

Acoustic Measurements for the Moog S-250 Vehicle in Hover

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Acoustic measurements for hover conditions and electric motor noise tests were conducted for the Moog S-250 research aircraft, an RPM-controlled quadcopter-type Urban Air Mobility (UAM) vehicle with four sets of contra-rotating rotors. The objectives of the study included determining the minimum far-field distance, the noise characteristics, and the potential for electric motor noise to contribute to the overall acoustic radiation for the full-scale UAM vehicle. Acoustic data for full-scale aircraft are critical for determining the impact of these vehicles on the surrounding communities. The results showed the far-field was reached by 8.1 single rotor diameters or 2.7 vehicle diameters as defined by the longest tip-to-tip rotor dimension for the vehicle. In hover, the peak acoustic radiation occurred at a declination angle of roughly 29° below the midplane between the upper and lower rotors. The lowest acoustic levels occurred below the aircraft. The electric motor noise studies, conducted with the rotors removed, showed motor noise radiated at shaft orders 17 – 20, whereas rotor noise covered the range of 2 – 24 shaft orders. There was some evidence that electric motor noise was present in previous ground run-up measurements.

I. Introduction

The Federal Aviation Administration released its first Concept of Operations document for Urban Air Mobility (UAM) in 2020 [1]. The term UAM was identified as applying to vehicles that move people and cargo in and around urban areas [2]. It was envisioned that these vehicles would be small, carry just a few passengers or light cargo, and fly short distances [3]. The intent of this new mode of transportation is to reduce travel time in congested urban areas. The ability to operate these vehicles in the urban environment will depend, in part, on the community noise response [4]. Research is underway to assess noise levels, identify appropriate metrics for judging the community response, and develop noise prediction tools that address the relative contributions of the multiple noise sources to overall vehicle noise signatures. The current study first investigates the minimum distance to the far-field for the full-scale vehicle as far-field measurements are necessary for propagating sound in the urban environment and determining noise levels on the surrounding communities. The sound characteristics of the vehicle in hover are then quantified and, finally, the electric motor levels and characteristics are assessed.

Significant research has focused on acoustic studies for small Unmanned Aircraft Systems (sUAS), aircraft with a maximum takeoff weight of 55 lb. The interest is the result of concern for noise exposure to communities. Studies have included outdoor flight and hover tests [5], laboratory investigations [6-8], numerical studies [9], and psychoacoustics investigations [10,11]. The studies have examined sound generation, acoustic levels and directivity,

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minimum far-field distance, and perception characteristics. Contributions from electric motor noise have also been investigated [12,13].

In contrast to sUAS research, acoustic studies for UAM are limited due to the early stages of development for many of these vehicles. Due to the broad range of configurations, it is envisioned that a reasonably sized database developed from vehicle measurements is required to fully describe the impact of these vehicles on communities and to validate prediction tools. Ground run-up tests for the Moog S-250 vehicle [14] and flight and hover tests for the Joby Aviation prototype vehicle have been published recently [15]. These two studies provided a first look at acoustic levels, directivity, and impact of configuration on the resulting acoustic radiation. The investigations reported here quantify the acoustic characteristics for the Moog S-250 vehicle in hover and investigate noise contributions from the electric motors.

The results of two acoustic tests for hover conditions, one at 15 ft (in ground effect) and one at 60 ft (out of ground effect), are reported. Ground effect is delineated by an increase in aerodynamic efficiency as a result of the vehicle operating close to the ground. The minimum distance to the far field is determined from the results of the combined hover tests. Sound hemispheres are constructed from the measurements with the vehicle out of ground effect and provide acoustic directivity and levels for the vehicle. Electric motor noise measurements for the vehicle with one motor powered and all rotors removed are provided and compared to the previous ground run-up measurements [14] and the results from the 60 ft hover test.

II. Experimental Setup

A. Hover Tests

The Moog S-250 research vehicle shown in Fig. 1 is a quadcopter-type, RPM-controlled, UAM aircraft with four sets of contra-rotating rotors and eight independently controlled axial-flux AC motors. Each rotor diameter is 92 in. The furthest tip-to-tip distance for the rotors is roughly 23 ft.



Fig. 1 The Moog S-250 research vehicle.

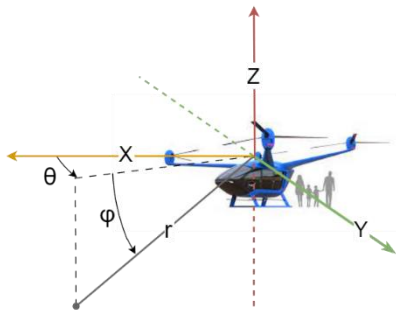


Fig. 2 The coordinate system used in the construction of noise hemispheres.

The vehicle is equipped with two dual-antenna single-frequency-band GNSS receivers. The system provided single point positioning with a maximum uncertainty of roughly 2 ft. Typically, the uncertainty for elevation is significantly greater than that for latitude or longitude so the latitude and longitude uncertainties are expected to be far less than 2 ft. The height above ground (AGL) was determined with a combination of a laser altimeter and LiDAR system resulting in an AGL uncertainty of roughly 0.6 ft. The hover elevations for the aircraft were determined from the aircraft altitude measurements and precise ground surveys of the hover locations obtained with a real-time kinematic (RTK) GNSS precise positioning system with centimeter accuracy. Additional recorded vehicle telemetry included RPM for each motor, vehicle orientation, and ambient pressure. All telemetry was UTC time stamped at the beginning of each flight.

Both hover tests used the coordinate system shown in Fig. 2 for data presentation. The plane containing the origin is centered between the planes containing the upper and lower rotors. The origin is centered on that plane between the centers of the eight motors. Geometric details for the vehicle are provided in ref. 14.

The initial hover test (Hover Test 1) took place near a taxiway at the Lunken Municipal Airport in Cincinnati, Ohio (see Fig. 3). The hover height was limited to 15 ft AGL. The objectives of the flight were to obtain acoustic levels for the aircraft in preparation for the follow-on hover test and to obtain an estimate of the acoustic far-field. While

previous ground run-up tests [14] indicated the acoustic far-field was reached by 100 ft, the array resolution was quite coarse and did not allow for a refined far-field distance determination. The microphone array used for Hover Test 1 is

shown in Fig. 4. The array allowed for acoustic propagation distances between 52 and 96 ft. The elevation angles for the four array arcs are provided in Table 1

The location of the second hover test (Hover Test 2) was the UAM development area at the Springfield-Beckley Municipal Airport in Springfield, Ohio (see Fig. 5). The vehicle hovered at the four locations indicated by red dots in the Figure. A different vehicle elevation was used for each hover position. For the far-field segment of the test, the vehicle maintained a heading that aligned the front of the aircraft with the Far-Field Array Spoke in the Figure. The far-field spoke was oriented at 52.3° relative to true north. This segment of the array was used to obtain directivity information that was combined with the results of Hover Test 1 to determine the minimum distance to the far field. For the construction of noise hemispheres, the vehicle hovered over the array origin at 60 ft AGL. The hover elevation of 60 ft was selected because results from Hover Test 1 (which will be discussed later) indicated the far field was reached by roughly 60 ft and, therefore, all microphones in the array are in the far field. Data were first acquired for the front of the vehicle at a yaw angle of 69.3° relative to true north (the $\theta = 0^\circ$ position). The vehicle rotated and held for data acquisitions (roughly 30 seconds) at 90° clockwise offsets starting from the $\theta = 0^\circ$ position. The data from four different headings were combined to produce the entire acoustic hemisphere.



