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Survey of Techniques for Reduction of Wind Turbine Blade Trailing Edge Noise

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Abstract

Aerodynamic noise from wind turbine rotors leads to constraints in both rotor design and turbine siting. The primary source of aerodynamic noise on wind turbine rotors is the interaction of turbulent boundary layers on the blades with the blade trailing edges. This report surveys concepts that have been proposed for trailing edge noise reduction, with emphasis on concepts that have been tested at either sub-scale or full-scale. These concepts include trailing edge serrations, low-noise airfoil designs, trailing edge brushes, and porous trailing edges. The demonstrated noise reductions of these concepts are cited, along with their impacts on aerodynamic performance. An assessment is made of future research opportunities in trailing edge noise reduction for wind turbine rotors.

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1 Wind Turbine Aerodynamic Noise

Efforts to quantify wind turbine noise have been ongoing for the past three decades [3, 4, 5]. There are two primary classes of noise sources on a wind turbine. These include mechanical noise due to vibrations in the drive train and gear noise, and aeroacoustic noise due to unsteady aerodynamic processes on the rotor. Mechanical noise, while it can potentially be a large contributor to overall wind turbine noise, is usually relatively straightforward to reduce using techniques to dampen or isolate mechanical vibrations in the nacelle, or by employing sound absorbing material [6]. Aeroacoustic noise is more difficult to mitigate, and is the dominant noise source on modern wind turbines [7, 8].

Aeroacoustic noise sources on a wind turbine can be divided into two main classes: airfoil self-noise, due to interaction of a nominally steady flow with the blades, and turbulent inflow noise, due to scattering of turbulent wind fluctuations by the blades. Airfoil self-noise is further divided into various noise mechanisms [9]; the two most relevant mechanisms are turbulent boundary layer-trailing edge noise (or, “trailing edge noise”), and blade tip vortex noise. Early models of wind turbine noise tended to address each of these possible noise sources and, up until very recently, it was difficult to assign prominence of one aeroacoustic noise source over the others. It has been known for some time that blade tip speed is limited by aeroacoustic noise, and trial-and-error design approaches have focused on tip shapes that resulted in relatively low noise.

Recent work in Europe has shed more light on the aeroacoustic noise mechanisms for utility-scale wind turbines. Detailed blade noise measurements were made for an 850 kW Gamesa G58 turbine [8] and for a 2.3 MW GE prototype turbine [10]. Both of these turbines are three-bladed upwind machines that can be considered representative of the current fleet of wind turbines in terms of aerodynamic and aeracoustic characteristics. The measurements were made with a microphone array that was able to resolve the amplitude and location of noise sources in the rotor plane and along the blade span. Important observations were made on the character of the blade noise, some of which shed light on the nature of the noise sources:

- Blade noise sources were much louder than mechanical noise sources located within the nacelle for both turbines.
- Blade noise sources were loudest near, but not at, the blade tips, indicating that tip vortex noise is not the dominant blade noise mechanism.
- The measured noise for an upwind observer on the ground varies with blade azimuth, and was 15 dB louder for a downward traveling blade (approximately the 3 o’clock position) than for an upward traveling blade (approximately the 9 o’clock position). This variation is consistent with predictions given by aeroacoustic theory for trailing edge noise. The noise directed towards the ground is louder during downward blade passage due to the combined effects of Doppler amplification and the directivity of the noise source.
- The blade noise intensity scales with the fifth power of the flow velocity relative to the blade at the source location. This matches the scaling that has been observed in trailing edge noise experiments and predicted by theory.

These observations convincingly demonstrate that, at least for frequencies above 500 Hz for the 850 kW turbine and above 250 Hz for the 2.3 MW turbine, the primary aerodynamic noise source is trailing edge noise. The amplitude modulation of the noise at the blade passage frequency (0.6 Hz at 12 RPM, for example) leads to the characteristic, and potentially annoying, swishing sound of a wind turbine rotor. Turbulent inflow noise may contribute to the noise spectrum of a wind turbine at low frequencies, and more research is needed to isolate and quantify this noise source. It is also important to note that blade surface imperfections due to manufacturing defects or damage can lead to very loud aerodynamic sources that can overwhelm normal operational noise.

Identification of trailing edge noise as the primary noise source on modern wind turbines allows it to be targeted by noise reduction methods. This survey identifies several trailing edge noise reduction techniques that have been proposed and/or attempted, in an effort to focus future research efforts into the most promising areas or areas that have not yet been fully explored.

