ABSTRACT

Joby Aviation is developing a six propeller, all electric vertical takeoff and landing piloted air taxi aircraft. The aircraft is designed for high density operations near residences and workplaces, so it is imperative that the acoustic emissions of the aircraft are minimized for community acceptance. It is important to compare not just the absolute sound levels but also the sound quality with conventional aircraft already known to the public. To showcase the difference between the Joby aircraft and similarly sized aircraft for a level flyover condition, Joby arranged a flight demonstration with two conventional fixed-wing aircraft and three commercial helicopters. All the aircraft were flown at approximately 100 knots (51 m/s) and 1500 feet (457 m) above ground level within minutes of each other in the same location to minimize variability. They were measured with the same equipment and processing methods. The results show that the peak Joby aircraft sound pressure level was 10 to 19 dB(A) below the conventional aircraft. The conventional aircraft noise levels were above the peak Joby level for 43 to 54 seconds during the flyover. The Joby aircraft was measured at 13 to 22 EPNdB lower than the conventional aircraft. Close examination of the spectra showed that Joby aircraft has greatly reduced tonal and low frequency content. When substituting the low ambient noise during the flight test with a realistic urban outdoor café environment, the Joby aircraft is below the ambient at all frequencies during the direct flyover which allows it to blend in with the ambient soundscape. The other conventional airplanes and helicopters exhibited large tones that rise above the café ambient for approximately one minute, and would impact a much larger area on the ground that is not directly under the flight path.

INTRODUCTION

Joby Aviation had been working on its eVTOL aircraft quietly since 2009. The aircraft is shown in Figure 1. Acoustics was a key driver in selecting the number of propellers and disk loading. Additionally, the propellers are designed to have low interactions with each other and the airframe to minimize the resulting unsteady loading. The propellers were designed with five blades and high solidity to allow for lower tip speeds than are possible for conventional helicopters. In forward flight, the propellers tilt down to avoid the tip speed and retreating blade stall restrictions of helicopters. During transition to or from hover, the propellers can also individually adjust their tilt, rotational speed, and blade pitch to avoid combinations that cause adverse acoustic effects due to blade vortex interactions (BVI). The propeller was designed after an extensive experimental and computational iterative design cycle (Ref. 1). Details of the aircraft design concept and evolution can be found in Stoll et al. (Ref. 2).

Since 2017, Joby Aviation has conducted more than one thousand flight tests. This test program across multiple aircraft has been focused on expanding the flight envelope, demonstrating performance (including a range demonstration of over 150 miles [241 km]), and improving the flight control system. Many flight tests have also been focused on better understanding the acoustic signature from the aircraft. Joby partnered with NASA's Advanced Air Mobility National Campaign to conduct over a week of acoustic flight tests across a wide range of flight conditions (Refs. 3, 4). These flights included a range of different departures, approaches, and flyovers. The large number of flights and large microphone field provided a tremendous amount of data to better understand the acoustics of the aircraft. The flyovers for the NASA flight test were performed at the lowest safe altitude to maximize the signal to noise ratio. Additional details and results from that acoustic flight test will be presented in upcoming publications.

The all-electric vertical takeoff and landing (eVTOL) industry first attracted wide notice when the Uber Elevate white paper (Ref. 5) was released in 2016. Among the several market feasibility barriers in the white paper, the importance of aircraft noise levels is highlighted. In order to achieve the large scale of operations that are desired, overflight noise levels will need to be low enough to not disrupt communities. Flights of commercial helicopters are often restricted due to their acoustic impact on nearby communities. The paper provided quantitative goals for eVTOL noise. It lists “a reasonable goal for vehicles is half that of medium-sized trucks today - 67 dB(A) at ground level from a VTOL at 250 ft altitude”.

It has been recognized that this new industry has important and unique acoustics considerations different from those of traditional fixed-wing and rotorcraft industries. A wide variety of aircraft configurations of interest exist. Uber and NASA have proposed configurations for research but neither intend to build these aircraft (Refs. 6, 7). None of these configurations use six tilting propellers like the Joby aircraft. Other companies are exploring different configurations with different number of propellers, types of propellers, and airframe interactions. Each configuration likely will have different acoustic properties which will change the relative importance of various acoustics sources. Examination of individual propeller designs reveals large differences in blade count, solidity, tip speed, design thrust loading, and tip shape. These propeller designs operate at different Reynolds numbers which affects the boundary layer transition and resulting broadband noise sources. The Reynolds number effects make scaled experiments less useful, especially for acoustics. Joby has used full scale outdoor testing extensively in its design process. This allows testing at the appropriate Reynolds number but does increase experimental scatter due to outdoor environmental factors and acoustic reflections.

