CONSIDERATIONS AND CONCERNS ABOUT WIND TURBINE NOISE

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ABSTRACT

The Wind Energy is the fastest growing type of renewable energy in the Brazil. The source is considered the Country's second largest source of electricity and ranks eighth place in the global installed capacity, according to the Global Wind Energy Council (GWEC) in 2017. This expansion of the Wind Energy is pushing the wind farms closer to populated areas, where the noise annoying potential is higher and land availability is lower. This article discusses importance of the aeroacoustic noise emitted by Horizontal Axis Wind Turbine (HAWT), in such a strong growth context. Noise prediction requires the use of appropriate models that can be interactively deployed during the conceptual design of new equipment. Also, this paper briefly discusses the need to develop specific wind turbine noise (WTN) regulations in Brazil, based on measurable parameters consistent with the nature of the sound source in question and its interaction with the environment.

Keywords: Airfoil self-noise. Trailing-edge noise prediction. Wind turbine noise. Wind Turbine Regulations. Horizontal Axis Wind Turbine (HAWT).

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RESUMO

A energia eólica é o tipo de energia renovável que mais cresce no mercado brasileiro, onde o crescimento da oferta deste tipo de energia aumenta rapidamente e é economicamente viável, é considerada a segunda maior fonte de energia do país no ano corrente e também ocupa o oitavo lugar no ranking global de capacidade instalada para geração de energia eólica, segundo o Global Wind Energy Council (GWEC) em 2017. Essa expansão da energia eólica está aproximando os parques eólicos das áreas povoadas, onde o potencial de incômodo proveniente do ruído é maior e a disponibilidade de terra é menor. Este artigo apresenta a importância da indústria eólica em dimensionar o risco de emissões de ruído, especialmente quando se trata de turbinas do tipo eixo horizontal (HAWT). A previsão de ruído requer o uso de aplicativo apropriado e esta análise deve ser considerada desde o início do projeto. Este artigo também mostra a necessidade de se elaborar regulamentações específicas de ruído de turbinas eólicas (WTN) no Brasil (como as existentes nos EUA e na Europa), com base em parâmetros de medição compatíveis com a natureza da fonte sonora em questão e sua interação com o meio ambiente.

Palavras-chave: Ruído Próprio de Aerofólios. Predição de Ruído de Bordo de Fuga. Ruído Proveniente de Turbina Eólica. Regulamentos de Turbina Eólica. Aerogerador de Eixo Horizontal (HAWT)

LIST OF ABBREVIATIONS AND ACRONYMS

Abbreviation	Meaning
ABNT	Associação Brasileira de Normas Técnicas
AM	Amplitude Modulation
AOA	Angle of Attack
ASME	The American Society of Mechanical Engineers
AWEA	American Wind Energy Association – USA
BEM	The Blade Element Momentum method
BL	Boundary Layer
BPF	Blade-Passing Frequency (Hz)
BPM	Brooks, Pope, Marcolini, Airfoil Self Noise Prediction Model
CFD	Computational Fluid Dynamics
CR	Community Reaction
dB	decibel
dB(A)	A-weighted decibel
dB(C)	C-weighted decibel
EPA	Environmental Protection Agency
FAPESP	Fundação de Amparo à Pesquisa do Estado de São Paulo - Brasil
FFT	Fast Fourier Transform
FP	Flat Plate
GE	General Electric
HAWT	Horizontal Axis Wind Turbine
IEC	International Electrotechnical Commission
kW	Kilowatt
LA	Low A-weighted noise emission (airfoil)
LBL	Laminar Boundary Layer
LE	Leading Edge
LFN	Low Frequency Noise (Hz)
LH	Left Hand
MW	Megawatt
NASA	National Air and Space Administration - USA
NREL	National Renewable Energy Laboratory – Department of Energy - USA
RANS	Reynolds-Averaged Navier Stokes (Equations)
R&D	Research and Development
SPL	Sound Pressure Level (dB)
SPL1/3	Sound Pressure Level for each 1/3 octave band (dB)
SPLA	A-weighted Sound Pressure Level (dB)
$SPL_{\alpha}; SPL_{a}; SPL_{alpha}$	Sound Pressure level (dB), contribution from the partially unattached flow at the suction side (noise deriving from AOA $\neq$ 0).
SPL_{p}	Sound Pressure level (dB), contribution from the pressure side of the airfoil.
SPL_{s}	Sound Pressure level (dB), contribution from the suction side of the airfoil.
SPW	Sound Power Level (dB)

