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Biomimetic Airfoils in Wind Turbine Design: Innovations in Noise Mitigation and Aeroacoustic Performance Inspired by Avian Morphology

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ABSTRACT

Wind turbines are a cornerstone of sustainable energy systems, yet their widespread adoption is often hindered by the aerodynamic noise generated by their blades, impacting both human settlements and wildlife. This review explores the emerging role of biomimicry in wind turbine airfoil design, with a particular focus on avian-inspired adaptations for aeroacoustic optimization. Drawing inspiration from owls and other silent-flying birds, features such as serrated leading and trailing edges, porous coatings, and flexible surfaces are examined for their ability to disrupt vortex shedding and stabilize boundary layers, leading to significant reductions in both tonal and broadband noise.

Experimental and numerical studies have demonstrated sound pressure level reductions of 2–10 dB, with certain optimized designs achieving even greater attenuation at specific frequencies. This paper critically reviews the aerodynamic mechanisms, computational modeling techniques, and fabrication strategies used to implement these biomimetic features, while addressing the performance trade-offs and structural challenges involved in full-scale turbine integration. By synthesizing current research and identifying future opportunities, including advanced materials and additive manufacturing. The review highlights how nature-inspired solutions can enable the next generation of quieter, more efficient, and ecologically harmonious wind energy systems.

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الجنيحات الهوائية المستوحاة بيولوجياً في تصميم شفرات توربينات الرياح: ابتكارات في الحد من الضوضاء وتحسين الأداء الصوت- هوائي المستلهمة من الطيور

ياسين القمش، كنزة بوشعالة، أشرف علي عمر، وفاء لحميلي .

ملخص: تُعدّ توربينات الرياح من أهم مصادر الطاقة المتجددة، إلا أن انتشارها الواسع يواجه تحديات مرتبطة بالضوضاء الهوائية الناتجة عن تفاعل الشفرات مع تدفق الهواء. تستعرض هذه الدراسة إمكانات التصميمات المستوحاة من الطبيعة، خصوصاً من أجنحة الطيور ذات الطيران الصامت مثل البوم، في الحد من الضوضاء وتحسين الخصائص الصوت–هوائية. وتشمل هذه الابتكارات الحواف المشرشرة، والأسطح المسامية، والبنى المرنة، التي تعمل على تعديل طبقة الحدود وتقليل الاضطرابات المسؤولة عن الضوضاء. كما يتناول البحث تحليلاً رقمياً وتجريبياً لفعالية هذه التصاميم، إضافة إلى مناقشة التحديات المرتبطة بتطبيقها على توربينات الرياح كبيرة الحجم. وتؤكد النتائج أن دمج هذه الحلول البيوميتيكية يوفر إمكانية تطوير شفرات أكثر هدوءاً وكفاءة، مما يعزز قبول استخدامها في البيئات السكنية والطبيعية.

الكلمات المفتاحية – الصوتيات الهوائية، الرياح، الرقائق الهوائية، الشفرات البيوميتيكية، الحد من الضوضاء، التصميم المستوحى من الطبيعة، المحاكاة العددية.

1. INTRODUCTION

The integration of wind energy as a dependable source of electricity has marked a significant stride in meeting the growing demands of both domestic and industrial sectors [1], [2], [3] . Its reliability is complemented by the strategic placement of wind turbines in close proximity to human settlements and natural habitats. However, the resulting noise pollution presents a substantial challenge, impacting both wildlife and human environments, thereby limiting the acceptance of wind energy systems [4] [5]. Conventional airfoil designs, although effective at generating lift and reducing drag, fail to adequately address aeroacoustic challenges such as leading-edge noise, trailing-edge turbulence and the wake, which are primary contributors to turbine noise. As such, researchers have turned to nature, particularly avian wings, as a source of inspiration for bio-inspired airfoil designs. The distinct characteristics of bird wings, such as serrated leading and trailing edges, porous surfaces, and flexible morphologies, have evolved over millions of years to enable silent flight while maintaining efficient aerodynamic performance. These adaptations offer a natural blueprint for passive noise reduction through flow control mechanisms, demonstrating the potential for reduced noise generation in wind turbines. Despite these promising characteristics, traditional airfoil designs have struggled to incorporate these features effectively, creating gaps in their ability to balance noise mitigation with aerodynamic efficiency. This review explores the application of bio-inspired airfoil designs for wind turbine noise reduction and aerodynamic optimization. It provides a comprehensive synthesis of recent advances in bio-inspired geometries, focusing on serrated edges, wavy leading-edge profiles, and porous surfaces, and evaluates their performance in terms of noise reduction and aerodynamic trade-offs. Furthermore, the review identifies critical gaps in current designs, particularly in scaling bio-inspired features to full-size turbines and addressing cost and durability considerations. Additionally, it proposes future research directions to facilitate the practical implementation of bio-inspired airfoils in the wind energy industry. By leveraging nature's elegantly optimized solutions, bio-inspired airfoil designs offer a promising pathway to overcoming one of wind energy's most persistent challenges—noise pollution—thereby enabling a more sustainable and socially acceptable deployment of wind energy systems.

Wind turbine noise is predominantly generated by aerodynamic interactions between the air and the turbine blades [6] [7]; it is the result of the interaction of unsteady fluid flow with an airfoil surface, involving various mechanisms. Leading edge noise manifests from the interaction of upstream turbulent flow with the airfoil's leading edge. Trailing edge noise is further categorized into broadband noise, generated when boundary layer turbulence interacts with the sharp trailing edge, and blade passage noise, produced by either vortex shedding or an aeroacoustics feedback loop [8]. Conventional airfoil designs, though efficient, encounter limitations in managing these phenomena [9]. To overcome these challenges, researchers have turned their attention to bird wings as a key inspiration source, to their airfoils, blades and wings seeking to leverage the natural adaptations observed in avian wings as an efficient approach to reduce noise in wind turbine blades. One promising approach involves bio-inspired or bird-inspired airfoils that emulate key characteristics found in bird wings. The natural features seen in bird wings, which have developed over millions of years to be extremely effective and silent during flight, serve as the blueprint for these biomimetic designs [10] [11] [12]. Bird wings are distinguished by their distinct airfoil shape, which consists of a thick leading edge, a narrow aft section, and a strongly cambered nature [13] [14] [15]. These features have a major impact on the force that bird wings generate overall. By actively adjusting the wings' outline, curvature, and flexibility, bird wings may efficiently produce lift, drag, and thrust [16] [17] [18]. For instance, swifts can stretch their wings to produce more lift during high-speed flight and increase sweep to generate reduced drag during low-speed flight or landing [10] [19]. Researchers have also explored the effect of using leading-edge serrations and surface ridges inspired by owl wings [20] [21], in an attempt to mimic their silent flight. Way back in 1934, Graham [22] identified three key features of owl wing feathers that allow for their stealth in the air - a wavy leading edge, fine trailing edge fringes, and a porous velvety upper surface coupled with a downy underside and thick feathering on the legs [23] [24]. He concluded these attributes prevented noise generation during gliding and flapping, unlike other birds, which would alert prey from their 3-6-meter-high perches within the short one-second flight time before capture [22]. The leading-edge serrations and surface ridges on owl wings have been found to reduce aerodynamic noise by changing the streamwise vortices [25] [26], resulting in the division of the large-scale tubular vortices into smaller horseshoe-shaped vortices with regularity. This change in vortex dynamics leads to sound pressure level reduction [27]. Moreover, researchers have explored the porous surface of bird wings as a potential means to reduce noise [28] [29]. When it comes to aerodynamics, specially designed bird-like airfoils meant to operate at the low Reynolds numbers typical of avian flight have shown promising results [30] [31] [32]. These bio-inspired airfoils excel at generating high lift coefficients, overcoming issues like the laminar separation bubble that normally cause significant efficiency losses in viscous flow regimes [33]. By mimicking the aerodynamic traits of birds, these innovative airfoil designs offer a compelling solution to one of wind energy's most persistent challenges – reducing turbulence-induced noise pollution. Quieter wind turbines could make this renewable energy source even more environmentally friendly. Therefore, this review examines the application of bio-inspired airfoil designs for wind turbine noise reduction. It begins by exploring biomimetic airfoil construction techniques, focusing on methods for translating avian wing geometries into practical designs. It then analyzes specific bio-inspired features like serrated edges, their noise reduction mechanisms, and implementation strategies. The review evaluates the numerical methods used in aerodynamic and aeroacoustic simulations, followed by an assessment of the trade-offs between noise reduction and aerodynamic performance. A literature benchmark compares noise reduction achievements across various bio-inspired designs. Finally, the article discusses the challenges of applying these concepts to full-scale wind turbines, addressing scalability and system-level considerations. This comprehensive approach aims to provide insights into the current state and future potential of bio-inspired airfoils in wind turbine noise mitigation.

