Conceptual Design Trade Studies for Acoustic Predictions of the NASA UAM Tiltrotor Reference Vehicle

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ABSTRACT

A toolchain of low- and mid-fidelity tools is applied to NASA's Urban Air Mobility tiltrotor reference vehicle to quantify trades in sizing, performance, and noise at the conceptual design level. The process includes conceptual sizing, comprehensive analysis, and acoustic analysis to design and analyze versions of the concept tiltrotor with differing design variables. Rotor tip speed is the primary design variable studied, with blade twist, blade taper, and blade number also considered. The noise metrics used are the FAA/EASA certification Effective Perceived Noise Levels for takeoff, flyover, and approach. Certification condition noise is calculated for all conditions in both conversion and airplane flight modes, with airplane mode flight resulting in noise 10-25 EPNdB quieter than conversion mode and tip speed variation providing noise reduction up to 9 EPNdB.

NOTATION

dB	Decibel
EPNdB	Effective perceived noise level, in decibels
EPNL	Effective perceived noise level (EPNdB)
ft/s	Feet per second
lb	Pounds
Lmax	maximum noise level, A-weighted, dBA
m	Meter
OASPL	Overall sound pressure level (dB)
psf	Pounds per square foot

INTRODUCTION

The emerging industry of Urban Air Mobility (UAM) intends to capitalize on advancements in technologies including electric propulsion and composite materials to enable short range transportation of people and goods in densely populated urban areas. A realization of UAM would reduce travel time and decongest roadways in urban areas by moving traffic to the airspace, benefitting those on the ground as well as in the air.

Due to the close working proximity of UAM vehicles to the public in urban areas, public response to noise is a critical component in the design of UAM aircraft. Therefore, it is important that noise quantification and reduction are included as driving requirements at the conceptual design stage and not as an afterthought to a design driven largely by other requirements (such as performance, vibration, and handling qualities). However, reliable acoustic predictions can be difficult to obtain, especially if computationally expensive and time-consuming high-fidelity computational fluid dynamics (CFD) is avoided, such as when studying a large design trade space. This work employs NASA's conceptual design tools to integrate acoustic analysis into conceptual design. To exemplify this methodology, high level trades on the NASA tiltrotor reference vehicle are conducted, balancing noise reduction and aircraft performance.

To support tool and technology development for UAM aircraft, NASA's Revolutionary Vertical Lift Technology (RVLT) project has created, and continues to develop and expand, a set of conceptual UAM Reference Vehicles (Ref. 1). These Reference Vehicles represent many different configurations, including single main rotor, multirotor, lift plus cruise, and vectored propulsion. All vehicles are designed to the same 75 nautical mile range, 6 occupant UAM mission (Ref. 2) to enable one-to-one comparisons of the different configurations. In addition, each configuration features versions with different powertrain systems, representing turboshaft, battery electric, and hybrid-electric propulsion architectures.

The baseline model for this study is the 2022 tiltrotor reference vehicle (Ref. 3), shown in Figure 1. The aircraft is a turboshaft powered, ~4,500 lb twin-tiltrotor with a cruising speed of around 170 knots. The primary acoustics-driven design consideration is a 550 ft/s hover tip speed, reduced by 50% to 275 ft/s in airplane mode. The chosen tip speed was intended to be a 'low noise' tip speed, but acoustic analysis was not performed at that time and is the focus of the current study.

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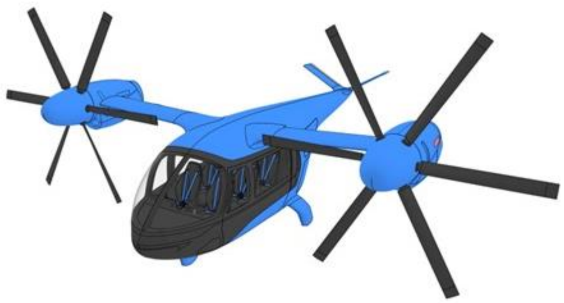

Figure 1. Rendering of the tiltrotor UAM reference vehicle in airplane mode

RVLT TOOLCHAIN

Vertical Take-Off and Landing (VTOL) aircraft conceptual design frequently employs software tools created to perform specific tasks in the design process, from preliminary sizing to comprehensive analysis to high-fidelity CFD. Many of these tools are in-house proprietary creations of various companies, tailored to their specific needs. Often these codes are not intended to enable simple compatibility with other software and stages of the design process.

RVLT is developing an integrated toolchain of conceptual design tools, aiming at improving workflow and connectivity between specialized codes. As a part of this development, validation and user training are primary goals. RVLT Toolchain workshops have been held to provide the public with the knowledge and best practices of this design process.

The RVLT Toolchain has been implemented in this body of work to facilitate the workflow, inputs, execution, outputs, and data processing to connect sizing, comprehensive analysis, and acoustic prediction codes. The work is performed as trade studies and parameter sweeps. No objective function or optimization algorithm was introduced in the design decisions. The toolchain codes and their use in this work are briefly described below, and more information regarding their use for acoustic predictions can be found in Ref. 4.

NDARC

The NASA Design and Analysis of RotorCraft (NDARC) (Ref. 5) tool provides the sizing and performance analysis of the concept aircraft for this work. With the input of configuration setup, sizing methodology, and mission requirements, NDARC implements semi-analytic and surrogate models at the component level to reach an iterative solution of aircraft sizing, weight, and performance.

NDARC includes a comprehensive description of the concept vehicle containing the results of higher fidelity tools via calibration of surrogate models. Cases are run in the order of seconds on a standard desktop, making it a useful and practical way to run many cases in a given design space. A large number of inputs are required to define an aircraft and its sizing scheme, but example and default configurations exist to set the majority of the parameters and leave the user in control of a more manageable set of design variables.

CAMRAD II

The Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics (CAMRAD II) (Ref. 6) tool is a commercial comprehensive analysis code capable of mid-fidelity analysis of rotor aerodynamics and structural dynamics. In this work, CAMRAD II provides higher fidelity (compared to NDARC) data to improve NDARC's rotor performance model, and provides the rotor blade position, loads, and conditions for acoustic analysis.

GENROC

NDARC employs a surrogate rotor performance model that contains equations to calculate induced power and drag coefficients of a rotor. Typically, this surrogate rotor performance model is calibrated manually by varying the equation coefficients to fit the higher-fidelity CAMRAD II rotor performance results for a particular rotor design. When performing many calibrations, it is beneficial to automate that process. The Genetic NDARC Rotor Calibration tool (GeNRoC) (Ref. 7) was developed to read in CAMRAD II data and use Open Multidisciplinary Design Optimization (OpenMDAO) (Ref. 8) to curve-fit the NDARC surrogate model to the CAMRAD II results with a genetic algorithm.

