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Wind Turbine Noise Reduction through Blade Retrofitting

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Abstract

This paper outlines a plan for the effective reduction of the audible sound level produced by aerodynamic noise from the power-generating turbine blades. The contribution of aerodynamic noise can be divided into two categories: inflow turbulence and airfoil self-noise. The base model and retrofit blade designs were modeled in SolidWorks. Subsequently, noise prediction simulations were conducted and compared to the base blade model to determine which modification provided the greatest benefit using SolidWorks Flow Simulation. The result of this project is a series of blade retrofit recommendations that produce a more acoustically efficient design and reduce noise complaints while enabling turbines to be placed in locations that require quieter operations.

Keywords

Wind Turbine Noise, Blade Retrofitting, Aerodynamic Noise, Electricity Generation

1. Introduction

Understanding the urgency of wind energy advancement and the kickback from local governments by rejecting wind farm development proposals results critical in the ongoing fight against Climate Change [1]. Wind turbines produce noise through both mechanical and aerodynamic mechanisms. Nacelle shielding is a widely accepted and frequently practiced method to reduce mechanical noise pollution, forcing aerodynamic noise sources to the forefront of complaints and concerns [2] [3].

Countries across the Globe have developed a growing concern and desire for a clean energy economy [4]. Most energy sources used today are from fossil fuels, a non-renewable energy source that introduces harmful greenhouse gas emissions [5]. As environmental changes have occurred, global temperature is used as a fundamental measurement for tracking the harmful effects of fossil fuels used as an energy resource [6]. This has remained the foundation of concern and motivation behind the utilization of clean energy technologies. The United States (U.S.) government has developed aggressive goals for energy alternatives, providing incentives, funding, and subsidies. According to the U.S. Department of Interior, climate change poses a threat not only to the environment, but to health, communities, and economic wellbeing. President Biden's Executive Order 14008 aims to tackle the climate crisis by committing to deploy 30 gigawatts of offshore wind by 2030, 15 gigawatts of floating offshore wind by 2035, and a target goal of permitting at least 25 gigawatts of onshore renewable energy by 2025 [7]. While wind energy proves to be a promising alternative energy source [8], wind turbines have generated complaints of excessive noise. This noise pollution yields negative health effects on human and wildlife habitats, such as annoyance and sleep disturbances. Due to this challenge, wind farm development is difficult in areas within proximity to human or wildlife populations. These health effects limit the locational use of wind turbines for residential homes and small businesses [9].

Wind turbines generate noise of two types: mechanical and aerodynamic. The mechanical noise is tonal and produced by the moving components within the nacelle. These components include the gearbox, generator, cooling system, hydraulics, and other auxiliary components. While mechanically induced noise is a major source of noise pollution, the use of nacelle shielding effectively provides a 3-5 dB noise reduction [10]. This modern mechanical noise reduction design is implemented using dampening techniques such as sound-absorbing materials and vibration suppression. The effective solutions for mechanical noise reduction are readily available and widely accepted, which pushes aerodynamic noise reduction into primary focus [11]. Aerodynamic noise sources are flow-induced and caused specifically by airflow interacting with different areas of the blade [12]. One category of aerodynamic noise is the inflow turbulence caused by the leading edge, resulting from the incoming atmospheric turbulence. The second category of aerodynamic noise is airfoil self-noise and is a result of trailing edge and tip noise. Of these three noise producers, the trailing edge is a major contributor [11].

Sound is measured in decibels (dB). As a relative comparison, wind turbines produce an average of 45 dB at 300 m (1000 ft) during normal operation. This is slightly greater than a refrigerator that operates at 40 dB and slightly less than a microwave operating at 50 dB [13]. To meet U.S. government renewable energy goals, noise pollution technology advancement is essential for onshore and offshore wind turbines. Lowering noise levels by 3 to 5 dB would be a noticeable reduction to the human ear [14]. This would provide health benefits to the surrounding population, yielding a greater use of wind turbines as a renewable energy source.

