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Journal

Proceedings of the Vertical Flight Society 74th Annual Forum and Technology Display

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Publication Date

2018-05-14

DOI

10.4050/f-0074-2018-12663

Aeroacoustic Analysis of a Lift-Offset Coaxial Rotor Using High-Fidelity CFD-CSD Loose Coupling Simulation

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ABSTRACT

This paper presents the investigation of acoustics of a lift-offset coaxial rotor in high-speed steady forward flight using high-fidelity Computational Fluid Dynamics (CFD) and Computational Structural Dynamics (CSD) loose coupling tools — Helios and RCAS. Acoustics of the lift-offset coaxial rotor is simulated using the acoustic prediction tool PSU-WOPWOP at eight chosen microphones positioned below the rotor plane. Three forward flight speeds at 100, 150, and 200 knots are selected to investigate the effect of lift-offset, flight speed, and separation distance on acoustics of the coaxial rotor. The total power of the three speed cases is validated against flight test data and shows good agreement. Strong blade-crossover interactions and self-BVI signatures of the coaxial rotor, which are sources of loading noise, have been captured in details via high-fidelity CFD simulations across all speed cases. It has been demonstrated that the magnitude of sound pressure level increases significantly with increasing flight speed and lift-offset. The strength of blade-vortex interaction sound pressure level (BVISPL) appears to decrease dramatically with increasing separation distance at 100 knots. However, higher speed cases do not show a significant reduction in BVISPL with increasing separation distance. Overall, this research study presents noteworthy and novel findings on acoustics of a lift-offset coaxial rotor.

INTRODUCTION

A high-speed capability is an important design requirement for military rotorcraft. In 1970s, the Sikorsky Aircraft Corporation applied the Advancing Blade Concept — also known as the lift-offset strategy — to a compound coaxial helicopter XH-59A (see Fig. 1) with auxiliary thrust engines, and demonstrated that it can achieve a cruise speed around 260 knots: faster than any other helicopter during that time (Ref. 1). A conventional helicopter often encounters dynamic stall problems on the retreating side of the rotor disk during high-speed steady forward flight, and the advancing side is not allowed to produce additional lift due to trim constraints. Therefore, the Advancing Blade Concept was implemented in the design of the XH-59A to fully exploit the lift potential of a coaxial configuration and to minimize the dynamic stall problem, so that the high-speed forward flight

performance of the vehicle can be improved. Each rotor with lift-offset will generate higher integrated lift on the advancing side of the rotor disk, and carry an individual rolling moment of opposite direction and equal magnitude. The combination of the individual rolling moments would sum to zero. The mathematical expression of lift-offset (L.O.) is given below:

$$L.O. = \frac{\Delta M_x}{T \cdot R} \quad (1)$$

where ΔM_x is the differential rolling moment between the upper and lower rotors, T is the total thrust, and R is the rotor radius. The legacy of the XH-59A program later aided the Sikorsky Aircraft Corporation to further improve its lift-offset coaxial models. The company introduced X2 Technology™ Demonstrator (see Fig. 2) and S-97 (see Fig. 3) Raider in 2000s and 2010s respectively. Advantages of a lift-offset coaxial design have been explored by various researchers from industry, government, and academia.

In 2009, Johnson (Ref. 2) used the rotorcraft comprehensive analysis software CAMRAD II (Ref. 3) to show that a coaxial

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Fig. 1: Sikorsky XH-59A.



Fig. 2: Sikorsky X-2.



Fig. 3: Sikorsky S-97 Raider.



Fig. 4: Conceptual drawing of SB>1 Defiant.

configuration with a lift-offset value around 0.25 can minimize rotor-induced and profile power. Afterward Johnson and Yeo (Ref. 4) continued the research on flight performance of a lift-offset configuration and demonstrated that the maximum lift capacity of a coaxial rotor can be improved with increasing lift-offset. Jacobellis et al. (Ref. 5) pointed out that the power requirement can be reduced by 17% during high-speed cruise with optimized trim settings for a notional XH-59A model. Due to recent studies on the lift-offset coaxial configuration, the Joint Multi-Role Rotorcraft (JMR) Technology Demonstrator program currently considers lift-offset coaxial designs for the next-generation military rotorcraft (see Fig. 4).

Though lift-offset coaxial rotors could attain relatively satisfying high-speed forward flight performance, they have a potential risk of producing impulsive noise due to aerodynamic interactions. The blade-vortex interaction (BVI) where a blade trailing vortex passes by an aft rotor blade in close distance could induce significant external noise. For a compound coaxial helicopter such as the XH-59A, where the rotor shaft does not need to be tilted to provide propulsive force due to the forward thrust provided by auxiliary engines, self-BVI, which means the interaction between rotor tip vortex and the blades of the same rotor, might occur at all forward speeds and increase the severity of impulsive noise. Kim and Brown (Ref. 6) discovered that rotor-to-rotor BVIs of a two-bladed lift-offset coaxial configuration, where trailing vortices from the upper rotor interact with the lower rotor, could be an intensive acoustic source. Rotor-to-rotor BVIs become greatest when trailing vortices aligned approximately parallel to a blade, and smallest when positioned obliquely against a blade. Walsh et al. (Ref. 7) also analyzed a lift-offset coaxial configuration based on XH-59A properties using the Rotorcraft Comprehensive Analysis System (RCAS) (Ref. 8) software, and identified highly impulsive acoustic signals. In 2016, Barbely et al. (Ref. 9) performed research on a two-bladed coaxial model without lift-offset and observed abrupt changes of pressure caused by blade-crossover events. She speculated that this source could trigger impulsive acoustic noise.

Results from these aeroacoustic studies, however, are limited to low-fidelity simulation models. Neither Barbely et al. nor Kim and Brown have considered a modern three- or four-bladed lift-offset coaxial rotor for their studies. To the best of authors' knowledge, none has used first-principled and high-fidelity CFD-CSD coupling to predict lift-offset rotorcraft acoustics. In this paper, the acoustic impulsiveness of a three-bladed coaxial rotor is investigated using high-fidelity CFD-CSD loose coupling simulation. Parametric studies are also performed to demonstrate the influence of physical parameters — forward flight speed, lift-offset, and rotor-to-rotor separation distance — on acoustics of a lift-offset coaxial rotor.

METHOD

In order to perform the research, a three-bladed lift-offset coaxial model of the XH-59A was chosen and developed using a publicly available technical report (Ref. 10). The basic properties of the XH-59A are listed in Table 1. Since the airfoil data of the XH-59A are not publicly available, airfoils similar to the actual airfoils were used: NACA-0026 was used for the rotor radius $R < 0.418$; NACA-63216 was used for $0.418 \leq R \leq 0.678$; NACA-23012 was used for $R > 0.678$. Blade Chord, thickness, and twist distributions are displayed in Figs. 5, 6, and 7.

Table 1: Basic Properties of the XH-59A.

Aircraft Length	41.67 ft (12.7 m)
Aircraft Height	8 ft (2.4 m)
Rotor Radius	18 ft (5.5 m)
Number of Rotors	2
Blades per Rotor	3
Vertical Separation Distance	2.5 ft (0.76 m)
Shaft Tilt Angle	0 deg
Nominal Rotor Speed	345 RPM
Nominal Rotor Tip Speed	650 ft/sec (198 m/sec)
Gross Weight	11,900 lb (5,398 kg)
Power Plants (Lift)	Two PT6-3
Power Plants (Thrust)	Two J60-P3A

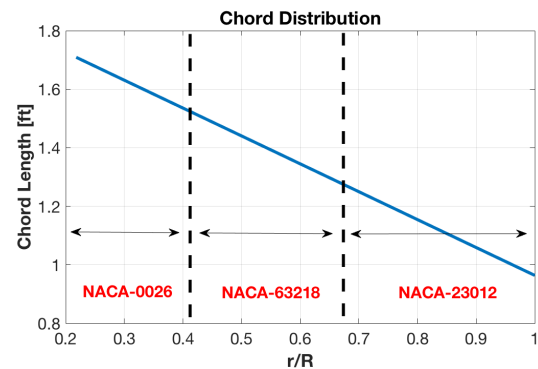


Fig. 5: Blade chord distribution.

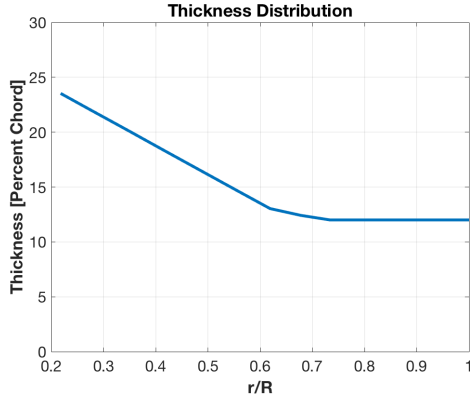


Fig. 6: Blade thickness distribution.

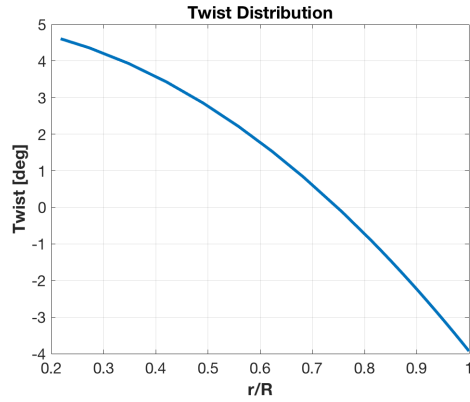


Fig. 7: Blade twist distribution.

CFD Mesh

The dual mesh methodology, dividing the entire mesh into near-body and Cartesian meshes, was implemented for CFD simulation. NASA's structured grid generation tool OVERGRID (Ref. 11) compatible with Chimera Grid tool (Ref. 12) is used for the generation of near-body meshes based on O-grid topology (see Fig. 8). Each blade is composed of three components: main blade, blade root, and blade tip. The dimensions of the main blade are 267 points (chordwise direction) x 189 points (spanwise direction) x 65 points (normal direction) with leading and trailing edge spacings equal to $0.05\% C_{tip}$ and $0.02\% C_{tip}$ respectively where C_{tip} is the chord length at blade tip. The dimensions of the root- and tip-cap grids are 118 points x 121 points x 65 points and 109 points x 103 points x 65 points respectively. The initial and end spacings in the normal direction of the volume grids are $5.0 \times 10^{-4}\% C_{tip}$ and $10\% C_{tip}$ for a dimensionless wall distance $y^+ = 1.0$, leading to approximately 5 million grid points per blade and 30 million grid points for six blades.

The off-body Cartesian mesh (see Fig. 9) is automatically constructed by the adaptive off-body Cartesian solver SAMARC (Refs. 13–15) in Helios (Refs. 16, 17), a high-fidelity 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. Eight levels of Adaptive Mesh Refinement (AMR) are used after the first rotor revolution in order to resolve rotor wake in the far-field. A small fixed refinement box enclosed the two rotors is specified in addition to AMR as a common practice to better capture near-body flow physics. The dimensions of the AMR and fixed refinement boundaries are specified in the following tables:

Table 2: Adaptive Mesh Refinement (AMR) Domain in Terms of Rotor Radius R ($R = 5.5$ m)

Direction	Lower Limit (R)	Upper Limit (R)
x	-1.25	3.50
y	-1.25	1.25
z	-1.25	1.25

Table 3: Boundaries of the Fixed Refinement Box in Terms of Rotor Radius R ($R = 5.5$ m)

Direction	Lower Limit (R)	Upper Limit (R)
x	-1.25	1.25
y	-1.25	1.25
z	-0.26	0.26

The dimensions of the Cartesian mesh are 20 radii away from the origin in each direction with the finest off-body spacing equal to $10\% C_{tip}$. The total amount of off-body Cartesian grid points is approximately 76 million at the first time step, and rises to around 130 million after the convergence of simulation results. Neither a fuselage nor rotor hubs are included in the CFD model.

