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Energy Procedia 160 (2019) 633–640

Energy Procedia

www.elsevier.com/locate/procedia

2nd International Conference on Energy and Power, ICEP2018, 13-15 December 2018, Sydney, Australia

Wind turbine noise and its mitigation techniques: A review

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Abstract

This paper discusses various noise generation mechanisms in wind turbines and potential noise reduction techniques. Special emphasis has been laid on reviewing aerodynamic noise sources and recent advances in mitigation of aerodynamic noise. Several studies on the effect of wind turbine noise on human health have linked wind turbine noise with annoyance and sleep disturbance. Thus, there is a need to reduce these noise emissions which can be achieved by targeting the specific noise sources. Techniques for mitigation of trailing edge noise, tip noise and leading-edge inflow noise have been discussed along with recent developments.

Selection and peer-review under responsibility of the scientific committee of the 2nd International Conference on Energy and Power, ICEP2018.

Keywords: Wind turbine noise; Trailing edge noise; Tip noise; Noise reduction; Aeroacoustics; Serrations.

1. Introduction

Withthe increasing global energy demand, wind turbines offer an effective way to harness the energy contained in the wind. To satiate an ever-increasing energy demand around the world, more wind farms are being established and it is becoming difficult to keep these wind farms very far from human population. As these turbines are placed in the vicinity of human habitats, several issues like noise, structural vibration and visual impact have been reported by the

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Selection and peer-review under responsibility of the scientific committee of the 2nd International Conference on Energy and Power, ICEP2018.
10.1016/j.egypro.2019.02.215

local communities. Among these, wind turbine noise is one of the major hindrances in the development of wind power industry [1]. Due to noise complaints by residents where these wind turbines are installed, several researchers have conducted studies to find the link between wind turbine noise and its potential implications on the mental and physical health of nearby residents.

An expert panel on wind turbine noise and human health [2] found sufficient evidence to establish a causal relationship between wind turbine noise and annoyance. The panel also found limited evidence for a causal relationship between wind turbine noise and sleep disturbance. Studies by Pedersen and Waye [3] on perception and annoyance due to wind turbine noise found that the proportion of people annoyed by wind turbine noise was larger than those annoyed by community noise sources at same A-weighted Sound Pressure Level (SPL) and the proportion increased rapidly with increasing SPL (see Fig. 1). The issue of annoyance is found to be more dominant in rural landscape than urban surroundings, capable of inducing sleep disturbance and a hindrance to psycho-physiological restoration [4].

These studies reveal that wind turbine noise causes annoyance and even sleep disturbance in some cases. Thus, there is a need to further address the issue of wind turbines noise due to its above discussed adverse effects on nearby communities. The aim of this paper is to review wind turbine noise mechanisms which are dominant in modern wind turbines and discuss some promising noise reduction techniques.

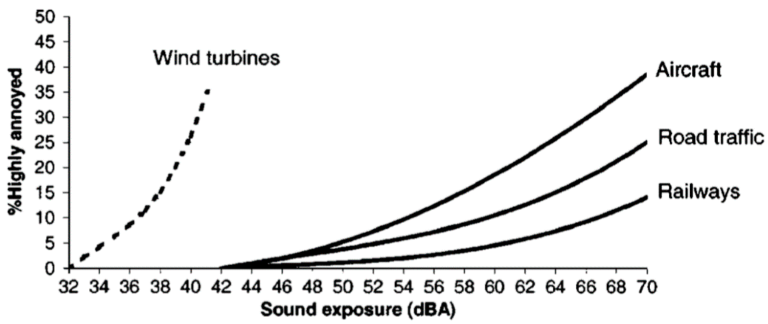

Fig. 1. A comparison between dose-response relationship of perception of wind turbine noise and transportation noise [3]

2. Global wind energy scenario

Wind turbines have become an integral part of the global energy landscape. It is noteworthy that the share of wind energy is 4.4% in total world electricity generation [5]. Wind energy has been on a steady rise for the past few years, as shown in global installed wind capacity presented in Fig. 2. In 2017 alone, global wind power generating capacity grew by 11% reaching over 539 GW [6].