Fig. 3 The aircraft position and microphone array locations used in Hover Test 1 at Lunken Municipal Airport.

Table 1 Distances and Angles for the Hover Test 1 Array

Array Radius (ft)	Propagation Distance (ft)	ϕ ($^\circ$)
50	52.2	16.7
60	61.8	14
73.7	75.2	11.5
95	96.2	9

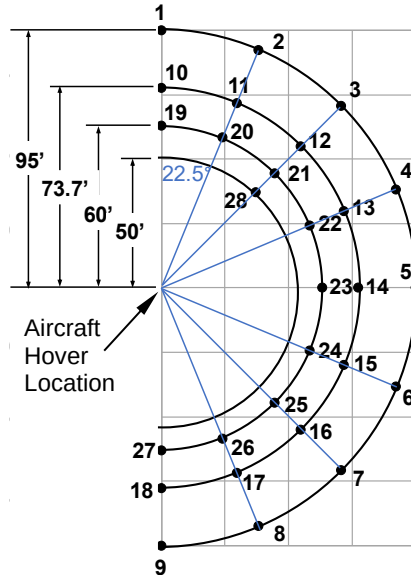


Fig. 4 Microphone array layout for the Lunken Airport hover test.

Details of the Hover Test 2 acoustic array projected to an aircraft center hemisphere are shown in Fig. 6. The red dots are the microphone locations associated with one aircraft orientation. The yellow dots are microphone positions associated with two additional aircraft orientations. Populating only a single quadrant of microphones allowed for an acceptable hemisphere resolution while using only $\frac{1}{4}$ of the number of microphones required to construct a hemisphere. The $\theta = 0^\circ$ hemisphere orientation in the Figure is the direction of the front of the aircraft for the first hover orientation. The color map indicates the maximum angle between the point on the hemisphere and the nearest microphone as measured along the line connecting the two points. Array details are provided in Table 2. On the surface of the hemisphere, the average distance from an arbitrary point to the nearest microphone is 6.1° . The furthest distance on the hemisphere to the nearest microphone is 12.4° .

Table 2 Hover Test 2 Array Hemisphere Surface Details

Average Angle to Nearest Microphone ($^\circ$)	Maximum Angle to Nearest Microphone ($^\circ$)	Minimum ϕ Angle from Horizon ($^\circ$)
6.1	12.4	14.55

The goal of the array design was to assign microphones on the ground that resulted in an even distribution of data points on a hemisphere. There is not a universally optimal method for the even distribution of points [16]. The approach selected here was to generate points using a geodesic polyhedron. Point distribution using the Fibonacci spiral method [17] was also explored. This alternate technique generates a

suitably even distribution of points but does not create straight lines (spokes) of selected points. The inclusion of a spoke in the array was advantageous as the directivity along the spoke was combined with the Hover Test 1 results to determine minimum distance to the far field. Other array design constraints included total microphone count, array deployment complexity, and maximum distance from the vehicle which impacts minimum angle from the horizon and signal-to-noise ratio.

GRAS 67AX ground array microphones were used for all hover tests. The microphones were calibrated for sensitivity each test day. Precise positioning of the microphones was achieved with an RTK GNSS system resulting in centimeter accuracy. An NI data acquisition system using PXIe-4499 cards was used for all acoustic measurements. The sampling rates for the first and second hover tests were 50,000 and 40,000 Hz, respectively. One continuous acquisition with initial GPS timestamping was used for each flight. The data were post-processed to include microphone frequency response. Unless otherwise specified, the data were corrected for background levels and atmospheric attenuation and have been de-propagated assuming spherical spreading (a far-field assumption). The de-propagation distances are specified in later sections of the manuscript. The results are presented as SPL with binwidths of 6.0135 and 4.8828 Hz for Hover Tests 1 and 2, respectively.

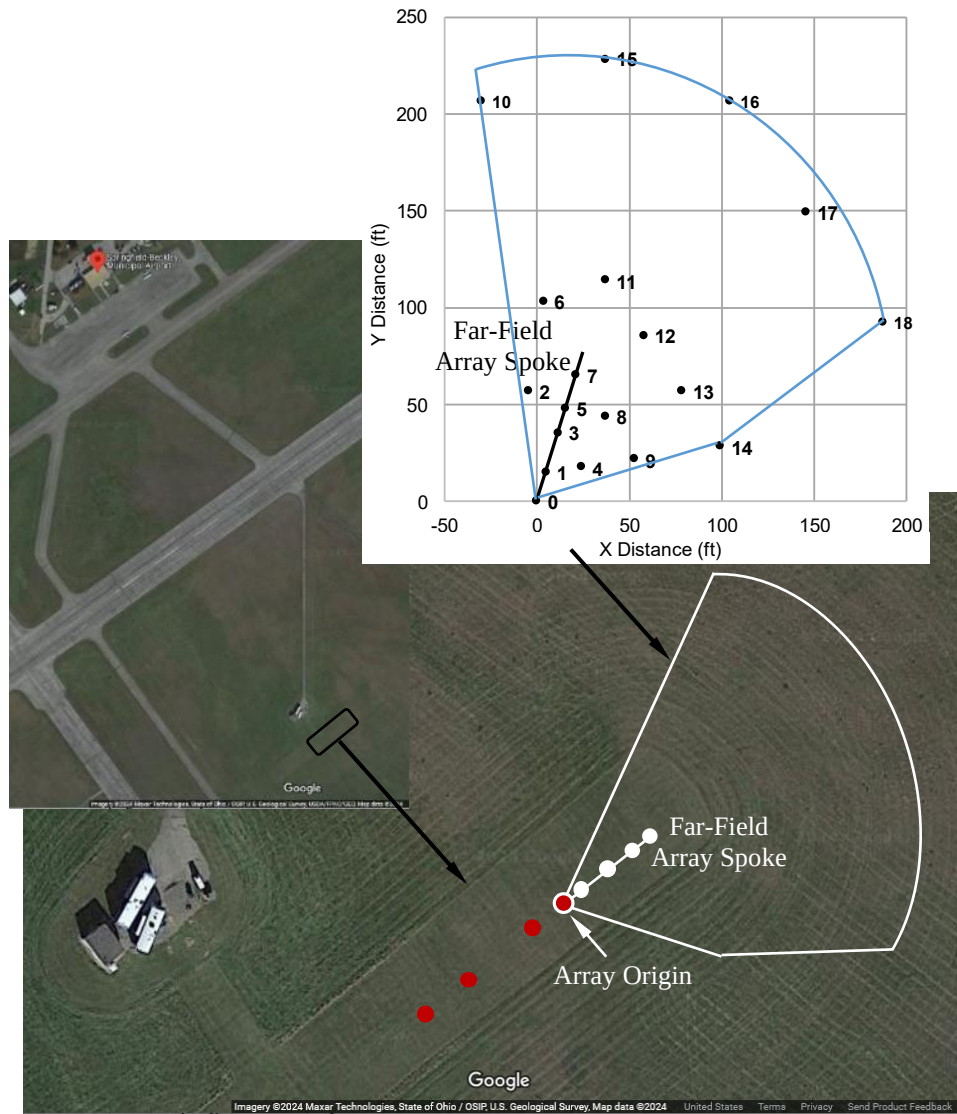


Fig. 5 The location of the hover test at the Springfield-Beckley Municipal Airport. The hover locations are shown by red dots and the microphone array location is outlined in white. The microphone locations within the array are also shown the upper right plot. Microphone 0 is the array origin.

