

Acoustic Predictions of the Moog S-250 in Hover

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Acoustic predictions were performed for the Moog S-250 vehicle to assess a NASA mid-fidelity prediction toolchain for Urban Air Mobility vehicles. Experimental data from a 60-foot hover test is used for comparison. The S-250 is an RPM-controlled vehicle in a quadcopter-type configuration with four sets of contra-rotating rotors and powered by eight independently controlled electric motors. A rotor blade identical to those used on the S-250 was 3D laser scanned. The resulting point cloud enabled the development of custom airfoil tables using OVERFLOW which led to accurate blade loading calculations. Seven observer locations are chosen to evaluate and compare with the measured hover data, which was mapped to a hemisphere with a radius of 12.5 feet, half of the largest rotor tip-to-tip distance between two separate rotors on different pylon arms. Noise predictions at observer locations near the hemisphere horizon capture the measured trends and power spectral density amplitudes within 6 dB for the first few harmonics. Observer locations under the vehicle predict lower levels than the experimental data relative to the observer locations near the horizon, but overpredict measured levels at the first blade passage frequency.

I. Introduction

Over the past decade, a myriad of electric vertical take-off and landing (eVTOL) vehicles have been under development. For eVTOL vehicles to be introduced into urban environments, they must produce acceptable noise levels. Prediction tools can be used to compute noise metrics and guide methods to reduce noise emitted by these vehicles. Designing eVTOL vehicles focused on producing little acoustic impact on communities has motivated researchers to invest time and resources into enhancement of prediction tools. Investigating isolated rotor noise is a first step in understanding how to reduce rotor noise from these eVTOL vehicles. This knowledge will become part of a larger strategy to reduce vehicle noise. Low-fidelity comprehensive and acoustic prediction tools are likely inadequate for accurately predicting the noise impact of a quadcopter-type urban air mobility (UAM) eVTOL vehicle. Low-fidelity tools typically use blade element momentum theory with a prescribed wake model for the aerodynamics and wake modeling. To gain a stronger understanding of the prediction accuracy using a mid-fidelity prediction toolchain, the Moog S-250 experimental aircraft is used as the test case by comparing with measured hover data [1].

Of interest are acoustic predictions for full-scale UAM vehicles. Existing datasets typically fall into two categories for full-scale testing, components (isolated rotor, etc.) or very limited set of full-vehicle measurements. Several research institutes have facilities which enable aerodynamic and/or acoustic measurements of isolated rotors or a small Uncrewed Aerial System (sUAS) aircraft. For example, Ref. [2] focuses on determining the acoustic far-field for multirotor aircraft using sUAS designs containing various number of rotors, rotor speeds, and rotor diameters on the

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order of between 1-2 feet (which is on the order of about 15% to 25% scale relative to the S-250). Additionally, a computational study was conducted on a 5-bladed rotor to, in part, identify specific noise sources and determining broadband noise contributions and investigate vortex-induced flow separation using mid- and high-fidelity tools [3]. Another component study conducted by Zawodny and Boyd investigate the rotor-airframe interaction to determine whether the airframe should be accounted for in a noise prediction [4]. Full-scale measurements of larger eVTOLs with a payload of over 200 pounds typically take advantage of outdoor testing. Acoustic measurements made by NASA on the Joby Aviation prototype eVTOL in hover and forward flight were conducted but lack publicly available vehicle information and rotor geometry. A high-fidelity computational model of the Joby Aviation prototype eVTOL was conducted to investigate individual propeller acoustics in hover and forward flight [5]. The previously mentioned studies are each important but do not make mid-fidelity comparisons of simulations to experiments, do not use custom built airfoil tables, do not use publicly available full-scale vehicle data, nor do not consider vehicles which use rotors with diameters of 7-8 feet.

The mid-fidelity acoustic prediction toolchain investigated uses CAMRAD II [6] to perform the aerodynamic analysis of the S-250. The solution is passed to the NASA Aircraft NOise Prediction Program 2 (ANOPP2) by way of AeroAcoustic Rotor Noise tool (AARON) [7] for the far-field noise prediction. One of the required inputs to CAMRAD II is airfoil tables containing lift, drag, and moment coefficients as a function of angle of attack and Mach number for the rotors used in a simulation. It is not uncommon to use a generic airfoil table that does not match the actual blade geometry with mid-fidelity prediction methods, but doing so may lead to inaccurate blade loadings. To enhance the computational accuracy of the simulations, custom airfoil tables are generated using AirFoil Table Generator (AFTGen) [8] coupled with the NASA computational fluid dynamics (CFD) Reynolds-Averaged Navier-Stokes (RANS) code, OVERFLOW [9]. An example of the blade used by the S-250 was obtained and 3D laser scanned using a FARO® Quantum scanner. The resulting geometry data was then used to create the aforementioned airfoil tables.

This paper compares measured data with simulations of the Moog S-250 vehicle during hover and out of ground effect at seven observer locations. The S-250 is a UAM research vehicle configured as a quadcopter with contra-rotating rotors. It should be noted that the rotors used on S-250 were not optimized to the vehicle and were chosen as an available commercial off the shelf offering that met the lift requirement of the research vehicle.

Below, section A describes how specific airfoils are extracted from the 3D blade scan, while section B details the generation of the airfoil tables, and section C discusses the prediction tools used to generate the acoustic spectra. The results section compares numerical results at seven observer locations to experimental data. Limitations of predicting acoustic radiation for a UAM vehicle using mid-fidelity prediction tools are also discussed.