AARON/ANOPP2

All acoustic predictions are generated by the Aircraft NOise Prediction Program 2 (ANOPP2) and ANOPP2's Aeroacoustic ROtor Noise (AARON) (Ref. 9). ANOPP2 is a collection of tools and frameworks that use Farassat's Formulations of the Ffowcs Williams and Hawkings equations (Ref. 10) for noise calculations. For this effort, Formulation 1A (F1A) was used with compact loading and compact thickness assumptions. The Brooks-Pope-Marcolini semi-empirical model is used to estimate broadband self-noise (Ref. 11). AARON is a FORTRAN interface tool that facilitates the use of ANOPP2 for rotorcraft. pyaaron, a python tool developed at NASA Langley, handles the connection of CAMRAD II and AARON, and adds capabilities to AARON, such as the prediction of certification conditions.

RCOTools

The input, output, and execution of NDARC and CAMRAD II is handled by Rotorcraft Optimization Tools (RCOTools) (Ref. 12), a set of Python libraries that are designed to be application wrappers for each code, as well as several others not used in this work. The Python based workflow allows users to combine its functionality with any other Python capability. For example, RCOTools modifies an NDARC input file for the desired trade, executes it, then parses the output and sends relevant parameters to modify and execute a set of CAMRAD II cases to create rotor calibration data. Figure 2 shows the workflow used in the design process.

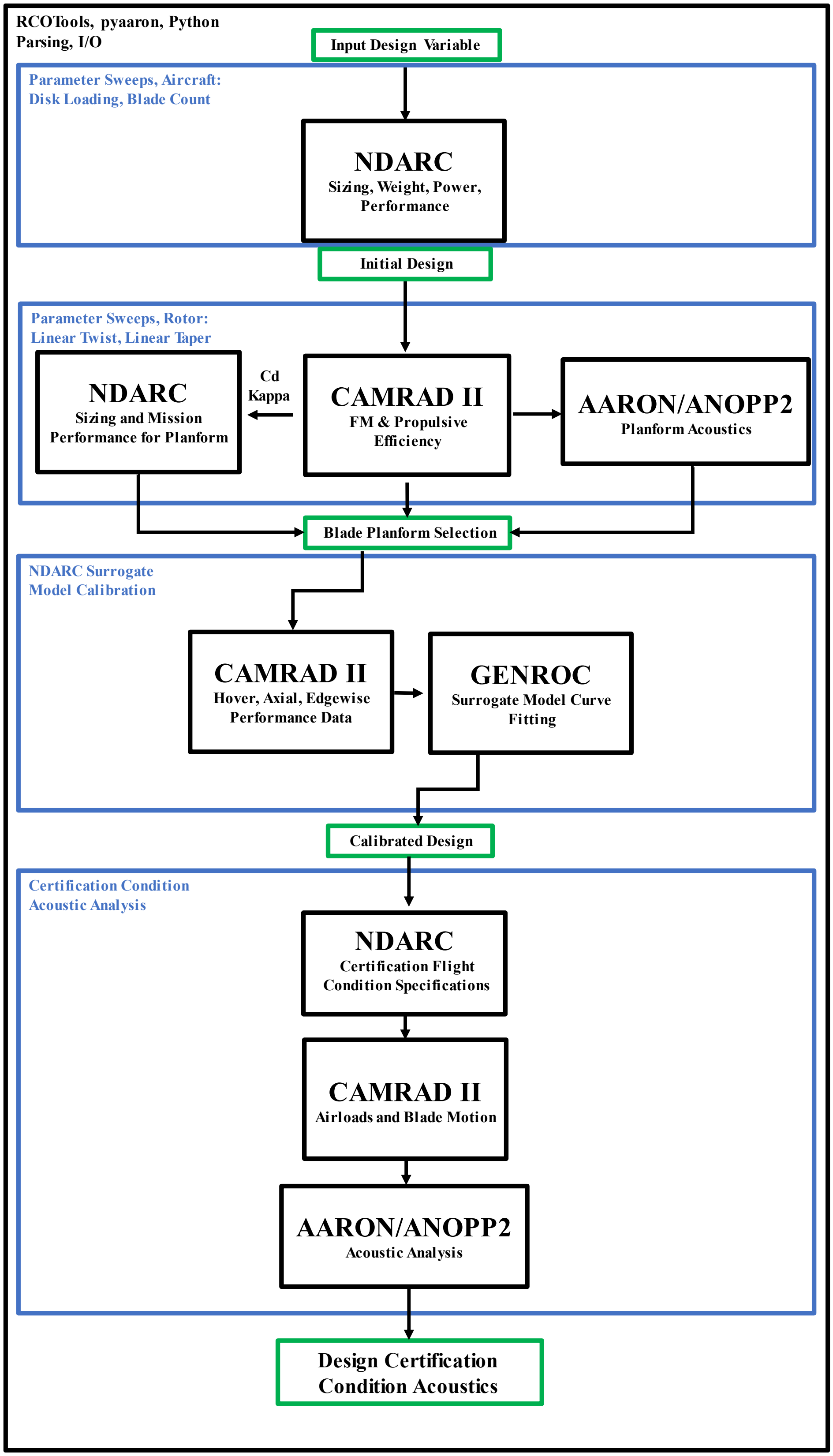

Figure 2. RVLT Toolchain workflow for the tiltrotor reference vehicle

MODELING APPROACH

The concept tiltrotor is modeled as a twin-proprotor tiltrotor. The configuration is similar to the XV-15 (Ref. 13) and subsequent V-22 (Ref. 14), with the primary difference being the use of a hingeless hub in the concept tiltrotor rather than the gimballed hub of the production tiltrotors. Each rotor has collective and cyclic control. The design also includes a 2-stage gearbox to reduce the cruise tip speed to 50% of the hover tip speed. The model analyzed in this work is turboshaft powered, but the trades are expected to be similar for other variants with different powertrains.

Two primary CAMRAD II models are used in this study: an isolated rotor to perform the planform analysis and NDARC surrogate model calibration, and a full-vehicle model including the airframe used for calculations at the certification conditions for acoustics evaluation. For modeling purposes, all CAMRAD rotors are modeled as rigid blades with a flap hinge and spring tuned to the design flap frequency of 1.07/rev. The development of a tuned structural blade model was outside the scope of the current work. Kottapalli, et al. (Ref. 15), describe acoustic effects of modeling with flapping rigid vs elastic blades in CAMRAD II and AARON. Reference 15 found noticeable differences in noise with elastic blades, which were minor because of high blade stiffness. Noise during various flight conditions was better in some and worse in others.