2. Project Test Site

The United States is observing higher rates of warming across the nation, but eight of the top ten states with the greatest rise in temperature in the last 20 years are in the Northeast [15]. This makes wind energy more desirable and provides an optimal location for a project test site. Seeking a wind farm with retrofit capability, wind energy demand, and noise complaints, Beaver Ridge Wind Farm in Freedom, Maine was the test site selected for enhancing noise reduction technology.

Beaver Ridge Wind Farm was commissioned in November 2008 as a 4.5 megawatt (MW), 3-turbine, wind project [16]. According to Patriot Renewables, these three General Electric 1.5 MW turbines produce approximately 12 million kilowatt-hours of emission-free electricity each year providing enough to power 2,000 homes and reduce CO_2 emissions by the equivalent of 630,000 gallons of gasoline consumed. The wind farm has also gained community disapproval due to noise pollution [17]. **Figure 1** shows nine residences within a one-mile radius of three turbines, labeled T1, T2, and T3. The closest three residences are Gerrish, Bloomstein, and Boulier and are within 400 meters of Turbine 3.

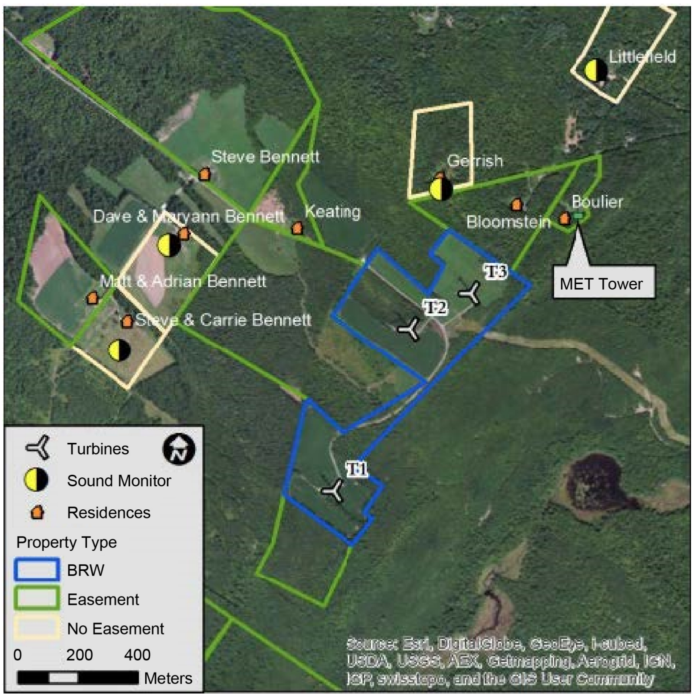

Figure 1. Beaver Ridge Sound Study Map [16][1].

A noise study was completed at Beaver Ridge from November 19 through December 16, 2013. According to the Patriot Renewables sound report, this study

[1]Reproduced from Beaver Ridge Wind | Patriot Renewables, LLC. (n.d.). https://www.patriotrenewables.com/projects/beaver-ridge-wind/.

used four testing sites with monitors placed no greater than 500 ft from a residence, and at least 25 ft from any structure capable of reflecting sound from the project. Sound is the variation in air pressure measured in decibels. The decibel can be weighted to mimic human perception. The most common weighted scale is "A", which provides results in dBA [18].

The four sites were equipped with a sound monitoring system comprised of a sound level meter, an audio recorder, and an anemometer to record wind speed. These turbines generate the highest sound power level at 924 kW. Therefore, the study criteria required sound data to be recorded at 10-minute intervals after the turbines reached the energy production level yielding the highest sound power. Testing was also performed during shutdown periods where background-only sound was recorded. A summary of the findings is shown in **Table 1**. At the Gerrish location, the background-only sound averaged 36 dBA. Since the turbine plus background sound averaged 42.7 dBA, the turbine is 6.7 dBA higher than the typical background for that area [18].