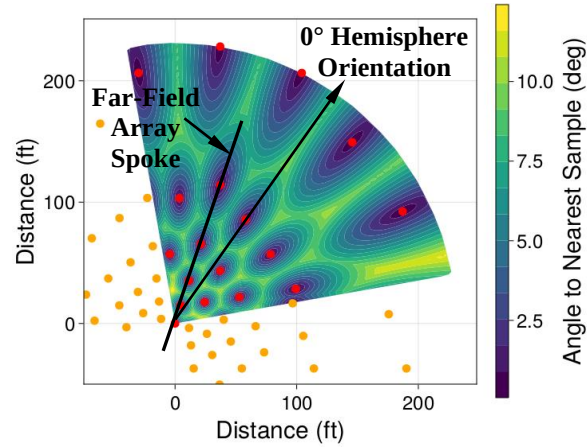


Fig. 6 The acoustic array used for Hover Test 2. The red dots are microphone positions for one aircraft orientation. The color map indicates the maximum angle to the nearest microphone.

B. Atmospheric Measurements

Atmospheric measurements were acquired during both hover tests with a U30 weather station (U30-NRC-000-10-S100-000). The station incorporates sensors for wind direction, wind speed, temperature, and relative humidity. Data is recorded at 10-second intervals. The sensors were positioned at a height of approximately 10 feet AGL. The pressure was taken from the weather stations at the airports and corrected to the aircraft altitude using the barometric pressure equation. The conditions for Hover Test 1 and 2 are provided in Table 3.

Table 3 Average and Peak Atmospheric Conditions for Hover Tests 1 and 2

	Average Temperature (°F)	Average Wind Speed (kts)	Peak Wind Speed (kts)	Relative Humidity (%)	Pressure (inHg)
Hover Test 1	80.2	1.2	4.5	49.87	30.28
Hover Test 2	68.33	6.7	8.8	88.85	28.81

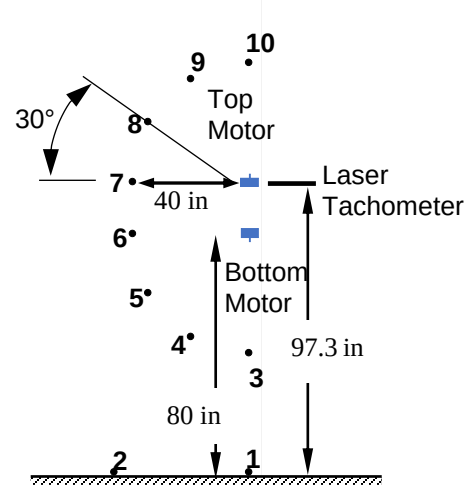
C. Electric Motor Noise Measurements

Electric motor noise measurements were conducted at Lunken Municipal Airport. The rotors were removed from the aircraft and the top left motor was powered. It should be noted that the acoustic levels for the loaded motors are expected to be higher than those for the unloaded motors so the frequency characteristics of the motor noise are of primary interest here. The nine-element array shown in the Figure 7 was used for the measurements. Microphones 7 – 10 were centered on the top motor at a distance of 40 in from the outer motor shell. Microphones 3 – 6 were centered on the bottom motor at a distance of 40 in from the outer motor shell. Microphones 1 and 2 were centered on the bottom motor at the distances indicated in the Figure. A combination of GRAS $\frac{1}{4}$ " and $\frac{1}{2}$ " pressure-field microphones were used in microphone location 3 – 10. GRAS 67AX ground array microphones were used for microphones location 1 and 2. The microphones were calibrated for sensitivity prior to the test. Microphones 1 and 2 were corrected for ground reflection.

Data were acquired with the NI system described in the previous sections at an acquisition rate of 200,000 Hz. For each acquisition, a constant motor acceleration or deceleration ramp was used which allowed for order tracking in post-processing. An outdoor grade tachometer centered on the top motor shell (see Fig. 7) acquired the phase angle data.



Fig. 7 The microphone array used for the electric motor noise measurements.



III. Results

A. Hover Test 1

Selected telemetry from one of two flights in Hover Test 1 is shown in Fig. 8. Also shown in the Figure is a schematic of the motor numbering convention. The yaw angle is relative to true north. The data shows the aircraft held at an altitude of 15 ft at three orientations offset by 90°. For each flight segment, the speeds of the eight motors are different which is to be expected for an RPM-controlled vehicle. As noted previously, the vehicle is in ground effect at 15 ft.

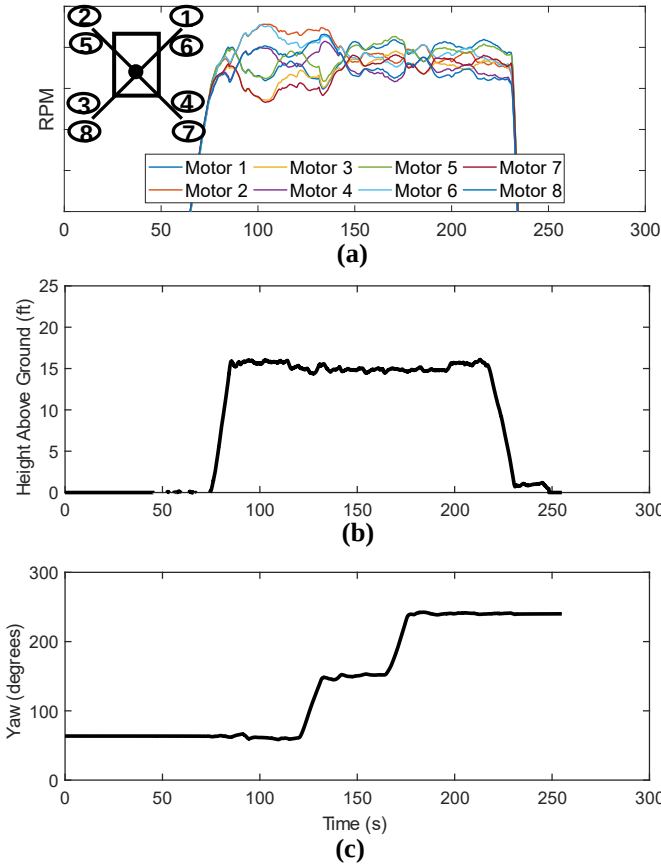


Fig. 8 The (a) motor speeds, (b) height above ground level, and (c) yaw of the vehicle for Hover Test 1.

