Journal of Advanced Research in Fluid Mechanics and Thermal Sciences 109, Issue 1 (2023) 27-40

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage:
https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/index
ISSN: 2289-7879

Turbulent Airflows over Serrated Wings: A Review on Experimental and Numerical Analysis

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ARTICLE INFO

Article history:
Received 5 June 2023
Received in revised form 8 August 2023
Accepted 20 August 2023
Available online 6 September 2023

Keywords:
Airfoils; acoustics; serrated; sound pressure level; noise

ABSTRACT

The serrations on the blade's cutting edge and trailing edge are supposed to assist humans deal with noise, but the main idea is for research and use in nature. This research examines trailing edge extension hydrodynamics. Further, reducing the turbulent wake intensity behind the TE increases aerodynamic performance while leaving the static pressure distribution (as averaged across the span) substantially unaffected. Computational Aero-Acoustics simulates aerodynamic and acoustic reactions. This work discusses the experimental and computer simulations of turbulent flows. This paper provides the research to the technical community in the energy field (often non-specialists of turbulent flow investigations) with a summary of experimental and numerical techniques for investigating flows over a serrated wing, with a focus on the airfoil's self-noise generation mechanism and its main fields of application. The reader can use the given bibliography to determine the best method for the case of interest. This purpose means the individual tactics aren't discussed further. Given the breadth of acoustics, the experimental and numerical methods in this study can be used to forecast noise across serrated wings. It verifies that both strategies are still necessary, performing unique but complementary tasks.

1. Introduction

More than a century ago, the flight of birds and the wings of birds served as inspiration for the development of aeroplanes. Most owl species, according to recent research and observations, are capable of quiet flight and may sneak up on their prey without making a peep. This could serve as a useful biological indicator in the development of more soundproof aircraft and other aerodynamic structures in the future. When an airfoil encounters turbulence at its trailing edge, the result of boundary layer instability, it generates broadband noise even in the otherwise smooth, high-Reynolds-number mean flow. This interaction can happen even in the case of a perfectly smooth flow. This is because the boundary layer turbulence convecting over the trailing edge of the airfoil is the primary driving factor behind these interactions so long as the airfoil is not stopped.

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https://doi.org/10.37934/arfmts.109.1.2740

To a large extent, "Howe's Theory" is utilised to calculate the amount of noise generated by serrations on the trailing edge. Adding serrations to the trailing edge, as proposed by Howe, is an effective way to reduce noise at the trailing edge. Many assumptions and approximations have been made by Howe's for determining the serration noise reductions.

According to Howe's theory, the noise reductions can be achieved by the following assumptions [20]:

i. The frequency spectrum of Surface pressure is unaffected by the serrations on the trailing edge.
ii. The magnitude of noise reduction is strongly reliant on geometrical wave length, height, and sound frequency.
iii. The noise produced by big eddies is unaffected by the presence of serrations whose length scales are greater than the amplitude of the serrations (low frequency region). Consequently, the desired noise reduction only occurs at high frequencies.

According to Lilley [10] the noise reductions can be achieved by the following assumptions:

i. The length of the serrations must be in the same order as of the turbulent boundary layer thickness at the T.E.
ii. The shape of the T.E. serration must be sharp sawtooth.

The researches have been done research on the different types of trailing edge serrations which are as follows:

i. Sawtooth serration- these are the vertical serrations along the blade or airfoil edges.
ii. Single edge serration- these serrations are made at one side of the airfoil and other side kept flat i.e., either on leading edge or trailing edge.
iii. Double edge serration- in this type of serrations, serrations have been made both side of the airfoil i.e., on the leading and trailing edge.
iv. Micro-serration- in this type of serrations, serrations have been made much smaller than the thickness of airfoil and creating a serration like a fan pattern.

However, there are some other types of serrations such as Sawtooth Serration, brush–like or comb–like, flow–permeable or boundary layer re-energised trailing edges or porous airfoils, Sinusoidal Serration, Triangular serrations, Quadratic spline serration, curved serration, elliptical trailing edge serration, iron shaped trailing edge serrations etc.

1.1 Theoretical Background of Trailing Edge Serrations and Associated Noise

Noise from wind turbines, fans, aeroplanes, etc., is dominated by tonal noise owing to instabilities and broadband self-noise; mechanical and electrical noise contribute very somewhat. The trailing edge serrations can be utilised to mitigate both types of noise. When no boundary layer transition occurs on the pressure side, tone noise owing to instability arises at low to medium Reynolds values for the baseline model. There are two main types of applications for serrations on the trailing edge:

i. Sawtooth type or cutting the trailing edge surfaces directly.
ii. Adding the serrated flat plate with the existing trailing edge.

