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A review of noise suppression methods for eVTOL aircraft: insights from the Joby S4

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Abstract. Electric Vertical Take-Off and Landing (eVTOL) aircraft are central to the development of the low-altitude economy; however, the noise generated by their operation severely hampers the large-scale implementation of Urban Air Mobility (UAM) and significantly reduces public acceptance. This represents a critical bottleneck that urgently requires resolution for the commercialisation of the low-altitude transport industry. This paper focuses on the noise reduction technology framework for eVTOLs, systematically reviewing the current state of the art, engineering applications, existing challenges and future trends in this field. It provides an in-depth analysis of the noise reduction design and practical outcomes of the Joby Aviation S4, a representative model, thereby offering theoretical and practical support for the iterative development and engineering optimisation of eVTOL noise reduction technologies. The research employs a systematic literature review approach, combined with the analysis of representative case studies. The research findings indicate that the diverse range of existing noise-reduction technologies can effectively mitigate noise issues in eVTOL aircraft. The bespoke noise-reduction design of the Joby S4 has been validated through testing as delivering excellent noise-reduction performance, serving as a high-quality reference solution for the engineering implementation of noise reduction in civil eVTOL models. However, the industry currently faces numerous challenges, including insufficient accuracy in noise prediction, difficulties in balancing multiple performance metrics, significant challenges in the practical implementation of active noise cancellation technologies, and a lack of standardisation in technical standards.

Keywords: eVTOL, noise suppression, Joby S4, aerodynamic noise, urban air mobility, low-altitude economy, propeller noise, passive control

1. Introduction

With the acceleration of urbanization and the growing severity of ground traffic congestion, the low-altitude economy has emerged as a strategic focus worldwide. Electric Vertical Take-Off and Landing (eVTOL) aircraft, as the core vehicles of low-altitude transportation, are widely regarded as a promising solution for future Urban Air Mobility (UAM) due to their vertical take-off and landing capability, potential for zero emissions, and flexibility in point-to-point operations. Nevertheless, the large-scale commercial deployment of eVTOL aircraft still faces multiple technical and societal challenges, among which noise remains one of the most critical [1, 2].

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Although eVTOL aircraft generally produce lower noise levels than conventional helicopters, the aerodynamic noise generated by their distributed propulsion systems during hover, take-off, landing, and transition phases can still cause noticeable disturbance to ground communities. In densely populated urban environments, even moderate noise levels may trigger resident complaints, restrict flight schedules, and hinder the planning and implementation of routes and vertiports [1, 2]. A large-scale European survey conducted by EASA further confirmed that noise ranked as the second major concern among citizens, after safety [2].

The noise characteristics of eVTOL aircraft differ significantly from those of traditional aviation vehicles. Their propulsion systems typically adopt distributed configurations such as multi-rotor, tilt-propeller, or ducted-fan configurations, resulting in more complex noise sources. These include rotor self-noise (thickness and loading noise) as well as interaction noise arising from rotor–rotor and rotor–airframe interference. Moreover, the dominant noise mechanisms vary across flight phases: interaction noise tends to be more prominent during hover, whereas self-noise often becomes the primary contributor in cruise. These distinctive features imply that noise suppression strategies developed for conventional rotorcraft or fixed-wing aircraft cannot be directly applied to eVTOL systems and must instead be tailored to their specific configurations and operational profiles [1].

Substantial efforts have been devoted by both academia and industry to eVTOL noise suppression, covering passive design optimization, active control techniques, and flight trajectory planning. Widely explored approaches include blade geometry optimization, reduction of tip speed, increase of solidity, application of serrated edges, acoustic treatments, and multi-rotor phase control. At the same time, different eVTOL configurations exhibit distinct noise signatures and require correspondingly differentiated suppression strategies. Among existing designs, the Joby Aviation S4 stands out as a representative tilt-propeller configuration. From the earliest design stages, low noise was established as a core objective, and the aircraft has accumulated relatively comprehensive full-scale flight test and wind-tunnel data, making it a valuable case for studying noise suppression in this class of vehicles.