A comparison between the background levels and the spectra for the vehicle during hover at the microphone 3 location (see Fig. 4) is shown in Fig. 9. Only microphone sensitivity corrections have been applied to the data. The background levels are well below those of the aircraft for all frequencies of interest. The background levels in Fig. 9 are typical of those obtained throughout the measurement region.

The acoustic results for microphones along the $\theta = 0^\circ$, -45° , and -90° spokes in Fig. 4 (relative to the front of the aircraft aligned with microphone 1) are shown in Fig. 10. The data have been propagated (assuming spherical spreading) to the microphone locations on the 95 ft arc and have been corrected for atmospheric attenuation. The variation in the elevation angle (ϕ in Table 1) for microphones along the 60 ft and 95 ft arcs is 5° . The data for the microphones along the 60 and 73.7 ft arcs collapse to that for the 95 ft arc indicating the far field is reached by a propagation distance of 61.8 ft. The data for the 50.0 ft arc shown in Fig. 10 (b) does not collapse to that of the 95 ft arc.

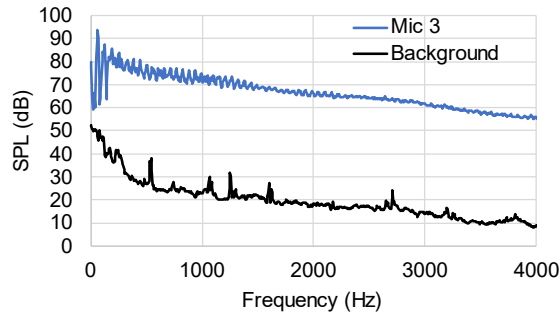


Fig. 9 A comparison of the background levels and the acoustic levels for the vehicle for one microphone on the 95' arc.

The overall sound pressure level (OASPL) as a function of distance for the microphones located on the $\theta = -45^\circ$ spoke is shown in Fig. 11. The expected slope for the far field (6 dB decrease with doubling of propagation distance) is indicated by a dashed line in the Figure. The data for the microphones located on the 60, 73.7, and 95 ft arcs follow the expected propagation behavior for the far field. The data for the microphone on the 50 ft arc does not follow the expected far-field propagation. Directivity results from Hover Test 2 for microphones along a spoke at $\theta = -36.6^\circ$ (relative to the front of the aircraft) for microphones located well beyond 100 ft from the aircraft (i.e., the far field) indicated the differences in

the levels for the propagated data from the 50 ft arc and those for the 95 ft arc in Hover Test 1 could not be explained by changes in directivity for the two measurement locations. These combined results indicate that the far field is not reached by a propagation distance of 52.2 ft. The far-field distance is, therefore, reached by roughly 8.1 single rotor diameters or 2.7 vehicle diameters, where vehicle diameter is determined by the furthest tip-to-tip distance of all rotors.

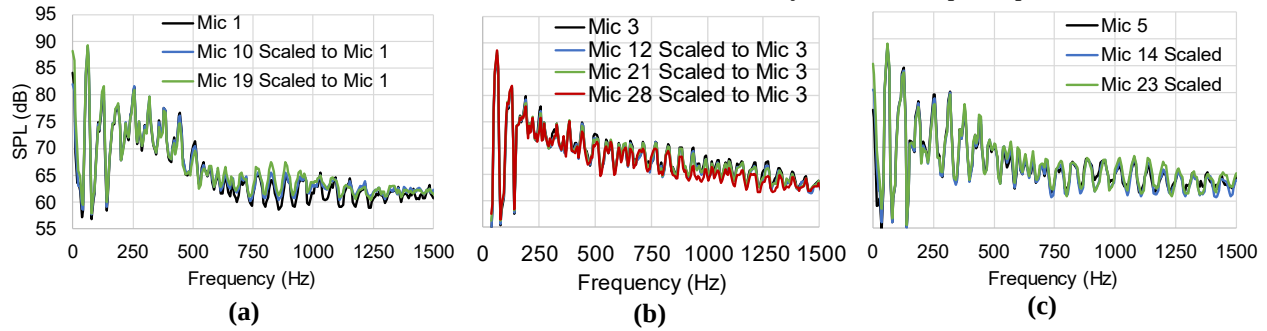


Fig. 10 The acoustic data acquired for microphones along the (a) $\theta = -0^\circ$, (b) $\theta = -45^\circ$, and (c) $\theta = -90^\circ$ spoke relative to an aircraft oriented toward microphone 1.

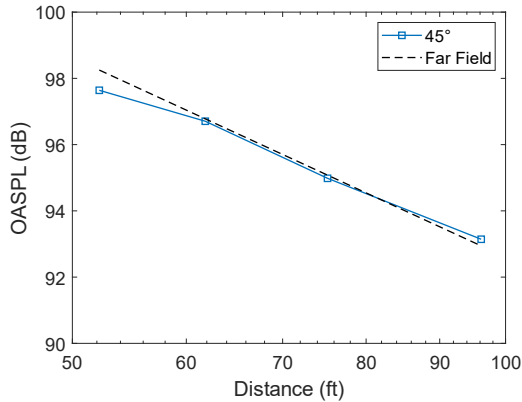


Fig. 11 A comparison of the measured reduction in overall sound pressure level with distance and that expected for the far field (6 dB reduction with doubling of distance).

B. Hover Test 2

The telemetry results for Hover Test 2 are shown in Fig. 12. The naming convention for the motors is the same as that used in Fig. 8 (a). The segments of the flight used in the far-field directivity studies and construction of the noise hemispheres are indicated by FF and R, respectively, in Fig. 12 (b). The four individual segments of the flight used to construct the noise hemisphere are indicated in Fig. 12 (c) with the angle relative to the front of the aircraft. The standard deviations for the yaw angles during the times used to compute the spectra for the hemispheres were less than 0.13° . Similar to the results from Hover Test 1, the speeds of the eight motors are different at any instant in time.

A comparison of the spectra obtained at microphone 15 (see Fig. 5) for the Moog vehicle in the $\theta = 0^\circ$ and for the background acquired at the same microphone is shown in Fig. 13. Microphone 15 has one of the largest propagation distances of all elements in the array. Only microphone sensitivity has been applied to the data. The levels of the vehicle are greater than 30 dB above the background levels for the first few blade-pass frequencies (BPFs). For higher frequencies where broadband noise dominates the spectrum, the vehicle levels are greater than 40 dB above those of the background.

The spectrum obtained at microphone 11 position with the aircraft in the $\theta = 0^\circ$ orientation is shown Fig. 14. The data have been de-propagated to a point on a hemisphere centered on the vehicle with a radius of 11.5 ft, roughly half the furthest tip-to-tip distance of the multiple rotors. The frequency ranges for the first five BPFs computed from the eight different rotor speeds are indicated by the colored horizontal lines. The vertical lines indicate the frequency ranges used to construct individual noise hemispheres for the first four BPFs.

