APLICATIONS OF AEROACOUSTIC THEORY TO WIND TURBINE NOISE

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"For average noise exposure, the GDG conditionally recommends reducing noise levels produced by wind turbines below 45 dB L_{den}, as wind turbine noise above this level is associated with adverse health effects." (World Health Organization, 2018)

ABSTRACT

The objectives of this technical paper are to (i) introduce the reader to the different aeroacoustic noise sources found in the Horizontal Axis Wind Turbines (HAWT), (ii) how these noise sources can be modelled using the aeroacoustic theory available and (iii) what is their relative contribution to the overall sound pressure level and spectra. The noise emission of aeroacoustic nature represents a potential deterrent to the increase in diameter and numbers of on-shore, utility-size HAWT equipment. In Brazil, where the wind-energy is growing rapidly and also attaining the highly desirable economic viability status. In this scenario it is important to remove other potential restrictions and look carefully at the aeroacoustic noise emission from the HAWT equipment and the social and environmental risks it could represent to the welfare of villagers and local dwellers close to the windfarms. The noise emission becomes increasingly important with the commissioning of ever larger-size wind turbines, coupled with the use of more sophisticated building materials, like carbon-fiber reinforced plastics (CFRP), which could allow further diameter increases without necessarily demanding decreased rotor speeds due to high bending-torsion moments at the root of the blades. The POLI-WIND research group was created in 2012, at Escola Politécnica da USP (POLI-USP), in order to understand the aeroacoustic noise problem associated with HAWT equipment and to provide

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the wind energy industry with practical solutions to help mitigate the noise emission problem. The aim of the research group is to help spread the wind energy conversion technology faster in Brazil and worldwide, reducing as quickly as possible the planetary impact from fossil fuel burning, while producing the necessary clean energy to match the demand of a developing society. Among the contributions developed by the POLI-WIND group to the wind energy industry, are an open source, free download code for predicting airfoil trailing-edge noise embedded in the Qblade[5] software and a family of quieter airfoils for large-size HAWT, with high aerodynamic efficiency.

Keywords: Wind Turbine Noise; Airfoil self-noise, Inflow noise.

[5] The Wind Turbine design environment put together by Technische Universität Berlin.

RESUMO

O objetivo deste trabalho é (i) apresentar ao leitor as diferentes fontes de ruído encontradas nas turbinas eólicas de eixo horizontal (HAWT), (ii) como elas podem ser modeladas usando a teoria aeroacústica clássica disponível e (iii) qual a contribuição relativa das fontes para a pressão sonora total e seu respectivo espectro. A emissão de ruído de natureza aeroacústica representa um empecilho potencial para o aumento do diâmetro e número de equipamentos HAWT, em aplicações terrestres. No Brasil, onde a energia eólica está crescendo rapidamente e alcançando a viabilidade econômica livre de incentivos, seria desejável que o ritmo do alastramento dessa tecnologia fosse ainda maior. Neste cenário é importante olhar atentamente para a emissão de ruído do equipamento HAWT e mitigar, desde o projeto, o risco socioambiental que ele representa para o bem-estar dos vilarejos e moradores próximos aos parques eólicos. A emissão de ruído torna-se cada vez mais crítica à medida que ocorre o comissionamento de turbinas eólicas maiores e que empregam materiais de construção mais sofisticados, como plásticos reforçados com fibra de carbono (CFRP), que não necessariamente demandam a redução da rotação dos novos rotores, já que resistem melhor ao aumento da carga de flexo-torção na raiz das pás. O grupo de pesquisa POLI-WIND foi criado em 2012, na Escola Politécnica da USP (POLI-USP), para entender o problema do ruído aeroacústico associado aos equipamentos HAWT e fornecer ao setor de energia eólica soluções práticas para ajudar a mitigar a emissão de ruído. O objetivo do grupo de pesquisa é ajudar a difundir a tecnologia de conversão de energia eólica mais rapidamente no Brasil e no mundo, reduzindo o mais rápido possível o impacto planetário da queima de combustíveis fósseis, enquanto permite produzir energia limpa necessária para atender à demanda de uma sociedade em desenvolvimento. Entre as contribuições já realizadas pelo grupo POLI-WIND para a indústria de energia eólica, estão um código aberto de download gratuito para a previsão de ruído de aerofólio, embutido no software QBlade, além de uma família de aerofólios mais silenciosos para HAWT de grande porte, de elevada da eficiência aerodinâmica.

Palavras-chave: Ruído de Turbina Eólica; Ruído Próprio de Aerofólio; Ruído Devido ao Nível de Turbulência no Vento Incidente.

LIST OF ABBREVIATIONS AND ACRONYMS

Abbreviation	Meaning
AOA	Angle of Attack
CDG	Guideline Development Group – World Health Organization
CFRP	Carbon-Fiber Reinforced Plastic
dB	decibel
dB(A)	A-weighted decibel
FW-H	Ffowcs-Williams and Hawkings equations for acoustic analogy
HAWT	Horizontal Axis Wind Turbine
WT	Wind Turbine
LE	Leading Edge
LFN	Low Frequency Noise (Hz)
NACA	National Advisory Committee for Aeronautics – USA
OASPL	Overall Sound Pressure Level (dB)
POLI – USP	Politechnic School - São Paulo State University - Brasil
POLI-WIND	Politechnic School Wind Energy Research Group - Brasil
QBlade	TU Berlin-developed, public domain, Wind Turbine Performance and Structural analysis software.
SPL	Sound Pressure Level (dB)
$SPL_{1/3}$	Sound Pressure Level for each 1/3 octave band (dB)
SPL_A	A-weighted Sound Pressure Level (dB)
TBL-TE	Turbulent Boundary Layer at the Trailing Edge
TE	Trailing Edge

LIST OF SYMBOLS

LATIN LETTERS

Letter	Meaning	Disambiguation, (section)	units
$\boldsymbol{A_b}$	Airfoil area		m^2
$\boldsymbol{c_0}$	Acoustic wave speed		m/s
$\boldsymbol{d}$	Cylinder diameter		m
$\boldsymbol{f}$	Sound or noise frequency		$1/s$
$\boldsymbol{f_s}$	Frequency, vortex shedding		$1/s$
$\boldsymbol{Hz}$	hertz		$1/s$
$\boldsymbol{h}$	Trailing Edge thickness		m
$\boldsymbol{I}$	Acoustic pressure intensity		w/m^2
$\boldsymbol{k}$	The wavenumber		$1/m$
$\boldsymbol{L_{den}}$	(Day Evening Night Sound Level) or CNEL (Community Noise Equivalent Level) is the average sound level over a 24 hour period, with a penalty of 5 dB added for the evening hours or 19:00 to 22:00, and a penalty of 10 dB added for the nighttime hours of 22:00 to 07:00		$dB(den)$
$\boldsymbol{l}$	Length; characteristic source or turbulence dimension; height of turbulent stream.		m