2. BIO-INSPIRED AIRFOIL DESIGN AND MODELING TECHNIQUES

2.1. Biomimetic Airfoil Construction: A Comprehensive Approach to Bionic Model Design

The journey from observing bird flight to creating biomimetic airfoils involves a series of intricate steps, beginning with the careful study of avian wing structures. Different methods can be used to extract these details as shown in the work of Liu et al. [9], who utilized laser scanning techniques to capture the surface geometry without contact. This data helps in determining factors such, as the shape of the airfoil, wing outline variations in chord length, distribution of twist angles along the wings span and creating a three-dimensional (3D) model of the flapping wing by aligning airfoil sections on the dynamic quarter chord line in object space [9]. While laser scanning provides highly accurate data, it relies on specialized equipment that may not be accessible to all researchers. Hence, lower cost alternatives like photogrammetry, can be sufficient to collect the measurements needed, with enough precision at a reduced cost, given that it already proved to be representative of detailed measurements to reconstruct insect wing kinematics [34].
Owl wings are treated as fixed wings due to their shape and features, when adapted for use in wind turbines, which contribute to flight and improved lift performance [35] [36]. This is a reasonable simplification since wind turbine blades operate in a steady, attached flow regime with a fixed angle of attack and high Reynolds number (compared to bird flights), relying primarily on pressure differences for lift generation [37], while flapping bird wings experience both attached and separated flow regimes, with dynamic angle of attack changes and additional unsteady lift [38]. In developing inspired airfoils PROFOIL emerges as a valuable tool for inverse design at multiple points. The airfoil designing process requires definitions of parameters, like thickness and curvature constraints. Specialized software such, as PROFOIL goes through rounds of adjustments to shape the airfoil until it reaches the desired characteristics. After the design phase additional refinements can be made following analysis or testing enabling modifications to factors, like camber, curvature, and other important parameters [10].
This approach was applied by Wang and Liu [39] to reconstruct the wing airfoil of a long-eared owl, which had been done based on the studies of Liu et al. [9]. Using mathematical equations to model the camber line and thickness distribution, and fitting the coefficients through least-squares regression, researchers were able to accurately recreate the owl's airfoil geometry at the 40% span location. The resulting bio-inspired airfoil exhibited favorable aerodynamic performance and low-noise characteristics, mimicking the key features that enable owls' remarkably silent flights [35] [36], and upon considering the owl's more complex spanwise variation, the aerodynamic fidelity to the biological inspiration can be maximized. Beyond reconstruction, published results indicate measurable functional gains: the reconstructed long-eared owl profile reported by Wang and Liu [39] achieved multi-dB noise attenuation while maintaining aerodynamic fidelity at moderate Reynolds numbers, linking inverse-design reconstruction directly to performance outcomes.

2.2. Bird Airfoils Bionic Coupling for Advanced Wind Turbine Blades Noise Reduction

The remarkable ability of some birds to fly silently, almost noise free, provides an inspiring model for engineers seeking to design quieter airfoils shapes, for wind turbines rotor blades. Owls, in particular, have evolved specialized wing features that suppress noise during flight (Figure 1). Their serrated leading edges, fringed trailing edges, and velvety upper surfaces coupled with downy feather coating all contribute to this stealth capability. These morphological features are not only visually distinct but also aerodynamically relevant, as they stabilize the boundary layer, delay separation, and reduce large-scale vortex shedding. Coupled implementations show that serration amplitude and wavelength directly influence vortex coherence, with optimized parameters breaking large-scale vortices into smaller structures with reduced acoustic signature [39,84]. Figure 1 provides a comprehensive visual breakdown of the owl's silent flight adaptations and their biomimetic applications. The top of the diagram features an owl in flight, with three key areas highlighted: (a) the leading edge, (b) the wing surface, and (c) the trailing edge. Image (a) shows the serrated or 'comb-like' structure of the leading-edge feathers, (b) displays the velvety texture of the wing's surface feathers, and (c) reveals the fringed structure of the trailing edge feathers. The central circular image (d, e, f) offers even closer views of these features: (d) shows the fine, hair-like structures of the leading-edge serrations, (e) depicts the downy, brush-like surface coating, and (f) illustrates the intricate structure of the trailing edge fringes.

The bottom row of the figure showcases how engineers and scientists have implemented these adaptations in their experimental work. Image (i) shows a manufactured leading edge with precisely spaced serrations, mimicking the owl's comb-like feather structure. Image (g) presents a technical drawing or prototype of an airfoil with serrated trailing edges, demonstrating how the owl's fringe-like feature is adapted for engineered surfaces. Finally, image (h) displays various surface textures and patterns, representing attempts to replicate the noise-reducing properties of the owl's velvety wing surface. While serrated trailing edges predate biomimetic work, owl-inspired studies advance beyond generic serrations by combining wavy leading edges, fringed/serrated trailing edges, and velvety or porous surface treatments, with parameter tuning performed in concert to exploit synergistic effects.