CFD-CSD Loose Coupling Simulation Setup

The CFD-CSD loose coupling simulation is achieved using the software RCAS and flow solvers (OVERFLOW and SAMARC) of Helios. In the first place, the coaxial configuration is trimmed based on six control variables — pilot collective, differential pilot collective, pilot lateral cyclic, differential pilot lateral cyclic, pilot longitudinal cyclic, and differential pilot longitudinal cyclic — for high-speed steady forward flight at an altitude of 3,000 ft. Details about these control inputs can be found in the report (Ref. 10). The shaft angle of attack is fixed at zero degrees when the auxiliary propulsion mode of the XH59-A is considered. The force equilibrium in the x-direction is achieved by summing rotor drag, fuselage drag, and forward thrust produced by auxiliary engines. Further, the desired lift-offset value of the coaxial configuration as described in Eq. 1 is accomplished by trimming the vehicle to a required differential rolling moment (M_x) and rotor thrust (T).

OVERFLOW (Refs. 18, 19) and SAMARC of Helios are then used to compute near- and off-body flow fields. A fifth-order spatial scheme and a second-order temporal scheme are used for time-accurate CFD simulations in both near- and off-body.

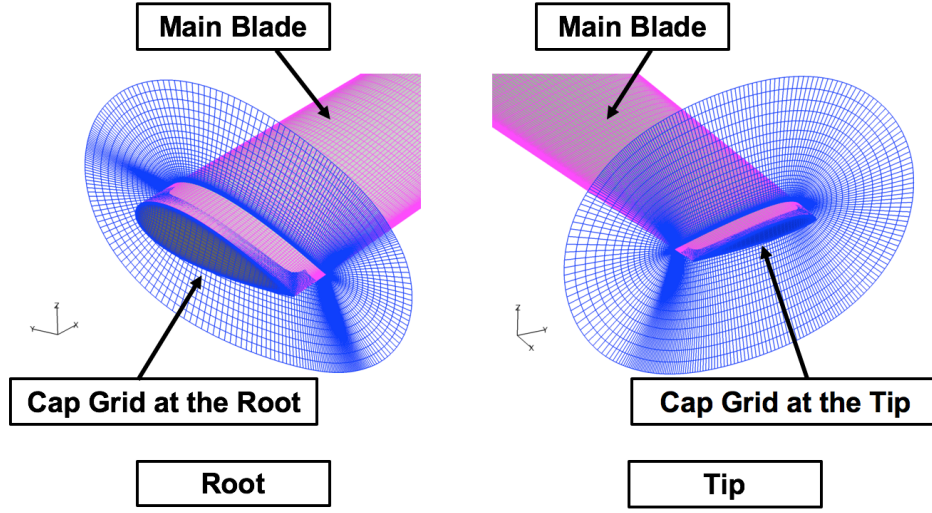


Fig. 8: The near-body mesh.

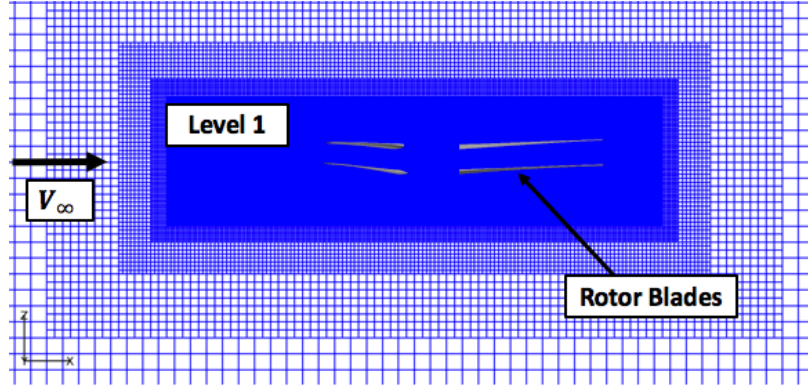


Fig. 9: The Cartesian mesh.

A dual-time-stepping method is implemented for the numerical approach with 20 time steps in the near-body calculation and 10 time steps in the off-body calculation. The detached eddy simulation (Ref. 21) coupled with the Spalart-Allmaras RANS turbulence model (Ref. 20) (SA-DES) is employed for turbulence modeling. In the interest of BVI prediction, a time step size equal to 0.25 degrees azimuth yielding 1440 time steps per rotor revolution is used throughout the research.

The frequency of the loose coupling simulation is set to every 180 degrees azimuth after the first rotor revolution. Blade surface flow solutions and deformed geometries are extracted at every two time steps (0.5°) over the last rotor revolution for acoustic analysis. A detailed description about CFD-CSD loose coupling can be found in the work written by Potsdam et al. (Ref. 22).

Acoustic Simulation Setup

PSU-WOPWOP (Refs. 23, 24), the acoustic simulation software developed at the Pennsylvania State University, is used

to predict far-field noise in this work. PSU-WOPWOP is a numerical implementation of Farassat's Formulation 1A (Refs. 25, 26) of the Ffowcs Williams and Hawkings equation (Ref. 27). PSU-WOPWOP has very general capabilities and can accept input data of varying fidelities. The equations of Farassat's Formulation 1A are displayed below:

$$p'(\vec{x}, t) = p'_T(\vec{x}, t) + p'_L(\vec{x}, t) \quad (2)$$

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

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

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 respectively the speed of sound and fluid density in the undisturbed medium; r is the distance between the source position $\vec{y}$ and the observer position $\vec{x}$; v_n is the normal component of fluid velocity on the blade surface; M_r is the Mach number 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 emission time or retarded time. All above quantities within the brackets of Farassat's Formulation 1A (in Eq. 3 and Eq. 4) are evaluated at the retarded time which is denoted by the subscript *ret*. Additionally, Farassat's Formulation 1A is calculated using the impermeable surface strategy, and quadrupole source is neglected.

Before discussing results computed by Farassat's Formulation 1A in PSU-WOPWOP, it is beneficial to understand the key terms and quantities in Eq. 3 and Eq. 4. In Farassat's Formulation 1A, the term $|1 - M_r|$ is the Doppler factor and can be computed by taking the dot product between the Mach number vector, $\vec{M}$, and the unit vector in the radiation direction, $\hat{r}$, i.e., $|1 - M_r| = |1 - \vec{M} \cdot \hat{r}|$. It is dependent on both the blade and observer positions. A small value of $|1 - M_r|$ will yield strong amplification of acoustic source. Furthermore, the quantity $\dot{l}_r$ of the first integral in Eq. 4 induced by impulsive aerodynamic interactions such as BVI could contribute significant acoustic source to loading noise prediction. A combination of large $\dot{l}_r$ and small $|1 - M_r|$ could produce intensive acoustic pressure signal, and vice versa. In comparison to the first integral in Eq. 4, the second and third integrals are generally small in magnitude because of r^2 in the denominators. These two integrals are often considered as near-field terms, and are only important in near-field acoustic prediction.

Microphone Positions

Eight microphones, each with a distance equal to approximately 5 rotor radii from the mid point between the upper and lower rotor hubs, are used to characterize acoustic impulsiveness of the lift-offset coaxial rotor. The eight microphones are surrounded in a circle with one rotor radius below the mid-point of the two hubs, and their positions are recorded in Table 4 in terms of the rotor radius (R) which is equal to 5.49 m. Two schematic diagrams indicating the microphone positions are illustrated in Figs. 10 and 11.

RESULTS

Three forward flight speeds (100, 150, and 200 knots) were selected for simulation and analysis. Information regarding the free-stream Mach number (M_∞), advancing-tip Mach number (M_{AT}), advance ratio (μ), and rotation rate (Ω) of the coaxial rotor at different flight conditions is displayed in Table 5. M_{AT} at 200 knots was kept the same as M_{AT} at 150

Table 4: Microphone Locations (referenced from the mid point of the two rotor hubs).

Microphone Number	Position (x,y,z), R (R= 5.49 m)
1	(-5.00, 0.00, -1.00)
2	(-3.54, -3.54, -1.00)
3	(0.00, -5.00, -1.00)
4	(3.54, -3.54, -1.00)
5	(5.00, 0.00, -1.00)
6	(3.54, 3.54, -1.00)
7	(0.00, 5.00, -1.00)
8	(-3.45, 3.45, -1.00)

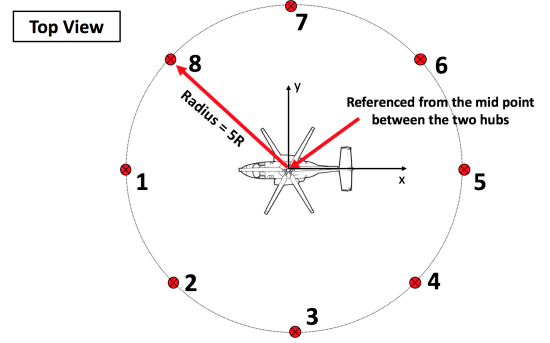


Fig. 10: Top view of the microphone positions (not drawn to scale).

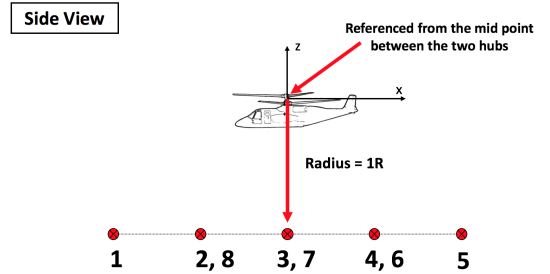


Fig. 11: Side view of the microphone positions (not drawn to scale).

knots by reducing the rotation rate to avoid highly nonlinear physics such as delocalization, which would not be well modeled with the impermeable surface approach. All simulations were performed at an altitude of 3,000 ft, and converged after 11 loose coupling iterations without intensive oscillatory behaviors. Figures 12 and 13 represent a sample convergence history of non-dimensional airloads for the 150 knots case with lift-offset equal to 0.2 at 75% span of the rotor blades.

Table 5: Flight conditions at 100, 150, and 200 knots.

Speed (knots)	M_∞	M_{AT}	μ	Ω (RPM)
100	0.15	0.74	0.26	345
150	0.23	0.82	0.39	345
200	0.30	0.82	0.59	300

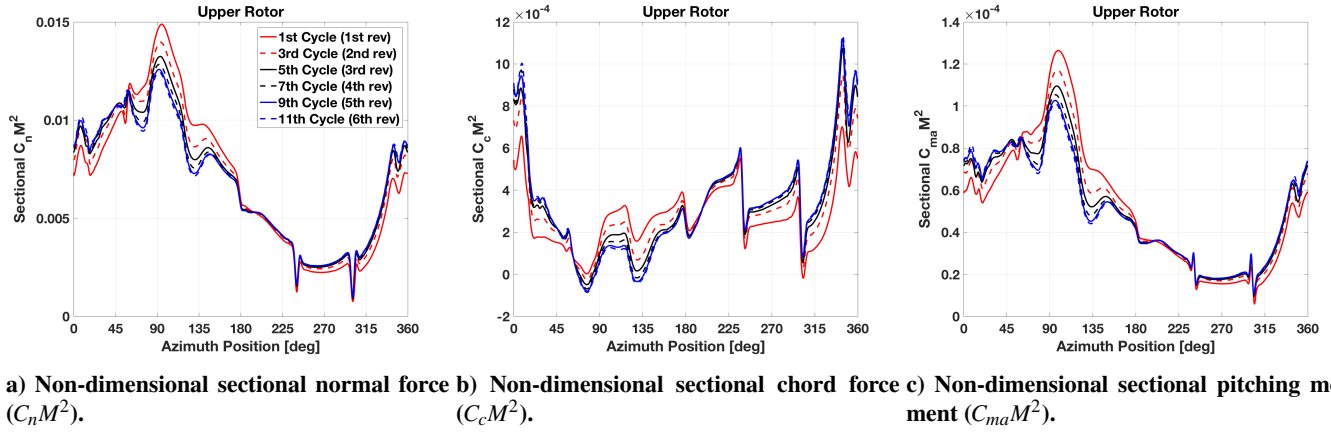


Fig. 12: Convergence history of non-dimensional sectional airloads at 75% span of the upper rotor.