M, M_a	Mach number		
M_c	Mach number, eddy convection		
R	Rotor radius, total		m
R	Ideal gas model constant of the gas	B.5 only	$J/kg.K$
Re	Reynolds Number		
Re_c	Reynolds Number, chord-based		
r	Rotor, blade radial position		m
r	Distance from source to observer point, in the far field		m
r_e	Observer distance to source, retarded		m
r_0	Location of the source		m
r_0	Distance between the center of the eddy and the edge		m
U_∞	Velocity, freestream		m/s

GREEK LETTERS

Letter	Meaning	Disambiguation, (section)	units
α	Normalized turbulence intensity u'/U	2.1	
δ^*	Displacement thickness		m
θ	Directivity angle. Angle between the observer position and the chordwise airfoil plane.	See Fig. 8	^{0}
Λ	Length, characteristic scale of the turbulence		m
ν	Viscosity, kinematic		m^2/s
ρ_0	Density, undisturbed fluid		kg/m^3
$\rho_0 c_0$	Impedance, acoustic, of the medium		kg/m^2s
Φ	Angle, directivity, between the observer and the edge plane, projected in the plane perpendicular to the edge.	See Fig 8	^{0}

1. NOISE SOURCES IN A HORIZONTAL-AXIS WIND TURBINE.

The aeroacoustic noise sources derived from the interaction of the flow with the Wind Turbine may be classified in three different categories: airfoil self-noise, inflow noise and noise from the interaction of the rotor flow and the tower. A typical flow around a WT rotor blade, with flow orientation, is depicted in Figure 1, which also displays the most important phenomena involved.

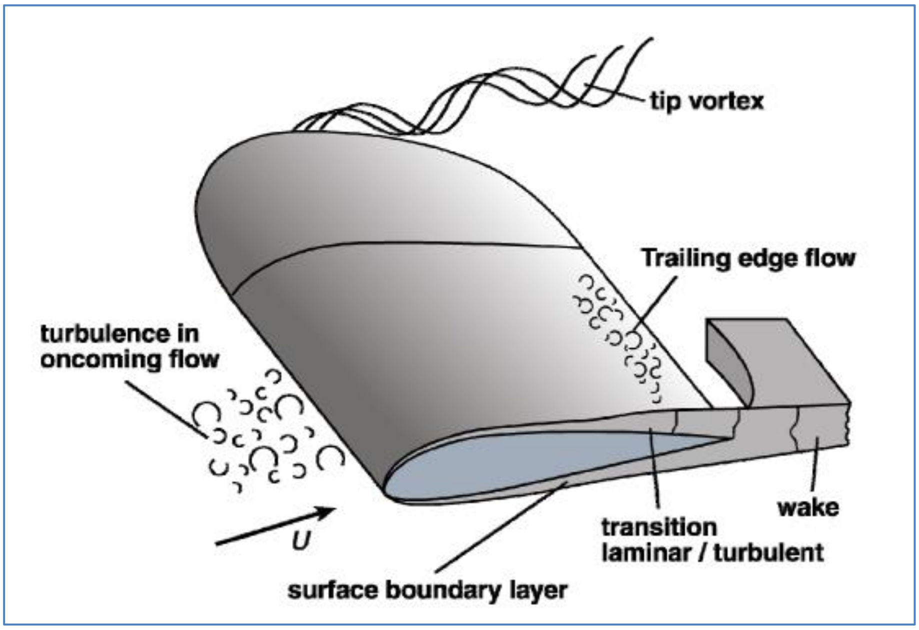

Figure 1 - Typical flow around a WT rotor blade (Wagner, Bareiß, & Guidati, 1996).

A list of the main mechanisms and sources is found in Table 1, along with a description of the noise characteristics (Rogers, Manwell, & Wright, 2006). Also, Blake (Blake, Mechanics of Flow-Induced Sound and Vibration, 1986 II) confirms these as the main acoustic noise sources, although other types of noise sources may arise from the flow interaction with equipment operating at higher Mach numbers, like ducted fan engines and helicopter rotors.

Table 1 – Aeroacoustic noise generation mechanisms. Adapted from the work of (Rogers, Manwell, & Wright, 2006).

Nature	**Mechanism**	**Noise characteristics**
Airfoil Self-Noise		
Trailing-edge noise	Interaction of flow with TE.	Broadband.
Tip Noise	Interaction of tip flow with blade tip surface.	Broadband.
Stall, separation noise	Interaction of turbulence with blade surface.	Broadband.
Laminar boundary-layer noise	Flow instabilities interacting with the blade surface.	Tonal.
Blunt trailing-edge noise	Vortex -shedding.	Tonal.
Noise from flow over holes, slits and intrusions	Unstable shear flows and vortex-shedding.	Tonal.
Inflow Noise	Interaction of blades with atmospheric turbulence.	Broadband noise.
Noise from the interaction of the rotor flow and the tower	Blades passing by the tower or wake interaction with the tower.	Related to the blade passing frequency (BPF).

In the following paragraphs, a brief description is made of the most relevant noise mechanisms introduced in Table 1.

1.1 The Trailing-Edge Noise

This source of noise is typical of the outboard sections of the WT blade, when $Re_C > 1x10^6$, the established flow is turbulent and the flow remains attached up to the TE. This is generally considered the main source of high frequency noise (750 Hz < f < 2 kHz) for large, modern WT, in low Mach number, smooth inflow regime (Brooks, Pope, & Marcolini, 1989); (Hubbard & Shepherd, 1990), (Wagner, Bareiß, & Guidati, 1996).

Acoustic field measurements accomplished within the European research project SIROCCO context, confirmed that the TBL-TE noise is the dominant noise mechanism for large wind turbines (Oerlemans, Sijtsma, & Méndez-López, Location and Quantification of Noise Sources on a Wind Turbine, 2007), (Kamruzzaman, Lutz, Nübler, & Krämer, 2011), (Oerlemans, Wind Turbine Noise: Primary Noise Sources, 2011).

The seminal investigation on this type of source is the work of Ffowcs-Williams and Hall (Ffowcs-Williams & Hall, 1970). For the eddies to produce any sound amplification while convecting along the edge, they must be close enough to the edge so that $kr_0 \ll 1$, where, k is the wave number and r_0 is the distance between the center of the eddy and the edge. For the eddies that match this requirement, the noise output from the turbulence quadrupoles are amplified by a factor of $(kr_0)^{-3}$ and the far field noise intensity associated with these sources depends on the fifth power of the typical fluid velocity. The exact shape of the TE is of importance only for relatively high-frequencies (Wagner, Bareiß, & Guidati, 1996), while the properties of the surface might influence the directivity function (Ffowcs-Williams & Hall, 1970).

