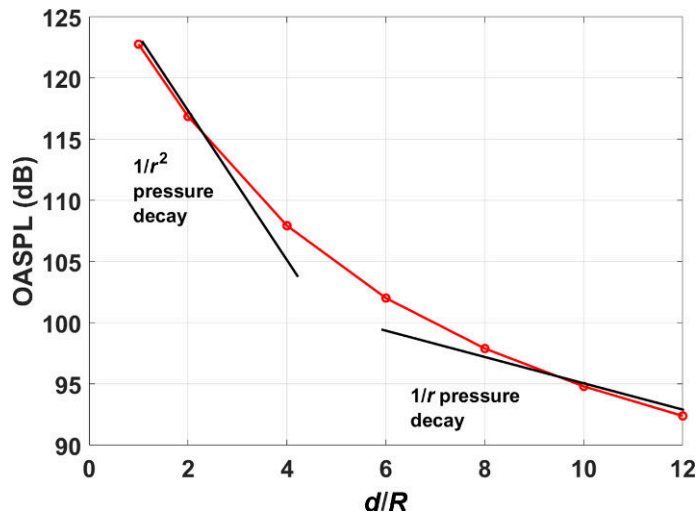


Fig. 11. OASPL variation as a function of the nondimensional observer distance for the 0% overlap case with $\Delta_{\text{finest}} = 10\% C_{\text{tip}}$.

lines are depicted in the graph, as a similar approach to that of Tinney and Siroshi (Ref. 38). It is demonstrated that the chosen observer distance of $10R$ is at a far-field acoustic decay region.

Figure 12 shows the OASPL results for each overlap case, and the minimum and maximum values of the color bar in each overlap case are 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. The maximum OASPLs of the 0%, 5%, 15%, and 25% overlap cases are 97.7, 98.2, 97.5, and 98.5 dB, respectively. The maximum OASPL locations of each overlap case are marked with white crosses in Fig. 12. The four rotor overlap cases show similar maximum OASPLs. The maximum OASPL of the 25% overlap case is about 1 dB higher than that of the 0% overlap case. Note that the maximum noise location is different for each overlap case so that these noise levels were obtained and compared at different observer locations. If the OASPLs are compared at the same location (e.g., the maximum OASPL location of the 25% overlap case), the noise difference could be much larger for the overlap cases, which will be discussed later in this subsection.

In order to investigate the differences in noise radiation pattern, the 0% overlap case is selected as the baseline for OASPL comparison with other overlap cases. According to Fig. 13, the 5%, 15%, and 25% overlap cases are 6.0, 7.2, and 6.6 dB higher than the 0% overlap case near $x = 32.0$ m, $y = 0.0$ m, and $z = 0.0$ m or in the rear region of the hemisphere. The 25% overlap case is also approximately 2 dB higher than the 0% overlap case directly below the center of the side-by-side rotor or at $x = 0.0$ m, $y = 0.0$ m, and $z = -32.0$ m. However, both 15% and 25%

