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A Review of Trailing Edge Bluntness and Tip Noise from Wind Turbine Blades

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Abstract: *One of the dominant noise sources from rotating machinery equipment is from trailing edge section of an airfoil as found in wind turbine blades. A computational study of noise mechanism due to trailing edge of blade for a three bladed 2 megawatt wind turbine was performed using the semi empirical noise model. The model predicts the sound power levels from trailing edge bluntness source using boundary layer displacement thickness on pressure and suction side of airfoil. At low Mach number flows (0.1884) and moderate to high Reynolds number (4.73 x 10^5 – 3.35 x 10^6) in span wise direction of blade, the pressure field on the surface of blade close to trailing edge causes the noise to radiate as result of interaction of the turbulent boundary layer. The trailing edge bluntness noise levels are illustrated for wind speed regime from 4 - 22 m/s. The extent of reduction in A-weighted total sound power level was analyzed using the trailing edge thickness and trailing edge angle between the lower and upper surfaces of airfoil. The influence of blade tip pitch angle configuration and tip geometry are also examined using tip noise mechanism. The results showed good agreement between total A-weighted sound power levels including tip and the validated experiments.*
Keywords: *Airfoil, Boundary layer, Sound power level, Reynolds number, Mach number, Wind turbine*

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I. Introduction

Wind turbine blades produce aerodynamic noise when they operate in grass land, open sea, or other terrain. Although wind turbines operate at significantly lesser speeds compared to jet aircrafts, different parts of turbine such as blades, gearbox, and generatorinteract togetherand are responsible for producing noise which can be heard at audible frequencies causing annoyance and health concerns to inhabitants. Different community inhabitants across the world have mixed views regarding the presence of wind turbine operation located near homes. Therefore, strict noise regulation standards are implemented in several countries like the UK, Germany, Denmark and Sweden where threshold noise level outside is 55 dB during day timeand at 40 dB at night time, a reduction of 15dB during day and night time. [6,10]. Rotating bladesalso cause shadow that creates annoyance through repeated patterns of light shadefalling on the houses. In the last century the wind turbine sizes have been predominantly smallerhowever, the size of modern wind turbines have changed due to technology advancements. The design of quieter wind turbine is dependent upon the tip speed of blade during operation.The longer blades usually tend to possess high tip speeds and the geometry of airfoil profiles used for the blade construction. It also drives the cost of energy for a given turbine since increased tip speed of blades tend to capture higher energy from a turbine but results in producing higher noise emissions. Broadband noise generation from wind turbines is characterized using the subsonic flows over the blade, turbulence intensity in atmosphere boundary layer, boundary layer thickness. Sound pressure level is physical quantityperceived by human ear which changes with respect to wind direction in atmosphereand causes "imission". It is found to vary with the distance between source and receiver as well as the surface characteristic. Sound power level is amount of energy per unit area transmitted from a source causing emission and does not depend ondistance between the source and receiver but varies with wind speed. Wind shear is an important factor which is measure of how wind speed increases with height and it influences the maximum noiselevels that may reach on ground level [10].Lighthill (1974) first developed aero acoustic analogy usingNavier Stokes equations for compressible flows. He derived inhomogeneous wave equation by rearranging the continuity and momentum equationscontaining fluctuating fluid density and velocity in flow field stress tensorterms which are responsible for generating noise in turbulent flows. Further he demonstrated that free turbulence is source of noise commonly found in open channel turbulent flows [18]. This model was extended and modified by Ffowcs Williams and Hall [2] for unsteady subsonic compressible flows over hard moving surfaces into consideration that used spectral scaling approach to determine trailing edge noise levels for all frequencies. In this paper broadband noise caused due to trailing edge thickness of the airfoil is predicted using numerical simulation based upon the model developed by Brooks Pope and Marcolini (BPM) which is valid for 20Hz and 20 kHz frequency region.Furtherresearch was contributed by Amiet (1989) who developed trailing edgeand turbulent inflow noise models for turbulent boundary layerwhich assumes the isotropic turbulence phenomenon in atmosphere. Inflow turbulence exhibits broadband noise characteristics that areobserved higher at low frequencies (20Hz - 200Hz)in sound spectrum andtonal noise peaks at infrasonic frequencies (<20Hz) by blades of wind turbine. It also depends upon the turbulence intensity, atmospheric length scales and the blade passing frequency for downwind machines.Low frequency noise from wind turbines are found to be indifferent from the background levels for frequencies less than 50Hz.Lowson (1994) extended the turbulent inflow model based onAmiet's theoryand added the low frequency correction factors containing the acoustic wave number term expressed in terms of the local blade chord and turbulent length scale. The influence of blade chord length in Lowson's formulation lays significance to this noise source.Hence, sound generation is connected with turbulence which manifests in complex manner as result of flow unsteadiness over blades and itspropagation over far field distances [5].Amiet's trailing edge noise model is valid for rotating machines like wind turbine as well as propeller, cooling fan equipment etc. Previous studies were conducted on the validity of this model by Vincent and Phillip (2010) who observed the broadband trailing edge noise over different frequency range using the test applications. In the present study the hypothetical 2MW wind turbine is considered with blade length of 37m and hub height of ~70m is chosen for assessing the trailing edge bluntness noise. The trailing edge thickness and trailing edge angle, degree of bluntness [1], are important parameters in this type of source.The turbulent flow interacts with the sharp trailing edge of airfoil and cause acoustic diffraction to occur resulting in noise.Yet another source of noise mechanism is due to blade tip element. The blade tip produce vortices which are shed in atmosphere as wakes andinteract with free stream turbulence layers in atmosphere to generate noise.The predominant flow separation length that occurs at the tip region of rotating blade is main factor responsible for this type of noise. The tip vortex formation noise was first developed by Brooks and Marcolini (1989) whoperformed experiments for both 2D and 3D airfoil models andconcluded that airfoils exhibited tonal noise characteristics in form of peaks at different Reynolds numbers.All the individual noise mechanisms discussed above are added logarithmically in order to predict the overall sound power level for a turbine thatis found to vary according to wind speed magnitude and receiver positions.

II. Objectives Of Study

1. To quantify the extent of reduction in total A weighted sound power level, dBA,as result of changes to trailing edge thickness of airfoil.
2. Compare the overall sound power levels for the 2MW wind turbine for a receiver located at distance of 80m from sourceand source height of 70m above ground with and without tip noise mechanism.
3. Evaluate the tip noise mechanism with varying tip shape or geometry and tip pitch angle setting and its influence on the A weighted sound power levels.