As illustrated in Figure 1, the geometrical parameters of trailing edge serrations are often connected with serration amplitude (A) and wave length (λ).

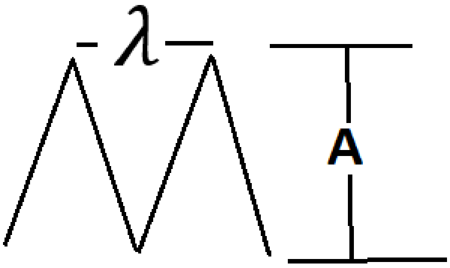

Fig. 1. Geometrical parameter of trailing edge serration

Mascha [7] states that investigating birds feather morphology have detected distinctive alterations in owls' feathers owing to the animals' requirement for quiet when flying. Long distal barbs (or reaping hooks) and comb-like features on an owl's primary feather are the consequence of bent barbs. The owl's bent pennulum puts barbules on the feathers' surface. Graham's [8] work on the silent flight of owls identified the feather modifications responsible for quiet flight.

Graham [8] identified and published the crucial three owl features responsible for quiet flight. The owl's feathers have a downy top surface, a comb at the leading edge, and a fringe at the trailing edge.

The findings of this study were used by Kroeger *et al.,* [9] and Lilley *et al.,* [10]. The comb at the leading edge, the fringes at the trailing edge, and the downy, fibrous upper surface of an owl wing are all seen in Figure 2. The owl's ability to glide quietly at 2–20 kHz emerged some 20 million years ago. Prey animals like voles and mice have hearing ranges that correspond to these frequencies. The wings of an owl are well-suited for both flight and making noise.

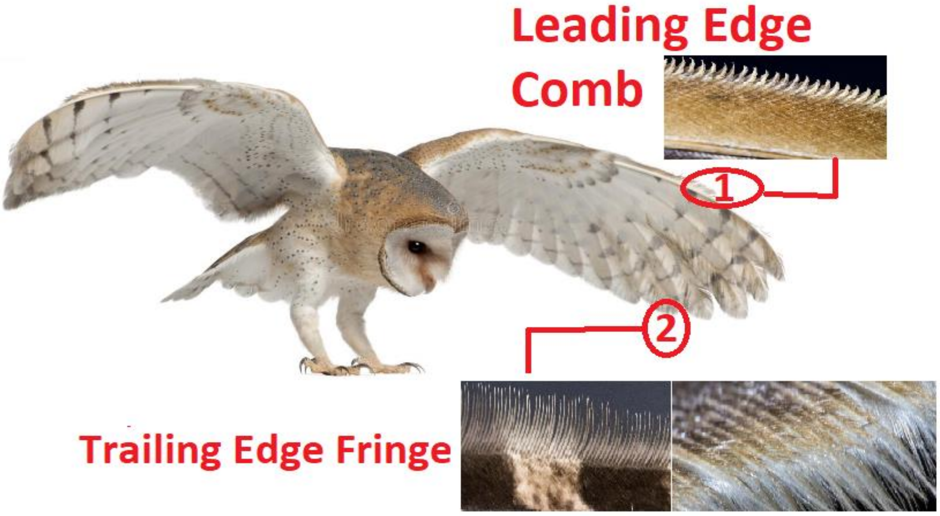

Fig. 2. Main characteristics of the owl's for achievement of the silent flight

An owl can fly at a 24 degrees angle while it hunts. At Re $1.5x10^5$, the owl's lift coefficient is 1. Flow separation at the leading edge hinders conventional airfoil stability. It then stalls. Geyer *et al.,* [11]. Figure 3 indicates that down feather filaments have a thin, smooth structure greater than Kolmogorov vortices. Flexible wing surfaces may soak up turbulent boundary layer energy in this way, making the bypass dissipation process crucial in reducing noise over 2 kHz. When compared to the harris hawk and the common kestrel, the barn owl's flight data had superior noise characteristics. Previous study has shown that quiet owl flight is most beneficial at medium to high frequencies (Figure 4). The third-octave frequency and sound pressure level in decibels (dB) are used to grade trailing edge noise.