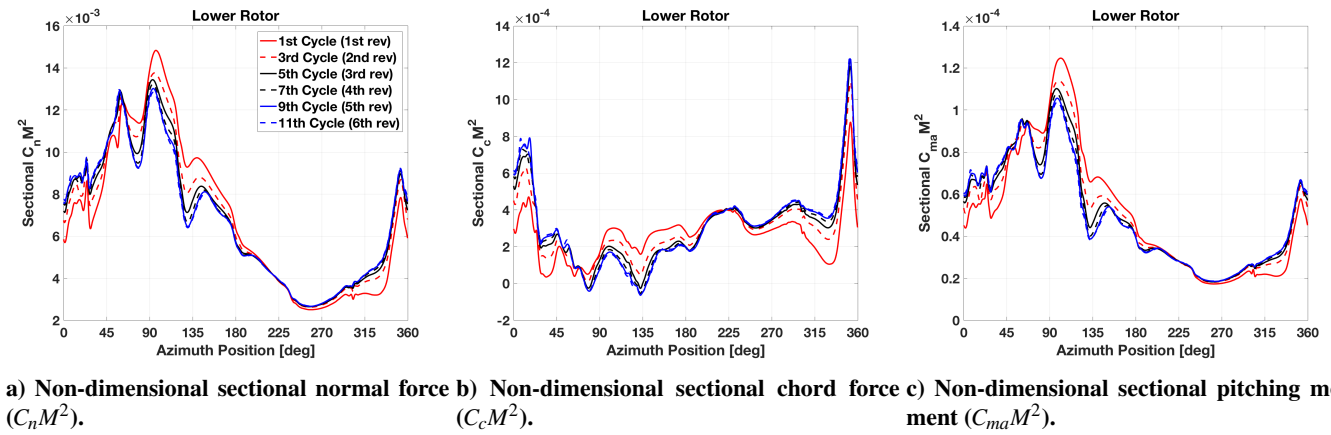


Fig. 13: Convergence history of non-dimensional sectional airloads at 75% span of the lower rotor.

Total Power Validation

Figure 14 shows the total power comparison between simulation results and available flight test data (Ref. 10). Since the lift-offset values of flight test data were not documented, lift-offset equal to 0.2 was chosen for power validation. It was also assumed that the jet propulsion power can be estimated based on a propeller propulsive efficiency (η). Johnson (Ref. 2) calculated the auxiliary propulsion power of a heavy-lift coaxial rotorcraft based on the same assumption with $\eta = 0.9$. Jacobellis et al. (Ref. 5) also followed the same assumption to compute the total power of a notional XH-59A model. In this research, the total power of the coaxial configuration was approximated using the following equation:

$$P_{total} = P_{upper} + P_{lower} + \frac{T_{aux} \cdot V_{\infty}}{\eta}, \quad (5)$$

where P_{total} is the total power, P_{upper} is the upper rotor power, P_{lower} is the lower rotor power, T_{aux} is the thrust produced by auxiliary engines, and V_{∞} is the free-stream velocity. $\eta = 0.9$ was used throughout this research. In all three selected flight speeds, the total power matches reasonably well with the flight test data.

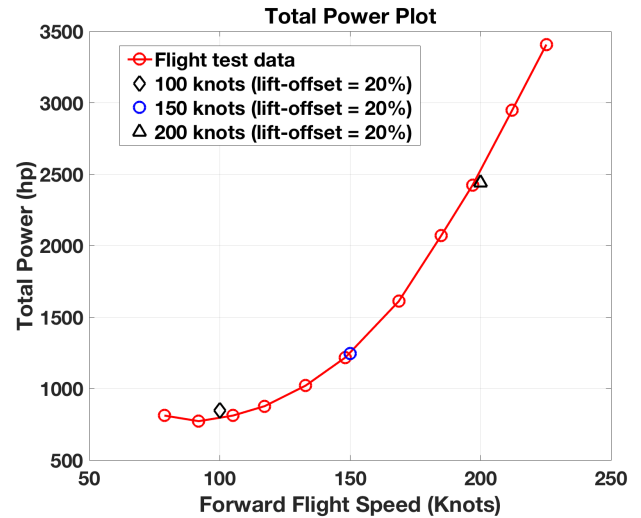


Fig. 14: Validation of total power.

100 Knots

Simulation results at 100 knots with lift-offset equal to 0, 0.1, and 0.2 were first evaluated to investigate acoustic characteris-

tics of the coaxial rotor at 100 knots. Figure 15 shows the vorticity magnitude iso-surface contour with q -criterion = 0.0001 at 100 knots with lift-offset equal to 0.2. No rotor-to-rotor BVI has been found from the iso-surface contour and dynamic animation, as is expected because of the high convection rate of the rotor wake during high-speed forward flight. Passe et al. (Ref. 29) pointed out that rotor-to-rotor interferences could be negligible at high speed during steady forward flight. Only self-BVIs, which means the interaction between rotor tip vortex and the blades of the same rotor, were found. It should also be remembered that the shaft angle of this vehicle is fixed at zero degrees and the rotor disk does not tilt forward to provide propulsive force. Thus it is likely to have self-BVIs at all forward speeds. Characteristics of aerodynamics and acoustics of the lift-offset coaxial rotor may vary depending on the shaft angle. Therefore, results in this work may not always be representative of acoustics of a lift-offset coaxial rotor, although a zero shaft angle is common for most compound rotorcraft.

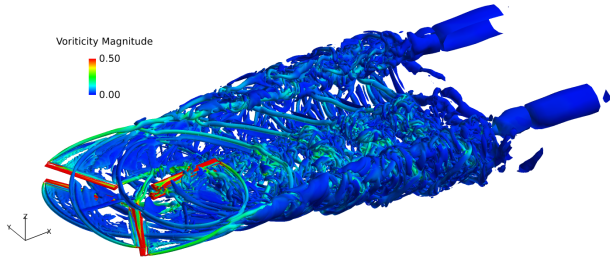


Fig. 15: Iso-contour of the vorticity magnitude at a forward flight speed of 100 knots with lift-offset = 0.2.

Figures 16 and 17 represent the azimuthal (time) derivative of sectional normal force of both upper (rotating in the counter-clockwise direction) and lower (rotating in the clockwise direction) rotors of the coaxial rotor at lift-offset equal to 0, 0.1 and 0.2. The azimuthal derivative of sectional normal force is considered as a direct source term in Farassat's Formulation 1A's loading noise as shown in $\dot{l}_r$, which serves as an indicator of impulsive acoustic sources. It shall be noticed that strong self-BVIs highlighted in red can be seen on the advancing side of the upper rotor near 50, 70, and 90 degrees azimuth in all lift-offset cases. Self-BVIs were also found near 90 degrees azimuth on the advancing side of the lower rotor. These self-BVIs in the first quadrants of both upper and lower rotors could lead to highly impulsive noise in acoustic prediction. The azimuthal derivative of sectional normal force was also plotted at the 75% span of both upper and lower rotors (see Fig. 18) to further identify the acoustic source position and the effect of lift-offset on acoustic sources.

In Fig. 18, the strength of the first two BVI events located near 50 and 70 degrees azimuth on both the upper and lower rotors is increased with increasing lift-offset. However, the strength of the third BVI event located around 95 degrees azimuth is reduced. The magnitude of self-BVIs highlighted in green and positioned on the retreating side of the upper rotor (around

300 degrees azimuth) and lower (around 280 degrees azimuth) rotor is also declined with increasing lift-offset. The strength and trajectory of self-BVIs was not studied in this paper, but could be investigated thoroughly in future work to understand the flow physics behind the scenes.

In addition to self-BVI events, abrupt changes of sectional normal force at every 60 degrees azimuth due to blade-crossover interactions, where the upper rotor blades are completely overlapped with the lower rotor blades, were discovered. These blade-crossover interactions are more intensive in magnitude (highlighted in green at every 60 degrees azimuth in Fig. 16) on the upper rotor than the lower rotor. This may be due to the suction side of the lower rotor having greater influence on the upper rotor than the pressure side of the upper rotor on the lower rotor. The strength of blade-crossover interactions also appears stronger on the retreating side of the upper rotor than on the advancing side of the upper rotor. This is due to a large influence of the lower pressure the suction side of the lower rotor on the advancing side of the upper rotor. It can also be seen that these impulsive loadings are reduced with increasing lift-offset since the separation distance is increased by increasing the lift on the advancing side. Barbely et al. investigated the blade crossover events in 2-D airfoil interactions (Ref. 9). Moreover, Fig. 18a shows a significant increase in magnitude of blade-crossover interactions on the retreating side of the upper rotor as lift-offset inclines.

Figure 19 shows the acoustic simulation results of thickness, loading, and total noise acoustic pressure at 100 knots with lift-offset equal to 0.2. It can be seen that the thickness noise acoustic pressure highlighted in black is relatively flat in shape and low in magnitude in comparison to the loading noise acoustic pressure at most microphone locations, except microphone 1 where the negative pressure peaks of the thickness noise acoustic pressure is maximum. The data shows the impact of the impulsive loading on the acoustic pressure as being the dominant source in regards to the total acoustic pressure. Because of this reason, this paper primarily focuses on the analysis of loading noise acoustic pressure.

According to results, microphones 2, 3, and 4, which are located toward the advancing side of the lower rotor, generate significantly higher impulsive signals with steeper positive and negative pressure peaks than microphones 6, 7, and 8 that are positioned toward the advancing side of the upper rotor. At microphones 2, 3, and 4, the advancing side of the lower rotor is thought to be an important noise source area due to the Doppler effect. The self-BVI and blade-crossover events in this area are believed to cause the impulsive signals. Though the total noise acoustic pressure at microphones 6, 7, and 8 are not very strong in comparison to microphones 2, 3, and 4, smaller positive and negative acoustic pressure peaks can still be detected and could be triggered by self-BVIs occurred on the advancing side of the upper rotor. A lift-offset comparison was also performed and shown in Fig. 20.

Based on Fig. 20, the 20% lift-offset case shows sharper acoustic pressure pulses across most microphone locations. The increase in magnitude of acoustic pressure at all micro-

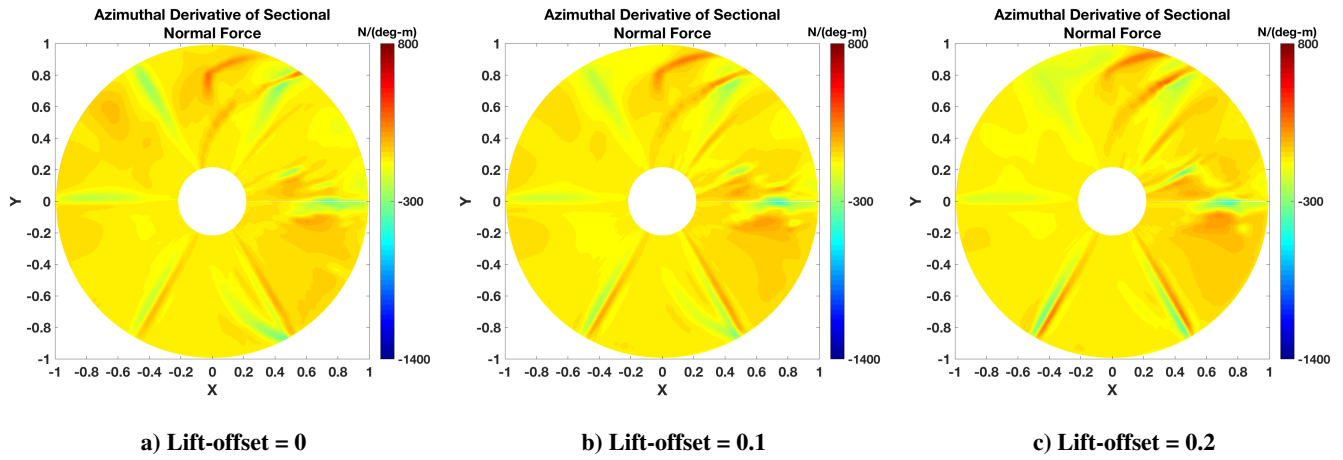


Fig. 16: The azimuthal derivative of sectional normal force of the upper rotor at 100 knots.