This paper aims to provide a systematic review of research progress in eVTOL noise suppression. Beginning with an investigation into the dominant noise-generation mechanisms of eVTOL platforms, it explores how these mechanisms shape the development of the low-altitude economy. Conventional noise suppression methods are then summarized. Building on this foundation, the Joby S4 is taken as a detailed case study to analyze its specific noise reduction design features and validation results. Finally, current technical challenges are discussed, and future research directions are outlined. The findings of this review are expected to benefit researchers and engineers engaged in eVTOL acoustic design, certification, and low-altitude economy planning. By systematically summarizing noise generation mechanisms, conventional suppression methods, and full-scale validation results from the Joby S4, this work provides practical design references and helps identify priority directions for future research, thereby supporting the development of quieter, more publicly acceptable urban air mobility systems.

2. Noise sources and generation mechanisms

The aerodynamic noise of eVTOL aircraft differs significantly from that of conventional helicopters, primarily due to the widespread adoption of distributed electric propulsion systems, which features multiple small-diameter rotors operating at distinct rotational speeds and close spatial intervals. The overall acoustic signature is dominated by two categories of sources—rotor self-noise and interaction noise—whose relative contributions vary markedly across different flight phases [1, 3].

Rotor self-noise originates from the interaction of the blades with their own boundary layers and near-field wakes. It comprises thickness noise, loading noise, Turbulent-Boundary-Layer Trailing-Edge (TBL-TE) noise, and tip-vortex noise. This category typically becomes the primary contributor during cruise, when rotational speeds are relatively low and the inflow is comparatively uniform [1, 4].

Interaction noise, by contrast, grows substantially more important during hover, take-off, landing, and transition. The principal mechanisms include rotor–rotor interaction (wake ingestion and tip-vortex encounters), rotor–airframe interaction (wake impingement on wings or fuselage), and, in ducted configurations, rotor–duct interaction. These interactions produce strong tonal components at the Blade-Passing Frequency (BPF) and its harmonics, together with elevated broadband levels, resulting in higher perceived annoyance [1-3].

In hover and transition, high disk loading combined with complex aerodynamic coupling usually yields the highest overall noise levels. In cruise, reduced tip speeds and cleaner inflow generally lower the overall sound pressure level and shift the spectrum toward broadband self-noise. Secondary contributions from electric motors and airframe components exist, yet they remain secondary to the rotor-generated noise under most operating conditions [1, 4].

A clear understanding of these source mechanisms is essential for developing effective noise-suppression strategies, because different sources respond to different design and operational measures.

3. Impact of noise on the low-altitude economy

Noise is widely recognized as one of the most critical non-technical barriers to the large-scale development of the low-altitude economy. Even if eVTOL aircraft produce substantially lower absolute noise levels than conventional helicopters, public acceptance remains highly sensitive to the frequency, duration and acoustic characteristics of such noise, particularly in densely built urban environments [1, 5].

Excessive or poorly managed noise can directly constrain operational feasibility. It may limit allowable flight schedules, restrict vertiport locations, increase minimum separation distances from residential areas, and raise the cost of environmental impact assessments and community engagement. In extreme cases, strong public opposition can delay or prevent the approval of specific routes and infrastructure, undermining the economic viability of urban air mobility services [5, 6].

Survey and modeling studies provide quantitative context for these impacts. Large-scale European surveys have ranked noise as the second major public concern after safety [2]. Parametric assessments further indicate that achieving a 10-15 dBA noise reduction relative to conventional light helicopters can substantially shrink the land area and population exposed to elevated DNL levels; for instance, a 15 dBA reduction (compared with a 10 dBA reduction) is estimated to cut the share of highly annoyed residents by roughly 85-91% across typical metropolitan areas [6]. Psychoacoustic tests also show that, at equivalent A-weighted sound exposure levels, annoyance responses to UAM vehicles and light helicopters are similar, but at the same observer distance UAM vehicles are typically quieter and less annoying [1]. These findings underscore that even moderate absolute reductions can yield large gains in community acceptance and operational flexibility.