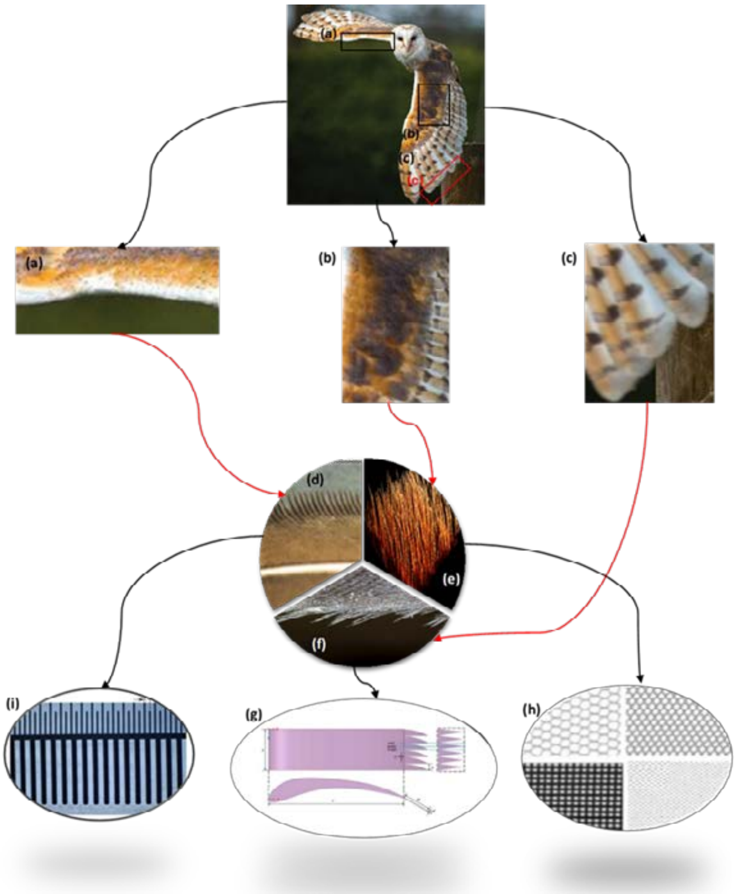

Figure 1: Highlighting Barn owl silent flight features, (a) Leading edge serrations, (b) Wing surface canopies (downy coat), (c) Trailing edge fringes [40]. Close up view of (d) the leading-edge serrations feathers [41], (e) isometrical closeup view of dorsal structure of the outer vane of barn owl feathers [42], and (f) close up view of the trailing edge serrations [43]. Scaled leading edge serrations of the bio-inspired wing models used by Rao et al. [44] (i), (g) Illustration of owl-based airfoil geometry with oblique-arc and conventional trailing-edge serration models [45], (h) fabric

canopies used to mimic the top downy coat of owl wing, mounted in a way that the flow direction was top to bottom [46].

2.2.1. Wavy Leading Edge

Barn owl, great horned owl, and other owl species (silent fliers) can fly low profile due to the serrated wavy structure of their wing's leading edge [47] [27]. According to Lang et al. [48], introducing this feature into the airfoil's leading edge reduces the sound pressure level of the aerodynamic noise.

To accurately reconstruct a bionic coupling airfoil's leading edge, Wang and Liu [39] considered it as a wavy structure described by a varying wavelength and amplitude. They combined this bio-inspired wavy leading edge with an owl contour to 3D print a "bionic airfoil" for aerodynamic testing. In addition to acoustic benefits, wavy-edge studies also report aerodynamic gains: experiments have shown stall-onset delay and improved lift behavior at moderate angles of attack, indicating that leading-edge waviness can simultaneously influence stability and tonal-noise suppression. Xing et al. [49] also used an existing airfoil as the baseline for introducing waviness. Specifically, they utilized a NACA 0012 profile, then mathematically modulated the chord length from the leading edge to maximum thickness to generate a sinusoidal spanwise variation, The chord length variation of the wavy leading edges airfoils along the wingspan follows the formula given in Equation (1). Meanwhile, the distinct shape of each spanwise section is defined by the mathematical relationship described in Equation (2).

$$c(z) = c + \frac{A}{2} cos\left(\frac{2\pi}{W} z\right) \quad (1)$$

$$\begin{cases} x_{new} = \begin{cases} \frac{x_{old}}{x_{max}}\left[x_{max} + \left(c(z) - c\right)\right] - \left[c(z) - c\right] & x_{old} < x_{max} \\ x_{old} & x_{old} \geq x_{max} \end{cases} \\ y_{new} = y_{old} \end{cases} \quad (2)$$

By adjusting the amplitude and wavelength parameters controlling the geometry, they produced 7 distinct configurations that preserved the mean projected area. In related manner, Xing et al. [50] systematically fabricated bioinspired wavy leading-edge airfoils to evaluate their aerodynamic impacts. The practical way of leveraging computational techniques to parametrize and generate the wavy structure, involves some simplifications compared to the complex quasi-fractal structures that exists on the wing's leading edge. So, investigating the impact of these simplifications versus directly replicating the natural shapes, could reveal some room for further improvement.

The approaches of Wang and Liu [39] as well as Xing et al [49] showcase common techniques for reconstructing owl-inspired wavy leading edges, to study their aerodynamic noise reduction properties. The airfoil's smooth curves are algorithmically modulated to introduce these bio-inspired undulations and surface patterns replicating nature's noise-suppressing designs (Figure 2). Although it has been found that serrated leading edge mimicry for airfoils results in noise reduction to some extent [51] [52], the attempt to translate owl's silent flight full outcome from a single feature presented on its wing, in order to get similar result for the bio inspired airfoils, blades and wings can be quite difficult to attain, given that it is taking part of multiple adaptations that owls developed over the course of their evolution years as stealthier fliers. The leading-edge serrations help initiate a controlled turbulent boundary layer flow from the start of the wing (it trips the boundary layer). This turbulent air remains attached longer and delays stall. Then the porous downy coating energizes the boundary layer and delaying turbulent breakdown, and finally the fine fringes at the trailing edge guides the turbulence smoothly until separation to avoid that aggressive vortex shedding that causes noise. To the authors knowledge no discussion on the relation of the interaction of the airflow turbulence with noise generation was founded in the literature. So, relying on leading edge serrations will likely not mitigate the additional noise sources farther along the blade surface.

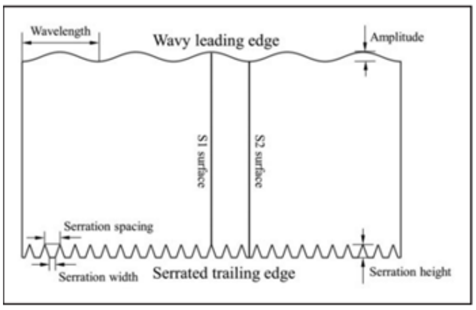

Figure 2. Designed parameters of bionic coupling airfoil [39].

2.2.2. Trailing Edge Serrations

The application of serrated trailing edges, inspired by owl wings, has become a common bioinspired technique for reducing wind turbine aerodynamic noise (Figure 3) [53].

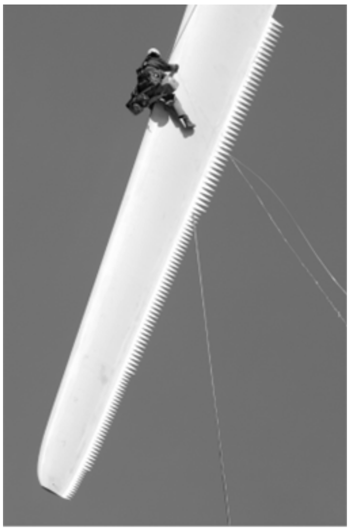

Figure 3. Climber removing trips of the trailing edge serrations mounted on wind turbines blades [55].