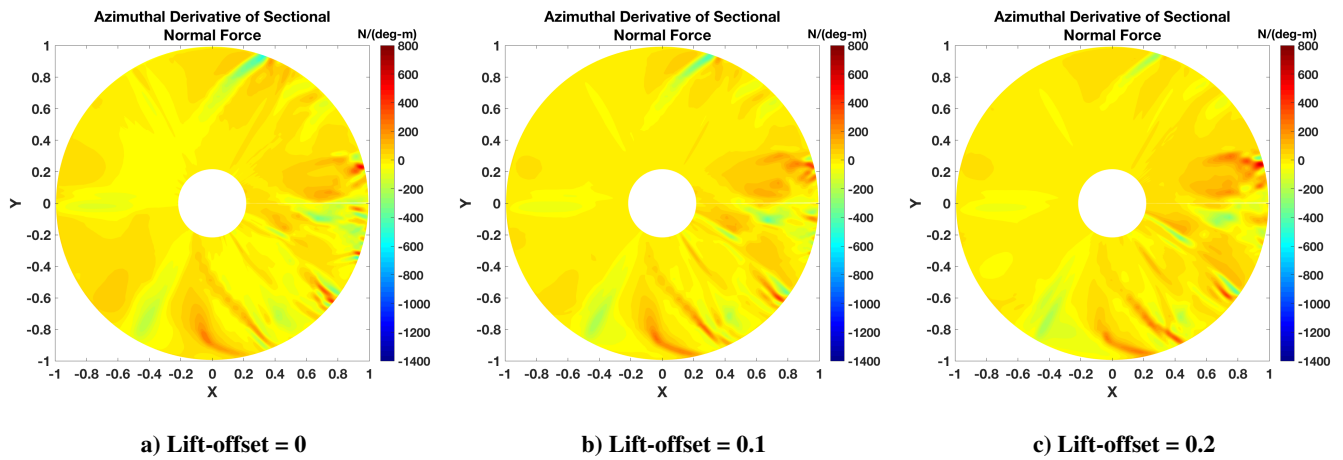


Fig. 17: The azimuthal derivative of sectional normal force of the lower rotor at 100 knots.

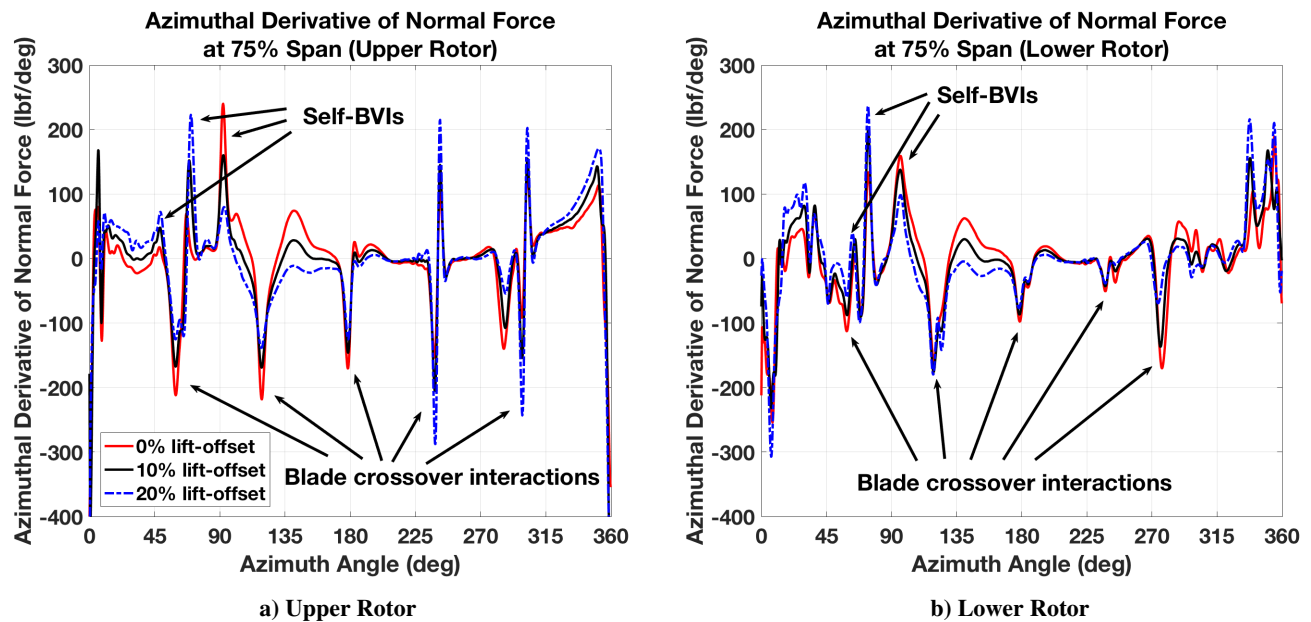


Fig. 18: The azimuthal derivative of sectional normal force at 75% span at 100 knots.

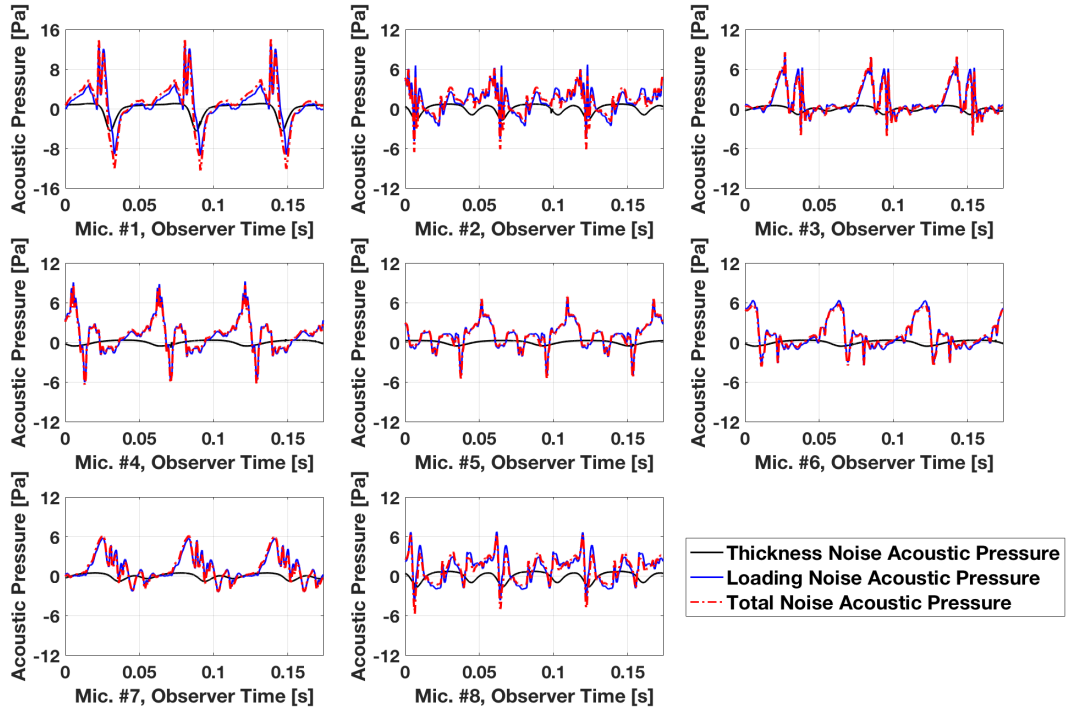


Fig. 19: Acoustic simulation results at 100 knots with lift-offset = 0.2.

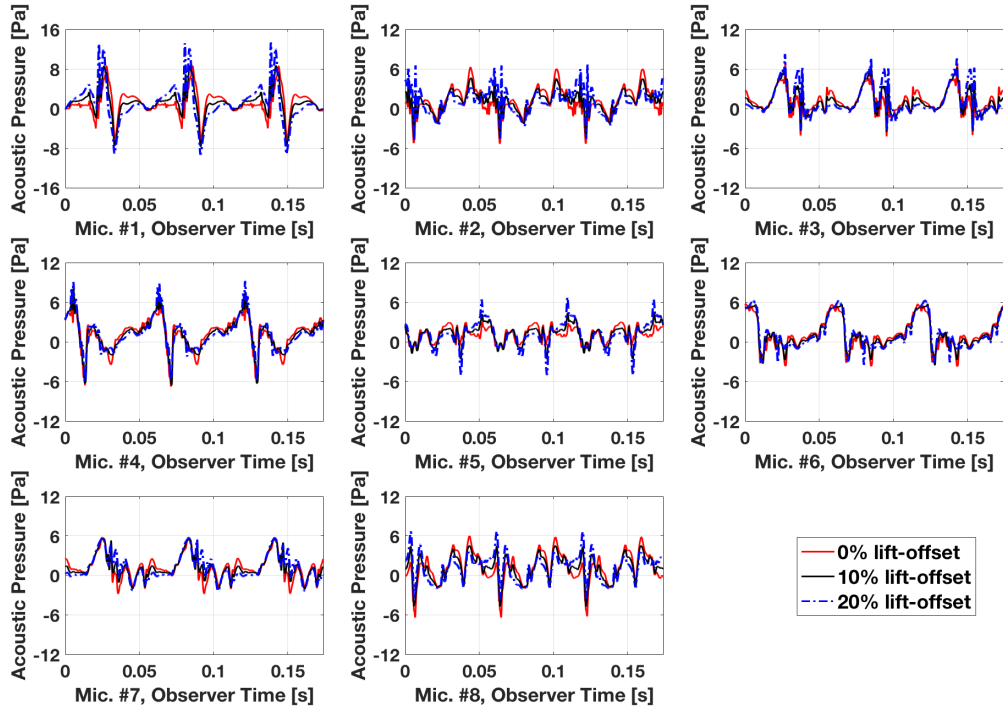


Fig. 20: Loading noise acoustic pressure at 100 knots with lift-offset = 0, 0.1, and 0.2.

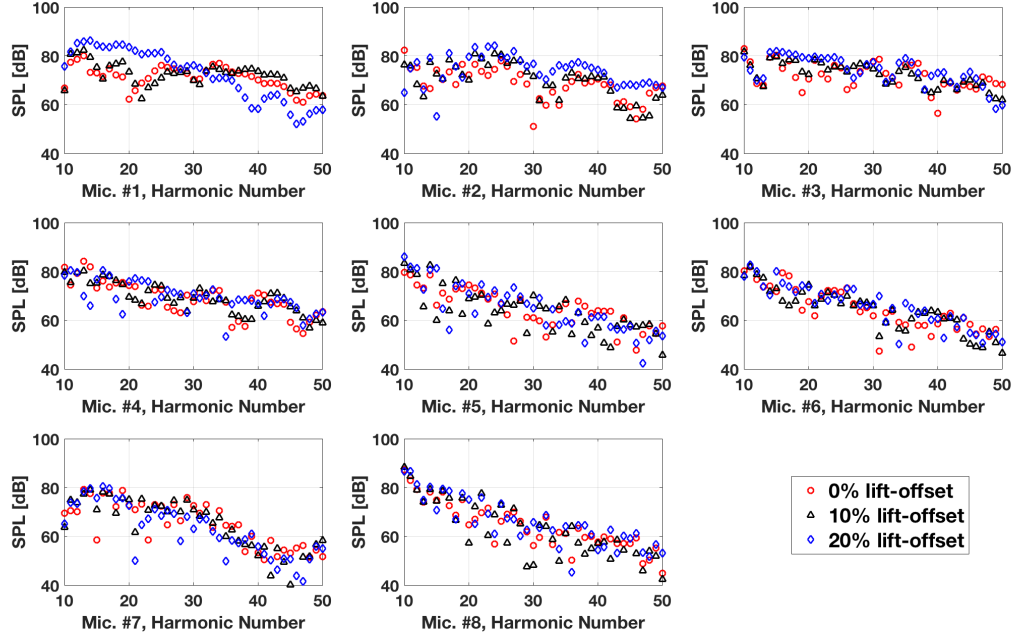


Fig. 21: Sound pressure level (SPL) spectrum at 100 knots.