From a regulatory perspective, noise performance is becoming an increasingly important factor in airworthiness certification and operational approval processes. Future noise certification standards for eVTOL aircraft are expected to be more stringent and community-oriented than traditional rotorcraft rules. Aircraft that fail to meet evolving acoustic expectations may face restricted operational envelopes or higher compliance costs [1, 7].

Moreover, noise influences the broader business case of the low-altitude economy. Quieter aircraft can support higher flight frequencies, denser vertiport networks, and greater public willingness to live and work near low-altitude corridors. Conversely, inadequate noise control may force operators to adopt conservative flight profiles or limit services to less noise-sensitive areas, reducing overall system efficiency and market potential [6]. Therefore, effective noise suppression is not merely a technical requirement but a foundational enabler for the sustainable growth of the low-altitude economy.

4. Conventional noise suppression methods for eVTOL aircraft

Noise suppression strategies for eVTOL aircraft can be broadly classified into passive design measures, active control techniques, and operational procedures. Most current approaches remain dominated by passive methods due to their reliability and relatively low system complexity [1, 3].

Passive design measures form the foundation of eVTOL noise reduction. The most effective and widely adopted approach is the reduction of propeller tip speed, typically achieved by increasing the number of blades and solidity while lowering rotational speed. High-solidity, multi-blade propellers allow sufficient thrust to be generated at lower tip Mach numbers, thereby attenuating both thickness and loading noise [3]. Blade geometry optimization—including airfoil selection, planform shaping, tip modifications (e.g., sweep, taper, or anhedral), and serrated trailing edges—further reduces broadband self-noise. In multi-rotor configurations, careful spatial arrangement of propellers is used to increase inter-rotor separation and minimize aerodynamic interactions that generate interaction noise. Airframe shielding and strategic placement of propellers relative to lifting surfaces can also provide limited acoustic benefit through scattering and reflection effects [1, 3].

Typical noise-reduction magnitudes reported in the open literature further illustrate the relative effectiveness of these approaches. High-solidity, multi-blade rotors running at reduced tip speeds offer significant tonal-noise advantages. For 8-ft-class eVTOL rotors, computational studies predict in-plane noise reductions of roughly 12-24 dB in hover (and 12-16 dB during moderate climb) when solidity is raised to around 0.2 and tip speeds are reduced accordingly. Under identical tip speeds, five narrower blades outperform configurations with fewer, wider blades [3]. Trailing-edge serrations applied to multi-rotor configurations have shown broadband reductions exceeding 9 dB for representative quadrotor designs, with larger benefits observed at higher tip speeds and lower blade counts [4]. Increasing blade number alone (e.g., from two to four) can yield on the order of a 10 dB reduction in tonal components for a given thrust. Active rotor-phase synchronization (synchrophasing) has experimentally achieved harmonic reductions of up to approximately 10 dB over limited azimuthal sectors, or global reductions of about 6 dB under optimized phase offsets. These magnitudes are configuration- and condition-dependent, and must be traded against aerodynamic efficiency, weight, and structural constraints; nevertheless, they confirm that passive tip-speed/solidity optimization remains the most robust single lever currently available for large absolute reductions.

Active control techniques remain less mature but are still under investigation. Synchrophasing (or "rotor phasing") among multiple propellers can be used to cancel tonal components through destructive interference. Independent control of rotational speed, blade pitch, and tilt angle allows real-time adaptation of operating conditions to avoid high-noise regimes during transition and low-speed flight. Closed-loop systems that sense acoustic emissions and adjust propeller states accordingly have been proposed, although full-scale implementation remains limited [3, 4].

Operational procedures offer complementary noise reduction without hardware changes. These include optimized flight-path angles, reduced climb/descent rates near populated areas, preferential routing away from noise-sensitive zones, and time-of-day operational restrictions. Such procedures are expected to play an

important role in early urban air mobility operations while vehicle-level noise performance continues to improve [1].

