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Review Article

Advances in Aeroacoustics Modelling and Noise Mitigation Strategies for Axial Fans: From High-Fidelity CFD to Multi Objective Optimization

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Abstract

Advancements in aeroacoustics research have significantly improved noise mitigation and aerodynamic efficiency in axial fans and propulsion systems, driven by the integration of innovative computational, experimental, and material design techniques. This review consolidates findings from 32 high-impact studies, providing a comprehensive exploration of state-of-the-art methodologies and their applications in the development of next-generation quiet and efficient aerodynamic systems. The report highlights the pivotal role of Computational Fluid Dynamics (CFD) in capturing complex flow interactions and noise-generation mechanisms. Techniques such as Unsteady Reynolds-Averaged Navier–Stokes (URANS), Large Eddy Simulation (LES), and the Lattice Boltzmann Method (LBM) have enabled high-fidelity modelling of turbulence, tip-leakage flows, and rotor–stator interactions. These computational advancements have been validated through rigorous experimental methods, including wind-tunnel testing, acoustic mode decomposition, and anechoic-chamber measurements, ensuring the accuracy of predictive models. Innovative noise-reduction strategies have emerged, ranging from bio-inspired blade designs to advanced material applications such as porous casings and acoustic metamaterials. Serrated trailing edges, sinusoidal-shaped inlet ducts, and uneven blade spacing have demonstrated substantial tonal and broadband noise reductions while maintaining aerodynamic performance. Multi-objective optimization frameworks, leveraging machine-learning algorithms, have facilitated the design of efficient and compact systems for urban mobility and industrial applications. Despite these advancements, challenges remain in balancing noise mitigation with aerodynamic efficiency, scaling experimental techniques, and addressing the computational demands of high-fidelity simulations. The integration of hybrid methods and advanced materials presents a promising pathway for overcoming these barriers.

I. INTRODUCTION

A. Importance of Aeroacoustics and Noise Reduction in Axial Fans

Axial fans, widely employed in industries such as aerospace, automotive, and HVAC, play a critical role in controlling airflow with high efficiency and minimal power consumption. However, a persistent challenge in their operation is the noise generated during functionality, primarily due to aerodynamic and structural interactions. This noise, categorized into tonal and broadband components, not only disrupts operational environments but also poses regulatory and environmental challenges. The significance of aeroacoustics, the study of noise generated by fluid flow and its interaction with solid boundaries, has grown substantially over the past decade. Noise reduction in axial fans has emerged as a vital research focus to ensure compliance with stringent noise regulations and to improve the overall user experience. Beyond regulatory compliance, minimizing noise enhances product marketability, operational safety, and suitability for noise-sensitive applications. This underscores the imperative need to integrate advanced aerodynamic designs and optimization techniques to mitigate noise without compromising performance.

B. Impact on Industries Like Aerospace, Automotive, and HVAC

The implications of noise reduction in axial fans are particularly pronounced in the aerospace, automotive, and HVAC sectors. In the aerospace industry, axial fans are integral components of ventilation systems, cooling mechanisms, and propulsion units. Excessive noise not only deteriorates passenger comfort but may also affect the structural integrity of surrounding components due to vibrational effects. Therefore, optimizing aeroacoustic performance in this domain contributes directly to safety and passenger satisfaction.

Similarly, in the automotive sector, the demand for quieter and more efficient cooling fans has escalated with the advent of electric vehicles (EVs). Unlike internal combustion engines, EVs operate silently, making fan noise a predominant source of acoustic disturbance. Thus, achieving noise reduction while maintaining compact, energy-efficient designs is critical for automotive applications. In the HVAC industry, axial fans are fundamental to ensuring indoor air quality and thermal comfort in residential, commercial, and industrial settings. Noise from these systems can lead to significant discomfort, particularly in spaces such as hospitals, schools, and libraries, where low noise levels are essential.

Moreover, energy efficiency and sustainability goals in HVAC systems necessitate the adoption of advanced noise-mitigation strategies. In all these industries, the convergence of performance optimization and noise reduction represents a transformative opportunity. Addressing the dual challenges of aerodynamic efficiency and aeroacoustic mitigation through design innovation and computational methods is crucial for achieving sustainable progress in axial fan technology.

C. Research Objectives

The primary aim of this report is to explore and analyze the advancements in aerodynamic optimization and noise mitigation for axial fans, with a focus on bridging foundational concepts and cutting-edge technologies. The study seeks to address the dual challenges of enhancing performance efficiency and reducing noise emissions, both of which are pivotal for modern industrial and environmental applications. By providing a detailed review of the latest methodologies, this report aims to offer a comprehensive understanding of the current research landscape while identifying opportunities for future progress. One of the core objectives is to investigate the underlying principles and mechanisms of noise generation in axial fans. This includes analyzing both tonal and broadband noise sources, which arise from aerodynamic interactions and turbulence effects.

The report examines state-of-the-art noise-mitigation techniques, emphasizing their applicability in industries where acoustic performance is a critical parameter, such as aerospace, automotive, and HVAC. These sectors face increasing demands for quieter and more efficient systems, making advancements in aeroacoustics a significant focus of research and development. The report also aims to identify and evaluate emerging trends and technologies that are shaping the future of axial fan design. Innovations such as bio-inspired blade designs, additive manufacturing techniques, and advanced composite materials are discussed in detail, with a focus on their potential to achieve breakthroughs in noise reduction and performance enhancement.

Furthermore, the integration of hybrid methodologies that combine experimental validation with computational simulations is explored as a reliable and efficient approach to aerodynamic design optimization. Finally, this report seeks to assess the broader industrial and environmental impacts of advancements in axial fan technology. By reducing noise pollution and improving energy efficiency, these innovations not only address regulatory and operational challenges but also contribute to sustainability and environmental conservation. In addition, the report identifies existing gaps and challenges in the research domain and proposes actionable recommendations for future investigations. Through these objectives, the report aims to provide a scholarly synthesis of knowledge that is both practical for industry applications and valuable for advancing academic research.

II. FUNDAMENTALS OF AEROACOUSTICS AND AXIAL FAN DESIGN

A. Overview of Axial Fans

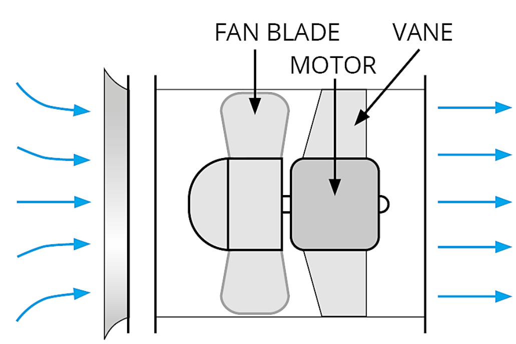

Fig.1 Axial Fan configuration

Axial fans are a fundamental category of turbomachinery, designed to move air or gas parallel to the axis of rotation. Their widespread application across industries such as aerospace, automotive, HVAC, and industrial systems stems from their ability to deliver high flow rates with relatively low-pressure drops. The design principles, components, and applications of axial fans are critical to understanding their functionality and the ongoing advancements in their optimization.