Design Variables

Silva and Johnson, Ref. 4, identify 19 noise mitigation techniques in rotor design. The primary variable of this work is the first item discussed: rotor tip speed. Rotor tip speed is well known to be a major driver of noise. This effort results in 6 tiltrotor designs at tip speeds of 450, 500, 550, 600, 650, and 700 ft/s. For each design tip speed, the secondary variable of rotor blade planform (linear twist and taper) is selected based on the performance and acoustics of the isolated rotor in hover and cruise. Rotor blade count and disk loading are selected, but their effect on noise isn't quantified at each tip speed to keep the design matrix manageable. Blade count is driven by required rotor solidity for the design tip speed. Disk loading is selected based on performance for each tip speed, and a diskloading of 10 psf was found to be favorable for all tip speeds It was held constant to remove the effect of disk loading on noise from the tip speed trade. These trades are intended to quantify the acoustic effects of these parameters to inform what design approaches for reducing noise might be worth implementing on the concept tiltrotor aircraft. A summary of these variables is shown in Table 1.

Table 1. Tiltrotor design variables

Design Variable	Values					
Hover tip speed, ft/s	450	500	550	600	650	700
(*number of blades*)	6	6	6	4	4	3
Linear twist, deg	-19 to -31					
Linear taper ratio	0.5, 0.7, 0.9, 1					

Blade count is selected for each tip speed to keep the blade aspect ratio around 9 to 14. As tip speed decreases, solidity grows, driving the blade count higher to keep within the desired aspect ratio range. Blade counts higher than 6 for this vehicle were found to have convergence issues and poor performance in comprehensive analysis, so blade count is not increased higher than 6. Figure 3 shows the resulting blade counts and solidity for each tip speed.

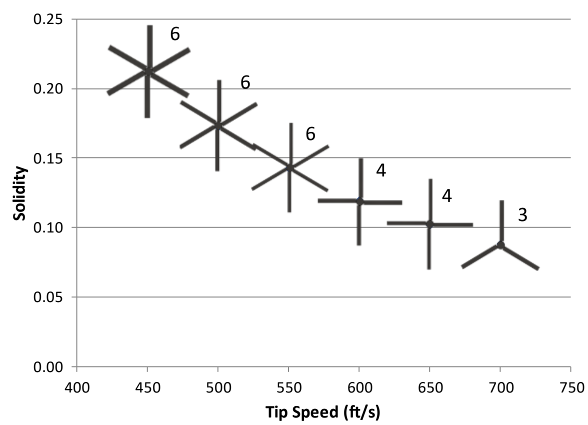

Figure 3. Sized solidity and blade count varying tip speed

FAA Part 36 Certification

FAR Part 36 (Ref. 16), Appendix K, "Noise Requirements for Tiltrotors Under Subpart K," is currently the most appropriate noise regulation for a UAM tiltrotor. In Part 36 Appendix K, the certification conditions are specified in VTOL/Conversion mode. Other than specifying the flight mode, the flight conditions are essentially identical to Appendix H, "Noise Requirements for Helicopters" which defines the noise certification conditions for helicopters and will be used for the primary noise metrics of this study. There are no certified civil tiltrotors with which to compare, but many certified helicopters exist, with available data for noise in Part 36 Appendix H conditions. Both Subparts H and K include takeoff, flyover, and approach requirements, each flown over 3 ground microphones, one at centerline and the others 150 m to port and starboard. All conditions are at sea level conditions at 25°C. Takeoff occurs at the best rate of climb 500 m from the center microphone starting at 20 m above ground level. Flyover is conducted at 90% maximum speed 150 m above ground level. Approach is performed at the same best rate of climb speed as takeoff and at a 6-degree descent angle, 120 m above ground level. EPNL (Effective Perceived Noise Level) is the evaluation metric for these conditions and its calculation is described in the regulation. All newly certified helicopters must meet Stage 3 noise requirements in takeoff, flyover, and approach, with a few special case exemptions. Subpart K does not specify stages for reduction of allowable noise. In both Subparts H and K, exceedance of the limit for one metric may be partially offset by margins below limits for the other conditions.

As of the time of this publication, no civil tiltrotor has been certified, and due to the more complex flight modes of proposed UAM vehicles, a different requirement may be levied for the vehicle state of conversion in each condition. Therefore, results in both conversion and airplane mode will be obtained for each condition, which should represent the likely extremes of noise for this tiltrotor. Conversion mode nacelle angle is not specified in the regulation, just that it must stay constant in the condition. The concept tiltrotor will perform the conversion mode certification conditions with the nacelles tilted to 75 degrees from horizontal in takeoff and flyover, and 85 degrees in approach. These nacelle tilt angles keep the fuselage pitch within 5 degrees of airspeed direction in trim found in comprehensive analysis. Airplane mode is defined as nacelles at 0 degrees (horizontal). The goal of this work is not to determine if the aircraft is certifiable or not, but rather to use the certification standards as a method of comparison for the effect of design variable changes.

PLANFORM TRADES

Performance

On the performance side of this trade, planform is determined by the combination of twist and taper that balances hover and cruise performance, represented in Figure 4 by Figure of Merit and propulsive efficiency for the design mission. The metric for taper used is the taper ratio, or ratio of tip chord to root chord. A taper ratio of 0.5 means the tip chord is 50% of the root chord, so a 'high taper' is represented by a numerically lower taper ratio. Figure 5 shows the concept tiltrotor's resized design gross weight with the CAMRAD II results of each twist and taper applied to the sizing mission. All tip speeds showed similar results, so only 600 ft/s is included here. The design point of no taper and -30 degrees of twist is preliminarily selected based on these results.

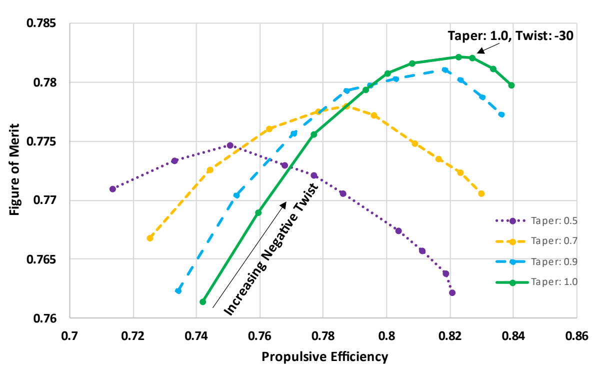

Figure 4. Figure of Merit vs propulsive efficiency twist and taper sweep, 600 ft/s

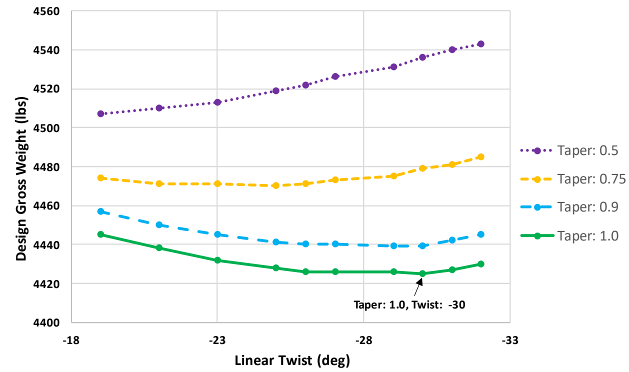

Figure 5. NDARC design gross weight varying blade planform, 600 ft/s

Acoustics

Full vehicle certification conditions are not simulated in the rotor planform acoustic trade, instead, the OASPL at a single observer point 45 degrees down and 10 rotor radii away from the hub center of a single isolated rotor is chosen as the metric. The OASPL at that point is calculated for the rotor in a hover orientation. The absolute number here should not be interpreted on its own as any meaningful representation of aircraft noise, rather, the difference in OASPL between twist and taper combinations points to the planform design that may result in lower noise of the full aircraft in certification conditions.