5. Noise suppression design and validation of the Joby S4

5.1. Aircraft overview and design concept

The Joby S4 is a six-tilt-propeller eVTOL aircraft designed from the earliest development stages with low community noise as a core objective. It features six five-bladed, high-solidity composite propellers capable of tilting between vertical and horizontal orientations, enabling both efficient hover and wing-borne cruise flight [8, 9]. The aircraft is intended to carry one pilot and up to four passengers over a range of approximately 100 miles at speeds up to 90 m/s (175 knots). From the conceptual design phase, acoustic performance was treated as a primary design driver rather than a secondary constraint, influencing propeller geometry, layout, and control strategy [8].

5.2. Main noise suppression design measures

Several interrelated design features contribute to the low-noise characteristics of the S4. First, the propellers employ a five-blade, high-solidity configuration that permits operation at significantly lower tip speeds than conventional helicopter rotors while still generating the required thrust. This reduction in tip Mach number directly attenuates both thickness and loading noise [8, 9]. Second, the spatial arrangement of the six propellers maximizes inter-rotor separation and minimizes adverse aerodynamic interactions between rotors and between rotors and the airframe. Third, each propeller offers independent control over rotational speed, blade pitch, and nacelle tilt angle. This independent control allows the aircraft to avoid high-noise operating regimes during different flight phases and to adapt the acoustic signature in real time [8]. Collectively, these measures—low tip speed, high solidity, optimized multi-rotor layout, and adaptive control—form the foundation of the S4's noise-suppression strategy.

5.3. Experimental verification and main results

The effectiveness of these design measures has been extensively validated through full-scale flight testing and isolated-propeller wind-tunnel experiments. In 2021, NASA and Joby conducted the first full-scale acoustic flight test of an Advanced Air Mobility (AAM) aircraft as part of the AAM National Campaign. A 58-channel distributed microphone array captured more than 100 test points covering hover (in and out of ground effect), departures, approaches, and level flyovers [8]. Results showed that full wing-borne cruise is the quietest phase of the flight envelope, while approaches consistently produce larger ground noise footprints than departures when comparing 65 dBA isoline areas. Hover measurements exhibited 2-5 dB variation within a single run and greater run-to-run variability [8].

Complementary high-fidelity data were obtained in 2023 through an isolated S4 propeller test in the National Full-Scale Aerodynamics Complex (NFAC) 40- by 80-Foot Wind Tunnel. Acoustic measurements across sweeps of blade pitch, RPM, flow angle, and wind speed revealed the existence of an optimum RPM for a given thrust level that minimizes noise; further reductions in RPM beyond this optimum can increase noise levels [9]. These controlled results confirm the noise-reduction benefits of the low-tip-speed, high-solidity design and provide essential validation data for computational tools.

In parallel, high-fidelity computational methods have been developed to predict approach and departure noise. CFD simulations performed in OVERFLOW, coupled with PSU-WOPWOP acoustic computations,

produced noise hemispheres at key waypoints along approach trajectories, which were then propagated via the Advanced Acoustic Mobility (AAM) framework.

Comparison with the 2021 flight-test data showed reasonable agreement, with mean absolute errors on the order of 3-4 dB(A). The observed discrepancies stem mainly from residual uncertainties regarding terrain effects and ground impedance, incomplete representation of airframe acoustic shielding within earlier model variants, and mismatches between simulated approach trim conditions and the actual flown departure trajectories. Progressive inclusion of terrain modeling and airframe shielding systematically reduced the mean absolute error, indicating that the underlying physical mechanisms are captured; remaining scatter is consistent with unmodeled local test-site features and propagation assumptions [10].

Overall, the combination of low tip speed, high-solidity blade design, optimized multi-rotor layout, and independent propeller control, supported by extensive full-scale and component-level validation, demonstrates that substantial noise reduction is achievable for tilt-propeller eVTOL configurations while preserving operational performance.

6. Challenges

Despite significant progress in eVTOL noise suppression, several critical challenges remain to be addressed before quiet and scalable urban air mobility can be fully realized.