Fig. 3. Represents the serrations at the leading edge and the trailing edge of the owl

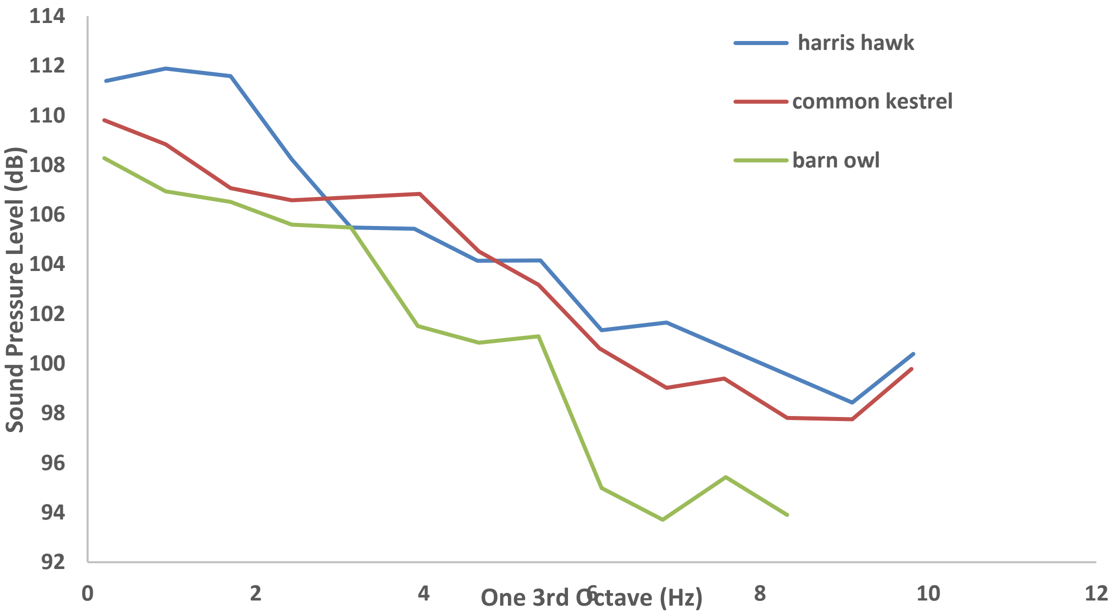

Fig. 4. One third octave frequency and the sound pressure level in dB from flyover measurements

1.2 Application of the Serrations

Noise and sound pressure are reduced by serrations. Serrations on an airfoil's trailing edge can cut down on the noise it makes. The serrations are longer when the frequency of the noise is low. The noise is not affected by changes to the serration on the trailing edge, coherences in the span, or the direction of flows. Uses for serrations include: Wind turbines (both onshore and offshore), Ceiling fan industries, HVLS fans, Nacelles or engine cover of the aircraft and Aircraft Wing. Serrations on the trailing and leading edges have been proven to act as valid passive noise reduction instrument/device for an airfoil. Serrated trailing edges are easy to make, set up, and maintain, according to Oerlemans *et al.,* [21]. Serrations are better than choices that are overly complex or need mechanical modifications. Serrated airfoils reduce noise, although installation alone doesn't account for all efficiency gains.

1.3 Source of Aerodynamic Noise Generations

High-speed action causes aerodynamic noise. Aerodynamics and equipment noise add up to body noise. Source bodies might be a wind turbine, aircraft, engine, or fan [57]. Aerodynamic noise created by air interacting with source bodies at high speeds is substantially more noticeable than mechanical noise. For estimating aerodynamic noise, Fleig *et al.,* [12]. created a computer model that accounts for each wind turbine blade's unique shape. This is a key step toward quieter wind turbine blades. This study's approach models and estimates acoustic emissions from various trailing edge, leading edge, and tip designs. Large-Eddy Simulation models the airfoil's acoustic field and the trailing and leading-edge turbulent fluctuations to test its performance. Real-world measurements corroborate the trailing edge's accurate flow characteristics. The trailing edge produced the most noise.

1.4 Self-Noise Generation Mechanism of Airfoil

When an airfoil's solid edge comes into contact with the turbulence in its own boundary layer, a sound known as "self-noise" is produced. Brooks *et al.,* [15] said solid and fluid interaction in the wake zone causes airfoil self-noise. Powell [16] initially investigated trailing edge noise. From the results of several in-depth studies, including Williams and Hall [17], additional researchers like Chase [18], Paterson and Amiet [19], Lee and Lee [36], and Howe [20] also provided a great deal of information. In low turbulence flows and low-pressure loading configurations, leading-edge noise is not the principal source of noise and must be studied apart from installation consequences [59].

Lighthill *et al.,* [13,14] suggested that trailing edge noise is a main source of noise, thus academics have concentrated on explaining it.