Nevertheless, the optimization of the parameters of these serrations for efficient noise reduction, as well as the exploration of viable manufacturing techniques, continue to be active subjects of investigation. In their recent work on airfoil trailing edge serrations, Cao et al. [36] aimed to address these issues through an efficient modeling approach. Specifically, they set the serration height to 15% of the chord based on recommendations from Gruber et al. [54], while using a wavelength-to-height ratio of 0.5. Additionally, the authors matched the serration flap angle to

the airfoil trailing edge angle following findings by Vathylakis et al. [55], though this approach is valid, it implies that the chosen values may not be globally optimized for the specific application, yet it showed improved noise attenuation.
Instead of solving the complete 3D geometries, Cao et al. [36] formulated a computational model that utilizes momentum source terms to replicate the aerodynamics of serrations, replacing solid geometry with these source terms. The source strengths for lift and drag forces are determined according to the local flow conditions, allowing for efficient assessment of different serration configurations, without the need for computationally intensive 3D simulations. This method not only streamlines the design process, but also opens up new possibilities for rapid iteration and optimization of serrated trailing edge designs in wind turbine applications. In contrast, Pereira et al. [56] employed actual physical models and geometries in their sensitivity-based parametric analysis, demonstrating that systematic modifications in serration height, wavenumber, and aspect ratio can provide valuable guidelines for achieving significant broadband noise reduction. Furthermore, in a subsequent, they study conducted a sensitivity-based parametric analysis on the scaling and geometric properties of trailing-edge serrations. They demonstrated that systematic modifications in serration height, wavenumber, and aspect ratio can provide valuable guidelines for achieving significant broadband noise reduction [57]. The results from both studies, reinforce the importance of detailed experimental analyses to complement computational models, ultimately contributing to the optimization of serrated trailing edge designs for effective noise mitigation. Additionally, Avallone et al. investigated novel iron-shaped serrations using numerical simulations, demonstrating that these designs can achieve approximately 2 dB more noise reduction compared to conventional triangular serrations for specific frequency ranges [58]. Their findings underscore the potential for enhanced noise mitigation through innovative serration geometries. Taken together, these studies show that tuning geometric parameters such as serration amplitude, wavelength, height-to-chord ratio, and aspect ratio directly influences vortex coherence and breakdown, with optimized values disrupting large-scale turbulent structures into smaller, less acoustically efficient vortices, thereby enhancing noise reduction.

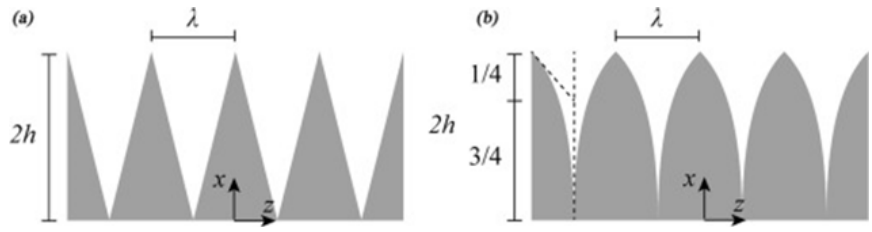

Figure 4. Sketch of the conventional (a) and iron-shaped (b) trailing-edge serrations [58].

The optimization of trailing-edge serrations underscores the complexity of replicating owl-inspired features. To evaluate and refine these adaptations, robust computational tools are essential, which leads directly into the numerical methods discussed in Section 2.3.

2.3. The Numerical Methods used for Aerodynamic and Aeroacoustic Analysis

Computational fluid dynamics (CFD) has enabled detailed simulations to capture noise generation mechanisms and optimize bio-inspired designs [59] [60]. Common numerical methods include:
• Reynolds-averaged Navier-Stokes (RANS).
• Large eddy simulations (LES).
• Direct numerical simulations (DNS) coupled with Ffowcs Williams-Hawkings (FW-H) acoustic analogy for far-field noise prediction [61].
LES directly computes large turbulent structures while modeling smaller eddies, offering a balance between accuracy and efficiency [62]. Solís-Gallego et al. [63] performed a wall-resolved LES model with adequate boundary layer and turbulence scale resolution to analyze the noise

reduction mechanisms in a typical wind turbine airfoil. The computations revealed Tollmien-Schlichting instabilities diffusing into turbulent flow prior to the trailing edge, eliminating tonal noise components. Comparisons to wind tunnel data showed good agreement, indicating effectiveness of well-resolved LES for analysis of such concepts. Similarly, Shiva Prasad Uppu and R. Naren Shankar [64] performed Transient large eddy simulations (LES) on a bio-inspired serrated NACA 0012 airfoil to capture unsteady flow effects. Surface pressure data was sampled at high frequency and far-field noise extraction was done using multiple virtual microphones. Comparisons to experiments demonstrated good prediction of noise reduction from the computational approach for two serrated geometries, indicating its effectiveness for analysis of such bio-inspired low noise concepts.

To analyze the aerodynamic and aeroacoustic characteristics, Li and Wei [65] employed the large eddy simulation (LES) technique coupled with the Ffowcs-Williams and Hawkings (FW-H) equation to obtain unsteady flows and noise predictions, which is the same approach that Qin et al. [66] used for their fan blade inspired by owl wing geometry and structure to investigate noise reduction and aerodynamic performance, in which they found that their bionic blade achieved better overall noise reduction without compromising efficiency. Additionally, post-processing methods including Q-criterion vortex identification, calculations of root-mean-square pressure fluctuations, and fast Fourier transforms were utilized to provide insights into flow physics and noise sources. Similarly, Yehia Salama [67] utilized an Embedded Large Eddy Simulation (ELES) approach coupled with the Ffowcs Williams-Hawkings (FW-H) aeroacoustic model to simulate the aerodynamics and noise generation from various airfoil designs. In the ELES method, the flow domain is divided into regions solved by Reynolds-Averaged Navier Stokes (RANS) and Large Eddy Simulation (LES). The RANS equations provide mean flow statistics while the LES resolves unsteady perturbations in regions needing higher fidelity. The FW-H model allows propagation of acoustic waves from the LES region to far-field observers, avoiding the need to expand the CFD domain. This combined approach allows simulation of the aerodynamics and aeroacoustics at reasonable computational cost compared to full LES or Direct Numerical Simulation (DNS).

In their work Boughou et al. [68] performed two-dimensional (2D) and three-dimensional (3D) computational fluid dynamics (CFD) simulations using ANSYS Fluent to analyze high-lift, low Reynolds number bird-like airfoils including seagull, merganser, and S1223 profiles. Various turbulence models were tested, with the transition shear stress transport (SST), where the γ-Reθ model best capturing laminar separation bubbles linked to noise reduction. Pressure distributions and velocity profiles provided insight into separation physics while 3D simulations examined three-dimensional flow effects. The γ-Reθ model's superior aerodynamic coefficient prediction and resolution of transitional flows and separation bubbles revealed noise mechanisms tied to biologically inspired natural laminar flow airfoil designs.

High-fidelity computational techniques like LES and DNS coupled with acoustic analogies effectively analyze noise mechanisms in bio-inspired airfoils [69], while transitional models like γ-Reθ and SST capture separation bubbles tied to noise reduction [70]. Comparisons to experiments validate these numerical methods. Additionally, at very low Reynolds numbers, 2D laminar and 3D LES simulations correctly predict unsteady aerodynamics of owl-like airfoils [68], while 2D and 3D RANS methods effectively analyze higher Reynolds number bio-inspired airfoils. However, accurately predicting stall requires experimental validation [70] [71] [72]. Overall, computational analysis provides indispensable insights into noise sources [73], transitional flows, and complex unsteady physics to guide bio-inspired low-noise airfoil designs, though continued advances in modeling and experimental confirmation remain essential.

The following table summarizes the major differences between the three computational models, highlighting the strengths and limitations of each.