NASA organized the Urban Air Mobility Acoustics Technical Working Group consisting of engineers from government agencies, academia, and industry in 2018. Each year there are two meetings immediately following the NASA Acoustics Technical Working Group Meeting. Joby has been an active participant in this working group from the initial meetings. A white paper from the working group discussing the current state-of-the-art, gaps, and recommendations for future work was recently published (Ref. 8). The working group is split into four areas of interest: Tools and Technologies, Ground and Flight Testing, Human Response and Metrics, and Regulation and Policy.

Among the most critical gaps is the lack of experimental data for vehicles of this type. Relevant experimental data is needed to drive computational tool development. Currently, the computational efforts intended to predict full scale eVTOL noise levels have usually been based on either the Uber or NASA proposed configurations. These configurations are not optimized for low noise and are not directly representative of any aircraft in active development. The predictions use a wide variety of fidelity for blade element aerodynamics (Ref. 9), broadband noise prediction (Ref. 10), auralizations (Ref. 11), high fidelity computational fluid dynamics (Ref. 12), and trim methodologies (Ref. 13). It is likely that advancements in all these prediction methods will be needed. Experimental efforts have been limited to small scale experiments usually with commercial drones (Ref. 14) with the notable exception of the Moog Surefly (Ref. 15). A joint workshop along the lines of the UH-60A Airloads Workshop (Ref. 16), HART-II International Workshop (Ref. 17), or AIAA Hover Prediction Workshop (Ref. 18) would greatly benefit computational tool devel-
opment. These workshops were based on compelling experiments that were of joint interest to government researchers, academia, and industry partners. Given the large variability in design of eVTOL aircraft, no such configuration for an experiment has been proposed. Due to the highly competitive and rapidly evolving nature of the industry, it is not likely that a company will allow full details of their design to be made public for research purposes in the near future.

Improvement in single event measurements and predictions are necessary to enable better understanding of noise impacts on a city. The Aviation Environmental Design Tool (AEDT) can be used to understand fleet noise levels (Ref. 19). The U.S. Department of Transportation Advanced Acoustic Model (AAM) software has recently gained the capability to model eVTOL acoustics using 1/12 octave band resolution (Refs. 20, 21). The higher frequency resolution is necessary to allow mixed fidelity time step analysis to allow computation of advanced acoustic metrics such as time varying loudness (TVL). AAM can use sets of sound spheres for the full variety of flight conditions to analyze complete flight profiles. It can help provide more relevant comparisons between aircraft and further research in community acceptability.

EXPERIMENTAL SETUP

The flyover test was conducted at Joby’s Electric Flight Base near Big Sur, California. The Joby aircraft was flown first. Once the Joby aircraft was on the ground, the conventional aircraft arrived in the flight area and were in the air simultaneously several miles from each other to ensure deconfliction and to allow sufficient distance from the flyover location such that their emitted noise level was not measured above the ambient noise at the flyover location. Each aircraft entered a holding pattern until it was directed to fly over the microphone location. For one mile before and after microphone location, each pilot was instructed to:

- Maintain approximately 100 knots (51 m/s)
- Maintain the same flight path directly over the microphone location
- Maintain 1500 feet (457 m) above ground level

The 100 knot or 51 m/s speed was chosen so that all aircraft would be able to fly the same speed. It is near the maximum speed of the Robinson R44 and Bell 206. The accuracy of the flight path, airspeed and altitude was later confirmed with GPS data. The flights took place in the early morning hours with the duration of the entire series of flyovers, including the Joby aircraft, lasting approximately two hours. The weather conditions throughout the flyovers were stable with overcast skies, 58°F (14°C), 73% relative humidity and calm winds. Due to the remote location, low ambient sound levels were observed during the test. With calm winds that morning, the ground speed and airspeed were approximately equivalent, which means that the 30 seconds before and after the maximum noise level represents ±1 mile (1.6 km) distance from the microphone location. This ensures that the LA values were not affected by changing aircraft conditions since all the aircraft were on-condition for the ±1 mile (1.6 km) segment.