To foresee the production of trailing edge noise, various frameworks were developed in the 1970s, usually based on one of three perspectives.

i. An acoustic model has been developed based on the Lighthill’s acoustic similarity. i.e., developed by Lighthill [13,14].
ii. A solution derived from the theory of linearized equations of hydro acoustics from special problems. This model was developed by Chase [18], Paterson and Amiet [19].
iii. Microphone installing approaches for recording pressure fluctuations or noise data recording.

Classical works by Llorente and Ragni [6] and Howe [20] illustrate reliable predictions of trailing edge noise. In this work, researchers employed the classical model proposed by Williams and Hall [17] to forecast noise owing to a formed turbulent boundary layer. This research predicts far-field noise owing to surface pressure changes near an airfoil's serrated and unserrated trailing edge (T.E).

2. Methodology

2.1 Geometrical Presentation and Receiver Location for Our Research

Llorente and Ragni [6] published TU-Delft wind tunnel research for aerodynamic calculations. This wind tunnel has a maximum test section velocity of 120m/sec, test section dimensions of 2.6 x 1.8 x 1.25, and a contraction ratio of 17.8. This wind generator has a 2.9-meter-diameter fan and a 525-kW direct current motor. Authors computed the overall pressure by averaging pressures recorded outside and near the wake profile. To compute static pressure in the free stream, we must first remove total pressure outside the wake zone from wind tunnel dynamic pressure. The NACA 643418 airfoil had a chord length of 250 mm and a span of 1225 mm. 50 pressure measuring tabs were inserted in the test portion to calculate wing pressure forces. Maximum experimental Rec was 1 x 10^6. Aluminium alloy trailing edge serrations were attached to the pressure side of the wing. Figure 5 illustrates.

Fig. 5. Wind tunnel test model of NACA 643418 airfoil

The NACA 643618 airfoil was evaluated in a wind tunnel using a two-bladed rotor and an un-coned blade, with more than 30% of the blade outboard. 21 and 31 RPM data was obtained. The appropriate data was captured using PROP. After examinations, it was noted: Tip speed of the rotor is 21 RPM and 31 RPM. By which it was realised that that the increments in energy were realised with 2 speed operation of the rotor and analytical prediction with experimental was well established at both the speeds. Loftin *et al.,* [24] and Khalil [58] tested NACA 643418 in a 2D low-turbulence wind tunnel at Langley. The test section was 3ft x 3ft x 7.5ft. In the wind tunnel, the Reynolds number may be adjusted using wind-tunnel-airspeed at atmospheric pressure. Reynolds number varied from 1.50 to 2.0 in the experimental area. Lift and drag force measurements were determined using the integrated pressure acting on all sides and a low turbulence wind tunnel with a 3-component balance for accuracy. Previous researchers developed a mathematical model for a family of airfoils with low drag [25-27]. Next, NCS programming created a virtual wind tunnel. Figure 6 compares theoretical, experimental, and NACA 643418 airfoil data.

Wortmann and Althaus [28] examined experimental performance in a Laminar Wind Tunnel (LWT). Full Laminar Wind Tunnel dimensions are 730mm, 2730mm, and 3150mm; test section top speed is 30m/sec; frequency range is 20Hz to 5KHz. Laminar Wind Tunnel is open return. NACA 643418 600mm chord features 30% flap. Aerodynamic properties were computed for an attack angle of 3 and Reynolds number of 2.5 x 10^6.

Figure 7 shows the results of hot wire prob tests on the NACA 643418 and NACA 0012 in a wind tunnel to assess the turbulent boundary layer and two-point velocity correlation. In inhomogeneous boundary layer turbulence with large gradients of kinetic energy, mean velocity, etc., integral correlation length scales are highly reliant on processing method.