III. Methodology

Sound pressure level exhibits dipole noise characteristic while the stress tensor term as quad pole characteristic according to Lighthill (1974) inhomogeneous wave equation[11]. However, noise radiated was limited to near field and does not account for directional nature of sound. This limitation was overcome by Ffowcs-Williams and Hawkings (FWH) who further developed the model for hard moving surfaces in two parts firstly for the accelerating motion of the moving surfaces i.e flat plate (airfoil) exerted forces on fluid which are described using monopoles and known as *thickness noise* and secondly with respect to moving surface which causes the fluid to be displaced and described using dipoles that are termed as *loading noise.* In this paper, the trailing edge noise model by Amiet (1989) is used for determining the surface acoustic pressure levels radiated from non stationary source subjected to unsteady compressible flows involving high frequency directivity functions, D_h The model considers the airfoil as flat plate with finite thickness at trailing edge and moving in rectilinear motion used to calculate the chord wise surface pressure distribution. The rectangular flat plate as shown in Figure 1(a) moves in free stream velocity U in the negative *x*-direction. This model was investigated further by Brooks and Hodgson [3] in which the trailing edge geometry was considered for assessing the influence on overall sound pressure level involving the high frequency directivity function D_h. The complete mathematical derivation of inhomogeneous wave equations representing the acoustic pressure field according to Lighthill acoustic analogy and modified by FWH can be found in [4],[9],[13],[15]. So, trailing edge noise from wind turbine blades exhibits broadband noise characteristics caused due to acoustic diffraction and edge scattering of velocity fluctuations in a turbulent boundary layer near trailing edge.

3.1 Trailing Edge Bluntness – Vortex Shedding

The wind turbine blades experience subsonic or low Mach number flows and operate in atmospheric boundary layers where the effects of air density, wind shear on sound pressure levels are found to be predominant. It depends upon the airfoil geometry, local angle of attack for the airfoils, and rotational speed of the turbine. This type of noise is also tonal in nature due to periodic vortex shedding that occurs in fully turbulent boundary layer and produces a distinct peak in the overall sound pressure level spectrum. The vortex shedding occurs when the boundary layer displacement thickness is of same magnitude of characteristic dimension of source which leads to excessive adverse pressure gradient on surface causing backflow in boundary layer near trailing edge of airfoil [20, 21]. They are approximated using these spectral functions, G4 and G5 and expressed in terms of ratio of trailing edge thickness and average boundary layer displacement thickness (see Eq.(5)) needed to compute the spectral functions G4 and G5 as given by Eq. (6) –Eq. (14). G4 represents the sharp peaks of acoustic spectrum and G5 is used to determine the shape of broadband acoustic spectrum (see Eq.(2) Strouhal number dependence) [1,17]. The spectral function $(G_5)_{\varphi=14^o}$ and $(G_5)_{\varphi=0^o}$ are solid angles determined using the symmetric NACA 0012 airfoil experiments [1]. It must be noted that bluntness noise becomes significant in sound spectrum when the $\frac{h}{\delta^*_{avg}}> 1$ and becomes predominant ~ 1kHz. The scaling expressions are function of flow angle of attack for airfoil at moderate Reynolds number and dependence of Mach number power 5.5 which represents better fit in spectrum. It must be noted that at low to moderate Reynolds number, and at subsonic speeds for the airfoils, the Mach number, the chord wise Reynolds number and boundary layer, displacement thicknesses for zero and non-zero angle of attack are obtained using the equations (5) - (16) in [1]. The 1/3rd octave SPL is approximated using the Eq.(1)

$$. \mathrm{SPL_{Blunt}} = 10.\log10\left[\frac{h\mathrm{M}^{5.5}\mathrm{L}\overline{\mathrm{D_h}}}{\mathrm{r_e^2}}\right] + \mathrm{G_4}\left(\frac{h}{\delta^*_{avg}},\varphi\right) + \mathrm{G_5}\left(\frac{h}{\delta^*_{avg}},\varphi,\frac{\mathrm{St}'''}{\mathrm{St}'''_{peak}}\right) \quad (1)$$

$$\mathrm{St}''' = \frac{fh}{\mathrm{U}} \quad (2)$$

$$\mathrm{St}'''_{peak} = \frac{0.212-0.0045\cdot\varphi}{1+0.235\left(\frac{h}{\delta^*_{avg}}\right)^{-1}-0.0132\left(\frac{h}{\delta^*_{avg}}\right)^{-2}} \quad \text{for}\left(\frac{h}{\delta^*_{avg}}\right) \geq 0.2 \quad (3)$$

$$0.1\left(\frac{h}{\delta^*_{avg}}\right) + 0.095 - 0.00243\varphi \text{ for}\left(\frac{h}{\delta^*_{avg}}\right) < 0.2 \quad (4)$$

$$\delta^*_{avg} = \frac{\delta^*_p+\delta^*_s}{2} \quad (5)$$

The spectrum peak is determined using the function G_4 and expressed using Eq.(6) & Eq. (7)

$$\mathrm{G_4}\left(\frac{h}{\delta^*_{avg}},\varphi\right) = 17.5\cdot log\left(\frac{h}{\delta^*_{avg}}\right) + 157.5 - 1.114\cdot\varphi \quad \text{for} \quad \left(\frac{h}{\delta^*_{avg}}\right) \leq 5 \quad (6)$$

$$169.7 - 1.114\varphi \quad \text{for} \quad \left(\frac{h}{\delta^*_{avg}}\right) > 5 \quad (7)$$

$$\mathrm{G_5}\left(\frac{h}{\delta^*_{avg}},\varphi,\frac{\mathrm{St}'''}{\mathrm{St}'''_{peak}}\right) = (\mathrm{G_5})_{\varphi=0^o} + 0.0714\cdot\varphi\left[(\mathrm{G_5})_{\varphi=14^o} - (\mathrm{G_5})_{\varphi=0^o}\right] \quad (8)$$

$$(\mathrm{G_5})_{\varphi=14^o} = \mathrm{m}\eta + \mathrm{k} \quad \text{for } \eta < \eta_0 \quad (9)$$