The microphones used for the measurement were 6 mm pre-polarized pressure condenser microphones at the ground surface, connected through a digitally controlled gain stage to a 16-bit linear PCM converter that records to an SD card at a 48 kHz sampling rate. At the flyover location, a linear array of these microphones was spaced several hundred feet apart along a line orthogonal to the intended flight path so that slight deviations of flight path of any aircraft would still result in

### Table 1: Aircraft Characteristics.

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>Type</th>
<th>Design Passengers including Pilot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joby</td>
<td>eVTOL</td>
<td>5</td>
</tr>
<tr>
<td>Cirrus SR22</td>
<td>Single Prop, Fixed Wing</td>
<td>4</td>
</tr>
<tr>
<td>Beechcraft Baron 55</td>
<td>Twin Prop, Fixed Wing</td>
<td>7</td>
</tr>
<tr>
<td>Robinson R44</td>
<td>Helicopter</td>
<td>4</td>
</tr>
<tr>
<td>Bell 206</td>
<td>Helicopter</td>
<td>5</td>
</tr>
<tr>
<td>Leonardo AW109</td>
<td>Helicopter</td>
<td>9</td>
</tr>
</tbody>
</table>

AIRCRAFT SELECTION

Joby Aviation arranged for a series of aircraft to be flown over the same location on the same day. Table 1 shows the basic characteristics of the Joby aircraft and the five chosen aircraft. These included two conventional propeller airplanes and three standard single main rotor with tail rotor helicopters. The helicopters included the Bell 206 and Robinson R44 which are common, four passenger designs with a cruise speed around 100 knots (51 m/s). It also included the larger Leonardo AW109, with a cruise speed around 150 knots (77 m/s). The Joby aircraft was flown remotely-piloted but near its maximum gross weight. It was flown with test equipment and cameras on the outside of the aircraft which have an unknown effect on the overall sound levels. None of the aircraft was flown at its maximum gross weight or a high speed that would be representative of a certification test. The types of available aircraft were restricted by the desire to have all aircraft available on the same day and location to get a direct one-to-one comparison with as little environmental variability as possible.
a direct flyover of a microphone. Later analysis of the aircraft GPS data confirmed that the flight paths of all the aircraft extended directly over the target microphone at the center of the linear array. The results reported in this paper are from this center microphone and have been corrected for free field conditions, since the microphones were placed at ground level and subject to pressure doubling. Ground impedance was not measured, therefore there is additional uncertainty in the derived free field sound pressure level values. However, the same configuration is used for all flights so the measured differences between aircraft are nearly exact.

All acoustic measurements were processed using a commercial noise and vibration software analysis tool with identical processing parameters for each recording. First, the raw data was transferred from the SD card to the PC and imported into the analysis tool. A 94 dB, 1000 Hz sine wave calibration tone was recorded by each microphone at the beginning and end of the test. The first step in the analysis process was to verify the correct level of the recordings using the recorded calibration tone. Once the calibration was confirmed, the L_{A,S} (A-weighted sound level, slow time weighting) was calculated using the function available in the analysis tool which follows the IEC 61672 standard. Additionally, autopower spectra were calculated over a 10 second range from –5 seconds to +5 seconds of the maximum level. The FFT processing parameters for the spectral calculations were:

- Hann window
- 1 Hz frequency resolution (1s time window)
- Energy averaging
- 50% overlap (20 averages)
- Linear RMS autopower

**RESULTS**

A video of the test with audio of each aircraft was released after the flight test (Ref. 22). The video does not quantify sound levels, but contains several seconds of audio of each aircraft as it overflew the microphone. Figure 2 shows the main result of the test: free field sound pressure level versus time for each aircraft during the flyover. The other aircraft were more than 10 dB(A) above the Joby aircraft levels for the duration of the flyover. At 1500 feet altitude (457 m), atmospheric attenuation also decreases the higher frequency content from the conventional combustion engines and transmission. The propeller aircraft, Cirrus SR22 and Beechcraft Baron 55, exhibited more forward directivity as indicated by the higher levels several seconds prior to the flyover as compared to several seconds after the flyover. The maximum measured values are summarized in Table 2.

The Robinson R44 had the lowest maximum value at 57 dB(A) and the Beechcraft Baron 55 had the highest at 63 dB(A). The aircraft also exceeded the maximum Joby level at 100 knots for 43 to 54 seconds as shown in Figure 3. Since each aircraft was flying at 100 knots (51 m/s), this means they were above the maximum Joby level when the aircraft were within approximately one mile of the overflight location. This test was focused on noise directly under the flight path so there was no attempt to examine the directivity effects of each aircraft. The Joby propellers are oriented the same as the traditional fixed-wing aircraft in the cruise condition. Helicopters in edgewise flight have higher directivity in the rotor disk plane and produce similar levels across a wide area (Ref. 23). The lower absolute level and directivity result in a greatly reduced area below the flight path above a specified level. More details of the Joby aircraft directivity will be available in upcoming publications about the flight test done under NASA’s Advanced Air Mobility National Campaign.