Figure 6 - Figure 11 show the results of planform on hover OASPL for each tip speed. Each plot spans 4 dB on the y-axis. It's important to note that the differences seen are typically small, however, interesting trends appear.

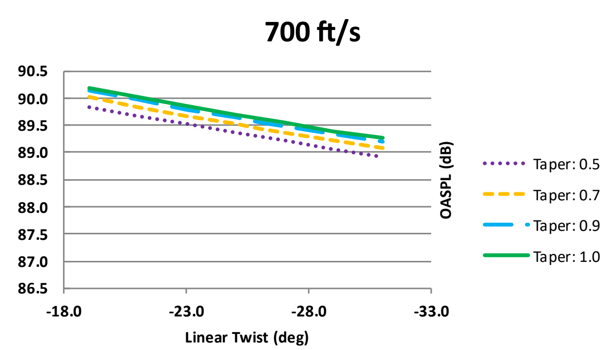

Figure 6. Linear twist and taper sweep OASPL, 700 ft/s, 3 blades

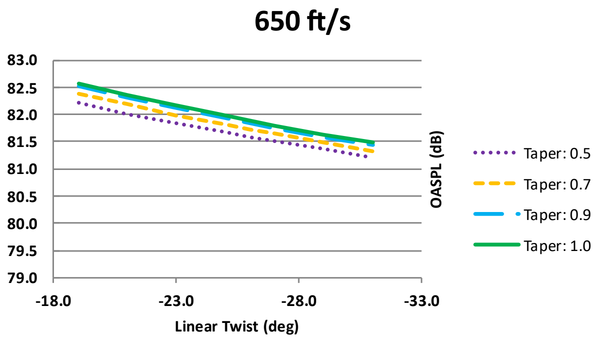

Figure 7. Linear twist and taper sweep OASPL, 650 ft/s, 3 blades

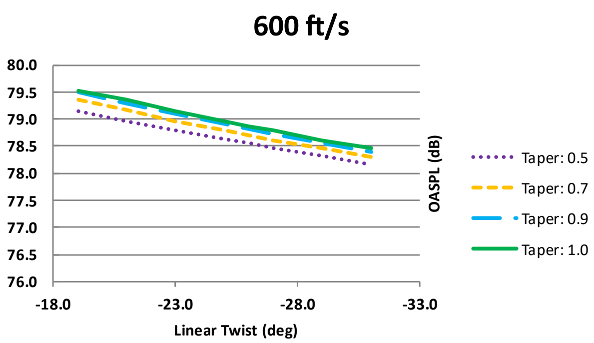

Figure 8. Linear twist and taper sweep OASPL, 600 ft/s, 4 blades

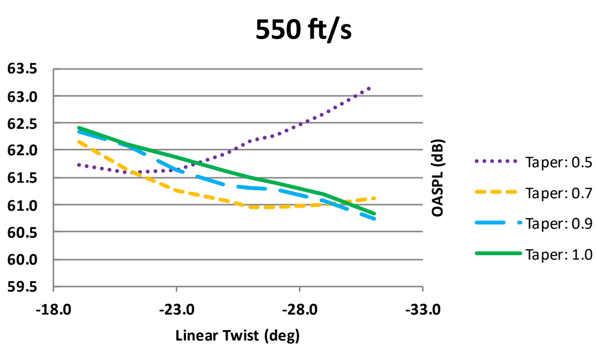

Figure 9. Linear twist and taper sweep OASPL, 550 ft/s, 6 blades

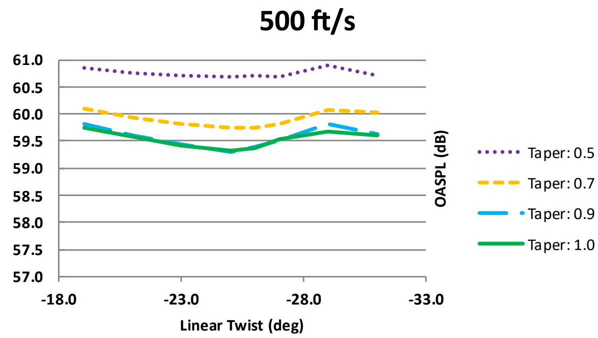

Figure 10. Linear twist and taper sweep OASPL, 500 ft/s, 6 blades

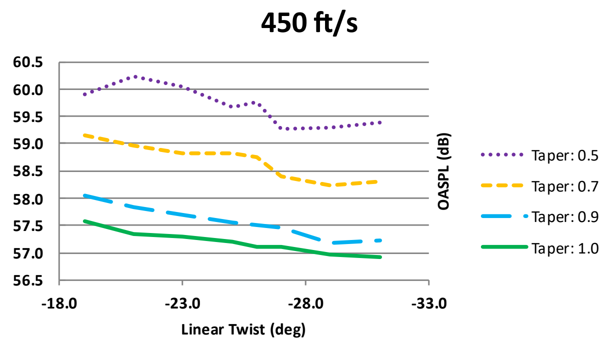

Figure 11. Linear twist and taper sweep OASPL, 450 ft/s, 6 blades

Blade count appears to have the greatest effect on the relationship of twist, taper, and OASPL. Tip speeds of 700-600 ft/s have 3-4 blades and the noise follows very similar trends. Increased taper and negatively increasing twist decreases hover noise. However, the differences are ~1 dB and are deemed not significant enough to influence the design.

Upon switching from 4 to 6 blades at 550 ft/s, the effect of twist and taper on noise changes. Most notable is that high tapers instead become louder by more significant (2-3 dB) amounts for the tip speeds of 550 to 450 ft/s. The effect of twist remains low, near 1 dB over the sweep for most cases, but shows less of a consistent effect. This change in trends is thought to be a result of blade count, further supported by running a 3-bladed 550 ft/s tip speed case. This case followed the same trends as the other 3-4 bladed rotor cases (Figure 12).

