Aerodynamic And Acoustic Design Of The Joby Aviation eVTOL Propeller

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ABSTRACT

Joby Aviation is developing a six propeller, all electric vertical takeoff and landing aircraft for the Urban Air Mobility mission. The two primary design goals of this aircraft are safety and low noise. 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. After flight testing the initial full scale prototype aircraft, a redesign process was undertaken to further improve the propeller acoustics. This process included rapid composite manufacturing to enable experimental tests of intermediate designs. The propellers were initially designed using a low fidelity lifting line and prescribed wake design code. Design studies were made based off this initial design using the high fidelity Navier-Stokes solver OVERFLOW and FW-H solver PSU-WOPWOP. This process resulted in an increased solidity, reduced tip speed, and a swept anhedral blade tip. The final design was tested and shown to have a 3 dBA decreased OASPL at a hundred foot radius and 45 degrees below the propeller plane in hover when producing the same thrust as the previous propeller design. The newly designed blade has been flight tested on the Joby production prototype aircraft.

INTRODUCTION

In the past few years, rapid progress has been made towards enabling a future of affordable Urban Air Mobility (UAM). In 2016, Uber published a white paper detailing their vision for on-demand transportation (Ref. 1). Since then, the Vertical Flight Society has added reported more than 400 eVTOL aircraft concepts and two dozen companies flying prototypes (Ref. 2). In February 2018, Joby Aviation announced a full-scale prototype was undergoing flight testing (Ref. 3). In January 2020, additional details of the next prototype were disclosed including an image of the aircraft shown in Figure 1 (Ref. 4).

Uber Elevate has released a series of common reference models (Ref. 5). NASA also has released several difference concepts (Ref. 6). While none of these designs use the same configuration as the Joby Aviation aircraft, they all utilize distributed electric propulsion. Distributed electric propulsion allows for a much wider variety of viable concepts (Ref. 7). These aircraft include tilt rotors like Joby, tilt wings (Ref. 8), tail sitters (Ref. 9), lift+cruise (Ref. 10), vectored thrust (Ref. 11), multi-copters (Ref. 12), and more. Low noise has been made a priority for many of these designs primarily by utilizing low tip speed and low disk loading propellers.

Nearly all commercial airline aircraft have two engines. The production of the large four engine Boeing 747 and Airbus A380 will soon stop and these aircraft are being replaced by are the more economic two engine, twin aisle Boeing 777 and Airbus A350. Turbofan engines become more power, fuel, and cost efficient as they become larger. This is also the reason most helicopters have one or two engines. The maintenance requirements and efficiency of electric motors are much less sensitive to changing scale, which allows concepts with many electric engines. Perhaps no concept better illustrates this than the NASA X-57. The X-57 is a modification of the two-engine Tecnam P2006T with fourteen electric motors (Ref. 13). Joby was heavily involved during the program and built the 60 kW cruise motors. This program was built off the success of Leading Edge Asynchronous Propeller Technology or LEAPTech program which was a collaboration between NASA, Empirical Systems Aerospace, and Joby Aviation (Ref. 14).

These new UAM aircraft face large challenges before widespread adoption can occur. Among the greatest is the need for low noise. The NASA Acoustics Technical Working group published a white paper laying out the current state of the art (Ref. 15). It describes numerous challenges predicting UAM noise levels, designing for low noise, measuring UAM noise levels, and understanding how noise levels of these aircraft will be perceived by the public.

It is vital that low noise be a design focus from the beginning in order to achieve community acceptance of these new aircraft. The design of the propeller itself is only one part of the overall design. The Joby aircraft was designed from the beginning with low noise as the number two priority behind only safety. Acoustics was a key driver in selecting the num-
number of blades and hover disk loading. Additionally, the propellers are designed to have low interactions with each other and the airframe to minimize the resulting unsteady loading. The Joby aircraft had been designed with five blades to allow for higher solidity propellers and lower tip speeds than are possible for conventional helicopters. The propellers can also individually adjust their tilt, RPM, and blade pitch to avoid combinations that cause adverse acoustic effects due to blade vortex interactions (BVI). One important aspect for acoustics that is difficult to analyze early in the design is the interaction noise. Unsteady interactions with the airframe and with other propellers have been shown to be a large factor in the total installed acoustics of aircraft (Ref. 16).