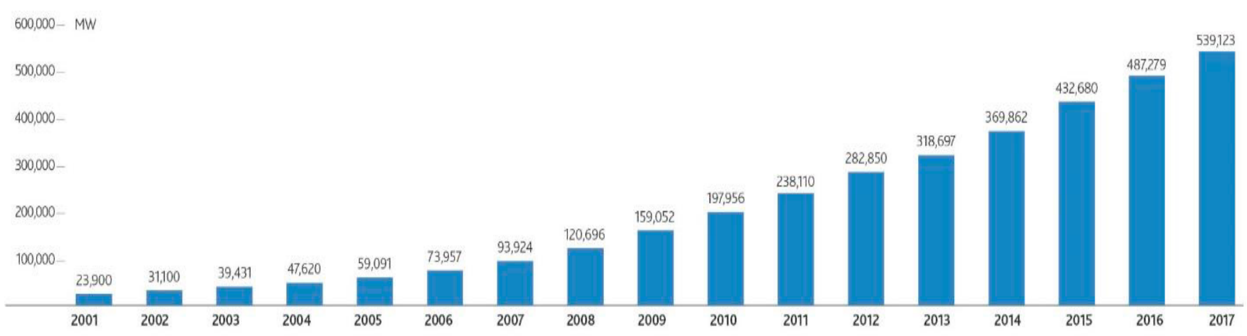

Fig. 2. Global cumulative installed wind capacity (2001-2017) [6]

According to the Global Wind Report (2018) by Global Wind Energy Council (GWEC), China, US, Germany and India are leading the global wind energy production followed by Spain, UK, France, Canada, Brazil and Italy which together account for 85% share of global wind energy capacity. These figures reflect an increasing reliance on wind energy around the world and the need to develop more efficient wind turbines with minimized noise for larger acceptance by communities.

3. Wind turbine noise

Noise generated from wind turbines are mainly of two types- mechanical and aerodynamic. Mechanical noise is generated from various machinery components in the wind turbine and is tonal in character. Aerodynamic noise is generated due to flow of air above the blades which interacts in different ways with the blade surface, leading to different aerodynamic noise sources. These mechanisms are discussed in detail in the following sub-section.

3.1. Mechanical Noise Sources

Mechanical noise in wind turbine is generated by various moving components present in the nacelle like gearbox, generator, cooling fans and other auxiliary devices. Mechanical noise is predominantly tonal in character, meaning that the noise generated from mechanical sources peaks around certain frequencies and is harsher to human ears than broadband noise. Mechanical noise can however be reduced to a large extent by properly shielding the nacelle, using sound absorbing materials and vibration suppression [7]. This reduction has resulted in aerodynamic noise becoming a dominant noise source in wind turbines which is the center of focus in this paper.

3.2. Aerodynamic Noise Sources

Aerodynamic noise is flow induced noise caused by interaction of flow structures with the blade wall. Aerodynamic noise from wind turbines can be classified as *inflow turbulence noise* and *airfoil self-noise*. Relative contribution of individual sources to total noise are shown in Fig. 3. These noise sources and their mechanisms are discussed in the following sub-sections.