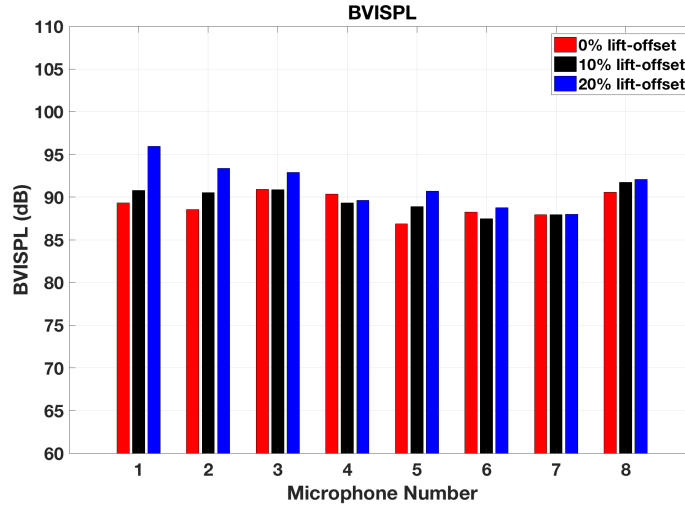


Fig. 22: BVISPL at 100 knots.

phone positions can be thought as direct outcomes of uprisings self-BVIs with increasing lift-offset. The reduction of negative acoustic pressure peaks at microphones 7 and 8 might be related to the reduced strength of blade-crossover interaction near 120 degrees azimuth on the advancing side of the upper rotor.

Further, sound pressure level (SPL) at every blade harmonic number is plotted and shown in Fig. 21. The SPL pulses are stronger in magnitude at higher lift-offset values at most microphones except microphone 7. BVI sound pressure level

(BVISPL) at 100 knots is also calculated by integrating the SPL spectrum from 10th to 50th blade harmonics to demonstrate the influence of lift-offset on acoustic impulsiveness. It is evident from Fig. 22 that higher lift-offset yields higher BVISPL across most microphone positions except microphone 7, which also matches with trends seen from the loading noise acoustic pressure plot.

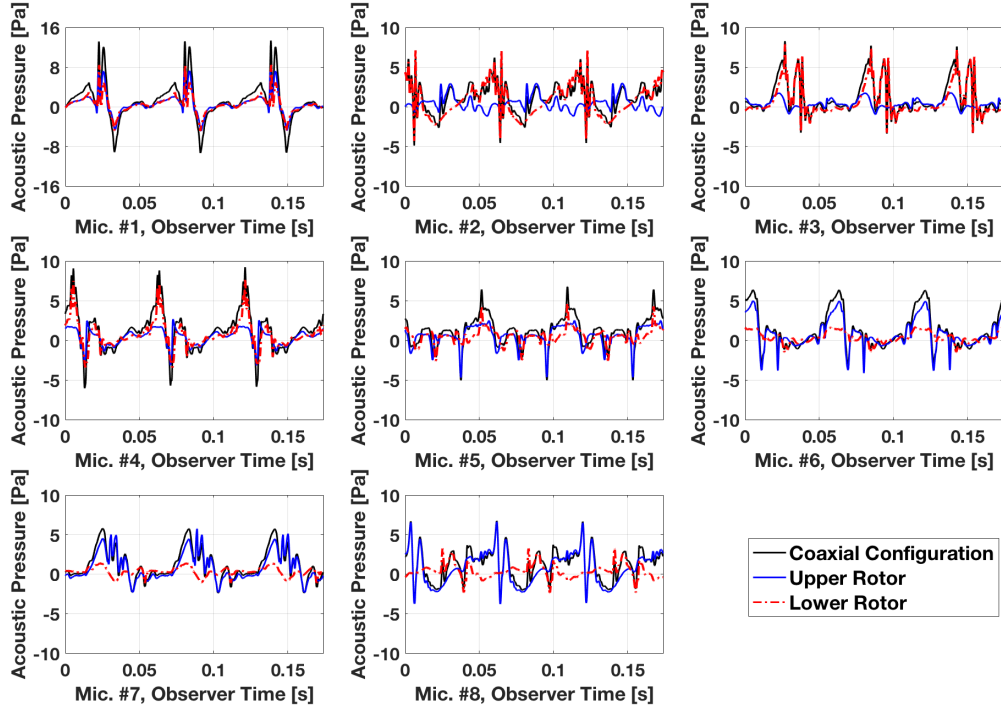


Fig. 23: Contributions of each rotor on loading noise acoustic pressure at 100 knots with lift-offset = 0.2.

Decomposition of the Coaxial Rotor at 100 Knots

The loading noise acoustic pressure of the coaxial configuration is decomposed into two components: upper and lower rotors. This decomposition process would clarify the acoustic source contribution from individual rotors. According to Fig. 23, the lower rotor at microphones 2 and 3 produced slightly higher acoustic pressure peaks than the upper rotor, possibly due to self-BVIs of the lower rotor in the first quadrant with minor contribution from blade-crossover events. Additionally, the upper rotor also experienced sharp positive and negative pressure pulses at microphones 6 and 7, which may be caused by self-BVIs of the upper rotor in the first quadrant with minor contribution from blade-crossover events. As mentioned earlier under the section Acoustic Simulation Setup, blade-tip Mach numbers will become large on the advancing sides of both upper and lower rotors, and could magnify the Doppler factor $1/|1 - M_r|$ in Farassat's Formulation 1A so that the advancing of each rotor becomes a major noise source area with respect to microphone positions.

An increase in Doppler amplification would also yield intensive noise sources, and may also explain why acoustic pressure pulses of the lower rotor are more impulsive than the upper rotor at microphones 2 and 3. The same ideology could be applied to outcomes seen from the upper rotor at microphones 6 and 7. Unlike microphones 2, 3, 6, and 7, both upper and lower rotors showed narrowed positive and negative pulses (the upper rotor line overlaps with the lower rotor line which

can be hard to see from the corresponding graph) at microphone 4. These sharp pressure pulses might be generated by a combination of blade-crossover interactions from the third and fourth quadrants of the upper rotor and self-BVIs from the first quadrant of the lower rotor, since the Doppler amplification is strong in those regions with respect to microphone 4. At microphones 1 and 5, both upper and lower rotors appear to be equally important in acoustic source contribution. At microphones 6, 7, and 8, the upper rotor is much more important than the lower rotor. At this microphone, the impulsive signal might be generated by the self-BVI on the advancing side of the upper rotor. Note that the blade-crossover events are not strong on the advancing side of the upper rotor. It shall also be kept in mind that the strength of acoustic source is heavily dependent on an observer's location.

150 Knots

Since one of main objectives of this research work is to characterize acoustics impulsiveness of a lift-offset coaxial rotor at high-speed forward flight, a case at 150 knots with lift-offset equal to 0.2 was also simulated and studied. Fig. 24 shows the iso-surface of vorticity magnitude with q-criterion equal to 0.0001. Other than self-BVIs, no trace of rotor-to-rotor BVI was detected. It can also be noticed that trailing vortices generated by the root of rotor blades located at 120 and 240 degrees azimuth are directly passing over the first blade located at 0 degrees azimuth in close proximity. These root-induced BVIs are also highly parallel with respect to the span of the

first blade. However, strong root-induced BVIs are unlikely to occur and are non-physical if a full configuration including a rotor hub is considered since the root vortices would be dissipated by the rotor hub. Self-BVIs, root-induced BVIs, and blade-crossover interactions can also be seen from Fig. 26b and 27b, which are the polar contours of the azimuthal derivative of sectional normal force. Fig. 28 further clarifies the azimuth position of these aerodynamic interactions. Self-BVIs of the upper and lower rotors are located around 60 and 90 degrees azimuth on the advancing sides of rotor disk. Root-induced BVIs of the upper and lower rotors occurred near 20 degrees azimuth. Blade crossover interactions appeared at every 60 degrees azimuth, but are significantly impulsive at 240 and 300 degrees azimuth of the upper rotor. All of above aerodynamic interactions could be considered as strong acoustic sources.

Similar to acoustic simulation performed at 100 knots, thickness noise, loading noise, and total noise acoustic pressure were plotted and shown in Fig. 29 for the 150 knots case. Microphones 2, 3, and 4 displayed steeper pressure peaks in comparison to microphones 6, 7, and 8. Microphone 5 shows weak negative spikes. Overall, the trends observed at 150 knots are identical to patterns shown at 100 knots.

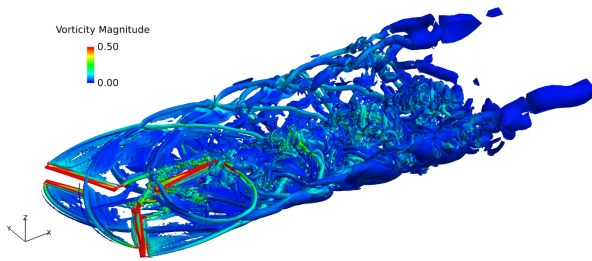


Fig. 24: Iso-contour of the vorticity magnitude at a forward flight speed of 150 knots with lift-offset = 0.2.

Decomposition of the Coaxial Rotor at 150 Knots

The loading acoustic pressure of the coaxial configuration was once again subdivided into two components — upper and lower rotors — for acoustic analysis (see Fig. 30). The lower rotor becomes the dominant contributor of acoustic sources at microphones 2 and 3 where self-BVIs occurred. It is believed that self-BVI on the advancing side of the lower rotor is one of major impulsive sources. The Doppler amplification factor is also expected to be greatest on the advancing side of the lower rotor, and further magnifies the strength of self-BVIs. The upper rotor, on the other hand, becomes the key contributor of acoustic sources at microphones 6 and 7, where self-BVI of the upper rotor is an important source of the noise. The magnitude of pressure pulses of both upper and lower rotors is comparable at microphones 1, 4, 5, and 8. Again, both self-BVIs and blade-crossover interactions could contribute to loading noise sources at microphone 4.

200 Knots

A higher speed case at 200 knots with lift-offset equal to 0.2 was also analyzed, and phenomena similar to 100 and 150 knots cases were observed. Figure 25 shows the iso-surface of vorticity magnitude at 200 knots. Only self-BVIs of the upper and lower rotors were observed (see Figs 26c and 27c). Self-BVIs were found near 45 and 80 degrees azimuth of both upper and lower rotors. Blade-crossover interactions can still be seen at every 60 degrees azimuth. Self-root induced BVIs are located near 10 degrees azimuth of the upper and lower rotors. Looking at Fig. 28, the magnitude of the first self-BVIs near 45 degrees azimuth on both the upper and lower rotors are much higher in strength than other aerodynamic interactions. On the upper rotor, the blade-crossover interaction at 300 degrees azimuth appears stronger than the blade-crossover interaction also occurred on the retreating side, but located at 240 degrees azimuth.

Acoustic simulation results (see Fig. 31) were reviewed again after investigating possible impulsive acoustic sources. Sharp negative peaks due to highly impulsive self-BVIs located near 45 degrees azimuth of both upper and lower rotors can be seen at microphones 2 and 6. The magnitude of pressure peaks are also increased at other microphone positions, especially at microphone 5, due to an increase in strength of self-BVI, blade-crossover, and root-induced BVI events. Strong root-induced BVIs occurred near 10 degrees azimuth have caused the magnitude of negative pressure spikes at microphone 5 to rise.

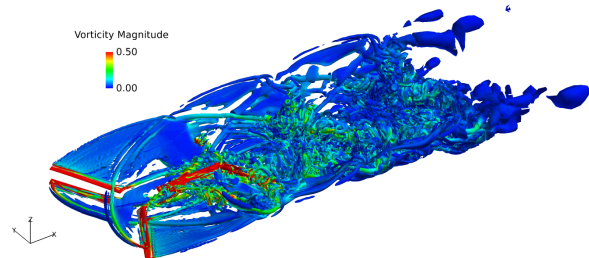


Fig. 25: Iso-contour of the vorticity magnitude at a forward flight speed of 200 knots with lift-offset = 0.2.

Decomposition of the Coaxial Rotor at 200 Knots

Figure 32 shows the composition of loading noise acoustic pressure of the coaxial configuration. Once again, the advancing side of the lower rotor contributes higher magnitude of acoustic sources to the full configuration at microphones 2, 3, and 4, while the advancing side of the upper rotor contributes greater sound sources at microphones 6, 7, and 8. Though microphone 4 still shows negative narrow pulses of the upper rotor, which could be the noise from the blade-crossover events on the retreating side of the upper rotor, the strength is relatively weaker than pressure peaks of the lower rotor.