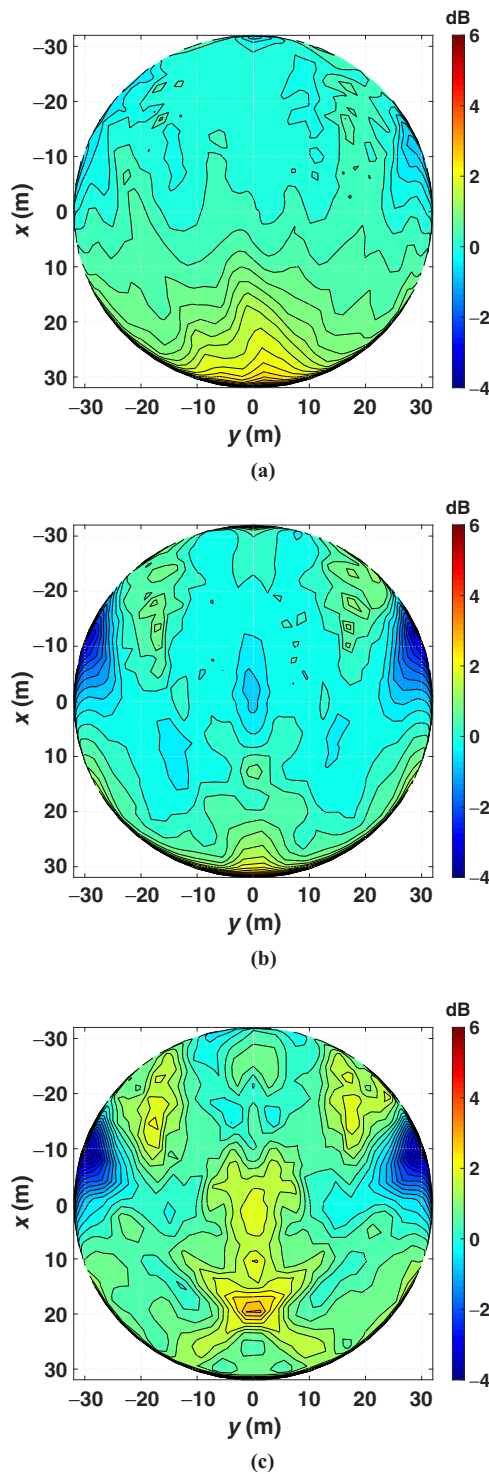


Fig. 13. OASPL comparison for the following overlap cases against the 0% overlap case: (a) 5% overlap; (b) 15% overlap; (c) 25% overlap.

overlap cases show a reduction of OASPL up to 3.7 dB on the sides of the hemisphere. These differences in radiation patterns are due to a combination of the noise source strength and acoustic interference.

A quantitative comparison of the total acoustic pressure as a function of observer time (t) among the four overlap cases is performed (see Fig. 14) at a virtual microphone position ($x = 8.72$ m, $y = -12.48$ m, and

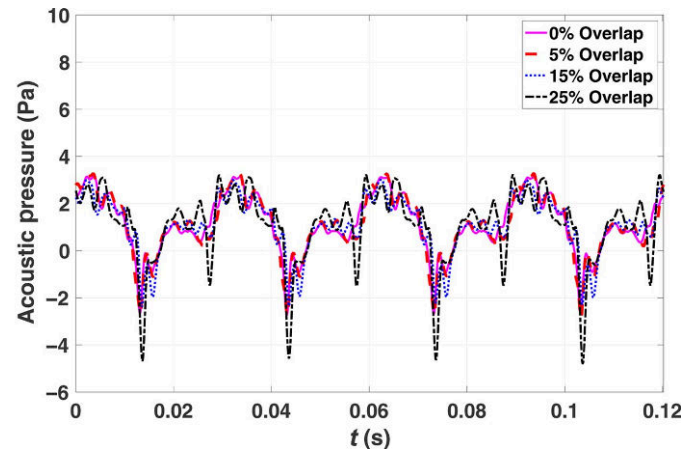


Fig. 14. Comparison of total acoustic pressure between the four overlap cases at the virtual microphone location ($x = 8.72$ m, $y = -12.48$ m, and $z = -28.14$ m).

$z = -28.14$ m), where the maximum OASPL occurs in the 25% overlap case according to Fig. 12. The 25% overlap case shows sharper periodic negative peaks than for the other three cases. At $t = 0.1036$ s, the negative pressure peak of the 25% overlap case is 2.8 Pa higher in magnitude than that of the 0% overlap case.

In order to justify the pressure peak differences and identify the acoustic source locations where the negative peaks occur, the first integrand of the loading noise equation of Farassat Formulation 1A (Ref. 35), which represents the noise source strength at a specific observer location is calculated at each spanwise node for a single blade over the last rotor revolution. This approach was also taken by Sharma et al. (Ref. 39) to analyze the acoustic sources of a coaxial rotor.

The magnitude of the noise integrand is mainly influenced by two factors: the Doppler amplification factor ($1/|1 - M_r|$) and source strength. 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 depends on the magnitude of $\dot{l}_r$, which is directly related to the magnitude of a sudden change of airloads in the acoustic radiation direction.

Figures 15 and 16 represent the noise integrand results for both left and right rotors, respectively, of the four overlap cases. The black solid lines represent the individual blade positions at the designated observer location and time. In each overlap case, the left rotor blades experience sudden loading changes at the given observer time and observer location while the right rotor blades do not. Moreover, 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. Therefore, the major contribution to the negative pressure peak at the given observer time comes from the left rotor.