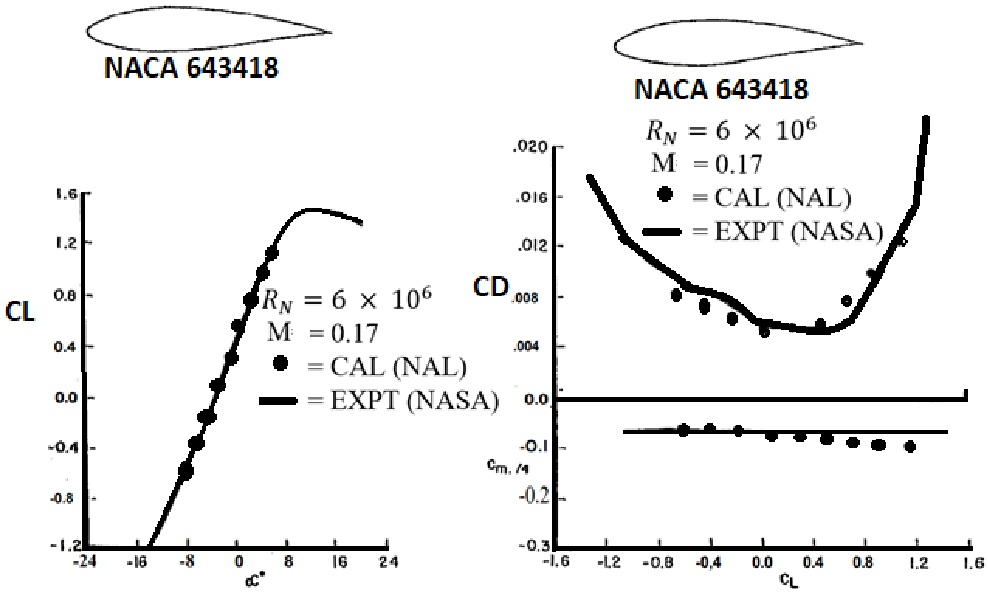

Fig. 6. The aerodynamic performance of NACA 643418

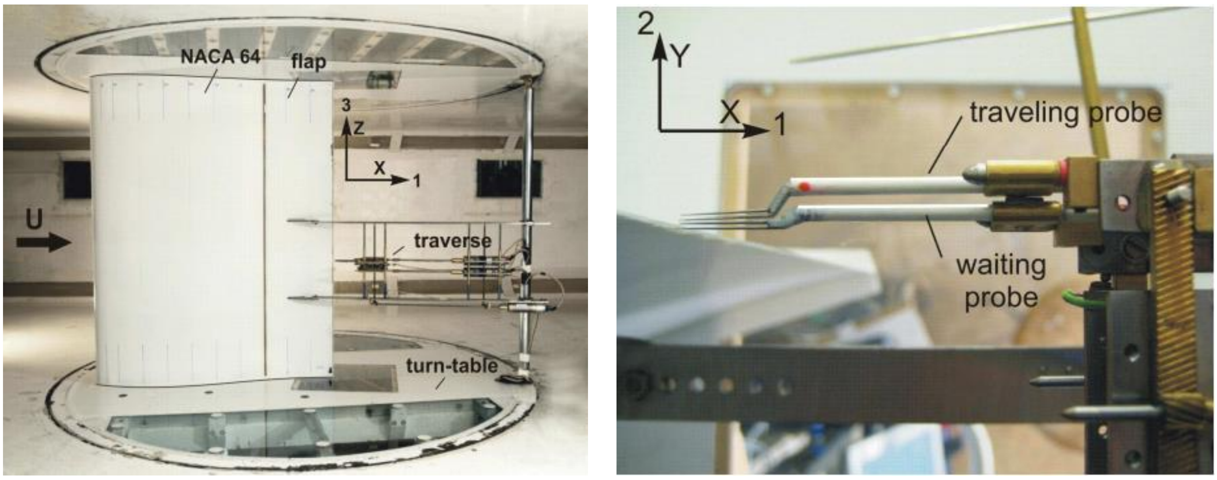

Fig. 7. NACA 643418 wing in the LWT with hot wire probe

Fans, wind turbines, and aeroplanes have all profited from years of research and development to reduce acoustic noise by optimising the wing/blade, according to Timmer [32]. For acoustic validation, Kamruzzaman *et al.,* [33] were used. Sound pressure was measured with an average error of 4 dB across the audible frequency band. Only 2D was studied.

Oerlemans *et al.,* [21] tested GE's 2.3 MW wind turbine. Using G.E. templates for different radial stations, the serrated sawtooth on the blade's trailing edge was created to be perpendicular to the flow direction. This study compares the noise reduction achieved by a sawtooth serration on the NACA651210 airfoil with Howe's theoretical projections [22]. A larger base sawtooth cause a lower turbulent length scale in the far wake. This effort can reduce engine, wing, and turbine noise.

Herr [35] conducted with the directional microphone and hot wire at the DLR Aeroacoustics Wind Tunnel in Braunschweig. Herr and Dobrzynski [22] detail the flat plate experiment setup. TE noise spectrum was evaluated using a directional microphone (elliptical mirror). Williams and Hawkings [30] provide background on specular resolution and gain calibration. Hot-wire measurements of integral boundary layer metrics near the trailing edge.