The Joby aircraft was tested at 95 and 100 knots (49 and 51 m/s) to assess the speed sensitivity. The results are shown in Figure 4. There was a difference in maximum value of 1 dB which is within the likely variability of the flight test measurement. Interestingly, the sound level of the Joby aircraft during the 100 knot (51 m/s) test exhibits an increase in noise level after the +20 second point. This was found to be due to noise contamination from a commercial passenger jet in the area at about 15000 feet (4572 m). It is notable that such a distant aircraft could still be heard and still affect the measurement above the sound of the departing Joby aircraft.

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>Airspeed</th>
<th>Airspeed</th>
<th>L_{A,S,max}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joby Aircraft</td>
<td>95 knots</td>
<td>49 m/s</td>
<td>45 dB(A)</td>
</tr>
<tr>
<td>Joby Aircraft</td>
<td>100 knots</td>
<td>51 m/s</td>
<td>46 dB(A)</td>
</tr>
<tr>
<td>Cirrus SR22</td>
<td>100 knots</td>
<td>51 m/s</td>
<td>59 dB(A)</td>
</tr>
<tr>
<td>Beechcraft Baron 55</td>
<td>100 knots</td>
<td>51 m/s</td>
<td>63 dB(A)</td>
</tr>
<tr>
<td>Leonardo AW109</td>
<td>100 knots</td>
<td>51 m/s</td>
<td>61 dB(A)</td>
</tr>
<tr>
<td>Bell 206</td>
<td>100 knots</td>
<td>51 m/s</td>
<td>58 dB(A)</td>
</tr>
<tr>
<td>Robinson R44</td>
<td>100 knots</td>
<td>51 m/s</td>
<td>57 dB(A)</td>
</tr>
</tbody>
</table>
Figure 3: Time above maximum Joby level at 100 knots (51 m/s).

Figure 5 shows the comparison of the measured spectra between the Joby aircraft and each of the individual conventional aircraft at the point of maximum sound level for each aircraft. The Cirrus SR22 spectrum exhibits common characteristics of single propeller aircraft. It has a prominent tone around 100 Hz from the first blade passage frequency. Subsequent harmonics of the blade passage frequency are also apparent. Even with A-weighting reducing the tone at 100 Hz from 64 dB to 45 dB(A), this tone is the primary contributor to the overall level. This tone, which represents the first blade passage frequency, is 25 dB(A) above the entire spectrum of the Joby Aircraft. The Joby spectrum shows just two tones, and they sit only 5 dB above the broadband. The Joby aircraft spectrum stays within a five dB band between 100 and 1000 Hz. This reflects the design intent to eliminate prominent tones that give the noise from small helicopter and propeller airplanes their dominant characteristics. The Joby propeller rotational rate is reduced by more than half of the hover rotational rate to approximately 250 revolutions per minute. In hover, the propeller must spin at a higher rate to generate the thrust to overcome the weight of the aircraft. In cruise flight, the propellers are tilted so they need to produce roughly 1/10th the hover thrust to overcome the aircraft drag.

The Beechcraft Baron 55 spectrum also has a strong tone around 100 Hz. The two propellers are spinning at slightly different speeds which creates slow variations, in addition to interference patterns during the flight due to differing path lengths to the observer. No similar interference patterns are seen in the Joby aircraft results with its six propellers. The Beechcraft Baron 55 has the highest overall level of any aircraft tested.

The three helicopters tested exhibit similar characteristics in their spectra. The Robinson R44 is the best selling general aviation helicopter since 1999 (Ref. 24). It is widely used around cities and familiar to most people. It is smaller and lighter than the Joby aircraft. The two blade rotor design results in a first blade passage frequency between 10 and 20 Hz which is reduced by more than 50 dB due to A-weighting. Another tone possibly from the tail rotor around 120 Hz is the highest contributor to the A-weighted spectrum.

The Bell 206 exhibits a similar spectrum to the Robinson R44 with additional tonal content from 200 to 400 Hz. These tones are still very apparent to the listener. Additional tones from the main rotor and tail rotor are prominent in the spectrum until around 800 Hz. The Leonardo AW109 is the largest helicopter tested. It is a twin turboshaft, four blade main rotor and two blade tail rotor design. The four blade main rotor results in a higher first blade passage frequency compared to the smaller two blade helicopters. The Leonardo AW109 has a higher typical cruise speed - around 150 knots (77 m/s) - which further increases its levels.