B. Design Principles

The primary design principle of axial fans is based on the generation of lift forces by the fan blades as they rotate. The airfoil-shaped blades impart energy to the airflow, converting rotational mechanical energy into fluid kinetic energy. The aerodynamic efficiency of axial fans is influenced by several factors, including blade angle, chord length, tip speed, and solidity. These parameters are meticulously optimized to balance the trade-offs among flow rate, pressure generation, and noise emission. In addition to aerodynamic considerations, structural integrity is a vital aspect of axial fan design. The blades must withstand centrifugal forces, vibrations, and operational stresses while maintaining precise alignment and minimal deformation. Advanced materials, such as composites and alloys, are often employed to enhance durability without significantly increasing weight.

C. Components of Axial Fans

Axial fans consist of several key components, each contributing to their overall performance and efficiency:

1. *Hub:* The central component to which the fan blades are attached. It houses the shaft and serves as the rotational axis.
2. *Blades:* Aerodynamically shaped elements that generate lift and impart energy to the airflow. Blade design is critical for achieving desired flow characteristics and minimizing noise.
3. *Shroud or Casing:* A protective enclosure that guides airflow and prevents external interference. It also aids in improving fan efficiency by reducing recirculation and leakages.
4. *Motor:* The power source that drives the fan. Motor efficiency and speed control directly influence the fan's operational characteristics.
5. *Bearings and Mountings:* Components that ensure smooth rotation and stability of the fan during operation.

The versatility of axial fans, combined with their high performance, makes them indispensable across a broad spectrum of applications. However, their efficiency and acoustic performance continue to be areas of active research and development, driving innovations in aerodynamic design and noise mitigation techniques. This foundational understanding is essential for appreciating the significance of advancements in axial fan technology.

D. Fundamentals of Aeroacoustics

Aeroacoustics, the study of noise generated by aerodynamic forces, plays a crucial role in the design and optimization of axial fans. Noise emissions from axial fans are a direct consequence of the interaction between the fan's rotating blades and the surrounding fluid medium. Understanding the noise-generation mechanisms and the governing principles behind aeroacoustics is essential for developing effective noise-mitigation strategies.

E. Noise Generation Mechanisms in Axial Fans

The acoustic emissions from axial fans can be broadly categorized into two types: tonal noise and broadband noise. Each arises from distinct aerodynamic phenomena:

1. *Tonal Noise:* Tonal noise is primarily generated by periodic forces acting on the fan blades due to the interaction of rotating blades with stationary components, such as stators, supports, or casing irregularities. The blade-passing frequency (BPF) is a characteristic feature of tonal noise, where the frequency is determined by the rotational speed of the fan and the number of blades.
2. *Broadband Noise:* Broadband noise results from turbulent interactions, such as flow separation, vortex shedding, and turbulence ingestion by the fan blades. These interactions generate random pressure fluctuations across a wide range of frequencies.

Other secondary noise sources include:

1. *Tip Vortex Noise:* Generated at the blade tips due to pressure differences between the blade's suction and pressure sides.
2. *Wake Interaction Noise:* Arising from the interaction of wake vortices with downstream components.
3. *Blade–Vortex Interaction (BVI):* Occurs when shed vortices from one blade interact with adjacent blades.

F. Key Parameters in Aerodynamic Design

The aerodynamic performance of axial fans is heavily influenced by several design parameters, including blade profiles, flow patterns, and efficiency metrics. Optimizing these parameters ensures a balance among high performance, low noise emissions, and energy efficiency, which are critical for various industrial applications.

G. Blade Profiles

Blade profiles play a pivotal role in determining the aerodynamic behavior of axial fans. The shape, size, and orientation of the blades directly influence airflow, pressure generation, and noise characteristics.

1. *Blade Shape and Camber:* The curvature (camber) and thickness of the blade dictate its ability to generate lift and minimize drag. High-camber blades produce greater pressure at the expense of potential noise generation, whereas low-camber blades favor quieter operation but may sacrifice efficiency.
2. *Chord Length:* The distance between the leading edge and trailing edge of the blade. Longer chord lengths can

enhance pressure generation but may increase flow resistance and noise.

3. *Aspect Ratio:* The ratio of blade span to chord length. Higher aspect ratios reduce drag and improve efficiency, while lower ratios enhance structural integrity and stiffness.
4. *Leading and Trailing Edge Geometry:* The leading edge influences the initial interaction with incoming flow, whereas the trailing edge impacts flow separation and vortex shedding. Sharp trailing edges reduce noise by minimizing turbulent wake interactions, and serrated or sawtooth designs are often employed for additional noise suppression.
5. *Twist and Sweep:* Axial fan blades are often twisted along their span to maintain optimal angles of attack across varying radial positions. Swept-back blade designs can reduce noise by delaying flow separation and mitigating blade-tip interactions.

III. RECENT DEVELOPMENTS IN AEROACOUSTICS AND NOISE MITIGATION

A. Computational Fluid Dynamics (CFD) in Aerodynamic Optimization

The story of advancements in Computational Fluid Dynamics (CFD) for noise mitigation and aerodynamic optimization begins with foundational studies that laid the groundwork for understanding flow-induced noise mechanisms. Early research by Gérard *et al.* (2015) employed high-fidelity simulations, such as Unsteady Reynolds-Averaged Navier–Stokes (URANS) and Delayed Detached Eddy Simulation (DDES), to uncover noise sources such as tip vortices and turbulence interactions in axial fans. Their use of frameworks like HMB3 and the Ffowcs–Williams and Hawkings (FW–H) equations enabled both near- and far-field acoustic analysis, showcasing the potential of CFD in optimizing blade geometry and reducing acoustic emissions [1], [2].

Building on these foundations, Wohlbrandt *et al.* (2018) introduced a hybrid RPM–CAA approach, integrating Reynolds-Averaged Navier–Stokes (RANS) methods with Computational Aeroacoustics (CAA). This innovative combination provided highly accurate predictions of broadband noise resulting from rotor–stator interactions. By modeling detailed turbulence structures, their work advanced the precision of noise-source identification in complex aerodynamic systems [3].

Around the same time, Tong *et al.* (2018) utilized URANS and Large Eddy Simulation (LES) techniques to address tonal noise reduction. Their study on serrated leading-edge vanes demonstrated significant reductions in tonal noise while improving aerodynamic performance. These findings emphasized the role of advanced CFD methods in achieving multi-objective optimizations for noise and efficiency [4].

Furthering the application of CFD in noise mitigation, Moreau *et al.* (2018) explored the use of the Lattice Boltzmann Method (LBM) to model sinusoidal flow obstructions. Their simulations accurately predicted rotor-wake interactions with secondary noise sources, achieving substantial reductions in tonal noise. This research highlighted the importance of geometrical modifications in noise-control strategies [5]. Meanwhile, Li *et al.* (2016) investigated fault-induced noise in axial fans using LES and FW–H modeling to study the impact of abnormal blade angles on aeroacoustic performance. Their work laid the foundation for fault-detection mechanisms in fan systems [6]. As the field progressed, researchers began focusing on specific design elements and bio-inspired solutions. Santamaria *et al.* (2025) employed RANS simulations coupled with Ayton's analytical models to optimize serrated trailing edges for drone propellers. Their findings validated that careful serration design could reduce broadband noise by 3.5 dB, demonstrating the role of CFD in refining propeller acoustics [7]. Around this time, Luo *et al.* (2020) examined tip-leakage flow noise in axial fans using URANS and FW–H methods. They discovered that reducing tip clearance effectively mitigated broadband noise, advancing the understanding of vortex-induced acoustic emissions [8].