Due to a lack of sufficient wind turbine measurement equipment, XFOIL performance has been employed to approximate NACA 0012 boundary layer measurements [15]. Drela [23] used Reynolds values between 1.1 and 1.6 for cambered airfoils and 2.1 to 7.9 for flat plates. All computations were done at 40 to 60 metres per second and 0 to 13 degrees of attack. Airfoils with a thickness of 0.15 to 1mm have the same trailing edge noise as a conventional wing. A brush-designed trailing edge would have 0.3 mm to 0.5 mm fibre diameter, 0 to 10 degrees fibre orientation, and 5 to 100 mm fibre length. This study aimed to examine von Karman vortex filaments and trailing edge boundary layer noise.

2.2 A Numerical and Computational Approach for Noise Prediction

Reducing the noise impact on the human's life is a major concern in this era. However, the trailing edge serrations are becoming very popular, because of ease of manufacturing, installation as well as the maintenance. Porous and brushes trailing edge serration are little difficult to manufacture.

2.2.1 The governing equations of the sound fields

Farassat and Brentner [29], and Williams and Hawkings [30] provide the traditional derivation for computing the acoustic field. Gutin [31] were the first to theorise about rotating body sound. At Gutin's time, theory and experiment were used to forecast noise qualitatively and quantitatively. Gutin's noise prediction formula is used today with minimal changes. Gutin contends that sound is best quantified in a fluid since the pressure is continually changing. His theory mathematizes pressure waves using homogenous satisfaction [31].

$$\frac{\partial^2 p}{\partial t^2} - C^2 \frac{\partial^2 p}{\partial {x_i}^2} = 0 \tag{1}$$

where, C is known as speed of sound.

The equations derived by Williams and Hawkings [30] can be expressed as follows:

$$\frac{1}{{a_0}^2}\frac{\partial^2 p'}{\partial t^2} - \nabla^2 p' = \frac{\partial^2}{\partial x_i \partial x_j}\{T_{ij}H(f)\} - \frac{\partial}{\partial x_i}\{[p_{ij}n_j + \rho u_i(u_n - v_n)]\delta\,(f)\} + \frac{\partial}{\partial t}\{[\rho_0 v_n + \rho(u_n - v_n)]\delta\,(f)\} \tag{2}$$

where, a_0 = is known as speed of sound in the far field, p' = is known as far field sound pressure level, $H(f)$ = is known as Heaviside function, f is known as the moving Kirchhoff surface, p_{ij} = is known as compressive stress tensor, n_j = is known as norm unit vector pointing exterior side, u_i = is known as velocity component in x_i direction, u_n = is known as normal component of velocity of fluid, v_n = is known as normal component of surface velocity, $\delta\,(f)$ = is known as Dirac delta function, ρ_0= is known as the fluid density without acoustic interreference.

The terms on the right side of the equations are defined as the

$\frac{\partial^2}{\partial x_i \partial x_j}\{T_{ij}H(f)\}$ = will contribute to quadrupole sources

$\frac{\partial}{\partial x_i}\{[p_{ij}n_j + \rho u_i(u_n - v_n)]\delta\,(f)\}$ = will contribute to dipole sources

$\frac{\partial}{\partial t}\{[\rho_0 v_n + \rho(u_n - v_n)]\delta\ (f)\}$ = will contribute to monopole sources

In incompressible flow, the effects of quadrupole sources are negligible or it can be ignored since it does not have any vital effects on the sound.

By using above equation, the light hill stress tensor can be rewritten as:

$$T_{ij} = \rho u_i u_j + p_{ij} - {a_0}^2\ (\rho\text{-}\rho_0)\ \delta_{ij} \tag{3}$$

and p_{ij} can be given as:

$$p_{ij} = p\delta_{ij} - \mu\ \left[\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} + \frac{2}{3}\ \frac{\partial u_k}{\partial x_k}\delta_{ij}\right] \tag{4}$$

where, p is defined as the reference pressure.

3. Results

3.1 Acoustic Behavioural Analysis of Serrated Trailing-Edge

Jaworski and Peake [34], and Herr [35] examined the impacts of trailing edge serration on NACA 643418 airfoils using a three-dimensional Reynolds averaged numerical simulation (RANS) model and a transitional smoothed suction-free transition (SST) turbulence model. Empirical methodologies for estimating aerodynamic data were utilised to check the numerical results, and TU-wind Delft's tunnel confirmed the results. The NACA-643418 airfoil was tested with and without trailing-edge serrations in a wind tunnel. The ANSYS Transition SST model was developed on a C-type hybrid grid, which combines an unstructured and structured grid [37].

Oerlemans *et al.,* [3,21] have presented numerical and experimental methodologies on trailing edge serrations. These have shown excellent noise reductions on 2D airfoils and 3D wings, especially in wind turbine sectors. First 2.3 MW horizontal wind turbine with trailing edge serrations. According to the findings, a serrated blade cuts background noise better than a smooth blade.