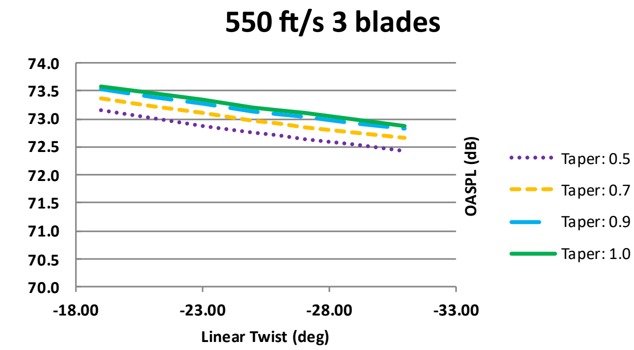

Figure 12. Linear twist and taper sweep OASPL, 550 ft/s, 3 blades

The most significant acoustic effect is low or untapered blades being quieter at low tip speeds and higher blade counts. In the case of planform selection, the acoustics and performance trend towards a similar result: less taper and more twist. These findings support the selection of an untapered blade with -30 degrees of twist from the performance results. This will be the planform used for the certification condition tip speed analysis.

TIP SPEED TRADES

In Ref. 4, four RVLT reference vehicles are analyzed for noise in certification conditions at varying tip speeds using the RVLT toolchain in a similar approach. These four concept designs include the quiet single main rotor (QSMR), side-by-side, quadrotor, and lift+cruise, pictured in Figure 13. In the original publication, the concept aircrafts' noise is compared to existing helicopters in the EASA Rotorcraft noise database (Ref. 17). In this work, the concept tiltrotor is plotted alongside those aircraft in Figure 14 - Figure 16 in both airplane (+) and conversion (X) mode to compare with existing helicopters and the other reference vehicles' tip speed variants. The values plotted are the average of the 3 observer points.

Figure 13. QSMR (top left), side-by-side (top right), quadrotor (bottom left), and lift+cruise (bottom right) reference vehicles

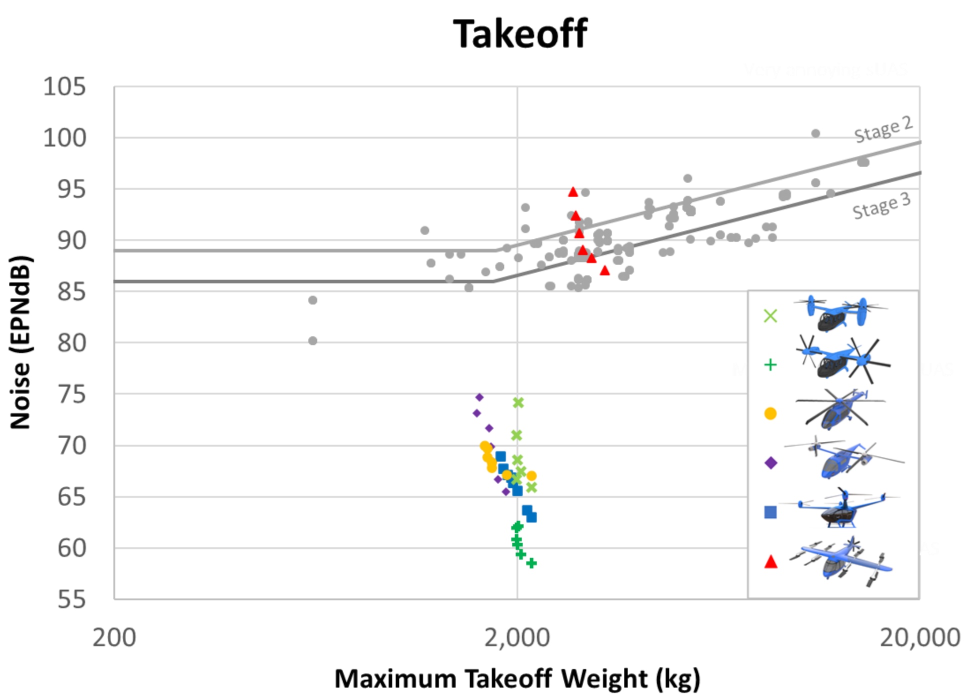

Figure 14. Takeoff certification noise for tiltrotor in airplane mode (+) and conversion mode (X) with RVLT reference vehicles varying tip speed, helicopter certification noise in gray

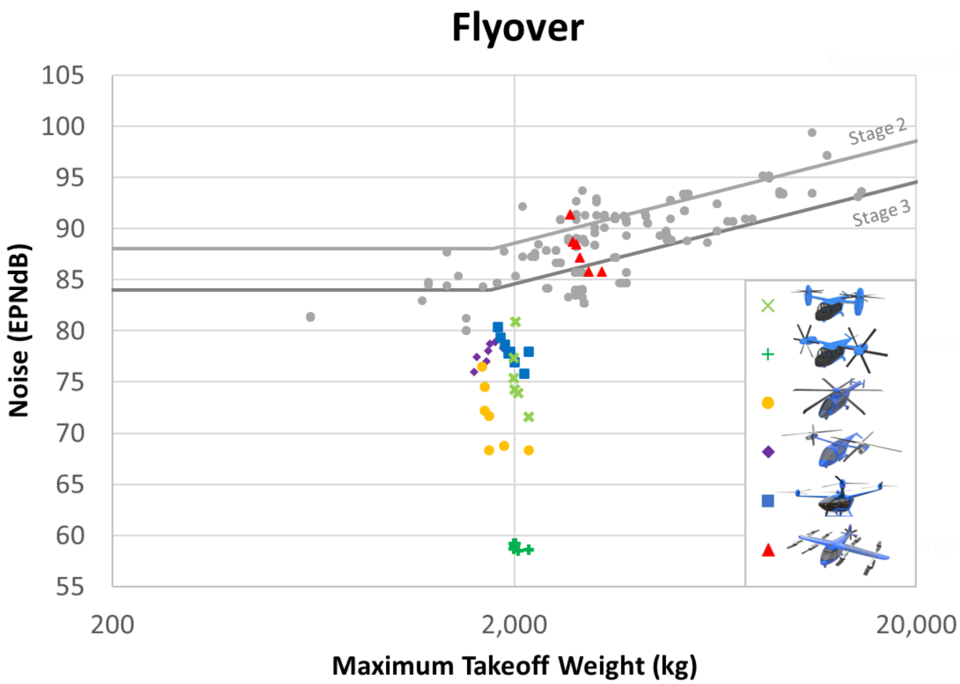

Figure 15. Flyover certification noise for tiltrotor in airplane mode (+) and conversion mode (X) with RVLT reference vehicles varying tip speed, helicopter certification noise in gray