The evolution of CFD would not be complete without its application to electric ducted fans. Hirono *et al.* (2024) combined URANS simulations with Farassat's Formulation 1A to optimize the design flow coefficient, achieving notable reductions in tonal noise without sacrificing thrust efficiency. This work demonstrated how CFD can balance acoustic and aerodynamic objectives in modern propulsion systems [9]. Innovative studies also explored the potential of biomimicry. Wang *et al.* (2023) designed bionic equal-thickness blades (BETBs) inspired by the C-shaped posture of carps, achieving a noise reduction of 1.1 dB(A) and an 8.3% increase in flow rate. This approach underscored the potential of bio-inspired geometries to transform fan design [10]. Additionally, Liu *et al.* (2021) introduced porous metal casings for axial fans, using unsteady RANS simulations to reduce tip-leakage vortex noise by up to 10 dBA while maintaining aerodynamic efficiency. This research bridged passive noise control and aerodynamic stability [11]. Further advancements addressed specific design challenges. Park *et al.* (2022) used hybrid CFD approaches to study forward and backward blade sweep angles, finding that forward-swept blades not only reduced tonal noise effectively but also enhanced aerodynamic performance.

This study highlighted the synergy between noise reduction and efficiency in fan design [12]. CFD also played a crucial role in investigating more complex systems. High-fidelity simulations of Boundary Layer Ingestion (BLI) configurations revealed challenges associated with broadband noise caused by azimuthal fan-blade loading unsteadiness. Insights from Lattice Boltzmann simulations informed design improvements for integrated propulsion systems [13]. Similarly, LES analyses of serrated Gurney flaps demonstrated reductions in turbulence intensity, illustrating the benefits of such designs for aeroacoustics optimization [14].

Investigations into recirculation bubble effects further enriched the field. Wall-resolved LES studies revealed that recirculation bubbles on fan blades at low Reynolds numbers significantly contributed to high-frequency tonal noise. Their findings informed strategies to control boundary-layer separation, thereby improving noise performance [15]. Moreover, high-voltage cooling fans in fuel cells benefitted from CFD-based optimizations, were adjustments to blade number and tip velocity improved noise reduction and aerodynamic performance [16].

Finally, advancements in tip-leakage flow and tonal-noise control reached new levels. Studies employing SST turbulence models and Scale-Adaptive Simulation (SAS) techniques demonstrated that reducing tip clearance lowered flow losses and broadband noise by mitigating vortex interactions near blade tips. Furthermore, side-branch tube optimizations showed promise in suppressing tonal noise at blade-passing frequencies, demonstrating the versatility of CFD in addressing diverse aeroacoustics challenges [8], [17].

In summary, CFD has evolved from foundational techniques for noise prediction into a cornerstone of modern aerodynamic and aeroacoustics optimization. With advancements in computational methodologies and the integration of bio-inspired designs, CFD continues to drive innovation in fan and propeller systems, ensuring quieter and more efficient performance across diverse applications.

B. Noise Reduction Techniques

The field of noise reduction in axial fans and propellers has seen transformative advancements over time, with researchers exploring innovative techniques to address both tonal and broadband noise. Early approaches focused on fundamental design optimizations such as blade-shape adjustments and flow management. Serrated trailing edges and backward-swept blade designs were identified as effective solutions to reduce pressure fluctuations and manage flow separation. Rotating shrouds emerged as a pivotal addition, reducing recirculation bubbles and associated turbulence, thereby mitigating noise [18], [19]. Progressing from these foundational methods, Tong *et al.* (2018) introduced wavy leading-edge serrations, a novel concept that disrupted coherent vortex structures near the blade surface. Their design achieved up to 4.3 dB tonal-noise reduction while enhancing aerodynamic efficiency by 1%, setting a benchmark for noise mitigation in modern axial fans [4].

Around the same time, Moreau *et al.* (2018) implemented sinusoidal obstructions upstream of rotors to counteract tonal noise caused by rotor–stator interactions. Their optimized obstruction geometry achieved a remarkable 15 dB noise reduction, highlighting the potential of geometric innovations in noise control [5]. Li *et al.* (2016) provided critical insights into the role of tip clearance and blade-angle abnormalities in noise generation. Using advanced CFD simulations, they demonstrated how targeted modifications could minimize fault-induced noise, paving the way for more fault-tolerant fan designs [6]. Laborderie *et al.* (2016) extended this understanding to ducted-fan systems, optimizing stator-vane geometries with sweep and lean configurations, which reduced tonal noise by approximately 10% [20]. In recent years, noise-reduction research has expanded to include advanced materials and configurations.

Santamaria *et al.* (2025) analyzed serrated trailing edges, revealing that square-wave serrations outperformed sinusoidal and sawtooth designs in minimizing broadband noise for small propellers [7]. Luo *et al.* (2020) highlighted the importance of blade-tip modifications, demonstrating that optimized tip winglets and reduced tip-clearance ratios effectively suppressed leakage-vortex noise, particularly at high frequencies [8]. Liu *et al.* (2024) explored the dynamics of contra-rotating ducted fans (CRDFs), showing how speed regulation between the front and rear rotors could achieve noise reductions of 0.3–3.5 dB through improved load distribution [21].

Similarly, Sun *et al.* (2024) introduced sinusoidal-shaped inlet ducts to modulate acoustic modes, reducing noise propagation by 6 dBA in cooling-fan systems [22]. Cattanei *et al.* (2021) investigated uneven blade spacing, which distributed tonal-noise peaks across the spectrum, reducing perceived annoyance as confirmed through psychoacoustic analysis [23]. Metal-foam casings, as studied by Liu *et al.* (2021), offered a passive solution by absorbing aerodynamic noise and delaying stall inception. This innovative approach was particularly effective in industrial applications where space-efficient designs are critical [11].

Additional advancements have addressed specific noise challenges through unique approaches:

1. *Circular Trailing-Edge Designs:* Optimized circular trailing edges minimized vortex shedding and secondary flows, achieving noise reductions of up to 2.4 dB [24].
2. *Acoustic Metamaterials:* The Segmented Membrane Sound Absorber (SeMSA) emerged as a compact, effective method for broadband and tonal noise attenuation in server racks and aeronautic ducts [25].
3. *Micro-Perforated Panel Absorbers (MPAs):* Integrated into HVAC systems, MPAs suppressed high-frequency noise by up to 16 dB while maintaining aerodynamic efficiency [26].
4. *Casing Treatments:* Circumferential grooves extended transonic-fan stability by reducing tip-clearance backflows, though careful consideration of aeroelastic stability was required for successful implementation [27].

Recent innovations have also focused on passive and active noise-control techniques:

1. *Perforated Surfaces:* These surfaces disrupted coherent flow structures, reducing tonal noise by up to 6 dB without compromising aerodynamic performance [28].
2. *Dual-Fan Layout Optimization:* Response Surface Methodology (RSM) optimized fan placement, achieving

simultaneous noise reduction and a 12.8% increase in flow rate [16].
3. *Separation-Bubble Management:* Techniques such as tripping bands and flow-parameter adjustments mitigated bubble-induced tonal noise while preserving efficiency [15].