The key aerodynamic interactions on the left rotor that influence the total acoustic pressure the most are (1) the advancing-side self-BVI events on blade 1 in each overlap case; (2) the separated flow and blade 4 interaction near zero degrees azimuth in each overlap case; (3) the rotor-to-rotor BVI interaction on blade 3 at 250 deg azimuth in the 25% overlap case. The strength of this rotor-to-rotor BVI event is stronger in magnitude (shown in darker blue color) in the 25% overlap case than the rotor-to-rotor BVI events of the other overlap cases. However, the strength of this rotor-to-rotor BVI event in the 25% overlap case is lower than the strength of the separated flow interaction at zero degrees azimuth. The maximum magnitude of the noise integrand contours for the 0%, 5%, 15%, and 25% rotor cases near zero degrees azimuth are approximately 60.0, 56.4, 53.0, and 61.3 Pa/m, respectively. The maximum magnitude of

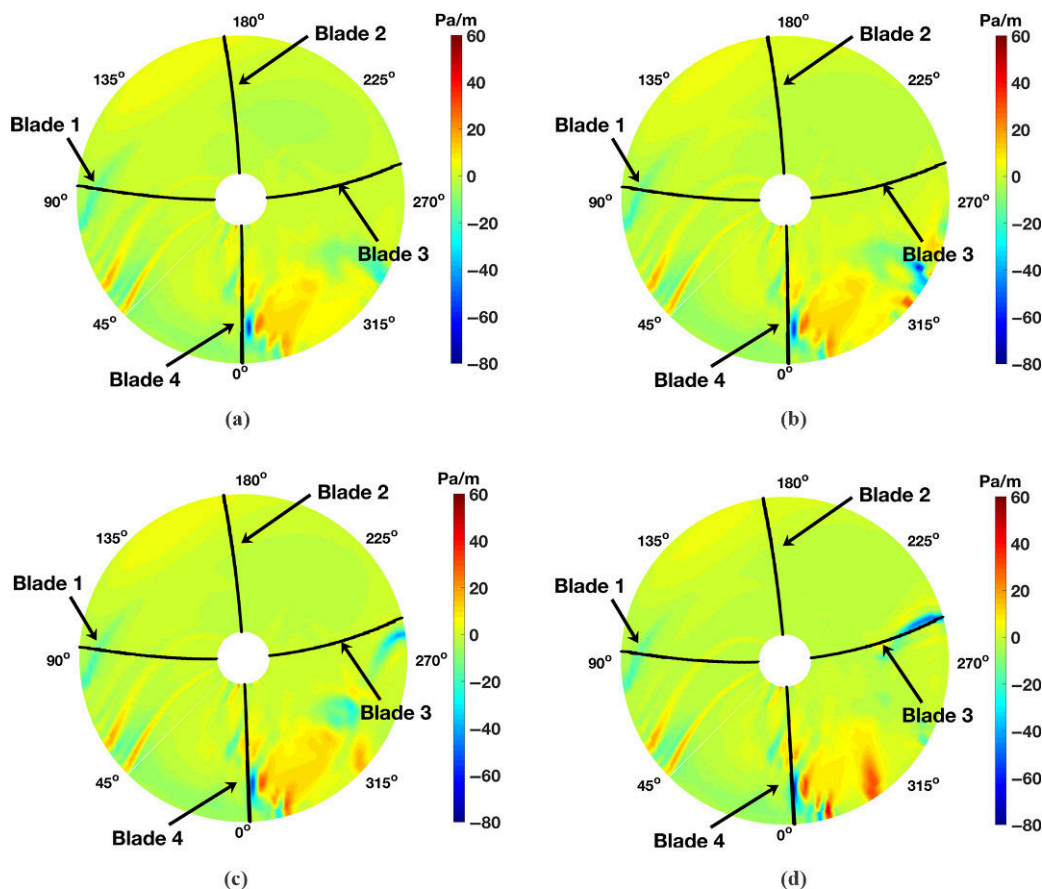


Fig. 15. Comparison of the loading noise integrand results from the left rotor (CW) along with the blade positions at an observer time of 0.1036 sec for the four overlap cases: (a) 0% overlap; (b) 5% overlap; (c) 15% overlap; (d) 25% overlap.

