

Anti-Phase Vortex Reduction Control for Rotor Noise Suppression

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An investigation is conducted in 2019 under the NASA Ames Center Innovation Funds (CIF) project entitled “Anti-Phase Vortex Reduction Control for Rotor Noise Suppression” to experimentally validate an anti-phase rotor noise suppression concept. The first objective of the investigation is to conduct computational fluid dynamics (CFD) simulations to investigate the noise characteristics of several anti-phase rotor designs. The second objective is to conduct a series of acoustic tests of anti-phase rotors in an anechoic chamber at Pennsylvania State University (PSU) to evaluate the merit of the anti-phase rotor concept.

The CFD investigation seeks to optimize the anti-phase alternating trailing edge patterns for rotor noise suppression. The design objective is to maximize the noise reduction while maintaining the aerodynamic thrust. The investigation is performed using a three-dimensional (3D) Unsteady Reynolds-Averaged Navier-Stokes (URANS) commercial solver STAR-CCM+ together with the Ffowcs-Williams and Hawkings (FW-H) formula to obtain the aerodynamic thrust and far-field noise level. An acoustic study is conducted for 13 anti-phase design candidates based on a proprietary rotor design. The CAD geometry of the rotor is furnished by PSU. These design candidates include different alternating trailing edge (TE) waveforms, TE segment lengths, TE deflection amplitudes, and transition characteristics. The best design candidate among those explored is an anti-phase rotor that has a four-period TE waveform which results in a reduction in far-field noise level of 2.1 dB in the hover condition and a reduction of 1.1 dB in the forward flight condition at 9.7 m/s.

A further acoustic study is conducted for a different rotor manufactured by APC. Five APC rotor design candidates are simulated. The best anti-phase design candidate for the APC rotor results in a reduction in far-field noise level of 4.0 dB in the hover condition. An in-phase design candidate is also studied. This in-phase design provides a noise reduction of 2.5 dB.

A series of acoustic experiments in the PSU anechoic chamber have been conducted in July 2019 and October 2019. Both anti-phase and in-phase rotors fabricated for the left-hand and right-hand rotations are tested. In the hover condition, all the rotors do not provide sufficient evidence of improved acoustic performance. However, the experimental data in the hover condition are deemed to be inconclusive due to the flow recirculation in the anechoic chamber caused by the rotor downwash. In the forward flight condition at 9.7 m/s, the anti-phase right-hand rotor produces a noise reduction by as much as 6.5 dB in the frequency range of 2000-4000 Hz, while the in-phase right-hand rotor produces a noise reduction by as much as 5 dB in the same frequency range. Both the anti-phase and in-phase left hand rotors offer no evidence of noise reduction. The difference in the acoustic performance of the left-hand and right-hand rotors could be explained by the location of the microphone array which is placed to the left side of the rotors. This microphone array location could

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create a bias in the sound pressure level in favor of the right-hand rotor. Using the average noise reduction values, the anti-phase 4H rotor could offer a noise reduction by as much as 3.5 dB while the in-phase 4I rotor could produce up to a 2.5 dB noise reduction. Both the computational and experimental results have provided sufficient evidence to support the noise suppression capability of the proposed anti-phase rotor concepts.

I. Introduction

Urban air mobility (UAM) has currently generated a great deal of interest in the aerospace industry. The UAM could open up a new aviation market for urban transportation that aims to dramatically decrease the door-to-door travel time for short-distance trips (20 - 200 miles).¹ The technological development of distributed electric propulsion (DEP) has enabled multi-rotor designs that are capable of reducing the cost of vertical take-off and landing (VTOL) by reducing the complexity of the design, operational cost via fuel savings, and fixed operating cost via insurance reductions.² These cost reductions could go a long way toward reaching the necessary technical and financial viability for a commercial market to develop.

Analyses have shown that, much like helicopters, noise is one of the primary technical challenges that need to be addressed in order to have full public adoption. Antcliff et. al. proposes an acceptable noise margin of 65 dBA at a distance of 250 ft which represents the acceptable community noise level created by large trucks.³ This criterion has been adopted by the burgeoning industry.⁴ The majority of UAM noise comes from the aircraft rotors. Rotor noise is a complex problem with many different potential sources. These noise sources are generally classified as loading noise, blade passing frequency noise, and blade vortex interaction (BVI) noise^{5,6}.

There have been several approaches to addressing rotor blade noise. Yung has conducted a comprehensive review of different approaches to BVI noise reduction.⁷ These include technologies to explicitly disrupt tip vortices like flow spoilers and end plates. There have been various attempts to develop wing tip geometries that would reduce the magnitude to the tip vortices. Investigations into a porous leading edge to create leading edge suction to reduce vortex shedding have been considered. There have also been investigations into the optimization of the rotor blade structures by leveraging the blade bending to disrupt the tip vortices and the BVI noise in particular.⁸ There have been proposed solutions for active twist mechanisms to actively reduce the BVI noise.⁹

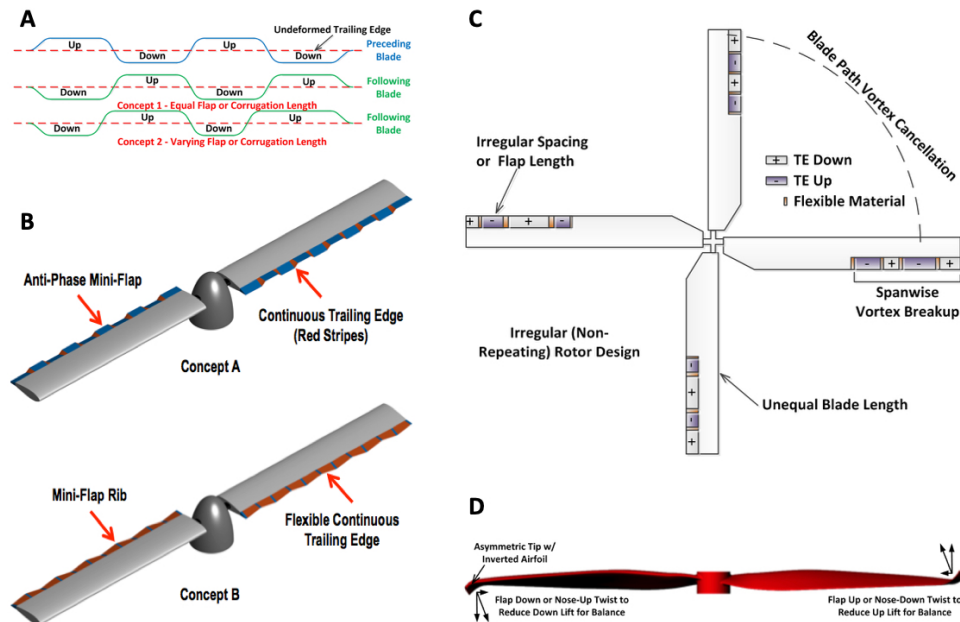


Figure 1. Anti-Phase Rotor Concepts

An anti-phase rotor noise reduction concept was proposed by Nguyen and funded by NASA ARMD CAS (Convergent Aeronautics Solutions) incubation project in 2018.¹⁰ Figure 1 illustrates the proposed concept. The anti-phase rotor concept is embodied by a continuous trailing edge (TE) shape modified in an anti-phase alternating pattern

from blade to blade. This anti-phase alternating TE waveform is hypothesized to provide a mechanism to disrupt the harmonic reinforcement of the blade vortex structure as a rotor blade goes through one complete revolution. This disruption could potentially result in an acoustic reduction.

A preliminary acoustic experiment was conducted in 2018 in the LifeSaver open-circuit wind tunnel at NASA Ames Research Center to evaluate the potential merit of the anti-phase rotor concept.¹⁰ Four 8-inch rotors with different anti-phase trailing edge designs and a baseline standard rotor were 3D printed for the experiment. The anti-phase rotor designs include an asymmetric winglet, and three anti-phase TE patterns having a corrugated, sine, and adjusted sine waveform as shown in Figure 2. The test results appear to confirm the acoustic benefit of the proposed anti-phase rotor concepts. Figure 3 shows the percentage acoustic reduction of the four anti-phase rotor designs normalized by the rotor thrust compared to the baseline standard rotor. The acoustic reduction is found at all three rotor rotational speeds. Among the tested anti-phase rotors, the corrugated design appears to offer better acoustic benefit than the other three designs. An interesting observation was noted in that the anti-phase rotor designs produce higher thrust than the baseline rotor at the same rotational speed. This is shown in Figure 4.

Anti-Phase Rotor Design

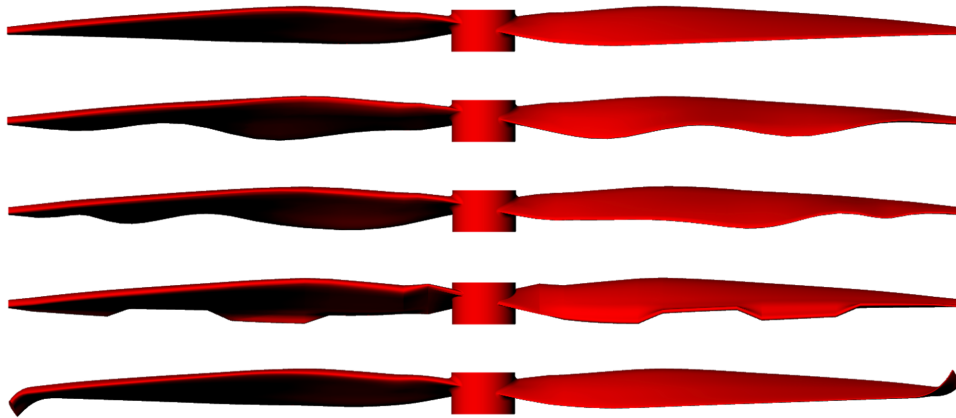
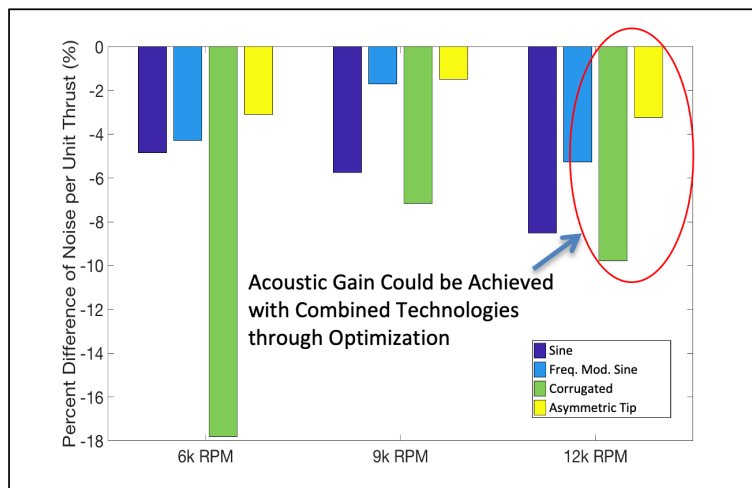


Figure 2. Anti-Phase Rotor Concepts Tested in NASA Ames LifeSaver Tunnel in 2018

Noise Reduction Per Unit Thrust in Descent at Different Speeds



Lower RPMs Increase Acoustic Gains

Figure 3. Acoustic Reduction of Anti-Phase Rotors

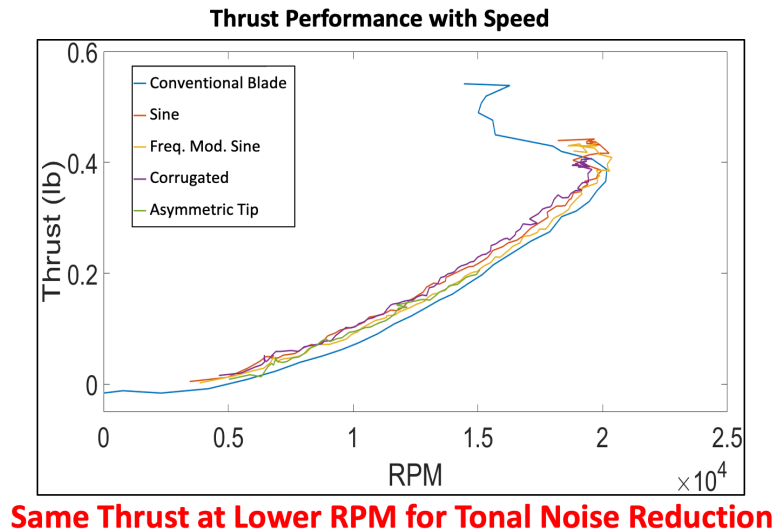


Figure 4. Thrust Enhancement of Anti-Phase Rotors

A follow-on effort to further investigate the anti-phase rotor concept is funded in FY 2019 by NASA Ames Center Innovation Funds (CIF) program. This effort has two objectives. The first objective is to conduct computational fluid dynamics (CFD) simulations to investigate the noise characteristics of several anti-phase rotor designs. The goal is to identify the best design candidate that offers the greatest noise reduction among the design candidates evaluated. The second objective is to conduct a series of acoustic tests of one or more anti-phase rotors in an anechoic chamber at Pennsylvania State University (PSU) to evaluate the merit of the anti-phase rotor concept under a grant with NASA Ames Research Center funded by the CIF project.

II. Anti-Phase Rotor Concepts

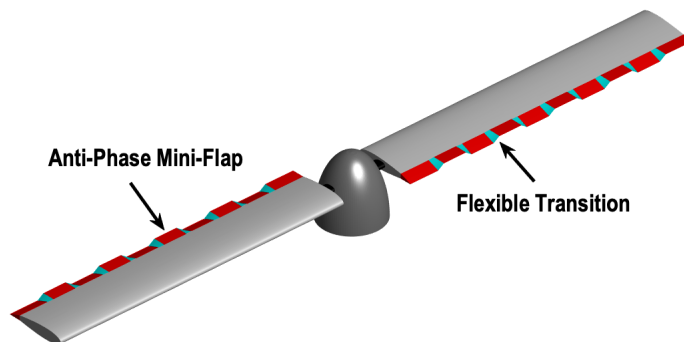


Figure 5. Anti-Phase Rotor

Figure 5 illustrates one embodiment of anti-phase rotor concepts. The embodiment is described by a continuous TE shape modified in an anti-phase alternating pattern from blade to blade so as to disrupt the harmonic reinforcement of the blade vortex structure in order to achieve an acoustic reduction. On one blade, the anti-phase TE pattern is 180° out of phase with respect to the anti-phase TE pattern on the other blade.

Figure 6 shows two embodiments of the anti-phase trailing edge patterns. One embodiment is described by the TE pattern on the preceding blade being 180° out-of-phase with respect to the TE pattern on the following blade. For example, if the TE of the preceding blade is in a downward deflection at a radial station, then the TE of the following blade is in an upward deflection of the same magnitude at the same radial position. In another embodiment, the TE pattern does not follow the exact 180° out-of-phase rule. This is shown by the first line and third line in Figure 6. To break up the harmonic reinforcement along the blade span, the anti-phase pattern is applied over several segments of the trailing edge with a constant length or varying length from blade to blade.

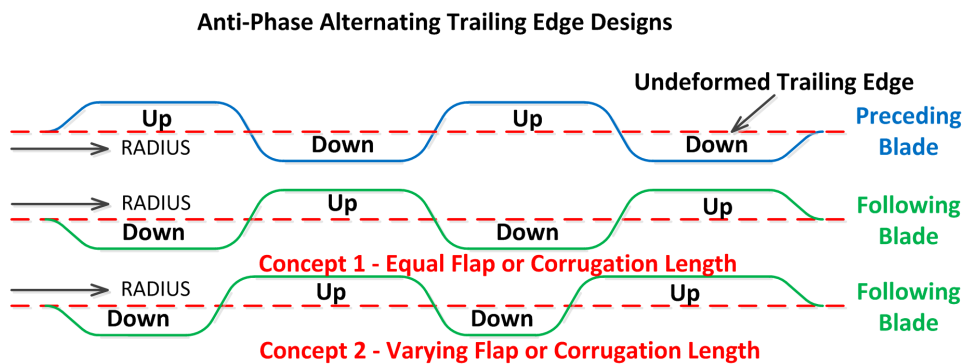


Figure 6. Anti-Phase Trailing Edge Pattern

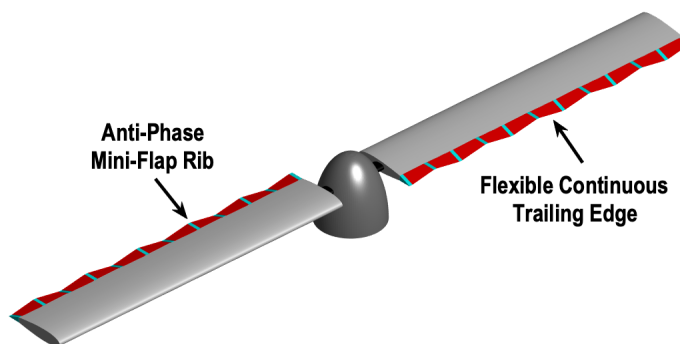


Figure 7. Anti-Phase Trailing Edge Pattern

The anti-phase TE can be accomplished by either a passive design or active design. A passive design has the advantage of the design simplicity and would target a minimum noise impact requirement during hover or descent. The disadvantage of a passive design is the negative impact on the aerodynamic performance of the rotor which could result in increased blade losses, hence increased rotor power. An active design provides more operational flexibility than a passive design. The active design would utilize a series of anti-phase mini-flaps or ribs with a continuous TE feature to provide a mechanism for adjusting the anti-phase TE pattern as needed or restoring the TE to a conventional undeformed state for improved rotor performance during cruise. The continuous trailing edge in an active design could be enabled by a flexible transition section in between the mini-flaps or a flexible skin over the entire trailing edge surface with ribs as illustrated in Figure 7. The disadvantage of an active design is the design complexity which could lead to an increase in weight and power for actuation systems. In addition, reliability is another operational factor that could negate the benefit of an active design.

Because of the nature of the blade loading with the increased tangential velocity toward the rotor blade tip, the tip vortices can be a significant noise source. Swept anhedral tip treatments are effective in reducing acoustic signatures

for transonic rotors. The anti-phase rotor concept can incorporate an anti-phase asymmetric blade tip design as shown in Figure 8. This concept involves the blade tip of one blade curved in an upward orientation while the blade tip of the other blade curved in a downward position. If the airfoil layout of the rotor blade continues into the curved blade tip regions, a radial force imbalance would result that could cause operational issues. One way to reduce the radial force imbalance due to the asymmetric blade tip design is to employ an inverted airfoil on one of the blade tips. A typical airfoil section with a positive camber is employed everywhere on the main blade surface. This airfoil is transitioned to an airfoil with zero camber near the blade tip region and a negative camber in the blade tip region.