$$2.5\sqrt{1-\left(\eta/\mu\right)^2} - 2.5 \quad \text{for } \eta_0 \leq \eta \leq 0 \quad (10)$$

$$\sqrt{1.5625 - 1194.99\eta^2} - 1.25 \quad \text{for } 0 \leq \eta \leq 0.03616 \quad (11)$$

$$-155.543\eta + 4.375 \quad \text{for } \eta \geq 0.03616 \quad (12)$$

$$\eta = log\left(\frac{\mathrm{St}'''}{\mathrm{St}'''_{peak}}\right), \eta_0 = -\sqrt{\frac{m^2\mu^4}{6.25+m^2\mu^2}} \quad (13)$$

$$k = 2.5\sqrt{1-\left(\frac{\eta_0}{\mu}\right)^2} - 2.5 - m\eta_0 \quad (14)$$

*m*and μ are the functions of degree of bluntness or ratio of trailing edge thickness to average boundary layer displacement thickness given by Eq.(78) & Eq. (79) found in [1]. $\varphi$is the angle between the sloping surfaces near trailing edge of airfoil.δ^*_p, δ^*_s are the pressure and suction side boundary layer displacement thickness. A complete set of equations used to determine the pressure and suction side displacement thicknesses required in the evaluation of trailing edge noise spectrum are found in [1]. They are found to be dependent upon the local angle of attack of airfoil sections of blade and free stream velocity. The Reynolds number is used to characterize the compressible turbulent flows over airfoil or flat plate sections with finite thickness. For an airfoil it is expressed in terms of the boundary layer displacement thicknesses for the pressure and suction side. Strouhal number characterizes the oscillating flows around the objects like flat plate, airfoils and also bluff bodies like cylinder. It establishes the physical relationship between the boundary layer thicknesses developed on airfoil trailing edge with respect to the free stream velocity for any given center frequency. Several aero-acoustic studies have been conducted by Moreau (2011) using flat plate in order to quantify acoustic pressure field for turbulent flows at low to moderate Reynolds number. The trailing edge noise uses the high frequency directivity function using the Eq. (15)

$$D_H(\theta, \emptyset) = \frac{2\sin^2(\frac{1}{2}\theta)\sin^2(\emptyset)}{(1+M\cos\theta).(1+(M-M_c)\cos\theta)^2} \quad (15)$$

Where $\theta, \emptyset$ the directivity angles made between the source and receiver line with respect to blade span and chord direction with respect to the coordinate system shown in figure 1(a). M is the Mach number and M_c is the critical Mach number. The term ($1+M_c\text{Cos}\theta$) in Eq.(15) represents the Doppler shift or convective amplification of acoustic waves produced near the trailing edge of airfoil. They travel as oscillating waves and interact with turbulent layers upstream of trailing edge resulting in feedback mechanism. At high vortex shedding frequencies viz. a large Strouhal number in order of 0.57, flow is dominated by viscosity of fluid and results in small scale flow instabilities of wake and oscillatory movement of fluid. On the other hand at low frequencies and at small Strouhal number in order of 10^{-4} high speed quasi steady oscillatory motion of fluid occurs. The Strouhal number and the spectral shape functions vary with shape of airfoil, inflow velocity conditions and local angle of attack which exhibits different boundary layer characteristics for zero and non-zero angle of attack [8, 9]. Howe (1991) investigated the trailing edge noise model and found that magnitude of acoustic pressure field can be reduced using the serrated structures located at the trailing edge of airfoil [11,12]. They are described using wavelength, λ indicating the spacing of serrations and thickness, h at the trailing edge as shown in figure 2 (a). The serrations reduce the amplitude of broadband and tonal noise components by preventing the flow separation and reducing the effective span length near the trailing edge. Further, it has been found by Moreau (2011) that using trailing edge serrations the experimental results obtained for noise attenuation does not show good agreement with theoretical predictions by Howe (1991) in terms of frequency and free stream flow. Hence, no trailing edge serrations are implemented in the study. Experiments conducted by BPM [1] used a reference chord length for test airfoil which was 60.96cm and boundary tripping was done with help of 2cm wide strip consisting of grit applied at 15% chord length to produce *tripping* of the boundary layer on airfoil. Tripping of boundary layer is found to reduce the noise levels in certain regions of sound spectrum [8]. The maximum height of trailing edge thickness used in the BPM model airfoil was 2.5mm which is ~ 4.1% of chord which represents a square or blunt tip while a zero height represented sharp tip. The velocity distribution in turbulent boundary layer flow is governed by log or power law due to rapid acceleration of fluid particles close to boundary. In the current numerical study boundary layer is not tripped but uses three different trailing edge thicknesses i.e. 0.1 %, 1 % and 2 % chord length of airfoils and the mean trailing edge bluntness angle of 5.6^0. The simulation test matrix is shown in table 2 and discussed in the next section. The structural properties of the turbine rotor blade are shown in figure 3 and table 1.

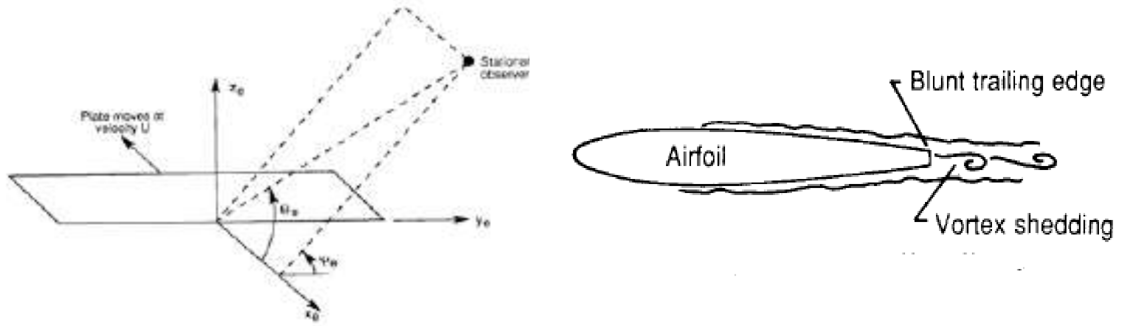


Fig1(a) Coordinate system for Directivity angles, $\boldsymbol{\theta}, \emptyset$[1]. Fig 1(b) Vortex shedding pattern at trailing edge [1]