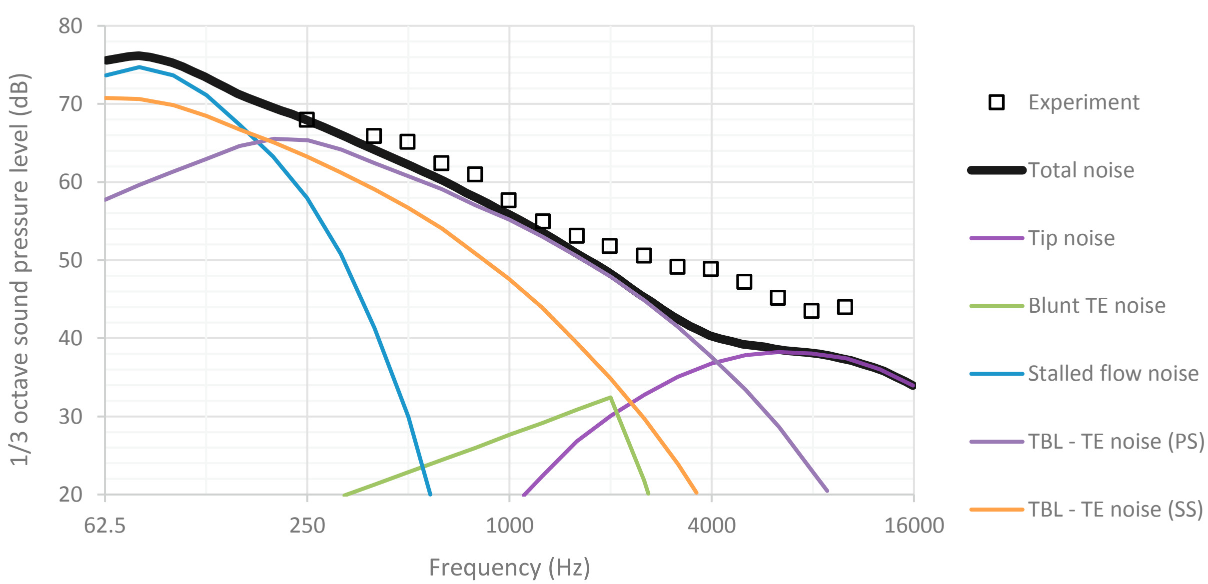

Fig. 3. Contribution of individual sources to noise from a wind turbine blade (reference tip) [7]

3.2.1 Inflow turbulence noise mechanism

Inflow turbulence (IT) noise is caused due to interaction of blade surface, especially the leading edge, with the oncoming atmospheric turbulence. This interaction of turbulent eddies with blade produces broadband noise which lies in the low frequency spectrum (up to 1000Hz) and is highly dependent on atmospheric turbulence intensity and turbulence length scale [7] (Fig. 4.a). Contribution of IT noise to total wind turbine noise has still not been completely investigated, especially due to its dependence on atmospheric stability and structure of turbulence. Recent experimental investigation by Buck et al. [8] carried out by measuring turbulence induced blade vibrations and comparison of directivity patterns show potential for characterization of IT noise for full scale wind turbines. Such experimental characterization can be instrumental in investigating the complete mechanism of this noise source.

3.2.2 Airfoil self-noise mechanisms

Turbulent boundary layer - trailing edge noise (TBL – TE)

Turbulent boundary layer - trailing edge noise, also known as trailing edge noise, is a dominating noise source in wind turbines which is of broadband nature with peak frequency lying between 500-1500Hz.TBL-TE noise occurs due to interaction of turbulent boundary layer with the sharp trailing edge of the airfoil (Fig. 4.c). At low Mach numbers, turbulent eddies are inefficient noise sources in free space or along an infinite plate, but on interaction with a sharp edge these turbulent eddies act as efficient noise sources and are strongly radiated into the atmosphere [7]. According to acoustic field measurements of Oerlemans *et al.* [9] contribution of trailing edge noise is most significant near tip region where flow velocity is high. The source strength shifts towards tip at higher frequencies.

Tip noise

Tip vortex is formed due to a cross flow generated by the pressure difference between pressure side and suction side. This tip vortex on interaction with the tip side and trailing edge leads to generation of tip noise, following the same noise mechanism as that of trailing edge noise [7] (Fig. 4.b). Itis of broadband character, typically lying in the high frequency region and is the dominant source in this range. Since human ears are most perceptible in the frequency range of 1-4 kH, tip noise becomes a prominent contributor to annoyance caused due to turbine noise.

Blunt trailing edge noise

A blunt trailing edge causes Von Karman type vortices resulting in tonal noise emission and can be seen as a sharp peak in a typical wind turbine noise spectrum (Fig. 4.d). This noise source is dependent on the shape of trailing edge, Reynolds number and the ratio δ^*/ t^* (where δ^* is the boundary layer displacement thickness and t^* is the trailing edge thickness) [7]. Normally blunt trailing edge noise can be eliminated through a sharp trailing edge.

Separated / stalled flow noise

Beyond a particular angle of attack, the blade gets stalled leading to large scale flow separation. The stalled flow is significantly unsteady and causes broadband noise emission (Fig. 4.e). Mild separation causes sound radiation from trailing edge, whereas deep stall causes noise radiation from the whole chord. It can be mitigated by avoiding stall conditions at the blade.

Laminar boundary layer noise

If the Reynolds number is less than about 10^6, the flow on both sides of the air foil may remain laminar up to the trailing edge (Fig. 4.f). In this case, boundary layer instabilities are likely to occur which can couple with trailing edge noise and resonate in a feedback loop. Such a condition will result in high levels of tonal noise from the turbine blade known as laminar boundary layer vortex shedding noise. It is found significant for small wind turbines where $Re < 10^6$. However, it can be avoided by tripping the boundary layer relatively far upstream of the trailing edge [7].