II. Technical Approach

A. Vehicle and Rotor Geometry

The Moog S-250 research vehicle, shown in Fig. 1a, uses a quadcopter-type rotor configuration that implements RPM-controlled contra-rotating rotors driven by eight independently controlled electric motors. The footprint, or farthest tip-to-tip distance, of the vehicle is approximately 23 feet. Table 1 contains available vehicle information. Quantities for the vehicle center of gravity and moment of inertia are based off the origin shown in Fig. 1b. Although present in the current CAMRAD II model, the vehicle weight, center of gravity, and moment of inertia information is not used here because the pilot control matrix is Moog proprietary at this time. Thus, the rotor RPMs are fixed and trim was not performed. If the pilot control matrix for RPM control becomes available, the model will be updated, and results will be disseminated.

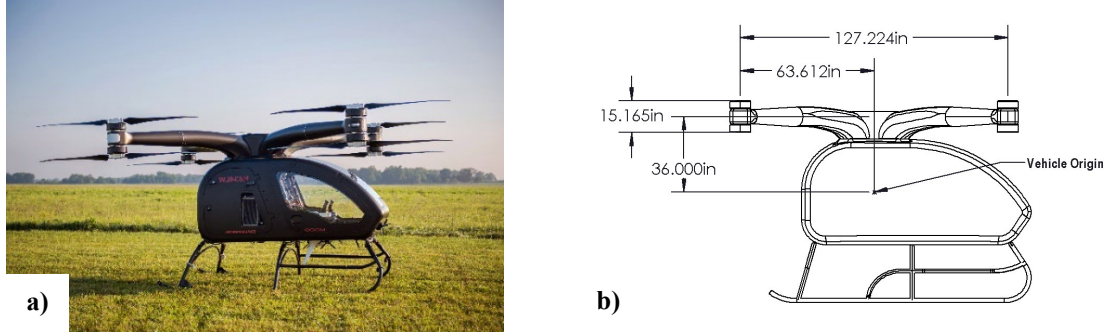


Fig. 1 The Moog S-250 research vehicle, a) photograph of vehicle before hover test, b) sketch of the S-250 with origin.

Table 1. S-250 Vehicle Information

Weight (lbf)	Number of Rotors	Rotor diameter (ft)
2088	8	7.67
CG_x (ft)	CG_y (ft)	CG_z (ft)
-0.2123	0.0331	-0.6276
I_{xx} (slug-ft ²)	I_{yy} (slug-ft ²)	I_{zz} (slug-ft ²)
1662	1753	1109

The 60-foot (altitude) hover test was conducted at Springfield-Beckley Municipal Airport. Acoustic hemispheres were constructed from ground array measurements. One quadrant of the hemisphere was measured at a time and the vehicle rotated 90 degrees (yaw) at a time to acquire data for each of the other quadrants of the hemisphere. Although the rotation and holds are not part of the current model, the resulting spectra from the hemisphere was used for the prediction. Details on the experimental setup, configuration, and results of the experiments are presented in Ref. [1]. Components of the vehicle telemetry were used to inform the CAMRAD II simulation and acoustic prediction; this includes the individual rotor speeds while the vehicle was in hover and spatial position of the vehicle.

Three laser scans of the rotor blade were conducted using a FARO® Quantum scanner at various resolutions. A point cloud of over 35 million points was deemed to provide adequate resolution along the leading and trailing edge. From this point cloud, slices were taken every 0.25 inches using Mastercam software. The resulting slices and associated points are shown in Fig. 2. Aerodynamic calculations were performed at stations 1 and 2 which have an $r/R = 0.7527$ and 0.9066 , respectively, where r/R is the ratio of local radius via the span distance relative to the overall blade radius. Scans at lower resolutions were conducted but were found to provide insufficient resolution along the leading and trailing edges to adequately resolve the curvature.

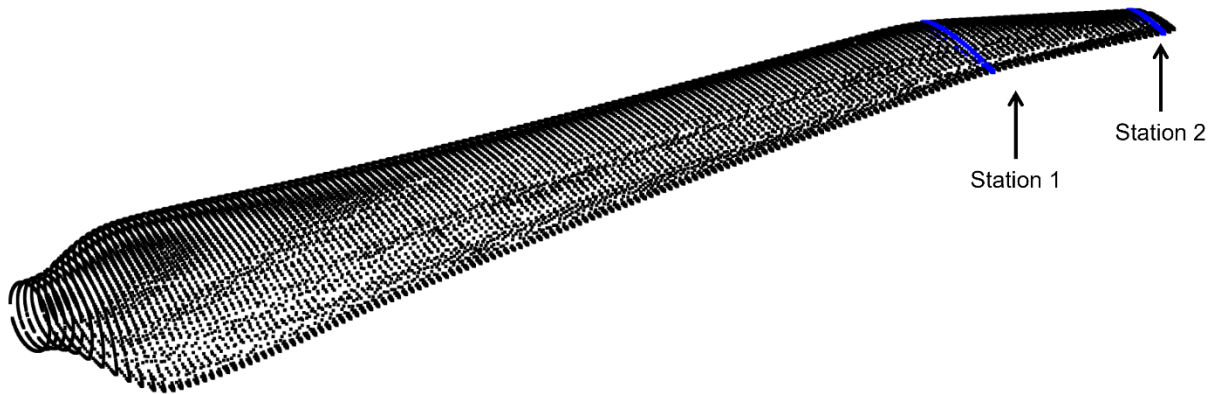


Fig. 2 Sliced cross-section of 3D blade scan.