3. Project Methodology

One of the most common ways to describe noise levels is the continuous equivalent sound level [16]. The sound power level is described as the sound energy constantly transferred per second from the sound source. Similarly, sound pressure level is the noise level dependent on distance and air resistance. The sound weakens as it travels through the air logarithmically. To determine the sound pressure level at the designated distance from the turbine, a formula has been developed by the International Energy Agency [19]. Equation (1) accounts for hemispherical spreading over a reflective plane where the source sound power and absorption coefficient are assumed to be broad band [19].

Table 1. Sound report summary.

Sound Monitor Name	Meters From Turbine	Feet From Turbine	Turbine Only Sound (Recorded)	Turbine + Background Sound
Gerrish	394 m	1300 ft	40.7 dBA	42.7 dBA
Littlefield	850 m	2800 ft	33.8 dBA	35.9 dBA
S&C Bennett	850 m	2800 ft	37.5 dBA	39.2 dBA
D&M Bennett	975 m	3200 ft	*Sound Data Unavailable*	

$$Lp = Lw - 10\log(2\pi r^2) - \alpha r \quad (1)$$

where:

Lp: calculated noise level or sound pressure level (dB);

Lw: sound power level at the source of the wind turbine (dB);

α: absorption coefficient due to atmosphere, (.005 dB/m);

r: distance from the source to the receiver (m).

The radius in theoretical calculations equates to the disclosed sound level distance. The absorption coefficient is a function of frequency, temperature, and humidity. Using the Crank-Nicolson Parabolic-Equation (CNPE) method, the absorption coefficient and geometric attenuation is calculated. The value of 0.005 dB/m is widely accepted as a universal absorption coefficient and is used for consistency.

According to the data collected by the noise study at Beaver Ridge [18], the average sound pressure level from 394 m (1292.65 ft) is 42.7 dB. The International Energy Agency formula provides the sound power level at the source of the wind turbine as 104.56 dB. It is estimated that for every 100 m (328.08 ft) sound travels, 1 dB will be lost due to refraction over the plane. Specific to Beaver Ridge parameters, 3.94 dB is expected to be lost over the total distance. Accounting for this adjustment, the source power level is the sum of the power level at the source of the wind turbine and the expected sound level loss. The corrected source power level provides a result of 108.50 dB. If a reduction of 3 dB is to be achieved, adjusting the sound power level to 105.50 dB will provide a calculated sound pressure level of 39.7 dB.

3.1. Design Philosophy

The turbine blade is the foundation of the energy absorption of the wind turbine process and holds monumental importance to the overall efficacy of the turbine [20]. Wind turbine blades are designed to generate maximum power from wind while maintaining low costs. Blades are designed using an airfoil, which is an uneven teardrop design approved for aerodynamic efficiency. Aerodynamic force is necessary for blades to drive the generator and produce electricity. As wind passes over the blade, it experiences lift and drag [21]. Lift causes the blade to rotate faster and drag slows the blades to prevent blade damage caused by excessive wind speed. Drag must be well balanced to protect the blade, without restricting turbine efficiency. The NACA 4412 airfoil has proven to be efficient in capturing enough kinetic energy for maximum energy generation, but noise pollution remains a concern [20].

Noise is caused by turbulent airflow created by the blade. Maintaining appropriate lift and drag while achieving a measurable noise reduction is the basis of blade design [22]. Aerodynamic innovators have provided the wind industry with solutions to address noise pollution through extensive research and development. Increased energy demand yields larger turbines, resulting in increased sound levels due to higher tip speeds. To mitigate this circumstance, wind farms have historically chosen to run their turbines in a "low noise mode", using a direct-drive pitch system to decrease the blade and rotor velocity [2]. This mitigation technique restricts energy production, limiting the (AEP) goals and associated revenue. Noise reduction retrofit solutions for wind turbines will allow operators to avoid noise-reduction modes and restore AEP. Three design concepts evaluated for retrofit implementation as noise reduction designs are vortex generators, serrations, and winglets.