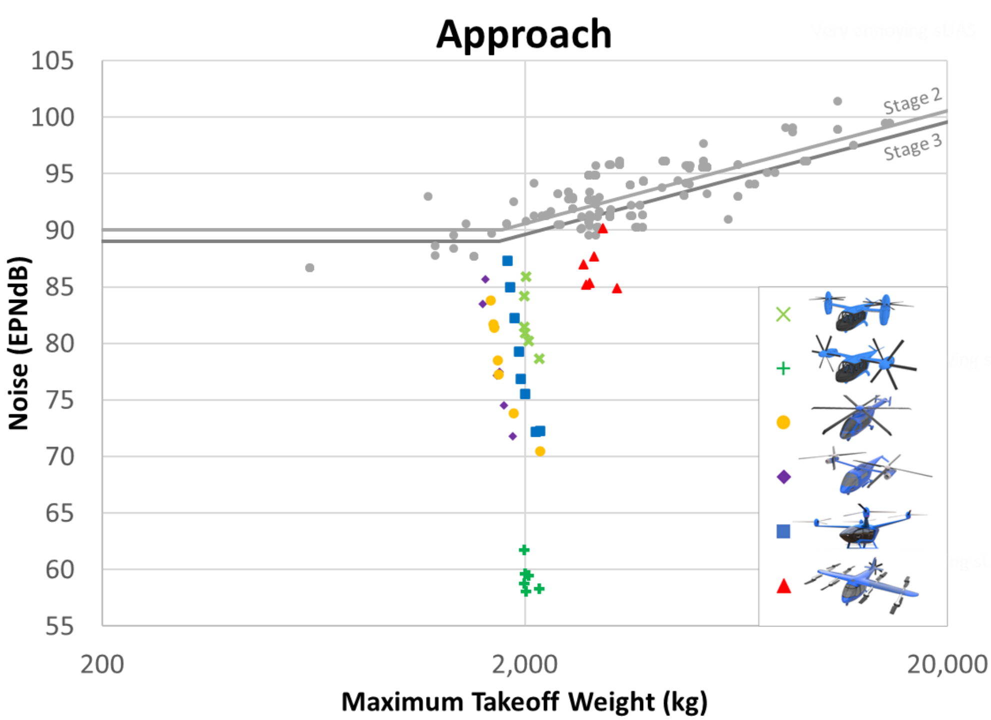

Figure 16. Approach certification noise for tiltrotor in airplane mode (+) and conversion mode (X) with RVLT reference vehicles varying tip speed, helicopter certification noise in gray

The concept tiltrotor in airplane mode is significantly quieter than any other rotorcraft, registering near 60 EPNdB for each certification condition. Airplane mode noise appears to be less sensitive to changes in tip speeds compared to the other reference vehicles, with a maximum of about 5 EPNdB difference between the loudest and quietest airplane mode tip speeds in any condition. Though it's worth noting that because airplane mode tip speed is half of hover/conversion tip speed, the difference between the lowest and highest case is only 125 ft/s as opposed to the 250 ft/s change seen by conversion mode. In airplane mode, Figure 17 shows that it is quiet enough for broadband noise to be the dominant source above thickness and loading.

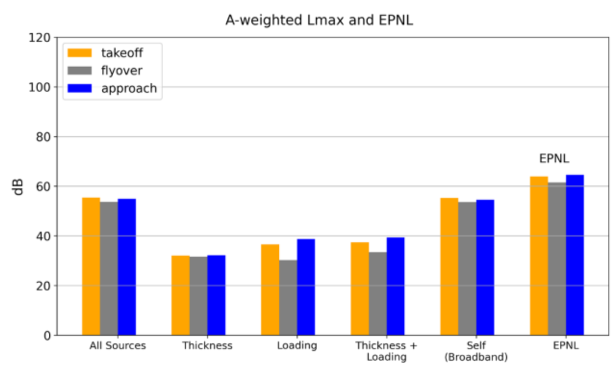

Figure 17. Airplane mode noise sources, 550 ft/s

The concept tiltrotor flying in conversion mode is louder than airplane mode, but is a similar noise level to the QSMR, side-by-side, and quadrotor reference vehicles. A notable difference is that tip speed change in approach (the highest noise condition) does not have as much of an effect on the noise for the tiltrotor as it does for the comparable reference vehicles.

A breakdown of the noise sources for each flight condition shows that loading noise is the dominant noise source in approach for conversion mode. 550 ft/s is included in Figure 18 and the noise source plots for the other tip speeds in airplane and conversion mode can be found in the Appendix.

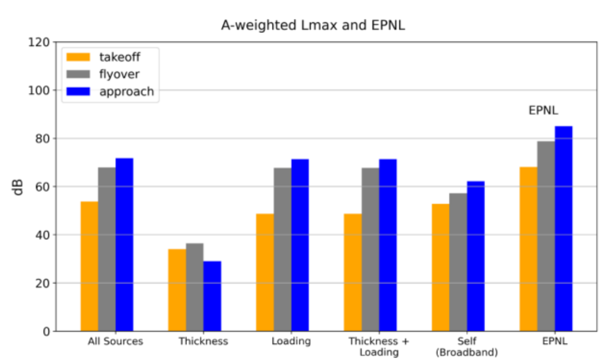

Figure 18. Conversion mode noise sources, 550 ft/s

The expected but nonetheless large disparity between conversion and airplane mode noise may serve as motivation for the operation of a UAM tiltrotor to perform as much of its mission in airplane mode as possible. Takeoff inevitably will include conversion, but the tiltrotor's takeoff is still relatively low noise compared to helicopters. Flyover will likely almost exclusively be performed in airplane mode during normal operation. Even assuming some successful approach noise reduction, conversion mode approach would still be tens of EPNdB louder than airplane mode, lending motivation to develop a flight control strategy to fly the majority of descent in airplane mode and convert at the nearest safe distance to the landing area.

The concept tiltrotor appears to not be as sensitive in terms of weight to tip speed changes as the other reference vehicles, indicated by its tight grouping of points along the horizontal (empty weight) axes of Figure 14 - Figure 16. Table 2 shows the change in empty weight, block time (total mission time), and flyaway cost in relation to the 550 ft/s baseline case (most desirable value in bold text). Negligible weight or speed change occurs with a tip speed increase from 550 ft/s. Weight and block time do begin to grow moderately with tip speed reduction below 550 ft/s. Flyaway cost is most sensitive to the tip speed change, so tip speed reduction does come with a cost penalty.