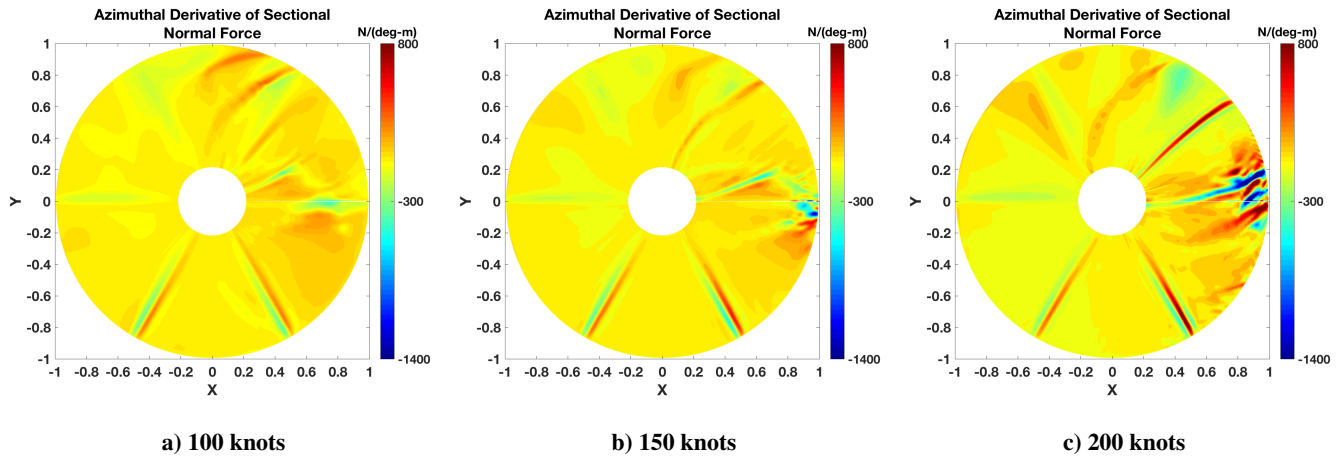


Fig. 26: The azimuthal derivative of sectional normal force of the upper rotor

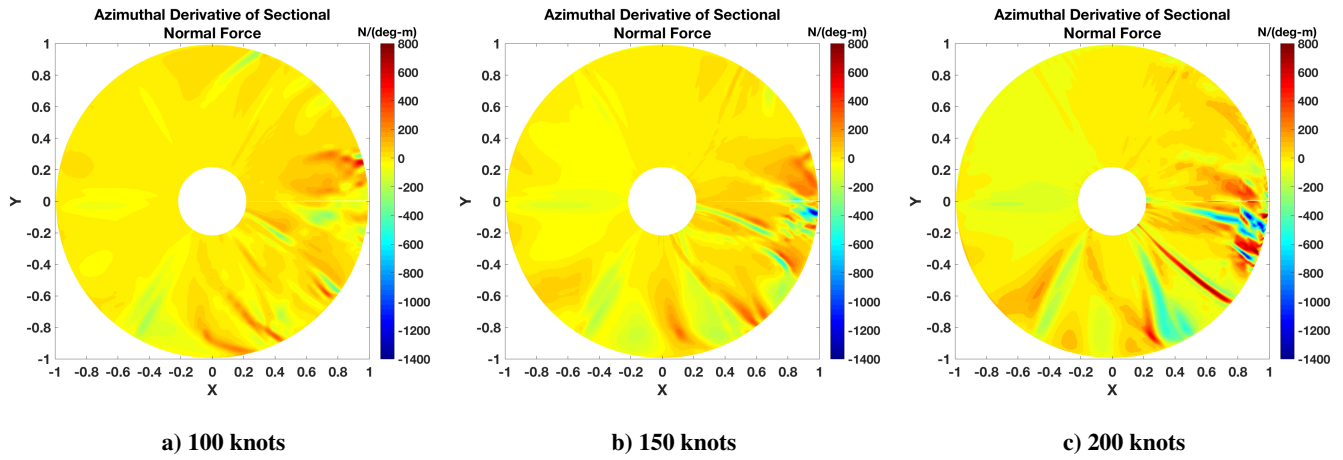


Fig. 27: The azimuthal derivative of sectional normal force of the lower rotor

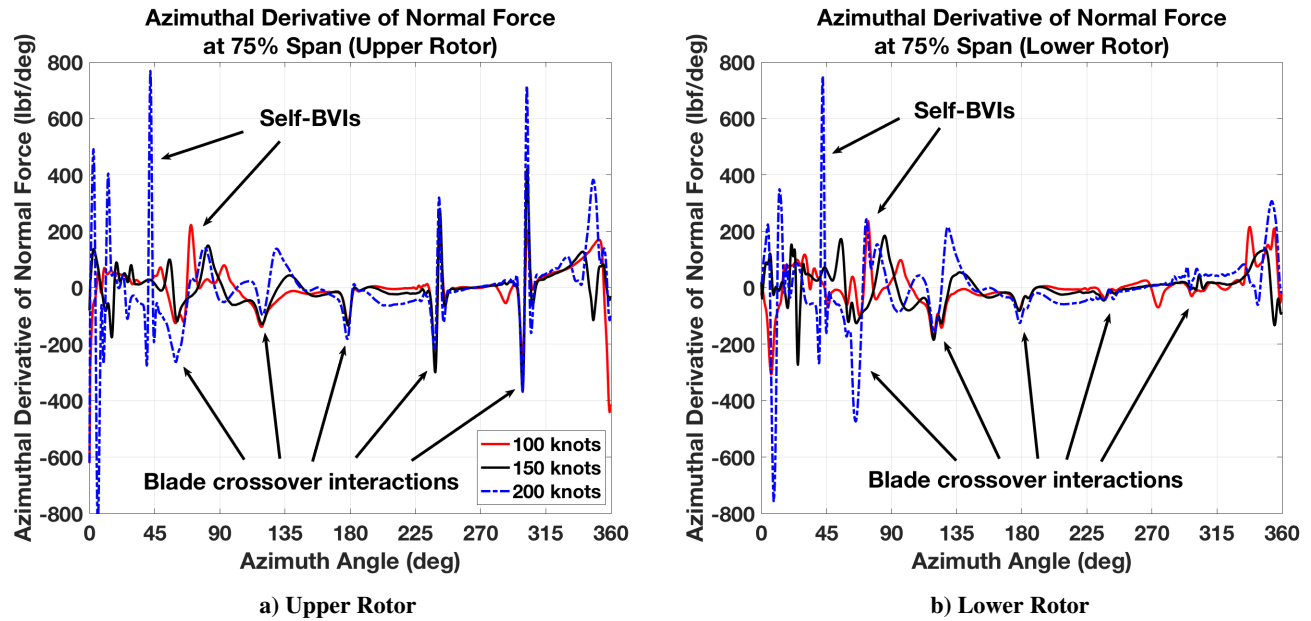


Fig. 28: The azimuthal derivative of sectional normal force at 75% span at 100, 150, and 200 knots.

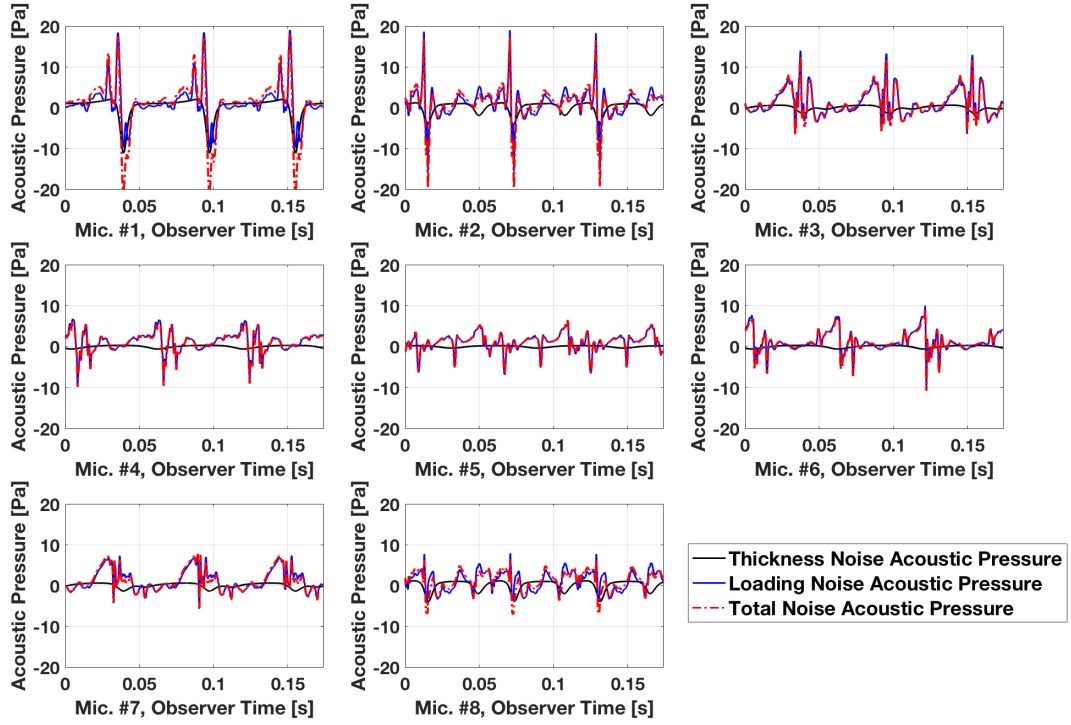


Fig. 29: Acoustic simulation results at 150 knots with lift-offset = 0.2.

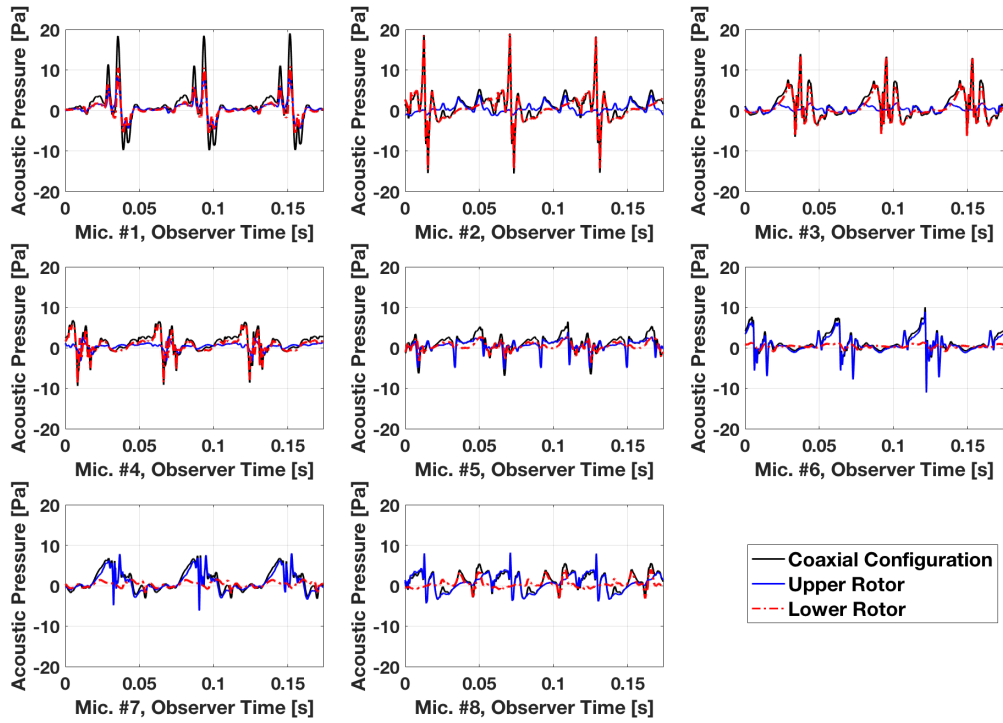


Fig. 30: Contributions of each rotor on loading noise acoustic pressure at 150 knots with lift-offset = 0.2.