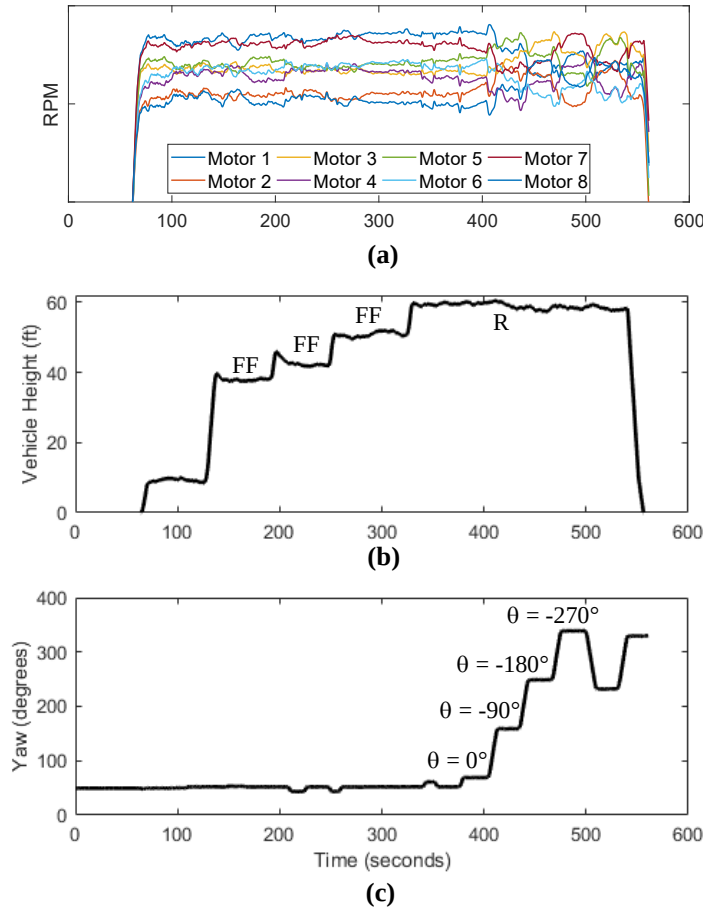


Fig. 12 The (a) motor speeds, (b) height above ground level, and (c) yaw of the vehicle for Hover Test 2.

The noise hemispheres for the first four BPFs are shown in Fig. 15 (a) – (d). The diameter of the hemispheres is 23 ft and, therefore, represents the largest tip-to-tip rotor distance for the aircraft. The coordinate system and origin are the same as those used in Fig. 2. An orthographic azimuthal projection is shown on the left of each figure. The arrow in the center of the figure indicates the location and orientation of the aircraft with the arrow pointing toward the front of the aircraft. The black dots indicate the points on the hemisphere that correspond to microphone locations on the ground. The red dashed circles on the orthographic azimuthal projections indicate the locations of $\phi = 27^\circ$ and 33° as indicated in Fig. 15 (a). Points on the hemisphere have been interpolated (not extrapolated) so the color map only encompasses elevation angles (ϕ) greater than 14.5° . The tips of the bottom rotors are located at $\phi = 3.6^\circ$ below the vehicle origin. It should be noted that previous ground run-up measurements [14] showed acoustic levels for the tones produced by the lower rotor were 5 – 10 dB higher than those for the upper rotor due to the counter-rotating configuration. The peak acoustic radiation occurs between $\phi = 27^\circ$ and 31° for BPFs 1 – 4, roughly 25° below the lower rotor tips. Peak levels decrease with increasing BPF. The locations of the peak levels do not appear to align with the locations of the rotors and their support arms although four regions of peak radiation are observed in

the orthographic projection for BPF = 1. The lowest acoustic levels occurred beneath the aircraft. The hover results in Ref. [15] showed the highest acoustic levels occurred beneath the aircraft.

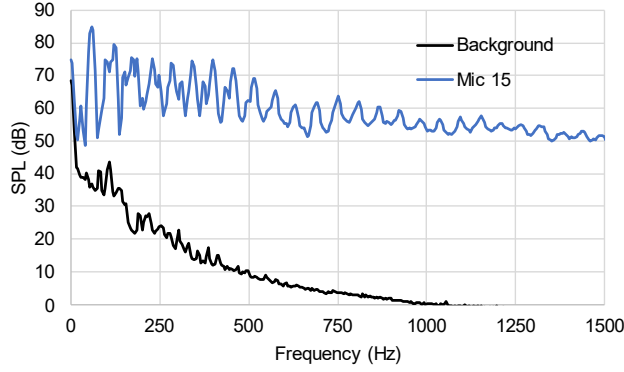


Fig. 13 A comparison of the spectra obtained at microphone 15 for the Moog vehicle in the $\theta = 0^\circ$ orientation (Mic 15) and for the background at that same microphone.

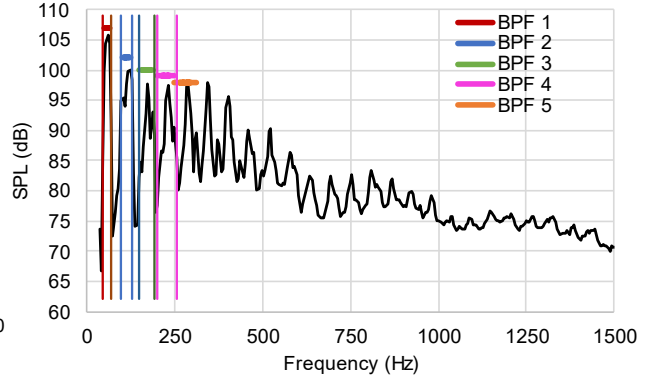


Fig. 14 The spectrum obtained from microphone 11 with the vehicle in the 0° orientation. The vertical lines indicate the frequency ranges used for each BPF when constructing the noise hemispheres. The horizontal BPF lines were computed from the eight motors speeds.