Table 2. Sizing results with varying tip speed

Tip Speed (ft/s) Conversion/ Airplane	Δ Empty Weight (%)	Δ Block Time (%)	Δ Flyaway Cost (%)
700/350	1.6%	-0.4%	**-5.7%**
650/325	0.2%	-0.3%	-4.6%
600/300	0.7%	**-1.1%**	-2.8%
550/275	**0.0%**	--	--
500/250	3.7%	1.2%	4.6%
450/225	8.1%	3.2%	10.6%

Table 3 and Table 4 contain the change in certification condition acoustics in relation to the baseline 550 ft/s case. In conversion mode, all conditions show generally decreasing noise with total tip speed reduction between 7 and 10 EPNdB. Takeoff has tangible reduction to 550 ft/s then effectively levels out. Flyover and approach both see noise reduction from 700 to 600 ft/s, then a very slight increase at 550 ft/s, possibly due to increasing from 4 to 6 blades, with continued reduction after. The largest reduction over a 100 ft/s variation occurs from 700 to 600 ft/s for all conditions.

Airplane mode shows an overall weak dependence on tip speed. Takeoff sees the closest to a linear trend with a mostly steady 3.6 EPNdB total decrease with tip speed. Flyover has no notable correlation, with each tip speed being within 1 EPNdB of the baseline. Approach noise is maximized at 550 ft/s with tip speeds above and below decreasing up to almost 4 EPNdB.

Table 3. Conversion mode noise with varying tip speed

Tip Speed (ft/s)	Δ Takeoff (EPNdB)	Δ Flyover (EPNdB)	Δ Approach (EPNdB)
700	7.5	5.5	4.4
650	4.2	2.0	2.7
600	1.9	-1.2	-0.6
550	--	--	--
500	0.7	-1.5	-1.3
450	**-0.8**	**-3.8**	**-2.8**

Table 4. Airplane mode noise with varying tip speed

Tip Speed (ft/s)	Δ Takeoff (EPNdB)	Δ Flyover (EPNdB)	Δ Approach (EPNdB)
350	1.3	0.0	**-3.7**
325	1.1	-0.5	-2.9
300	-0.5	-0.1	-2.1
275	--	--	--
250	-1.4	**-0.6**	-2.2
225	**-2.3**	**-0.6**	-3.4

CONCLUSIONS

This work demonstrates the use of the RVLT Toolchain for acoustic predictions of the RVLT tiltrotor reference vehicle. Rotor tip speed, blade twist, blade taper, and blade count were varied to analyze their effect on aircraft noise.

1. Airplane mode is exceptionally quiet in all conditions. Conversion mode is similar to the QSMR, side-by-side and quadrotor reference vehicles, and generally quieter than existing helicopters of similar weight. Tiltrotor operations should be developed to minimize time in conversion mode where possible to benefit from the low noise in airplane mode.

2. Insignificant weight change and significant conversion mode noise reduction from 700 to 550 ft/s lends a strong argument for a design tip speed of 600 ft/s or less. 450 ft/s has the overall lowest noise but comes with an 8% weight increase and 10% cost increase from 550 ft/s.

3. Rotor blade twist and taper were found to have small effects on isolated rotor noise, with desirable planforms for performance aligning with lower noise.

4. Disk loading was held constant in this study. Future work to quantify the effect of disk loading on certification noise for the concept tiltrotor is recommended. Further work may also include tip shape effects, non-linear twist to reduce negative tip loading, trim state changes, higher harmonic control, and other noise reduction techniques.

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APPENDIX

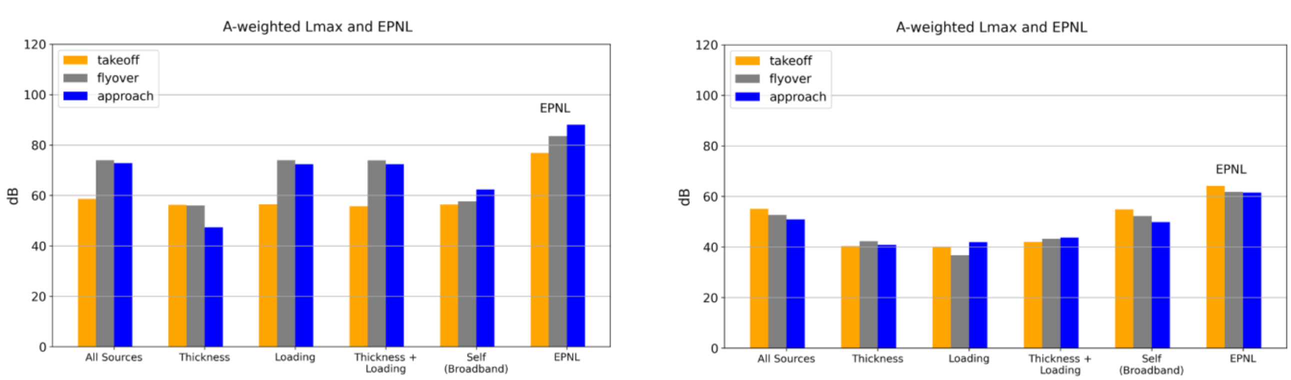

Figure A 1. Conversion (left) and airplane (right) mode noise sources for certification conditions, 700/350 ft/s, 3 blades

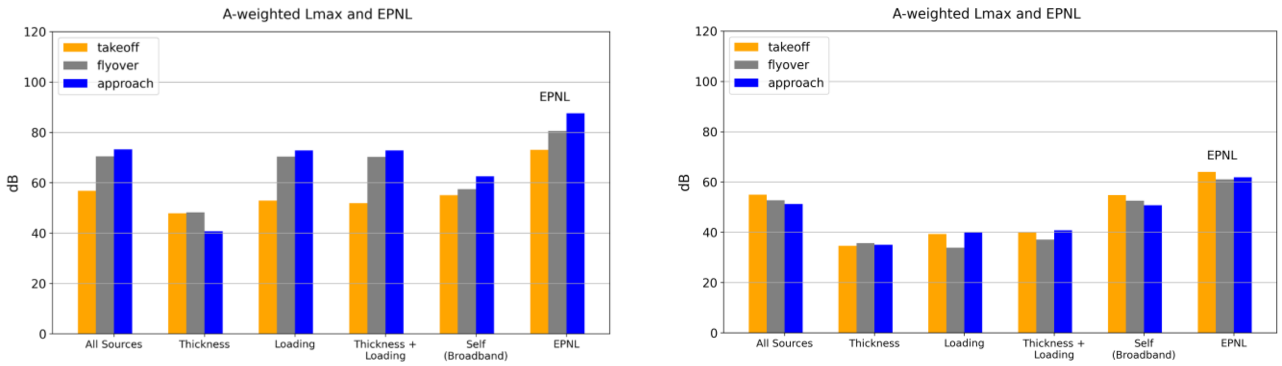

Figure A 2. Conversion (left) and airplane (right) mode noise sources for certification conditions, 650/325 ft/s, 4 blades