3.2 Tip Noise

Tip noise is radiated when the turbulent separated flow near the tip region of the blade is shed in form of wake. This type of noise varies with slope of the lift curve (Eq. (22)) and tip angle of attack. The length of separated flow on the tip region is function of corrected tip angle of attack and referenced to chord wise Reynolds number. The vortex formation occurs with a turbulent core in the flow field and slope of lift curve determines loading on tip section of blade. The tip geometry is varied using the tip chord of blade by selecting a flag which represents the roundedness or flatness of the tip. A sharp tip, round tip and blunt tips are defined by a chord length of 0.15m, ~0.24m, ~ 0.4m respectively in present numerical analysis. This type of noise is tonal in nature and usually scales with square of Mach number and parabolic fit with Strouhal number dependence. The 1/3rd octave representation for tip noise mechanism is evaluated using the Eq.(16)

$$\mathrm{SPL_{Tip}} = 10.\log 10\left[\frac{\mathrm{M_{max}^3}\,\mathrm{M}^2 l^2 \overline{\mathrm{D_h}}}{\mathrm{r_e^2}}\right] - 30.5(\log St'' + 0.3)^2 + 126 \quad (16)$$

For blades with rounded tips the length of separated flow region and scales with the chord, tip angle of attack

$$\mathrm{St}'' = \frac{\mathrm{f}l}{\mathrm{U_{max}}} \quad (17)$$

$$\frac{l}{\mathrm{c}} = 0.008 \cdot \alpha_{\mathrm{Tip}} \quad (18)$$

$$\frac{\mathrm{M}}{\mathrm{M_{max}}} = (1 + 0.036 \cdot \alpha_{\mathrm{Tip}}) \quad (19)$$

For flat or blunt tips the length of separated flow region (Eq. (18) - Eq. (22)) are scaled using tip angle of attack

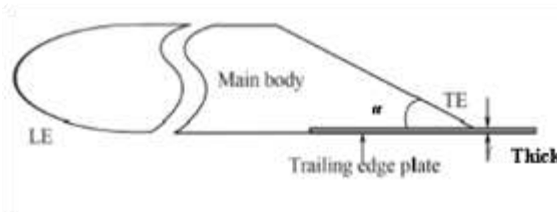
$$\frac{l}{\mathrm{c}} = 0.0230 + 0.0169 \cdot \alpha'_{\mathrm{Tip}} \quad \text{for} \quad 0^0 \le \alpha'_{\mathrm{Tip}} \le 2^0 \quad (20)$$

$$0.0378 + 0.0095 \cdot \alpha'_{\mathrm{Tip}} \quad \text{for} \quad \alpha'_{\mathrm{Tip}} \ge 2^0 \quad (21)$$

$$\propto'_{\mathrm{Tip}} = \left[\frac{\frac{\partial \mathrm{L}'}{\partial \mathrm{y}}}{\left(\frac{\partial \mathrm{L}'}{\partial \mathrm{y}}\right)_{\mathrm{ref}}}\right].\alpha_{\mathrm{Tip}} \quad (22)$$

Where L' is the lift per unit span length at span wise position y. The sectional lift curve slope is represented by $\frac{\partial \mathrm{L}'}{\partial \mathrm{y}}$ at the span wise position y of the blade and proportional to circulation strength which is required for twisted and tapered blade of varying chord lengths, St'' is the Strouhal number and $\overline{\mathrm{D_h}}$ is the high frequency directivity function, r_e is the effective distance between the source and receiver, *l* is the length of separated flow region size defined by the tip geometry. M is the Mach number corresponding to the tip region of airfoil and M_{max} is the maximum Mach number. $\propto'_{\mathrm{Tip}}$ is the corrected angle of attack for the tip region of airfoil dependent upon the tip loading of blade and expresses the deviation with respect to reference case. α_{Tip} is the actual angle of attack near tip section and for blades with large aspect ratio [1]. Overall A-weighted sound power level can be written as logarithmic sum of the individual noise mechanisms viz. TBL-TE, TI, TEB-VS and Tip noise sources.

$$\mathrm{SPL_{Total}}\,[\mathrm{dBA}] = 10.\log 10\left[10^{\frac{\mathrm{SPL\ TBL-TE}}{10}} + 10^{\frac{\mathrm{SPL\ TI}}{10}} + 10^{\frac{\mathrm{SPL\ TEB-VS}}{10}} + 10^{\frac{\mathrm{SPL\ Tip}}{10}}\right] \quad (23)$$



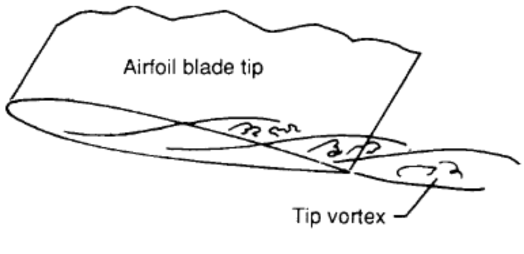


Fig2 (a) Trailing edge thickness & angle of airfoil [7] Fig 2(b) Schematic of tip vortex formation of airfoil [1]

IV. Results and Discussion

The noise mechanisms simulated in present study are for the source height of ~ 70m while the receiver height is ~2m placed at 80m from the source location in downwind direction. The downwind location is chosen as the worst case scenario since the noise levels are perceived maximum by observer. The ground surface roughness is 0.05 is obtained using the power law [8] equivalent to wind shear of 0.1 in atmosphere The airfoils for the blade used in BEM computations are constitute NACA0012, NACA 6302 and NACA 63xxx series. Table 1 show the turbine configuration used in the numerical simulation and Figure 3 shows the chord and twist distribution for the rotor blade of 37m. The computational code consisted of the angle of attack definitions obtained from the BEM computations and required for determining the average boundary layer displacement thickness from pressure and suction side of airfoils to evaluate sound pressure levels.