Based on Chen *et al.,* [38], and Liu *et al.,* [55], they ran a simulation to decrease the noise from the bionic wing's serrated trailing edge. Also, numerical and experimental results matched well. Chen *et al.,* [38] created a bionic fan inspired by the long-eared owl's wing using the Taguchi method, enabling for efficient aerodynamic optimization. This 40% longer bionic wing was designed using owl wing cross-section data. In the for-profit programme, finite volume was used for numerical simulation [39].

Shen *et al.,* [43] devised a splitting technique for viscous-acoustic turbulent flows utilising the 3D compressible Navier Stokes equations. Code created in Ellipsys3D by the technical university of Denmark, Ris National Laboratory, department of wind energy, Michelsen [40] and Sørensen [41] solves filtered incompressible flow equations. Ellipsys3D uses a typical pressure-velocity coupling system, a Green-Gauss node-based gradient scheme, and a discretized finite volume technique with constrained central differencing for momentum.

The momentum equations were discretized using a second-order backward central differencing approach [42]. To eliminate pressure separation oscillation, an upwind approach was designed using Quadratic-Upstream-Interpolation-for-Convective-Kinematics. Since there is no optimal value for SIMPLE's relaxation parameters, the solution is indifferent to them. Shen *et al.,* [43] used SIMPLEC algorithms for consistent or better solutions.

According to Moreau and Doolan [44] and Niknahad [60], reducing high-frequency band noise with trailing edge serrations reduced vortex shedding. Noise suppression needed a larger wavelength-to-amplitude ratio. Moreau reduces band noise by 13 dB. Xu and Li [45] investigated and confirmed the noise suppression potential of the NACA0018 airfoil with a Reynolds number of $1.4\text{x}10^5$. Aerodynamic performance is unaffected. DNS and LES are very reliable, making it difficult to implement numerical simulation (LES).

Han *et al.,* [46] analysed the flow over the trailing edge of NACA 0012 airfoils with sinewaves at zero angle of attack in a uniform stream with a Reynolds number of 2 105. The results show that 2D spanwise vortices near airfoil trailing edges generate aerodynamic noise. Miotto *et al.,* [47] suggested a method for determining aeroacoustics transfer function using leading edge noise. This study used DNS for increased trailing edge serrations on the NACA0012 airfoil at Reynolds number $5\text{x}10^4$. This technique is valid for a broad span wing in subsonic compressible flow with high frequency disturbances, and it accounts for trailing edge scattering of the aerodynamic back effect.

Howe [48,49] developed the first theoretical and analytical model for reducing trailing edge sound waves at low Mach number with zero angle of attack. He introduced trailing edge serrations that ignore external noise sources. Changing the surface pressure at the trailing edge can impact turbulent eddies.

For the sawtooth trailing edge serrations, the noise reduction is in the order of 10:

$$log\ log\ \left[1+\left(\frac{6h}{\lambda}\right)^2\right],$$

and for the sinusoidal trailing edge serrations, the noise reduction is in the order of 10:

$$log\ log\ \left(\frac{6h}{\lambda}\right)\ dB.$$

The above formulation has been done on the assumption of $\frac{fh}{u_\infty} \gg 1$, where, $h, \lambda, f, and\ u_\infty$ are the amplitude of the serrations, wavelength of the serrations, acoustic frequency, and main stream velocity respectively.

According to Howe theory, reduction in noise can be decrease by either increasing the frequency or by decreasing $\frac{\lambda}{h}$. In other words, the noise reduction can be greatly reduced by either narrower serrations or sharper serrations was best experimentally presented by Gruber *et al.,* [52], Pröbsting [54], Chong *et al.,* [50,52], Oerlemans *et al.,* [21], Lee and Lee [36], and Moreau and Doolan [51] and Brooks *et al.,* [15].

The phenomenon of prediction of noise reduction on the basis of $\frac{\lambda}{h}$ parameter is as follows:

For both sawtooth and sinusoidal type serrations, if $\frac{\lambda}{h} > 1$, noise level predictions were very similar in both sawtooth and sinusoidal type serrations, if $\frac{\lambda}{h} < 1$, greater noise level reductions for both sawtooth and sinusoidal type serrations due to narrower serrations or sharper serrations at the root and peak regions.