3.2. Vortex Generators

Vortex generators (VGs) are aerodynamic elements developed to address leading edge noise. Leading edge noise is generated in response to airflow separation as incoming air streams over the blade surface. As air collides with the solid surface, viscosity causes the air closest to the surface, called the boundary layer, to slow down making energy leave the airflow [23]. As a result, friction propagates upward. Airflow continues over the curved surface and pressure decreases until it reaches the middle of the blade chord, which is the line that directly joins the leading edge to the trailing edge. Then, an increase in pressure introduces an adverse pressure gradient making air move from low pressure to high pressure. Blade stalling occurs when low-pressure air is no longer able to overcome the pressure gradient, creating an area of reversed flow called a separation bubble. Once air separates from the surface, eddies are formed, producing turbulence. VGs are designed to delay and reduce airflow separation, forcing air closer to the blade surface which prevents excessive turbulence and subsequent noise [24].

VGs are a standardized component available for wind turbine blade retrofitting made of Acrylonitrile Styrene Acrylate (ASA) [25]. ASA is an amorphous thermoplastic accepted for high impact resistance, favorable thermal stability, and UV resistance [26]. VGs are designed as a pair of plates or vanes fixed at a specific angle (β) relative to airflow [27]. The vanes are triangular due to the optimal aerodynamic performance provided by increasing the maximum lift coefficient, stalling delay, and the elevated lift-to-drag ratio at high angles of attack. VG geometry is determined through ratios related to the length of the highest point of the triangular vane with a counter-rotating arrangement of $\beta = 18^\circ$ as illustrated in the pair of vortex generators in **Figure 2** [27]. The height (h) is related to the boundary layer produced by the NACA 4412 airfoil. The boundary layer thickness decreases along the blade's length as the velocity increases, decreasing the VG height (h). VG arrangement is specific to flow simulation results and requires design evaluation. Therefore, the vanes of the component may not be consistently parallel to the corresponding adjacent vanes shown in **Figure 2**.

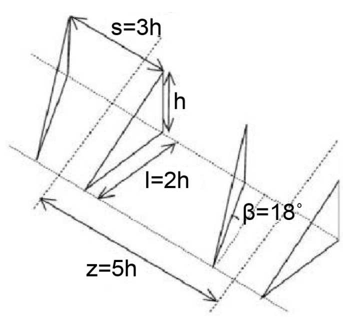

Figure 2. Vortex generator design Methodology.

The placement of VGs on the blade is determined by the airflow profile [25].

They adhere forward to the point where the laminar flow becomes turbulent, which is dependent on the Reynolds number, angle of attack, and boundary layer conditions. The turbulent separation point adjusts with the deviation in the angle of attack. VG placement requires experimental determination with local airflow simulations due to chord length variations along the length of the blade [28]. The root of the blade is circular in structure and interacts with air at a lower velocity, resulting in increased air separation. With a 13.8-degree angle of attack, the blade energy efficiency is most favorable, and the optimal VG placement is between 20% - 30% of the chord length. The application of VGs on the inner third of the blade improves both turbine efficiency and noise generation [23].

3.3. Serrations

Serrations are aerodynamic elements, developed to address trailing edge noise using a sawtooth pattern. As the blade slices through the air, high pressure creates a lift on the upstream or bottom side of the blade as the low pressure moves on the downstream or upper side of the blade [29]. When air reaches the trailing edge, a violent mixing of high- and low-pressure air occurs. Pressure fluctuations are perpendicular to the flow and radiate as strong sound waves [29]. Serrations separate the immediate collision and create a milder interaction between the two airflows.