The design hover tip speed is a critical value for both performance and acoustics. It is well known that tip speed is a primary factor in reducing helicopter and fixed wing propeller noise levels. Past research has shown the ability to decrease helicopter noise levels by 17-20 dB OASPL in hover by reducing operating RPM to 67% nominal levels but at greatly reduced gross weight and performance (Ref. 17). As the tip speed is reduced, unsteady loading from other sources can also increase in magnitude so that further RPM reductions do not result in lower noise levels (Ref. 18). The tip geometry of the blade can also be designed to reduce the noise due to BVI during landing (Ref. 19). The tip speed is kept well below levels that could result in high-speed impulsive noise from shocks on the advancing blade.

**EXPERIMENTAL VALIDATION**

Due to the limited acoustics experimental data in the literature for propellers of similar design and the high importance of propeller broadband levels, experimental data was considered essential. While an anechoic environment is ideal for acoustics testing, recirculation in hover can increase measured noise levels even for small propellers (Ref. 20). All testing was desired to be a full scale due to the importance of boundary layer transition which places further restrictions on the available anechoic facilities. To enable rapid design, build, and test cycles, onsite outdoor static testing was the most practical option for testing. This allowed tests of new designs to be made on an almost weekly basis. The tests were designed with ground adjustable blade pitch. For each blade pitch, the RPM was swept from a low RPM to the maximum allowable RPM. This was a much wider thrust range than the range relevant to hover design but made it easier to extract trends between designs. Tests were done in periods of low wind and often repeated to bound the experimental variability. The test stand with a sample propeller is shown in Figure 2. The test stand is close to the propeller and is not acoustically treated. The geometry and motor noise is expected to contribute to the measured acoustics. These experimental effects are likely constant between designs which allows for comparisons between designs. Later efforts were made to improve the experiment setup by reducing the motor noise by using a motor unit of the same design as used on the aircraft and moving to a better test location to reduce non-propeller acoustic sources.

The unsteady Reynolds-Averaged Navier Stokes code solver OVERFLOW 2.2m (Ref. 21) was used for aerodynamic simulations. OVERFLOW has been widely used and validated in rotorcraft and fixed wing industries. It has been used to predict helicopter rotor acoustics in low-speed descending flight (Ref. 22) and high-speed forward flight (Ref. 23). The flow solver was run with 5th order Roe upwind scheme and the
The blade surface pressures were converted for input into the Fluent Williams-Hawkings (FW-H) Solver PSU-WOPWOP (Ref. 26). Broadband self-noise predictions using the Brooks, Pope, and Marcolini method (Ref. 27) were also made in PSU-WOPWOP (Ref. 28). The broadband method is based off test data of a NACA 0012 airfoil. It also assumes smooth incoming flow and does not account for the turbulence in the wake. Simulations were run for around ten revolutions for each case. A single node of the local Joby cluster with two, ten-core Intel Xeon E5-2630v4 was able to run two revolutions per day. This speed allowed for the full range of blade pitches and RPMs that were experimentally tested to be compared to computed results. Python and Fortran scripts were written to automatically post process the results, convert data for PSU-WOPWOP, run PSU-WOPWOP, and extract the acoustic results. GNU Octave (Ref. 29) scripts were written to automate plotting and comparisons to test data.

The computed and measured 1/3 octave unweighted spectra are shown for the propeller that was flight tested on the earlier prototype aircraft in Figure 3. The loading noise predicted by PSU-WOPWOP using the computed blade surface pressures from OVERFLOW underpredicts the measured levels for the first few blade passage frequencies. The accuracy tends to increase for the higher tip speeds. The predicted broadband levels also match the experimental levels better at the highest tip speeds. The broadband model underpredicts the middle frequency range which results in the computed values underpredicting the overall A-weighted sound pressure level. Trends with increasing blade pitch and RPM were better captured than absolute levels. Future testing in a large anechoic facility may be required to generate higher quality experimental data. No attempt was made to adjust the broadband model for the different airfoils of the propeller.