Table 4. 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)
Empty Gross Weight	1,040 kg (2,292 lb)	2,406 kg (5,305 lb)
Maximum Takeoff Weight	1,738 kg (3,831 lb)	4,218 kg (9,300 lb)

the noise integrand contour for the 25% rotor case near 240 deg azimuth (46.0 Pa/m), where the rotor-to-rotor BVI event occurs, is 25.0% lower than that of the separated flow and blade interaction. Since the strength of the separated flow and blade interaction is similar among the four overlap cases and the strength of the rotor-to-rotor BVI event is less than that of the separated flow and blade interactions, the maximum OASPL differences between the four cases are also expected to be small. These noise integrand results show different relative contributions from the impulsive loading noise sources shown in Fig. 10, where the rotor-to-rotor BVI has the largest magnitude of the impulsive loading. The relative importance in impulsive loading noise contributions can be changed depending on the source–observer distance and the Doppler effect.

Acoustic comparison against conventional helicopter noise

In this subsection, the A-weighted sound pressure level (SPL) of the side-by-side rotor with 0% and 25% overlaps is compared against the flight-test data of the Bell 430 (Ref. 40), a conventional helicopter, in two simulation cases: an approaching 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 directly below the vehicle. Although our predictions do not include broadband noise and are free of the ground reflection, the intention of this comparison is to provide a context on how UAM aircraft noise compares with conventional helicopter noise. The aircraft properties and freestream velocities of the