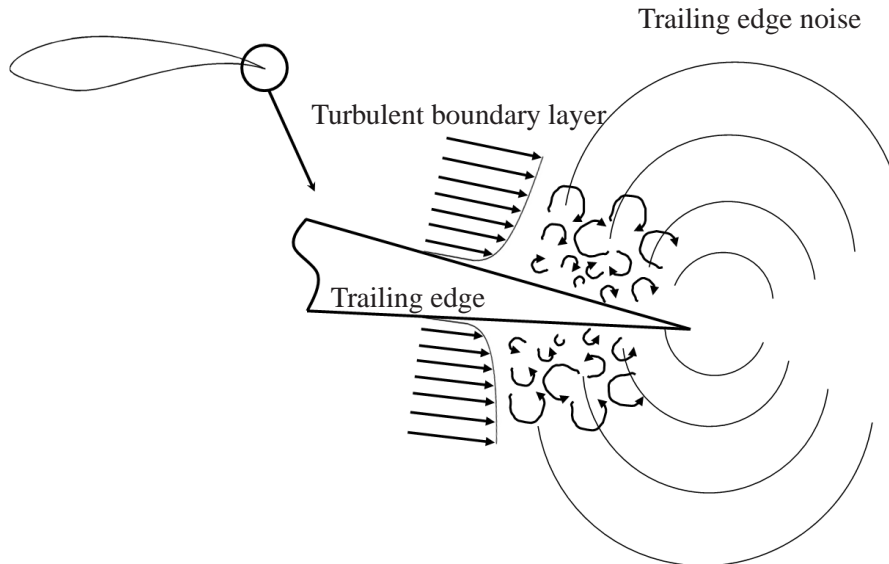


Figure 1. Generation of noise by a turbulent boundary layer passing over an airfoil trailing edge.

2 Airfoil Trailing Edge Noise

Noise may be generated at the trailing edge of an airfoil by two distinct processes: blunt trailing edge vortex-shedding noise, or “blunt TE” noise, and turbulent boundary layer trailing edge noise, or “TBL-TE” noise. Blunt TE noise occurs when the airfoil has a trailing edge of finite thickness, resulting in a blunt base. When this base is large enough relative to the thickness of the boundary layers at the trailing edge, a quasi-regular pattern of vortices is shed from the base. The pressure fluctuations associated with the vortices interact with the trailing edge to generate sound, typically composed of a relatively loud, narrow-band tone. Blunt TE noise is not considered to be a significant problem on modern, utility-scale wind turbines. This noise source is relatively well-characterized and it is eliminated by a simple remedy: maintaining a small-enough trailing edge thickness to prevent vortex-shedding. This is readily achievable using current manufacturing practices on utility-scale wind turbines.

TBL-TE noise, referred to hereafter as “trailing edge noise,” is caused by scattering of turbulent fluctuations within the blade boundary layer at the trailing edge, resulting in radiation of broadband noise (see Figure 1). Theoretical scaling laws for trailing edge noise have been established for some time. For example, the intensity of low-speed¹ trailing edge noise is described by the experimentally verified relation [11, 12, 9]:

$$\langle p^2 \rangle \propto \frac{\rho_0^2}{c_0} \frac{U^5 L \delta}{r^2} D \quad (1)$$

where $\langle p^2 \rangle$ is the sound pressure intensity observed at a distance r from the trailing edge. The fluid density and speed of sound are ρ_0 and c_0 , and the fluid velocity in the vicinity of the edge

¹Low-speed, or incompressible, flow models require that the Mach number, or ratio of fluid speed to speed of sound, is less than about 0.3. This condition is satisfied for wind turbine flows.

is U . L is the spanwise extent of the flow (length of the blade section, for example), while δ is a measure of the boundary layer thickness at the edge. D is a directivity function that is a function of the angle of the observer to the edge; theoretical forms are also available for D . The scaling of noise intensity with U^5 highlights the role of aerodynamic noise as a design constraint for wind turbine rotor tip speed. The local velocity over a blade section at radius R is $U \sim \Omega R$, where Ω is the rotational speed of the rotor. Given the U^5 scaling relationship, a 15% increase in rotational speed would therefore increase noise by about 3 dB. Conversely, a 3 dB reduction in aerodynamic noise through design changes would allow for a 15% increase in turbine rotational speed. When coupled with blade structural design improvements, this increase in rotational speed can reduce system loads and enable lighter, cheaper rotors and drive trains [13].