One unique feature of these spectra is the relative levels of the low, middle, and high frequencies. Small UAVs have much smaller blade radii which results in much higher frequency tones at the blade passage frequencies. Helicopters by contrast have much larger blade radii and stronger low frequency tones. The Joby propellers have a much more even spectrum across the low and middle frequency range. The reduction in tonality and high frequency content is expected improve the sound quality.

Traditional helicopter designs have a fixed main rotor tip speed and use variable pitch for control. Small UAVs typically use fixed blade pitch and variable RPM for control. The Joby aircraft can use vary pitch and RPM. Prior to blade stall, thrust increases linearly with blade pitch and with the square of RPM. A low blade pitch and high RPM can achieve the same total thrust as a higher blade pitch and lower RPM. To better understand these effects on the acoustics, the propellers were tested at a full range of blade pitches and RPMs. The resulting measured and computed acoustics are shown in Figure 4 at a hundred foot radius and 45 degrees below the propeller plane. At a constant tip speed, measured sound levels slowly increase with blade pitch until the blade starts to have locally stalled flow which results in rapidly increasing noise levels. The minimum unweighted and A-weighted noise levels for a particular thrust level occurred at different tip speeds and blade pitches. The computed result captures these overall trends but does not capture the details. Higher grid resolution is required to more accurately capture the location of blade stall, but this remains a large computational challenge.

**PROPELLER DESIGN STUDY**

A design study was undertaken with the primary goal of improving the propeller acoustics without large amounts of performance degradation. Due to the high importance of acoustics for the design goals of the aircraft, some performance reduction was acceptable. In any design study, it is important to first understand the design goals, then define the parts of the design that are fixed, and the variables that can change. Low noise was an important driver during configuration selection and preliminary design. At this time, the major elements of the aircraft were already designed and fixed. The design goals of this study were the set in order of priority to be:
Figure 3. Acoustics validation for the same blade pitch at low (top), medium (middle), and high (bottom) tip speed.

Figure 4. Measured and computed acoustics for range of tip speeds and blade pitches.

- Minimize the A-weighted OASPL at 45 degrees below the propeller plane and 100 feet radius in hover
- Minimize power in hover
- Minimize power in cruise

The flight condition and acoustic metric chosen to minimize will have a large impact on the final design. Hover was chosen for simplicity and also due to the design flexibility of the Joby aircraft. All flights will start and end with a hover so it will always be an important condition for acoustics levels. Improvements in acoustics in hover will likely result in improved acoustics near the landing location. A single point 45 degrees below the propeller plane was chosen to balance the in-plane and out-of-plane noise levels. Minimizing total full aircraft noise near vertiports was the primary design goal; understanding the full aircraft acoustics during transition was deemed too complex for this design study. Even for a single propeller, there are large number of acoustics metrics and
propeller flow conditions that could have been chosen. Additionally, although care was taken to keep the props away from each other and the airframe, any prediction of full aircraft acoustics will need to account for these interactions.

An isolated propeller condition at some point during transition could have been chosen. The Joby aircraft can individually adjust the nacelle tilt and RPM to avoid combinations that result in large BVI events. The best acoustic metric for propeller optimization for UAM use is an area of active research. It is well know the limitations of A-weighting for helicopters and UAS systems (Refs. 31–35) but it was used in this case for simplicity. Improved metrics that better model the impact of these new aircraft on communities will need to be created based off early operations of these aircraft.

The power and torque requirements in hover and cruise flight are critical for sizing the electric motors and battery systems. Performance effects in cruise and hover were considered throughout the design process. Electric motors allow for a wide range of RPM in hover and cruise flight. As the aircraft transitions to high speed flight, power requirements decrease and the propeller RPM also decreases. As the RPM decreases, the available motor power decreases. The motor must be sized for the required torque and power in all phases of flight. Increasing the propeller chord and decreasing the propeller tip speed can result in conditions where the motor has power available but is unable to provide the required torque. The ability to adjust propeller RPM as the aircraft speed changes allows the propeller twist rate to be designed for a specific advance ratio. This simplifies the blade design and removes the need for nonlinear twist rates on turboshaft-powered tilt rotors like the XV-15 (Ref. 36).