Table 1: Turbine configuration

Parameter	Value
Cone angle, deg	0
Tilt angle, deg	3
Hub height, m	70
Blade Radius, m	37
Rated speed, rpm	17
Max twist, deg	13
Max chord, m	3.22
Type of turbine	Upwind, pitch regulated
No of blades	3
Rated power, MW	2

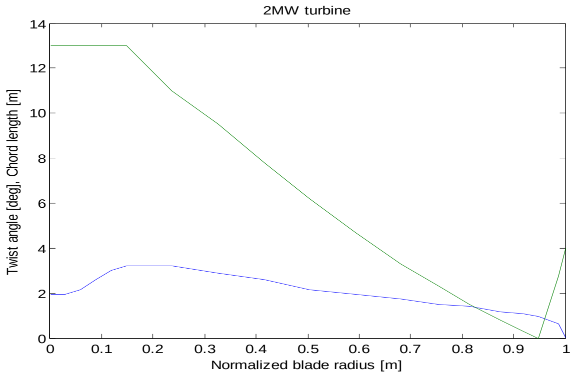


Fig.3 Chord and Twist properties of 2MW wind turbine

The aerodynamic noise radiated from wind turbine rotor is calculated first by discretizing the rotor blade into individual airfoil sections typically on order of 15. Sound pressure level for each section of blade source is calculated relative to observer position and added. The sound pressure level for individual sources are added logarithmically as in Eq.(23) to calculate the total noise level, dB. The flow over airfoils is quasi steady and2D in nature and noise levels are calculated at every time step in the simulation. The source term in numerical simulation ignores far field acoustic wave propagation and assumes that feedback from acoustic field to source is negligible. The SPL is measured in units of dB which is proportional to logarithm ratio of sound intensity to reference value and given by Eq. (24)

$$\text{SPL} = 10\log\left(\frac{I}{I_{ref}}\right) = 20\log\left(\frac{p}{p_{ref}}\right) \quad (24)$$

Where I is the sound intensity and equal to 10^{-12} W/m^2, p is the root mean square sound pressure. The reference mean square pressure, p_{ref} is 20μPa. The sound intensity is critical parameter in selection of blade length for MW turbines and proportional to turbulent length scale. At low and positive angle of attack the boundary layer on pressure side of airfoil shows the laminar flow pattern while the boundary layer on suction side remains in turbulent state near the trailing edge. The numerical simulation was conducted in GITAM University and Sreyas Institute of Technology DELL Desktop workstations with 4 GHz, 2GB RAM. The MATLAB simulation took ~3 hours for each case run in the test matrix shown in table 2. There was no change in turbine configuration present in table 1 and receiver positions between individual runs of simulation for consistency reasons.

4.1 Case Investigation

Table 2 Comparison of Maximum Sound Power Level, dB (A)

Simulation Matrix			Wind Speed			
Type of Noise Mechanism	**Parameter**	**Type**	**4 m/s**	**8 m/s**	**15 m/s**	**22 m/s**
Trailing Edge Bluntness	TE Thickness TE angle	I	113.80	113.99	114.47	114.81
SPL, dB	TE Thickness TE angle	II	120.37	120.44	121.39	121.63

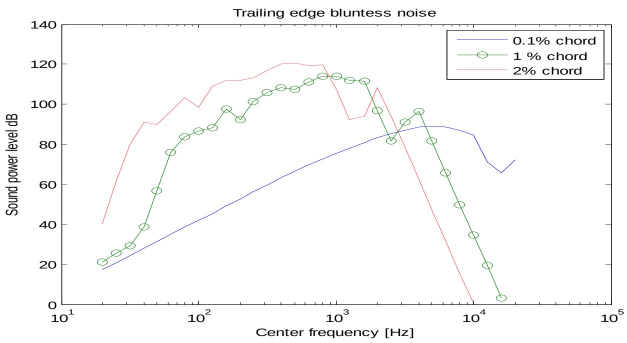


Fig.4 Influence of trailing edge thickness on TEB-VS noise [dB] at 0.1%, 1 % and 2% chord length

The receiver position is placed at distance of 2.2R from the turbine at a ground height of ~2m. R is the blade radius, m. The type I in the matrix is simulated using the trailing edge thickness of 1 % chord length and type II using the trailing edge thickness of 2 % chord length of airfoils. The maximum sound power levels, dB (A), for each of the types are shown in table 2 at four different wind speeds *4m/s, 8m/s, 15m/s and 22m/s* respectively. The average Reynolds number corresponding to the wind speeds are $1.3x10^6$, $2.6x10^6$, 4.87 x 10^6 and 7.15 x 10^6. It is evident that by decreasing the trailing edge thickness the bluntness noise contribution will reduce and found to vary in Strouhal number range 0.0533 – 0.5908. Two humps are observed for thickness of 1% & 2% chord length, near 1 kHz caused due to boundary layer displacement thickness from suction side of airfoil and at 2 kHz from pressure side of airfoil in the sound spectrum. Further from Figure 4 the peaks of sound power level are found near 1 kHz in sound spectrum for 1 % and 2% chord length while for 0.1 % chord length it appears to shift near 10 kHz with lower magnitude. Therefore, at lower thickness and bluntness angle, this type of noise does not show significant variations in the sound spectrum. The physics of the flow over airfoil is governed by the chord Reynolds number determining the laminar and turbulent flow regimes at different angle of attack conditions. Alternately the flow conditions are governed by the flow velocities and the airfoil characteristics used for the blade. Previous studies [1] have also shown that airfoils with porosity have improved noise reduction due to suction of boundary layer on surface and cause the flow to energize that can withstand adverse pressure gradient near trailing edge [20]. The maximum reduction of sound power levels between the type I and type II test matrix are found to reach ~20dBA.

4.2 Extent of SPL Reduction

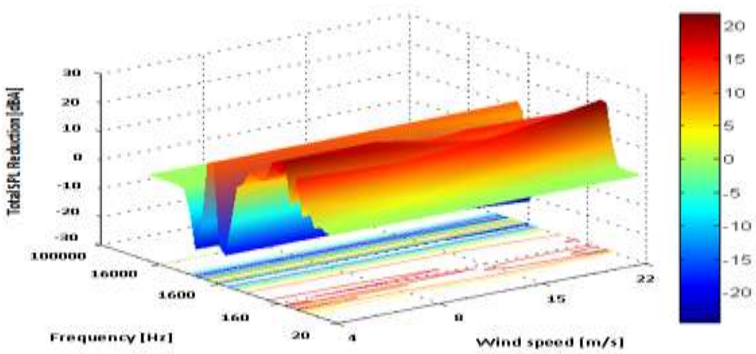


Fig.5 Extent of reduction in Total SPL (dBA) for change of 1 % trailing edge thickness