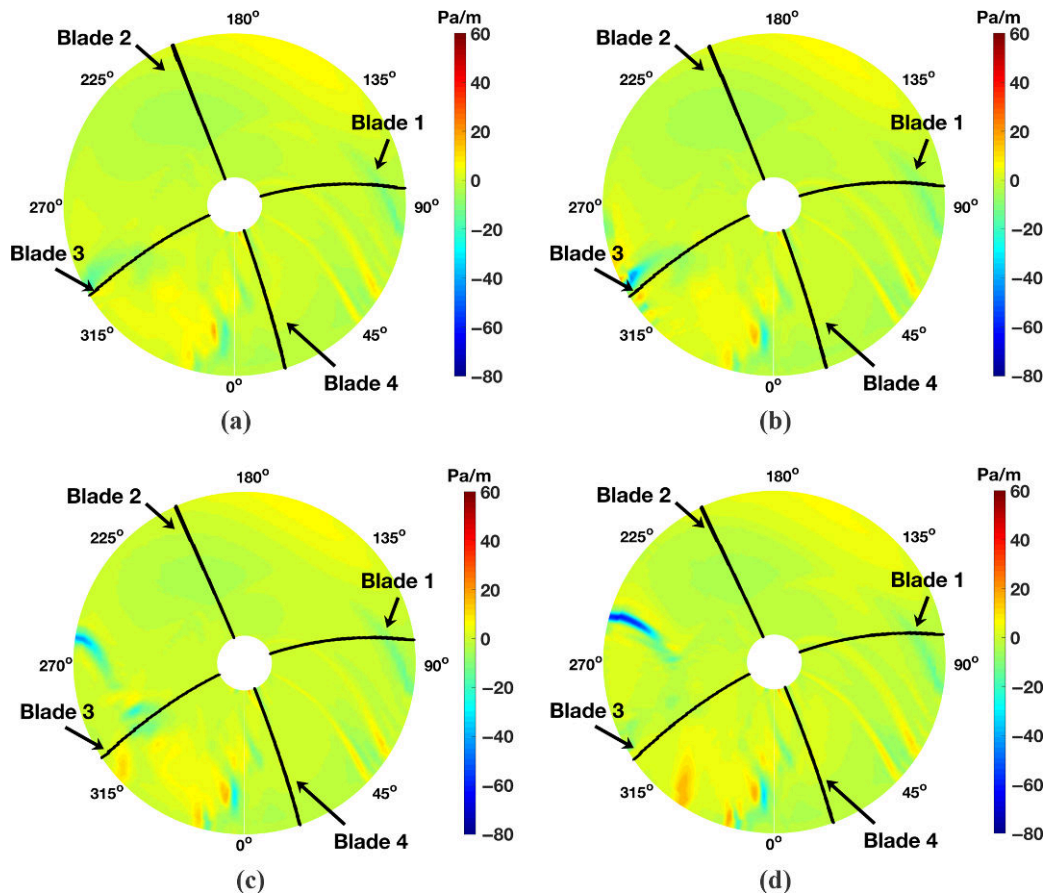


Fig. 16. Comparison of the loading noise integrand results from the right rotor (CCW) along with the blade positions at an observer time of 0.1036 sec for the four overlap cases: (a) 0% overlap; (b) 5% overlap; (c) 15% overlap; (d) 25% overlap.

two vehicles are shown in Table 4. The acoustic results of the side-by-side rotor analyzed in this section are computed based on the CFD simulations with the finest wake-grid spacing equal to 5% C_{tip} .

Figures 17(a) and 17(b) represent comparisons of A-weight SPL for the flyover and overhead cases. The A-weighted SPLs of the side-by-side rotor configurations and the Bell 430 are comparable around 1000 Hz. A comparison of OASPL, which is calculated by integrating the A-weighted SPL spectrum from 100 to 5000 Hz, is shown in Table 5. In the approaching scenario, the OASPL of the Bell 430 is 17.7 and 16.8 dBA higher than the noise levels of the side-by-side rotor with 0% and 25% overlap, respectively. On the other hand, the OASPL of the Bell 430 is 8.1 and 5.9 dBA higher than the noise levels of 0% and 25% overlap configurations, respectively, in the overhead scenario. Based on the OASPL results, the Uber's initial guideline (Ref. 41) of 15 dB quieter than conventional helicopter noise is not met in the overhead scenario. As noted earlier, however, this comparison is not complete. The Bell 430 has an empty weight 131% heavier than the side-by-side rotor; further, its maximum take-off weight is 2.4 times that of the side-by-side rotor. If a helicopter with a similar weight as the side-by-side rotor is used for the comparison, the noise difference would be even smaller so that it would be even more challenging to meet the Uber's guideline. More noise comparisons with other helicopters are suggested in the future to confirm this challenge.

Acoustic comparison against various background noise

A general consensus regarding the public acceptance of UAM aircraft is that the UAM aircraft noise should not exceed background

noises (Ref. 41). In this subsection, the one-third octave band SPLs of the side-by-side rotor with 25% overlap are calculated and compared against the rural, park, community, and freeway background noise levels measured by Begault (Ref. 42) in the San Francisco Bay Area, California. The UAM aircraft could fly in any of these zones, and its noise higher than the background noises could disturb the local communities. In this study, 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), 1000 ft (305 m), and 1500 ft (457 m).

Figure 18 shows the A-weighted one-third octave band SPL and OASPL comparisons between the side-by-side rotor noise and various background noises. According to Fig. 18(a), the side-by-side rotor noise level slightly exceeds the freeway noise level even at an altitude of 1500 ft around 500 Hz. The noise risk is more evident at lower altitudes in a wider frequency range. Although the high-frequency contents at a frequency greater than 2000 Hz are completely masked by the freeway and community noise, the current calculation does not consider the broadband component of rotor noise (see Ref. 14). The UAM aircraft noise could also become louder when multiple aircraft operate simultaneously. Additionally, Fig. 18(b) shows that the OASPL of the side-by-side rotor is 3.3 and 12.0 dBA higher than the freeway and community noises at an altitude of 250 ft, respectively. The OASPL of the side-by-side rotor also exceeds Uber's limitation of 62 dBA at 500 ft (Ref. 41). Overall, noise reduction technology as well as noise abatement operational procedures should be developed in order to accommodate the public acceptance of quiet UAM operations.