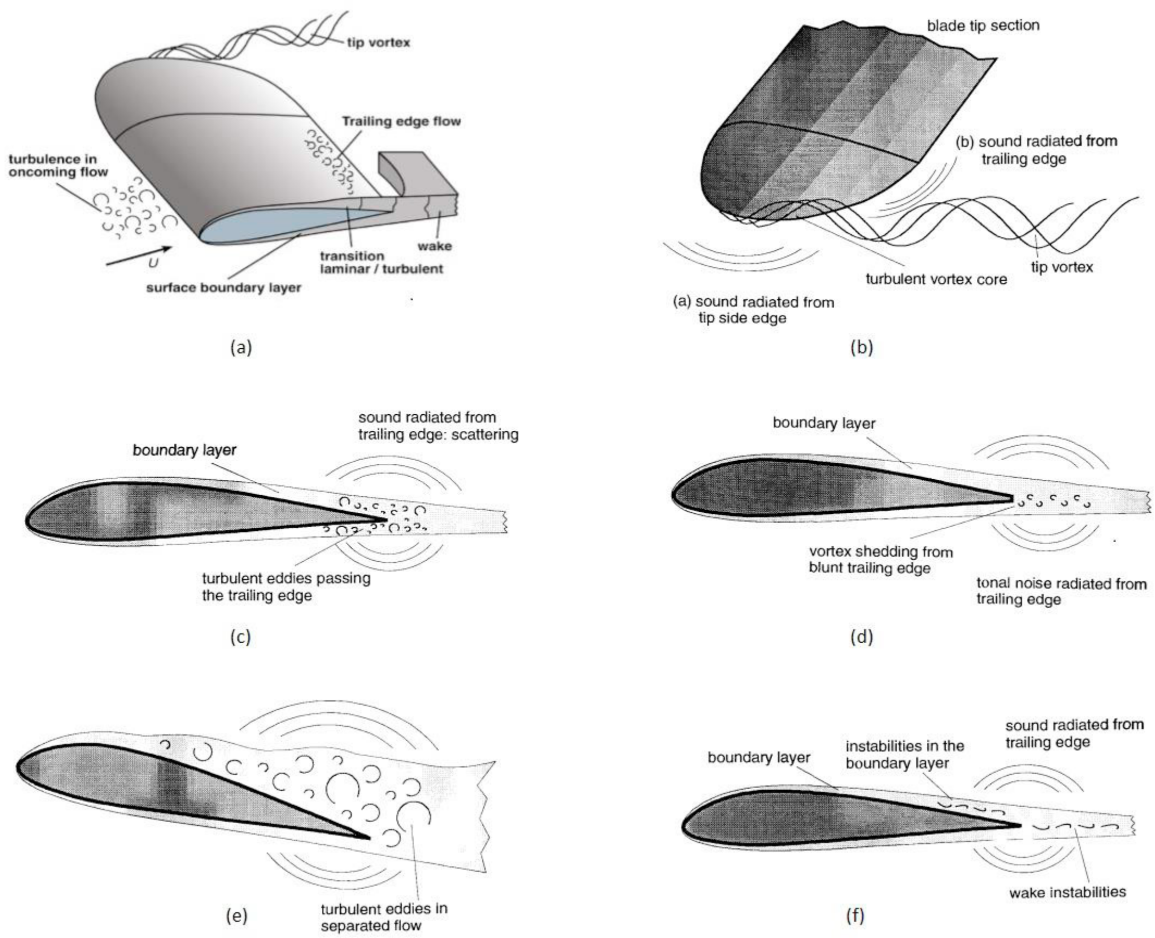

Fig. 4. (a). Flow over the outer section of a wind turbine blade; (b - f) Airfoil self-noise mechanisms [7]

4. Noise reduction techniques

Various experimental and numerical techniques have been developed for noise mitigation by taking advantage of our understanding of the noise mechanisms which provide an insight into the aero-acoustic characteristics of wind turbines. Some promising aerodynamic noise mitigation techniques targeting dominant noise sources have been discussed in this section.