The cross-sections at stations 1 and 2 are shown in Fig. 3. The extracted airfoil points are oriented, shifted, and scaled such that the leading edge begins at (0, 0) and the trailing edge is located at (0, 1). During this process, the airfoil

chord and thickness are extracted and the thickness divided by chord (t/c) is computed. Table 2 contains a list of these properties with respect to the radial span.

Table 2. Airfoil properties

r/R	Chord (in)	Thickness (in)	t/c
0.7527	3.4539	0.3394	0.09827
0.9066	1.702	0.1946	0.11434

Interpolation using a parametric spline approximation is used to add additional points and generate equally spaced points along each airfoil slice/curve. The coordinates are imported into AFTGen, which uses grid clustering along the leading and trailing edges to improve the solution convergence rate in OVERFLOW.

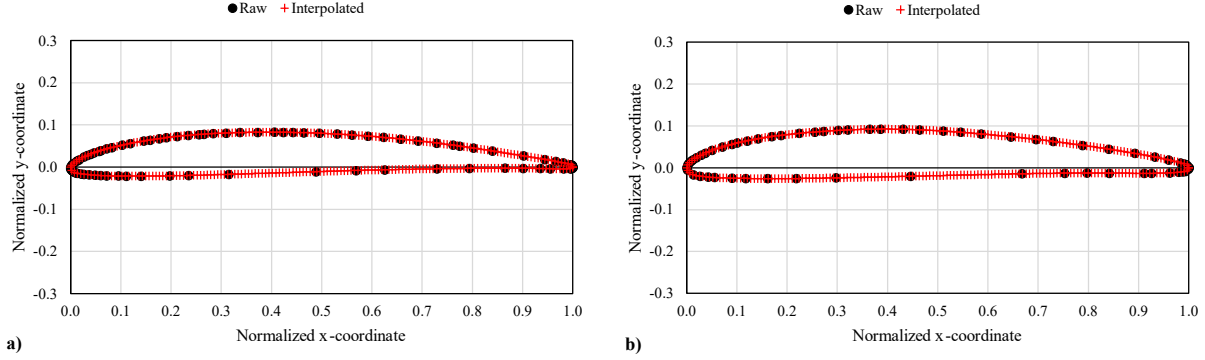


Fig. 3 Interpolated airfoil coordinates compared to the raw scanned values a) $r/R=0.7527$ and b) $r/R=0.9066$.

B. Airfoil Table Generation

The NASA OVERFLOW CFD code was used with AFTGen to simplify the generation of airfoil tables for various conditions. Each selected airfoil section for the fixed-pitch rotors was analyzed using a specific range of angle of attack (AoA) and Mach (Ma) numbers, based on the local conditions of the rotor determined from the vehicle configuration used in the hover test. Each airfoil section employs the same numerical scheme within OVERFLOW, using the fully turbulent Spalart-Allmaras model with Courant-Friedrichs-Lewy (CFL) ramping from 0.25 up to 5. For each airfoil section a Reynolds-Mach (Re/Ma) proportionality constant is used such that each Mach number investigated in the RANS simulation uses the correct Reynolds (Re) number, i.e. the Reynolds number each blade section would experience at the given Mach number [10]. The conditions used in the simulations are shown in Table 3. Local environmental conditions during the hover test were used to calculate Re and can be found in ref. [1].

Table 3. OVERFLOW run conditions for selected airfoil sections.

r/R	Twist ($^{\circ}$)	Ma_{Local}	$-AoA$ ($^{\circ}$)	$+AoA$ ($^{\circ}$)	$-Ma$	$+Ma$	Re/M
0.75	5.5	0.47	-8	14	0.1	0.55	2.05E6
0.91	3.91	0.57	-8	12	0.1	0.65	1.01E6

AFTGen was utilized to grid each airfoil using an O-grid, employing built-in tools with 201 periodic points around the chord and 101 in the direction normal to the section as the base inputs. Fig. 4 shows an example of the airfoil grid for the most inboard station. The result of this grid yielded a converged solution at each angle of attack and Mach number combinations investigated.

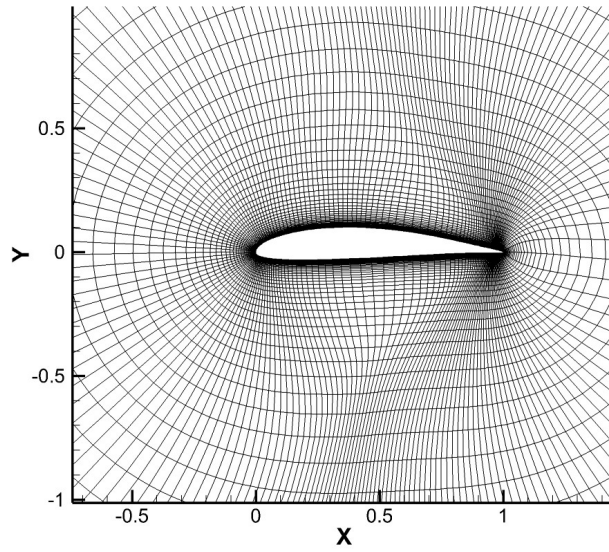


Fig. 4 Example of grid used for OVERFLOW calculations.