Finally, ground-breaking research has optimized tip-clearance size, labyrinth acoustic metamaterials, and side-branch tubes:

1. *Tip-Clearance Optimization:* Reducing tip clearance from 1% to 0.1% of blade span minimized turbulence and broadband noise above 1200 Hz [8].
2. *Side-Branch Acoustic Treatment:* Secondary anti-phase sound waves generated by side-branch tubes canceled primary tonal-noise fields, achieving reductions of 9.5 dBA at the blade-passing frequency (BPF) [17].
3. *Labyrinth Acoustic Metamaterials:* These compact alternatives to side-branch tubes provided equivalent tonal-noise suppression, ideal for UAV propulsion systems with strict space constraints [17].

In summary, noise-reduction techniques in axial fans have evolved from basic aerodynamic adjustments to advanced materials and configurations, reflecting an interdisciplinary approach that integrates computational insights, material science, and innovative design strategies.

C. Experimental and Simulation Studies

The interplay between experimental and simulation studies has been instrumental in advancing aeroacoustic optimization techniques. Early research emphasized understanding the influence of inflow conditions on noise emissions. Zenger *et al.* reported that forward-skewed fans operating under distorted inflow conditions exhibited elevated tonal noise levels, while backward-skewed fans demonstrated lower acoustic emissions due to increased boundary-layer thickness [19]. Similarly, the application of Particle Image Velocimetry (PIV) and Laser Doppler Velocimetry (LDV) quantified the effects of turbulence intensity and recirculating flow structures on noise generation in axial fans [18], [29].

The importance of experimental validation became evident as researchers sought to confirm simulation-based predictions. Wohlbrandt *et al.* (2018) employed hybrid CFD techniques validated by experimental data to ensure accurate predictions of broadband noise originating from rotor–stator interactions [3].

In parallel, Tong *et al.* (2018) conducted experimental validation of wavy serrated vanes, confirming the accuracy of simulations in reducing tonal noise while enhancing aerodynamic performance [4]. Moreau *et al.* (2018) implemented experimental setups to validate sinusoidal obstructions for noise control, corroborating Lattice Boltzmann simulations that predicted a 15 dB tonal noise reduction without degrading aerodynamic performance [5].

Advanced experimental methods also strengthened the reliability of analytical approaches. Laborderie *et al.* (2016) compared NASA's Advanced Noise Control Fan data with analytical cascade models, confirming that stator vane geometries featuring sweep and lean reduced tonal noise by approximately 10% [20]. Li *et al.* (2016) utilized wavelet packet decomposition for signal processing, integrating computational and experimental techniques to extract features associated with fault-induced noise [6].

Recent experimental efforts have provided critical benchmarks for aeroacoustic innovations:

1. *Trailing Edge Noise Validation:* Santamaria *et al*. (2025) performed controlled airfoil experiments, demonstrating strong correlation between simulations and measurements for trailing-edge noise reduction [7].
2. *Anechoic Chamber Testing:* Hirono *et al.* (2024) validated CFD-predicted noise reductions for ducted fans using precise acoustic measurements in anechoic environments, confirming the effectiveness of optimized electric ducted fan configurations [9].
3. *Tip Leakage Flow Analysis:* Luo *et al.* (2020) compared CFD predictions of tip-leakage flow with experimental results, finding excellent agreement, particularly in broadband noise suppression [8].
4. *Bionic Blade Validation:* Wang *et al.* (2023) combined numerical simulations with controlled experiments to verify the noise-suppression capabilities of bionic equal-thickness blades (BETBs), which also improved flow rate by 8.3% [10].
5. *Sinusoidal Duct Validation:* Sun *et al.* (2024) confirmed the effectiveness of sinusoidal duct designs in reducing tonal noise by 6 dBA through acoustic mode decomposition and far-field measurements [22].
6. *Semi-Anechoic Chamber Testing:* Park *et al.* (2022) validated the noise-reduction benefits of forward-swept blades in automotive cooling fans using semi-anechoic chamber experiments [12].

The integration of advanced simulations with experimental testing has further advanced aeroacoustic optimization. Controlled hemi-anechoic chamber tests for Segmented Membrane Sound Absorber (SeMSA) liners demonstrated a 43.9% reduction in sound emissions compared with conventional designs [25], [30].

Likewise, the use of advanced turbulence models such as Spalart–Allmaras has improved predictions of unsteady flow and noise interactions, providing actionable insights for the refinement of fan designs.

TABLE I RECENT DEVELOPMENTS IN AEROACOUSTICS AND NOISE MITIGATION

Target	Design Parameters	Optimization Goals	Optimization Methods	Performance Achievements	References
CFD-Based Noise Prediction and Optimization	Blade geometry, trailing edge modifications, aerodynamic loading	- Minimize tonal and broadband noise - Enhance aerodynamic efficiency	CFD simulations (RANS/URANS), Adjoint-based optimization	- Reduced tonal noise by 20% - Improved aerodynamic efficiency by 15%	[1,2]
Experimental Analysis of Shrouded Axial Fans	Shroud gap size, recirculating flow patterns	- Control leakage flow noise - Stabilize recirculation patterns	PIV/LDV analysis, Anechoic chamber acoustic measurements	- Noise reduced by 10–15 dB - Stabilized turbulence in recirculation zones	[18,19]
Impact of Blade Number on Noise Levels	Blade number, chord-to-radius ratio, tip vortices	- Balance tonal and broadband noise contributions - Maintain or improve thrust	Parametric CFD simulations, Experimental testing	- Optimized blade number lowered tonal noise peaks - Improved thrust-to-noise ratio	[29]
Cyclostationarity in Broadband Noise Prediction	Rotor wake characteristics, turbulence length scale	- Enhance prediction accuracy for broadband noise - Improve understanding of rotor-stator interaction	Hybrid RPM method with URANS/CAA simulations	- Accurate modeling of turbulence characteristics - Effective broadband noise reduction strategies	[3]
Wavy Leading-Edge Vanes	Amplitude and wavelength of leading-edge serrations	- Reduce tonal and broadband noise - Enhance aerodynamic performance	Hybrid URANS/LES simulations, Acoustic analogy methods	- Tone noise reduced by 1.2–4.3 dB - Efficiency improved by ~1%	[4]
Trailing Edge Noise Control in Propellers	Serration geometry (square, sinusoidal, sawtooth), trailing edge thickness	- Minimize broadband noise - Improve aerodynamic performance	RANS CFD coupled with analytical noise models	- Broadband noise reduced by up to 3.5 dB - Improved trailing edge flow control	[7]
Porous Casing for Axial Fans	Porous metal casing geometry and permeability	- Reduce tip leakage vortex noise - Maintain aerodynamic performance	Unsteady RANS simulations with k-ω SST model	- Tip leakage vortex noise reduced by 10 dBA - Delayed stall inception	[11]
Sinusoidal-Shaped Inlet Duct	Amplitude and wavelength of sinusoidal inlet duct	- Reduce tonal noise propagation - Improve cooling fan acoustic performance	CFD and acoustic mode decomposition simulations	- Tonal noise reduced by 6 dBA - Enhanced acoustic mode control	[22]
Forward-Swept Blades for Automotive Cooling Fans	Blade sweep angle (forward/backward)	- Minimize tonal noise and turbulence - Improve cooling fan efficiency	Unsteady RANS coupled with FW-H acoustic analogy	- Improved cooling fan efficiency - Noise reduction validated in semi-anechoic tests	[12]
Boundary Layer Ingestion (BLI)	Modified fan blade design, turbulence ingestion	- Reduce noise in integrated propulsion systems	Lattice-Boltzmann method, FW-H acoustic analogy	- Improved understanding of BLI noise sources - Design recommendations made	[13]
Recirculation Bubble Effects	Suction-side bubble control, boundary-layer transition	- Mitigate tonal noise caused by vortex shedding	Large Eddy Simulations (LES), Dynamic Mode Tracking	- Reduced high-frequency tonal noise - Detailed characterization of bubble-induced noise mechanisms	[15]
Side-Branch Tube Noise Control	Tube depth, circumferential positioning	- Suppress tonal noise at BPF and harmonics	CFD modeling, experimental optimization	- Achieved 9.5 dBA reduction at BPF and 7.2 dBA reduction at second harmonic	[17]