Measurements of trailing edge noise in wind tunnels have been very useful in validating the theoretical scaling laws and in developing semi-empirical noise models. Brooks *et al.* [9] characterized the self-noise (including trailing edge noise) of the NACA 0012 airfoil with the aid of a comprehensive measurement campaign in an anechoic wind tunnel. The noise of wind turbine-specific airfoils has been measured in other, more recent anechoic wind tunnel studies [14, 15, 16]. Numerical simulation of trailing edge noise [17, 18, 19] offers a tool for detailed investigation of noise reduction methods.

Despite this accumulated knowledge of airfoil trailing edge noise, actually reducing it is difficult. There are several reasons for this. First, boundary layer turbulence, the primary source of the noise, is very robust in the sense that it is not easy to control. Modification of the turbulent boundary layer upstream of the trailing edge to reduce the energy of sound-producing fluctuations may be possible through, for example, suction or blowing through the foil surface. However, this type of solution is likely to be complex and impractical. Modification of the noise-producing characteristics of the trailing edge boundary layer through airfoil shape changes *is* possible, and is discussed in Section 4. Other passive shape changes at the trailing edge offer promise, but these approaches often highlight a second difficulty: the primary trailing edge noise source may be reduced, but one or more other noise sources may be introduced. An example of this is the often-observed increase in high-frequency noise associated with trailing edge serrations, discussed in Section 3. Third, any noise-reducing modification to the trailing edge over the outer part of the blades must not decrease aerodynamic performance or increase (too much) the contribution of tip-vortex noise. Lastly, wind turbines operate over a range of wind speeds, yaw angles, and turbulent inflow conditions, resulting in a corresponding range of local flow conditions over the outboard region of the blades. This means that noise reduction techniques must be effective over a range of conditions as opposed to only for a single design point.

Thus, the wind turbine blade trailing edge reduction problem is complex, and involves a variety of opposing constraints. The trailing edge noise problem has not received a great deal of attention to date by the aerospace community, since other noise sources typically dominate fixed- and rotary-wing aircraft noise problems (*e.g.* flap side-edge noise, landing gear noise, jet noise, and blade-vortex interaction). The wind turbine research community, particularly in Europe, has proposed and tested a number of approaches for trailing edge noise reduction. The following sections survey these approaches and highlight both the noise reduction possibilities as well as the potential penalties associated with each approach.

3 Serrated Trailing Edge

Howe [20], using aeroacoustic theory, showed how a serrated, or saw-tooth, trailing edge may be made quieter than a straight trailing edge. Large noise reductions (8 dB or more) are shown to be possible for serrated edges aligned at an angle of less than 45 degrees with the mean flow over the trailing edge. The frequency range over which the reductions occur is given by $\frac{\omega\delta}{U_c} > 1$, where ω is the radial frequency of the noise, δ is the thickness of the trailing edge boundary layer, and U_c is the convection velocity of turbulent eddies past the trailing edge. Howe's theoretical treatment is comprised of a solution to an acoustic scattering problem, where incident unsteady pressure fluctuations in the turbulent boundary layer are scattered at the sharp trailing edge, causing some of the fluctuation energy to be radiated as sound. The radiated noise is loudest for an incident pressure wave that is aligned with the edge and traveling normal to the edge. As this pressure wave passes over the edge, it encounters a sudden change in acoustic impedance, resulting in the scattering of noise. The serrations can be viewed as a means of distributing this sudden change in impedance over a finite distance, thereby reducing the strength of the scattering process. Trailing edge noise theory also demonstrates that the noise intensity of a turbulent flow passing over a sharp edge scales with $\cos^3 \beta$, where $\pi/2 - \beta$ is the angle between the edge and the flow [12]. Serrations may be viewed as way to introduce an angle β all along a trailing edge, without actually sweeping the trailing edge.