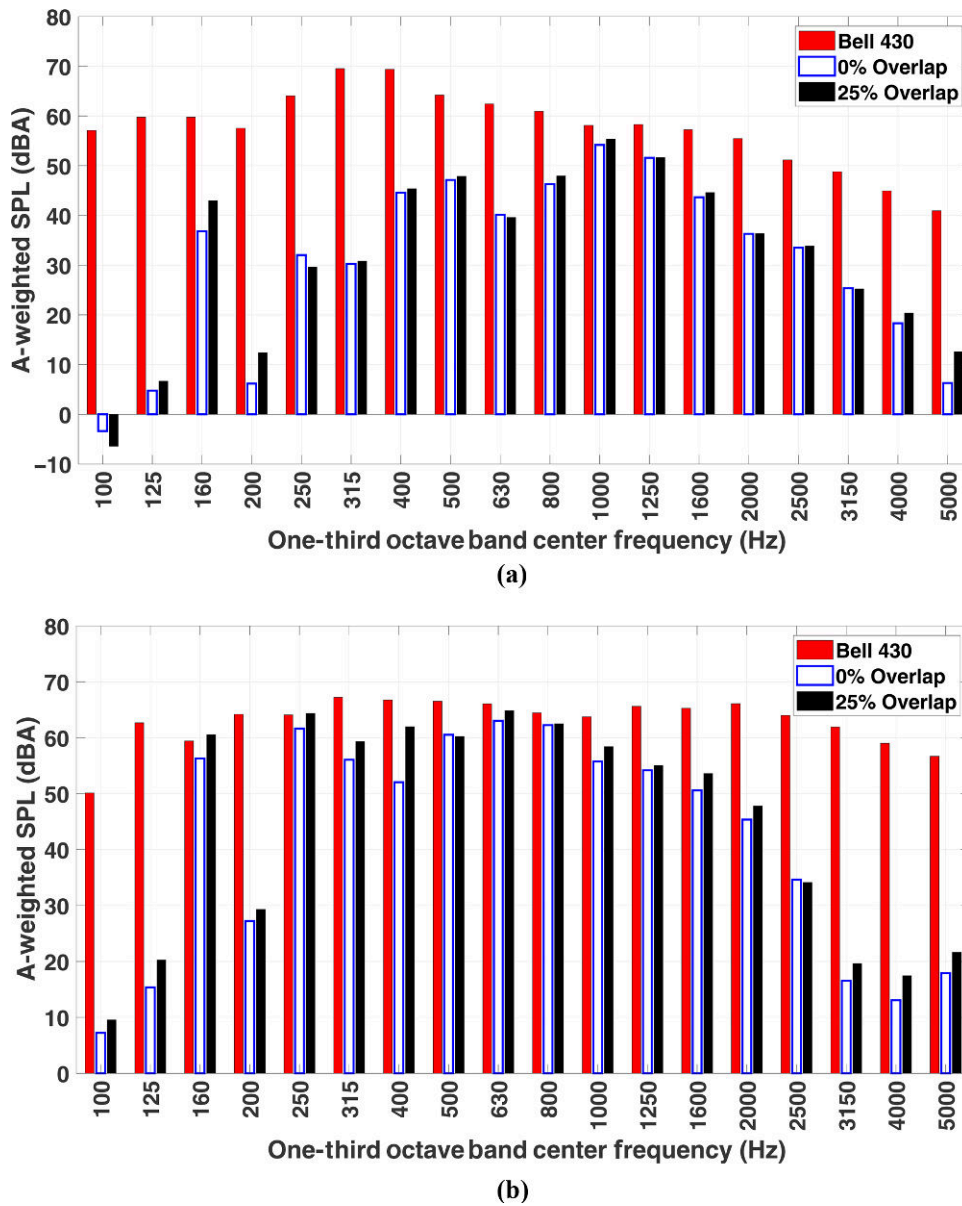


Fig. 17. Noise comparison between the side-by-side rotor and the Bell 430 in two flight scenarios: (a) approaching case; (b) overhead case.

Table 5. A comparison of OASPL.