Large noise reductions are observed for frequencies <2 kHz and increase in noise levels for frequencies > 5kHz. These noise reductions are achieved for change in trailing edge thickness from 1% to 2 % for the blade. It must be noted that extent of noise reduction, dBA depended upon the Strouhal number range and varied with critical frequency corresponding to $\frac{St'''}{St'''_{peak}}$. Figure 5 indicates contours of reduction of overall A weighted sound power levels that vary for free stream wind speeds

4m/s, 8m/s, 15m/s and 22m/s. The amplitude of tonal and broadband noise components is affected by the thickness of trailing edge and trailing edge angle. Further at low frequencies between 100 and 1100 Hz the total noise level is reduced with peak reduction at 200Hz order of 20 dBA. On the contrary for high frequencies, at 1.25 kHz and 1.6 kHz and between 2 – 5 kHz, the trailing edge noise increases the total SPL, in order of 15dBA which indicates the effect of degree of bluntness has deteriorating effect on the total SPL dBA. For higher wind speeds this effect is more pronounced than at lower wind speeds, when the boundary layer displacement thickness on the airfoil surface is found to develop gradually until it eventually mixes with free stream velocity. The trailing edge angle or slope between the airfoil surfaces also show similar effect forming the vortex wake due to adverse pressure gradient near the trailing edge surface. The wake formed due to turbulent boundary layer interaction with the trailing edge results in noise radiation which extends further by interacting with the inflow turbulence near the leading edge through a feedback mechanism. The feedback mechanism is caused due to the formation of T-S (Tollmein-Schlichting) oscillating waves which are observed in laminar boundary layer region near the leading edge of airfoil and indicate the onset of turbulence. These turbulent waves travel downstream along the chord direction of airfoil element and interact with the trailing edge and process is repeated. Previous studies [22] have shown that exact reason behind this feedback mechanism is not known clearly and requires further investigation.

4.3 Effect of tip shape and tip pitch angle

The tip noise discussed in section 3.2 was simulated using varying tip geometries viz square tip, round tip and sharp tip configurations. From table 3 and Figure 8, the maximum tip noise level of 75.94 dBA is found for blunt tip which has tip chord length of 2% of maximum chord length of the blade. The round tip SPL dBA has value of 68.36 dBA and lie between that of sharp and blunt tip. The chord length at tip section is ~1.5 % of maximum chord length. The sharp tip blade is found to reduce the noise levels by ~ 10dBA relative to the round tip configuration. Most of the turbine manufacturers do not consider tip noise as major constraint during the design process due to its less contribution at very high frequency region in overall SPL level of spectrum. Further, the total A weighted noise spectrum was calculated using the tip noise contribution from the blunt tip configuration. This represents the worst case scenario. It is also true for the receiver position, i.e. 0 deg where the maximum noise levels are observed and at wind speed of 8 m/s which is near the rated wind speed of the 2MW machine. The tip angle of attack is set to 3^0 for which the slope of tip lift curve was chosen as 1.1. From figure 6 it can be observed that total SPL dBA including tip showed marked deviations at high frequencies region of sound spectrum i.e. >10 kHz where the Strouhal number is in range of 0.013-0.25. The total SPL level includes turbulent inflow noise but compares using with and without tip noise mechanisms. From figure 7 near low frequency region, 10-100 Hz, the total SPL dBA with tip is higher than without tip contribution however, the total SPL, dBA does not include the turbulent inflow noise mechanism.

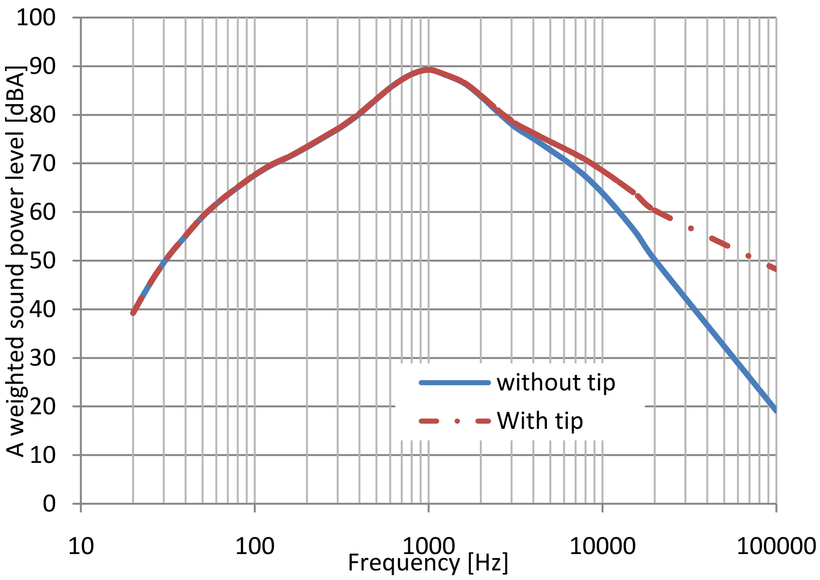


Fig.6 Comparison of Total SPL (dBA) with, without tip noise at 8m/s, 0 deg observer position with blunt tip geometry and at 3^0 tip angle of attack.

From figure 8 it must be noted that SPL dBA levels for only the tip noise are compared for different tip configurations and not the total SPL dBA in order to observe the effect of tip geometry. The sharp tip configuration produces lower noise levels and its peaks in the sound spectrum are observed at high frequency ~ 10 kHz while for round and sharp tip, it found near 1 kHz. The shift in peak noise levels are attributed to the magnitude of boundary layer separated flow region near the tip of blade and tip angle of attack. Further from figure 9 for large tip angle of attack, the peak noise magnitudes are found to decrease due to turbulent separation of flow over the tip region.