First, the accurate prediction of complex interaction noise continues to pose substantial difficulties. Rotor–rotor and rotor–airframe interactions, particularly during transition flight, involve highly unsteady and three-dimensional flow phenomena that current computational tools still struggle to capture with sufficient fidelity and efficiency.

Second, multi-objective design trade-offs remain unavoidable. Measures that effectively reduce noise—such as lower tip speeds, higher solidity, or specialized blade geometries—often come at the expense of aerodynamic efficiency, structural weight, range, or manufacturing cost. Balancing these competing requirements within a single vehicle design remains an open problem.

Third, active control technologies, including rotor synchrophasing and closed-loop acoustic feedback systems, show promising laboratory results but lack extensive full-scale validation under realistic flight conditions. Issues of robustness, certification, and real-time computational burden further limit their near-term adoption.

Finally, noise certification standards and community metrics for eVTOL aircraft are still evolving. Existing frameworks based primarily on A-weighted levels may not adequately capture the distinctive tonal and temporal characteristics of distributed-propulsion noise, nor fully reflect public annoyance in urban soundscapes. Aligning technical performance with regulatory expectations and societal acceptance therefore remains a key challenge.

Addressing these issues will require continued advances in high-fidelity prediction methods, multi-disciplinary optimization frameworks, full-scale experimental campaigns, and the development of perceptually relevant noise metrics tailored to the unique operational environment of the low-altitude economy.

Once the remaining acoustic barriers are effectively addressed, eVTOL aircraft are positioned to evolve from experimental demonstrators into a practical new mode of urban and regional transportation. Quiet, community-compatible operations would unlock higher flight frequencies, denser vertiport networks, and broader public acceptance, thereby enabling the low-altitude economy to scale beyond niche applications.

Looking ahead, research is expected to concentrate on several still-maturing technologies that have already been partially demonstrated on platforms such as the Joby S4. Priority directions include:

• higher-fidelity prediction and real-time modeling of complex rotor–rotor and rotor–airframe interaction noise, especially during transition;

• robust, certifiable active control strategies (including multi-propeller synchrophasing and closed-loop acoustic feedback) that can be validated at full scale under realistic flight conditions;

• multi-disciplinary optimization frameworks that systematically balance noise reduction against aerodynamic efficiency, structural weight, range, and cost;

• the development and regulatory adoption of perceptually relevant noise metrics that better reflect urban annoyance than traditional A-weighted levels alone.

Progress in these areas, building on the design philosophy and validation experience of low-noise configurations such as the Joby S4, will be essential for translating laboratory and flight-test advances into commercially viable, socially acceptable urban air mobility systems.

7. Conclusion

This review examines the state-of-the-art in noise-reduction technologies for eVTOL aircraft, focusing on lessons drawn from the Joby S4 as a representative low-noise vehicle design. The distinctive acoustic characteristics of distributed electric propulsion systems—dominated by rotor self-noise in cruise and interaction noise during hover and transition—necessitate dedicated suppression strategies that go beyond those developed for conventional rotorcraft.

Passive design measures, especially the combination of low tip speed, high solidity, and multi-blade propellers, currently form the cornerstone of practical noise reduction and have been successfully demonstrated at full scale by the Joby S4. Complementary approaches, including blade geometry optimization, synchrophasing (rotor phasing), and carefully planned operational procedures, offer additional avenues for further improvement. Nevertheless, significant challenges remain in accurately predicting complex interaction noise, managing multi-objective performance trade-offs, maturing active control technologies, and aligning technical solutions with evolving certification standards and community expectations.

Looking ahead, the sustainable development of the low-altitude economy will depend not only on continued advances in vehicle-level acoustic design, but also on the integration of high-fidelity prediction tools, multidisciplinary optimization, full-scale validation, and perceptually relevant noise metrics. By systematically addressing these interrelated technical and societal dimensions, the eVTOL community can move closer to realizing quiet, publicly acceptable, and commercially viable urban air mobility.

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