OASPL	0% Overlap	25% Overlap	Bell 430
Approach	57.6 dBA	58.5 dBA	75.3 dBA
Overhead	69.1 dBA	71.3 dBA	77.2 dBA

Conclusions

High-fidelity CFD simulations were carried out to study the acoustic characteristics of NASA's six passengers side-by-side rotor with 0%, 5%, 15%, and 25% overlap in steady forward flight at a freestream velocity of 115 kt using the high-fidelity rotorcraft simulation software suite CREATETM-AV Helios. The acoustic simulations were carried out using the acoustic prediction tool PSU-WOPWOP based on an impermeable surface approach and a hemispherical grid with a radius equal to 10R. The effect of the finest wake-grid spacing on the acoustic predictions of the side-by-side rotor was first analyzed. The physical noise

sources of the side-by-side rotor were identified based on high-fidelity CFD simulations and noise integrand analyses. 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 strength of the acoustic sources and the resulting noise was explored for each overlap case. Comparisons between the side-by-side rotor noise, the noise of a conventional helicopter, and various background noises were also performed in order to assess UAM vehicle noise emissions in the perspective of public acceptance and annoyance. The following conclusions were drawn based on the results presented and analyzed in this paper:

- (1) A finest wake-grid spacing of 10% C_{tip} is good enough for the acoustic predictions of the side-by-side rotor in steady forward flight in comparison with the 5% C_{tip} case.
- (2) BVI events, particularly the rotor-to-rotor BVI events, and separated flow and blade interactions are the most dominant noise sources of the side-by-side rotor.

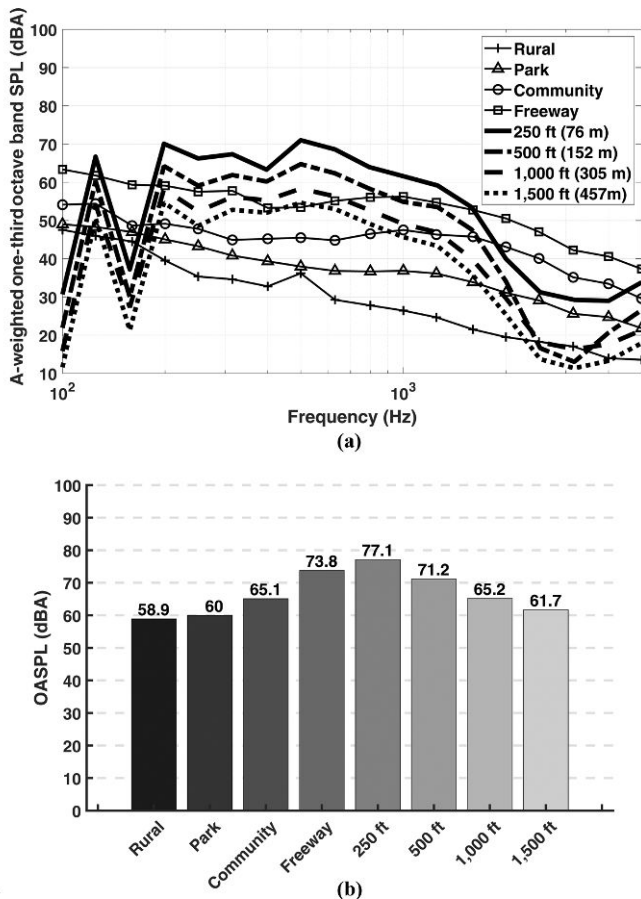


Fig. 18. Background noise comparison for the 25% overlap case: (a) comparison of A-weighted one-third octave band SPL; (b) comparison of OASPL.

(3) The 0%, 5%, 15%, and 25% overlap cases show similar maximum OASPLs. However, the noise radiation patterns of the four cases are different. The 15% and 25% overlap cases show higher OASPL in the rear region and the region directly below the side-by-side rotor.

(4) The A-weighted SPL of the side-by-side rotor is comparable with the noise of a conventional helicopter in both overhead and approaching scenarios.

(5) The noise of the side-by-side rotor with 25% rotor overlap could not be completely masked by the freeway noise even at an altitude of 1500 ft or 457 m. The UAM noise impact is much more severe in other places considering their lower background noise levels. In addition, the noise level exceeds Uber's UAM noise guideline of 62 dBA at 500 ft. Moreover, the high-frequency broadband noise was not incorporated in the current noise calculation, which implies that the actual noise level of the side-by-side rotor could become higher than the noise levels shown in this study. The noise level is also expected to increase when multiple vehicles operate simultaneously, and, therefore, noise source reduction and trajectory optimization with a goal to reduce UAM vehicle noise and increase the public acceptance should be pursued in the future.

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