Howe's theoretical developments inspired a number of experimental investigations into reducing trailing edge noise of wind turbine blades using trailing edge serrations. Jakobsen and Andersen [7] took single-microphone measurements of the noise from a Vestas V-27 rotor incorporating several modifications to the blade trailing edge, including application of 5 mm long serrations glued to the pressure side of the rotor blade. No significant change in the aerodynamic noise was observed in this experiment. This is not surprising, since subsequent research has shown the length and alignment of these serrations to likely be inadequate. Dassen *et al.* [21] studied the noise from a number of flat plate and two-dimensional airfoil models fitted with serrations in an open jet wind tunnel. The serrations were 50 mm long and spaced 5 mm apart. Chord Reynolds number ranged from 750,000 to 1.4×10^6 . Frequency-dependent reductions in noise of between 5 and 10 dB were measured for the baseline flat plate configuration, compared to theoretical predictions of 10 to 20 dB reductions. A flat plate case was included with serrations that were misaligned with the plate trailing edge by fifteen degrees at zero angle of attack; in this case, the noise was actually increased over the baseline plate without serrations. The airfoils tested included the NACA 0012, 63-618, 63-018, and 4418 foils. Frequency-dependent noise reductions for the airfoils ranged from 0 to 10 dB.

Field tests of trailing edge serrations installed on a 16 m diameter turbine are described in [22]. Boundary layer trips were applied to the blade leading edges to ensure that the trailing edge boundary layer was turbulent. Blade noise was only measured at an upwind position and for the blade azimuth at the downward-traveling position. Straight serrations that followed the blade suction-side contour near the trailing edge demonstrated a reduction in total sound pressure level of 2 dB, dominated by reductions in noise at relatively low frequencies. However, the straight serrations resulted in a significant increase in noise at high frequencies. The overall noise reduction was im-

proved to 3.5 dB by bending the serrations to follow the trailing edge flow stagnation streamline; the high frequency noise was reduced from the straight serrations, but was still increased over the baseline blade. Curving and bending the serrations to better follow the stagnation streamline did not result in further reduction, due to the presence of an unexplained tonal noise source for this configuration.

In a separate field experiment [23], serrations were attached to a blade on a 1 MW active stall controlled turbine and the noise was measured using a parabola antenna for high frequencies and a microphone array for low frequencies. The serrations were applied along 5 meters of blade span, ending 1 meter from the blade tip to avoid interaction of the tip vortex with the serrations. Reductions in noise of up to 4.5 dB were observed for frequencies up to 1250 Hz, while for frequencies greater than 2000 Hz the noise levels increased. A total noise reduction of 2 dB was achieved. The reductions were achieved over a range of pitch angles from -1 to +3 degrees relative to the operational pitch angle, and no impact of the serrations on turbine performance was observed.

Oerlemans *et al.* [1] applied serrations to one blade of a 2.3 MW variable speed, variable pitch turbine. The serrations were attached to the pressure side of the blade and aligned with the anticipated flow path near the trailing edge. They were applied over the outer 12.5 meters of the blade, and their length was designed to be approximately 20% of the local airfoil chord, which varies as a function of radial position along the blade (see Figure 2). Measurements were made using a microphone phased array, which enabled identification of noise source positions, amplitudes and frequency content. For a ground observer upwind from the turbine, overall sound pressure levels were decreased by an average of 3.2 dB over a range of wind speeds from 6 m/s to 10 m/s. The minimum reduction achieved was 1.8 dB near a wind speed of 6 m/s, while the maximum reduction was 5.0 dB near 10 m/s. The lower reduction at low wind speeds was attributed to increased high-frequency blade tip noise due to higher blade tip loading (lower blade pitch) at these conditions.

Petitjean *et al.* [24] recently conducted both wind tunnel and field experiments on blades and blade sections with serrated trailing edges. In the wind tunnel they measured trailing edge noise for two General Electric proprietary airfoil models with and without a serrated trailing edge. The tests were performed with boundary layer trips at a chord Reynolds number of 1.2 million. Decreases in 1/3-octave-band sound pressure level were frequency dependent, varying from reductions of up to 5 dB at low frequencies and increases of up to 5 dB at high frequencies. Interestingly, the amount of noise reduction was highly dependent on the airfoil shape to which the serrations were applied. One of the airfoils showed noise reductions over most of the measured frequency range ($1000 \text{ Hz} < f < 20,000 \text{ Hz}$), while the other airfoil showed reductions over a much more limited range ($< 2000 \text{ Hz}$). Serrations were then applied to blades on three full-scale turbines, with rated power of 1.5 MW, 2.5 MW, and 2.75 MW. Single downwind microphone measurements were made and noise reductions were presented in 1/3 octave band A-weighted sound pressure levels. The serrations resulted in noise reductions of 4-6 dB(A) at 500 Hz, 2-4 dB(A) at 1000 Hz, and marginal reduction at 2000 Hz.