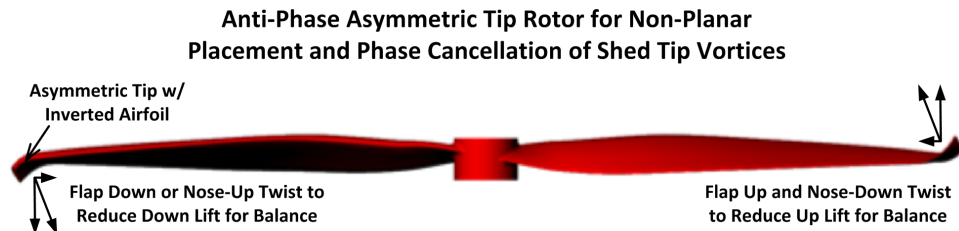


Figure 8. Anti-Phase Rotor with Asymmetric Blade Tip Design

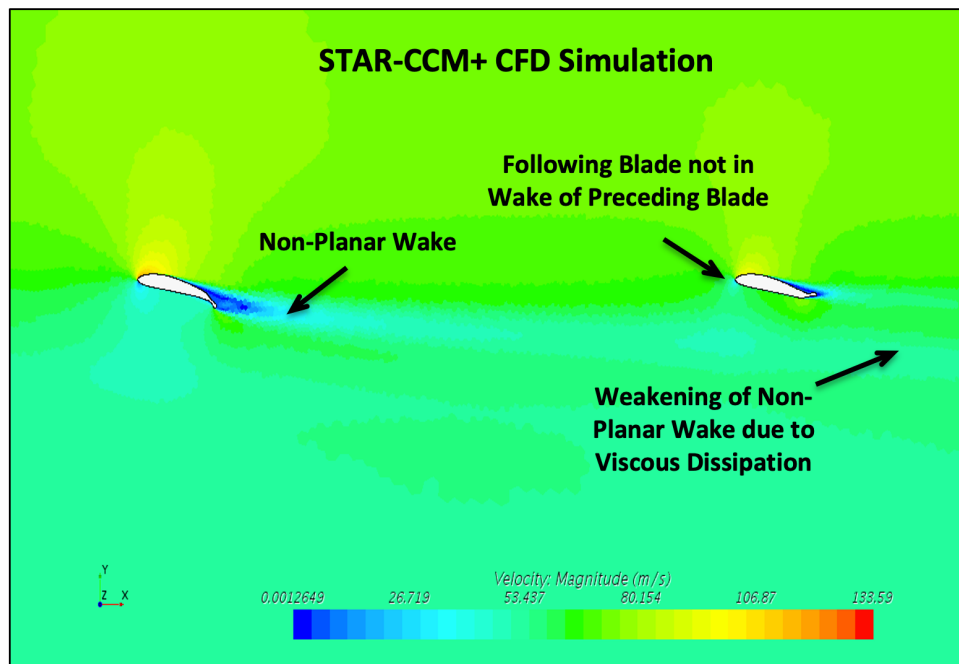


Figure 9. CFD Simulation of Anti-Phase Rotor

The mechanisms of the noise reduction of the anti-phase rotor concepts perhaps could be explained by Figure 9. A two-dimensional (2D) CFD simulation is performed using STAR-CCM+. Two rotor airfoils at a given radial station are modeled using a periodic boundary condition at the inlet of the preceding rotor airfoil with a downward deflected trailing edge and at the exit of the following rotor airfoil with an upward deflected trailing edge, as shown in Figure 9. The velocity contour plot of the CFD simulation in Figure 9 shows that the preceding airfoil sheds off a wake with an increased strength while the following blade sheds off a much weaker wake. Because of the downward deflected trailing edge of the preceding airfoil, its wake completely bypasses the following blade instead of impinging on the following blade. The two wakes of unequal strength can be seen to be non-interacting, thereby reducing the blade vortex interaction. Figure 10 illustrates the non-interacting downwash and upwash created by the downward and upward deflected trailing edges of the preceding and following blades, respectively.

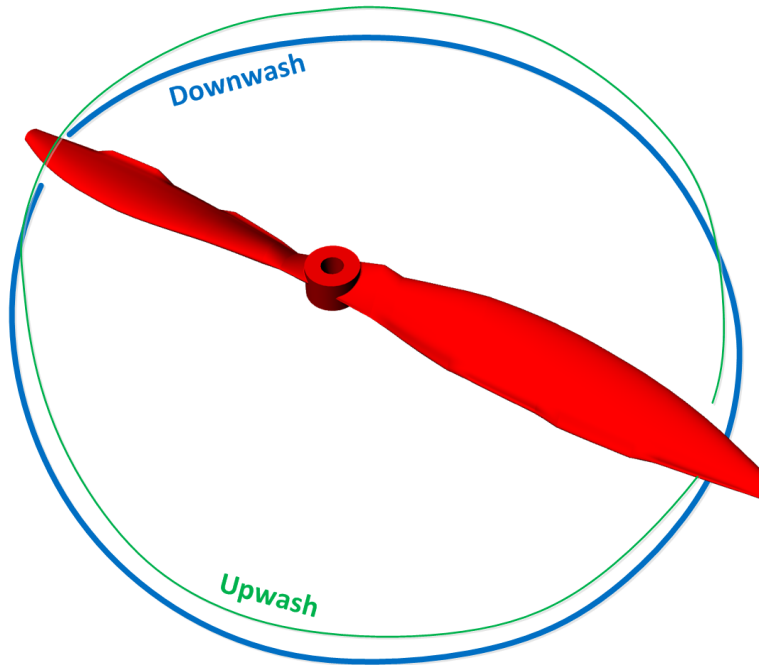


Figure 10. Non-Interacting Upwash and Downwash of Anti-Phase Rotor

Another possible mechanism of the noise reduction is the breakup of a large coherent blade vortex structure into smaller vortices. Figure 11 illustrates the downwash velocities created by a conventional rotor. The lift force generates a pair of equal-strength vortices as shown in the top figure. The anti-phase rotor breaks up the two vortices into smaller vortices created by the alternating unequal-strength downwash velocities. The breakup of the coherent vortex structure generated by a rotor can reduce blade vortex interactions, thereby resulting in lower noise.

Vortex Breakup of Anti-Phase Rotor Concept

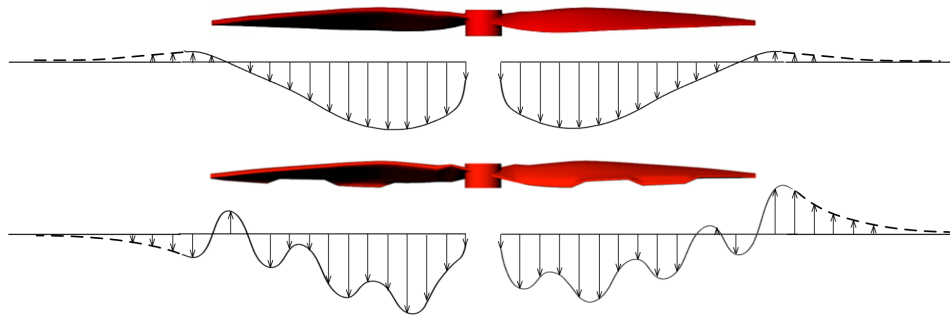


Figure 11. Vortex Breakup of Anti-Phase Trailing Edge Rotor Concept

Furthermore, the lift creation of a downward deflected trailing edge in comparison to that of an upward deflected trailing edge in an alternating trailing edge pattern could also contribute to the noise reduction. An airfoil tends to perform more efficiently with a downward deflected trailing edge up to a certain deflection than with an upward deflected trailing edge. The L/D ratio tends to increase as the trailing edge is deflected downward to a certain value. Downward deflected trailing edge has been used as a mechanism for drag reduction for fixed-wing aircraft.⁶ As the trailing edge deflects upward, the “kink” in the lower surface could induce an early flow separation that effectively reduces the upwash angle of the flow exiting the trailing edge. The net effect is that for the same downward and upward deflection of the trailing edge, the incremental up-lift created by the downward deflected trailing edge is greater than the incremental down-lift created by the upward deflected trailing edge. This results in a net overall increase in thrust

at the same rotor speed. Conversely, the rotor speed can be reduced to achieve the same amount of thrust, thereby lowering the tonal noise generated by the blade passing frequency.

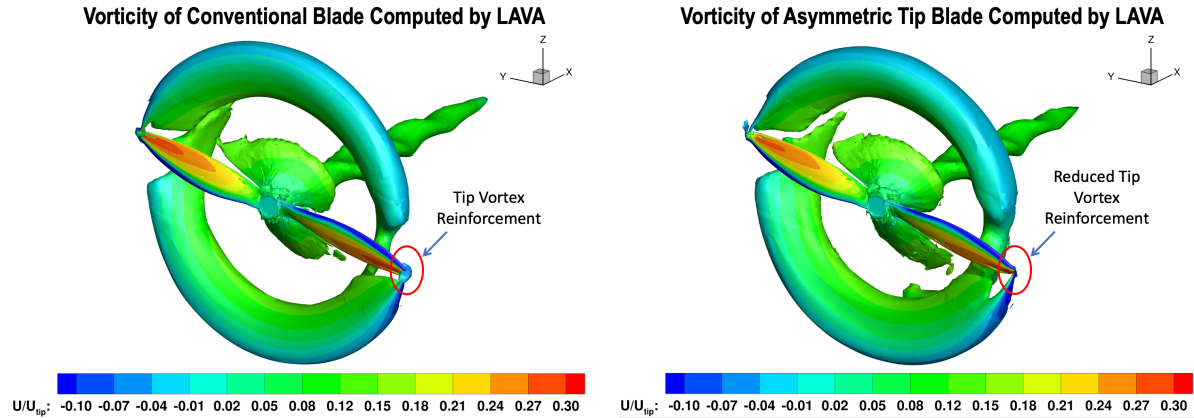


Figure 12. Tip Vorticity Computed by LAVA CFD

The mechanism of noise reduction of the asymmetric blade tip design could be explained by Figure 12. A high-fidelity CFD simulation of the asymmetric blade tip design is performed using LAVA, a NASA Ames high-fidelity CFD code. The vorticity contour plot of the asymmetric blade tip design is compared to that of the corresponding conventional straight blade design. It may be apparent from Figure 12 that the vorticity at the blade tip of the conventional straight blade design has a higher accumulation than that of the asymmetric blade tip design. This could suggest that the reduction in the harmonic reinforcement of the blade tip vortex structure could be a possible mechanism of noise reduction of the asymmetric blade tip design.

Figure 10 illustrates a pair of co-rotating tip vortices which create an offset between the two tip vortices. This offset thus effectively mitigates the effect of the following blade flying into the wake created by the tip vortex of the preceding blade, thereby resulting in lower blade tip vortex noise.

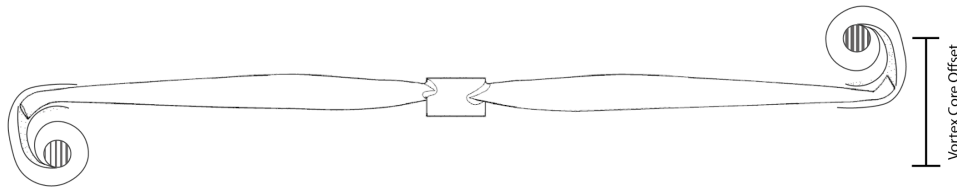


Figure 13. Offsetting Tip Vortices of Asymmetric Blade Tip Design

III. Numerical Investigation

To better understand the noise reduction mechanisms of the anti-phase rotor concept and to achieve the maximum noise reduction while matching the thrust requirement, an acoustic optimization study is performed using the commercial CFD software STAR-CCM+. The investigation is performed using a three-dimensional (3D) Unsteady Reynolds-Averaged Navier-Stokes (URANS) commercial solver STAR-CCM+ with $k - \omega$ Shear Stress Transport (SST) turbulence model and Ffowcs-Williams and Hawkins (FW-H) formula to obtain aerodynamic thrust and far field noise level. Two parametric acoustic studies of two different rotor designs are conducted. The first rotor design is a rotor manufactured by KDE which uses a proprietary geometry. The CAD geometry of the KDE rotor is created from a laser scanning measurement performed by PSU. The second rotor design is a rotor manufactured by APC who furnishes the rotor geometry.

PSU initially provides a baseline rotor geometry to NASA for CFD as shown in Figure 14. This rotor is supposed to be a KDE rotor. However, it is revealed much later that this initial rotor geometry is not exactly the same as the geometry of the KDE rotor that PSU is planning to test which is shown in Figure 15. This discrepancy creates a concern that the experimental data may be difficult to interpret and cannot be directly compare to the CFD results.

PSU then decides to acquire the APC rotor for testing. The geometry of the APC rotor, shown in Figure 16, is provided by APC through PSU. Both rotors are nominally 18 inches in diameter.

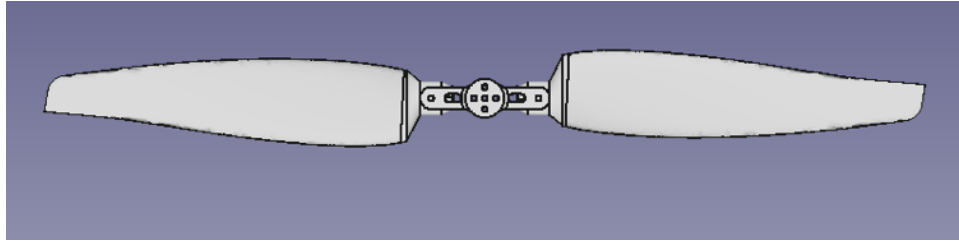


Figure 14. Initial KDE Rotor Furnished by PSU

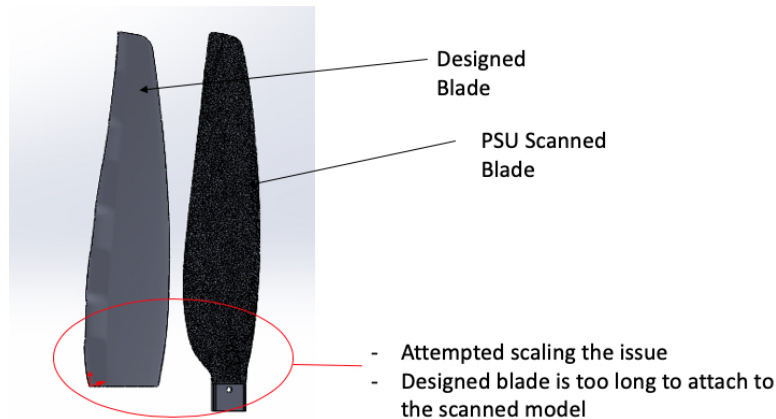


Figure 15. Initial KDE Blade (Design Blade) Compared to KDE Blade to Be Tested (PSU Scanned Blade)

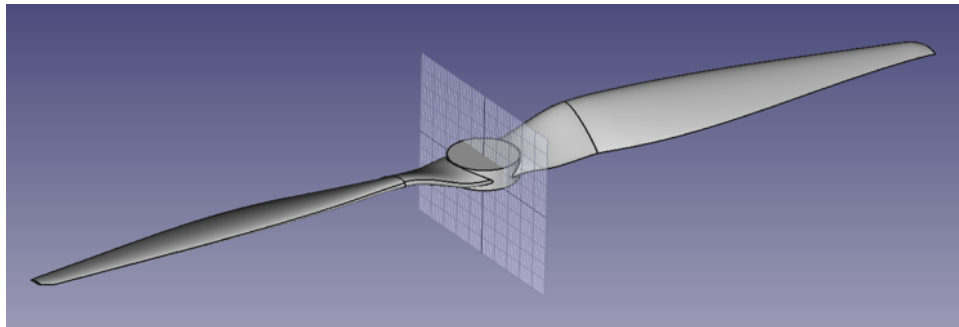


Figure 16. APC Rotor

A. Computational Approach

1. Governing Equations

Due to the expected rotor tip speed to be no greater than Mach 0.31, the flow is essentially incompressible. The incompressible URANS equations are expressed as follows:

$$\sum_{i=1}^3 \frac{\partial u_i}{\partial x_i} = 0 \quad (1)$$

$$\rho \left(\frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j} \right) = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} \quad (2)$$

where the viscous shear stress tensor τ_{ij} is given by

$$\tau_{ij} = \tau_{ij}^L + \tau_{ij}^T \quad (3)$$

$$\tau_{ij}^L = \mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \mu \frac{\partial u_k}{\partial x_k} \delta_{ij} \quad (4)$$

The closure turbulence model used to evaluate the turbulent shear stress τ_{ij}^T and viscosity μ is the $k - \omega$ SST turbulence model.¹¹ The SST turbulence model combines the advantages of the $k - \omega$ and $k - \varepsilon$ turbulence models to give superior performance in simulating the wall boundary layer and freestream flow, thus the $k - \omega$ SST model is chosen for all the cases in this study. The equations are

$$\frac{\partial k}{\partial t} + u_j \frac{\partial k}{\partial x_j} = P - \beta^* \omega k + \frac{\partial}{\partial x_j} \left[(v + \sigma_k v_T) \frac{\partial k}{\partial x_j} \right] \quad (5)$$

$$\frac{\partial \omega}{\partial t} + u_j \frac{\partial \omega}{\partial x_j} = \frac{\gamma}{v_T} P - \beta \omega^2 + \frac{\partial}{\partial x_j} \left[(v + \sigma_\omega v_T) \frac{\partial \omega}{\partial x_j} \right] + 2(1 - F_1) \frac{\sigma_{\omega 2}}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j} \quad (6)$$

where

$$P = \frac{\tau_{ij}}{\rho} \frac{\partial u_i}{\partial x_j} \quad (7)$$

The turbulent eddy viscosity is given by

$$v_T = \frac{a_1 k}{\max(a_1 \omega, \Omega F_2)} \quad (8)$$

$$\mu_T = \rho v_T \quad (9)$$

The turbulent shear stress is calculated using

$$\tau_{ij}^T = 2\mu_T \left(S_{ij} - \frac{1}{3} \frac{\partial u_k}{\partial x_k} \delta_{ij} \right) - \frac{2}{3} \rho k \delta_{ij} \quad (10)$$

F_1 and F_2 represent blending functions. The model constants can be calculated by

$$\phi = F_1 \phi_1 + (1 - F_1) \phi_1 \quad (11)$$

2. Ffowcs Williams-Hawkings (FW-H) Equation

The Ffowcs Williams-Hawkings (FW-H) equation is the generalization form of Lighthill's acoustic analogy and is derived primarily from Farassat's Formulation 1A. It is the exact rearrangement of the generalized derivatives of the continuity and momentum equations into the form of the inhomogeneous wave equation. The general form of the FW-H equation is,¹²

$$D^2 p' = \frac{\partial}{\partial t} [\rho_0 v_n \delta(f)] - \frac{\partial}{\partial x_i} [l_i \delta(f)] + \frac{\partial^2}{\partial x_i \partial x_j} [T_{ij} H(f)] \quad (12)$$

where $D^2 = 1/c_0^2 \partial^2 / \partial t^2 - \partial^2 / \partial x_k^2$ is the wave operator. $H(f)$ is the Heaviside function. Using the free-space Green's function to compute the sound pressure at the observer's location x , the solution can be formulated as

$$p'(\vec{x}, t) = p'_T(\vec{x}, t) + p'_L(\vec{x}, t) + p'_Q(\vec{x}, t) \quad (13)$$

The first term on the right hand side refers to the monopole (or thickness) term. It arises from the displacement of the fluid as the body passes through. The second term on the right hand side is the dipole (or loading) term.

It occurs from the unsteady motion of the force distribution on the body surface. Both of these noise sources are surface-related. The third term on the right hand side is the quadrupole (volume source) term and results from the non-linearities present in the flow.

There are two types of surfaces that can be used in the formulation. An impermeable FW-H surface acts as a filter of wall boundary conditions from which the noise originates. This type of surfaces will produce sound levels only from the monopole and dipole sources. A permeable FW-H surface acts as a filter of internal interface boundaries. This surface is a fine mesh region that surrounds all the sources of noise: monopole, dipole, and quadrupole. In STAR-CCM+, the FW-H model uses a concept developed by Brentner and Farassat referred to as the advanced time approach or the source-time-dominant approach. The algorithm looks forward in time to see when the receiver perceives the generated sound waves. This advanced time algorithm makes a distinction between the emission and reception times. The emission times of the acoustic signal from each surface will be constant while the reception time for those signals will be different. As a result, the emission times are fixed and the signals arriving to the receiver are accumulated at their respective emission time slot. The overall acoustic signal at the receiver is the summation of the individual acoustic signal from each 6 source surface during the same emission time. The goal of FW-H model is to predict the small amplitude acoustic pressure fluctuations at the location of the desired receiver. It predicts the propagation of sound in free space using analytical integral solutions to the generalized wave equation and does not include any effects such as reflections and refractions. This approach is used in the simulations performed in this study to predict noise levels of the receivers in the far field.

In this study, the governing equations are solved by the commercial CFD solver STAR-CCM+. The finite-difference schemes are second-order accurate in both space and time. The time discretization is second-order implicit backward differencing. The second-order Roe scheme is used for the spatial discretization.

B. Computational Model and Mesh

Figure 17 shows the computational mesh around the rotor. A cylindrical shape is used to create the extent of the domain. The domain is divided into three regions: the outer domain, the rotating domain, and the permeable domain. The outer domain specifies the volume of air in which the rotor rotates. This volume should be large enough in order for the boundary conditions to be satisfied at the boundaries. The permeable domain is created for acoustical purposes. In order to include the quadrupole sources in the prediction of the noise levels, a permeable surface needs to be created. The diameter of this surface is set to be at three times the rotor diameter. The mesh in this domain can be dense enough to avoid acoustic dissipation, while maintaining a relatively coarser mesh in the outer domain. This reduces the number of cells of the mesh and eventually reducing the computational cost of the simulation. The rotating domain is used to specify the rotational speed of the rotor. It is set away from the rotor in order to ensure that there are no changes in the parameters across the interface. The permeable surface would rotate after every time step, causing a re-mesh and change in the computation of fluxes at the interface. The total number of the nodes in the three domain is about 4 million. A receiver is placed at 1 m below from the rotor center to measure the noise level. Figure 18 shows the receiver location.