1.2 The Tip Noise

Since the local flow velocity is largest at the tip of the rotating WT blades and all noise sources originated from the interaction between the boundary layer and the airfoil display a fifth or sixth order dependence on the flow speed as will be discussed shortly, it may be expected that the outboard portion of the blades will radiate most of the noise. Indeed, this fact may be fully confirmed in Figure 2.

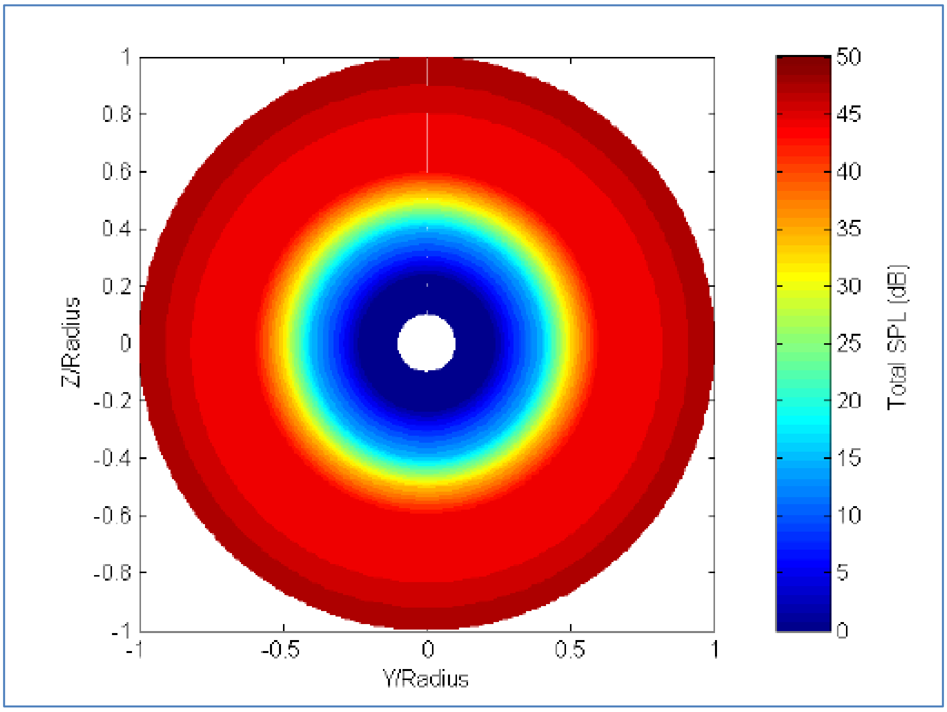

Figure 2 - Average distribution, over 5 minutes, of noise sources that contribute to total SPL, as observed 32.5 m upwind, at the height of the hub, for an AOC WT in steady 8 m/s wind with no turbulent inflow noise (Moriarty & Migliore, 2003).

In practice, when the difference in pressure level between two regions is larger than 15 dB, the contribution of the lower source may be neglected (Bistafa, 2011). In the case of the AOC WT depicted in Figure 2, operating in 8 m/s wind with no inflow noise, this translates into practical terms as all relevant noise sources being in the outboard range of the rotor, or $r/R > 0.5$.

This is also confirmed by other field measurements by Oerlemans (Oerlemans, Wind Turbine Noise: Primary Noise Sources, 2011), as depicted in Figure 3.

Apart from being a region of high flow velocity and noise radiation, there seems to be no remarkable contribution from the particular 3D-flow around the tip, for the overall noise radiated. Brooks et at. (Brooks, Pope, & Marcolini, 1989) compared 2-D and 3-D airfoil noise data, for the same airfoil and flow conditions, and proposed a high frequency, broadband model for this source. A direct spectra comparison for the 2-D and 3-D cases showed that only the 1/3 octave bands above 12 kHz where increased by 1-2 dB. It is important to add that the airfoil was at the significant angle of attack (AOA) of $10.8°$, since the airfoil employed was the symmetrical (NACA 0012) and it is naturally necessary to produce lift for the induced-drag vortex to be present around the blade tip.

Figure 3 - Average distribution, over many revolutions, of the noise source distribution in the azimuthal plane, for a typical, modern, large-size WT, projected over a picture of the WT, for illustration purposes only (Oerlemans, Wind Turbine Noise: Primary Noise Sources, 2011)

1.3 The Stall-Separation Noise

While for attached flow the TE Noise is the dominant mode, beyond stall the separation noise is the dominant Airfoil Self-noise mode. At stall, the noise may increase by more than 10 dB relative to TE Noise emitted by low-alpha, attached flows (Brooks, Pope, & Marcolini, 1989). According to the same authors, there were no predictive models for Separation Noise then, and also the extensive bibliographic research accomplished since then did not unveil any such model.

According to Brooks et al. (Brooks, Pope, & Marcolini, 1989), a successful noise prediction method for this source would have to consider the gradual increase of noise from separation, as the airfoil angle of attack in increased and becomes dominant at deep stall.

1.4 The Laminar Boundary Layer Noise

When the rotor blades, or a section, operate at or under the transition Reynolds number ($Re < 10^6$), the laminar flow region might extend up to the TE in certain conditions. In this case, a resonant interaction, of tonal nature, might occur as the TE noise waves travel upstream and couple with the Tollmien-Schlichting waves of the laminar BL, producing vortex shedding. The noise tones produced are related to the vortex shedding frequency at the TE (Brooks, Pope, & Marcolini, 1989). Also, in the case of the laminar flow, a laminar separation bubble may occur.

Both phenomena, the non-linear process of feedback of the noise on the instabilities of the laminar flow and the formation of the laminar bubble, may originate tonal noise, but these mechanisms are usually more relevant for small scale WT, where $Re < 10^6$ (Oerlemans, Wind Turbine Noise: Primary Noise Sources, 2011), and even then the tonal noise may be prevented by tripping the boundary layer far upstream of the TE.