While experiments have indicated that trailing edge serrations can reduce wind turbine blade trailing edge noise, the fundamental mechanisms for the noise reduction are not well-understood.



Figure 2. Trailing edge serrations on the blade of a GE 2.3 MW prototype turbine. From [1]. Reprinted with the author's permission.

Numerical simulations of the flow past an airfoil with trailing edge serrations have been performed in an attempt to identify the physical mechanisms responsible for noise reduction [25, 26]. These simulations solve the fluid flow equations directly, without resorting to a turbulence model, and are therefore limited to a chord Reynolds number of only 50,000. However, the simulations capture the fundamental interaction of a turbulent boundary layer with serrations that are appropriately scaled relative to the boundary layer thickness. Two serration geometries were considered, one with relatively short serrations and one with relatively long serrations. Similar to some experiments, the short serration simulations demonstrated a decrease in low-frequency noise and an increase in high-frequency noise. The long serrations reduced noise for all frequencies above a certain onset frequency. The structure of the turbulence near the trailing edge and in the wake indicates some differences between the flow with and without serrations. However, the study does not offer a new explanation for noise reduction mechanism, nor does it directly test the basic mechanism of reduced scattering efficiency at an inclined edge theorized by Howe.

4 Low-noise Airfoils

Trailing edge noise from a particular airfoil depends sensitively on the shape of the airfoil. This is because, along with the external flow conditions, the airfoil shape determines the development of the turbulent boundary layers that interact with the trailing edge to produce noise. Details of the turbulent boundary layer, such as mean shear and velocity fluctuation distribution normal to the surface, are important factors in the efficiency of noise generation. These can be manipulated through passive airfoil shape changes that change the mean pressure gradient over the foil surface and thus influence evolution of the boundary layer.

This approach is explored in [27], where the noise is measured for two newly designed quiet airfoils and compared to the noise of a baseline NACA 64-418 airfoil. The design seeks to minimize boundary layer thickness and maximize skin friction coefficient at the trailing edge, since theory indicates these characteristics lead to low trailing edge noise. For untripped conditions, the new airfoil designs were 2-4 dB quieter over a range of low frequencies, but at higher frequencies exhibited a blunt trailing edge tone due to manufacturing limitations. With a leading edge boundary layer trip applied, the new airfoils were actually louder than the NACA airfoil, although it must be noted that tripped conditions were not considered in the design of the new foils. An undesirable consequence of the design changes was that the new airfoils exhibited increased sensitivity of lift performance to leading edge roughness.

A similar design approach for airfoil trailing edge noise reduction is taken in [28]. A flow model is constructed using a panel code with viscous corrections, coupled with a local Reynolds stress turbulence model to obtain properties of the turbulent trailing edge boundary layer that are then used as input to a noise model. The model is calibrated using experimental flow diagnostics applied to measure trailing edge boundary layer properties for a variety of airfoils. The method was applied to optimize the shape of three wind turbine airfoils used for an existing turbine. The constraints on airfoil shape were quite severe, given that the new airfoils were required to integrate smoothly into an existing blade design in a manner that did not greatly increase manufacturing costs. Nonetheless, wind tunnel tests indicated that the optimized airfoils exhibited noise reductions from 1 to 3.5 dB at design conditions, while maintaining or improving aerodynamic performance. A similar design method was employed by [29] to generate low-noise airfoil shapes, beginning from a baseline NACA 63-418 airfoil. The analysis indicated possible noise reductions from 1 to 3 dB, depending on the enforced geometric and performance constraints. The noise reduction mechanism was found to be related primarily to reduction in turbulence kinetic energy in the trailing edge boundary layer. Resulting shape changes involved a de-cambering of the airfoil and flattening of the airfoil thickness near the trailing edge.