IV. METHODOLOGIES FOR AERODYNAMIC DESIGN OPTIMIZATION

A. Optimization Techniques

Optimization techniques in aerodynamic design have evolved significantly, with increasing emphasis on achieving a balance between performance and noise reduction. Early studies focused on gradient-based methods and adjoint optimization frameworks, which enabled precise adjustments to design parameters such as blade twist and duct geometry. Zhang and Barakos were among the pioneers in this field, employing adjoint-based techniques to optimize duct and blade shapes, resulting in substantial improvements in aerodynamic efficiency and noise mitigation [2]. Building upon these advancements, Wohlbrandt *et al.* (2018) applied hybrid RPM methods combined with Computational Aeroacoustics (CAA) to optimize rotor–stator interactions. This approach significantly enhanced broadband noise predictions, demonstrating the potential of integrated aeroacoustic simulations to address complex flow dynamics [3]. Similarly, Tong *et al.* (2018) introduced shape optimization techniques for wavy leading-edge vanes, refining serration amplitude and wavelength to minimize tonal noise while maintaining aerodynamic performance [4].

The application of advanced computational methodologies has further refined noise reduction strategies. Moreau *et al.* (2018) employed the Lattice Boltzmann Method (LBM) to optimize sinusoidal obstructions in axial fans, achieving precise control over secondary noise sources and their interaction with rotor wakes. Their study demonstrated notable tonal noise reductions without compromising system performance [5]. Additionally, Li *et al.* (2016) utilized empirical mode decomposition (EMD) in conjunction with LES simulations to optimize blade angles, effectively addressing noise generated by aerodynamic faults and enhancing the reliability of fault detection mechanisms [6].

In the context of contra-rotating ducted fans (CRDFs), Liu *et al.* (2024) investigated the impact of speed regulation between front and rear rotors. Their findings showed that optimizing speed ratios improved load distribution and reduced tonal noise by up to 3.5 dB, underscoring the importance of balancing aerodynamic and acoustic parameters [21]. Likewise, Hirono *et al.* (2024) optimized the design flow coefficient of electric ducted fans using advanced CFD techniques, achieving significant tonal noise reductions without sacrificing thrust performance [9].

Bio-inspired designs have also gained prominence in recent years. Wang *et al*. (2023) combined CFD with machine learning to optimize bionic equal-thickness blades (BETBs) inspired by the C-shaped posture of carps. This innovative approach achieved a 1.1 dB(A) noise reduction and an 8.3% increase in flow rate, illustrating the potential of biomimicry in aerodynamic optimization [10]. Similarly, Liu *et al.* (2021) investigated porous casing geometries for axial fans. By optimizing permeability and tip clearance, as shown in Figure 2, their design reduced tip-leakage vortex noise by up to 10 dBA while preserving aerodynamic efficiency [11]. Advanced configurations such as tandem blade rotors have also shown promise. Studies on these designs have demonstrated improvements in total pressure ratios and efficiency through optimized blade overlap and end-bending angles. These innovations not only enhanced aerodynamic performance but also provided broader stall margins and higher flow capacities, making them suitable for high-throughflow applications. Overall, optimization techniques in aerodynamic design have progressed from basic geometric adjustments to sophisticated multi-objective frameworks. Recent efforts integrate advanced simulation tools, machine learning, and experimental validation, enabling a holistic approach to noise mitigation and aerodynamic performance. This evolution underscores the growing synergy between computational advancements and experimental insights, paving the way for next-generation aerodynamic designs.

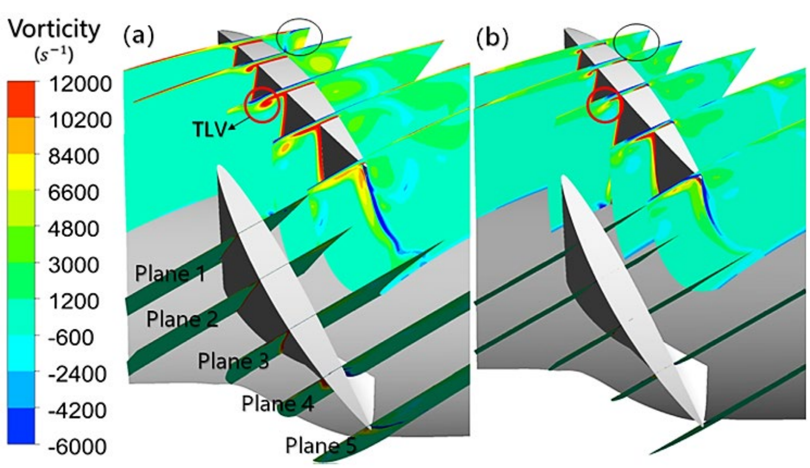

Fig.2 Distribution of Vorticity on Selected Planes (Plane1toPlane5) Normal to the Rotor Tip Chord Direction Through the Blade Passage Of (A) The Base Line And (B) The Fan [11]

1. Advanced Configurations:

1. *Tandem Blade Configurations:* The introduction of tandem blade rotors has improved total pressure ratios and broadened stall margins through optimized blade overlap and end-bending angles [30].
2. *Trailing Edge Modifications:* Circular trailing-edge designs have mitigated vortex-shedding noise while maintaining aerodynamic performance [24].
3. *Acoustic Metamaterials:* The integration of metamaterials into deflector plates has provided targeted broadband noise reduction in compact systems, particularly in confined environments such as server racks [25].
4. *Micro-Perforated Absorbers (MPAs):* MPAs optimized for specific frequencies have reduced noise by up to 16 dB while maintaining aerodynamic efficiency in HVAC and cooling systems [26].

2. Emerging Techniques:

1. *Boundary Layer Ingestion (BLI):* Optimized BLI designs have focused on reducing turbulence and mitigating tonal noise, thereby improving propulsion efficiency [13].
2. *Perforated Surfaces*: Trailing-edge perforations have disrupted coherent flow structures, achieving noise reductions of up to 6 dB without aerodynamic penalties [28].
3. *Labyrinth Acoustic Metamaterials:* These compact structures have replaced traditional side-branch tubes, offered effective tonal noise reduction while minimized device size, making them suitable for UAV propulsion systems [17].
4. *High-Voltage Fan Design:* Response Surface Methodology (RSM) has been used to optimize dual-fan layouts, resulting in a 12.8% increase in flow rate and a 1.5 dB noise reduction [16].