Table 1: Table highlighting the major differences between the numerical methods.

Numerical method	Strengths	Limitations
Reynolds-Averaged Navier-Stokes (RANS)	-Efficient for large-scale applications and steady-state flows. -Suitable for bio-inspired airfoils with higher Reynolds number.	-Uncapable of resolving unsteady flow. -Limited in capturing aeroacoustics noise generation mechanisms.
Large-Eddy Simulations (LES)	-Accurate in resolving large-scale turbulence and unsteady flows. -Effective in coupling with Ffowcs Williams-Hawkings acoustic analogies.	-Computationally expensive, especially for high-Reynolds numbers and large-scale wind turbines. -Requires fine grid resolution near walls, increasing the computational time.
Direct Numerical Simulations (DNS)	-Its accuracy is unmatched in resolving all turbulence scales. -Excel at capturing complex noise generation mechanisms at low-Reynolds numbers.	-Immense computational cost making it impractical for large-scale applications. -Limited to simplifies geometries or specific flow conditions.

3. THE TRADE-OFFS BETWEEN NOISE REDUCTION AND AERODYNAMIC PERFORMANCE

Having reviewed construction approaches and numerical analysis techniques, it is now critical to assess the aerodynamic penalties that often accompany noise reduction strategies. This section examines those trade-offs in detail. Although some of the bird airfoils and bird like airfoils proved their ability to reduce noise significantly through the bionic coupling (wing shape and feather adaptations) and their wing's special streamlined geometry, [74] [75] [76] these biological designs often come at the cost of aerodynamic performance. Many of the features incorporated into bird inspired airfoils that allow birds to fly silently, such as downy, flexible surface feathers that minimize flow separation and muffler-like trailing edge fringes that soften noise, also reduce aerodynamic efficiency and lift capabilities in certain conditions. A numerical investigation of the aerodynamic and aeroacoustic behavior of owl inspired airfoils by Güzey et al. [77] showed that the modified NACA0012 airfoil with leading edge serrations achieved an OSPL reduction by 20% versus the NACA0012 baseline, yet for AoA > 12°, these serrations negatively affects the aerodynamic performance.

The way the bionic adaptations can affect the air flow behavior around the airfoil can be seen in the work of Ibren Hassan et al. [78], where they investigated the impact of trailing edge modifications (serrated, comb, comb-serrated), on aerodynamic performance and flow structure of airfoils, and found out that modifications caused early pressure drop and uneven skin friction on surfaces, that promotes early transition to turbulence which reduces lift, creates instability, yet, in literature, the serrated trailing edge proved its ability to mitigate the aerodynamic noise generated [79] [80] [81]. In their investigation on the introduction of serrations along the trailing edge of airfoils impacts their aerodynamic behavior and the characteristics of the turbulent wake that forms behind the airfoil, Liu et al. [82] found that significant aeroacoustic benefits resulted from implementing serrated edges, but these came at the cost of aerodynamic trade-offs. While serrated trailing edges substantially reduced near wake turbulence intensity (attributed to complex tip and root flow interactions) and decreased velocity power spectrum across a wide frequency range, the serrated cambered NACA 65(12)-10 airfoil suffered noticeable reductions in lift coefficient at low angles of attack as well as increased drag at higher angles. The degree of trade-off varied depending on parameters like serration geometry and angle of attack. However, their findings clearly demonstrate that effective low-noise serrated airfoil designs require balancing coupled aerodynamic and aeroacoustic factors.

4. LITERATURE BENCHMARK OF BIRD INSPIRED AIRFOILS NOISE REDUCTION

The implementation of bionic coupling techniques for bird-inspired airfoils has demonstrated effective reduction of sound pressure levels in wind turbines across multiple studies. It was found that bionic blades with non-smooth leading edges and curved serrations decreased noise by 6.9 dB compared to a baseline blade [83]. Further optimizations of the design parameters by Li et al. [84]. achieved noise reductions upwards of 8.42 dB. Similarly, Gao [85] showed that coupling a bionic airfoil and sawtooth trailing edge led to combined aerodynamic and aeroacoustics noise attenuation of 7.9 dB. Beyond rotational noise, researchers applied sinusoidal and ridged leading edges to mitigate wind buffeting noise [84]. Table 1 benchmarks recent research work exploring the noise reduction potential of bio-inspired airfoil designs for wind turbines and aircraft propellers. A range of biological inspiration sources are covered, from the owl wing to the long-eared owl and even the downy owl coat. The noise reduction mechanisms vary from disrupting spanwise vortices and altering vortex shedding to inducing turbulence modifications near the trailing edge. However, a common theme across designs is leveraging unsteady flow control and boundary layer manipulation to attenuate noise emission. Reported overall sound pressure level reductions range from 1.2-10 dB, with optimized bionic designs achieving over 30 dB attenuation at particular frequencies. While most works rely on numerical prediction [86], some include experimental validations in wind tunnels or full-scale turbine testing [87]. Comparing the various studies, several trends emerge. Firstly, designs incorporating leading edge modifications, such as wavy or undulated profiles, consistently show significant noise reductions, with some studies reporting up to 33.9 dB attenuation at specific frequencies [49]. Trailing edge modifications, particularly serrations and finlets, also demonstrate notable noise reduction capabilities, typically in the range of 1.2-10 dB overall sound pressure level reduction [88], [89], [90]. Interestingly, combined approaches that integrate both leading and trailing edge modifications tend to yield the most substantial noise reductions. For instance, the bionic coupling blade with undulated leading edge and curved serrated trailing edge achieved noise reductions of up to 8.42 dB [84], while the integrated bionic airfoil design inspired by a long-eared owl wing reached 7 dB reduction [39] (Figure 5).

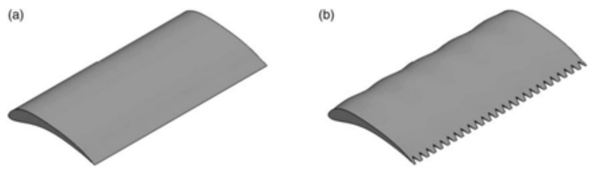

Figure 5. Geometrical models of two types of bionic airfoils:
(a) bionic airfoil; and (b) bionic coupling airfoil [38].

Another trend observed across studies is the frequency-dependent nature of noise reduction. Many designs show more significant attenuation at higher frequencies (typically above 1-2 kHz), while some may even increase noise at lower frequencies (Figure 6) [42][90]. This highlights the importance of considering the full frequency spectrum when evaluating and optimizing these bio-inspired designs. Reported overall sound pressure level reductions range from 1.2-10 dB, with optimized bionic designs achieving over 30 dB attenuation at particular frequencies. While most works rely on numerical prediction [86], some include experimental validations in wind tunnels or full-scale turbine testing [87]. The presented research showcases the potential of bio-inspired airfoils for enabling quieter next-generation wind turbines, though further optimization and validation is needed to deploy these concepts practically. Noise-reduction results in the literature include broadband OASPL decreases typically in the 2–10 dB range, and frequency-specific peak attenuations that can exceed 30 dB at targeted harmonics. We distinguish these two cases explicitly to avoid ambiguity. The summary table provides a useful benchmark for comparing various biologically derived noise mitigation strategies on equal footing, revealing both the promise and challenges of these innovative approaches.