4.1. Reduction of inflow turbulence noise

Dependence of inflow turbulence noise on atmospheric turbulence doesn't allow for much flexibility to mitigate noise from this source. However, changes in leading edge shape are found to significantly affect noise generation [10]. Based on this characteristic, many different leading-edge profiles have been proposed to mitigate IT noise. Bio-mimetic exploration for noise reduction by leading edge modification has been a topic of interest for many researchers. Experimental study of Hansen *et al.* [11] based on the concept of tubercles found in Humpback whale flipper used sinusoidal leading edge for reduction of tonal noise components. Tubercles with large amplitude and small wavelength were found to be effective in reducing tonal noise with a marginal penalty for lift. The mechanism is postulated to be affected by steam-wise vortices generated from troughs of tubercles which enhance momentum exchange in the boundary layer thereby altering its stability characteristics and frequency of velocity fluctuations in the shear layer near the trailing edge. Also, as the location of separation varies due to sinusoidal leading edge the separation line gets disturbed leading to changes in shear layer stability and frequency of velocity fluctuations.

Experimental and numerical studies by Chaitanya *et al.* [12] and computational studies of bio-inspired leading-edge serrations based on adaptations of Barn owl by Agrawal and Sharma [13] have further explored sinusoidal leading edge for its effectiveness in reducing broadband noise. Recent experimental investigations by Chaitanya *et al.* [14] on different leading-edge profiles highlighted leading edge slits as being superior to single wavelength leading edge profile for low frequency noise reduction. The new profiles have two dominant noise and highly coherent compact noise sources per serration wavelength which undergo destructive interference to mitigate noise from the leading edge. As much as 15dB noise reduction was achieved with leading edge slits as opposed to just 7dB for conventional single wavelength serrations. The effect of these new profiles on aerodynamic performance of airfoil remains to be explored.

Fig. 5. (a) Design of sinusoidal leading edge [13]; (b) Experimental setup of leading edge serrated airfoil [12]; (c) Leading edge slits [14]

4.2. Reduction of trailing edge noise

Since TBL-TE is the dominant noise source for most wind turbines, a number of mitigation techniques have been developed for its control. A survey of TE noise reduction techniques by Barone [15] provides an overview of several methods devised to mitigate TE noise. Trailing edge noise is directly proportional to $\cos^3\gamma$ (see Fig. 6) as per the analytical derivation using semi-infinite flat plate approximation [16]. This dependence on $\cos^3\gamma$ shows that noise is scattered most effectively when the path of turbulent eddies is perpendicular to the trailing edge. Trailing edge serrations provide a way to reduce the angle between eddy path and edge below 90°, thus decreasing the scattering of sound. Experimental observations on full scale wind turbine of 94m diameter with serrations have reported reductions of 3.2 dB [17]. However, since these serrations cannot always be aligned to the flow direction due to variable incoming flow velocity, they lead to increased sound level at higher frequencies [10].

To overcome this problem of flow alignment with serrations, the concept of trailing edge brushes was introduced. Experimental investigations by Herr [18] and Finez *et al*. [19] prove the advantage of trailing edge brushes over serrations in reducing airfoil noise. Porous trailing edge works similar to trailing edge brushes for reducing sudden change in acoustic impedance encountered at the abrupt edge by near blade flow. Studies by Geyer *et al.* [20] and Kinzie *et al.* [21] show potential in this technology for noise reduction, however, conclusive full scale experimental studies are required.

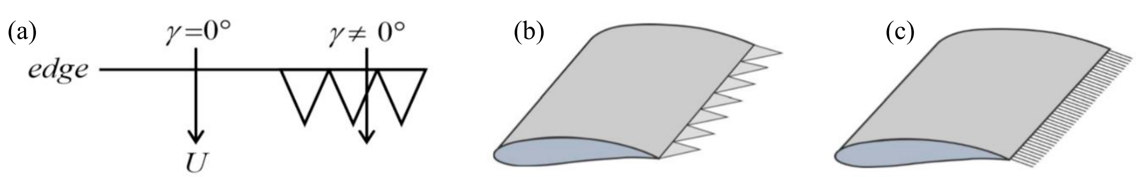

Fig. 6. (a, b) Trailing edge serrations; (c) Trailing edge brushes [10]

4.3. Reduction of tip noise

Tip noise is a dominant source of noise from wind turbines at high frequencies. Madsen and Fuglsang [22] initially identified tip vortex strength and extension of separation region with tip noise and suggested non-separating tip vortex tip as a probable solution. Fleig *et al.* [23] carried out numerical analysis of ogee type tip shape using acoustic analogy and gained 5dB noise reduction for frequencies above 4kH. Later experimental work by Kinzie *et al*. [21] over blunt, slender and ogee type tip explored the effectiveness of these tip shapes in mitigating tip noise. The selected tip shapes were designed to minimize the vortex wetted length and the interaction the vortex and side edge. Both slender and ogee tips proved to be effective in providing a reduction of 5-6 dB in Overall SPL.