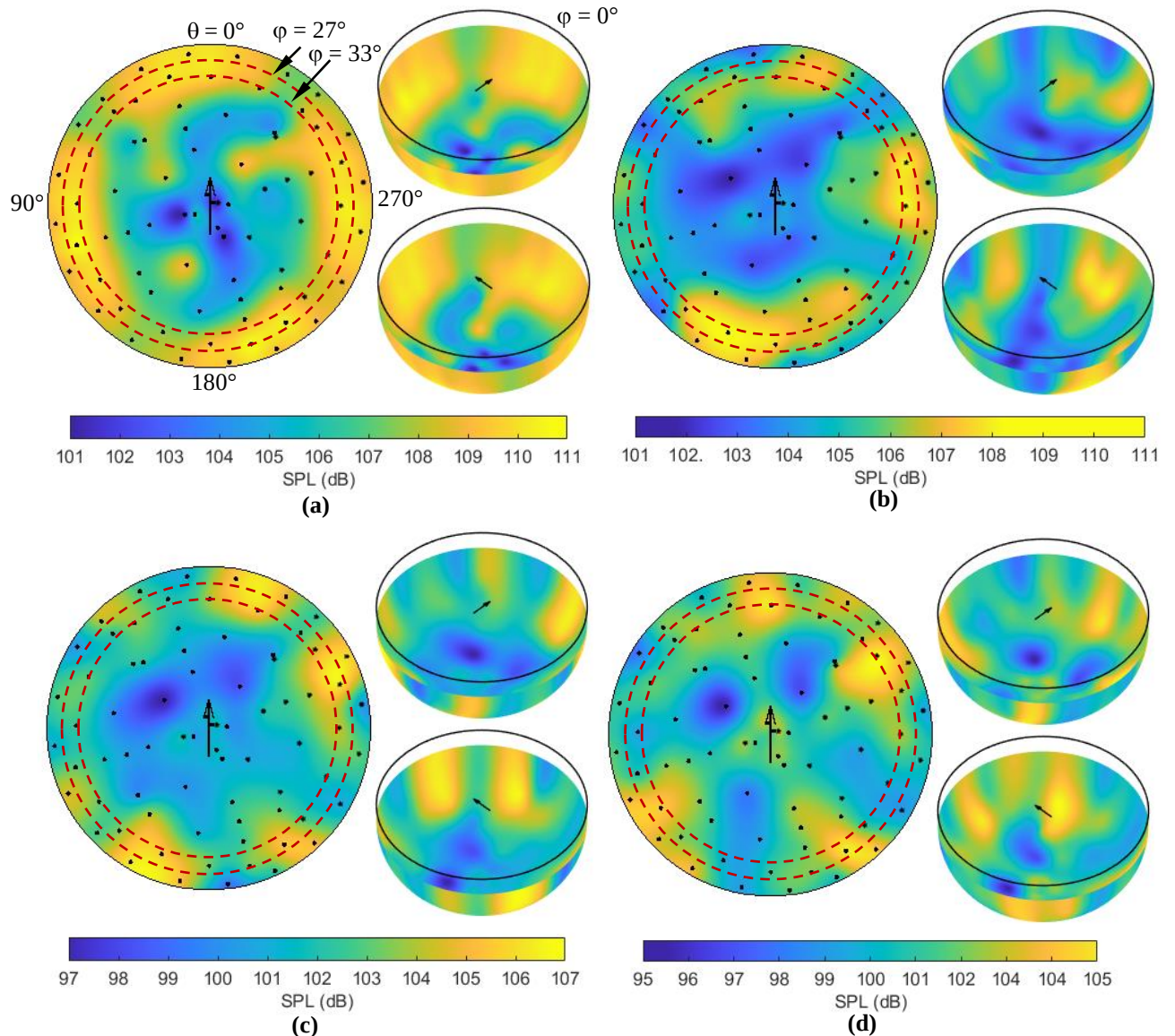


Fig. 15 The acoustic amplitudes on an 11.5 radius hemisphere centered on the aircraft for (a) BPF = 1, (b) BPF = 2, (c) BPF = 3, and (d) BPF = 4. The orientation of the front of the aircraft is indicated in each figure.

C. Electric Motor Noise Test

Figure 16 shows motor speed versus time for one of the electric motor acoustic acquisitions. The calculated values were obtained from the tachometer signal. Also included in the Figure is a constant acceleration ramp of 21 RPM/s which closely matches the calculated motor speeds. The results are typical of those for all acceleration ramps. The deceleration ramps were roughly equal to -21 RPM/s. Order tracking results were obtained for each acceleration/deceleration ramp and averaged over 30 runs to obtain average order maps.

Order tracking results are shown in Fig. 17. The order binwidth is 0.1666. Also shown in the Figure are the peak sound pressure levels. It should be noted that the motors are not loaded. Loaded motor levels are expected to be higher. While the ground microphones were corrected for ground reflection, the data were not corrected for propagation effects so the levels at microphone 1 are expected to be 3.2 dB lower than those for microphones 7 – 10 due to spherical spreading. The peak amplitudes occur at the top and bottom of the motor (microphones 1 and 10) and for order 60 at microphone 8. For all microphones, acoustic radiation occurs at orders 17 – 20. For microphone 1, the peak radiation occurs at order 30 and tones are also observed for orders 35 – 40, 53 – 55, and 60. The peak radiation for order 60 occurs at microphones 8 and 9 (not shown). For orders 17 – 20, the peak acoustic radiation occurs for speeds between 1000 and 1150 RPM and between 1650 and 1750 RPM for microphones 1 and 10. The peak radiation for orders 30 and 60 occurs at speeds between 1700 and 2000 RPM. The results of the electric motor experiments show that each shaft order of interest for acoustics has preferred radiation angles and motor speeds. The preferred angles and speeds are not the same for all shaft orders.

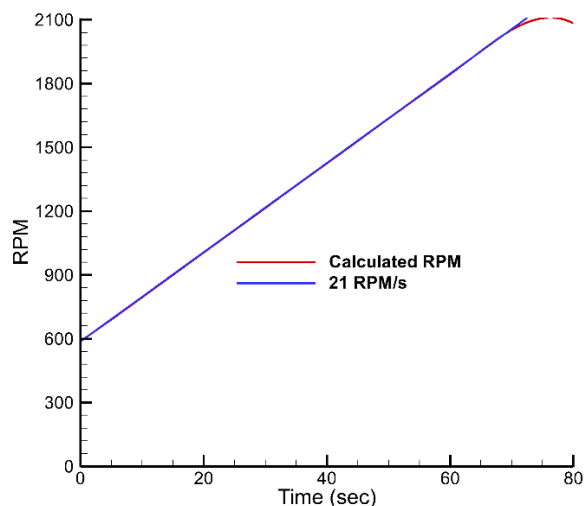


Fig. 16 The calculated motor speeds obtained from the tachometer readings. Also shown is a constant motor acceleration ramp of 21 RPM/s.

remain the same or decrease with increasing frequency until the motor tone frequency range is reached and an increase in tone amplitude is observed for shaft order 19 (relative to shaft orders 18 and 20). In the motor tone frequency range, tones occur at odd shaft orders that are expected for the motors but less likely for rotor related tones of a two-bladed rotor. While it is possible to achieve odd orders with two blades, there is little evidence of odd orders in the rotor data at lower frequencies. The tones produced in the range of shaft orders 17 – 20 are likely associated with the motors. The tones produced at shaft orders 60 and higher may not be associated with electric motor noise as only the order 60 tone was identified in the electric motor data. Additionally, the shaft order 60 tone peaked at a speed of roughly 1800 RPM, well above the speeds in Fig. 18. The shaft order 30 tones present in the electric motor tests would not appear in these measurements due to the limited motor speeds.

The spectra for microphones 0, 7, and 11 (see Fig. 5) from the Hover Test 2, with the aircraft nose aligned with microphone 7, are shown in Fig. 19. The ranges of frequencies for BPF 1 – 6 for the eight motors are shown in the Figure with motor shaft orders 17 – 20 identified. While it is not possible to differentiate the motor and rotor tones in these measurements with multiple simultaneous shaft speeds, the decrease in the amplitudes of the rotor tones with increasing frequency up to the frequency range where motor tones are expected is the same for the hover data and for the ground run-up data with one powered motor. The similar trend is an indication that electric motor noise is possibly contributing to the acoustic radiation in the frequency range of shaft orders 17 – 20. The higher motor shaft orders (30 and 60) where electric motor noise was apparent in the motor measurements do not appear to be important in the far-field hover data.