Serrations are an upgrade component that does not require engineering customization. The material of choice must be able to withstand the deformations experienced with aerodynamic loads, making the use of ASA a prima candidate [25]. Serrations are panels designed with two components, a plate, and teeth [30]. The plate of the serration panel is the adhesion surface to the blade and point of contact with the teeth along the long axis. The teeth have a height, h, which is proportionally calculated to the boundary layer thickness determined using Equation (2), where Δ is the thickness of the boundary layer, c is the coefficient having a value of 0.37, L is the chord length, and Re is the Reynolds number [30].

$$\Delta = c\ L\ (1/\mathrm{Re})/5 \tag{2}$$

The blade is divided into numbered sections related to the boundary layer thickness as it varies with chord length [30]. Each section correlates to a different tooth height, H.

The teeth are equilateral triangles and fixed to the plate at a consistent downward 2-degree angle referred to as the angle of serration. The height of the teeth, H, the width of the triangular base, W, and the apex angle, α make up the teeth geometry as shown in **Figure 3** [30]. The plate height, S, has a minimum value of half the height of the teeth, H.

The successful design height to width ratio is 2:1, yielding an apex angle of 28 degrees. The tooth height is 18% - 22% of the chord length correlated to that section of the blade. Chord length variations require mean values to be determined

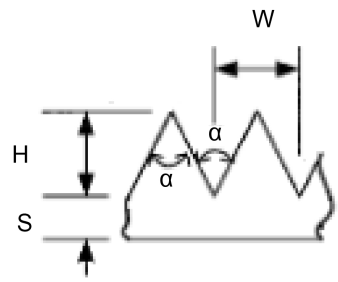

Figure 3. Serration panel geometry [30].

for consistent tooth heights within a single section of serration panels [30]. Serration panels are manufactured into 24-inch sections and mounted on the trailing edge using a wet adhesive at different lengths down the blade [25]. Typically, serration upgrades adhere to the outer third of the turbine blade, but the span of serration placement is dependent on the specific goals to be achieved [30].

3.4. Winglet

Winglets are an addition to the wind turbine blade that provides the blade tip with curvature. As air flows across the tip, the higher-pressure air rushes to lower pressure and creates vortices [31]. These vortices reduce lift, lessen efficiency, and create noise. The curvature of the winglet reduces the high-pressure air from bleeding into the low-pressure air at the tip [31].

Winglets are manufactured using a lightweight material to improve the power coefficient, Cp, without impacting the load on the turbine blade [32]. The core of the winglet is made of an epoxy foam that prevents water absorption [33]. It is covered by fiberglass epoxy skin with a thickness of 1 - 5 mm [33] and designed using height, cant angle, sweep angle, and twist angle [32].

The height of the winglet is 1.5% of the turbine's rotor diameter [34] yielding a length of 3.5ft (1.1 m). A downstream swept blade with a point directed to the pressure side provides the greatest benefit for diffusing the velocity gradient. The cant angle is 40 degrees, independent of the blade length, and proportional to the winglet height. The sweep angle is maintained at 25% of the blade length with a 10-degree twist angle [32]. The winglet is designed to reduce vorticity specifically at the blade tip. It is mated adhesively and bolted at 97.3% of the blade length [32].

3.5. SolidWorks Part Models

The authors used the VG design philosophy and produced the VG part specific to the NACA 4412 flow simulation results. **Figure 4** shows the SolidWorks Vortex Generator Design model.

Serration panel ratios from previous works were used as a template for the team's final serration design. Modifications were made to achieve the panel length of 24 inches. The specific length was determined for the commitment of application feasibility. Figure 5 provides the Serration Design from SolidWorks.

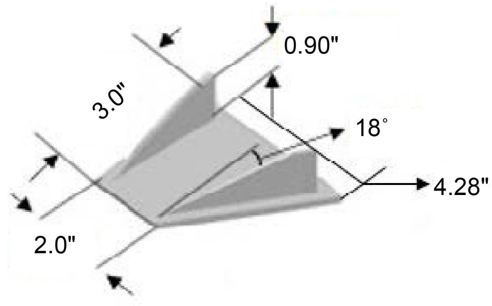

Figure 4. Vortex Generator SolidWorks Design.