The anti-phase rotor geometries are created by deflecting the trailing edges of several spanwise sections of the rotor blades at their three-quarter chord points from the leading edges. A 3D surface loft is then constructed from these rotor blade sections.

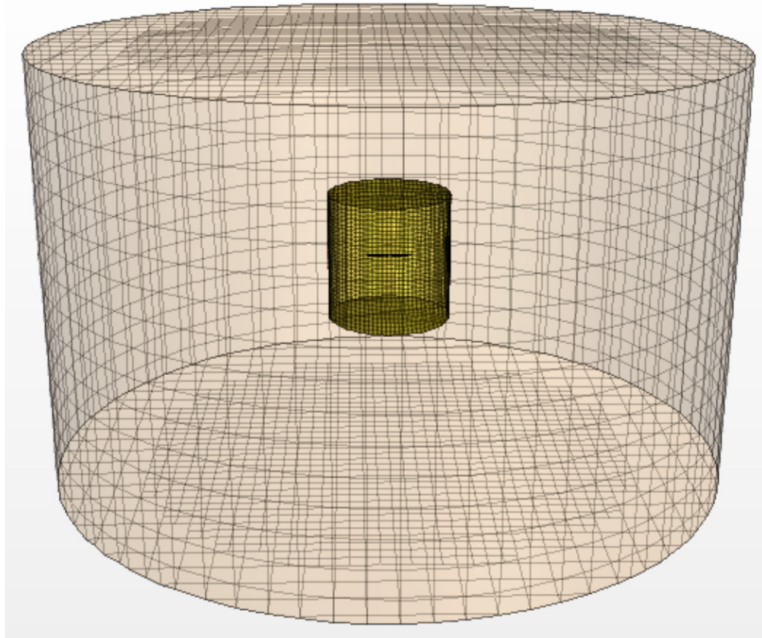


Figure 17. CFD Mesh

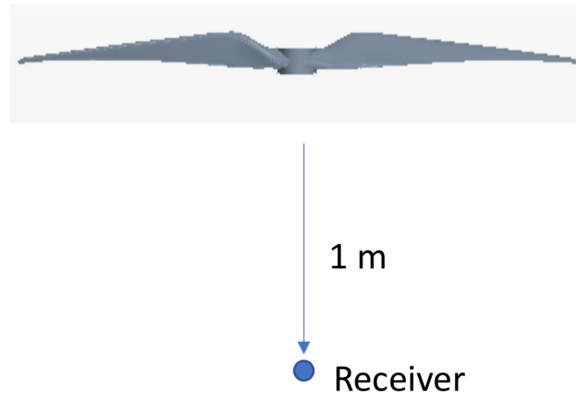


Figure 18. CFD Mesh

C. Computational Results

1. KDE Rotor

A parametric acoustic study of 13 anti-phase design candidates of the KDE rotor with different alternating TE waveforms, alternating TE length, TE deflection amplitude, and degrees of transition sharpness as listed in Table 1. These design candidates are designated by a numeral and a letter. The numeral designation indicates the number of periods of the TE waveform. Up to five-period TE waveforms are investigated. The letter designation indicates certain physical characteristics of the particular anti-phase TE design. The nominal TE deflection amplitude of the TE waveform is 10° in the majority of the design candidates. The changes in thrust and noise reduction in hover condition are listed in Table 1. The rotor speed is 4000 rpm in all cases.

Table 1 shows that as the number of periods in the TE waveform increases up to four while keeping all other parameters the same, the noise reduction increases up to +2.0 dB corresponding to design candidate 4A. Figure 19(a) illustrates the TE deflection amplitude of design candidate 4A. The one-period waveform actually results in a noise increase by 1.5 dB. The five-period waveform has a lower noise reduction than the four-period waveform. In all cases,

the thrust increases for all the design candidates. This is consistent with the hypothesis of the mechanism of thrust increase as discussed previously and also confirms the experimental results in the NASA Ames LifeSaver tunnel. The best design candidate in the hover condition is design candidate 4C which achieves a 5.1% increase in thrust and +2.1 dB noise reduction. Both the thrust increase and noise reduction increase of design candidate 4C are the largest.

Design Candidate	Number of Periods	Segment Length Fraction η	Deflection Amplitude ($^{\circ}$)	Phase Shift ($^{\circ}$)	Segment Transition (%)	Thrust Change (%)	Noise Reduction (dB)
Baseline	0	1	0	0	0	0	0
1A	1	1/2	10	180	40	+5.0	-1.5
2A	2	1/4	10	180	40	+4.0	+0.2
3A	3	1/6	10	180	40	+2.5	+0.3
3B	3	0.175, 0.183, 0.142	5, 10, 15	180	60, 50, 80	+4.0	+0.5
3C	3	1/6	15, 10, 5	180	80, 40, 20	+5.0	-0.8
3D	3	0.2, 0.167, 0.135	9, 12, 15	180	50, 60, 60	+2.0	+0.3
4A	4	1/8	10	180	80	+4.0	+2.0
4B	4	1/8	5	180	80	+2.1	+1.1
4C	4	1/8	6, 9, 12, 15	180	80	+5.1	+2.1
4D	4	1/8	10	90	80	-0.2	+1.5
4E	4	1/8	10	180	40	+3.8	+2.1
4F	4	1/8	10	180	90	+4.1	+1.9
5A	5	1/10	10	180	80	+2.8	+0.4

Table 1. KDE Anti-Phase Rotor Design Candidates in Hover Condition

A few design candidates explore the effects of modulating the TE deflection amplitude along the blade span, such as, design candidate 3B which employs a three-period TE waveform with a varying TE deflection amplitude from 5° at the blade root to 15° at the blade tip, design candidate 3C which employs a reverse TE deflection amplitude modulation, and design candidate 4C which employs a four-period TE waveform with a TE deflection amplitude modulation from 6° at the blade root to 15° at the blade tip as shown in Figure 19(b). It can be seen that in general increasing the TE deflection amplitude modulation toward the blade tip produces an increase in the noise reduction. The converse is true.

The TE deflection amplitude has a strong effect on the noise reduction. As the TE deflection amplitude increases up to a certain value, the noise reduction also increases. This is seen in design candidates 4A and 4B.

All but one design candidates employ equal TE segment lengths for all the TE waveforms. For example, design candidate 4A employs a four-period TE waveform with 8 equal TE segment lengths. Design candidate 3D is the only one that explores the effect of frequency modulation by varying the TE segment lengths which are equal to $0.2r$, $0.167r$, and $0.135r$ where r is the blade radius, for the first, second, and third period from the blade root to the blade tip. This is shown in Figure 19(c). The effect of frequency modulation is observed to be minor on the noise reduction.

All but one design candidates employ the standard 180° phase shift in the TE waveform between the two rotor blades. Design candidate 4D, shown in Figure 19(d), explores the effect of phase shift modulation by employing a 90° phase shift. The decrease in the phase shift from 180° is seen to produce a decrease in thrust and lower noise reduction. This seems to confirm the merit of the anti-phase rotor design which implies a 180° phase shift.

Design candidates 3B, 3C, 3D, 4E, and 4F explore the effect of the segment transition characteristics as the TE deflection amplitude changes from a negative to a positive value and vice versa. Figure 19(e) illustrates the TE deflection amplitude of design candidate 3C. The transition modulation is indicated by the percentage of the transition length to the semi-segment length. Thus, a 0% transition implies a perfect square wave and a 90% transition shows a gradual increase (or decrease) in the TE deflection amplitude at the midpoint of the TE segment. All other design candidates employ a 80% transition. The effect of the transition is observed to produce a small increase in the noise reduction as the transition decreases by comparing design candidates 4A, 4E and 4F.

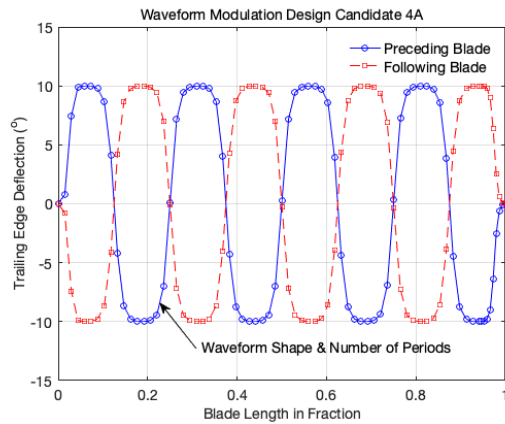
Table 2 shows the computation results for design candidates 4A, 4E, and 4F in the forward flight condition at a

forward speed of 9.7 m/s corresponding to an advanced ratio of 0.1. The effect of forward flight is seen as an increase in noise and a slight increase in thrust as well for design candidate 4A. In order to compare the noise reduction at the same thrust level, the angle of attack on the rotor is reduced to -1° . The thrust levels are nearly the same as that of the baseline rotor. All the anti-phase rotor design candidates still show varying levels of noise reduction ranging from +0.2 dB for design candidate 4F to +1.1 dB for design candidate 4E. Based on the results from Tables 1 and 2, design candidate 4E appears to offer the best noise reduction in both the hover and forward flight conditions.

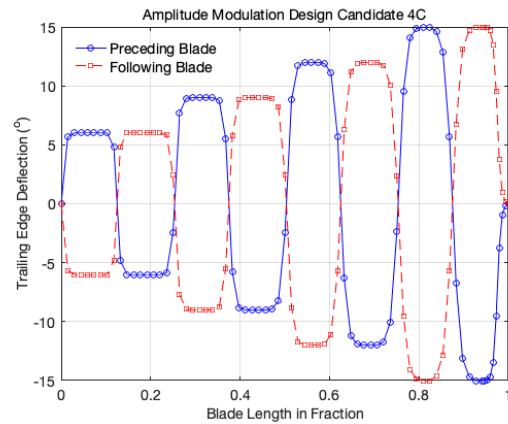
Design Candidate	Angle of Attack ($^\circ$)	Thrust Change (%)	Noise Reduction (dB)
4A	0	+4.5	-2.0
4A	-1	-0.1	+0.6
4E	-1	-0.2	+1.1
4F	-1	+0.2	+0.2

Table 2. KDE Anti-Phase Rotor Design Candidates in Forward Flight Condition at 9.7 m/s

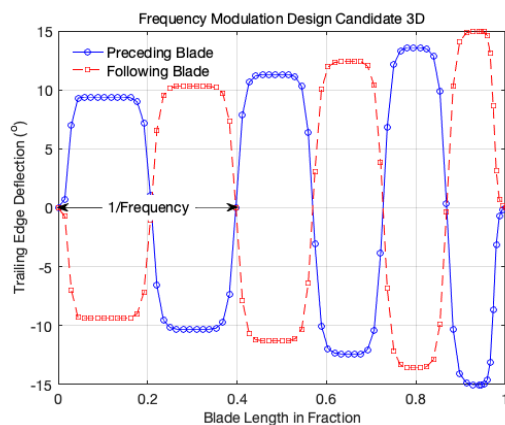
Figure 19 shows the TE waveforms of the selected anti-phase rotor design candidates of the KDE rotor.



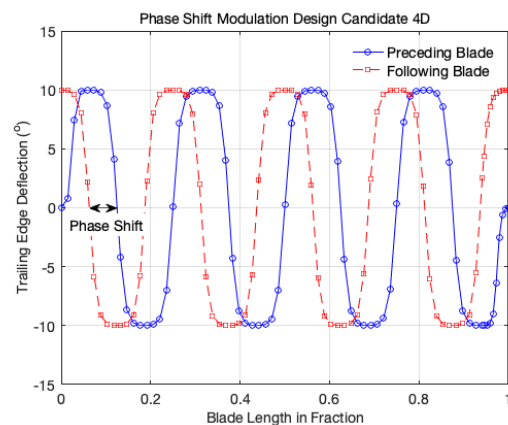
(a) 4A Design



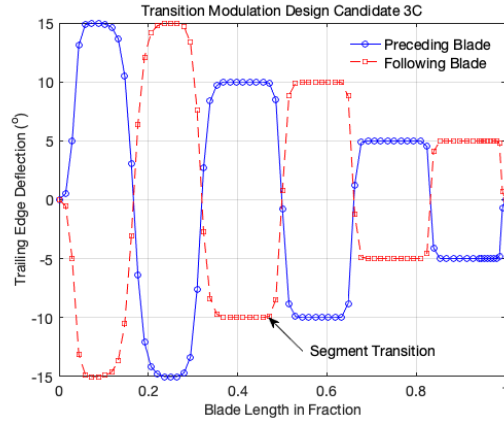
(b) 4C Design



(c) 3D Design



(d) 4D Design



(e) 3C Design

Figure 19. Select KDE Anti-Phase Rotor Trailing Edge Waveforms

2. APC Rotor

A small number of design candidates for the APC rotor are investigated. Using the results for the KDE anti-phase rotors as a guide, the design candidates for the APC rotors are selected to all have a four-period TE waveform. The APC rotors are simulated at 3200 rpm. The computational results for six different design candidates are shown in Table 3. Comparing APC design candidates 2A and 4A to the corresponding KDE anti-phase design candidates, the APC design candidates appear to produce a slightly more noise reduction than the corresponding KDE design candidates while the thrust levels between the two sets of design candidates are similar.

Design Candidate	Number of Periods	Segment Length Fraction η	Deflection Amplitude (°)	Tip Deflection (°)	Phase Shift (°)	Segment Transition (%)	Thrust Change (%)	Noise Reduction (dB)
Baseline	0	1	0	0	0	0	0	0
2A	2	1/4	10	0	180	40	+4.7	+1.0
4A	4	1/8	10	0	180	80	+3.3	+1.8
4E	4	1/8	10	0	180	40	+3.7	+2.7
4G	4	1/8	15	0	180	40	+0.5	+2.9
4H	4	1/8	10	10	180	40	+3.2	+4.0
4I	4	1/8	10	10	0	40	+3.9	+2.5

Table 3. APC Anti-Phase Rotor Design Candidates in Hover Condition

Two new anti-phase design candidates are investigated with design candidates 4G and 4H. For comparison, an in-phase design is also examined with design candidate 4I. Design candidate 4G employs a larger TE deflection amplitude of 15°. At this TE deflection amplitude, it appears that the blade is near or in stall. This is evident in the reduced thrust level from that for design candidate 4E which has a TE deflection of 10°. The noise reduction is slightly better with design candidate 4G than 4E, but the blade performance in stall is hardly desirable.

An interesting observation is seen with design candidate 4H. All of the design candidates up to now employ TE waveforms that starts at the blade root and ends at the blade tip at a zero TE deflection as shown in Figure 19. Design candidate 4H, however, does not transition to a zero TE deflection. Instead, the TE deflection of the last segment at the blade tip is kept constant all the way to the blade tip as shown in Figure 20(a). As a result, the positive lift created at one of the blade tips of the anti-phase rotor generates a larger tip vortex roll-up than that if the TE deflection were to be brought to zero at the tip. At the same time, the negative lift created at the other blade tip generates a larger tip vortex

in the opposite direction than that with the zero TE deflection at the tip. The net effect is that these two tip vortices are non-coplanar, thereby reducing the tip vortex interaction, similar to the co-rotating tip vortices illustrated in Figure 13. Design candidate 4H achieves a 4.0 dB noise reduction, the largest of all the design candidates investigated so far. This result coupled with the test data for the anti-phase rotor with asymmetric tips conducted in 2018 suggests that the asymmetric lift creation at the rotor blade tip could be a strong mechanism for noise reduction.

The in-phase design candidate 4I shown in Figure 20(b) interestingly also shows a noise reduction of 2.5 dB. This noise reduction is speculated to come mostly from the alternating TE waveform. Thus, this data provides the evidence that the alternating TE waveform is a source of noise reduction as postulated in Section 2. Comparing to the anti-phase design candidate 4H, it can be seen that the additional 1.5 dB noise reduction comes from the anti-phase TE design. Therefore, this data also confirms the noise reduction effectiveness of the anti-phase rotor design as postulated in Section 2. Furthermore, these two data points also suggests that the alternating TE waveform may produce a larger noise reduction than the anti-phase TE design.

Figure 20 shows the TE waveforms of the design candidates of the APC rotor.

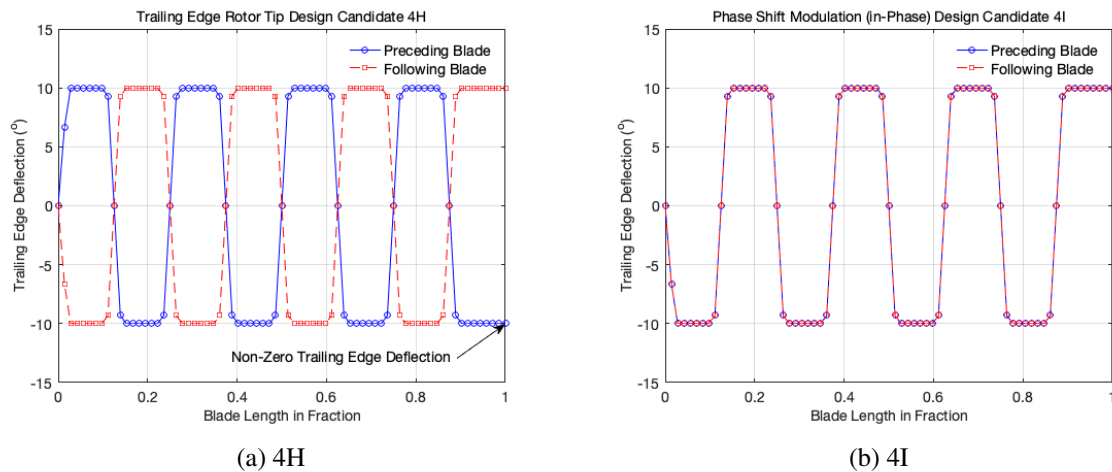


Figure 20. Select APC Anti-Phase Rotor Trailing Edge Waveforms

D. Acoustic Evaluation by CHARM / PSU-WOPWOP

CHARM is a commercial rotorcraft aeromechanics software package developed by Continuum Dynamics, Inc. (CDI). It is widely used in the rotorcraft industry. Under a NASA funded effort, CDI is developing new capabilities in CHARM for a new class of UAM DEP vehicles. CHARM is a vortex-lattice solver with semi-empirical methods for aeromechanics prediction of rotorcraft. PSU-WOPWOP is an aeroacoustic code developed by Brentner et al.¹³ Unsteady blade loading predicted by CHARM is used by PSU-WOPWOP to predict rotor acoustics. An acoustic evaluation of a subset of the KDE design candidates is conducted using CHARM by CDI. The acoustic evaluation by CHARM / PSU-WOPWOP could provide increased confidence in the CFD acoustic prediction by STAR-CCM+.

In this study, CHARM does not model the actual blade airfoil profiles but instead model the airfoil profiles as a NACA 0012 airfoil with varying chord and twist as shown in Figure 21. Because CHARM does not model the actual blade profiles, the absolute comparison with the CFD results is not considered. Rather, the trend in the CHARM results is sought for comparing with the CFD results.

Two vortex lattice models of the baseline KDE rotor are created with a one-row lattice and a five-row lattice to predict the propagation of the sound pressure level (SPL) at one diameter beneath the rotor. In contrast, the SPL computed by STAR-CCM+ is at about two diameters beneath the rotor. Figure 22 illustrates the two models in CHARM.

Figure 23 shows the overall and BVI SPLs of the baseline rotor computed with the one-row lattice model and five-row lattice model in the forward flight condition at 9.7 m/s corresponding to an advanced ratio of $\mu = 0.1$ and a zero shaft angle or an attack of attack of $\alpha_s = 0$. The overall SPLs for both models are very similar. Therefore, the

one-row lattice model is sufficient for the acoustic evaluation. In the forward flight condition, the BVI SPL constitutes about 86% of the overall SPL of the baseline rotor.