Figure 18 shows acoustic spectra from ground run-ups of the vehicle [see Ref. 14] with all rotors mounted and the left front top motor powered. The powered motor is the same as that used in the electric motor noise experiments. The data were acquired at average motor speeds of 1036 RPM [Fig. 18 (a)] and 1255 RPM [Fig. 18 (b)]. The lower rotor was allowed to windmill. The speed of the windmilling rotor was recorded and found to be significantly lower than that of the powered rotor. There was no evidence of tones associated with the windmilling rotor in the spectra. The binwidth for the spectra is 3.0518 Hz. The data acquired at 25 ft is likely in the near field for the rotor related sources and in the far field of the motor related sources. Also shown in the figure are the blade-pass frequencies up to 30 – 40 BPF and relevant motor shaft orders for motor tones.

At 1036 RPM, rotor tone amplitudes are found to decrease with increasing BPF up to a frequency range where motor tones are expected to be produced (shaft order 17 – 20). For 1255 RPM, the rotor tone amplitudes

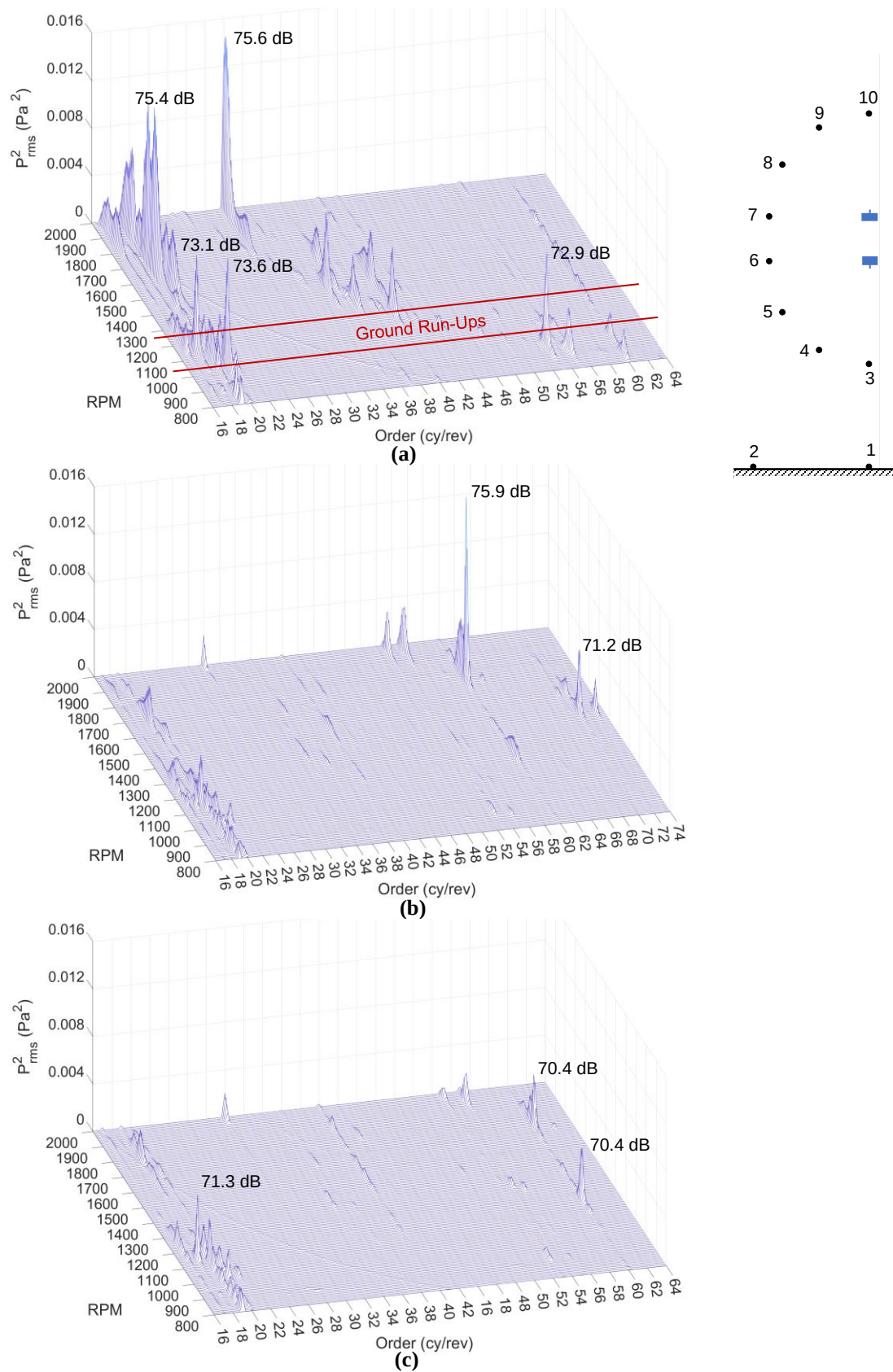


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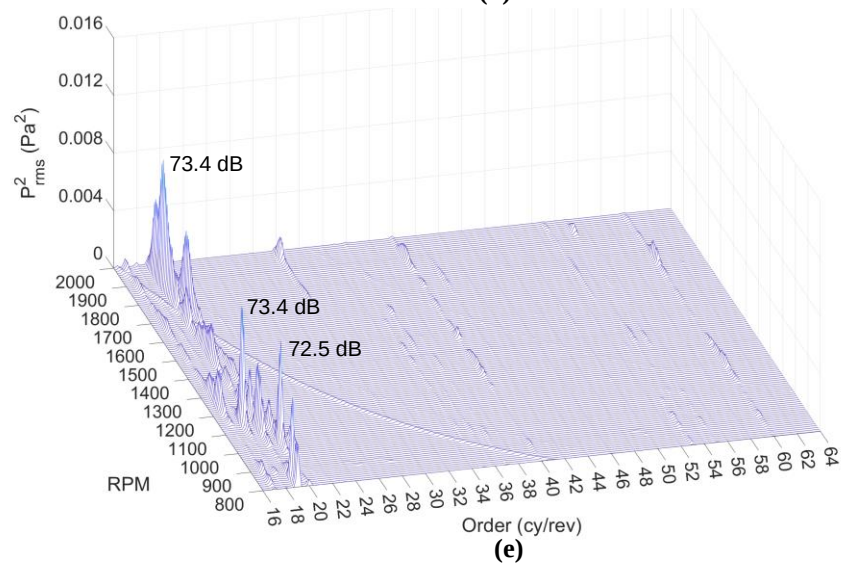
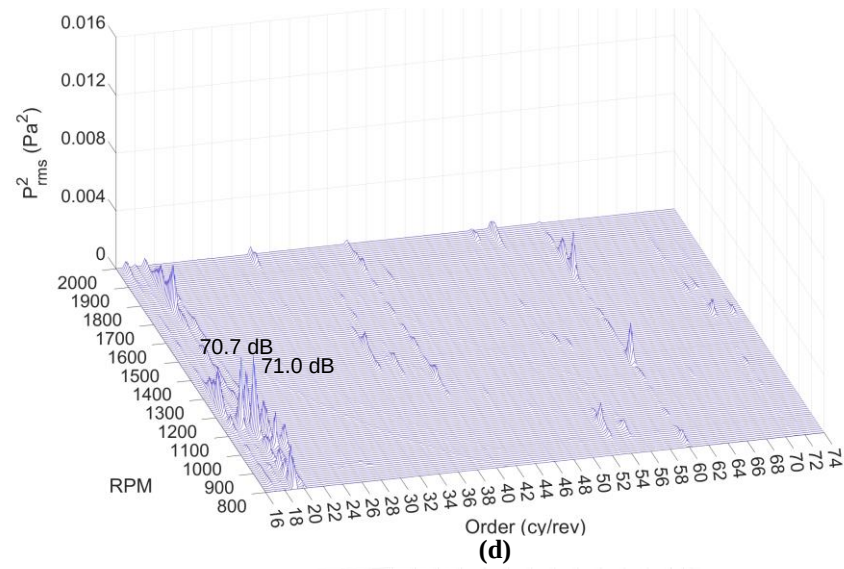