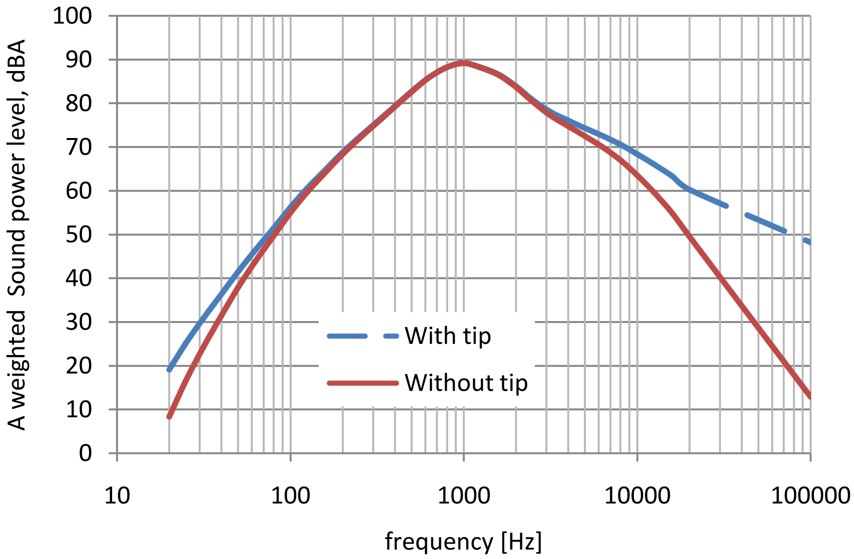


Fig7 Comparison of Total SPL, dBA, without inflow turbulence but including tip and not including tip noise levelsat 8m/s, 0 deg observer position with blunt tip geometry and at 3^0 angle of attack.

This is similar to the boundary layer tripping which also shows reduction in noise levels than blades with clean airfoils [8]. However, for large aspect ratio blades the effect of pitch angle setting does not dominate the overall sound power level in acoustic spectrum. In current study the maximum sound power level obtained due to the influence of tip pitch angle is found at -2^0 and decreases with increasing tip pitch angle of attack. This is due to the onset of stall phenomenon on airfoil leading to large flow separation lengths. Table 4 shows the maximum SPL dBA for different tip pitch angle of blade, and value of 95.98 dBA is observed at -2^0. As the pitch angle is increased the noise level decreases at a given wind speed. With round tip geometry the effect of tip pitch angle on the overall sound power levels can be observed predominantly in low to medium frequency region of spectrum [4].

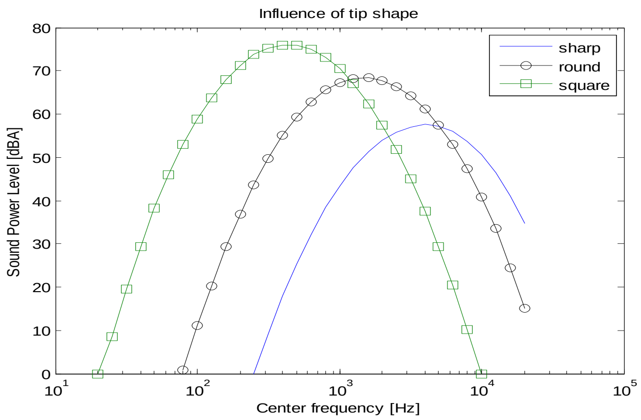


Fig.8 Comparison of tip noise levels [dBA] with varying tip geometry

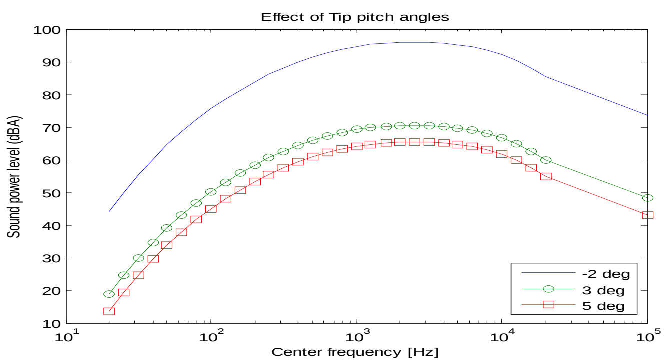


Fig.9 Effect of tip pitch angle on tip noise levels [dBA] with blunt tip

Table 3 Tip shape influence on SPL (dBA)

Tip shape	Maximum Sound Power level, dB(A)
Sharp tip	57.55
Round tip	68.36
Blunt tip	75.94

Table 4 Tip pitch angle influence on SPL dBA

Tip pitch angle, deg	Maximum Sound Power level, dBA
-2	95.981
3	70.515
5	65.381

Figure 10 represents the overall sound power spectra consisting of trailing edge noise mechanism due to turbulent boundary layer from suction; pressure and separation stall noise, bluntness noise, turbulent inflow and tip noise sources. It is compared with the total sound power level, dBA. The total SPL dBA is obtained using the Eq.(23) by logarithm addition of individual noise mechanisms. The turbulent inflow noise and TBLTE values are taken from [19] for comparison. Previous studies [4, 13, 16] Wei *et al* have shown that the power output from wind turbine is affected by the reduction of noise levels. The extent of reduction in total SPL (dBA) is tradeoff between the optimization of noise and power levels from the given turbine. A detailed study on tradeoff and optimization between power and acoustic emissions from turbine using the blade pitch angle orientation are available in [16].

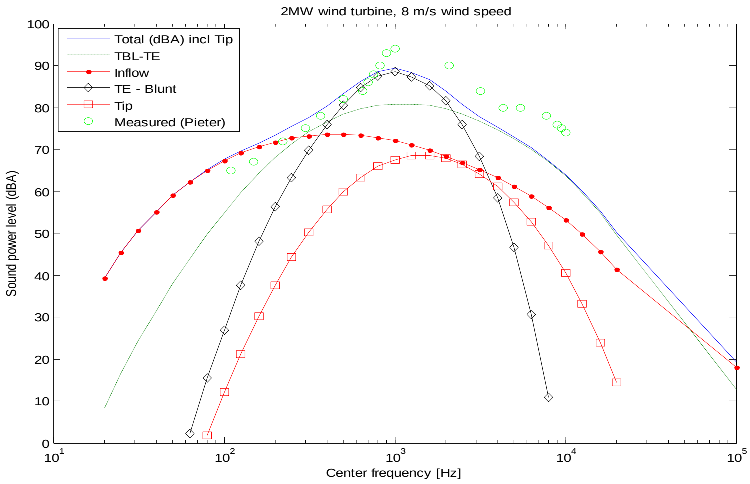


Fig.10 Comparison of noise mechanisms with total SPL [dBA] and measured results [9] for 2.3MW turbine