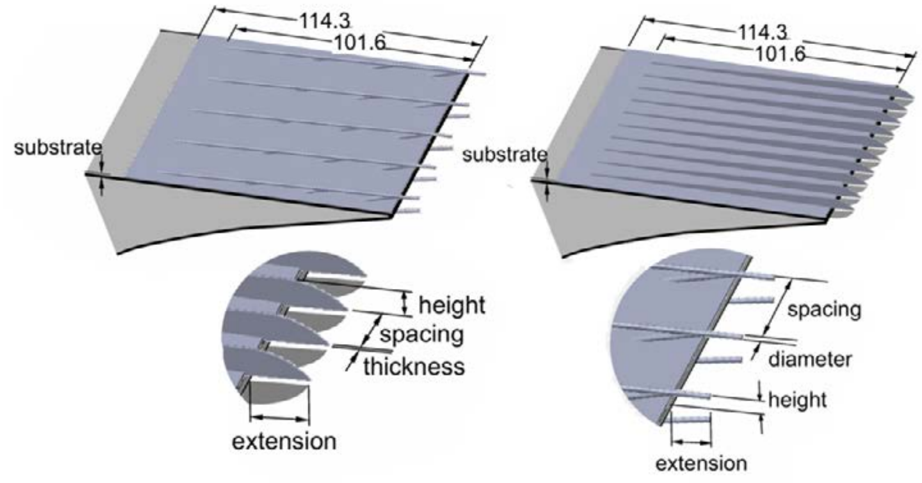

Figure 6. Schematics of two finlet designs (mm) specimen subject of Bodling et al. study [43].

Table 2. Overview of biomimetic airfoil concepts for enabling low-noise wind turbines.

Airfoil Design	Noise Reduction Mechanism	Noise attenuation	Testing Conditions	Ref.
Bionic coupling blade with undulated leading edge and a curved serrated trailing edge	Disrupt spanwise vortices and alter vortex shedding patterns	-Bionic coupling blade => 6.9 dB (compared to baseline NACA 63-415) -Further optimization reached 8.42 dB noise reduction	->Numerical simulations using k-omega SST turbulence model ->Incoming flow velocity of 10 m/s ->Acoustic predictions by Ffowcs Williams-Hawkings's equation	[84]
Integrated bionic airfoil design inspired by a long-eared owl wing's 40% cross section, featuring a coupling with undulated leading edge, and serrated trailing edge	Altering streamwise vortices and vortex dynamics.	-Bionic airfoil => 2-6 dB (compared to conventional airfoil) -Leading edge treatment (alone) => 2dB -Coupled bionic airfoil => 7dB	->Numerical simulations at chord-based ->Re=54000 ->Acoustic predictions using Ffowcs Williams-Hawkings's equation	[39]
Standard blade with serrated trailing edge + Optimized airfoil shape for the outer 30% SIROCCO blade	Affecting the scattering at the trailing edge and changing the boundary layer structure and turbulence	- Serrated blade => overall noise reductions of 1.2-3.2 dB across tested wind speeds. -Optimized airfoil => overall noise reductions of 0-1 dB across tested wind speeds. (At low frequencies)	->Field tests were done on a 2.3 MW wind turbine with 94 m rotor diameter. ->The blades were tested clean and tripped at wind speeds of 6-10 m/s. ->A 148 microphone horizontal array was used to locate noise sources. ->Measurements were taken upwind and downwind of the turbine.	[90]

Seven wavy leading-edge airfoils, based on the NACA 0012 standard model, with sinusoidal profiles tested across varying amplitudes (A) and wavelengths (W).	Wavy leading edges enhance momentum exchange and improve boundary layer stability to reduce trailing edge noise	-All 7 wavy leading edges reduced trailing edge broadband noise and tonal hump -Noise reduction up to 33.9 dB at 3552 Hz frequency with A40W10 airfoil	->Semi-anechoic wind tunnel facility ->Incoming flow velocities from 20-70 m/s ->Geometric angles of attack from 0-15 degrees (effective angles ±5 degrees) ->52 microphone planar array, 450mm downstream of airfoil trailing edge	[49]
Wavy leading-edge airfoil A10W10	-Wavy leading edges induce streamwise vortices. -Interaction disrupts shedding vortices at trailing edge. -Turbulence intensity reduction near trailing edge.	-Maximum SPL reduction of 35 dB at 4688 Hz (4 times vortex shedding frequency) -Local max SPL reductions of 7 dB at 1074 Hz and 13.8 dB at 3516 Hz -OASPL reduction between 3.1-6.3 dB	->Chord-based Re=400,000 ->Angle of attack: 0 degrees	[50]
Baseline NACA 0012 with an array of fences at the trailing edge inspired by the downy coat of owl wing	Fences disrupt the alignment of airflow along the span at lower frequencies (<1500 Hz). This should reduce trailing edge noise based on Amiet's theory.	- 1.8 dB reduction at high frequencies (>1500 Hz) near trailing edge. - Increase at low frequencies (<1500 Hz) in simulations due to vortex shedding.	->Chord based Re= 30000 ->Numerical simulations using the FDL3DI solver. -> Surface pressure spectra from CFD were analyzed rather than far-field noise.	[43]
NACA 0012 baseline airfoil modified with finlet fences near trailing edge (H/δ^* = 1.0 and H/δ^* = 2.26)	-Fences increase source-scattering separation distance. -Spanwise coherence at low frequencies reduction	- $H/\delta*$ = 1.0 fence reduces far field SPL for 500 Hz – 5 kHz by up to 10 dB - Noise reduction with $H/\delta*$ = 2.26 fence for the frequencies above 1.5 kHz - Higher noise reduction with taller $H/\delta*$ = 2.26 fence for frequencies >2 kHz	-> Numerical simulations using FDL3DI solver. -> Implicit large eddy simulations -> Chord based Re = 50000 -> Angle of attack $\alpha = 0°$ -> Boundary layer tripped at 5% chord	[88]
Bio-inspired airfoil design uses finlet fences near the trailing edge. Two finlet fence designs tested: single-step and stair-step. (NACA 0012 baseline)	Fences steer turbulent air away from the back of the airfoil. This makes the edge scattering process less efficient, reducing noise.	Far field noise reduced up to 10 dB between 500 Hz - 5 kHz for stair-step fence design. No reduction for single-step fence.	->Rec = 5×10^5 (chord based) Angle of attack $\alpha = 0°$ ->Flow tripped using a trip wire at 5% chord to induce transition. ->LES simulations using high-order accurate finite-difference flow solver. ->Far field noise predicted using Ffowcs Williams-Hawkings acoustic analogy.	[89]
NACA 0012 with two serrated trailing edge designs tested - wide serrations and narrow serrations	- Flow disturbance and noise scattering reduction at the trailing edge - Noise source modification instead of scattering the sound	- Wide serration reduced noise by 2 dB more than narrow serration in mid frequencies - Noise reduced up to 10 dB with serrated trailing edges compared to baseline unmodified airfoil	-> Numerical simulations using large eddy simulation (LES) turbulence model. -> Angle of attack 0°. -> Far-field noise prediction using isolated microphone at 1.5 m distance.	[91]

To consolidate the findings from the wide range of studies reviewed in this section, it is useful to present a comparative synthesis. While individual works highlight specific bio-inspired adaptations and their corresponding acoustic benefits, a direct juxtaposition of noise attenuation outcomes with aerodynamic trade-offs provides clearer insights into their overall effectiveness.