The lift, drag, and moment coefficient plots for $r/R=0.75$ are presented in Fig. 5. For this section, the Mach number range is 0.1-0.55 and the angle of attack range is -8 to $+14$ degrees. The OVERFLOW angle of attack range is outlined using vertical bars on each plot. The angles of attack outside that range are blended from a VR-12 base table but were not used in the simulations because the OVERFLOW conditions covered the angles of attack for the vehicle in hover. Overall, the solutions are reasonably well behaved and are similar to VR-12 tables. This airfoil station is important because traditionally $r/R=0.75$, or the three-quarter radial station, is from where the blade setting angle is measured.

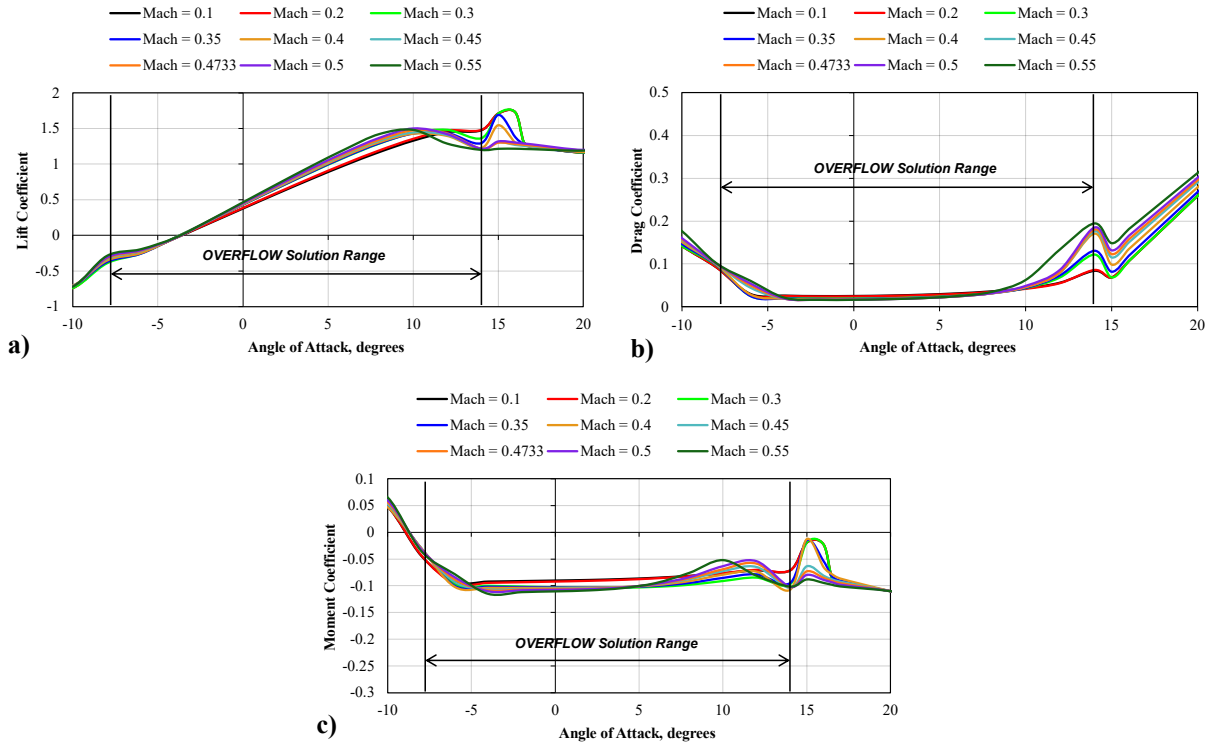


Fig. 5 Lift coefficient a), drag coefficient b), and moment coefficient c) for $r/R=0.75$

There is a clear trend in Fig. 5 for the lower Mach number results at this radial station. Separation is seen at the lowest two Mach numbers at the 75% radial station, that is Mach numbers ≤ 0.2 , and is an expected behavior. Furthermore, the lift coefficient increases with Mach number and follows the Prandtl-Glauert rule (see ref. [11], page 750) in the linear angle of attack region (-10° to $+10^\circ$).

The lift, drag, and moment coefficient plots for the airfoil section near the rotor blade tip at $r/R=0.91$ are presented in Fig. 6. For this section, the Mach number range is 0.1-0.65 and the angle of attack range is -8 to $+12$ degrees.