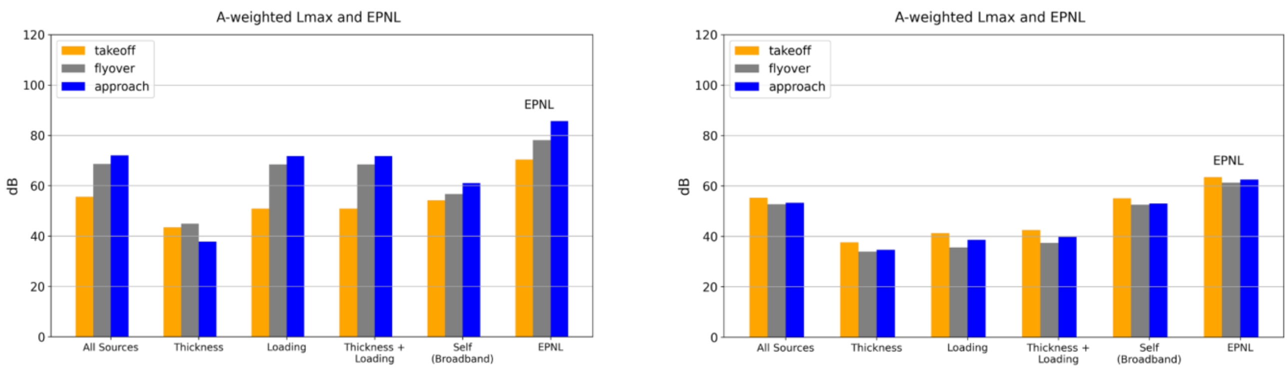

Figure A 3. Conversion (left) and airplane (right) mode noise sources for certification conditions, 600/300 ft/s, 4 blades

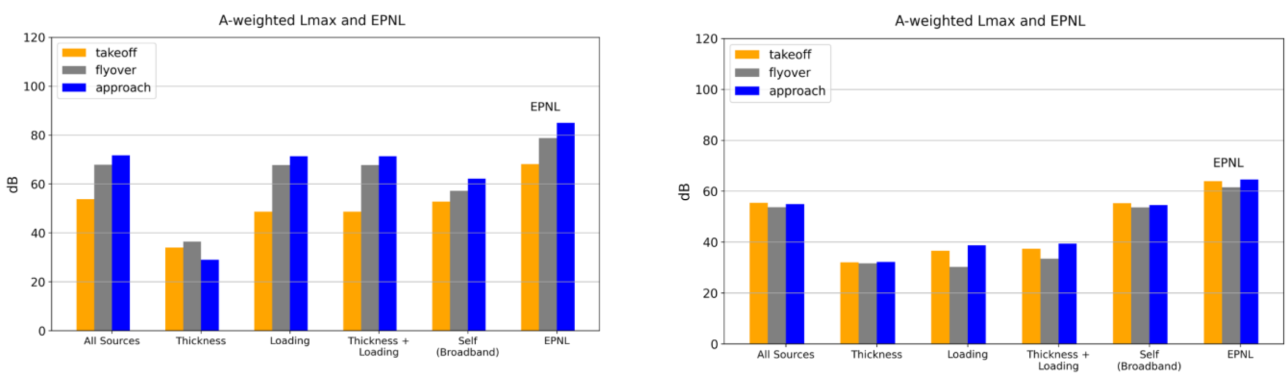

Figure A 4. Conversion (left) and airplane (right) mode noise sources for certification conditions, 550/275 ft/s, 6 blades

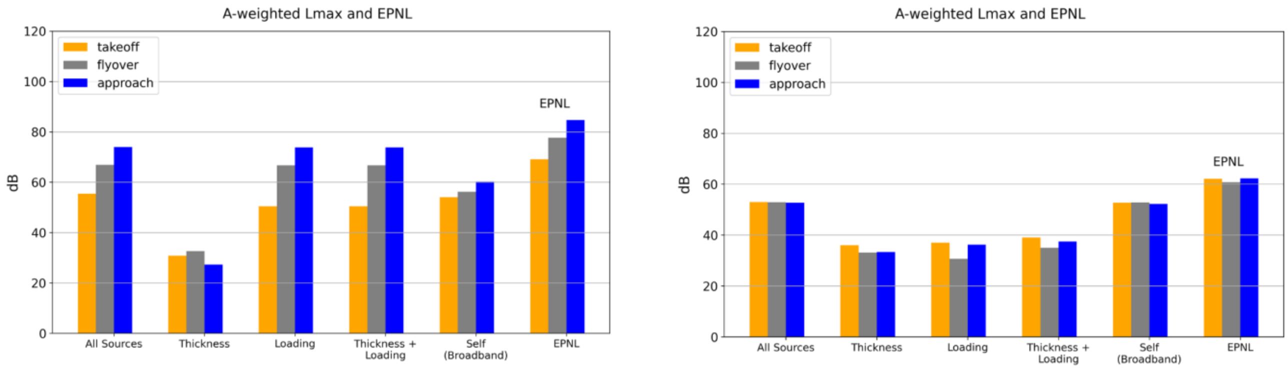

Figure A 5. Conversion (left) and airplane (right) mode noise sources for certification conditions, 500/250 ft/s, 6 blades

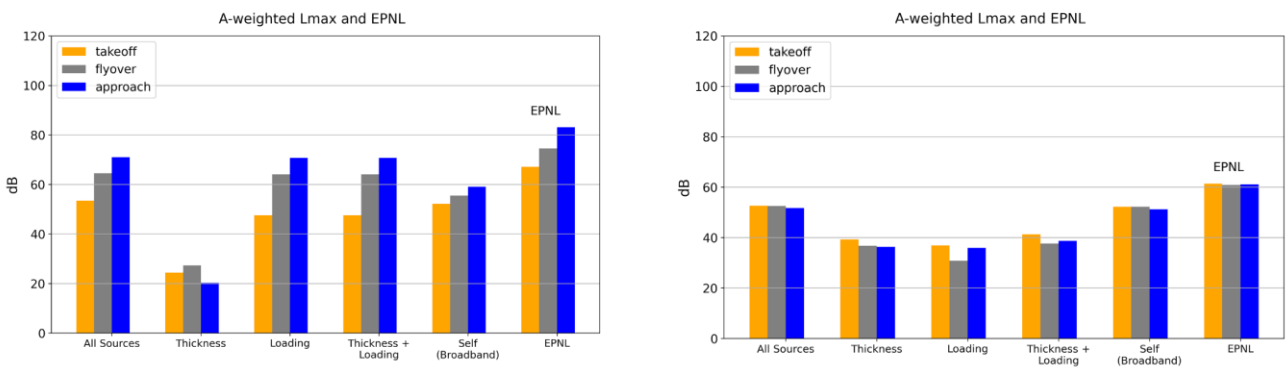

Figure A 6. Conversion (left) and airplane (right) mode noise sources for certification conditions, 450/225 ft/s, 6 blades