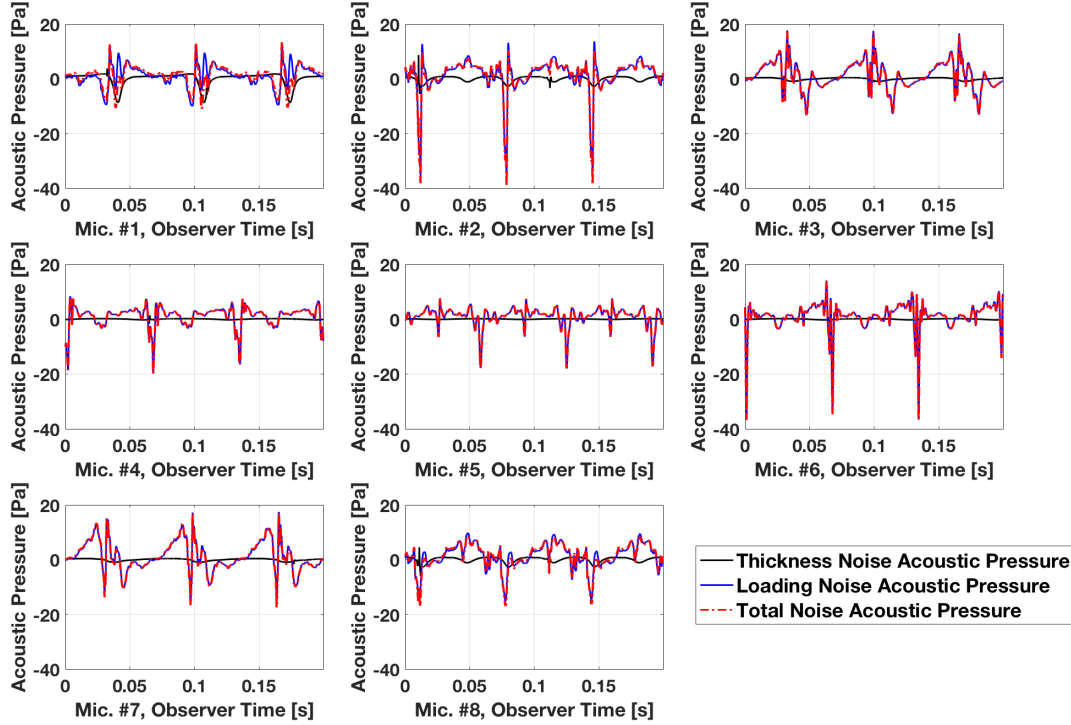


Fig. 31: Acoustic simulation results at 200 knots with lift-offset = 0.2.

Finally, microphone 1 shows equivalent source contribution from upper and lower rotors.

Effect of Flight Speed

As part of parametric study, the effect of forward flight speed on the strength of acoustic sources and far-field noise predictions was performed by keeping the lift-offset value at 0.2. Figure 28 will be used again to illustrate the effect of speed. As the forward speed increases, the magnitude of self-BVIs increased significantly on the advancing sides of both upper and lower rotors. The strength of blade-crossover interactions also escalated notably on the retreating side of the upper rotor. Further, the distance between adjacent self-BVI signatures becomes larger in the first quadrant of both upper and lower rotors according to Fig. 27. The shift in positions of self-BVIs is directly related to the wake convection rate at high speeds. Because of the high wake convection rate, the number of self-BVI events is reduced from three to two as the speed increases from 100 to 150 knots based on Figs 26 and 27. Additionally, the strength of root-induced vortices near zero degrees azimuth gradually grow stronger with increasing speed, and can lead to highly impulsive pressure signals at microphone 5. In general, an increase in strength of acoustic sources should yield stronger acoustic pressure pulses.

Figure 33 shows a comparison of loading noise acoustic pressure across 100, 150, and 200 knots with lift-offset equal to

0.2. It can be clearly seen that the strength of acoustic pressure pulses at most microphone positions except microphone 1 increases significantly with increasing speed, which is in conjunction with observations made from aerodynamic simulations. Microphone 2 and 6 are influenced the most because they are positioned toward the advancing side of the lower rotor where impulsive self-BVIs are evident. It should also be noticed that the difference between the 100 and 150 knots cases is smaller than the difference between 150 and 200 knots cases. Though the magnitude of self-BVIs in the first quadrants of both upper and lower rotors increased with increasing speed, the number of self-BVI events was reduced from three to two. It is possible that the boost in self-BVI strength is compensated for the reduction of the number of self-BVI events.

In order to demonstrate the effect flight speed on SPL, SPL versus blade harmonics was plotted and shown in Fig. 34. The 200 knots case shows higher SPL than the 100 and 150 knots cases at most microphone positions which accords with trends seen from the acoustic pressure plot or Fig. 33. BVISPL was also compared and shown in Fig. 35 at different microphone position and between the speed cases. BVISPL of the 200 knots case appears to be much higher than the other two cases across most microphone positions except microphone 1. The difference between 100 and 200 knots is as large as about 15 dB, especially at microphones 2 and 6.

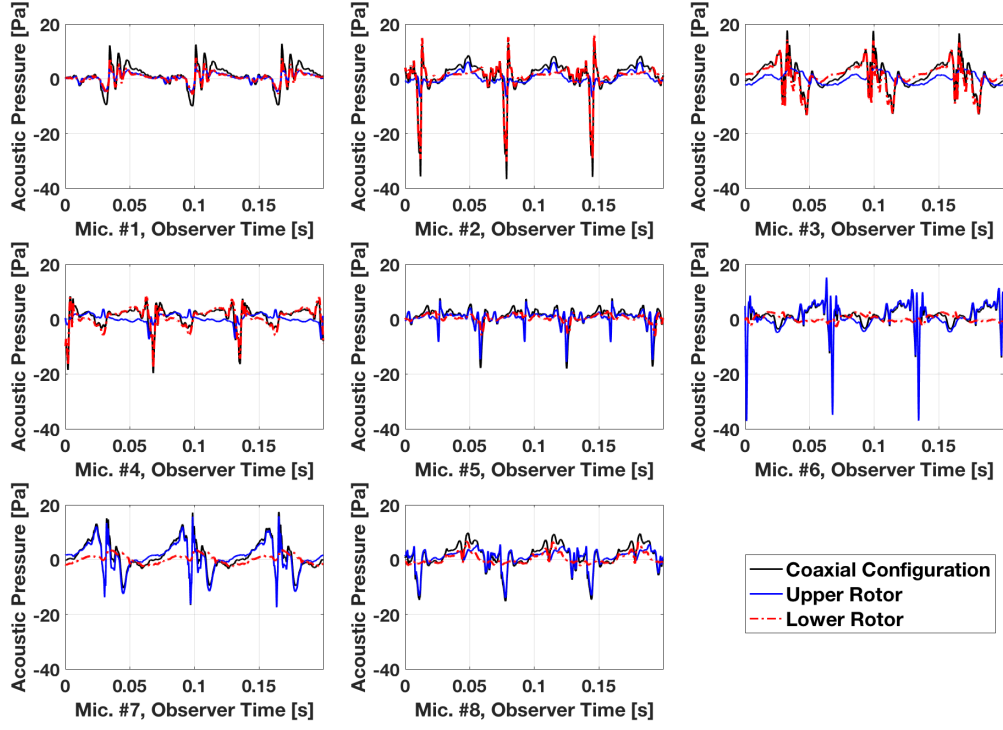


Fig. 32: Contributions of each rotor on loading noise acoustic pressure at 200 knots with lift-offset = 0.2.

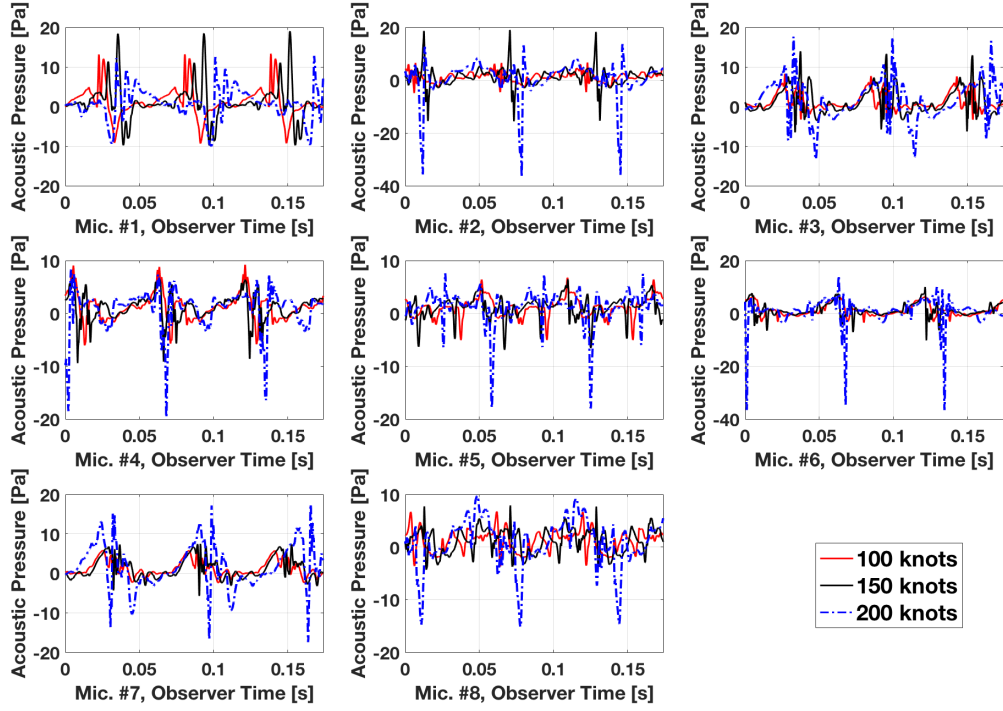


Fig. 33: Comparison of loading noise acoustic pressure with lift-offset = 0.2

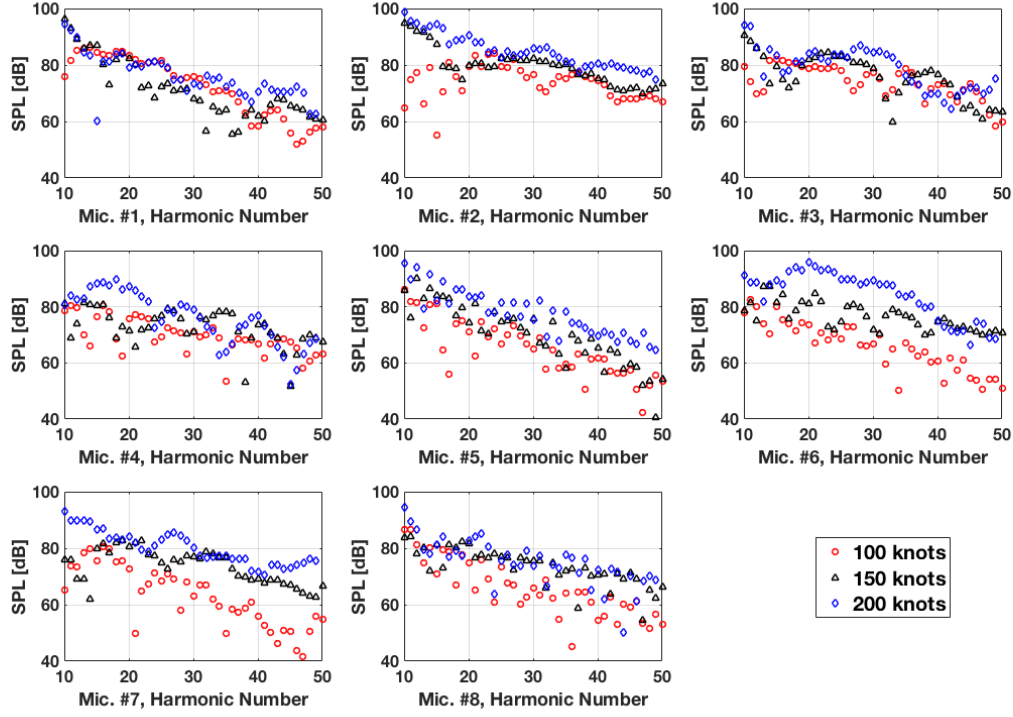


Fig. 34: Comparison of SPL at various speeds.