The hump in the sound power level spectrum observed at 1 kHz is attributed to vortex shedding of blunt trailing edge of airfoil. The frequency of such vortex shedding is indicated using the Strouhal number. This frequency is found to vary with the magnitude of free stream velocity and the turbulent boundary layer displacement thickness [15]. The hump decreases at high frequency and its amplitude decreases with decreasing flow velocity. The narrow large amplitude hump extends from 500 Hz to 1100 Hz and has a maximum sound power level of 91 dBA at 900 Hz. For frequencies below 1 kHz the experimental results from Pieter (2015) [9] show good agreement and found lower compared to the numerical results obtained for the hypothetical 2MW turbine. However, at frequencies greater than 1 kHz the deviations are observed to be higher for the total A weighted sound power level. This can be attributed partly to the blade properties used for 2.3MW turbine in his experimental model and receiver position i.e. upwind or downwind, as well as distance of 115m from the turbine used for the measurements. Further from figure 10 it can be observed that turbulent inflow noise dominates the low frequency region of the spectra. The effect of including tip shape can be observed at frequencies > 10 kHz. It can be noted that trailing edge noise can be masked by turbulent inflow noise and even background noise levels in certain frequency regions that may not occur during experimental measurements.

The Strouhal number variation is observed from 0.001 to 10 for the free stream wind speeds 4, 8, 15 & 22 m/s at which the total sound power level, dBA is found rising and the tonal amplitude from the trailing edge vortex shedding source. It is noted to shift to higher frequencies at low mach number flows and for thicker trailing edge or higher bluntness ratios, the total sound power level, dBA is observed to shift to lower frequencies. Figure 12 shows the variation in Total SPL, dBA with Strouhal number range for frequencies between 20Hz – 10kHz. From figure 11 it can be observed that at higher frequencies in spectrum, the Strouhal number does not increase for a given flow configuration, i.e. low mach number and moderate to high Reynolds number flows. It indicates that total sound power level from turbine is functionally dependent also on the angle of attack experienced by the airfoil sections of blade for the range of flow configurations considered.

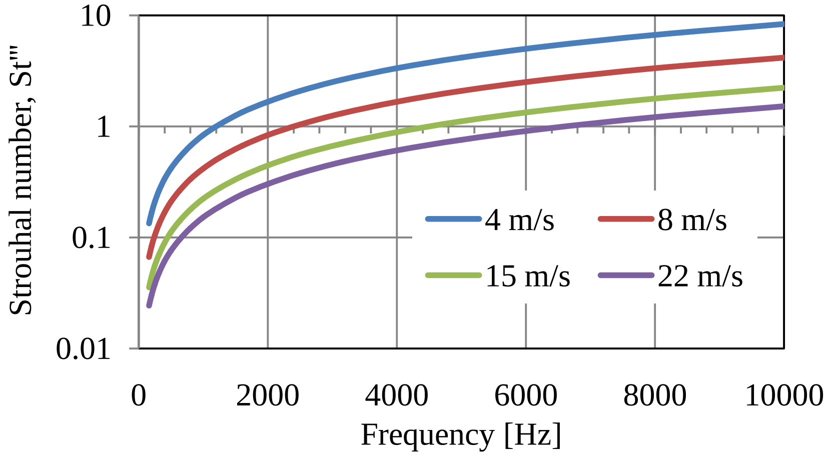


Figure 11 Strouhal number range variation for free stream wind speeds, 4, 8, 15 & 22 m/s

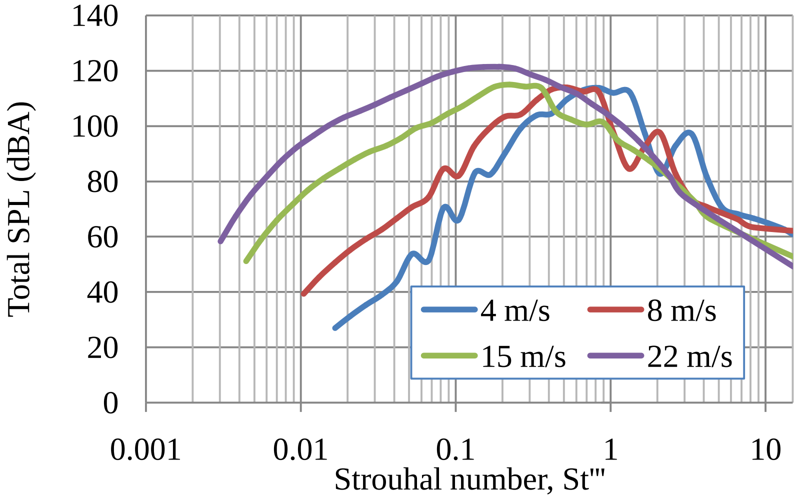


Figure 12 Total sound power level [dBA] variation with Strouhal number & low Mach number flow configurations for bluntness ratio scaled with 2% chord length of blade.

V. Conclusions

The trailing edge noise mechanism was studied using the BPM model that predicts the sound pressure and power levels for 2MW turbine. It exhibits broadband and tonal noise characteristics in different regions of sound spectrum. The effect of trailing edge thickness affects the total A weighted sound power level in the form of tonal peak or hump observed near 1 kHz region and dominates the overall sound power spectrum. The corrections to the BEM computed angle of attack and tip lift curve slope are important to determine the tip noise mechanism. The tip noise levels also show tonal characteristics and found to vary with tip angle of attack at moderate Reynolds number. Sharp tip geometry produces lower tip noise magnitude compared to round tip and blunt tip configurations. The large tip pitch angles settings also found to reduce tip noise magnitudes and affect the power output from the turbine. The experiment results show good agreement with numerical simulations outputs for the overall A weighted sound power level spectrum The extent of reduction in total A weighted sound power level is of order of 15-20 dBA for an increment of 1 % trailing edge thickness and found between 400-1000Hz region of spectrum.

VI. Acknowledgements

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List of Abbreviations

SPL – Sound Pressure Level, Sound Power Level
TSPL- Total A Weighted Sound Power Level
dB – Decibel
dBA – A weighted decibel
BEM – Boundary Element Momentum
TBL-TE – Turbulent Boundary Layer Trailing Edge
TEB-VS – Trailing Edge Bluntness Vortex Shedding
TI – Turbulent Inflow
LE, TE – Leading Edge, Trailing Edge
R – Blade radius, m
MW – Megawatt
BPM – Brooks Pope Marcolini

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