Low-noise airfoils designed using the method in [28] were incorporated into one blade of a Gamesa 850 kW G58 turbine [30] and a GE 2.3 MW prototype turbine [30, 1], and the blade noise was measured using a microphone array. The Gamesa turbine blade with optimized airfoils suffered from two flaws: the shape was found to deviate from the design shape due to an improvised manufacturing process for this blade, and the blade was fitted with an anti-erosion strip at the leading edge that acted as a boundary layer trip. The result was a minimal (0.6 dB) reduction in blade noise for the optimized blade versus the baseline blade. For the GE turbine, depending

on the wind speed, reductions in overall noise for the optimized blade between 0 and 1 dB were observed, less than the wind tunnel testing had indicated. Part of this underperformance was attributed to additional high-frequency noise of the optimized blade that may have been due to increased tip loading and associated tip vortex noise. However, the low-frequency noise reduction was also less than expected and the cause for this discrepancy was unknown. It was speculated [30] that significant operation of the airfoils at off-design conditions due to instationary turbulent wind conditions may have contributed to the discrepancy.

5 Trailing Edge Brushes

The attachment of closely spaced, brush-like, fibers to a trailing edge has been demonstrated to reduce trailing edge noise in laboratory experiments. Figure 3 shows trailing edge brush attachments employed in one wind tunnel study. The mechanism for noise reduction may be the replacement of the sudden impedance mismatch at a hard trailing edge with a more gradual change in impedance over the brush extension. An alternative explanation is that the porous nature of the brushes dampens turbulent fluctuations in the boundary layer that lead to trailing edge noise.



Figure 3. Trailing edge brush attachments. In this photograph, each brush consists of a single row of polypropylene fibers. From [2]. Reprinted with permission of the American Institute of Aeronautics and Astronautics.

Herr and Dobrzynski [31] demonstrated the noise-reduction potential of trailing edge brushes on a flat plate geometry in an open-jet wind tunnel. While the noise reductions were large, the presence of blunt trailing edge vortex-shedding tones on the flat plate model obscured the applicability to sharp-trailing edge airfoils where such tones would not be expected. Further experiments in the same facility, on a NACA 0012 with a very small trailing edge thickness, demonstrated broadband noise reductions from 5 to 10 dB at zero airfoil angle of attack, and approximately 2 to 7 dB at an angle of attack of 7 degrees [32]. A small brush spacing (< 1 mm) was more effective than larger spacings, while a flexible brush fiber offered a small advantage over stiff fibers. The chord Reynolds numbers for these experiments ranged from 1.1 to 1.6 million.

Finez *et al.* [2] performed experiments with a flexible trailing edge brush applied to a cambered airfoil at relatively low chord Reynolds number (up to 347,000). They observed decreases in trailing edge noise intensity of up to 3 dB over a wide frequency range. Hot wire measurements in the near-wake of the foil showed that the brushes reduced the spanwise coherence length of the

boundary layer turbulence, which would account for about 40% of the observed noise reduction. This means that the brushes act to break-up turbulent eddies in the boundary layer that efficiently radiate noise when they encounter a sharp edge. This observation was used to suggest a design criterion that relates brush diameter to the coherence length of the boundary layer turbulence.

Trailing edge brushes were applied on a 850 kW Gamesa wind turbine blade with accompanying noise measurements by a microphone array [30]. Two types of brushes were applied, but no details of the brush characteristics are given. A noise decrease of 0.5 dB was reported for one brush and a noise increase of 2 dB for the second brush. The ineffectiveness of the brushes was “possibly because the improvised brushes were too short” [1]. The lack of detail provided on this experiment leaves the effectiveness of trailing edge brushes in reducing noise on large-scale wind turbine blades an open question.

6 Porous Surface

Howe [33], using aeroacoustic theory, showed that trailing edge noise could be reduced by introduction of a porous surface near the trailing edge. The analysis considers turbulence on only one side of a flat plate immersed in a uniform flow, neglects viscous effects, and ignores the possible modifications of the boundary layer turbulence by the porous surface. This idealized analysis, however, provides insight into design considerations for application of this concept to trailing edge noise reduction. Most importantly, a smooth introduction in porosity in the flow direction is more effective than a sudden step from an impermeable surface to a porous surface. The smooth distribution of porosity eliminates sudden changes in acoustic impedance, which causes acoustic scattering of boundary layer turbulence into radiated noise.