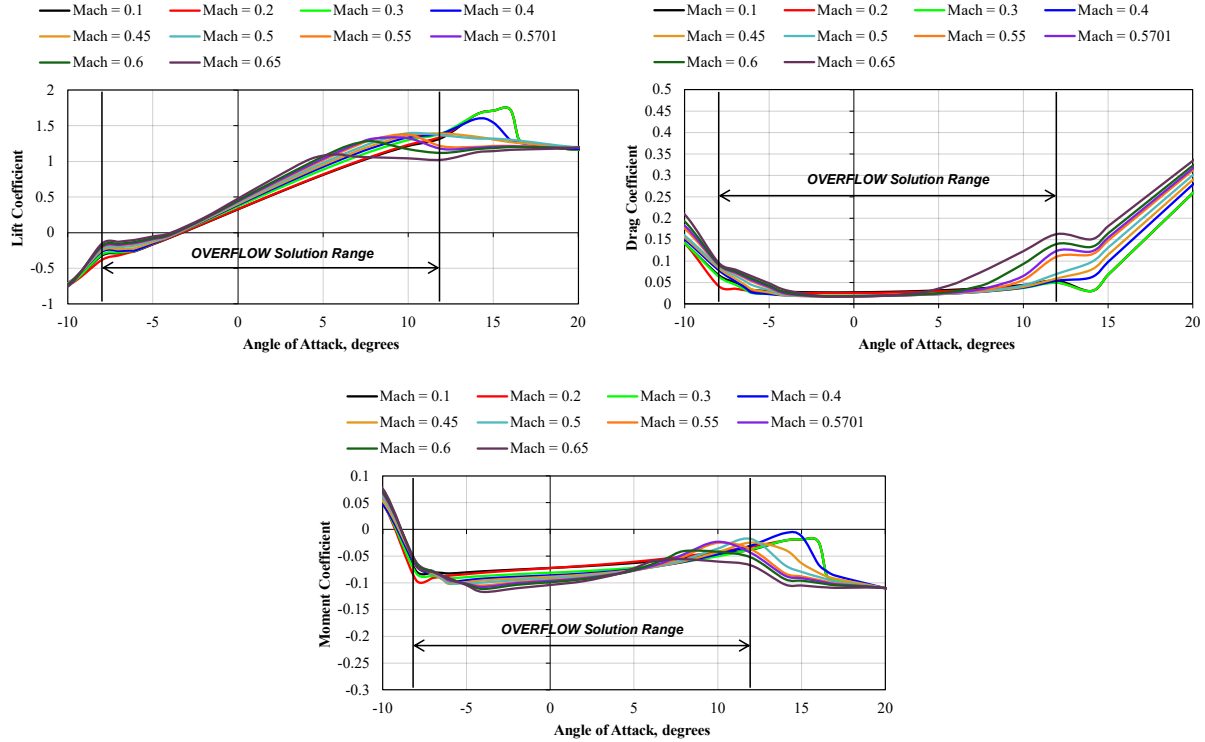


Fig. 6 Lift coefficient a), drag coefficient b), and moment coefficient c) for $r/R=0.91$

Again, the lowest two Mach numbers for this section show the same separation as in the previous charts. The Prandtl-Glauert rule is maintained at this radial blade section as well.

Each of the airfoil sections investigated display unique characteristics. Although the effective blade section angle of attack for each station was unknown before running the CAMRAD II simulation, results indicate the angle of attack range covered by OVERFLOW was adequate. The values computed and used in the simulations are discussed in the next section. Airfoil tables for additional inboard stations, such as $r/R=0.4$ and 0.6 , can be generated using the established framework to determine if they can contribute to improved blade loading information and corresponding acoustic prediction.

C. Prediction Tools

The comprehensive analysis tool, CAMRAD II, was selected to analyze the S-250 due to the complexity of the eVTOL configuration and control scheme. The S-250 is an RPM controlled eVTOL with contra-rotating rotor blades. In hover, the eight rotors operate at eight different rotor speeds. CAMRAD II is used to model this type of eVTOL vehicle due to its ability to incorporate a nonuniform inflow and free wake geometry. Additionally, CAMRAD II can model the averaged interference effects between the upper and lower rotor blades. The current model adopts a simplified approach by assuming the rotors are rigid, but it can be updated if elastic properties become available.

CAMRAD II computes blade motion, blade loading, and the vehicle trim state for use in generating a far-field noise prediction using ANOPP2 [7]. It should be noted that CAMRAD II can do RPM controlled trim, but the T-matrix which maps the pilot controls to the vehicle rotor controls is Moog proprietary for this vehicle at this time. For this simulation, the RPM of each rotor is given a fixed value and held constant. The intent of the simulation is to model

the vehicle in hover and compare the acoustic result to measured data. The S-250 rotor RPM information was acquired via the electric motor electronic speed controllers using onboard telemetry during a 60-foot hover test, and an average RPM is computed for each rotor. The numbering scheme shown in Fig. 7 is implemented in the model.



Fig. 7 Rotor numbering scheme used on the S-250 research vehicle and implemented in the CAMRAD II model.

The averages are taken over a period of just under 0.5 seconds while the vehicle RPM data appeared to be reasonably steady. The result is presented in Table 4. The fixed rotor collective angle for rotors located on the upper plane are set to 5.5 degrees and rotors on the lower plane are set to 6 degrees. Both are measured from the $r/R=0.75$ spanwise location. It should be noted that the CAMRAD II simulation includes the 8 rotors but does not include the aerodynamic effects of the vehicle fuselage, pylons, or electric motors. The effective blade section angle of attack computed by CAMRAD II for $r/R=0.75$ and 0.91 are 4° and 11° , respectively.

Table 4. Individual rotor RPMs used in the CAMRAD II simulation.

Rotor 1	Rotor 2	Rotor 3	Rotor 4	Rotor 5	Rotor 6	Rotor 7	Rotor 8
1768	1510	1774	1700	1679	1610	1873	1609

By default, ANOPP2 needs to select a frequency bin width, usually the longest blade passing period, in which to produce an acoustic solution which is challenging for a vehicle with multiple rotor speeds [7]. To account for this, an extended reception time and period is required to distinguish between the individual blade passage frequencies (BPF). The resulting frequency bin width was 0.25 Hz, which resolved 6 of the 8 individual rotor BPFs. Because some of the rotors were at close to the same speed (RPM), it was not necessary to resolve all rotor BPFs. Additionally, the experimental data was acquired at a much wider bin width.