1.5 The Blunt Trailing-Edge Noise

The frequency f_s of vortex shedding behind cylinders of diameter d is a simple function of the Strouhal number, which is a function of the Reynolds number only.

$$\frac{f_s\, d}{U_\infty} = F\left(\frac{U_\infty\, d}{\nu}\right) \qquad (1-1)$$

On the other hand, the problem of vortex shedding from lifting surfaces is much more complex (Blake, Mechanics of Flow-Induced Sound and Vibration, 1986 I), involving viscous boundary regions on the surface and details of the geometry of the trailing edge. Blunt, i.e., non-sharp TE edges may be characterized by thickness, radius, or angle, depending upon the type of geometry. Blake (Blake, Mechanics of Flow-Induced Sound and Vibration, 1986 II), shows that the Strouhal number for sharp and blunt TE airfoil geometries is a function of the flow regime and bluntness parameter, h/δ^*, where h is the TE thickness.

As the bluntness parameter increases above 0.25, $h/\delta^* > 1/4$, a secondary hump appears in the sound spectrum and it increases in energy and decreases in band-width (Blake, Mechanics of Flow-Induced Sound and Vibration, 1986 I), becoming eventually a tonal noise, frequently described in the bibliography as airfoil *singing* noise, for large enough h/δ^* ratio. The reason for this behavior is that fluctuating forces will prevail, resulting in dipole-type noise of tonal character (Wagner, Bareiß, & Guidati, 1996).

This tonal noise may be illustrated by looking at Figure 4, which shows the distinctive signature of blunt TE noise. For the tripped case, a secondary hump is formed and for the untripped case a quasi-tonal noise is characterized.

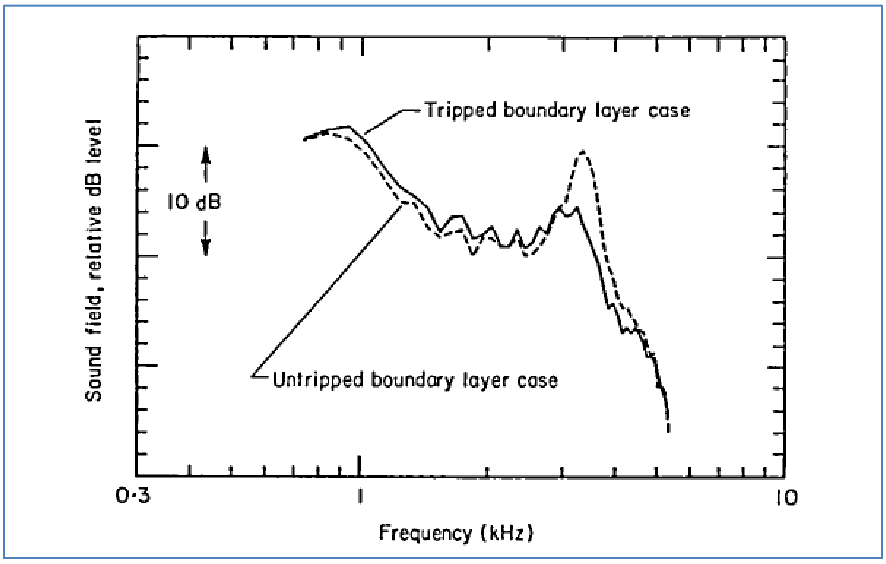

Figure 4 - The sound spectrum for a blunt TE NACA0012 airfoil, with spectral "hump" near 3 kHz (Brooks & Hodgson, 1981).

Figure 5 shows the effect of sharpening the TE on the noise spectrum.

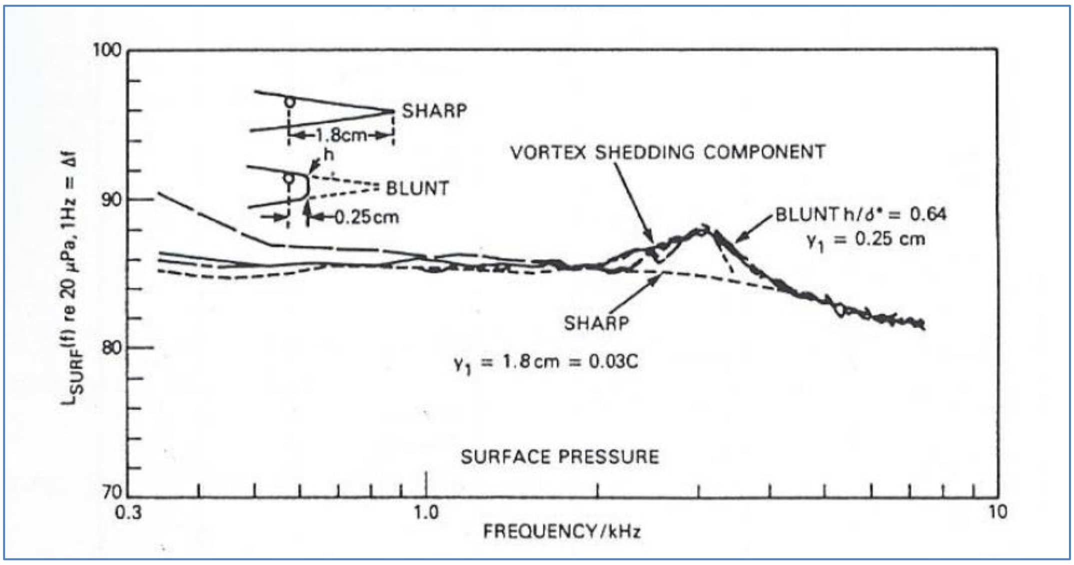

Figure 5 - Radiated sound for sharp and blunt TE NACA0012 airfoil, LE tripping (Brooks & Hodgson, 1981) data, adapted by (Blake, Mechanics of Flow-Induced Sound and Vibration, 1986 II).

Figure 6 shows a direct comparison of WT broadband spectra for sharp and blunt TE blades for the same 50 kW wind turbine.