While the first full scale prototype was flown in 2017, design efforts continued for the first production prototype. The overall aircraft design did not have major changes so the following fixed variables were fixed:

- Radius
- Blade count
- Hover thrust target
- Cruise thrust target
- Cruise airspeed

With these restrictions, the design space to change the propeller design was limited to:

- Blade chord distribution
- Hover RPM
- Cruise RPM
- Blade tip shape
- Airfoil design and selection

Acoustics in cruise were not directly considered. In cruise, the propellers will be producing much lower thrust than hover, the RPM will be further lowered to reduce power requirements, and the distance to observers on the ground will be much greater than during takeoff and landing; therefore, the aircraft is expected to be inaudible on the ground regardless.

Through experimentation, airfoil characteristics have been demonstrated to affect both the intensity as well as the perceived sound quality of the propeller in hover. Experimental results were compared against relative airfoil characteristics to determine the dominant acoustical drivers of airfoil design. For the final blade selection, an airfoil was designed that balanced favorable acoustic characteristics in hover with forward flight efficiency in cruise.

**SOLIDITY STUDY**

A baseline propeller was initially designed to optimize hover and cruise performance. From this baseline design, a systematic study of increasing the solidity and decreasing the blade tip speed was conducted to understand the changes in the broadband levels. Many of the blades built and tested during the new propeller blade design study are shown in Figure 5. The acoustic prediction methods using OVERFLOW and PSU-WOPWOP are well validated and understood for larger helicopter rotors but the prediction of the broadband levels is much less well validated. By scaling up the mean chord and reducing the blade RPM, the blade loading ($C_T/\sigma$) was kept constant. The blade twist rate and taper ratio was kept constant for most of the study. The blades were custom-made and produced by Joby for this design study. These blades were only intended for this hover test so detailed design of the blade structural properties was not done. The difference in elastic properties especially the decreased torsion stiffness of the smallest chord blade likely affected the acoustic results. After the blades were produced, they were laser scanned to examine the differences between the initial design and produced blades. Some of these laser-scanned geometries were used to create grids for computations using OVERFLOW. The blades did not have leading edge protection that would be required for production blades.

The measured acoustics results for three designs are shown in Figure 6 and Figure 7. The blade pitch for these tests are the same but the tip speed of the propellers are adjusted to the same total thrust. The test was run for a wide range of blade pitches and RPMs allowing for comparisons at different $C_T/\sigma$ values. The trends for a wider range of blade loading were similar except for the values near the maximum blade loading. For the first few blade passage frequencies, the highest tip speed propeller has the highest absolute levels. As the frequencies increase, the differences between the propeller designs decrease. For these plots, the highest chord blade has twice the mean chord of the lowest chord blade. The medium chord blade has the lowest mid and high frequency content which results in the lowest A-weighted OASPL. Since these designs have the same airfoils, twist, and taper ratios, the power required for these blades was similar. The torque
required from the motor increased as the tip speed decreased and the chord increased. Recordings of these tests were made and played back using headphones. Qualitative differences in the sound and frequency content were evaluated but no systematic study to evaluate perception was done.

Concurrently, this study was being done computationally. This allowed for exact chord scaling without manufacturing variation or experimental variability. The geometries manufactured and tested were not identical to ones used in this computational study. Runs were made by increasing the mean blade chord and reducing the propeller tip speed results to maintain the same blade loading. The original “VE” blade was designed without direct consideration of the acoustics. As the blade chord was increased and tip speed decreased, the hover performance decreased across the desired thrust range as shown in Figure 8. The performance decrease with increasing chord is expected as the original blade chord and tip speed was chosen to maximize performance. A similar power requirement increase was seen in cruise flight due increased skin friction drag from the increased blade chord. The required motor torque also increased which requires a larger and heavier motor. These effects were monitored to ensure that the overall design was still able to meet its performance requirements. Improving acoustics was prioritized over aircraft performance in this study.

Figure 9 shows the computed acoustics for an observer 45 degrees below the propeller plane at one hundred feet radius. Increasing the mean blade chord and decreasing the tip speed was shown to decrease the A-weighted sound pressure level. Larger reductions were seen when reducing the tip speed to 85% the original value with very limited differences between the 30% increased mean chord with 85% original tip speed and the 75% increased mean blade chord and 75% original
tip speed blades. The computed result for the 100% increased mean blade chord and 70% reduced tip speed showed a larger noise reduction than the experimental data.