The following summary table integrates these results, offering readers a concise overview of the key noise reduction achievements reported in the literature alongside their associated aerodynamic performance impacts. This comparative perspective facilitates a more holistic evaluation of the advantages and limitations of different bio-inspired strategies.

Table 3. Integrative summary of bio-inspired airfoil designs: noise reduction achievements versus aerodynamic trade-offs.

Bio-inspired feature	Noise reduction mechanism	Reported attenuation	Aerodynamic trade-offs	References
Wavy leading edge (NACA 0012 modifications)	Disrupts shedding vortices; enhances boundary layer stability	Up to 33.9 dB at specific frequencies; 3–6 dB OASPL	Minor lift penalty at higher AoA; frequency-dependent effectiveness	Xing et al. [49,50]
Trailing edge serrations (conventional triangular)	Reduces turbulent scattering at TE; modifies wake turbulence	1–10 dB broadband reduction	Lift reduction and drag increase at higher AoA	Gruber et al. [54]; Pereira et al. [56,57]
Curved/iron-shaped serrations	Enhances destructive interference in broadband ranges	+2 dB compared to triangular serrations at select frequencies	Requires precise manufacturing; uncertain large-scale durability	Avallone et al. [58]
Porous/velvety coatings (owl downy surface analogues)	Energizes boundary layer; delays separation and turbulent breakdown	2–5 dB SPL reduction (numerical/ experimental)	Significant durability and maintenance challenges outdoors	Chen et al. [26]; Clark et al. [46]
Coupled leading + trailing edge modifications	Combined disruption of spanwise and streamwise vortices	6.9–8.4 dB OASPL reduction	Cumulative aerodynamic penalties if not optimized; sensitive to scaling	Li et al. [84]; Wang & Liu [39]
Finlets/fences near trailing edge	Increase source–scattering separation; reduce coherence	Up to 10 dB between 500 Hz–5 kHz	Local drag rise; possible increase in low-frequency noise	Bodling et al. [43]; Gu et al. [52]

5. Discussion: Bird Airfoils Aerodynamic And Aeroacoustics Use Limitations for Wind Turbine Blades

Though bird-inspired airfoils offer benefits for wind turbines, scaling up these bio-inspired shapes presents aerodynamic and structural challenges distinct from avian flight conditions.

Despite the encouraging results at model scale, significant limitations remain in translating bio-inspired airfoils to full-scale operational wind turbines. Structural trade-offs are among the most pressing concerns. For instance, serrated trailing edges tested on Nordex turbines increased annual energy production by approximately 1%, yet they also led to a 10–15% rise in ultimate loads, potentially reducing component lifetime [98]. This highlights that noise mitigation measures can inadvertently accelerate fatigue or structural degradation if not carefully engineered. Researchers employ strategies like custom airfoil families, increased thickness, rounded trailing edges, computational optimization, and experimental validation to improve performance (Doolan and Moreau 2022). However, noise remains a concern, for example thicker profiles can smooth pressure distributions to reduce noise but increase drag, incorporating smart materials like piezoelectric elements for vibration control, could further enhance the structural adaptability and damping capacity of advanced bio-inspired blades [92]. CFD analysis by Kaviani and Moshfeghi [93] showed a seagull airfoil geometrically resembling the thin, highly-cambered S1223 (Figure 7), which is thin and highly cambered resulting in high lift characteristics [94], achieved significantly higher lift coefficients across -14° to 20° angles of attack compared to the S809 airfoil. For example, at 20 degrees angle of attack, the lift coefficient was 118% higher. In addition to that, the thickness of the airfoil influences drag - the thinner S1223 and seagull airfoils exhibited lower pressure drag due to reduced flow separation compared to the thicker S809 airfoil, especially at higher angles of attack. Material durability is another barrier. Features such as porous coatings or flexible surfaces are prone to wear under outdoor conditions, including ultraviolet exposure, moisture, and particulate erosion. While they perform well in laboratory settings, ensuring long-term reliability in harsh environments is still unresolved. Similarly, complex serration geometries or downy-inspired textures pose manufacturing and maintenance challenges when scaled to blades exceeding 60–100 meters.

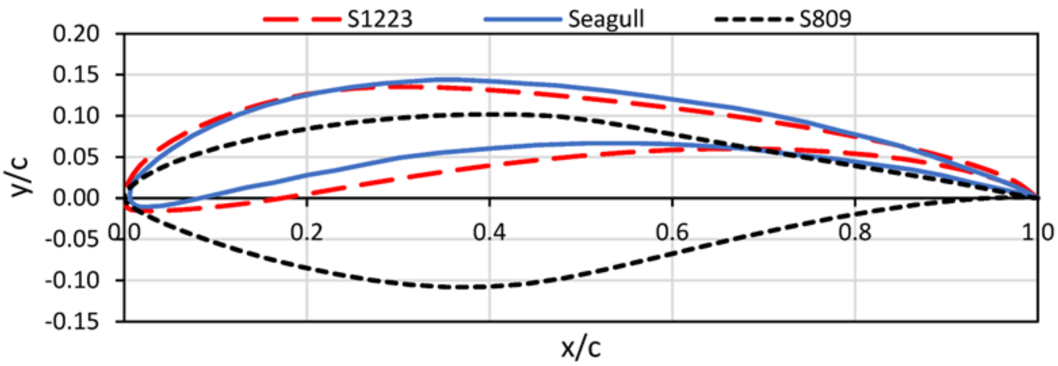

Figure 7 Comparison of S1223, S809, and the seagull airfoil profiles [93].

Aeroacoustic scaling itself introduces further complexity. Many bio-inspired adaptations demonstrate strong attenuation in the kilohertz range relevant to small-scale testing, yet full-scale wind turbines generate dominant noise at lower frequencies (below 1 kHz). Bridging this frequency gap requires either hybrid designs or multi-feature integration, supported by high-fidelity simulations and field trials.

Rounded trailing edges mitigate vortex shedding noise, however a study conducted by Shreyas et al. [95], concluded that increasing trailing edge radius causes a reduction in lift and aerodynamic efficiency, along with an increase in drag coefficient for the two tested airfoils (FX 63-137 and S1223). Recent numerical studies on the rounded trailing edge airfoil DBLN-526 have shown its potential for noise reduction and maintaining aerodynamic performance compared to other airfoils [96] [97]. The unique "step" design feature on the lower surface fixes the transition location, leading to smaller and more stable turbulent separation zones. This reduces overall pressure fluctuation, unsteady air loads, and noise. The aerodynamic lift and drag coefficients also matched well with experiments.

The key enabler is the rounded trailing edge along with strategic lower surface shaping that controls boundary layer transition. Overall, rounded trailing edges, when properly designed, can enable noise reduction without compromising time-averaged aerodynamic performance. In contrast, according to Llorente and Ragni [98] a study of trailing edge serrations on a Nordex wind turbine blade showed that the serrations increased the lift coefficient by acting as flaps with reduced length (Figure 8).

This increased the annual energy production by 1% compared to the original blade. However, the serrations also caused a 10-15% increase in ultimate loads, which could potentially reduce component lifetime.

Figure 8 NACA64s418 model implemented in the studied wind turbine (on the left) [98].