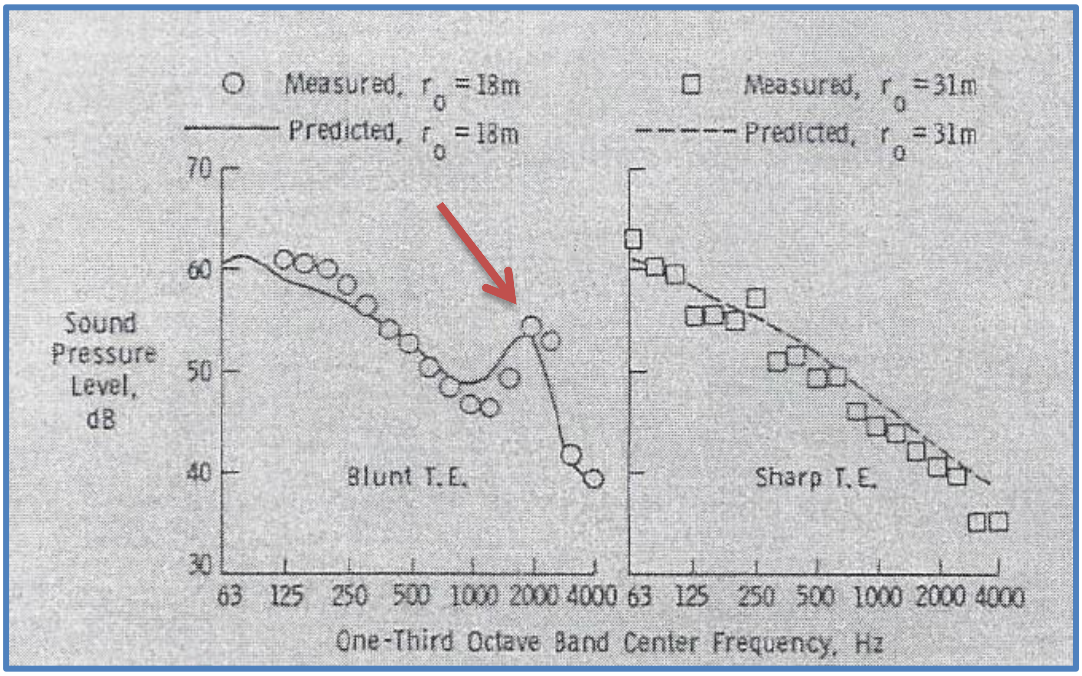

Figure 6 - Measured (continuous lines) broadband noise spectra for a U.S. Wind Power Inc. machine with blunt and sharp TE (Grosveld, 1985).

A broad comparison study of typical TE shapes and their relative amplitudes of tones (singing) may be found in Blake (Blake, Mechanics of Flow-Induced Sound and Vibration, 1986 II). Some simple TE geometries may reduce the singing to 1% or less, compared to the fully blunt TE configuration, as shown in Figure 7.

According to Grosveld (Grosveld, 1985), the smaller the TE thickness, the higher the peak frequency of shedding, so that sharpening the TE effectively shifts the peak away from the audio range, to the ultra-sound region of the spectrum. The practical limit of sharpening the TE is of major concern for construction and installation purposes and it is important to recognize, when modeling, that there exists no fully sharp TE in practice. While Wagner et al. (Wagner, Bareiß, & Guidati, 1996) consider the typical TE thickness to be in the 1-3 mm range, depending on the blade chord and operation condition, a consultation made directly with the industry (Sloth, 2011) revealed that, for current, large size WT, TE thicknesses are typically specified in the range of 2 to 5 mm for the 1/3 outboard part of the blade, but are often seen manufactured with thicknesses from 10 to 20 mm. Chord lengths in this blade range (50 m span) are typically 0.6 to 1 m - leading to a specified TE percentage of 0.2 to 0.8 % chord, and realized percentages of 1 to 3% of the chord.

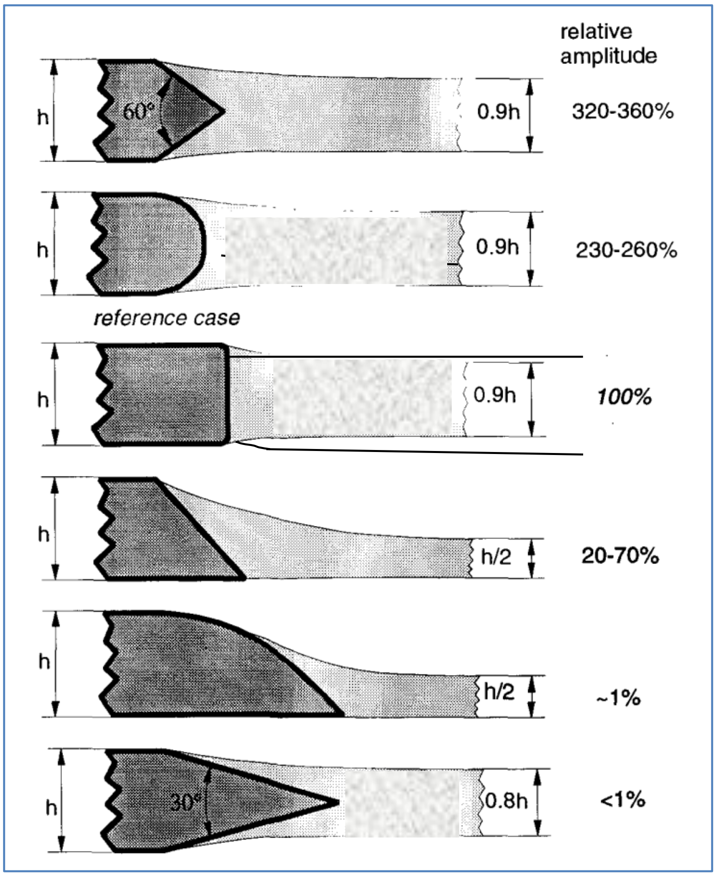

Figure 7 - A summary of airfoil TE shapes and relative tone noise amplitude, (Wagner, Bareiß, & Guidati, 1996).

The evaluation of the consequences of the TE thickness in the blade singing sensitivity will depend not only on the thickness dimension itself, but also on the geometry of the TE and on the boundary layer displacement thickness at the TE.

1.6 Noise from Flow over Holes, Slits and Intrusions

Deviations from design geometry do not occur solely in the blade TE thickness. The overall blade shape may display geometric deviations due to manufacturing tolerances, but also imperfections may originate or aggravate during the WT assembly, erection and operation. The classic situations that will add to geometrical imperfections and surface roughness are hail storms, lightning strikes, bird impact, insect impact (which will stick to the surface), dust, oil, loose tapes and slits.

There seems to be some different points-of-view concerning the consequences of the described surface imperfections. While Wagner et al. (Wagner, Bareiß, & Guidati, 1996) state that any unwanted disturbance to the flow around the blade may cause additional noise, Brooks and Hodgson (Brooks & Hodgson, 1981) showed that a tonal noise may be avoided by the tripping of the BL, which is triggered by the imperfections described.

While Oerlemans (Oerlemans, Wind Turbine Noise: Primary Noise Sources, 2011) expects the boundary layer on either side of the airfoil might remain laminar up to the trailing edge for chord-Reynolds number below $1x10^6$, the reality of the operating conditions seems to be very different, as Eisele et al. (Eisele, Pechlivanoglou, & Nayeri, 2013) report that WT field tests could not reproduce low turbulence wind tunnel test data since the presence of even the small surface waviness and dust were enough to cause boundary layer transition. Since the cumulative presence of dust, dents, scratches and insects seems the rule rather than exception in the operating environment of such large equipment, Oerlemans' assertion in this matter seems to be applicable only to the realm of small-scale WT or brand-new equipment.