The application of porosity to reduce trailing edge noise had been investigated experimentally by Hayden *et al* [34] in the context of externally blown flaps for aircraft. Porous metal sheets were applied to the leading and trailing edge of the flaps, resulting in noise reductions of 5 to 10 dB. Later experiments [35] were conducted with a jet blown over a flat plate with and without porous extensions. Peak noise reductions of up to 10 dB were measured for the plate with a porous trailing edge extension. Note that this experimental setup differs from the airfoil trailing edge configuration in that flow exists only on one side of the plate and the flow consisted of a “wall jet” rather than a turbulent boundary layer.

Further application of the porous trailing edge concept to airfoils is discussed in [36], with limited noise measurements given for a NACA 0012 airfoil. Reduction in turbulent boundary layer trailing edge noise as well as elimination of vortex shedding noise are demonstrated. Various design configurations for the trailing edge are presented, including a solid block of porous material at the trailing edge, porous shells with internal compartments, and porous shells with a single internal cavity.

Trailing edge noise from airfoils with an entirely porous surface has been measured in [37] and [38]. Depending on the resistivity of the porous material, the trailing edge noise at low and medium frequencies is decreased relative to a baseline airfoil with an impermeable surface. At high frequencies, the porous airfoils generate louder trailing edge noise than the baseline airfoil, possibly due to increased roughness noise associated with boundary layer turbulence scattering over a non-smooth surface. The aerodynamic performance of the porous airfoils suffers, with a measured loss of lift and increase in drag that are both inversely proportional to the resistivity of the porous material.

Airfoils with only the trailing edge region constructed from porous material were tested in the wind tunnel [24]. The trailing edges were made from two different porous materials: metallic foam and hollow sphere foam. They were applied to a proprietary General Electric airfoil and tested at a chord Reynolds number of 1.2 million. Both porous trailing edges resulted in noise reductions below 2 kHz, with a 5 dB reduction at 1 kHz. However, the noise amplitude (in dB) increased with frequency such that at 20 kHz, the noise had increased by 15-20 dB over the baseline foil. The source of this noise increase is not clear, but may be related to scattering by the rough surface or by modification of the turbulent boundary layer by the porous surface. Airfoil performance with

the porous trailing edges was not documented in [24].

Application of porous trailing edges to wind turbines has evidently only been investigated by the experiments of [7]. The outer one meter of a Vestas V-27 rotor was given a thickened trailing edge, to which a piece of porous polyurethane foam with triangular cross-section was glued. This effectively gave the outer section of the blade a sharp, porous trailing edge. The measurements indicated insignificant changes in the reported A-weighted sound power levels, but this single limited result cannot be considered conclusive.

7 Conclusions and Recommendations

A survey of methods for turbulent boundary layer trailing edge noise reduction reveals several approaches that have been considered or applied in past studies. Serrated trailing edges, trailing edge brushes, and porous surfaces all act in some way to reduce the intensity of the turbulence/edge interaction by spreading the impedance mismatch over a finite distance in the flow direction. Low-noise airfoil shapes seek to tailor the characteristics of the trailing edge boundary layer such that less noise is scattered at the edge.

Of these technologies, the most successful demonstration of trailing edge noise reduction on large-scale wind turbines has been with trailing edge serrations. In [1], overall sound pressure levels were decreased by an average of 3.2 dB over a range of wind speeds from 6 m/s to 10 m/s on a 2.3 MW test turbine. Similar levels of reductions were reported in [24]. However, in [1] the noise reduction was dependent on wind speed, and the lowest reduction was near the lower part of the wind speed range. This is problematic, since wind turbine noise is often most perceptible at low wind speeds when the background noise from the wind is relatively low and ineffectively masks the turbine noise. It was conjectured that lower pitch setting at low wind speeds led to higher tip loading and correspondingly higher blade tip vortex noise. If this is the case, then blade tip vortex noise competes with trailing edge noise at low wind speeds (for this particular turbine), and a mitigation strategy for the tip vortex noise is also required. Alternatively, the serrations may not be performing as well at lower wind speeds due to decreased performance at the local flow conditions (angle of attack, in particular). Further wind tunnel experiments on both two-dimensional airfoil models as well as three-dimensional tip geometries would be very useful in further investigating this question.

Low-noise airfoils are a very attractive option for noise reduction, since they add no complexity to the blade design or manufacture processes. Low-noise airfoil designs have been shown to reduce trailing edge noise significantly in wind tunnel tests, but the limited field test results to date were disappointing. The noise reduction achieved using this method may be somewhat sensitive to the as-manufactured blade shape, external turbulent inflow conditions encountered in the field (versus more ideal wind tunnel conditions), or some combination of these two effects. Reconciling the difference in wind tunnel and field test results might be achieved by incorporating more detailed *in situ* flow-field measurements on the turbine blades to accompany noise measurements. Precise shape measurement of the as-manufactured blades would also be useful to determine proximity to the design shape.