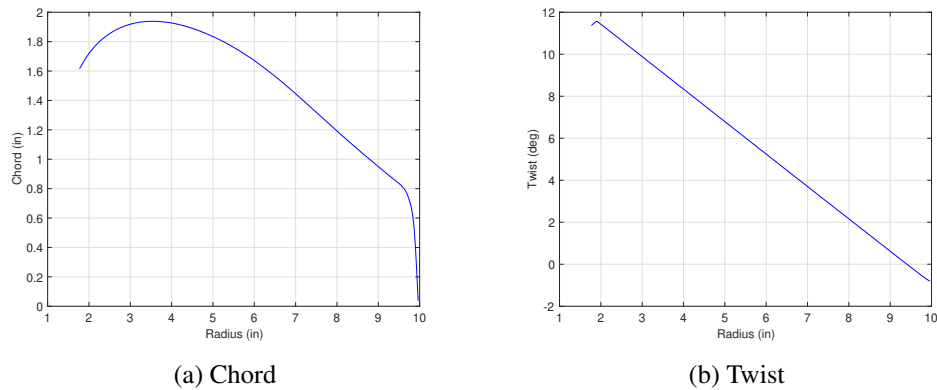


Figure 21. KDE Rotor Geometry

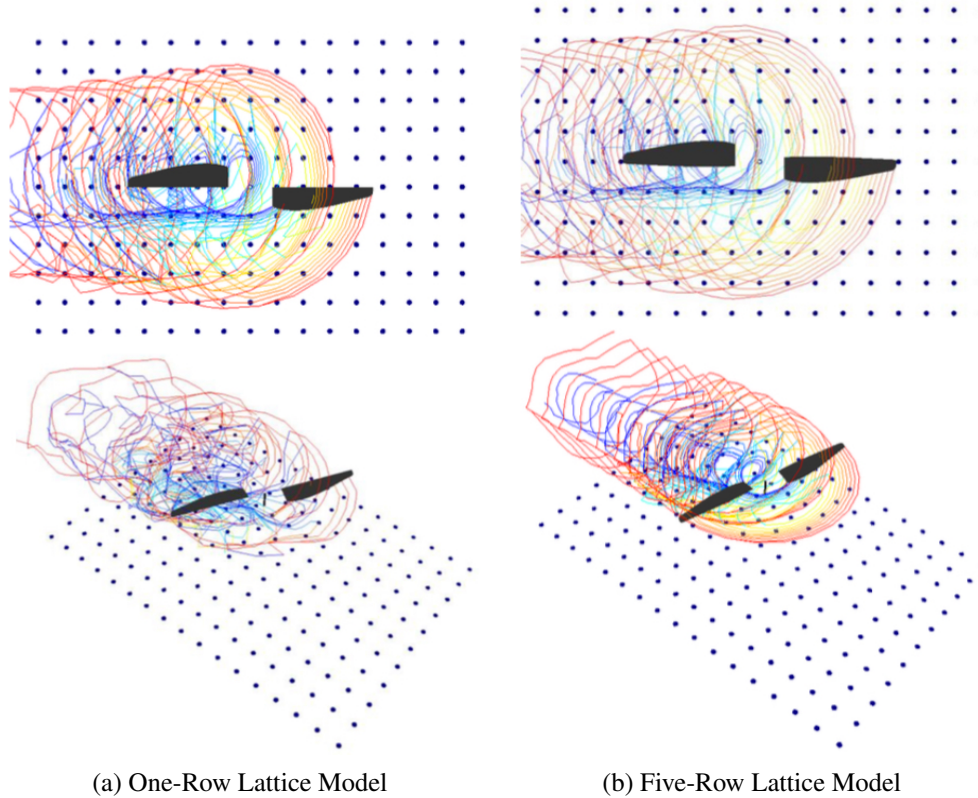


Figure 22. CHARM Models of KDE Equivalent Baseline Rotors

Figure 24 shows the overall SPLs of the baseline and anti-phase rotor design candidates 2A, 3B, 4A, 4C, and 5A. The overall SPLs of the anti-phase rotors generally increase by 2 dB to 8 dB. The general increase in the SPL could be due to the general increase in the thrust level produced by the anti-phase rotors. The CHARM results do not attempt to match the thrust level produced by the anti-phase rotors. The CHARM results in Figure 24 seems to support the trend found in the CFD results that design candidate 4A generally produces lower noise than most of the other design candidates.

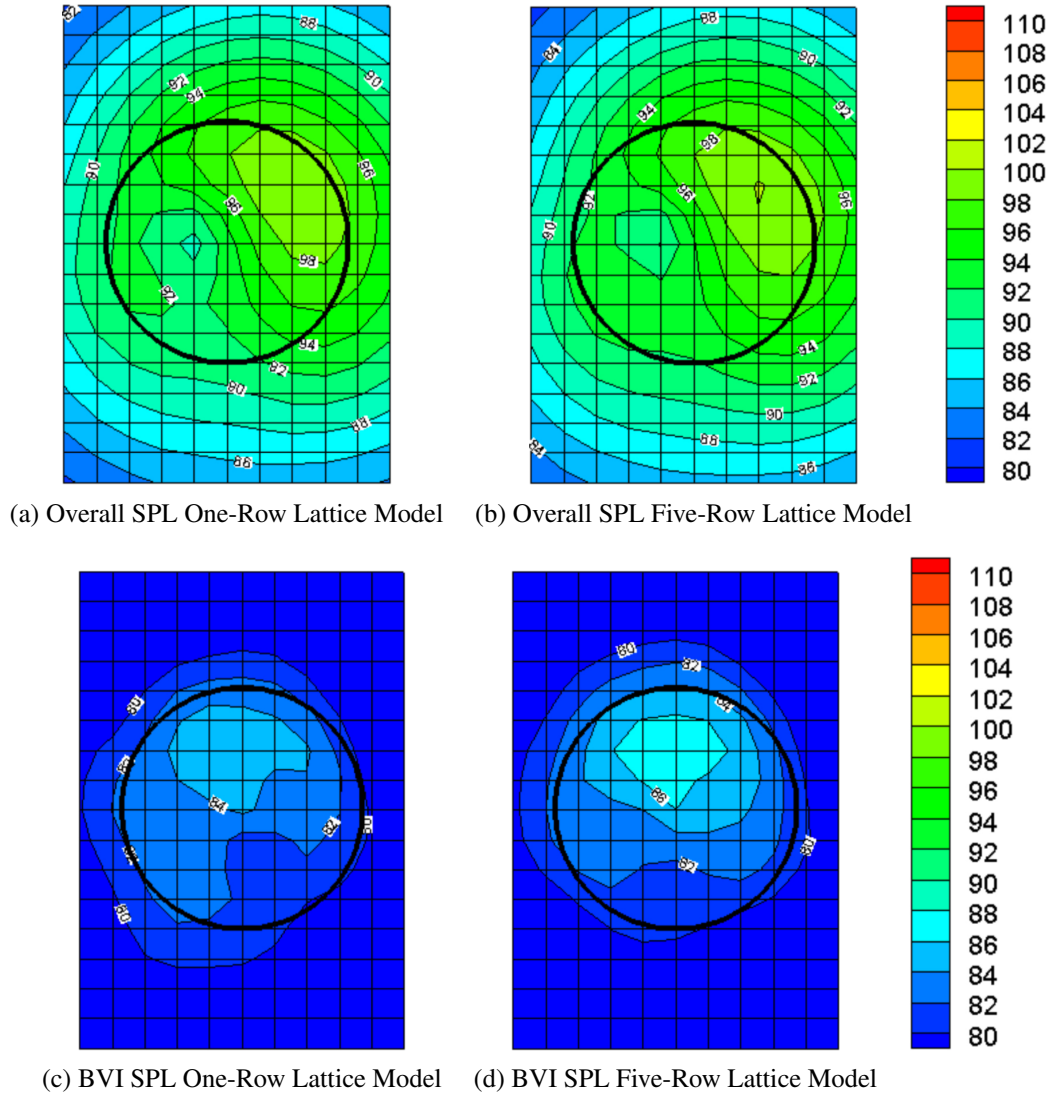


Figure 23. SPL of Baseline Rotor at 9.7 m/s and $\alpha_s = 0^\circ$ Computed with One-Row and Five-Row Lattice Models

An acoustic evaluation in forward flight is conducted in CHARM at a forward flight speed of 16 m/s corresponding to an advance ratio of $\mu = 0.15$ and a shaft angle of $\alpha_s = 6^\circ$. This flight condition is known to produce BVI in the HART rotor.¹⁴ Figure 25 shows the overall SPLs of the anti-phase rotor design candidates. Both design candidates 2A and 3B produce more noise than the baseline rotor by 2 dB. On the other hand, the other design candidates produce less noise than the baseline rotor by as much as 4 dB achieved with design candidate 4A. Both sets of CHARM results for two different forward flight conditions indicate that design candidate 4A has lower noise characteristics than the other design candidates. This observation is consistent with the CFD results which also indicate that the four-period TE waveform in general produces better noise reduction than the other TE waveforms.

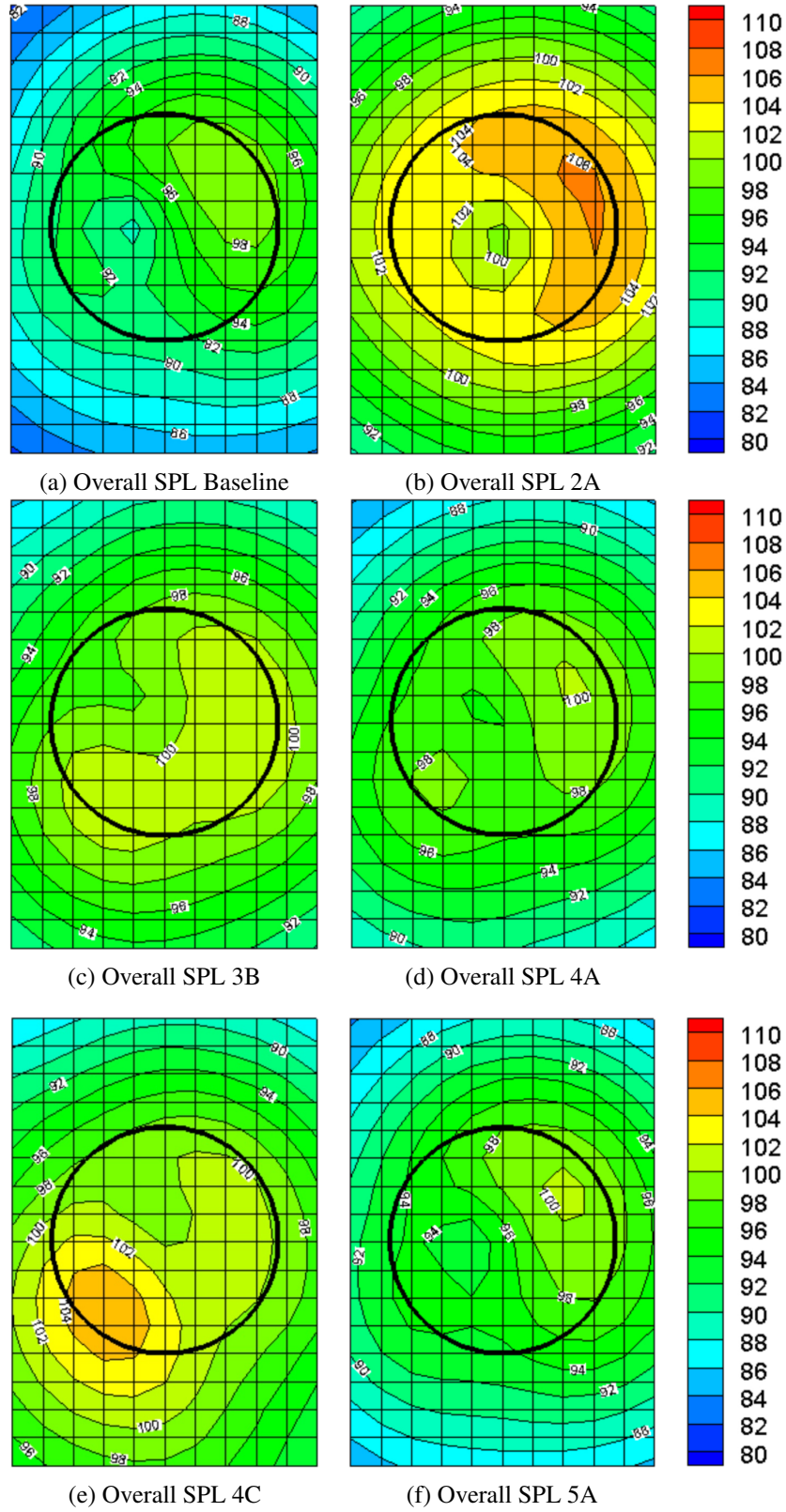


Figure 24. SPL of Baseline and Anti-Phase Rotors at 9.7 m/s and $\alpha_s = 0^\circ$

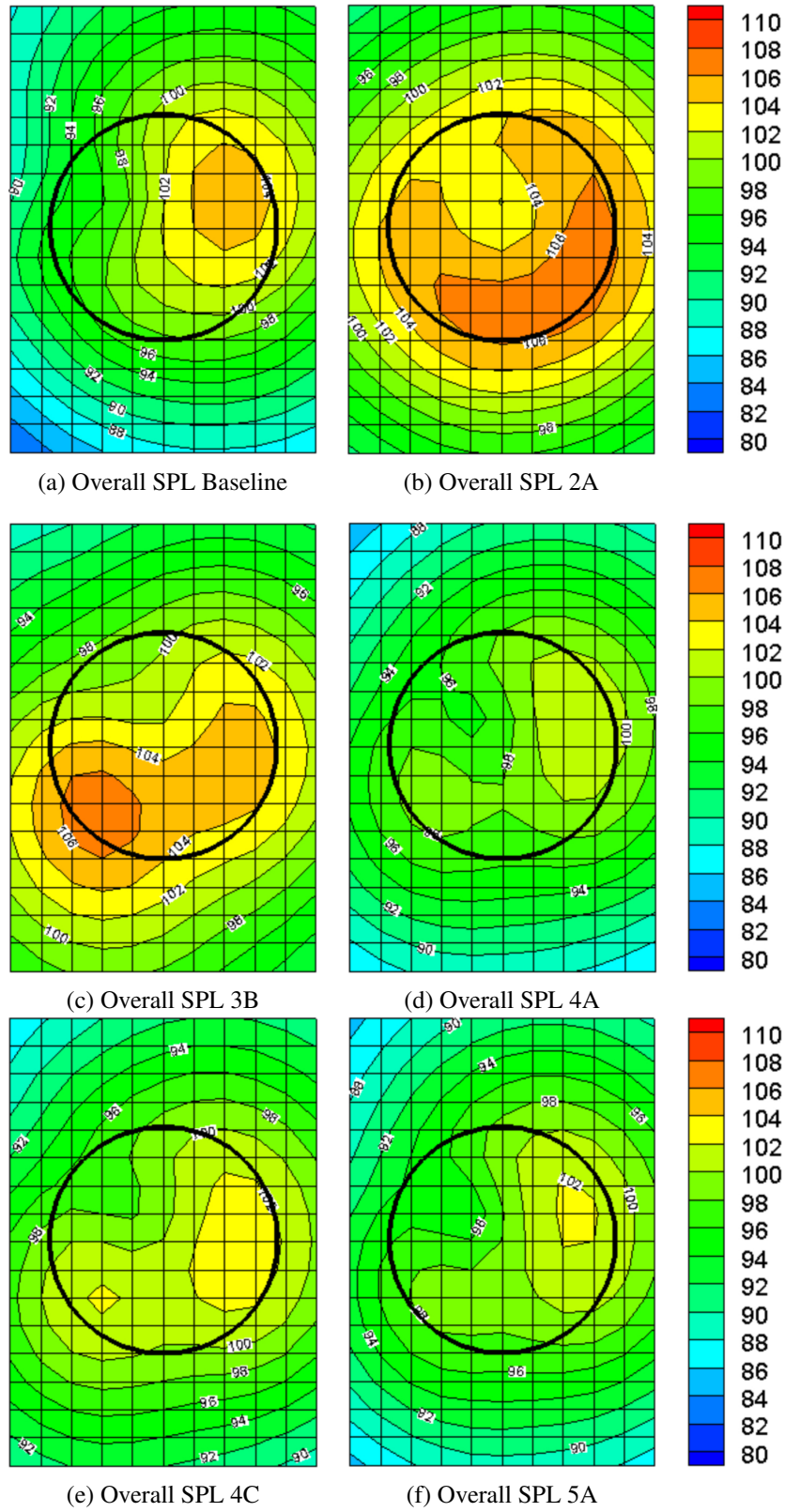


Figure 25. SPL of Baseline and Anti-Phase Rotors at 16 m/s and $\alpha_s = 6^\circ$

IV. Experimental Investigation

Two acoustic test entries were conducted in July 2019 and October 2019. The first test entry involves both the KDE and APC rotors. During this test entry, the APC rotor was first fabricated with an in-phase 4I rotor design. The APC anti-phase 4H rotor was tested during second test entry along with the in-phase 4I rotor. The experimental results for first test entry have been reported in Ref.¹⁵ This paper reports the experimental results of the second test entry. The details of the experiment can be found in Ref.¹⁶

A. Experimental Setup

An experimental investigation of the noise reduction characteristics of the anti-phase rotor is conducted in the PSU anechoic chamber called the PSU high speed jet noise facility as shown in Figure 26. Figure 27 shows the anechoic chamber and the microphone array setup. The anechoic chamber has a theoretical cut-off frequency of 500Hz and contains a forward flight duct that allows for different flight conditions to be tested such as forward flight and side gust conditions.

PSU has developed a novel acoustic test rig that allows for the creation of an experimental acoustic sphere around a noise source. The test rig pictured in Figure 28(a) consists of a half-circular microphone array, shown in Figure 28(b), that has 19 housings for 1/2-inch microphones. The separation angle between each microphone is 10° . The array is installed on a post and can be rotated manually around the axis. Rotating the whole microphone array around the pole allows for the creation of a complete experimental acoustic sphere around the noise source. The test rig has the flexibility to test any noise source including unmanned aerial vehicle (UAV) rotors in multiple configurations such as single rotor, co-axial counter rotating rotors, co-axial same direction rotors as well as scaled down helicopter rotors.

The rotor system can be configured for a single rotor or co-axial rotors. Each rotor has two blades. The two co-axial rotors can be activated or shut down independently to allow for single or co-axial rotor configuration tests. The angular velocity is measured by two optical RPM sensors. Thrust and power are quantified by two sets of force and torque sensors, respectively. Details are seen in Figure 29. Both a RPM and a thrust control are developed for the test setup. For the tests, only the bottom rotor is activated and used.