2. APLICATIONS OF AEROACOUSTIC THEORY TO WTN

The different aspects of the aeroacoustic theory may find different applications in the noise prediction engineering practice, depending upon the flow regimes and the dominant noise producing mechanisms. For instance, the steady, harmonic noise from a propeller is caused by steady loads at the rotating blades and occurs at multiples of the BPF. The mechanism of noise production is the displacement of air by the motion of the body, giving rise to monopole sound, and the forces acting from the body on de fluid, giving rise to dipole sound. Because it does not depend on the viscous flow interaction and can be calculated in a straightforward manner, this kind of noise is referred to as *deterministic noise*. This form of self-noise is called *Gutin noise* (Theodorsen & Regier, 1946) and may be computed with good accuracy, but it is not a significant noise source for current design HAWTs since, according to Blake (Blake, Mechanics of Flow-Induced Sound and Vibration, 1986 II), the Gutin noise is generally important at nearly sonic tip speeds, i.e., high Mach numbers.

There are also applications of the Ffowcs Williams & Hawkins (FW-H) equation (Ffowcs-Williams & Hall, 1970) for the deterministic, harmonic fan noise, where the loads at the blades (source terms) are computed either using Blade-Element Momentum BEM methods (Hansen, 2008), (Burton, Sharpe, Jenkins, & Bossanyi, 2008) or *vortex-lattice methods* (Gupta & Leishman, 2005), which are inviscid in nature, and thus cannot model the source strengths coming from the interaction between the turbulence and the WT blade.

For the high-frequency noise originated from the turbulent flow, the Lighthill equation (Lighthill, 1962) provides, in principle, the opportunity to obtain an exact solution. However, knowing the source term for the solution of the Lighthill equation (the strength of the Lighthill tensor) implies having previously obtained the detailed solution for the turbulent flow field, which is almost never possible or practical, which prevents the direct noise computation.

For the application of the FW-H equation in the prediction of noise originated from the interaction between turbulence and the WT blades, the same difficulties arise and the procedures generally have to rely on a considerable amount of empirical input. For this reason, this type of noise is called *non-deterministic* or *semi-empirical* noise. For subsonic, turbulent flows interacting with the blades, the primary noise sources are the fluctuating Reynolds stresses (Lighthill tensor) originating quadrupole sound and the sound reflection and scattering in the presence of the rigid airfoil surface, which may give rise to dipole-type sound when the airfoil may be treated as a compact source.

The aeroacoustic theory formulations have led to the proposal of some noise prediction models and many noise prediction formulations or methods. IN the following paragraphs the key mechanisms of flow-induced noise and the nature of the spectra they produce are discussed.

2.1 Noise from Free Turbulence

This subject was the original motivation of Lighthill´s research (Lighthill, 1962), due to the increasing concern of noise emitted by jet propulsion. The Lighthill analogy led to a solution of the inhomogeneous wave equation with the aid of Green´s Function, leading to the quadrupole-type source radiation. The pressure fluctuating field solution is also presented for time and frequency domains.

Lighthill (Lighthill, 1962) also deduced that for the jet noise, the acoustic intensity is proportional to the eighth power of the flow Mach number

$$I \propto \rho_0 c_0^3 M^8 \left(\frac{l}{r}\right)^2 \alpha^2 \qquad (2-1)$$

where $M = U/c_0$, l is the typical dimension in the turbulent region, α is the normalized turbulence intensity and r is the distance from the source to the observer.

2.2 Noise from Turbulence Interaction with the Airfoil Edges

According to Oerlemans (Oerlemans, Wind Turbine Noise: Primary Noise Sources, 2011), the Mach number of the flow around the outboard part of a typical WT blade is of the order 0.2. From Eqn. $(2-1)$, the resulting acoustic intensity from free turbulence at this small Mach number would be weak ($I \propto M^8$), leading to the conclusion that, for small Mach numbers, the radiated aerodynamic noise from an airfoil will be dominated by the interaction between the turbulence and the airfoil edges and surface.

The subject was first formally treated by Ffowcs-Williams and Hall (Ffowcs-Williams & Hall, 1970) while investigating sound generation by turbulence in the vicinity of a scattering half-plane and was later treated in a more general approach by Blake (Blake, Mechanics of Flow-Induced Sound and Vibration, 1986 II). According to Blake, the sophistication of analytical modeling of flow-edge interactions evolved following the work of FW-Hall (Ffowcs-Williams & Hall, 1970), to include physically realistic acoustic and aerodynamic interactions, and so did the mathematical complexity of the models. In his development, it is assumed that (i) the disturbances created by the flow-edge interaction do not feed-back on the turbulence, i.e. the only interaction of importance is the acoustic one, and (ii) the size of a typical eddy scales on the typical dimension l of the turbulent region (see Figure 8).

The effect is therefore dependent on the turbulence length scale. For TE noise the turbulence length scales usually employed are the boundary layer thickness (Wagner, Bareiß, & Guidati, 1996), or the displacement thickness, δ^* measured at the TE (Oerlemans, Wind Turbine Noise: Primary Noise Sources, 2011), and for inflow turbulence noise l is the scale of the incident eddies.

The resulting acoustic intensity was found to depend on the fifth power of the flow Mach number, for non-compact source behavior

$$I \propto \rho_0 c_0^3 cos^3(\bar{\theta}) M^5 \frac{sl}{r^2} \alpha^2 . sin(\varphi) sin^2\left(\frac{\theta}{2}\right) \qquad (2-2)$$

where α is the normalized turbulence intensity and the length scales and angles are depicted in Figure 8.

Equation (2-2) is valid for both trailing-edge noise and leading-edge noise (high-frequency inflow turbulence noise), with suitable turbulence length scales selected for each case, as highlighted above, and it is the basis of several edge-noise prediction models since it is the dominant type of noise source at low Mach number flows (M<<1).