Trailing edge brushes and porous trailing edges are similar in concept, in that they both attempt to alleviate the abrupt edge encountered by the near-blade flow. Trailing edge brushes have been examined in recent wind tunnel experiments, and show promise for trailing edge noise reduction. A careful field experiment applying brushes on a wind turbine is yet to be published. Porous trailing edges received some attention in the 1970's and 1980's, but little fundamental work has been done in the last two decades. The theory of Howe indicates that significant noise reductions are possible, and this concept deserves further study. The appendix sketches the broad outlines of a potential research effort to investigate this concept for wind turbine blades. A potential advantage of the porous trailing edge is that it does not require protrusions from, or extensions of, the blade.

A potential practical issue is the clogging of the porous surface by dirt and debris, although this issue is expected to be more severe at the blade leading edge rather than the trailing edge.

8 Appendix: Porous Trailing Edge Concept

This Appendix investigates the possibility of applying a porous trailing edge treatment to the tip region of a wind turbine blade. The theory developed by Howe [33] provides a rational starting point for design of a trailing edge treatment. Howe considers the case of turbulent boundary layer flow over the trailing edge of a flat plate, with a porous surface extending a length l upstream of the trailing edge. The porous surface is comprised of circular apertures of radius R ; the apertures are applied over an area A , with total porous area \mathcal{A} . The major assumptions underlying the theory are:

- large aperture Reynolds number $\frac{4\omega R^2}{\nu}$, such that viscous effects on the unsteady flow through the apertures can be ignored;
- independence of the flow through different apertures;
- low Mach number flow, such that the acoustic source region is small compared with the acoustic wave-length (a good approximation for wind turbine flows);
- turbulent eddies within the boundary layer are large compared with the aperture size;
- the boundary layer turbulence itself is unaffected by the presence of the apertures.

The theory gives relations for the radiated trailing edge noise in terms of the non-dimensional *aperture parameter*,

$$\lambda = \frac{8}{\pi^2} \frac{\mathcal{A} l}{A R}. \quad (2)$$

Two cases were considered in [33]: case I, the case of uniform number density of holes in the porous region; and case II, the case of number density increasing linearly from zero at the start of the porous region to a maximum value at the trailing edge. Case II removes the sudden jump in impedance and associated acoustic scattering that occurs when the flow encounters the beginning of the porous region. Optimal values of the aperture parameter, giving maximum trailing edge noise reduction, are

$$\text{case I : } \lambda = 0.89, \text{ case II : } \lambda = 1.25. \quad (3)$$

The predicted noise reduction is very large for a narrow band surrounding a “preferred” frequency (> 30 dB reduction), and then reduces to 5 to 10 dB reduction for higher frequencies. Case I exhibits a series of smaller peaks in noise reduction at the high frequencies, whereas case II provides more uniform noise reduction at high frequencies.

While these theoretical results indicate the potential for significant trailing edge noise reduction, several fundamental and applied research questions remain. Careful experiments are needed to verify the assumptions of the theory, especially the assumption that the boundary layer turbulence is unaffected by the porous surface. If the boundary layer turbulence is somehow modified, difference noise source characteristics may result. Fundamental wind tunnel experiments, initially

on a simple flat plate geometry, are also needed to verify the noise reduction potential of the concept. The theory may also be used to investigate different porosity distributions other than the two cases investigated in [33], in order to find an optimal distribution that maximizes trailing edge noise reduction.

Application to an airfoil raises several practical research questions. How is the porous surface applied? Through material selection for the trailing edge region, post-manufacture machining, or some other process? What is the configuration of the internal structure of the trailing edge - a single cavity separating the upper and lower porous surfaces, two divided and sealed cavities, or some other configuration? An important question is the effect of the porous surface on airfoil lift and drag, as this will have important consequences on energy capture in the wind turbine application. The extent of the porous trailing edge surface, and the configuration of the trailing edge structure will likely impact the airfoil performance. These questions will require a systematic wind tunnel investigation prior to demonstration on a wind turbine blade in the field.

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