III. Results

Comparisons from several microphone locations are presented in this section. The measured acoustic data has the ambient background levels subtracted, has been depropagated to hemisphere radius of 11.5 feet from the center of the thrust mid-plane (the midpoint between the upper and lower rotors), has been corrected for atmospheric attenuation, and has been corrected for pressure doubling from the ground [1]. The data are presented as narrowband power spectral density (PSD) expressed in decibels (dB) [12].

$$PSD = 10 \log \left(\frac{p^2}{\Delta f * t_{ref} * p_{ref}^2} \right) \quad (1)$$

Where p^2 and Δf are the contribution to the mean square pressure from a spectral bin and the bin width, respectively. The normalization quantities are $p_{ref} = 20 \mu Pa$ and $t_{ref} = 1s$.

A sound hemisphere was constructed using the geodesic polyhedron microphone layout. Fig. 8 shows an overhead view of the first blade passing frequency (BPF) hemisphere with dots indicating microphone locations and red dots indicating microphone locations selected for comparisons with simulations in this manuscript. The labels 1-7 were added to the red dots for clarity when comparing simulations to the measurements. The vehicle orientation is indicated on the hemisphere using a directional arrow. The hemisphere in Fig. 8 was generated by summing the squared pressure over the BPFx1 frequency range for each microphone then converting back to PSD using the bin width spanning the BPFx1 range. The BPFx1 range is encompassed between the green dashed lines on Fig. 9a. Nineteen microphones were used for this hover test to measure one quadrant of the hemisphere. The vehicle rotated into four different orientations and the data were combined to construct the hemisphere. The S-250 vehicle was equipped with GPS but did not use precise positioning, which may impact the accuracy of acoustic prediction. Microphone locations were selected to determine the ability to simulate the source directivity based on the BPFx1 hemisphere. It should be noted

that fifteen microphone locations were investigated and show the same general trend discussed for the seven microphone locations presented herein. For angles near the horizon, regions of maximum and minimum radiation were selected. Additionally, points beneath the aircraft where the radiation is a minimum were also investigated.

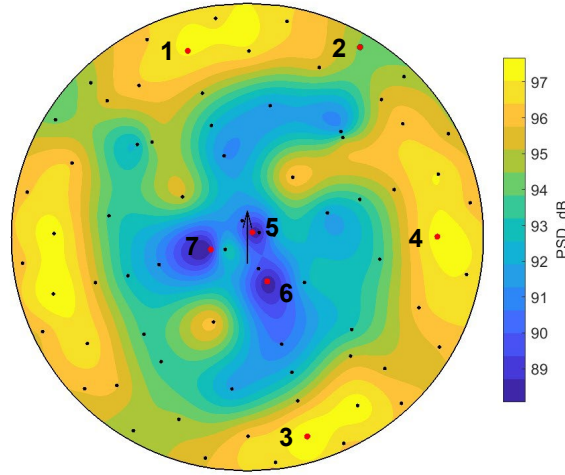


Fig. 8 Overhead view of noise hemisphere containing acoustic amplitudes on an 11.5-foot radius hemisphere of BPFx1 from 60-foot hover test with microphones shown using dots, specific microphone locations chosen for simulation comparison are shown in red, the vehicle orientation is shown with the arrow.

The comparison of the measured and computed results for microphone 1 is presented in Fig. 9. Only the data for the first BPF are presented in Fig. 9b. Although the peak locations are the only valuable information regarding the predicted sound levels, the spectra are shown using a curve to better identify the rotor blade passing frequencies. From here on only the peak amplitude locations are extracted and shown for clarity. It should be noted that six frequency peaks are identified in the simulation dataset for each BPF. While the eight rotors had unique rotational speeds, the rates of rotors 1 and 3 as well as rotors 6 and 8 are very close together. Producing a simulation time history with the resolution required to identify these peaks would increase the simulation time tremendously and would yield little benefit to the final comparison with the experimental data. The simulation captures the experimental peak amplitude for BPFx1 for four of the simulated rotors and overpredicts by 6-9 dB for the other 2 simulated rotors. The rate of decrease in the predicted peak values with increasing BPF does not match the measured trends and, therefore, it is possible that the simulations may lack fidelity.

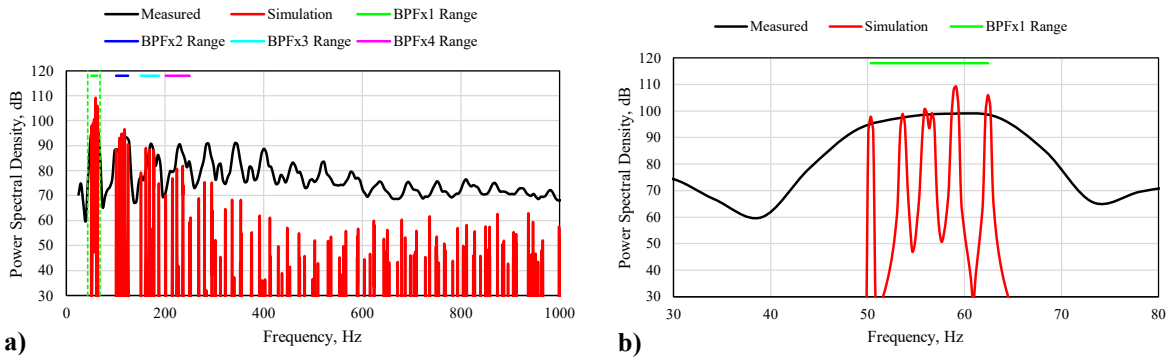


Fig. 9 Prediction comparison of experimental normalized Power Spectral Density to simulation of S-250 in 60-foot hover, a) wide frequency range up to 1000 Hz, b) detailed view of BPFx1.