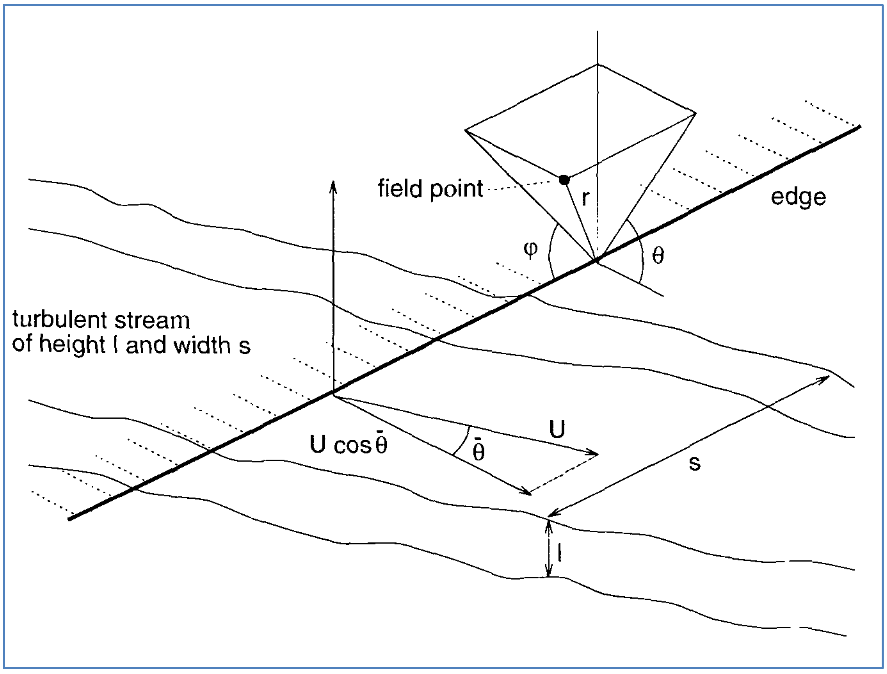

Figure 8 - Basic geometry employed by BLAKE to study the wall jet incident on the TE of a semi-infinite plane (Blake, Mechanics of Flow-Induced Sound and Vibration, 1986 II), p. 726, adapted by (Wagner, Bareiß, & Guidati, 1996).

However, when the incident eddies are much larger than the typical airfoil chord, $c{\sim}1\ m$, so will be the acoustic wavelength of the noise emitted ($f < 50\ \mathrm{Hz}$), and for this range of infrasound the airfoil may be considered a compact source (Oerlemans, Wind Turbine Noise: Primary Noise Sources, 2011). In that case the acoustic intensity will depend on the sixth power of the flow Mach number (Wagner, Bareiß, & Guidati, 1996):

$$I \propto \rho_0 c_0^3 M^6 \left(\frac{A_b}{\Lambda \mathrm{r}}\right) \alpha^2 . cos^2(\theta) \qquad (2-3)$$

where A_b is the area of the airfoil, Λ is a characteristic length scale of the turbulence, and θ is the angle between the airfoil surface and the observer. The expression has a dipole-type directivity function.

3. Relative Contribution of the Noise Sources to the Overall SPL and Spectra.

It is not feasible, in the field, to obtain the experimental spectrum radiated from the individual self-noise sources. Nevertheless, the total noise spectra may be inferred from partial models, validated to some extent for each of the individual sources, against wind tunnel or jet-flow potential-core tests. These modeling tools make it possible to evaluate the relative importance of the individual noise sources.

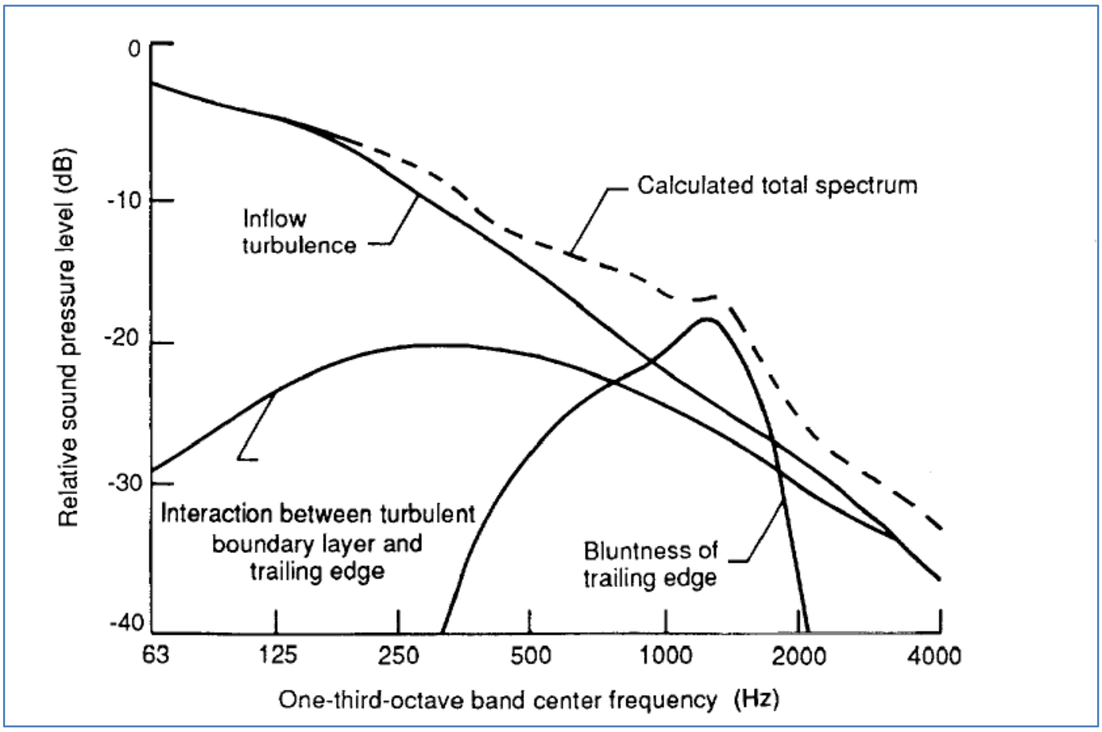

Figure 9 - Broadband noise prediction contributions, from different mechanism noise sources, at 100 m from a MOD-2 WT, operating in a 9.8 m/s wind and producing 1.5 MW (Grosveld, 1985).

First, by considering all aerodynamic noise sources, i.e. LFN, inflow turbulence and airfoil self-noise, Grosveld (Grosveld, 1985) unveiled the broadband noise prediction contributions, at an observer distance of 100 m, calculated over the axis line of a MOD-2[6] HAWT.

Figure 9 shows that inflow turbulence is the dominant mechanism in the low frequency range, while the interaction noise, between the TBL and the TE edge, steadily grows and later decays after the peak (which is Strouhal number-dependent) reaching a SPL level equivalent to the inflow noise close to 1 kHz and higher. The TE bluntness also has a broadband nature but is marked by a tone between 1 kHz and 2 kHz.

[6] The MOD-2 HAWT was the precursor of the modern HAWT in many aspects, having been designed by NASA and manufactured by Boeing from 1982 to 1988. The equipment had a 91 m diameter rotor in an upwind position, but the rotor had only two blades. http://www.boeing.com/history/products/mod-2-mod-5b-wind-turbine.page accessed on June,2016.