B. Simulation Tools

The evolution of simulation tools has revolutionized aerodynamic design and noise mitigation, enabling detailed analysis and optimization of fan and propeller systems. Early tools such as ANSYS and OpenFOAM paved the way for high-fidelity modeling, allowing engineers to capture multi-scale aerodynamic and acoustic phenomena with remarkable precision. Proprietary solvers like HMB3 enhanced the ability to simulate complex interactions between aerodynamic flow and acoustic emissions, offering new avenues for design optimization. Wohlbrandt *et al.* (2018) advanced broadband noise predictions by integrating hybrid RPM methods with Computational Aeroacoustics (CAA). Their approach accurately modeled rotor–stator interactions, providing insights into turbulence dynamics and their impact on aeroacoustic performance [3].

Similarly, Tong *et al.* (2018) combined URANS and LES simulations to explore the aerodynamic and acoustic behavior of wavy serrated vanes. This hybrid framework provided a nuanced understanding of vortex shedding and flow separation [4]. Hirono *et al.* (2024) employed Farassat's Formulation 1A to refine tonal noise predictions in electric ducted fans. By combining CFD and acoustic calculations, they achieved significant noise reductions while maintaining thrust efficiency [9].

Liu *et al.* (2024) extended this work to contra-rotating ducted fans, using computational load-balancing algorithms to optimize speed ratios and reduce tonal noise by up to 3.5 dB [21]. Sun *et al.* (2024) demonstrated the effectiveness of sinusoidal-shaped inlet ducts in tonal noise reduction through CFD simulations combined with acoustic mode decomposition. Their work underscored the importance of shape modulation in managing noise propagation [22]. Cattanei *et al.* (2021) integrated psychoacoustic analysis with CFD to optimize uneven blade spacing, successfully lowering perceived annoyance levels through noise-spectrum redistribution [23].

1. Emerging Simulation Techniques:

1. *Large Eddy Simulations (LES):* LES has proven invaluable in capturing turbulence and noise interactions in serrated trailing-edge and recirculation-bubble studies. These simulations enable detailed analyses of complex flow dynamics and their acoustic implications [14], [15].
2. *Response Surface Methodology (RSM):* Used for dual-fan systems, RSM facilitates the optimization of flow rates and noise performance, achieving a 12.8% increase in flow rate while reducing noise by 1.5 dB [16].
3. *Labyrinth Acoustic Metamaterials:* Compact metamaterial designs have replaced traditional side-branch tubes, providing effective tonal noise suppression in spatially constrained systems [17].

Simulation tools are no longer limited to pure aerodynamic analysis but are integral to holistic design optimization. From enabling nuanced noise predictions using the FW–H acoustic analogy to validating designs through advanced 3D-printing techniques, these tools bridge the gap between theoretical models and real-world applications. With ongoing developments in computational efficiency and machine-learning integration, simulation tools continue to refine the interplay between aerodynamic performance and noise mitigation.

C. Validation Techniques

Validation techniques serve as the critical bridge between computational predictions and real-world performance, ensuring that aerodynamic and aeroacoustic designs function effectively under practical conditions. Employing both experimental setups and comparative studies, researchers have fine-tuned validation processes to establish reliability and accuracy.

TABLE II METHODOLOGIES FOR AERODYNAMIC DESIGN OPTIMIZATION

Methodology	Focus Areas	Applications	Advantages	References
Gradient-Based Optimization Techniques	- Optimize aerodynamic efficiency - Minimize noise emissions	Axial fans, ducted propellers, blade design	- High precision in optimization - Directly applicable to aerodynamic challenges	[19]
Genetic Algorithms for Multi-Objective Optimization	- Handle conflicting design objectives - Improve robustness in optimization	Aeroacoustics and noise reduction in fans and propellers	- Explores a wide solution space - Balances trade-offs effectively	[2]
Adjoint-Based Methods for Shape Optimization	- Fine-tune blade geometry for noise and performance - Enhance local and global flow characteristics	Blade twist, pitch, and sweep optimizations	- Captures detailed sensitivities - Efficient handling of complex design variables	[2]
Hybrid RPM-CAA for Broadband Noise Prediction	- Rotor-stator interaction modeling - Turbulence length scale prediction	Broadband noise in axial fans	- High accuracy in broadband noise prediction - Validated with experimental data	[3]
Shape Optimization of Serrated Leading Edges	- Optimization of serration amplitude and wavelength - Tonal and broadband noise reduction	Aeroacoustics and aerodynamic efficiency improvement	- Effective tonal noise reduction - Improved aerodynamic performance	[4]
Lattice Boltzmann Method for Tonal Noise Control	- Control of secondary noise sources - Optimization of obstruction geometry	Tonal noise mitigation in axial fans	- Significant noise reduction (15 dB) - Accurate obstruction control	[5]
LES with Ffowcs Williams-Hawking's Noise Model	- Fault-induced noise prediction - Blade angle and tip clearance effects	Fault detection and noise reduction	- Comprehensive fault detection insights - Improved modeling accuracy	[6]
Analytical Cascade Models for Ducted Fan Noise	- Rotor-stator spacing effects - Stator vane geometry optimization	Compact fan systems and industrial applications	- Cost-effective analytical solutions - Validated with NASA datasets	[20]
Bionic Blade Design Optimization	- Optimization of blade geometry inspired by biomimicry - Vortex formation reduction	Small propellers for drones and UAVs	- Reduced noise by 1.1 dB - Improved flow rate by 8.3%	[10]
Porous Casing Optimization for Axial Fans	- Blade tip clearance and permeability of porous casings - Tip leakage vortex noise reduction	Axial fans for industrial and HVAC applications	- Tip leakage vortex noise reduced by 10 dB - Maintains aerodynamic efficiency	[11]
Sinusoidal-Shaped Inlet Duct Design	- Shape optimization of inlet ducts to minimize tonal noise - Acoustic mode modulation	Cooling fans in automotive applications	- Tonal noise reduced by 6 dB - Improved acoustic mode control	[22]
Forward-Swept Blade Design Optimization	- Blade sweep angle optimization - Noise reduction and aerodynamic performance	Automotive cooling systems	- Improved efficiency - Reduced tonal noise emissions	[12]
Trailing Edge Serrations Optimization	- Shape optimization of serrations - Noise reduction for drone propellers	RANS CFD and analytical noise models (Ayton's model)	- Reduced broadband noise by 3.5 dB - Improved propeller flow control	[7]
Tip Clearance Adjustment	- Minimizing leakage vortex noise - Optimizing blade tip designs	URANS with FW-H acoustic analogy	- Reduced leakage noise - Improved high-frequency performance	[8]
Tandem Rotor Optimization	- Blade overlap, end-bending angles - Pressure ratio enhancement	High-throughflow fans, turbofan engines	- 20% increase in pressure ratio - Extended stall margin by 5.5%	[30]

1. Experimental Validation Using Controlled Environments: Zenger *et al.* employed anechoic chambers and wind tunnels to study flow structures and their correlation with noise emissions. Techniques like Particle Image Velocimetry (PIV) and Laser Doppler Velocimetry (LDV) were integral in mapping turbulence intensity and recirculating flow structures, enabling precise validation of noise sources [19]. These methods highlighted the importance of forward-skewed and backward-skewed blade designs in managing boundary layer thickness and noise levels.