Table 1 displays the many serrations used by researchers, Gruber *et al.,* [52] developed innovative serration treatments to reduce high-frequency noise [52,54]. Sawtooth serrations minimize noise by 2 to 4 dB in the 1KHz to 7KHz and 7KHz to 20KHz frequency ranges. Raising the serration depth and lowering the slit distance reduced the noise level. Non-deterministic trailing edge serrations lower wideband noise by 3dB.

Table 1
Different serrations adopted by various researchers

Serration Type	Noise Type	Bionic Object(s)	$R_{ec}=10^5$	AOA (°)	Author's	Year
Directly cutting serrations	Turbulent boundary layer	SD 2030 airfoil	2.15, 2.56, 3.18	0	Qiao *et al.,* [1]	2013
Directly cutting serrations	Instability tonal	NACA 0012 airfoil	1 to 6	0,5,15	Chong *et al.,* [2]	2013
Flat plate inserts	Trailing edge	Model scale wind turbine	1.6	0	Oerlemans *et al.,* [3]	2001
Flat plate inserts	Turbulent boundary layer	NACA 0018 aifoil	1.32, 2.63, 5.26	0, 3, 6	Arce *et al.,* [4]	2015
Flat plate inserts	Turbulent boundary layer	NACA 0018 aifoil	3.95	5	Avallone *et al.,* [5]	2016
Directly cutting serrations	Instability tonal	NACA 0012 airfoil	1.5	−5, 0, 5, 10, 15	Llorente and Ragni [6]	2012
Flat plate inserts	Turbulent boundary layer	NACA 6512-10 airfoil	2.15 to 8.62	−5, 0, 5, 10, 15	Lilley [10]	2013
Flat plate inserts	Trailing edge	NACA643418	30	0, -5, +5	Paterson and Amiet [19]	2019
Flat plate inserts	Trailing edge	Full scale wind turbine	1.6	0	Oerlemans *et al.,* [21]	2009
Directly cutting serrations	Turbulent boundary layer	NACA 0012 airfoil	2 to 6	15	Chong *et al.,* [50]	2012
Flat plate inserts	Turbulent boundary layer	Flat plate	0.78 to 4.20	0	Moreau and Doolan [51]	2012
Directly cutting serrations	Instability tonal	NACA 0012 airfoil	1 to 6	15	Gruber *et al.,* [52]	2013
Directly cutting serrations	Trailing edge	NACA 0012 airfoil	2 to 6	0	Chong *et al.,* [56]	2015

Serrations induced by direct cutting of airfoils create horseshoe vortices, according to Jones and Sandberg [53], Pröbsting [54], and Liu *et al.,* [55]. Noise is caused by the bluntness of the sawtooth or the upwash and downwash oscillatory flows between the serrations. Intensity of low-frequency tonal noise is proportional to flow rate and serration amplitude. Chong *et al.,* [2,56] that woven wire mesh serrations or thin brush bundles, synthetic foams, and porous metal can minimise tonal noise. Broadband self-noise and narrow-band tone noise were reduced in frequency and amplitude.

Qiao *et al.,* [1] explained trailing edge serrations' noise-reduction method best. The turbulence's speed varies by location and direction. Thus, aerodynamics may be utilised to estimate noise reduction at low and medium frequencies as well as noise increase at high frequencies.

4. Conclusions

This discourse shows full preparation. However, noise reduction and innovation are needed. Frequencies reduce background noise. Sawtooth, sinusoidal, and cambered sawtooth trailing edge serrations lower noise by 6 and 3 dB. Serration kinds, techniques, theories, and empirical formulations can lower noise by 9 dB. Change noise's form, size, or pattern. No study has examined adding turbine blade tips to wind turbine designs to lessen tip vortices, a major noise source, or devising a system resembling high lift devices in aircraft wings to reduce turbulent friction and noise. Bio-inspired trailing edge serrations are porous. Aerodynamics and all-frequency noise are improved by the poro serrated trailing edge. quiets 4+ dB. Nature-inspired trailing edge serrations lower noise by 5 dB. Bio-inspired noise reduction devices have unknown scaling and design. Bioinspired trailing edge devices reduce noise 10 dB. Recently, significant data pertaining noise and trailing-edge flow has been revealed. Grid spacing for a third-order upwind difference scheme and the Smagorinsky constant Given a sufficient grid spacing and the Smagorinsky constant, the surface pressure distribution and trailing edge surface pressure spectra of the airfoil agreed with high-frequency experimental data. Experimental results matched trailing edge vortex shape and turbulent velocities. The trailing edge vortex pressure spectra and acoustic field matched experimental results at wind turbine flow and noise simulation frequencies. High-Reynolds LES simulations require a precise airfoil grid.

Acknowledgement

This research was not funded by any grant.

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