Fig. 10 shows comparisons at four microphone locations near the horizon. As previously mentioned, the peak levels for each BPF have been extracted and shown for clarity. The measured data indicates maximums for the first BPF at microphone locations 1, 3, and 4. Each of these observer locations (1, 3, and 4) contain points that lie on top of the measured data for BPFx1. Conversely, the data suggests a minimum close to the location of microphone 2. The simulation exhibits an overprediction for each rotor at BPFx1. Similarly, the BPFx2 – BPFx4 harmonics are well

captured by the simulation model for microphones 1,3, and 4 with a few peak amplitudes that underpredict or overpredict the measured data. The microphone 2 location captures the peak levels at BPFx3. By increasing the resolution of the hemisphere used in the experiment or generating a simulated hemisphere, it would be possible to identify where the minimum sound levels occur. Additionally, it is unclear if the location of the rotors in relation to vehicle components are contributing to a noise source or contributing to a propagation issue. Assumptions made in the CAMRAD II model such as considering the blade as rigid may result in some prediction inaccuracies.

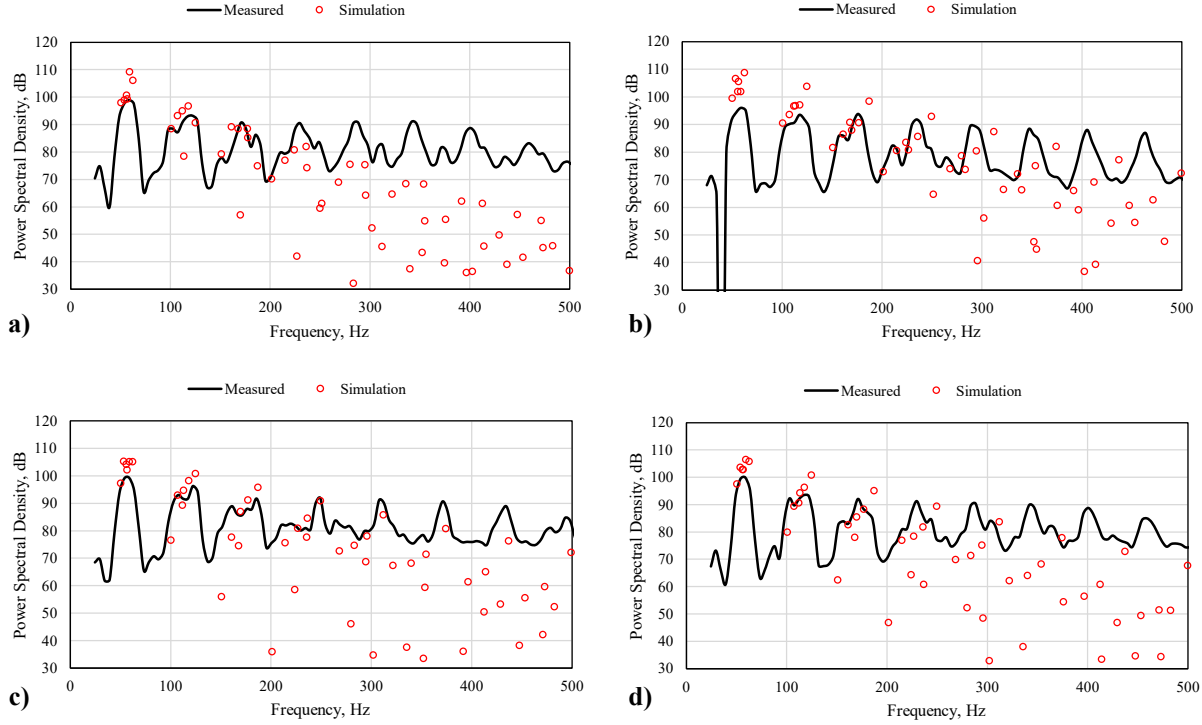


Fig. 10 Comparison between measured data and simulations for a) Mic 1, b) Mic 2, c) Mic 3, d) Mic 4

Fig. 11 shows a comparison of the predicted amplitudes at microphone locations 5-7 beneath the vehicle. The amplitudes for BPFx1 are overpredicted, on average, by around 2-10 dB. At BPFx2, the amplitudes are in line with the measurements, however, after BPFx2 the amplitudes are underpredicted. The predicted peak levels for microphone locations 5-7 are, on average, more than 4 dB lower than that of microphone locations 1-4. The trend of predicting lower peak noise levels at directivity angles beneath the vehicle is captured although the peak levels are not. The deviation to the measurement, which stays relatively flat, of the rate of roll off in the simulation peak amplitude with increasing BPF may indicate that fidelity is missing from the numerical model.