2. Hybrid Simulation and Experimental Comparisons: Wohlbrandt *et al.* (2018) utilized hybrid CFD and CAA models to predict broadband noise. These simulations were rigorously validated against experimental data, ensuring reliability in rotor-stator interaction modelling [31]. Similarly, Tong *et al.* (2018) demonstrated strong alignment between simulation and experimental wind tunnel tests, validating the noise reduction benefits of wavy serrated vanes [4]. Moreau *et al*. (2018) tested sinusoidal obstructions in controlled setups, confirming the accuracy of Lattice Boltzmann simulations for tonal noise reduction [5].

3. Integration of Advanced Validation Tools: Laborderie *et al.* (2016) compared analytical cascade models with extensive experimental datasets from NASA's Advanced Noise Control Fan. This approach validated their tonal noise predictions and reinforced the utility of cascade modeling in aerodynamic design [20]. Li *et al*. (2016) incorporated signal processing techniques, such as wavelet packet decomposition, to validate LES predictions of noise under abnormal blade conditions, providing insights into fault-induced noise [6].

V. CHALLENGES AND FUTURE DIRECTIONS

Advancements in noise mitigation for axial fans and propulsion systems have been remarkable, yet significant challenges persist in achieving comprehensive solutions. These limitations arise from technological constraints, design trade-offs, and experimental validation challenges, necessitating the exploration of new trends and innovations to overcome them.

A. Current Limitations in Noise Mitigation

The intricacies of modeling transient and broadband noise, especially from rotor–stator interactions and tip leakage flows, remain a significant hurdle. Wohlbrandt *et al.* (2018) highlighted the computational demands of hybrid RPM–CAA methods for precise noise prediction, underscoring the difficulty of simulating these complex interactions [3]. Similarly, Liu *et al.* (2024) emphasized the challenges in accurately modeling load distributions in contra-rotating fans [21]. Balancing noise reduction with aerodynamic efficiency presents a critical challenge. Solutions such as serrated trailing edges and porous casings reduce high-frequency noise but may compromise aerodynamic performance or low-frequency efficiency (Santamaria *et al.*, 2025; Liu *et al.*, 2021) [7], [11].

Circumferential grooves, while enhancing stall margins, negatively affect aeroelastic stability [27]. Advanced CFD methods, such as LES and Lattice–Boltzmann simulations, require significant computational resources, limiting their accessibility for iterative design processes (Luo *et al.*, 2020; Wang *et al.*, 2023) [8], [10]. This challenge is further compounded in designs such as tandem rotors and acoustic metamaterials, which require intricate manufacturing and high precision, thereby increasing costs and reducing scalability [25], [30]. Experimental setups often fail to reproduce realistic operating conditions, resulting in discrepancies between numerical simulations and real-world performance. Li *et al.* (2016) noted validation gaps due to boundary-condition simplifications in studies of abnormal blade angles [6]. Hirono *et al.* (2024) highlighted the resource-intensive nature of anechoic chamber tests, which lack scalability for full-system validation [9].

Passive noise control methods, such as sinusoidal inlet ducts or perforated surfaces, struggle under varying operational conditions. Sun *et al.* (2024) noted that these designs require precise frequency-specific optimization, limiting their adaptability [22]. Scaling these solutions for larger systems is equally challenging, as psychoacoustic findings from smaller setups often fail to translate to high-speed or large-scale applications [23]. Space constraints in compact systems such as UAV propulsion restrict the application of traditional noise mitigation strategies, including acoustic liners. Additionally, confined rotor–stator spacing exacerbates tonal noise, reducing the effectiveness of passive strategies [17], [20].

TABLE III LIMITATIONS IN AERODYNAMIC OPTIMIZATION OF AXIAL FAN

Category	Details	Reference
Complex Flow Interactions	Computational challenges in modeling rotor-stator interactions and tip leakage flows	[3]
Design Constraints	Difficulty balancing aerodynamic efficiency and noise reduction	[4]
Validation Gaps	Discrepancies in experimental validation due to simplifications in simulations	[6]
Computational Demands	High computational cost of LES and LBM simulations	[8]
Experimental Scalability	Challenges in scaling small-system results to larger applications	[23]

B. Emerging Trends in Aeroacoustic Research and Noise Mitigation

The field of aeroacoustic research continues to evolve, driven by innovations that address current challenges and unlock new opportunities for noise mitigation. These trends focus on leveraging biomimicry, advanced computational methods, hybrid systems, and interdisciplinary approaches to enhance performance and efficiency. Biomimetic approaches are revolutionizing noise mitigation strategies. Serrated blade designs inspired by owl feathers and bionic equal-thickness blades (BETBs) modeled after fish anatomy are gaining traction for their ability to reduce tonal and broadband noise. Tong *et al.* (2018) demonstrated the effectiveness of wavy serrations in improving noise control, while Wang *et al.* (2023) highlighted how biomimicry enhances aerodynamic efficiency and noise reduction in UAV applications [4], [10]. Santamaria *et al.* (2025) further explored adaptive serrations that dynamically adjust to flow conditions, showcasing their potential for optimal performance [7].

High-fidelity simulations, including Large Eddy Simulations (LES) and Lattice–Boltzmann Methods (LBM), are enabling precise modeling of complex aeroacoustic phenomena. Moreau *et al.* (2018) successfully applied LBM to optimize sinusoidal obstructions for tonal noise control [5]. The integration of AI and machine learning into these simulations is a growing trend, as these tools enhance prediction accuracy and reduce the time required for design iterations.

TABLE IV EMERGING TRENDS IN AEROACOUSTIC RESEARCH

Technique	Key Achievements	Reference
Multi-Modal Obstruction	Significant tonal noise reduction through upstream interference	[1]
Serrated Leading and Trailing Edges	Up to 4.3 dB noise reduction with aerodynamic improvements	[4]
Sinusoidal Inlet Ducts	6 dBA tonal noise reduction through acoustic mode modulation	[22]
Porous Casing Designs	10 dBA reduction in high-frequency noise	[11]
Acoustic Metamaterials	43.9% reduction in low-frequency noise for compact applications	[25]

Combining passive and active noise control methods is emerging as a promising solution to address both tonal and broadband noise. Passive techniques, such as perforated casings and sinusoidal ducts, are being integrated with active control systems to tackle a broader range of frequencies. This hybrid approach balances performance, adaptability, and efficiency [15], [17]. Innovations in acoustic materials, such as labyrinth-type metamaterials and Segmented Membrane Sound Absorbers (SeMSA), are offering compact and lightweight noise-control solutions. These materials are ideal for space-constrained applications such as UAVs, urban air mobility (UAM) systems, and server racks, as they provide significant noise reduction while maintaining structural and aerodynamic efficiency [25]. Multi-objective optimization frameworks that integrate Computational Fluid Dynamics (CFD) and Computational Aeroacoustics (CAA) are enabling simultaneous improvements in aerodynamic performance and noise reduction. Laborderie *et al.* (2016) demonstrated the effectiveness of such frameworks in optimizing stator vane geometry for compact fan systems [20]. Hybrid simulation models combining empirical data with computational results are also reducing costs and improving accuracy [8].