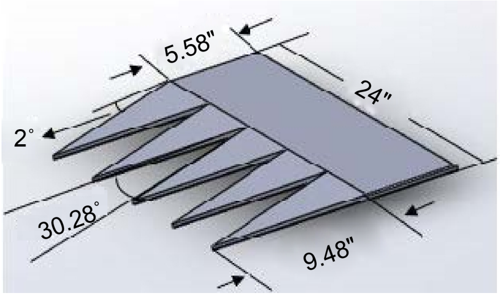

Figure 5. Serration SolidWorks Design.

The winglet, a geometrically complex structure, required the greatest engineering analysis for modeling. Figure 6 shows the Wind to Watts Winglet SolidWorks Design.

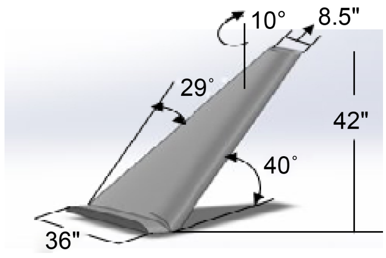

Figure 6. Winglet SolidWorks Design.

3.6. Acoustic Analysis

After modeling the base blade and additive parts for the VGs, Serrations, and winglet, each part was mated to the base blade in SolidWorks. Each modified blade was tested in a simulation environment comparable to the Beaver Ridge location using the noise prediction feature of SolidWorks' Flow Simulation. This software uses a Fast Fourier Transformation (FFT) algorithm to predict acoustic sound levels generated by turbulent air moving over a surface.

After loading the blade into the flow simulator, an analysis was performed by excluding internal spaces and focusing on the geometry of the blade's exterior. The flow simulation software used air at a standard pressure of 1 atm (1 bar, 14.7

psi) and a temperature reflecting Beaver Ridge's annual average of 52.5˚F [35]. Air velocity in the simulation environment mimicked the maximum rated speed of the base blade at 29 m/s or 65 mph [16]. This velocity was consistent throughout all stages of analysis and a standard gravity of 9.81 m/s^2 was also factored.

Figure 7 shows the flow results of the original base blade from the sectional cut view with a color gradient that shows varying dB output of the top plane. The analysis produced a peak noise output of approximately 91 dB, 1 - 2 meters behind the trailing edge of the blade.

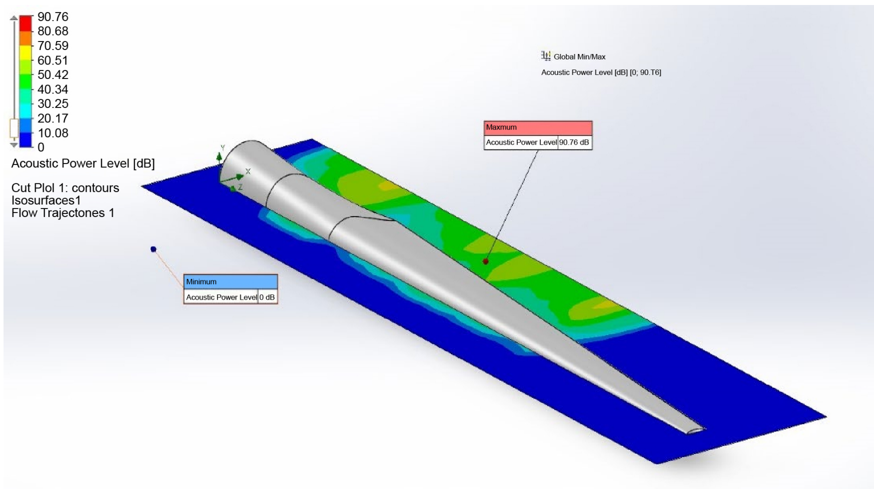

Figure 7. Sectional View - Top Plane.