Optimized shapes aim to minimize flow separation and pressure gradients. Stiffer blades may transmit less vibration-induced noise. The influence of Reynolds number on aeroacoustic outcomes remains underexplored as well. Many bio-inspired treatments that attenuate noise at low-Re test conditions (often at higher acoustic frequencies) confront a different landscape at utility-scale Re, where dominant content shifts below 1 kHz. This scaling mismatch complicates direct extrapolation and highlights the need for studies that map geometry-parameter effects across Re and frequency bands relevant to full-scale rotors. Ultimately, a multi factor focusing approach is needed, as noise depends on multiple factors including rotor-turbulence interactions [99] [100], wake interference [101] [102], and overall system design [103]. Airfoil shape can contribute to noise reduction through bio-inspired concepts [104], but practical trade-offs exist between efficiency, structural integrity, and noise performance.

6. FUTURE DIRECTIONS AND RESEARCH OPPORTUNITIES FOR BIO-INSPIRED WIND TURBINE DESIGNS

The potential of bio-inspired airfoil designs for wind turbine applications is vast, but several challenges remain in transitioning these concepts from research to real-world implementation. One key area for future research is the optimization of bio-inspired airfoil designs for larger wind turbines. Current designs, which often focus on smaller-scale models, need to be adapted for full-scale turbines that have significantly larger dimensions and operate under more complex flow conditions. The challenge lies in maintaining the unique aerodynamic properties of these bio-inspired shapes while ensuring structural stability under high wind loads and variable atmospheric conditions. One realistic solution for this challenge is the application of additive manufacturing and advanced composite materials for this type of designs, which can play a transformative role in the industry. Additive manufacturing allows for the precise fabrication of complex geometries that are difficult or impossible to produce, using traditional manufacturing methods [105] [106]. This technique also enables rapid prototyping and testing, which can significantly accelerate the design iteration process. Researchers should explore the use of advanced materials like graphene-reinforced composites or shape-memory alloys that can provide the required strength and flexibility for these novel designs without compromising performance. By integrating these materials, it would be possible to create airfoils that are not only structurally robust but also capable of dynamically adapting to changing wind conditions. Furthermore, the refinement of computational models is critical. While current Computational Fluid Dynamics (CFD) models are effective in simulating the aerodynamic and aeroacoustic performance of conventional airfoils, they may not fully capture the complex interactions of bio-inspired features like serrations, flexible surfaces, or porous coatings, which also the case for capturing the acoustic data of the far field noise. The development of more sophisticated multi-physics models that incorporate fluid-structure interaction (FSI) and aeroelastic effects will be essential for accurately predicting the behavior of these designs under real-world conditions. Additionally, integrating machine learning techniques into these simulations could help identify optimal configurations more efficiently by learning from large datasets of simulation results.

Another key challenge is the scalability and system-level integration of bio-inspired airfoil designs. While small-scale prototypes have demonstrated success in laboratory settings [106] [107] [35], scaling these designs for large wind turbine blades, which can span over 100 meters in length, presents unique material and manufacturing challenges. The increased surface area and length of these blades mean that any structural weaknesses or inefficiencies in the design will be magnified. Therefore, researchers must develop scalable fabrication methods and conduct full-scale field tests to evaluate the durability and performance of these bio-inspired designs over extended operational periods. This also includes considering the impact of environmental factors such as temperature fluctuations, moisture, and UV exposure, which can affect the long-term stability of bio-inspired materials.

6.1. Broader Environmental and Social Implications:

Beyond technical challenges, bio-inspired airfoil designs have significant potential to improve the environmental and social acceptability of wind energy systems. One major advantage of these designs is their ability to reduce noise pollution, making it feasible to deploy wind turbines closer to residential areas and wildlife habitats. This could expand the viable locations for wind farms, helping to increase the global capacity for wind energy generation without the negative social impacts traditionally associated with turbine noise, similar opportunities have been identified in regions such as the Gaza Strip, where wind resource potential remains underutilized due to environmental and infrastructural constraints [109]. The reduced noise levels also have positive implications for wildlife conservation, as studies have shown that high noise levels can disrupt the natural behaviors of birds and other animals in the vicinity of wind farms [110].

However, the introduction of bio-inspired features may also lead to unintended consequences that must be addressed through comprehensive environmental impact assessments. For example, the introduction of porous coatings or flexible surfaces could alter the way wind turbines interact with avian species or airborne insects, potentially creating new hazards. Therefore, any new design must be evaluated not only for its technical performance but also for its potential ecological impact. Additionally, public perception and acceptance of wind energy projects could be positively influenced by the adoption of bio-inspired airfoil designs. The idea of using nature's own solutions to reduce environmental impact resonates with sustainability goals and can be a compelling narrative for stakeholders, policymakers, and the public.

In summary, to advance the development of bio-inspired airfoil designs for wind energy, a comprehensive interdisciplinary approach is necessary—one that leverages engineering innovation, cutting-edge materials science, and a nuanced understanding of ecological dynamics. Addressing the current challenges, such as balancing aerodynamic performance with structural durability and scalability, will require the use of advanced manufacturing technologies, like additive manufacturing, to fabricate complex geometries and precisely control material properties at the micro- and nano-scale. Additionally, implementing bio-inspired designs on full-scale wind turbines introduces several ecological considerations, especially in terms of mitigating potential disruptions to avian and bat populations. To tackle this, integrating computational fluid dynamics (CFD) modeling with real-world environmental data will be crucial for accurately simulating how these innovative airfoil designs interact with the surrounding habitat. This integration not only helps in refining design parameters but also allows for proactive strategies to minimize adverse ecological impacts.

7. CONCLUSIONS

This review has provided a comprehensive examination of the potential of bio-inspired airfoil designs, drawing from the advanced aerodynamic and aeroacoustic features found in avian wings, to address the pressing challenge of noise reduction in wind turbines. By leveraging adaptations such as serrated leading and trailing edges, porous coatings, and flexible surfaces, these bio-inspired designs have demonstrated the capacity to attenuate aerodynamic tonal and broadband noise through mechanisms such as vortex disruption and boundary layer modification. The inclusion of an integrative summary table in this review highlights how reported noise reductions (ranging from 2 dB up to over 30 dB at specific frequencies) often come with aerodynamic trade-offs such as reduced lift or increased drag. Furthermore, the expanded discussion critically appraises the limitations in translating these concepts to utility-scale turbines, including structural load increases, material durability issues, manufacturing complexity, and the challenge of frequency scaling. The unique contribution of this review lies in its interdisciplinary approach, bridging aerodynamic theory with practical applications in wind energy systems. It establishes a clear link between the fundamental aerodynamic principles of avian-inspired geometries and their impact on noise reduction, offering researchers and engineers a consolidated resource for understanding both the potential and limitations of these designs. By continuing to explore nature's elegantly optimized mechanisms—while also addressing the critical challenges of scalability and durability—researchers can pave the way for future innovations that enhance the efficiency and sustainability of wind energy, ultimately contributing to the broader goal of developing environmentally harmonious and socially acceptable renewable energy solutions.

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Nomenclature

CFD	Computational fluid dynamics
SPL	Sound pressure level
OSPL	Overall sound pressure level
TE	Trailing edge
LE	Leading edge
RANS	Reynolds averaged Navier-Stokes
LES	Large eddy simulations
DNS	Direct numerical simulations
FW-H	Ffowcs-Williams and Hawkings
SST	Shear Stress Transport
ELES	Embedded Large Eddy Simulations