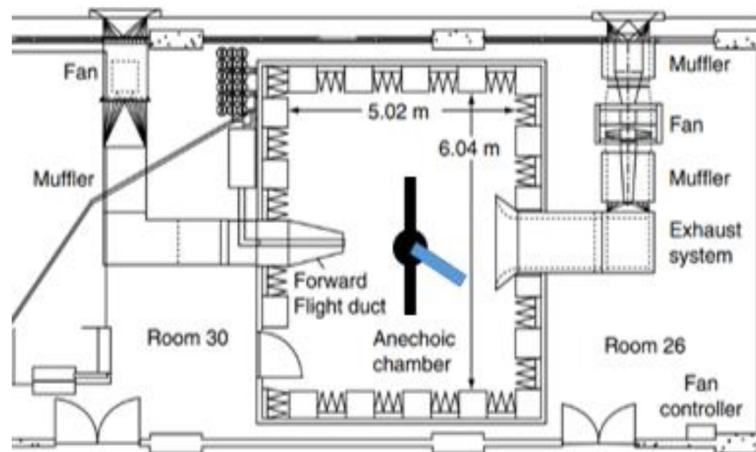


Figure 26. Anechoic Chamber with Forward Flight Duct at Pennsylvania State University

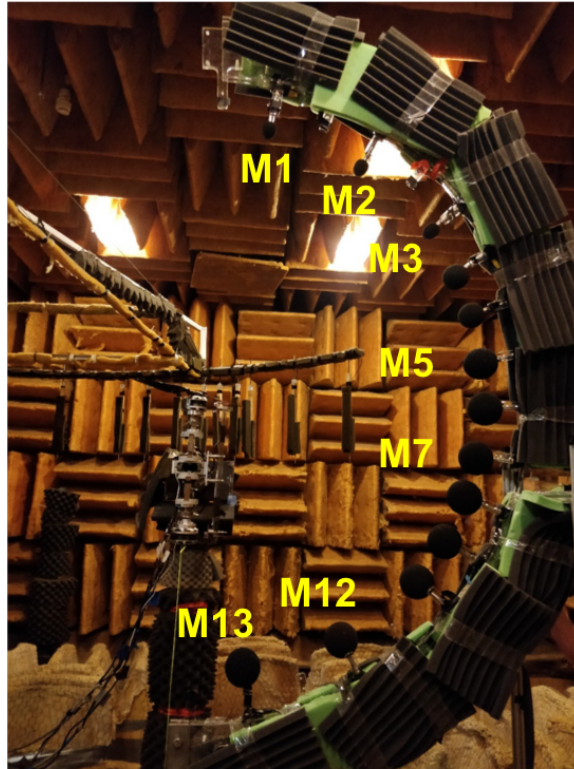


Figure 27. Anechoic Chamber

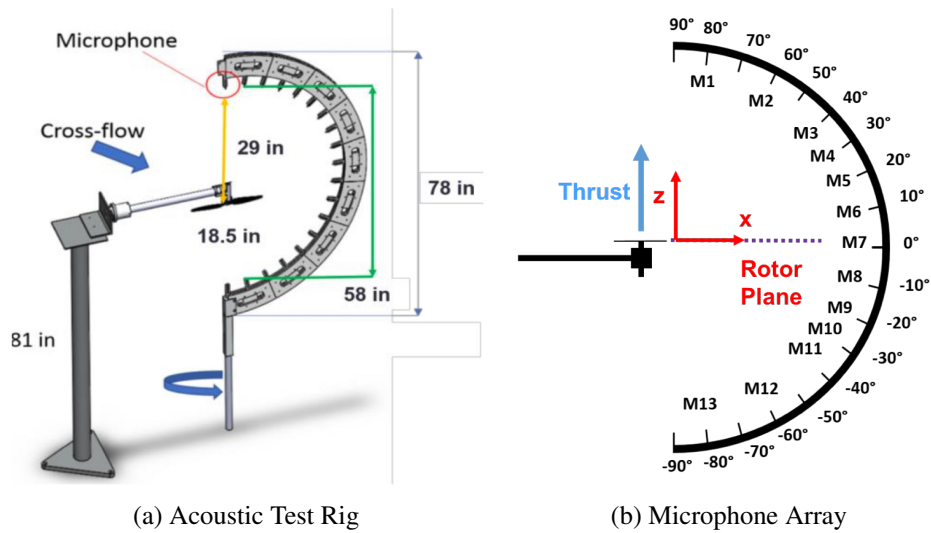


Figure 28. Acoustic Test Rig with Microphone Array

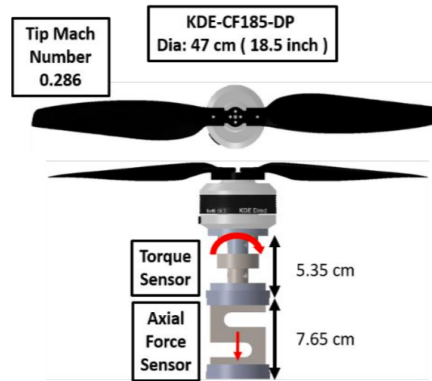


Figure 29. Acoustic Test Rotor and Sensors

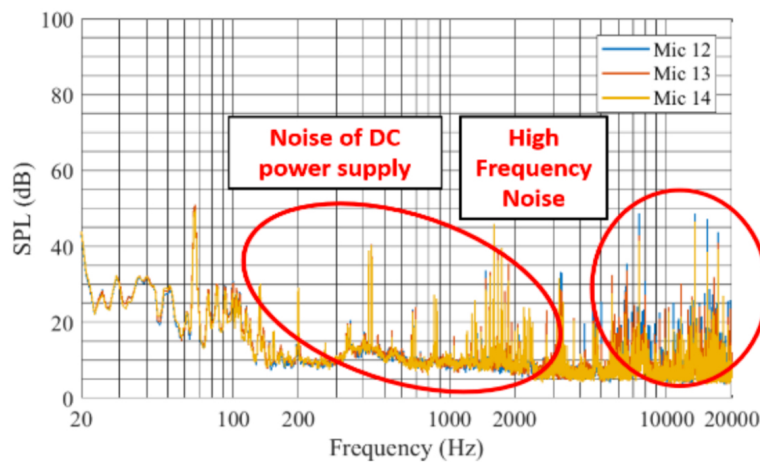


Figure 30. Background Noise Level Mic 12 – 14, No Blades, @ 4000 RPM and Wind Tunnel Speed of 0 m/s

A background noise measurement has been conducted in preparation for the acoustic test. The background noise level of the test chamber is documented as the baseline acoustic reading. Figure 30 shows the background noise from microphones 12 to 14 when the motor spins at 4000 RPM without the rotor installed. The microphone choice displayed here is arbitrary. A fast Fourier transform (FFT) and a running average are used to generate Figure 30. The limitation of such a method could be that a periodic noise will be displayed to be around its average value. Two major components on top of the baseline reading are seen. They are the DC power supply noise and the high frequency noise. The DC power supply sits in the anechoic chamber with the experimental setup due to current limitations of available connection points. This is set to be mitigated and improved in the future. The high frequency noise is determined to be the noise from the motors. This high frequency noise will be present all throughout the series of test. The removal of this high frequency noise from the experimental data plots in subsequent cases would be more representative of the incremental noise produced by the setup. This method of displaying data is preferred by rotorcraft acousticians.

B. Acoustic Test in July 2019

The tested blades for the anechoic chamber and data acquisition verification are modified to incorporate the anti-phase trailing edge designs. The first design of the anti-phase trailing edge rotor blades is based on design candidate 4A of the KDE rotor. The numerical investigation of the KDE rotor is based on the initial geometry furnished by PSU. NASA provides PSU with the CAD geometry of the initial modified KDE rotor for design candidate 4A. However, it is discovered that the original CAD geometry of the KDE rotor furnished by PSU for NASA to conduct CFD simulations is different from the actual KDE rotor to be tested (see Figure 15). As a result, PSU has to modify the actual KDE rotor geometry to incorporate the anti-phase trailing edge design. The modified rotor blades are shown in Figure 31.

The modification involves removing the TE portion of the KDE baseline blade and gluing an anti-phase TE fabricated by 3D printing back to the partially cut blade. Because the cutting and gluing cannot be accurately controlled, the actual shape of the modified KDE anti-phase rotor could deviate from the intended 4A design.



(a) KDE Blade with Trailing Edge Cuts (Top) and Completed Trailing Edge Modified Blade (Bottom) (b) Front View of Completed Trailing Edge Modified Blade

Figure 31. KDE Anti-Phase Rotor Blade with Design Candidate 4A

The second tested rotor is based on the APC in-phase 4I design candidate which is accidentally fabricated as an in-phase 4I design instead of the intended anti-phase 4H design. Upon this discovery, a verification of the KDE rotor is made and confirms that the KDE test rotor is indeed an anti-phase design. The APC rotor blades are fabricated by 3D printing. The in-phase rotor has two identical rotor blades since the TE waveforms are the same for both blades. Both the APC baseline and in-phase 4I rotors are shown in Figure 32. Small pieces of tape can be seen at the tip of the APC baseline rotor which are for rotor balancing. It should be noticed that the APC test rotors are fabricated in a right-hand rule sense which produces the thrust vector by a counter clockwise rotation. This rotation becomes a factor during the October 2019 test entry as discussed later.



(a) APC Baseline Rotor



(b) APC In-Phase 4I Rotor

Figure 32. APC Baseline and In-Phase 4I Rotors

The summary of the experimental results of the July 2019 test entry is provided as follows:

1. Hover Condition

The KDE baseline and anti-phase 4A rotors are tested at 3200 RPM under the hover condition. The comparison of the aerodynamic performance of the rotors is shown in Table 4. The anti-phase 4A rotor produces 16.4% less thrust

than the KDE baseline rotor. The torque of the anti-phase rotor is 5.6% smaller than that of KDE baseline rotor. The power loading is defined as the thrust divided by the power, where the power is equal to the rotor torque times the angular velocity. The power loading is a measure of the efficiency of a rotor or the amount of thrust per unit of power. The power loading of the anti-phase 4A rotor is 11.5% smaller than that of the KDE baseline rotor, indicating that the anti-phase rotor is less efficient than the KDE baseline rotor. This lower efficiency is not observed in the CFD results. The discrepancy is likely attributed to the difference in the actual geometry of the KDE rotor in the testing and the geometry analyzed by NASA in the CFD simulations as well as the imprecise fabrication process by cutting and gluing the anti-phase TE which could cause the TE angle to deviate substantially from the intended design. Therefore, the test results of the modified KDE anti-phase rotor cannot be directly compared to the CFD results.

Design Candidate	Average RPM	Average Thrust (N)	Average Torque (Nm)	Power Loading (s/m)
Baseline	3203.0033	11.5285	0.2705	0.1271
4A	3202.2600	9.6335	0.2554	0.1125

Table 4. Aerodynamic Performance Comparison of KDE Baseline and Anti-Phase 4A Rotors in Hover Condition

Figure 33 shows the OASPL (Overall Sound Pressure Level) directivity plot which presents the OASPL at different azimuthal angles around the rotor. As seen, the KDE anti-phase 4A rotor, labeled as 'modified', does not offer any noise reduction.

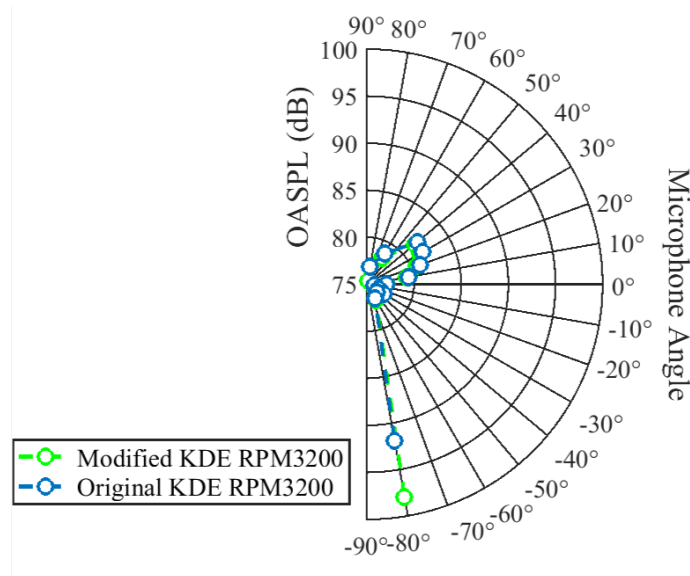


Figure 33. OASPL Directivity Plot of KDE Baseline and Anti-Phase 4A Rotors in Hover Condition

Next, the APC baseline and in-phase 4I rotors are tested at 3200 RPM in the hover condition. The comparison of the aerodynamic performance of the two rotors is shown in Table 5. The in-phase 4I rotor produces 3.1% larger thrust, but 11.7% greater torque than the APC baseline rotor. Therefore, the power loading of the APC in-phase 4I rotor is 7.7% smaller than that of the APC baseline rotor, thus indicating less efficiency with the in-phase 4I rotor. Figure 34 shows the OASPL directivity plot. The in-phase 4I rotor, labeled as 'modified', only offers a minor noise suppression in the hover condition.

The experimental data of the APC in-phase rotor in the hover condition does not agree with the CFD results but generally agrees with the CHARM results. However, as noted by the PSU research staff, acoustic tests in the hover condition generally cannot provide conclusive experimental results because it is well-known that the downwash created by the rotor causes the flow in the anechoic chamber to recirculate back to the rotor. This flow recirculation which is not present in the actual flight operation could introduce a noise reflection, hence uncertainty in the experimental data.¹⁷ To improve acoustic testing in hover, PSU suggests that new experimental techniques would need to be developed

in order to eliminate the flow recirculation. Thus, the experimental results for the APC in-phase rotor in the hover condition should be interpreted with a high degree of uncertainty.

Design Candidate	Average RPM	Average Thrust (N)	Average Torque (Nm)	Power Loading (s/m)
Baseline	3198.90	8.8763	0.2033	0.1303
4H	3201.43	9.1471	0.2268	0.1203

Table 5. Aerodynamic Performance Comparison of APC Baseline and In-Phase 4I Rotors in Hover Condition

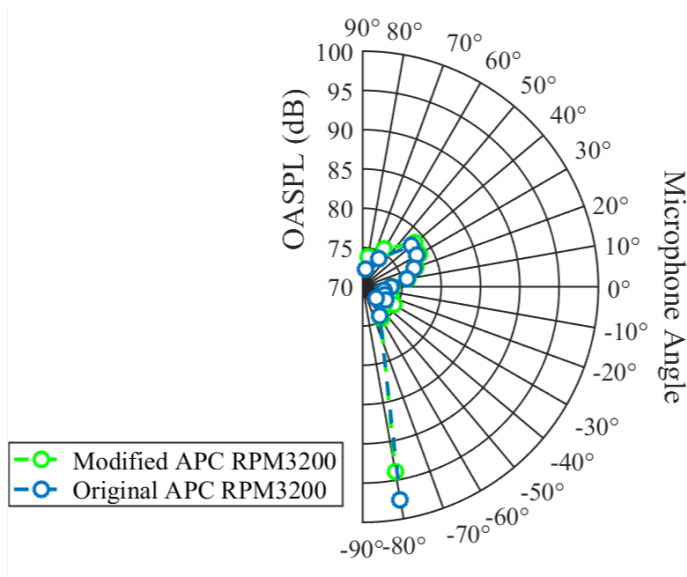


Figure 34. OASPL Directivity Plot of APC Baseline and In-Phase 4I Rotors in Hover Condition

2. Forward Flight Condition at 9.7 m/s

The APC baseline and in-phase 4I rotors are also tested at 3200 RPM in the forward flight condition at 9.7 m/s. The comparison of the aerodynamic performance of the two rotors is shown in Table 6. The APC in-phase 4I rotor produces 5.23% larger thrust and 3.3% more torque than the APC baseline rotor. The power loading of the APC in-phase 4I rotor is 2.1% greater than that of the APC baseline rotor, thus indicating that the APC in-phase 4I rotor is aerodynamically more efficient than the APC baseline rotor.

Design Candidate	Average RPM	Average Thrust (N)	Average Torque (Nm)	Power Loading (s/m)
Baseline	3200.27	9.56	0.207	0.1375
4H	3199.90	10.06	0.214	0.1406

Table 6. Aerodynamic Performance Comparison of APC Baseline and In-Phase 4I Rotor in Forward Flight Condition at 9.7 m/s

Figure 35 shows the OASPL directivity plot which indicates that the APC in-phase 4I rotor offers up to 2 dB noise suppression across a wide range of the microphone zenithal angles.

Figure 36(a) shows the comparison of the SPL spectra at the M4 microphone location (see Figure 28) between the APC baseline and in-phase 4I rotors. The SPL spectra indicate a clear evidence of a significant noise reduction due to the APC in-phase 4I rotor across a wide human audible frequency range of 20-20000 Hz. The experimental results thus confirms that an in-phase rotor design could also offer a noise reduction benefit which is originally stipulated for an anti-phase rotor design.

Figure 36(b) shows the SPL spectra in the low frequency range of 20-200 Hz. The first peak corresponds to one times the rotor angular speed of 53.3 Hz or one-per-rev. The APC baseline rotor produces 65 dB at this frequency whereas the APC in-phase 4I rotor reduces this SPL to 46 dB, a 30% reduction. The second peak corresponds to the blade passing frequency at twice the rotor angular speed, or two-per-rev, at 106.7 Hz. The SPLs between the APC baseline and in-phase 4I rotors are similar at this frequency although a 1 dB reduction in the SPL with the in-phase 4I rotor is discernible. The third peak corresponds to three times the rotor angular speed, or three-per-rev, at 160 Hz. The APC in-phase 4I rotor virtually eliminates this peak produced by the APC baseline rotor. Thus, it can be seen that the APC in-phase 4I rotor offers a significant noise reduction in a low frequency range. This frequency range can cause a sensitivity in the human hearing because a low-frequency sound wave can travel farther than a high-frequency sound wave.

One interesting observation can be made is that the APC in-phase 4I rotor somehow produces significant SPL reductions at all odd multiple integers of the rotor angular speed. This is evident in Figures 36(a), (b), and (c) which show the SPL peaks at the odd multiple integers of the rotor angular speed up to 700 Hz. In most cases, the APC in-phase 4I rotor virtually eliminates these peaks. On the other hand, the SPL peaks at the even multiple integers of the blade angular speed are only slightly reduced. The physics of the noise reduction at the multiple odd and even integers of the rotor angular speed is not well understood and needs to be further investigated. One possible speculation is that the one-per-rev and the odd multiple integers of the blade angular speed could be associated with a rotor blade that encounters its own wake which occurs once in a revolution. The SPL reductions at these frequencies could be due to the breaking up of the blade vortices with the alternating TE waveforms which weakens the blade vortices as they travel around in one revolution.

Figure 36(c) and (d) shows a broadband noise reduction of up to 4 dB with the APC in-phase 4I rotor in the frequency range of 2000-4000 Hz. This frequency range is thought to be a frequency range in which human hearing tends to be most sensitive to noise annoyance.

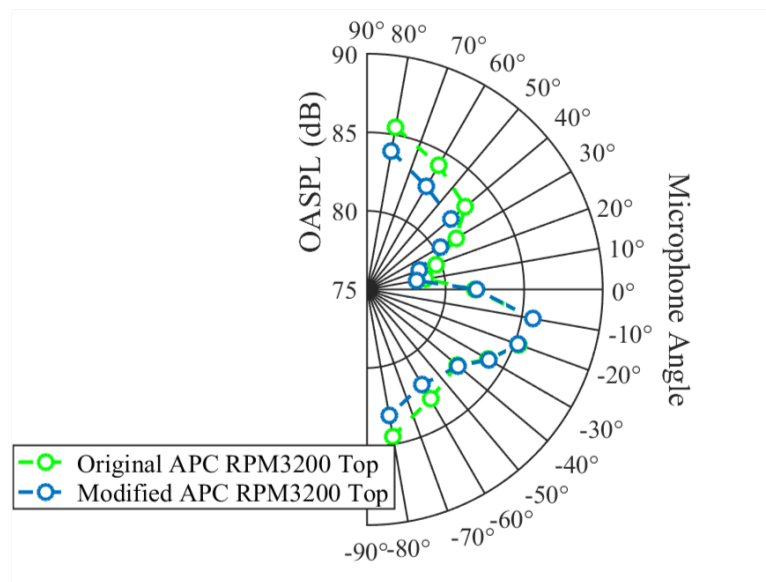
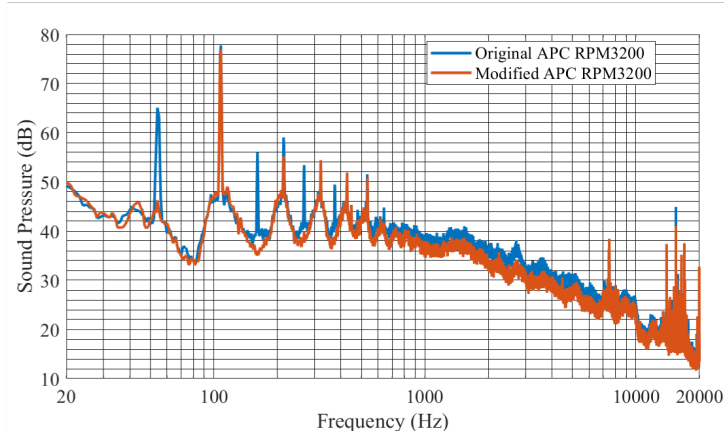
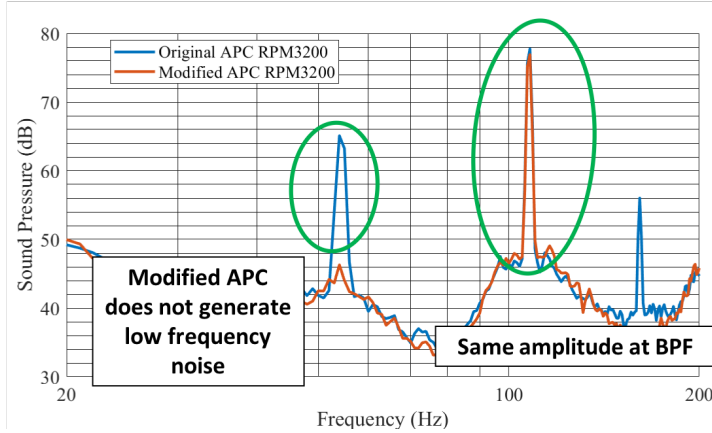


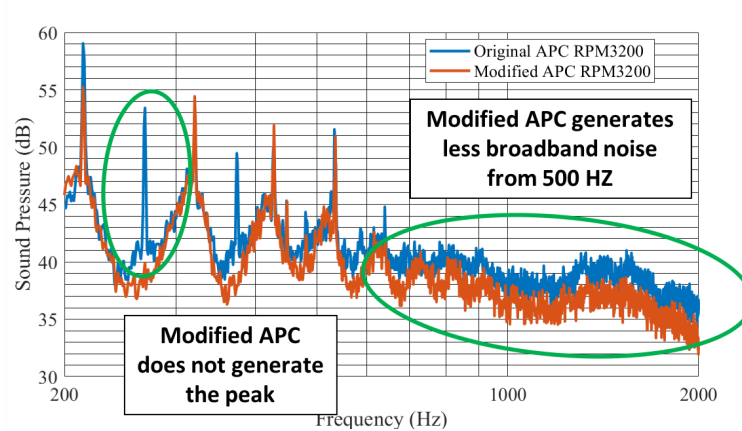
Figure 35. OASPL Directivity Plot of APC Baseline and In-Phase 4I Rotors in Forward Flight Condition at 9.7 m/s



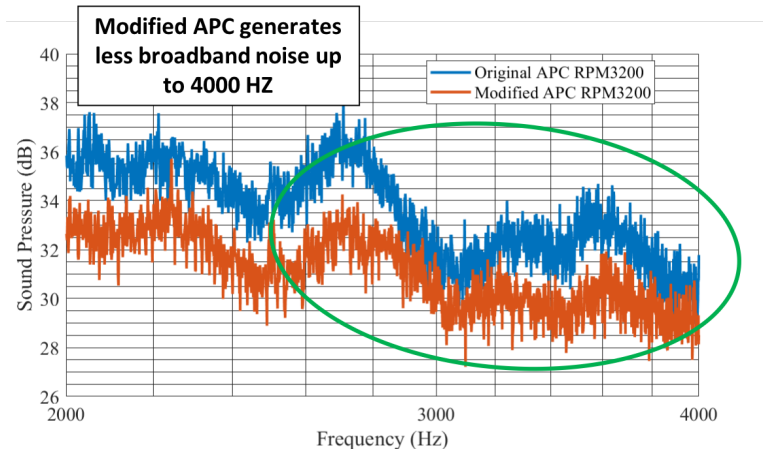
(a) SPL Spectra of APC Baseline and In-Phase 4I Rotors in Frequency Range of 20-20000 Hz



(b) SPL Spectra of APC Baseline and In-Phase 4I Rotors in Frequency Range of 20-200 Hz



(c) SPL Spectra of APC Baseline and In-Phase 4I Rotors in Frequency Range of 200-2000 Hz



(d) SPL Spectra of APC Baseline and In-Phase 4I Rotors in Frequency Range of 2000-4000 Hz

Figure 36. SPL Spectra of APC Baseline and In-Phase 4I Rotors at M4 Microphone Location in Forward Flight Condition at 9.7 m/s

C. Acoustic Test in October 2019

The July 2019 test entry reveals a noise suppression benefit of an in-phase rotor design. During the October 2019 test entry, six APC rotors are fabricated: a baseline rotor, an anti-phase 4H rotor, and an in-phase 4I rotor, each of which is fabricated for the left-hand clockwise (CW) rotation and right-hand counter-clockwise (CCW) rotation. They are illustrated in Figure 37.