Recent numerical investigations by Maizi *et al.* [24] for reducing tip noise by using reference tip and shark tip provided 7% noise reduction with shark tip but with a penalty in power of 3%. However, this computational aero-acoustic (CAA)analysis using Detached Eddy Simulation (DES) for resolving flow field and Ffowcs-Williams-Hawkings equation for acoustic calculation demands very high computational power. Deshmukh *et al.* [25] implemented an extended annular domain methodology which included the tip region in an annular domain to perform a parametric study of blended winglets for improved aerodynamic and aero-acoustic performance. This methodology provides a way to significantly reduce the computational cost (up to 75%) and resulted in about 25% noise reduction at mid-high frequencies along with enhanced torque output. Such low cost CAA methodologies can open the domain to extensive tip shape design optimization for noise reduction and power enhancement.

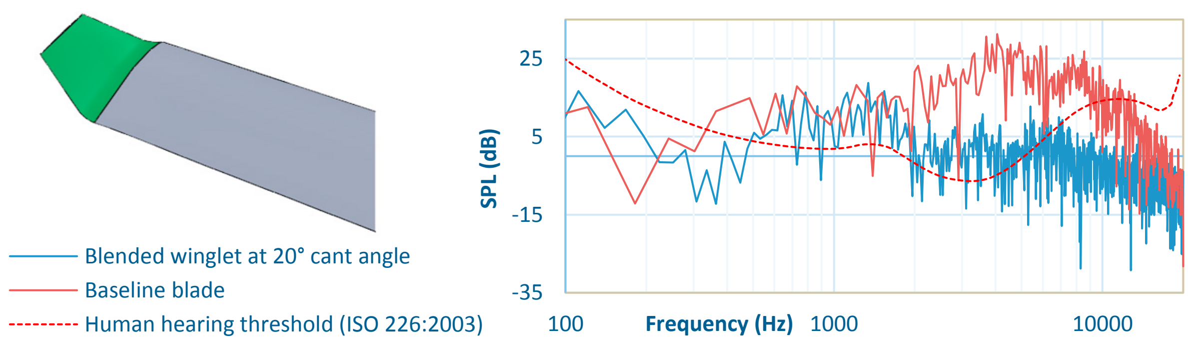

Fig. 7. Tip noise reduction through blended winglet: frequency spectrum of baseline blade vs blade with winglet [25]

5. Discussion

A review of various aerodynamic noise source mechanisms and techniques for noise reduction in wind turbine provided an insight into the fundamental nature of wind turbine aero-acoustics. Trailing edge noise and inflow turbulence noise are dominant in the low frequency region. Tip noise dominates the high frequency part of noise spectrum. Tip shape controls the strength and separation length of tip vortex which affects tip noise. Most of the noise with trailing edge as the source is generated from outbound portions of the blade where the flow velocity is higher. Blunt trailing edge noise, stall separation noise and laminar boundary layer noise are less significant as they can be easily regulated. Several techniques for noise mitigation have been discussed. Methods like serrated trailing edges for trailing edge noise reduction are already being used in some turbines but more effective methods for noise control are needed. Trailing edge brushes and porous trailing edges are potential technologies which can help gain extra trailing edge noise reduction. Lot of work has been done in identifying and mitigating inflow turbulence noise. Bio-mimicry has yielded leading edge serrations and slits for reduction of noise from this source. Leading edge slits have been shown to outperform serrations and provide very significant noise reduction. Tip noise reduction can be achieved by optimizing tip shape for reduced vortex strength and less interaction of vortex with tip edges. Computational aero-acoustics can help in faster optimization of blade shape to reduce noise by introducing less computationally expensive numerical techniques. Most of these technologies require further experimental validation and full-scale field tests.

6. Conclusions

The present paper reviewed several wind turbine noise mechanisms and mitigation methods along with the impact of noise from wind turbines on human life. Wind turbine noise is found to be more annoying than other community noise sources. Thus, effective methods for reducing wind turbine noise are required for minimizing human discomfort and prospective disorders. The effect of modifications on blade for noise reduction should not affect its aerodynamic performance or a tradeoff should be reached. Computational methods can ease design of low-noise blades by reducing time and effort. Full scale field implementation of new methods is required to examine their effectiveness in actual running conditions and interaction of noise from multiple wind turbines in farms.

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