Fig. 17 Order tracking results for microphones (a) 10, (b) 8, (c) 7, (d) 6 and (e) 1.

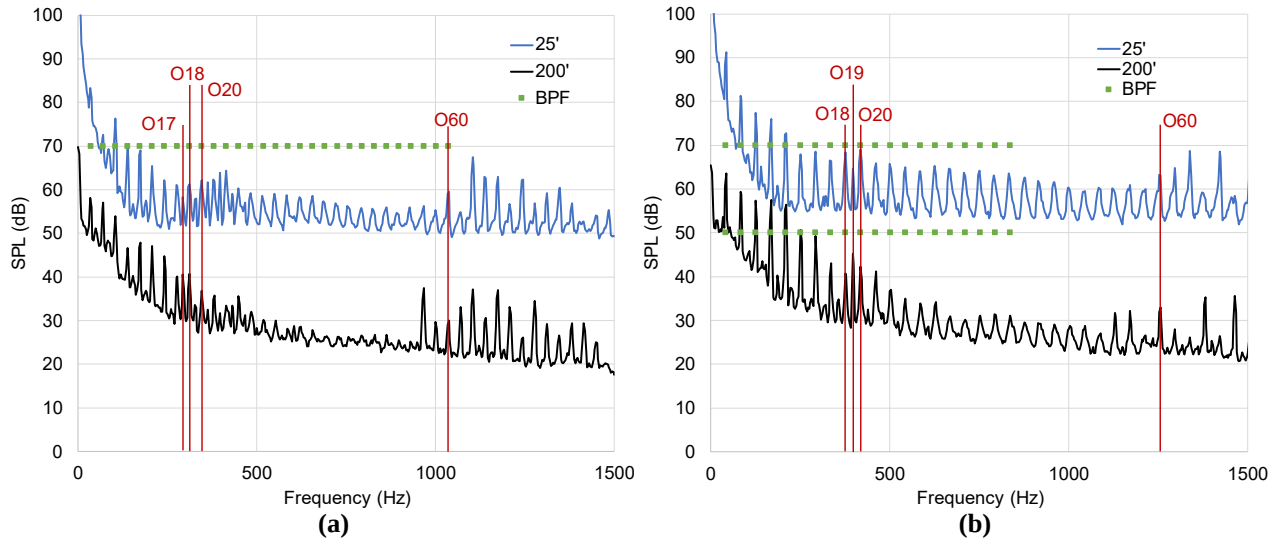


Fig. 18 The acoustic spectra from ground run-up tests [14] with one top motor powered and all rotors mounted for (a) 1036 RPM and (b) 1255 RPM. The green squares indicate blade-pass frequencies and the relevant shaft orders for electric motor noise are shown in red. The ground distances from the center of the aircraft to the microphones are indicated in the legend.

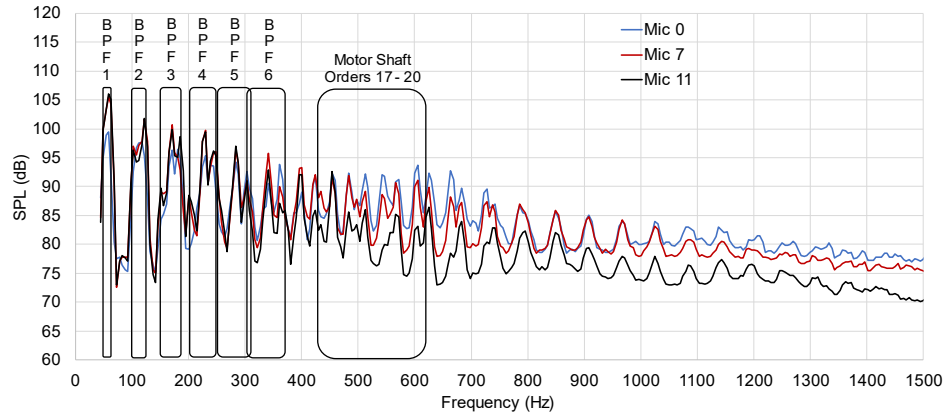


Fig. 19 The acoustic spectra from the 60' hover test for the indicated microphones. The aircraft nose was aligned with microphone 7 for these measurements. Also shown are the ranges of blade-pass frequencies for the eight rotors and the range of frequencies relevant to electric motor noise.

IV. Conclusion

Acoustic measurements were obtained for the Moog S-250 research vehicle at 15 and 60 ft hover heights, elevations that were in and out of ground effect, respectively. The 15 ft hover results were combined with the directivity from the 60 ft hover test to determine the minimum distance to the far field. The far field was reached by a propagation distance of 8.1 single rotor diameters or 2.7 vehicle diameters, where vehicle diameter is the largest tip-to-tip rotor distance for the vehicle.

Measurements for the 60 ft hover tests were used to construct noise hemispheres to determine general noise characteristics for the vehicle. Peak levels for blade-pass frequencies 1 – 4 occurred at declination angles between 27° and 31° which were roughly 25° below the lower rotors. While each pair of rotors operates in each other's potential field, the lower rotors also operate in the downwash (i.e., the wake) of the upper rotors and, therefore, are expected to

produce higher acoustic levels than those from the upper rotors which was verified in previous ground run-up measurements [14]. The lowest acoustic levels for the vehicle occurred beneath the aircraft.

Electric motor noise tests were conducted with the rotors removed from the aircraft. The resulting levels are expected to be lower than those for the loaded motor (motor with rotor). The motors were found to produce tones at shaft orders 17 – 20, 30, and 60. Tones that appeared to be associated with the electric motors were identified at shaft order 17 – 20 in ground run-up data obtained with one motor and rotor powered. While it was not possible to differentiate between electric motor and rotor tones in the hover data, significant acoustic radiation occurs at shaft orders found to be important for electric motor noise.

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