(a) APC Anti-Phase 4H Left-Hand CW Rotor



(b) APC Anti-Phase 4H Right-Hand CCW Rotor



(c) APC In-Phase 4I Left-Hand CW Rotor



(d) APC In-Phase 4I Right-Hand CCW Rotor

Figure 37. APC Anti-Phase 4H and In-Phase 4I Left-Hand and Right-Hand Rotors

Figure 38 illustrates the rotations of the anti-phase 4H left-hand and right-hand rotors in relation to the forward flight speed emulated by the jet flow velocity. The microphone array is located to the left side of the rotors. Thus, for the left-hand rotors, the left side is the advancing side where the relative airspeed is the sum of the forward flight speed and the tangential speed. Conversely, for the right-hand rotors, the left side is the retreating side where the relative speed is the difference between the forward flight speed and the tangential speed.

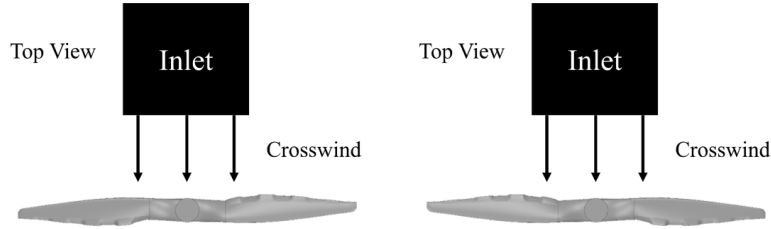


Figure 38. APC Anti-Phase 4H Left-Hand and Right-Hand Rotors in Forward Flight Condition

The summary of the experimental results of the October 2019 test entry is provided as follows:

1. *Hover Condition*

1. APC Right-Hand Rotors in Counter-Clockwise Rotation:

To directly compare to the July 2019 test entry, the results for the APC right-hand rotors are presented first. Table 7 presents the comparison of the aerodynamic performance of the APC right-hand rotors in the hover condition with matching RPM. Comparing to Table 5, the thrust produced by the baseline rotor differs by 8.3% from the mean of the two thrust values. This could suggest that the variability in the thrust could be due to the physical differences in the blade fabrication.

Design Candidate	Average RPM	Average Thrust (N)	Average Torque (Nm)	Power Loading (s/m)
Baseline	3199.23	9.6444	0.2174	0.1324
4H	3199.69	8.3318	0.1828	0.1360
4I	3204.87	9.6644	0.2303	0.1250

Table 7. Aerodynamic Performance Comparison of APC Right-Hand Rotors in Hover Condition with Matching RPM

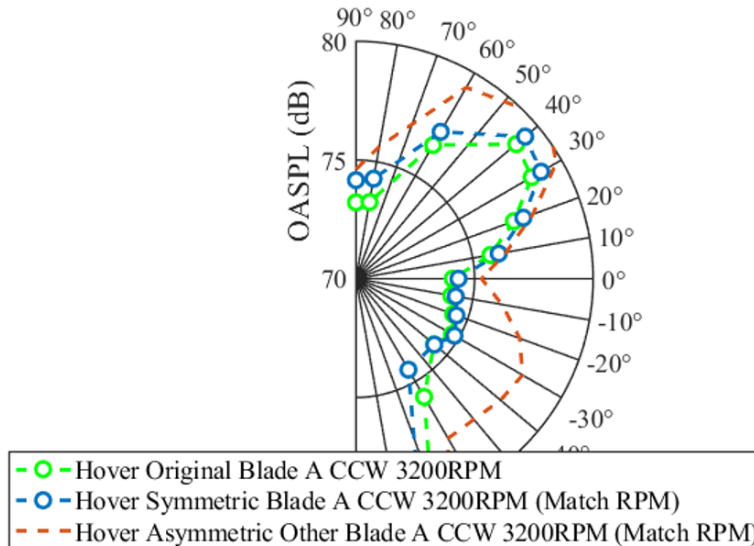


Figure 39. OASPL Directivity Plot of APC Right-Hand Rotors in Hover Condition with Matching RPM

Figure 39 is the OASPL directivity plot of the APC right-hand rotors in the hover condition with matching RPM. The plot shows that the in-phase 4I right-hand rotor, labeled as 'symmetric', produces similar OASPL as

the baseline rotor, labeled as 'original'. The anti-phase 4H right-hand rotor, labeled as 'asymmetric', produces higher OASPL by as much as 2.575 dB. As will be seen later for other test conditions, this OASPL directivity plot of the anti-phase 4H rotor appears to be drastically different from the other directivity plots. As discussed earlier, the flow recirculation during a hover test could introduce a significant source of uncertainty in the experimental data. Other factors could include the physical differences in the blade fabrication. It is unclear how much these sources of uncertainty could contribute to the overall SPL of the anti-phase 4H right-hand rotor in the hover condition.

The APC right-hand rotors are also tested in the hover condition with matching thrust as opposed to matching RPM. Table 8 presents the comparison of the aerodynamic performance of the APC right-hand rotors in the hover condition with matching thrust.

Design Candidate	Average RPM	Average Thrust (N)	Average Torque (Nm)	Power Loading (s/m)
Baseline	3199.23	9.6444	0.2174	0.1324
4H	3399.13	9.4669	0.2108	0.1262
4I	3150.44	9.3788	0.2244	0.1267

Table 8. Aerodynamic Performance Comparison of APC Right-Hand Rotors in Hover Condition with Matching Thrust

Figure 40 is the OASPL directivity plot of the APC right-hand rotors in the hover condition with matching thrust. The OASPL characteristics of the baseline and in-phase 4I right-hand rotors in the hover condition with matching thrust are similar to each other. The OASPL of the anti-phase 4H right-hand rotor is higher than those of the baseline and in-phase 4I right-hand rotors. Again, the discrepancy in the data as compared to the simulation results could be due to flow circulation in the hover conditions.

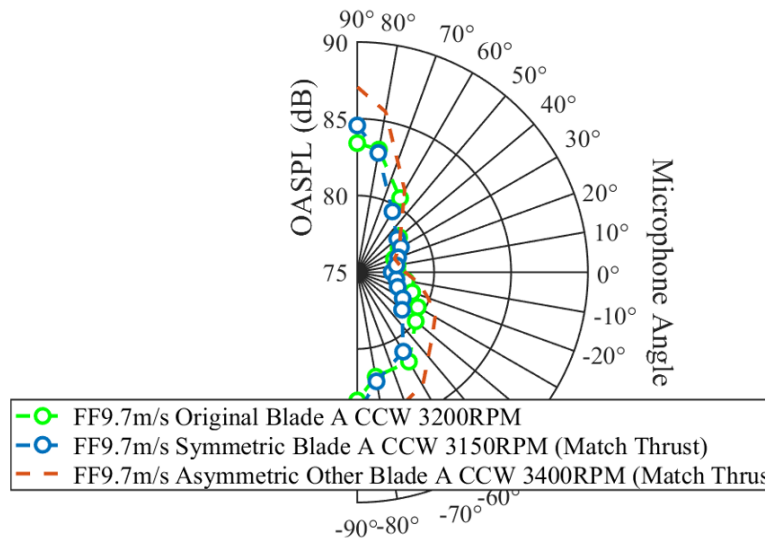


Figure 40. OASPL Directivity Plot of APC Right-Hand Rotors in Hover Condition with Matching Thrust

2. APC Left-Hand Rotors in Clockwise Rotation:

The comparison of the aerodynamic performance of the APC left-hand rotors in the hover condition with matching RPM is presented in Table 9. It is noted that the baseline left-hand rotor produces lower thrust than the baseline right-hand rotor at the same RPM. Ideally, both of these rotors should produce the same thrust. Therefore, the thrust discrepancy is perhaps indicative of the physical differences between the two rotors. The thrust discrepancy is also much larger for the anti-phase 4H right-hand and left-hand rotors at the same RPM. The in-phase 4I left-hand rotor produces slightly higher thrust than the anti-phase 4H left-hand rotor. Both the 4H

and 4I left-hand rotors produce more thrust than the baseline left-hand rotor. So, qualitatively, these data give the same trend as the simulation results.

Design Candidate	Average RPM	Average Thrust (N)	Average Torque (Nm)	Power Loading (s/m)
Baseline	3199.28	9.0210	0.1993	0.1351
4H	3197.38	9.9642	0.2387	0.1247
4I	3196.95	10.0673	0.2502	0.1202

Table 9. Aerodynamic Performance Comparison of APC Left-Hand Rotors in Hover Condition with Matching RPM

Figure 41 is the OASPL directivity plot of the APC left-hand rotors in the hover condition with matching RPM. The OASPL of both the 4H anti-phase and 4I in-phase left-hand rotors are about the same but slightly larger than the OASPL of the baseline left-hand rotor. Again, the results could be influenced by flow recirculation issue.

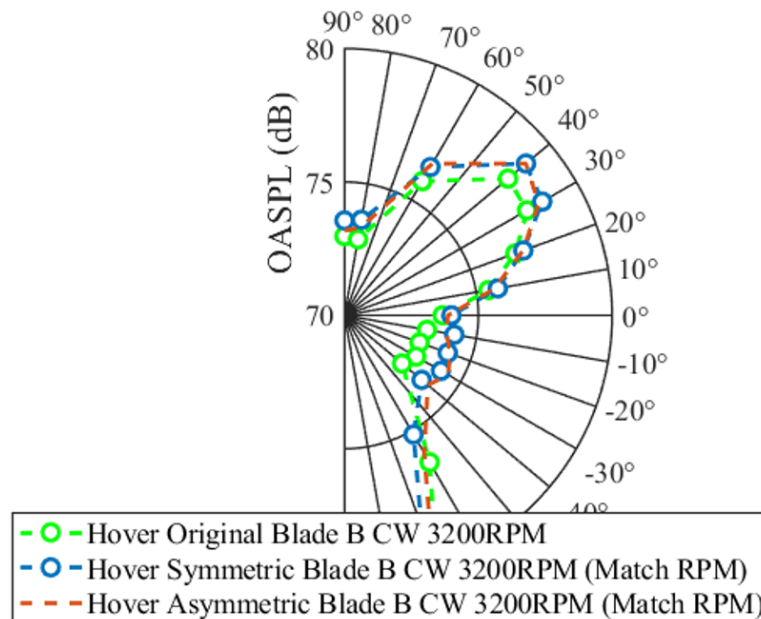


Figure 41. OASPL Directivity Plot of APC Left-Hand Rotors in Hover Condition with Matching RPM

Table 10 presents the comparison of the aerodynamic performance of the APC left-hand rotors in the hover condition with matching thrust.

Design Candidate	Average RPM	Average Thrust (N)	Average Torque (Nm)	Power Loading (s/m)
Baseline	3199.28	9.0210	0.1993	0.1351
4H	3070.62	9.1930	0.2160	0.1324
4I	3069.13	9.2730	0.2248	0.1284

Table 10. Aerodynamic Performance Comparison of APC Left-Hand Rotors in Hover Condition with Matching Thrust

Figure 42 is the OASPL directivity plot of the APC left-hand rotors in the hover condition with matching thrust. All the three rotors produce about the same OASPL.

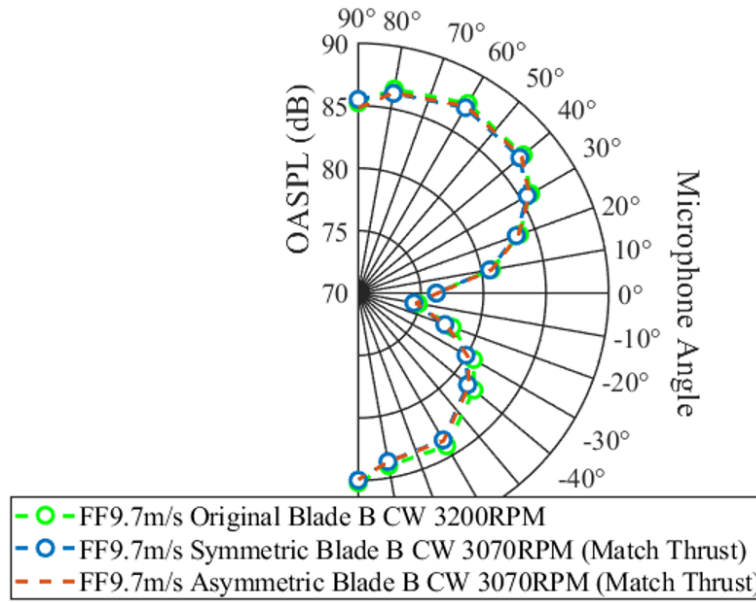


Figure 42. OASPL Directivity Plot of APC Left-Hand Rotors in Hover Condition with Matching Thrust

2. Forward Flight Condition at 9.7 m/s

1. APC Right-Hand Rotors in Counter-Clockwise Rotation:

The APC rotors are tested in the forward flight condition at 9.7 m/s. The aerodynamic performance of the anti-phase 4H and in-phase 4I right-hand rotors in the forward flight condition with matching RPM are compared to the baseline right-hand rotor in Table 11. It is of interest to note that the power loading of the anti-phase 4H right-hand rotor is the largest, thus indicating the highest aerodynamic efficiency since the power loading is the ratio of the rotor thrust to the rotor power. Both the anti-phase 4H and in-phase 4I right-hand rotors produce higher than power loading than the baseline right-hand rotor by 27.0% and 21.3%, respectively.

Design Candidate	Average RPM	Average Thrust (N)	Average Torque (Nm)	Power Loading (s/m)
Baseline	3199.80	8.9001	0.2151	0.1235
4H	3200.22	8.8130	0.1676	0.1569
4I	3202.17	10.2647	0.2044	0.1498

Table 11. Aerodynamic Performance Comparison of APC Right-Hand Rotors in Forward Flight Condition with Matching RPM

The OASPL directivity plot of the APC right-hand rotors in the forward flight condition with matching RPM is shown in Figure 43. It is of interest to note the dip in the OASPL of the anti-phase 4H right-hand rotor at the 0° microphone angle indicating a noise reduction.

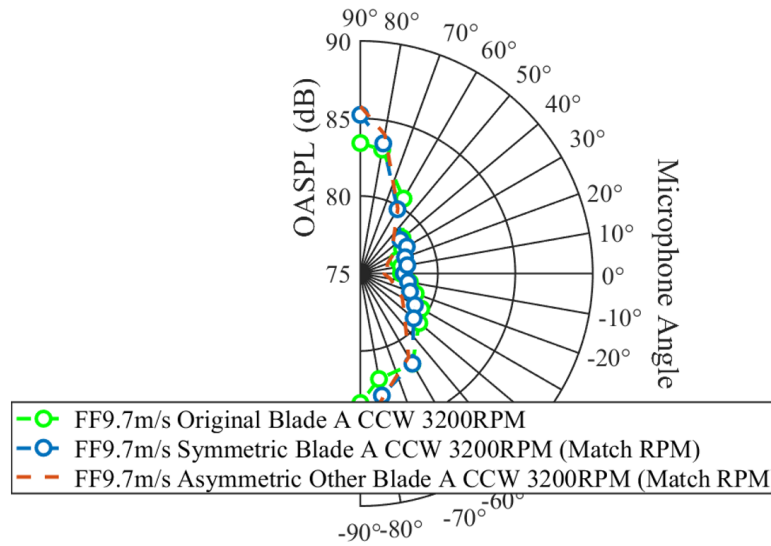
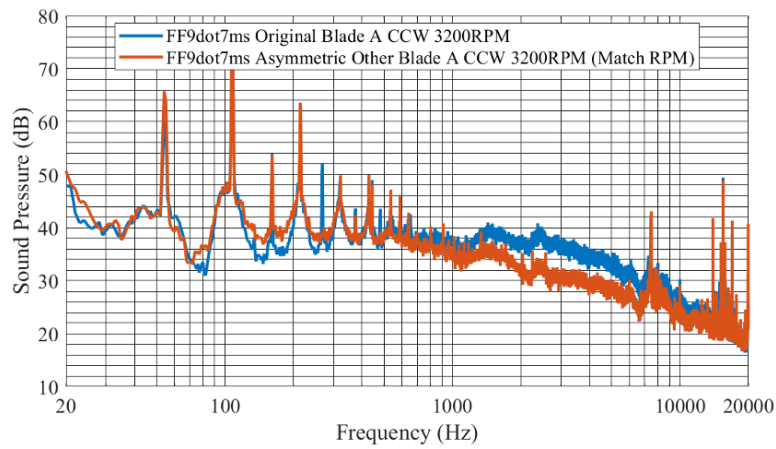
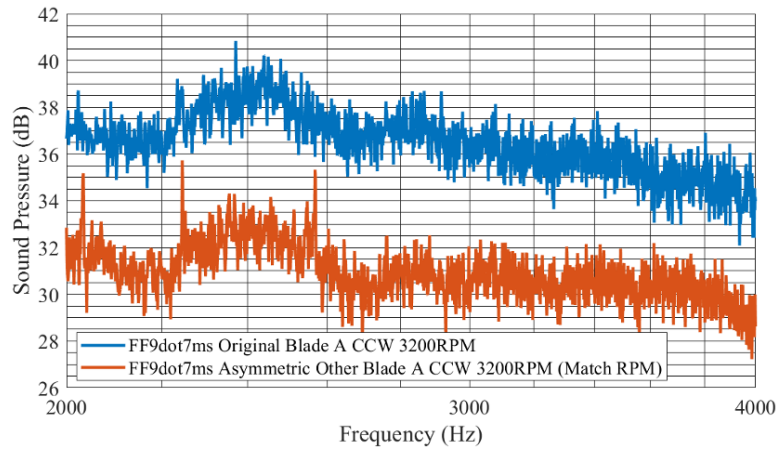