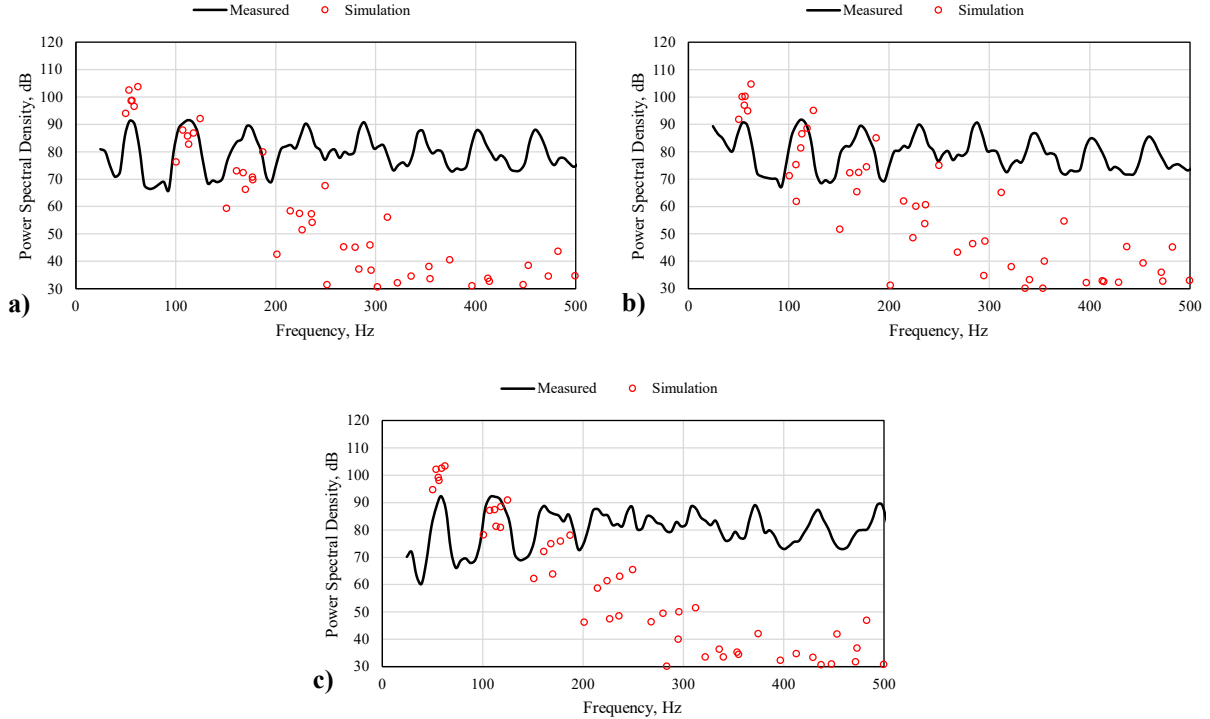


Fig. 11 Comparison between measured data and simulations for a) Mic 5, b) Mic 6, and c) Mic 7

As previously mentioned, CAMRAD II, for this case, is only modeling the aerodynamics of each rotor and of rotor-rotor interactions. The disparity between the simulation and the measured data is possibly caused in part by the interaction of the rotor and pylon arm due to their proximity to one another (as well as the fuselage). An example of these effects was shown in ref [4], where a fundamental comprehensive study was conducted on a smaller rotor and a rod that was incrementally positioned closer to the rotor. When the rod is positioned farthest from the rotor, the measured falloff in peak amplitude with increasing BPF very closely resembles that of the simulation in Fig. 9a. Conversely, when the rod is positioned close to the rotor the noise characteristics resemble the falloff seen in the experimental data. For the S-250 vehicle, the distance between the rotor and pylon arm is about 4 inches, which could cause an increase in source noise levels. Consequently, the impact of the S-250 fuselage may contribute to noise shielding at observer locations beneath the vehicle. Coupling the numerical model with CFD will likely be required to accurately model the impact the bluff bodies have on the rotor blade source noise.

IV. Conclusions

Experimental acoustic measurements of the Moog S-250 eVTOL in hover and out of ground effect were conducted and compared with numerical simulations using CAMRAD II in combination with the NASA ANOPP2 acoustic prediction framework. A 3D scan of the S-250 rotor blade was performed and contained over 35 million data points. The data points from the 3D scan were extracted at two blade section locations and used to create custom airfoil tables with the NASA OVERFLOW CFD solver using AFTGen to streamline the process.

The resulting power spectral density at BPFx1 demonstrated agreement within about 6 dB of the experimental measurements for observer locations near the horizon, with several simulation peak amplitudes matching the measurement. BPFx2-BPFx4 also contain several peak amplitudes that match well with the measured data, albeit with a couple of outliers. After BPFx4 there is roll off of the amplitudes with frequency that is not captured in the data for BPFx4 and greater. For observer locations under the vehicle, the first BPF is over predicted. Shielding due to the vehicle fuselage may be impacting the measurements and shielding is not captured in the current simulation. The second BPF is captured at these microphone locations. Additionally, the current CAMRAD II model treats the blade as if it is rigid, though elastic blades could be used if the blade structural properties were available. The impact of this in the current simulation is unknown. Furthermore, the current model has no trim state because the rotor RPMs are

fixed, by incorporating RPM trim into the CAMRAD II model would increase realism and perhaps improve the predictions.

The current CAMRAD II model produces blade motion and loading inputs that are used in the ANOPP2 acoustic prediction and yield a less than favorable comparison to measured data in some cases. By coupling CAMRAD II with a CFD tool like either the NASA OVERFLOW or FUN3D code, it would be possible to incorporate the vehicle geometry within the model. Using this paradigm the specific vehicle components that result in a significant noise source could be identified and quantified. Additionally, future work is planned to investigate the installation effects using a single rotor or rotor pair with the accompanying pylon at a fixed RPM and would provide the data to determine if the fuselage is required to obtain an adequate prediction of the measured sound of the S-250 in hover.

Acknowledgments

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