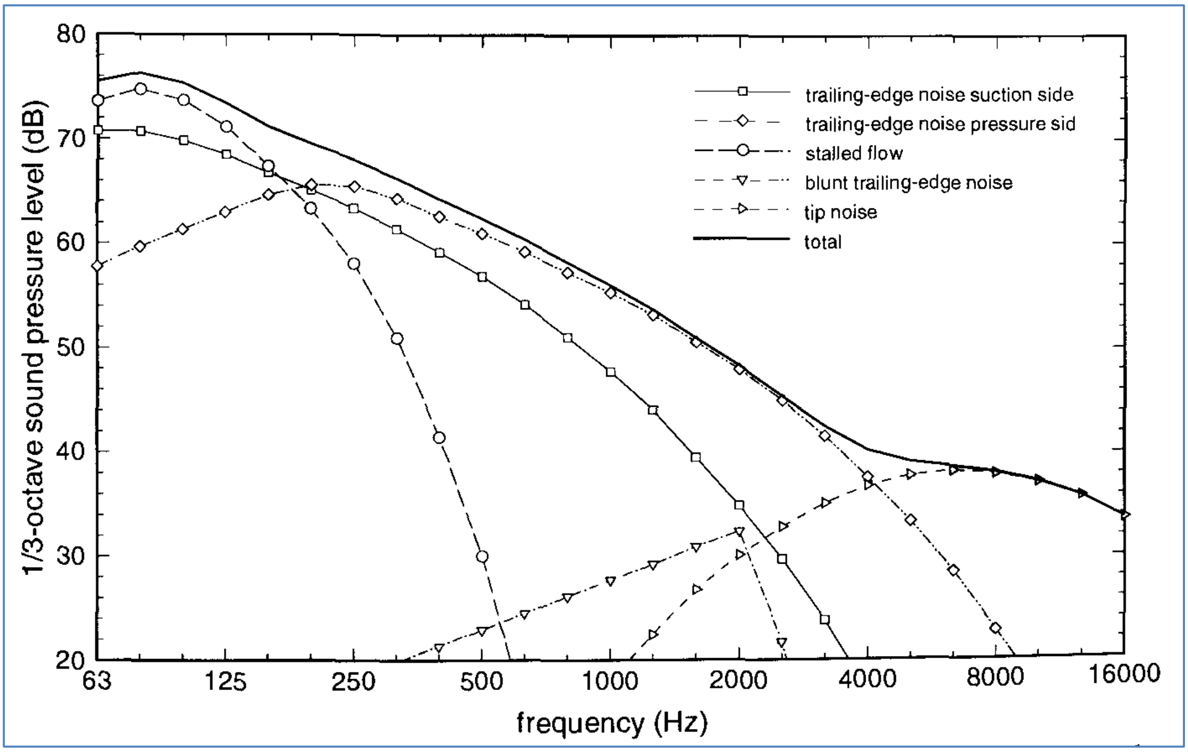

Figure 10 - Calculated contributions of airfoil self-noise individual sources, for a WT blade, and the total SPL spectrum, after (Bareiss, Guidati, & Wagner, 1994).

Figure 10 displays only airfoil self-noise spectra calculated for a blade, from models of individual contributions of the different mechanisms, plus the total noise spectrum. It is evident from the figure that the blade spectrum is dominated by the TE noise for most of the frequency range and then by the tip noise. While it seems that stalled flow contribution is sizeable, it is restricted to low frequencies and should become less important after A-weighting of the SPL, under the criterion of audio annoyance only. In fact, Petitjean et al. (Petitjean, Drobietz, & Kinzie, 2011) presented an A-weighted, 1/3 octave band spectrum for a large-size, modern-type General Electric WT, with all the relative contributions from the flow-induced noise mechanisms and the results confirms the basic relative spectral and level contributions depicted in Figure 10.

All spectra discussed strongly suggest that the most relevant mechanism of aerodynamic noise generation in a modern, large size WT in nominal wind speed conditions, non-stalled operation, is the turbulent boundary layer TE noise.

4. Conclusions

Apart from mechanical noise sources, which are controllable through classical techniques, a large-size HAWT equipment is home for many distinct aeroacoustic noise sources, originated from the inflow turbulence, the interaction of the flow (both turbulent and laminar) with the airfoil surfaces, and the interaction of the flow with the support structure. Table 2 summarizes the main noise sources, noise intensity dependence on Mach number as per discussed aeroacoustic theory and their relative spectral shape and level importance.

Table 2 – Main HAWT noise sources, models and relative importance for modern, large size rotors.

Nature	**Noise characteristics**	**Dependence on Mach number**	**SPL and spectral contribution**
Inflow Noise	Broadband noise.	$I \propto M^6$ for compact source behavior $I \propto M^5$ for non-compact source behavior.	Significant contribution in lower frequencies.
Airfoil Self-Noise			
Trailing-edge noise	Broadband.	Generally, $I \propto M^5$.	Most relevant aeroacoustic noise contribution, higher frequencies predominance.
Tip Noise	Broadband.	Region of high Mach number, but small chord.	There seems to be no remarkable contribution from the particular 3D-flow around the tip, for the overall noise radiated.
Stall, separation noise	Broadband.	No model available	The noise may increase by more than 10 dB relative to TE Noise.
Laminar boundary-layer noise	Tonal.	Low Mach and Reynolds numbers, vortex-shedding dependent	More relevant for small scale WT. May be prevented by tripping the boundary layer far upstream of the TE.
Blunt trailing-edge noise	Tonal.	Function of the flow regime and bluntness parameter, h/δ^*	h/δ^* should be kept small, for low or zero contribution.
Noise from flow over holes, slits and intrusions	Tonal.	Fabrication and operation dependent.	Careful manufacturing process planning, tight tolerances and early transition are desirable for low noise signature

It is possible to conclude that the desired characteristics for a well-designed WT rotor, in respect to noise emission, would include a blade optimized for low TE noise and Tip noise, while being as much insensitive as possible with regards to inflow noise. A tripped flow would also avoid laminar boundary-layer originated noise. Also, all those characteristics should have no negative impact on the blade ability to perform an efficient energy conversion.

As far as aeroacoustic noise is concerned, it is also important to notice that the manufacturing process of the blades should also receive careful attention, since TE bluntness and surface imperfections will also contribute to the final WTN level and could add tonal noise, which presence is often penalized when measuring WTN in order to verify compliance with specific, applicable standards.

Like in any other typical design, an engineering tradeoff has to be achieved between the noise sources, and it is important to remember that the main objective of the WT manufacturer is the energy conversion performance of the equipment. The more recent noise-constraint requirements are additive to those and do not replace or take priority over them.

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