Based on these computed results and experimental data, a 55% chord increase and 80% original rotational tip speed was chosen for the next blade design. From this baseline platform, the blade tip shape was further optimized to improve acoustics.

![Figure 8. Computed hover performance with increasing chord and decreasing tip speed.](image1)

TIP SHAPE STUDY

The blade was originally designed using a prescribe wake analysis code. The Joby aircraft does not have retreating blade lift requirements like traditional helicopters which allows for higher tip taper ratios. The 55% increased mean chord blade was used as a baseline. A grid was created by keeping a constant chord for the last 10% of the blade radius. A second grid was created where the tip chord was decreased by 50% and blended with the original blade at 90% span. The constant tip chord resulted in higher thrust for the same reference blade pitch. The increased tip loading resulted in lower performance and increased the noise as shown in Figure 10. The increased blade pitch had a much smaller effect on performance and acoustics. The original blade taper and tip chord was kept for the final design.

![Figure 10. Computed change in acoustics with increasing and decreasing tip chord.](image2)

Originally, the quarter chord line of each blade design was kept constant. The high amounts of tip taper resulted in small amounts of leading edge sweep but greater amounts of trailing edge sweep. A computational study was made examining increasing the leading edge and quarter chord sweep. A small amount of quarter chord sweep was adopted which resulted in small predicted performance and acoustic benefits.

An additional study was made to design the tip anhedral. Moderate amounts of anhedral were found in computations to improve hover performance and have no effect on cruise performance. High amounts of anhedral resulted in flow separation and decreased hover performance. The anhedral was found to have no effect on the computed acoustics. This is to be expected as none of the inputs to the broadband model were changed. Anhedral was not considered during the development of the broadband model.

The taper, sweep, and anhedral studies were not validated with experimental data. With limited time and manufacturing constraints, the solidity study was prioritized for testing due to the higher uncertainty with broadband noise predictions.
DESIGN VERIFICATION

After finalizing the blade chord, tip taper, and tip anhedral design, a final blade was designed with these features. Small adjustments were made for manufacturing considerations. An initial prototype was built and tested to compare performance and acoustics to the original design with the results shown in Figure 11. Across the desired hover thrust range, the new propeller design was around 3 dBA quieter than the original design. The decreased tip speed resulted in larger drops in levels at the first few blade passage frequencies. The sound of the aircraft with the newly designed blades has been described as “a lower-intensity, lower-frequency sound quite unlike the urgent, high-pitched swarm-of-bees-like noise often associated with drones and large multicopters” (Ref. 37).

CONCLUSIONS

An experimental and computational effort was made to further reduce the acoustics of the Joby Aviation aircraft. The resulting blade was measured to have a 3 dBA reduction at 45 degrees below the propeller plane at 100 feet compared with the previous design producing the same thrust. During the course of this design, the recent advancements in high fidelity computational fluid dynamics, computational acoustic predictions, and rapid composite manufacturing led to an improved design that would not have been previously possible. However, further future research has the possibility to improve these designs and reduce noise levels during flight operations. The importance of UAM aircraft acoustics will likely only increase as these aircraft become more common in our communities. While different UAM concepts may have unique acoustics design needs, the following list of areas of need for further research should apply to most designs:

- What blade loading, $C_T/\sigma$, results in the lowest noise? Does this value change for different numbers of blades, scale, or disk loading?
- What acoustic measurement metric and measurement location is the most applicable for propeller design for UAM aircraft?
- What improvements can be made to the prediction of broadband acoustics?
- How does the airfoil design affect broadband noise levels?
- How can subscale acoustics testing support UAM design?
- What is the relative importance of tonality and frequency content for UAM aircraft? How will this affect public perception of these aircraft?
- How should outdoor experiments of large low-noise propellers be conducted to minimize experimental variability? How can the effects of atmospheric turbulence be analyzed?
- How should unsteady interactions with other propellers and the airframe be modeled during the design process?

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REFERENCES