Figure 43. OASPL Directivity Plot of APC Right-Hand Rotors in Forward Flight Condition with Matching RPM



(a) SPL Spectra of APC Baseline and Anti-Phase 4H Right-Hand Rotors in Frequency Range of 20-20000 Hz

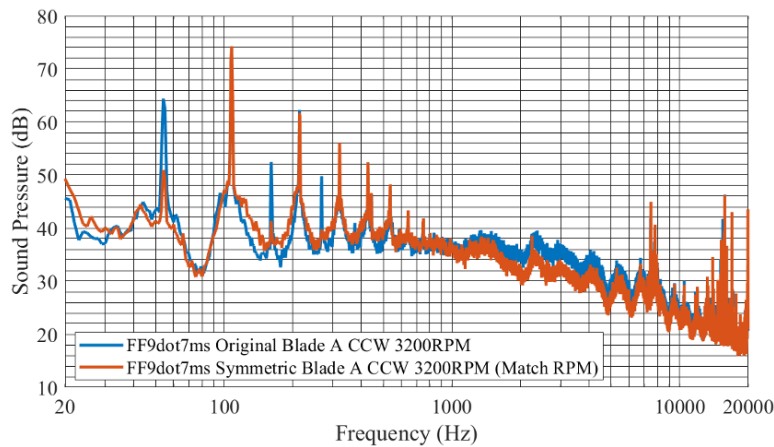


(b) SPL Spectra of APC Baseline and Anti-Phase 4H Right-Hand Rotors in Frequency Range of 2000-4000 Hz

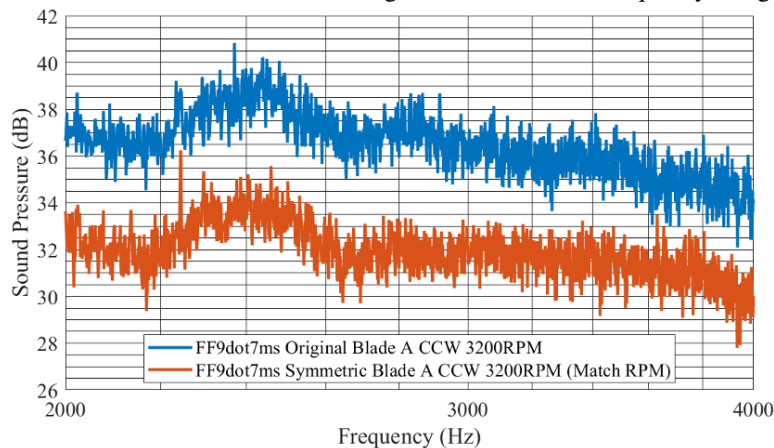
Figure 44. SPL Spectra of APC Baseline and Anti-Phase 4H Right-Hand Rotors at M11 Microphone Location in Forward Flight Condition with Matching RPM

Figure 44(a) presents the broadband SPL spectrum of the anti-phase 4H right-hand rotor at the M11 microphone location in the frequency range from 20 to 20,000 Hz in comparison to the baseline right-hand rotor in the forward flight condition with matching RPM. The spectrum shows a noise reduction of the anti-phase 4H right-hand rotor in the frequency range starting from about 700 Hz to well above 10,000 Hz. Figure 44(a) is the SPL spectrum in the frequency range of 2000-4000 Hz which clearly shows the noise reduction by as much as 7 dB at about 2800 Hz. Thus, the experimental data in the forward flight condition with matching RPM confirms the noise reduction effectiveness of the anti-phase rotor.

Figure 45(a) is the broadband SPL spectrum of the in-phase 4I right-hand rotor at the M11 microphone location which shows a noise reduction in the frequency range of 1000-5000 Hz as compared to the baseline right-hand rotor. The noise reduction is less than that due to the anti-phase 4H right-hand rotor in Figure 44(a). Figure 45(b) shows the noise reduction of the in-phase 4I right-hand rotor by as much as 5 dB at a frequency of about 2800 Hz. The experimental data shows that the in-phase 4I rotor can also achieve the noise reduction which suggests that the alternating TE waveform does contribute significantly to the noise reduction.



(a) SPL Spectra of APC Baseline and In-Phase 4I Right-Hand Rotors in Frequency Range of 20-20000 Hz



(b) SPL Spectra of APC Baseline and In-Phase 4I Right-Hand Rotors in Frequency Range of 2000-4000 Hz

Figure 45. SPL Spectra of APC Baseline and In-Phase 4I Right-Hand Rotors at M11 Microphone Location in Forward Flight Condition with Matching RPM

The APC rotors are also tested in the forward flight condition with matching thrust. Table 12 shows a comparison of the aerodynamic performance of the APC right-hand rotors in the forward flight condition with matching thrust. Both the anti-phase 4H and in-phase 4I right-hand rotors are more aerodynamically efficient than the baseline right-hand rotor by 14.7% and 24.1%, respectively. By matching thrust, the in-phase 4I right-hand rotor is slightly more aerodynamically efficient than the anti-phase 4H right-hand rotor.

Design Candidate	Average RPM	Average Thrust (N)	Average Torque (Nm)	Power Loading (s/m)
Baseline	3199.80	8.9001	0.2151	0.1235
4H	3398.11	9.7685	0.1937	0.1417
4I	3148.42	10.0207	0.1982	0.1533

Table 12. Aerodynamic Performance Comparison of APC Right-Hand Rotors in Forward Flight Condition with Matching Thrust

Figure 46 is the OASPL directivity plot of the APC right-hand rotors in the forward flight condition with matching thrust. The anti-phase 4H right-hand rotor produces a higher OASPL than the both the baseline and in-phase 4I right-hand rotors. This may be due to the increase in the blade tonal or passing frequency noise since the anti-phase 4H right-hand rotor somehow produces a much lower thrust at the same RPM than the other rotors, thereby requiring a higher RPM in order to match thrust.

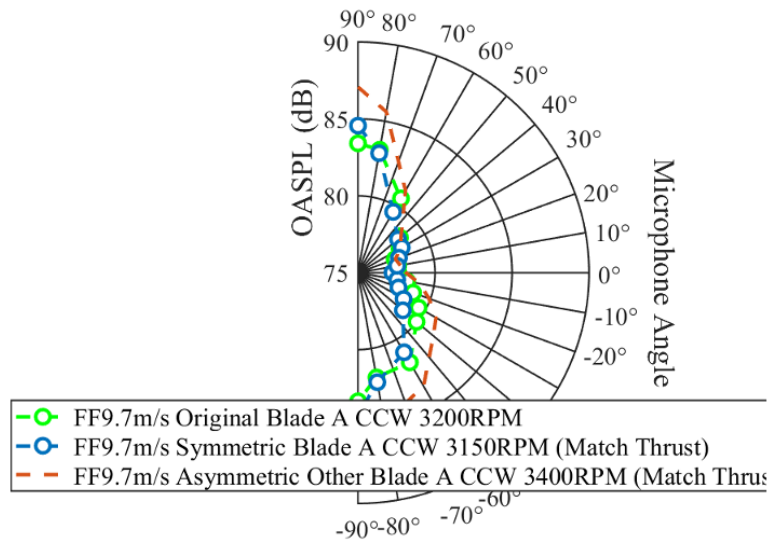
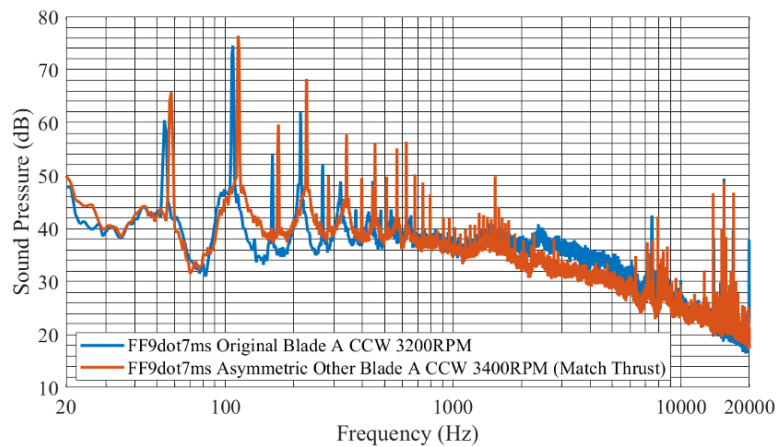
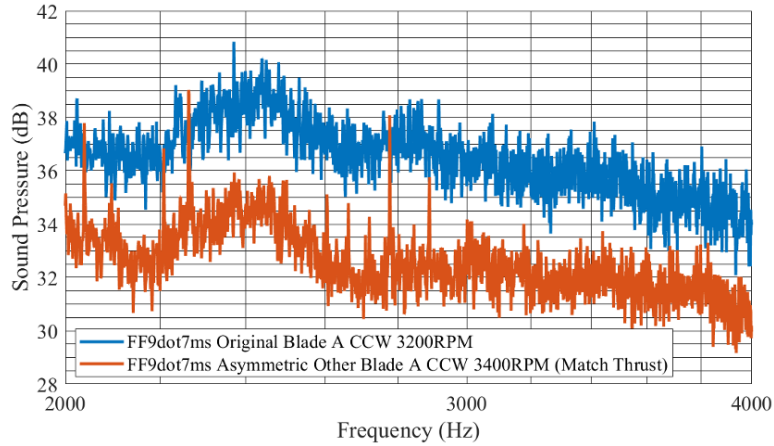


Figure 46. OASPL Directivity Plot of APC Right-Hand Rotors in Forward Flight Condition with Matching Thrust



(a) SPL Spectra of APC Baseline and Anti-Phase 4H Right-Hand Rotors in Frequency Range of 20-20000 Hz

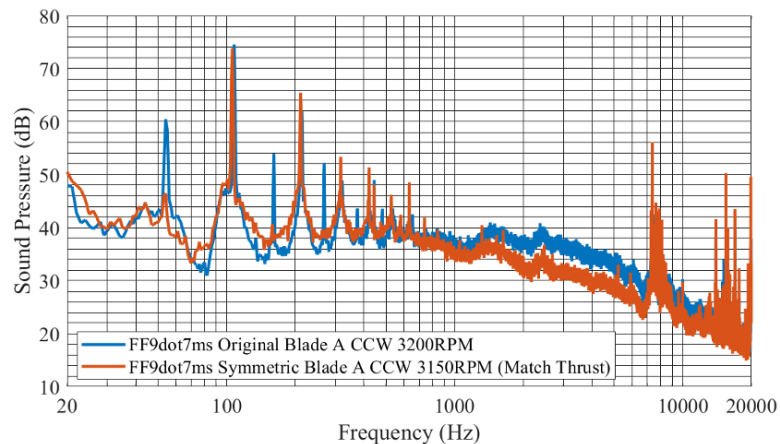


(b) SPL Spectra of APC Baseline and Anti-Phase 4H Right-Hand Rotors in Frequency Range of 2000-4000 Hz

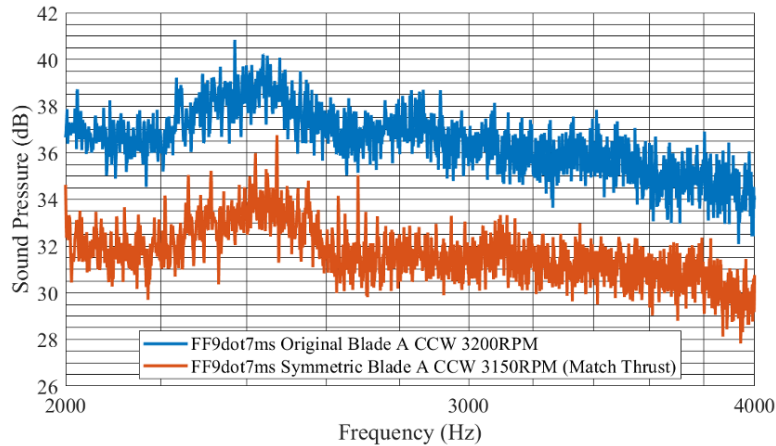
Figure 47. SPL Spectra of APC Baseline and Anti-Phase 4H Right-Hand Rotors at M11 Microphone Location in Forward Flight Condition with Matching Thrust

Figure 47(a) is the broadband SPL spectrum of the anti-phase 4H right-hand rotor at the M11 microphone location in comparison to the baseline right-hand rotor in the forward flight condition with matching thrust. The anti-phase 4H right-hand rotor produces higher blade passing frequency noise below about 1000 Hz due to the increase in the RPM in order to match thrust. Nonetheless, the anti-phase 4H right-hand rotor does produce a noise reduction over a frequency range of 1500-8000 Hz. Figure 47(b) is the SPL spectrum of the anti-phase 4H right-hand rotor in the frequency range of 2000-4000 Hz showing as much as 5 dB noise reduction at a frequency of 2800 Hz.

Figure 48(a) is the broadband SPL spectrum of the in-phase 4I right-hand rotor at the M11 microphone location in the forward flight condition with matching thrust. Comparing to Figure 47(a), the in-phase 4I right-hand rotor has a slightly greater noise reduction than the anti-phase 4H right-hand rotor in the frequency range above 1000 Hz. Figure 48(b) shows the SPL spectrum of the in-phase 4I right-hand rotor in the frequency range of 2000-4000 Hz. The in-phase 4I right-hand rotor produces a noise reduction by as much as 5 dB at a frequency of 2800 Hz.



(a) SPL Spectra of APC Baseline and In-Phase 4I Right-Hand Rotors in Frequency Range of 20-20000 Hz



(b) SPL Spectra of APC Baseline and In-Phase 4I Right-Hand Rotors in Frequency Range of 2000-4000 Hz

Figure 48. SPL Spectra of APC Baseline and In-Phase 4I Right-Hand Rotors at M11 Microphone Location in Forward Flight Condition with Matching Thrust

2. APC Left-Hand Rotors in Clockwise Rotation:

The aerodynamic performance of the APC left-hand rotors in the forward flight condition with matching RPM is compared in Table 13. Both the anti-phase 4H and in-phase 4I left-hand rotors produce more thrust by 6.1% and 7.9%, respectively. All the three left-hand rotors have about the same power loading.

Design Candidate	Average RPM	Average Thrust (N)	Average Torque (Nm)	Power Loading (s/m)
Baseline	3197.72	9.6841	0.2152	0.1344
4H	3198.13	10.2725	0.2242	0.1368
4I	3198.56	10.4514	0.2378	0.1312

Table 13. Aerodynamic Performance Comparison of APC Left-Hand Rotors in Forward Flight Condition with Matching RPM

Figure 49 is the OASPL directivity plot of the left-hand rotors showing that all the three left-hand rotors have about the same OASPL.

Figure 50(a) is the broadband SPL spectrum of the anti-phase 4H left-hand rotor at the M11 microphone location in comparison to the baseline left-hand rotor in the forward flight condition with matching RPM. The spectrum shows a very slight noise increase due to the anti-phase 4H left-hand rotor above 2000 Hz. Figure 50(b) is the SPL spectrum of the anti-phase 4H left-hand rotor in the frequency range of 2000-4000 Hz showing a slight noise increase compared to the baseline left-hand rotor. Comparing to the SPL spectrum of the anti-phase 4H right-hand rotor in Figure 47, the anti-phase 4H left-hand rotor produces no noise reduction. The difference could be perhaps explained by the location of the microphone array which is placed on the left side of the rotors. For the anti-phase 4H right-hand rotor, the microphone is on the retreating side of the right-hand rotor which sees a lower relative airspeed. Moreover, the TE at the blade tip of the anti-phase 4H right-hand rotor is in the downward deflection which generates a rolled-up tip vortex. The situation is in reverse with the anti-phase 4H left-hand rotor. The microphone is on the advancing side of the left-hand rotor which sees a higher relative airspeed. The TE at the blade tip of the anti-phase 4H left-hand rotor is in the upward direction which generates a rolled-down tip vortex associated with a reduced lift. The lift reduction could lower the aerodynamic efficiency, hence noise. To account for the microphone location, one possibility is to take the average of the noise reduction of the right-hand and left-hand rotors. This may represent a hypothetical noise reduction if a microphone were to be placed at the center of the rotor.

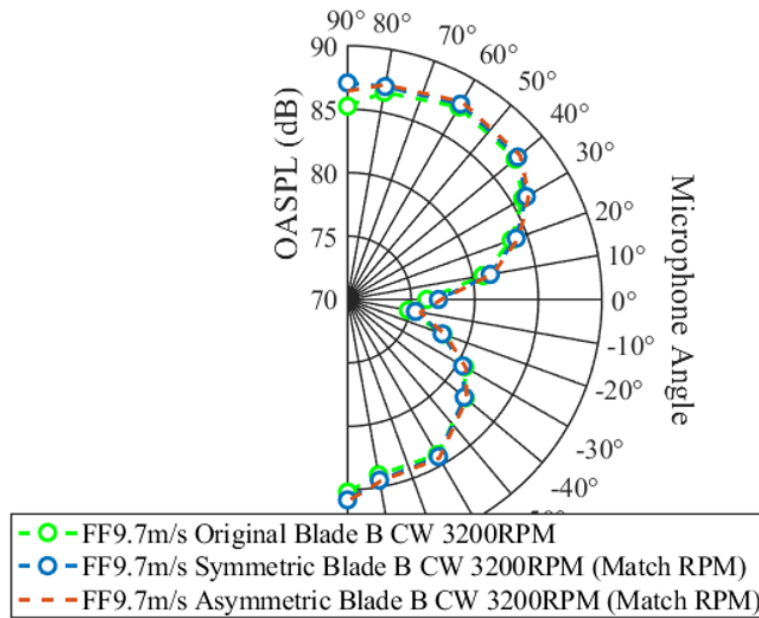
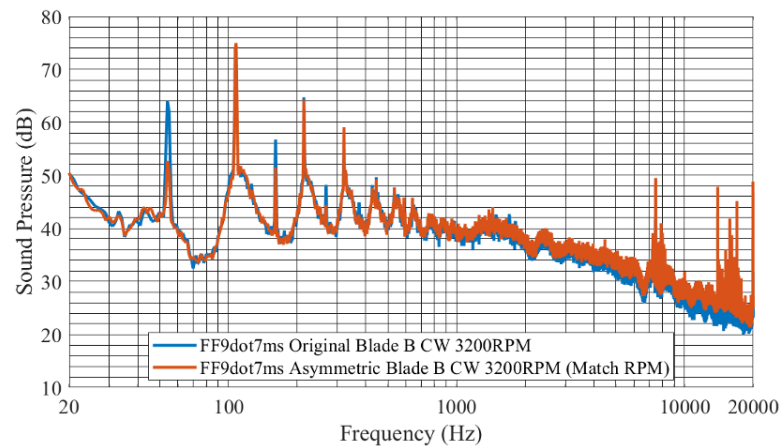
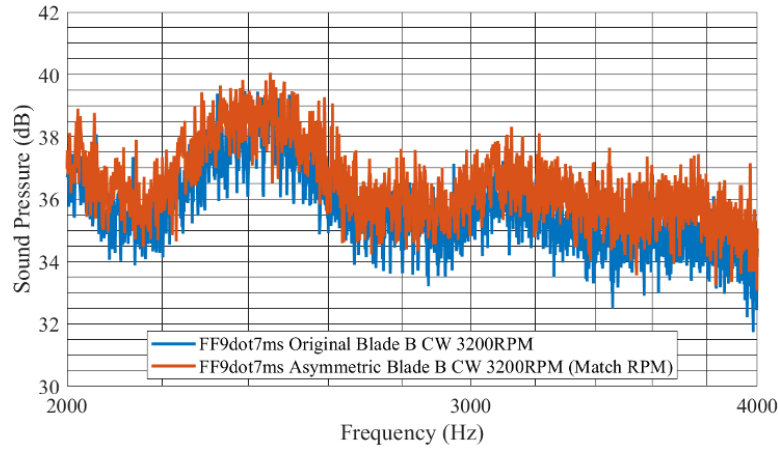


Figure 49. OASPL Directivity Plot of APC Left-Hand Rotors in Forward Flight Condition with Matching RPM

Figure 51(a) is the broadband SPL spectrum of the in-phase 4I left-hand rotor at the M11 microphone location in comparison to the baseline left-hand rotor in the forward flight condition with matching RPM. The in-phase 4I left-hand rotor produces a slight noise increase in the frequency range of 2000-4000 Hz as shown in Figure 51(b). Comparing to Figure 50(b), the anti-phase 4H left-hand rotor shows a lower SPL than the in-phase 4I left-hand rotor.