Figure 8 displays the sound output generated along the length of the blade from root to tip. The data evaluation revealed the design improvements focus to be on the first 10% - 50% of the blade.

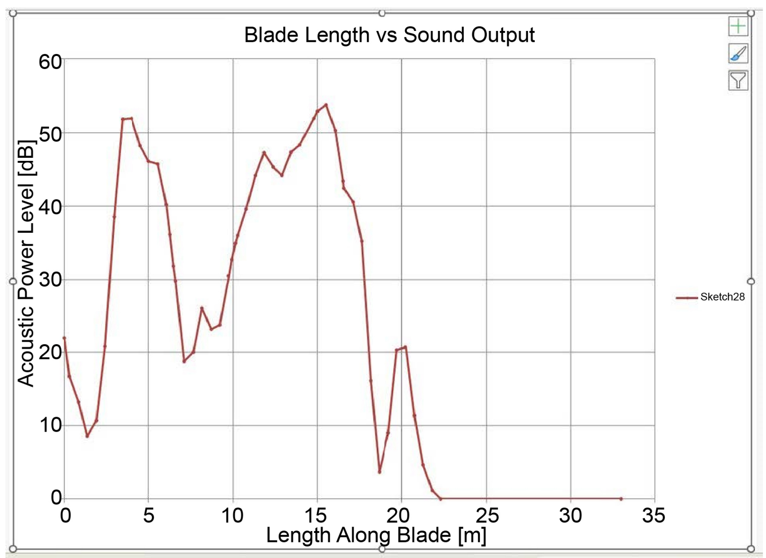

Figure 8. Blade Length vs Sound Output.

Acoustic evaluation results for Beaver Ridge Wind Farm are shown in Table 2. The most successful noise reduction was experienced with the VG design, which focused on turbulent flow and subsequent noise reduction on the 10% - 30% of the blade closest to the root. VGs effectively placed between 4 - 15 meters of blade length provided a noise reduction of 15 dB.

Table 2. Acoustic evaluation results.

Description	Vortex Generator	Partial Serrations	Full Serrations	Vortex Generator + Full Serrations	Winglet
Noise Reduction	15.59	1.41	11.95	6.08	-2.42

The partial serration design resulted in a 1.41 dB reduction and full serrations yielded a 11.95 dB reduction. The VG and full serration blade combination revealed a 6.08 dB reduction, and the winglet showed an increase in sound by 2.42 dB. Winglets are a complex 3-D structure and introduce difficulty in accurate flow simulation. Winglets are historically and continuously studied with wind tunnels for more representative noise reduction reports.

4. Final Remarks

The project goal was to implement a noise reduction retrofit solution, available for application at any wind farm experiencing noise complaints. The solution objectives were to be cost-effective and financially feasible in support of the U.S. government's renewable energy goals and to specifically reduce wind turbine noise by a minimum of 3 dB. The target was reached by addressing the most common noise-generating locations of the wind turbine blades known as the leading edge, trailing edge, and blade tip. Noise can be improved at these locations using vortex generator, serration, and winglet design concept solutions.

The leading-edge solution implements vortex generators to smooth turbulence at the airfoil flow surface. The resulting airflow behavior reduces the Reynolds number of turbulent flow on the trailing edge of the blade at full operational speed. The trailing edge solution adds serrated or feathered edges that reduce the turbulent boundary layer. Finally, the wingtip approach bonds a blade sleeve with an elongated sweep to the tip of the blade to reduce tip-induced turbulent vortices.

A 3dB noise reduction was achieved by implementing one or a combination of the design concepts. Recommendations are specific to blade length, turbine type, and environmental conditions. The testing of each solution was performed using parameters from the project test site.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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