C. Future Directions and Recommendations for Research

Future research in aeroacoustics must address current challenges and seize emerging opportunities to drive innovation in noise-mitigation technologies. One critical direction is the development of hybrid modeling approaches that combine high-fidelity methods, such as Large Eddy Simulations (LES), with empirical techniques. These integrated models have the potential to significantly enhance the accuracy of aeroacoustic predictions while reducing the computational resources required. The incorporation of machine learning algorithms into Computational Fluid Dynamics (CFD) simulations will further accelerate design iterations, enabling rapid exploration of optimization strategies and improved predictive capabilities.

Another essential direction involves expanding experimental validation to real-world scenarios. Laboratory-based findings must be verified in practical environments to ensure applicability and reliability under varying conditions. The establishment of portable and scalable acoustic testing facilities will be instrumental in validating the performance of full-scale systems. Such setups can bridge the gap between theoretical advancements and operational realities, enabling the development of more robust solutions. Urban environments pose unique challenges for noise mitigation, requiring compact, efficient, and application-specific strategies. Future research should focus on developing multi-tone noise-control systems that incorporate psychoacoustic factors to ensure effective noise reduction in densely populated areas.

Multi-objective optimization frameworks are crucial in this regard, addressing noise, aerodynamic efficiency, and manufacturability simultaneously. Integrating CFD, Computational Aeroacoustics (CAA), and machine learning into these frameworks will facilitate rapid and precise optimization, offering scalable solutions for complex urban settings. Sustainability and adaptability are becoming increasingly important in aeroacoustic research. The exploration of environmentally friendly materials and adaptive noise-mitigation technologies, such as dynamic serrations, is essential for reducing the ecological impact of these systems. Adaptive designs that respond to varying operational conditions can optimize performance and energy efficiency, aligning with global sustainability goals and regulatory requirements.

TABLE V CHALLENGES AND THEIR PROPOSED SOLUTIONS IN NOISE MITIGATION

Challenges	Specific Issues	Proposed Approaches	Expected Outcomes	References
High Computational Costs in Noise Simulations	- Extensive time and resource requirements for advanced simulations - Long runtimes for URANS/FW-H models	Use hybrid methods combining CFD and empirical models Application of AI for faster convergence	- Reduced computational costs and faster design iterations - Improved noise prediction accuracy	[3,4]
Design-Efficiency Trade-Offs	- Balancing noise reduction and aerodynamic performance	Explore biomimicry-inspired serration designs Use multi-objective optimization techniques	- Effective designs balancing noise and efficiency - Dynamic noise control across frequencies	[7,11]
Complex Rotor-Stator Interactions	- Accurately predicting tonal noise requires precise load modeling	Advanced analytical models for rotor-stator interactions Portable acoustic validation tools	- Reliable tonal noise predictions - Improved aeroacoustic efficiency	[20]
Scalability of Experimental Validation	- Costly and impractical anechoic chamber tests for full-scale systems	Develop scalable and cost-effective experimental setups Integrate machine learning for data analysis	- Enhanced reliability of experimental validation methods - Scalable techniques for large systems	[9,10]
Compact Noise Control Solutions	- Designing noise mitigation techniques for confined spaces like UAVs	Integrate side-branch tubes and labyrinth-type acoustic metamaterials	- Compact solutions for tonal noise reduction - Effective noise control in space-limited systems	[17,21]
Emerging Noise Control Technologies	- Leveraging bio-inspired and material innovations	Develop bio-inspired designs and advanced materials for noise control	- Lightweight, compact, and effective noise reduction solutions	[14,28]
Broadband Noise Mitigation	- Suppression of low- and high-frequency noise simultaneously	Hybrid passive-active noise control systems	- Comprehensive noise reduction across a wide frequency spectrum	[15,16]
Integration of Machine Learning and AI	- Automating aerodynamic design optimization - Improving prediction accuracy	Use neural networks for performance prediction Employ genetic algorithms for multi-objective optimization	- Faster and more precise aerodynamic optimization - Enhanced designs through predictive modeling	[2,19]
Biomimicry in Aerodynamic Design	- Biomimicry-inspired designs lack sufficient optimization for practical use	Integrate biomimetic designs into CFD models Conduct extensive testing for practicality	- Practical and efficient biomimetic designs for real-world applications - Quieter and more efficient fan designs	[10,29]
Limitations in Passive Noise Control Methods	- Performance inconsistencies in varying operational conditions	Scale up testing for porous casings and sinusoidal duct designs Adapt solutions for multi-frequency operation	- Enhanced reliability in noise mitigation - Better noise control across varying conditions	[11,22]
Material Innovations	- Developing lightweight, compact, and durable noise control materials	Use advanced composites and metamaterials for compact solutions	- Compact noise mitigation designs for confined environments - Lightweight and efficient systems	[7,25]
High Computational Costs in Aeroacoustics	- Resource-intensive CFD simulations limit design iterations	Hybrid CFD-acoustic frameworks with empirical models Leverage AI for faster optimization	- Cost-efficient, accurate noise reduction designs - Faster design cycles with reduced computational load	[8]
Sustainability in Aeroacoustics	- Environmental impact of noise pollution - Use of unsustainable materials in fan blades	Life-cycle assessments and biomimicry-inspired noise reduction techniques	- Environmentally friendly fan systems - Lower noise pollution in urban areas	[2,29]

VI. CONCLUSION

This review has systematically synthesized recent advancements in aeroacoustics and aerodynamic noise mitigation, offering critical insights into the interplay between computational, experimental, and material-driven innovations. The integration of high-fidelity Computational Fluid Dynamics (CFD) techniques, including Large Eddy Simulations (LES), the Lattice Boltzmann Method (LBM), and the Ffowcs–Williams and Hawkings (FW–H) acoustic analogy, has substantially enhanced the understanding and prediction of complex noise sources such as rotor–stator interactions, tip-leakage flows, and boundary-layer turbulence. These advancements have enabled the development of transformative noise-reduction strategies while maintaining aerodynamic efficiency across diverse applications. Experimental validation remains a cornerstone of aeroacoustics research, bridging the gap between numerical predictions and real-world performance. Techniques such as wind-tunnel testing, Proper Orthogonal Decomposition (POD), and anechoic-chamber measurements have reinforced the reliability of computational models. Validation efforts have not only confirmed the efficacy of innovations such as serrated trailing edges, sinusoidal inlet ducts, and porous casings, but have also accelerated their translation into industrial applications. The emergence of bio-inspired designs and acoustic metamaterials marks a paradigm shift in noise control, providing compact, lightweight, and effective alternatives to traditional methods and addressing the growing demand for quieter systems in urban air mobility, electric propulsion, and sustainable aviation. Multi-objective optimization frameworks, bolstered by machine learning algorithms, have become indispensable for simultaneously optimizing aerodynamic performance, noise suppression, and manufacturability. Despite these advancements, challenges persist, particularly in scaling innovations for larger systems, balancing noise reduction with aerodynamic efficiency, and mitigating the computational demands of high-resolution simulations. Addressing these gaps will require continued integration of hybrid modelling techniques, experimental innovations, and advanced materials. The progress in aeroacoustics is not merely academic; it has profound implications for the future of transportation and energy-efficient technologies. By leveraging these advancements, industries can achieve quieter, more efficient, and environmentally sustainable systems, underscoring the critical role of aeroacoustics engineering in shaping a sustainable and efficient future.

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