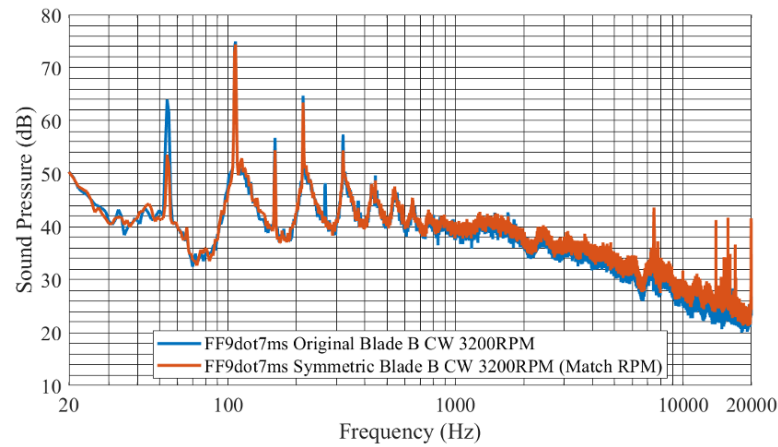


(a) SPL Spectra of APC Baseline and Anti-Phase 4H Left-Hand Rotors in Frequency Range of 20-20000 Hz

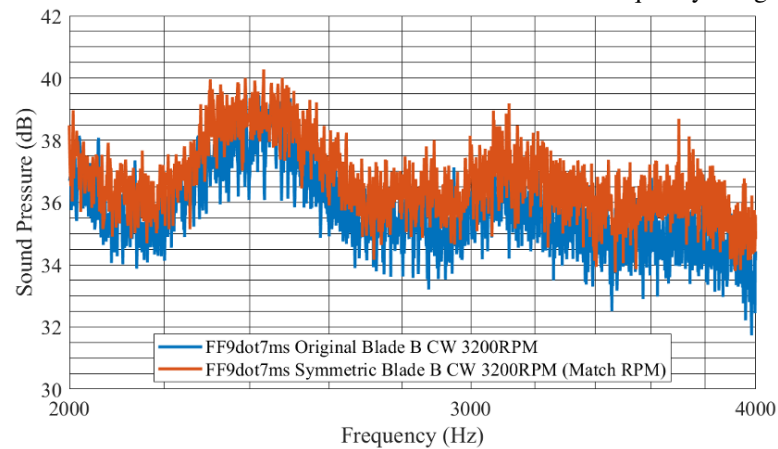


(b) SPL Spectra of APC Baseline and Anti-Phase 4H Left-Hand Rotors in Frequency Range of 2000-4000 Hz

Figure 50. SPL Spectra of APC Baseline and Anti-Phase 4H Left-Hand Rotors at M11 Microphone Location in Forward Flight Condition with Matching RPM



(a) SPL Spectra of APC Baseline and In-Phase 4I Left-Hand Rotors in Frequency Range of 20-20000 Hz



(b) SPL Spectra of APC Baseline and In-Phase 4I Left-Hand Rotors in Frequency Range of 2000-4000 Hz

Figure 51. SPL Spectra of APC Baseline and In-Phase 4I Left-Hand Rotors at M11 Microphone Location in Forward Flight Condition with Matching RPM

Table 14 shows the comparison of the aerodynamic performance of the APC left-hand rotors in the forward flight condition with matching thrust. The anti-phase 4H and in-phase 4I left-hand rotors produce a higher power loading than the baseline left-hand rotor by 7.8% and 3.6%, respectively.

Design Candidate	Average RPM	Average Thrust (N)	Average Torque (Nm)	Power Loading (s/m)
Baseline	3199.28	9.0210	0.1993	0.1351
4H	3070.85	9.5668	0.2042	0.1457
4I	3072.44	9.8164	0.2181	0.1399

Table 14. Aerodynamic Performance Comparison of APC Left-Hand Rotors in Forward Flight Condition with Matching Thrust

Figure 52 is the OASPL directivity plot of the APC left-hand rotor in the forward flight condition with matching thrust. The plot shows a very slight noise reduction in the downward direction. Otherwise, there is little difference in the SPL among the three rotors.

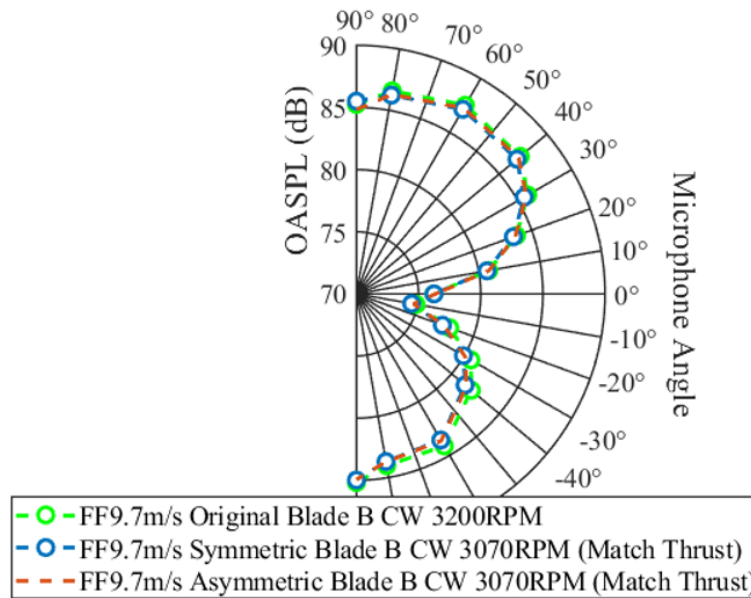
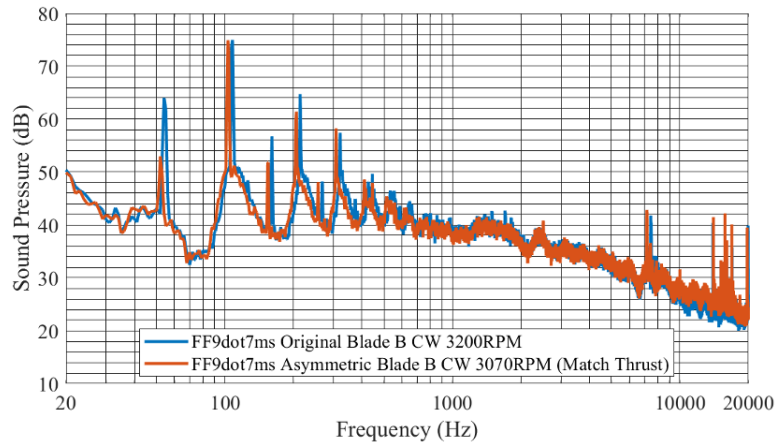


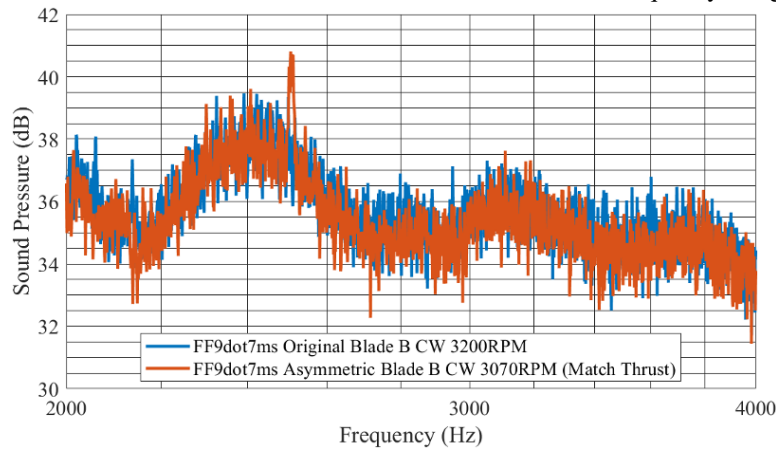
Figure 52. OASPL Directivity Plot of APC Left-Hand Rotors in Forward Flight Condition with Matching Thrust

Figure 53(a) is the broadband SPL spectrum of the anti-phase 4H left-hand rotor at the M11 microphone location in comparison to the baseline left-hand rotor in the forward flight condition with matching thrust. A noticeable noise reduction of about 11 dB at the 1/rev blade passing frequency can be seen in the spectrum. There is very little difference in the SPL between the anti-phase 4H and baseline left-hand rotors in the frequency range of 2000-4000 Hz as shown in Figure 53(b).

Figure 54(a) is the broadband SPL spectrum of the in-phase 4I left-hand rotor at the M11 microphone location in comparison to the baseline left-hand rotor in the forward flight condition with matching thrust. A noticeable noise reduction of about 10 dB at the 1/rev blade passing frequency can be seen in the spectrum. There is very little difference in the SPL between the in-phase 4I and baseline left-hand rotors in the frequency range of 2000-4000 Hz as shown in Figure 54(b).

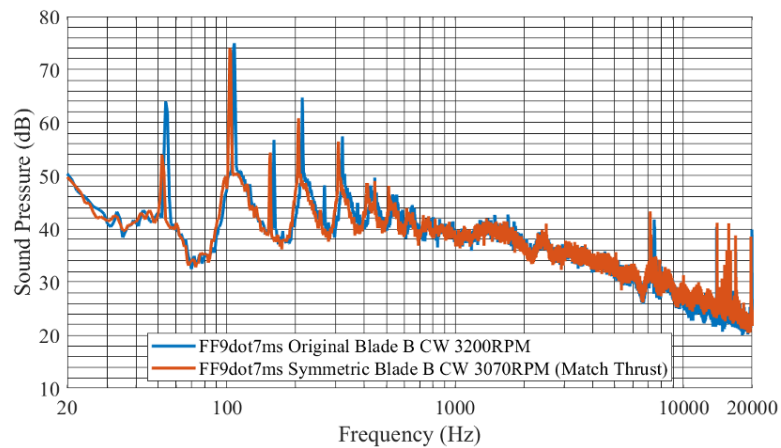


(a) SPL Spectra of APC Baseline and Anti-Phase 4H Left-Hand Rotors in Frequency Range of 20-20000 Hz

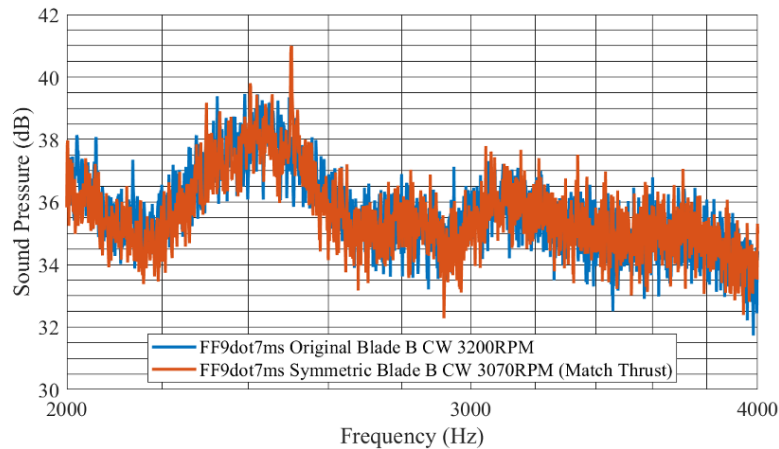


(b) SPL Spectra of APC Baseline and Anti-Phase 4H Left-Hand Rotors in Frequency Range of 2000-4000 Hz

Figure 53. SPL Spectra of APC Baseline and Anti-Phase 4H Left-Hand Rotors at M11 Microphone Location in Forward Flight Condition with Matching Thrust



(a) SPL Spectra of APC Baseline and In-Phase 4I Left-Hand Rotors in Frequency Range of 20-20000 Hz



(b) SPL Spectra of APC Baseline and In-Phase 4I Left-Hand Rotors in Frequency Range of 2000-4000 Hz

Figure 54. SPL Spectra of APC Baseline and In-Phase 4I Left-Hand Rotors at M11 Microphone Location in Forward Flight Condition with Matching Thrust

V. Conclusions

An investigation of an anti-phase rotor technology is conducted in 2019 to validate computationally and experimentally the potential noise suppression merit of the proposed anti-phase rotor technology.

A CFD investigation is conducted to explore a design space of the anti-phase alternating trailing edge design for rotor noise suppression. The design objective is to maximize the noise reduction while maintaining the aerodynamic thrust. The investigation is performed using a 3D Unsteady Reynolds-Averaged Navier-Stokes (URANS) commercial solver STAR-CCM+ with $k - \omega$ Shear Stress Transport (SST) turbulence model and Ffowcs-Williams and Hawkings (FW-H) formula to obtain aerodynamic thrust and far-field noise level. A parametric acoustic study is conducted for 13 anti-phase design candidates for a 18.5-inch rotor manufactured by KDE. The best design candidate for the KDE rotor has a four-period TE waveform which results in a reduction in far-field noise level of 2.1 dB in the hover condition and a reduction of 1.1 dB in the forward flight condition at 9.7 m/s.

A further parametric acoustic study is conducted for 4 anti-phase design candidates and one in-phase design candidate for a different rotor manufactured by APC. All the 5 APC rotor design candidates have a four-period TE waveform which is found from the first study to have better acoustic performance than the other TE waveforms. The best design candidate for the APC rotor denoted by 4H results in a reduction in far-field noise level of 4.0 dB in the hover condition. The 4H design candidate employs an anti-phase rotor tip whereas all the other design candidates employ TE waveforms that have zero deflections at the rotor tip. The in-phase 4I design candidate also shows a noise reduction of 2.5 dB.

In addition, an acoustic prediction is conducted using a commercial rotorcraft aeromechanics code called CHARM developed by Continuum Dynamics, Inc. CHARM has an acoustic predictive capability provided by PSU-WOPWOP, an acoustic code developed by PSU. CHARM is used to evaluate the acoustic characteristics of a subset of the KDE anti-phase rotor design candidates. The results computed by CHARM also indicate a noise reduction for a four-period anti-phase rotor design in forward flight.

Two acoustic experiments in the PSU anechoic chamber have been conducted in July 2019 and October 2019. In the first test entry, an anti-phase 4H rotor design for the KDE rotor and an in-phase 4I rotor design for the APC rotor are tested. It is discovered that the APC in-phase 4I rotor is fabricated by accident. In the hover condition, both the KDE and APC rotors do not provide sufficient evidence of improved aerodynamic performance and noise reduction. However, the experimental data in the hover condition are deemed to be inconclusive due to the flow recirculation in the anechoic chamber caused by the rotor downwash. In the forward flight condition at 9.7 m/s, the APC in-phase 4I rotor produces 2.1% higher aerodynamic efficiency than the APC baseline rotor the same RPM. Moreover, the APC in-phase 4I rotor offers evidence of noise suppression by as much as 2 dB in the overall SPL across a wide range of the microphone zenithal angles. The APC in-phase 4I rotor has a lower noise in the low frequency range than the APC baseline rotor. It virtually eliminates the sound pressure levels at all the odd multiple integers of the rotor angular

speed. In the noise annoyance sensitive frequency range of 2000-4000 Hz, the APC in-phase 4I rotor produces as much as a 4 dB noise reduction.

In the second test entry, four different APC rotors are tested: an anti-phase 4H left-hand rotor, an anti-phase 4H right-hand rotor, an in-phase 4I left-hand rotor, and an in-phase 4I right-hand rotor. In the hover condition, the acoustic data for the four rotors do not provide any evidence of the noise reduction benefit. This could be due to the potential acoustic reflection created by flow recirculation of the rotor downwash. In the forward flight condition at 9.7 m/s, the anti-phase 4H right-hand rotor produces a significant noise reduction by as much as 7 dB in the frequency range of 2000-4000 Hz when the RPM is matched and 5 dB when the thrust is matched. The in-phase 4I right-hand rotor also produces a noise reduction by as much as 5 dB in the frequency range of 2000-4000 Hz when the RPM or thrust is matched. However, both the anti-phase 4H rotor and in-phase left-hand rotors do not show any noise reduction benefit in the high frequency range but show a noticeable noise reduction of 11 dB and 10 dB at the 1/rev blade passing frequency. The difference in the acoustic performance of the left-hand and right-hand rotors could be explained by the location of the microphone array placed to the left side of the rotors. This microphone array location could create a bias in the sound pressure level in favor of the right-hand rotor. If the averages of the sound pressure level measurements of the right-hand and left-hand rotors are taken, perhaps the bias could be removed. Using the average noise reduction values, the anti-phase 4H rotor could offer a noise reduction by as much as 3.5 dB while the in-phase 4I rotor could produce up to a 2.5 dB noise reduction.

Both the computational and experimental results therefore have provided sufficient evidence to support the noise suppression capability of the proposed anti-phase rotor concepts.

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References

- ¹Moore, M. D., “Personal Air Vehicles: a Rural/Regional and Intra-Urban On-Demand Transportation System,” *Journal of AIAA*, Vol. 2646, 2003.
- ²Duffy, M. J., Wakayama, S. R., and Hupp, R., “A Study in Reducing the Cost of Vertical Flight with Electric Propulsion,” 17th AIAA Aviation Technology, Integration, and Operations Conference, 2017, p. 3442.
- ³Antcliff, K. R., Moore, M. D., and Goodrich, K. H., “Silicon Valley as an Early Adopter for On-Demand Civil VTOL Operations,” 16th AIAA Aviation Technology, Integration, and Operations Conference, 2016, p. 3466.
- ⁴“Volocopter VC2,” https://www.volocopter.com/assets/pdf/2017_04_Design_specifications_2X.pdf, 2017. Accessed: 2018-06-3.
- ⁵Wright, S., “The Acoustic Spectrum of Axial Flow Machines,” *Journal of Sound and Vibration*, Vol. 45, No. 2, 1976, pp. 165–223.
- ⁶Kurtz, D., and Marte, J., “A Review of Aerodynamic Noise from Propellers, Rotors, and Lift Fans,” 1970.
- ⁷Yung, H. Y., “Rotor Blade–Vortex Interaction Noise,” *Progress in Aerospace Sciences*, Vol. 36, No. 2, 2000, pp. 97–115.
- ⁸Hardin, J. C., and Lamkin, S. L., “Concepts for Reduction of Blade/Vortex Interaction Noise,” *Journal of Aircraft*, Vol. 24, No. 2, 1987, pp. 120–125.
- ⁹Chen, P. C., Baeder, J. D., Evans, R. A., and Niemczuk, J., “Blade-Vortex Interaction Noise Reduction with Active Twist Smart Rotor Technology,” *Smart Materials and Structures*, Vol. 10, No. 1, 2001, p. 77.
- ¹⁰Cramer, N., Nguyen, N., Hernandez, S., and Storms, B., “Investigation of Anti-Phase Asymmetric Quiet Rotor Technology,” AIAA Aerodynamics Conference, AIAA-2019-1070, Jan. 2019.
- ¹¹Menter, F., “Two-Equation Eddy-Viscosity Turbulence Models for Engineering Applications,” *AIAA Journal*, Vol. 32, No. 8, 1994, pp. 1598–1605.
- ¹²Ffowcs Williams, J. and Hawkins, D., “Sound Generation by Turbulence and Surfaces in Arbitrary Motion,” *Philosophical Transactions of Royal Society of London, Series A, Mathematical and Physical Sciences* (1934-1990), 264:1151, 1969, pp. 321-342.
- ¹³Brès, G.A., Brentner, K.S., Perez, G., and Jones, H. E., “Maneuvering Rotorcraft Noise Prediction,” *Journal of Sound and Vibration*, Vol. 39, No.3-5, August 2003, pp. 719–738.
- ¹⁴Spletstoesser, W., Kube, R., Wagner, W., Seelhorst, U., Boutier, A., Micheli, F., Mercker, E., and Pengel, K., “Key Results from a Higher Harmonic Control Aeroacoustic Rotor Test (HART),” *Journal of the American Helicopter Society*, Vol. 42, No. 1, 1997, pp. 58–78.
- ¹⁵Xiong, J., Nguyen, N., and Cramer, N., “Acoustic Optimization for Anti-Phase Asymmetric Rotor,” AIAA Applied Aerodynamics Conference, AIAA-2020-1496, January 2020.

¹⁶Zahirudin, R., Yan, S., Nguyen, N., Xiong, J., and Palacios J., "Experimental Acoustic Characterization of Anti-Phase Asymmetric Rotors," Vertical Flight Society Forum, October 2020.

¹⁷Weitsman, D., Stephenson, J. H., and Zawodny, N. S., "Effects of Flow Recirculation on Acoustic and Dynamic Measurements of Rotary-Wing Systems Operating in Closed Anechoic Chambers," The Journal of the Acoustical Society of America, Vol. 148, No. 3, 2020.