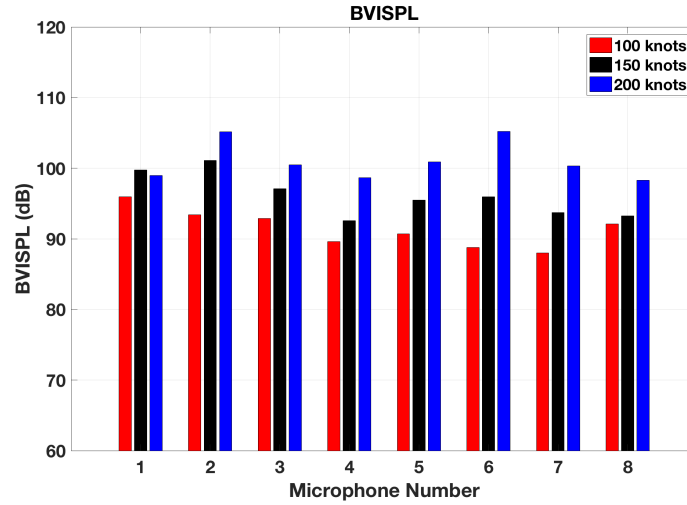


Fig. 35: Comparison of BVISPL at various speeds.

Effect of Separation Distance

The separation distance between the upper and lower rotors of the lift-offset coaxial configuration is also considered as a key parameter affecting both aerodynamics and acoustics of the vehicle. Therefore, a parametric study of separation distance is conducted in this research at 100, 150, 200 knots with lift-offset equal to 0.2. The separation distance of the origi-

nal coaxial configuration is increased by 50% or from 2.5 ft to 3.75 ft. To demonstrate the effect of separation distance, polar contours of the azimuthal derivative of sectional normal force are plotted again at 100 knots (see Fig. 36). The blade-crossover interactions originally located at 240 and 300 degrees azimuth on the upper rotor become weaker in magnitude and can hardly be seen. Figure 37 shows that the third self-BVI event located near the 90 degrees azimuth of both

upper and lower rotors is dropped in magnitude. The strength of blade-crossover interaction at 0 or 360 degrees azimuth is also reduced.

BVISPL was also plotted (see Fig. 38) for the parametric study of separation distance. At 100 knots, a clear distinction between the original configuration and the modified configuration with a separation distance equal to 3.75 ft can be seen. BVISPL has been dramatically reduced from microphone 2 to microphone 7. Microphone 8 is not influenced significantly by the separation distance since the aerodynamic interactions located in the second quadrant of the upper rotor are weak in strength. Self-BVIs and blade-crossover interactions are hardly noticeable at microphone 8. More interestingly, the effect of separation distance does not tend to affect BVISPL at higher speeds by much at most microphone positions except microphone 2. Microphone 2 still shows a large reduction in BVISPL at 150 and 200 knots probably due to weaker self-BVIs.

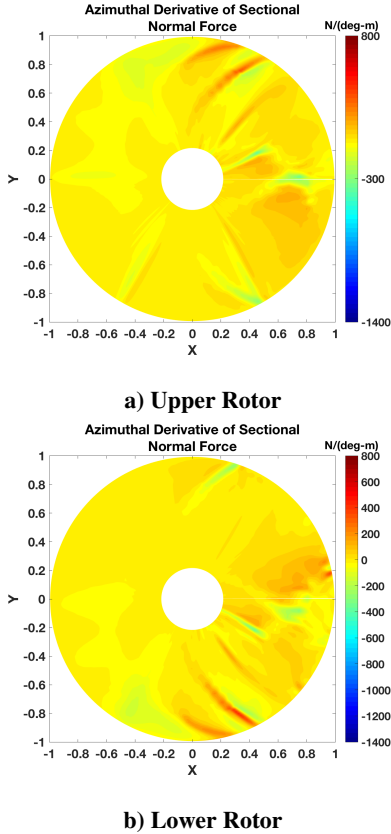


Fig. 36: The azimuthal derivative of sectional normal force at 100 knots with lift-offset = 0.2 and separation distance = 3.75 ft.

CONCLUSIONS

High-fidelity CFD-CSD loose coupling simulations at the three flight speeds — 100, 150, and 200 knots — were performed to study the acoustics of a three-bladed lift-offset coaxial rotor in high-speed steady forward flight. The acoustic prediction tool PSU-WOPWOP is used to analyze acoustic

data at eight microphone positions which are positioned in a circle beneath the coaxial rotor. Parametric studies were also conducted to investigate the effect of lift-offset, flight speed, and separation distance on acoustics. The following conclusions can be drawn from results discussed in this paper:

1. The total power computed based on the propeller efficiency assumption shows good agreement with available flight test data.
2. Self-BVI and blade crossover interactions are the most dominant aerodynamic interactions induced by a lift-offset coaxial rotor at high-speed forward flight and a shaft angle of zero degrees. Root-induced BVI also appears strong at high speed, but may not be physical in a real application where the inboard section of rotor blades and hubs are considered.
3. The strength of self-BVI and blade-crossover interactions are heavily dependent on lift-offset and forward flight speed. These aerodynamic interactions increased substantially with increasing lift-offset and forward flight speed.
4. According to iso-surface of vorticity magnitude at 100, 150, and 200 knots, rotor-to-rotor BVI is less likely to occur at high speed due to the high convection rate of the rotor wake.
5. Although both self-BVI and blade-crossover events generate significant impulsive loading on the rotor disk, it is thought that self-BVI is a more dominant factor considering the Doppler amplification effect and acoustic directivity. For example, the self-BVIs are more dominant on the advancing side than the blade-crossover events while, on the retreating side, the blade-crossover events are more dominant than the self-BVI events. In the acoustics point of view, the advancing side with respect to observers is more responsible for acoustics so that self-BVI events are more important than the blade-crossover events. However, the blade-crossover events could still be important and should not be neglected.
6. BVISPL shows that higher lift-offset can increase noise up to 6 dB.
7. The magnitude of BVISPL is more sensitive to the separation distance between the two rotors at a lower speed than at a higher speed. BVISPL becomes dramatically lower as much as 10 dB for the 100 knots case with longer separation distance than the original model. At 200 knots, the difference between the two separation cases is relatively small.

Though acoustic characteristics have been studied using high-fidelity simulation tools at various lift-offset values, flight speeds, and separation distances, impulsive aerodynamic interactions from an aerodynamic perspective is not thoroughly studied. The flow field of a lift-offset coaxial rotor such as tip

vortex strength and trajectory should be investigated more in details to better understand the fundamental physics of noise sources. The further study of the quantification of the relative importance of BVI and blade-crossover interaction noise is recommended in future work. Additionally, the shaft angle of attack could be another key parameter to investigate, since it will greatly change the BVI events in terms of magnitude and location and also the associated acoustics.

ACKNOWLEDGMENTS

This research was partially funded by the Government under Agreement No. W911W6-17-2-0003. The U.S. Government is authorized to reproduce and distribute reprints for Government purposes notwithstanding any copyright notation thereon. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the Aviation Development Directorate or the U.S. Government.

The authors would also like to thank: Dr. Roger Strawn from the U.S. Army Aviation Development Directorate (ADD) for providing the DoD High Performance Computing (HPC) resources and summer internship for the first author; Mark Potsdam, Jain Rohit, Dr. Beatrice Roget, and Dr. Wel Chong (Ben) Sim from ADD for their beneficial advices and assistance on learning Helios; Neal Chanderjian and Williams Chan from NASA Ames for their technical advices on rotorcraft simulation and mesh generation; Professor Farhan Ghandi and the Ph.D. student George Jacobellis from the Rensselaer Polytechnic Institute for sharing their CSD model of the XH-59A.

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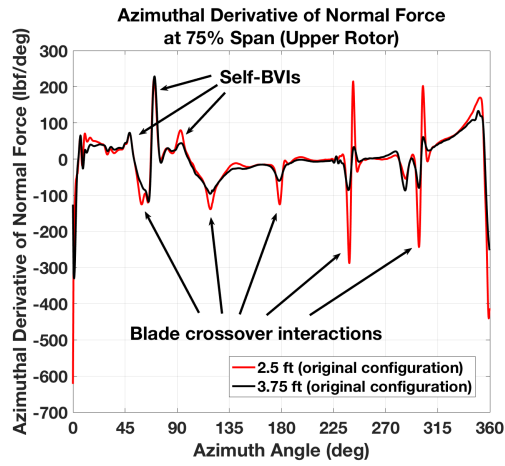
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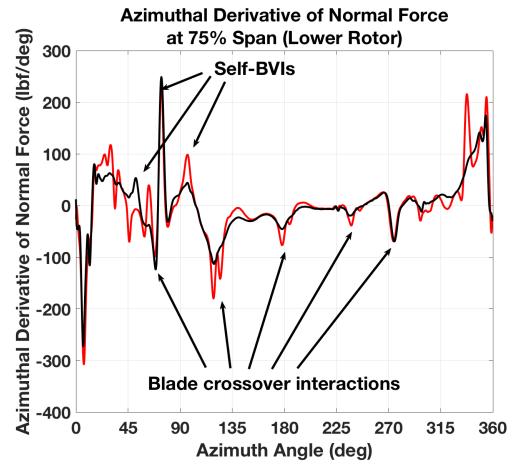
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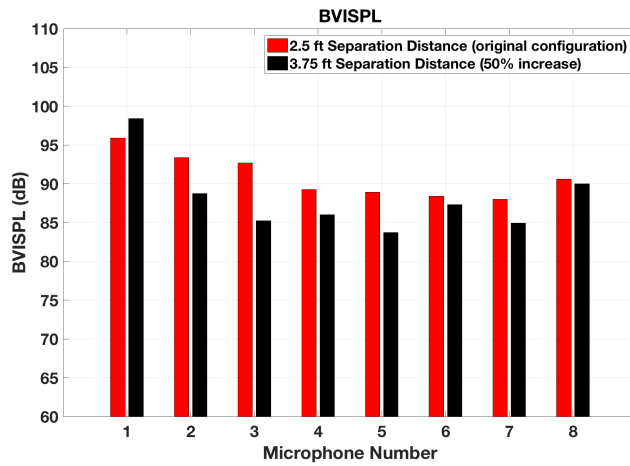


a) Upper Rotor

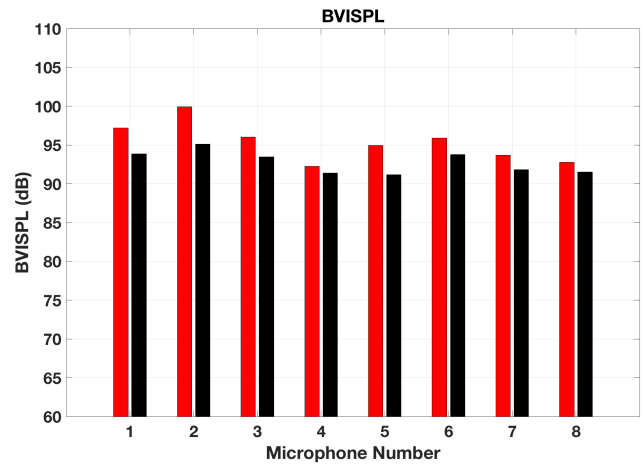


b) Lower Rotor

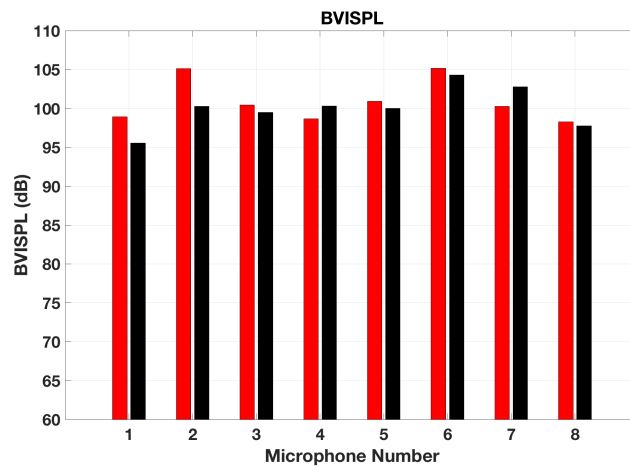
Fig. 37: The azimuthal derivative of sectional normal force at 75% span at 100 knots with lift-offset = 0.2 and separation distance = 3.75 ft.



a) 100 Knots



b) 150 knots



c) 200 knots

Fig. 38: BVISPL for the parametric study of separation distance.