Other acoustic metrics like effective perceived noise in decibels (EPNdB) and tone corrected perceived noise level (PNL(T)) provide an adjustment to account for the extra subjective noisiness of pronounced tones. The most appropriate noise metric for eVTOL aircraft is an area of active research. The computed EPNdB for the aircraft are shown in Figure 6. These values are for the flown flight test at 1500 feet (457 m), 100 knots (51 m/s) and not for the flyover noise condition or processed in the same manner as certification tests. The fixed-wing Cirrus SR22 and Beechcraft Barron 55 are 19 and 22 EPNdB above the Joby level. The helicopters are 13 to 18 dB higher. The difference between the Joby aircraft and the conventional aircraft in EPNdB is higher than the difference in \( L_{A,S,max} \) levels. This is due to the additional tone penalty. The EPNdB calculation only has a tone correction factor for the maximum tone and does not apply to additional tones that are present in the other spectra. Additional tone penalties would increase the value for the other aircraft.

Figure 7 compares the spectra of the Joby aircraft and Robinson R44 with two different ambient spectra. The Robinson
R44 was the quietest conventional aircraft during the over-flight test. The ambient at the test site is shown in yellow. A good signal to noise ratio is observed at the test site until about around 4000 Hz. The other ambient environment is taken from a calibrated recording of an outdoor café. It is a common outdoor environment with moderate background noise levels at 55 dB(A) which is below normal conversation. The café ambient levels are above the measured Joby level for the entire spectrum at the time the Joby aircraft is directly overflying the recording. This means that the Joby aircraft would be nearly imperceptible to an observer in the café environment even when it flies directly overhead. The Robinson
Figure 6: EPNdB comparison of the Joby aircraft and other aircraft.

Figure 7: Measured spectra of the Joby aircraft and Robinson R44 helicopter with two different ambient environments.

R44, like all other conventional aircraft tested, has low frequency tones from the main rotor and tail rotor that are nearly 20 dB(A) above the café ambient. These tones would be above the café ambient for nearly a minute during the flyover event. They would also be present above the café ambient levels over the large area on the ground that isn’t directly below the flight path. Low frequency tones can also penetrate buildings and indoor environments.

This is only one ambient environment. Ambient environments present different acoustic spectra across cities and during the course of the day. Many urban environments are dominated by noise from vehicle traffic especially trucks. Other cities, buildings, and indoor environments have larger impacts from boat, commercial aircraft, railroad, and conventional helicopter traffic. Additional research will be needed to improve the understanding of how noise levels can blend into common environments.

**CONCLUSIONS**

Flyover noise data for the Joby prototype has been shown for the first time. The difference in overall sound level and sound quality are apparent in the video posted in August 2021 but this paper provides technical data to describe the differences quantitatively. The maximum sound pressure level of the Joby aircraft was measured to be 10 to 19 dB(A) and 13 to 22 lower EPNdB than the conventional aircraft tested. The aircraft were flown at the same speed, altitude, and location to minimize differences. In practice, each of the aircraft will be flown at a different speed and altitude best suited to individual use. However, as a technical study of the differences in the acoustic signature of each aircraft, the authors chose to minimize differences in flight conditions as much as possible. The Joby aircraft is not only much quieter than the conventional aircraft in this study, but it also exhibits greatly reduced tonal content. The consequence of this is that the Joby aircraft is perceived to be even quieter than the metrics suggest. The noise goal from the Uber white paper has been demonstrated for flyover flights. Due to the low flyover noise levels, it is anticipated that noise levels in departure and approach conditions will be more critical than flyover noise. The departure and approach conditions were the focus of additional acoustics flight tests by Joby during NASA’s Advanced Air Mobility National Campaign.

The best acoustic metric for comparing eVTOL aircraft with each other and conventional aircraft is an area of active research. Additional research and studies are being undertaken by researchers in the NASA UAM Acoustics Technical working group and others. It is likely that no single metric can fully account for the unique character of eVTOL noise. The metric will likely need to take into account the sound level, frequency content, duration, multiple tones, and ambient environment. Future computational validation efforts are needed to separate the noise sources from propellers, airframe, and other sources. The relative contribution of propeller loading, broadband, and airframe noise sources is unknown. Additional computational and experimental efforts will be focused on departure and approach noise. The difficulty in accurate computational predictions in these flight regimes is increased due to the aircraft acceleration rate, aircraft flight control surfaces, changing propeller tilt angle, multiple propellers, propeller wake interactions, airframe interactions, and non-unique trim. It is expected that experimental measurements in urban environments will be further complicated by changing ambient noise levels, microphone positioning, urban canyon wind conditions, and acoustic reflections.

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