SST	**Shear Stress Transport (turbulence modeling)**
TBL	**Turbulent Boundary Layer**
TE	**Trailing Edge**
TKE	**Turbulent Kinetic Energy (per unit mass) (m2/s2)**
TSR	**Tip-Speed Ratio**
W	**watt**
WPF	**Wall Pressure Fluctuations**
WPS	**Wisconsin Public Service – USA**
WT	**Wind Turbine**
WTN	**Wind Turbine Noise**
XFLR5	**The XFOIL software with graphic user interface.**
XFOIL	**Hybrid, Potential Flow and Integral Boundary Layer Solver.**
2-D, 2D	**Two-Dimensional (method)**
3-D, 3D	**Three-Dimensional (method)**
%HA	**Percentage of Highly Annoyed People**

LIST OF SYMBOLS

LATIN LETTERS

Letter	Meaning	Units
C_P	Power coefficient	
D	Wind Turbine Rotor diameter	m
F_V		N
f	Sound or noise frequency	$1/s$
L_{dn}	Day-and-night sound pressure levels	dB
L_{eq}	Equivalent Sound Pressure Level	dB
L_p		dB
L_W	linear model for WT Sound Power Level (SPW)	dB
L_{WA}	Individual Sound Power Level	dB
L_{10}	Exceedance level limit for 10% of the time	dB
L_{90}	Exceedance level limit for 90% of the time	dB
P	Acoustic power for a dipole-type source	
P_{mec}	Available mechanical power	W
$p(t)$	Time signal of acoustic pressure	Pa
R	Rotor radius, total	m
r	Distance from source to observer point, in the far field	m
SPL	Sound Pressure Level	dB
U	Velocity, local flow	m/s
U_∞	Velocity, freestream	m/s

GREEK LETTERS

Letter	Meaning	Units
λ	Tip Speed Ratio (also TSR)	
μ	Viscosity, dynamic or first coefficient	$Pa.s$
ν	Viscosity, kinematic	m^2/s
ρ_0	Density, undisturbed fluid	kg/m^3
σ	Modal value of the wind speed	m/s

1. INTRODUCTION

Wind energy is one of the most important renewable energy sources nowadays and its rapid expansion worldwide is pushing the wind farms closer to the populated areas. This entails one of the main obstacles to the use of wind turbines, the noise produced by them, which annoys residents and the local fauna in the vicinity. The noise emitted by wind turbines, by its particularities and in the conditions described must follow strict rules, already existing in the USA and Europe but not in Brazil, that warns nearly future problems.

Helpfully, the advances in the projects of wind turbines may predict appropriately the noise produced by them and avoid future neighborhood and legal problems for the installation of wind parks.

2. WIND TURBINE NOISE (WTN)

"Noise emission is one of the major obstacles for a further spread of onshore wind turbines and significantly affects public acceptance" (Herrig, Wurz, Kamruzzaman, & Kramer, 2007).

A wind turbine radiates noise of mechanic and aerodynamic origins. Mechanical noise may originate in the generator and, in the case of indirect-drive units, from the gearbox, this noise is transmitted along the structure before it gets airborne, radiated from its own surfaces like the the tower and the rotor blades. With the adoption of the WT rotor in an upwind position for HAWT and adoption of the direct-drive system, the mechanical noises, illustrated in Figure 2.1, and the rotor/tower wake interaction problems have been minimized.

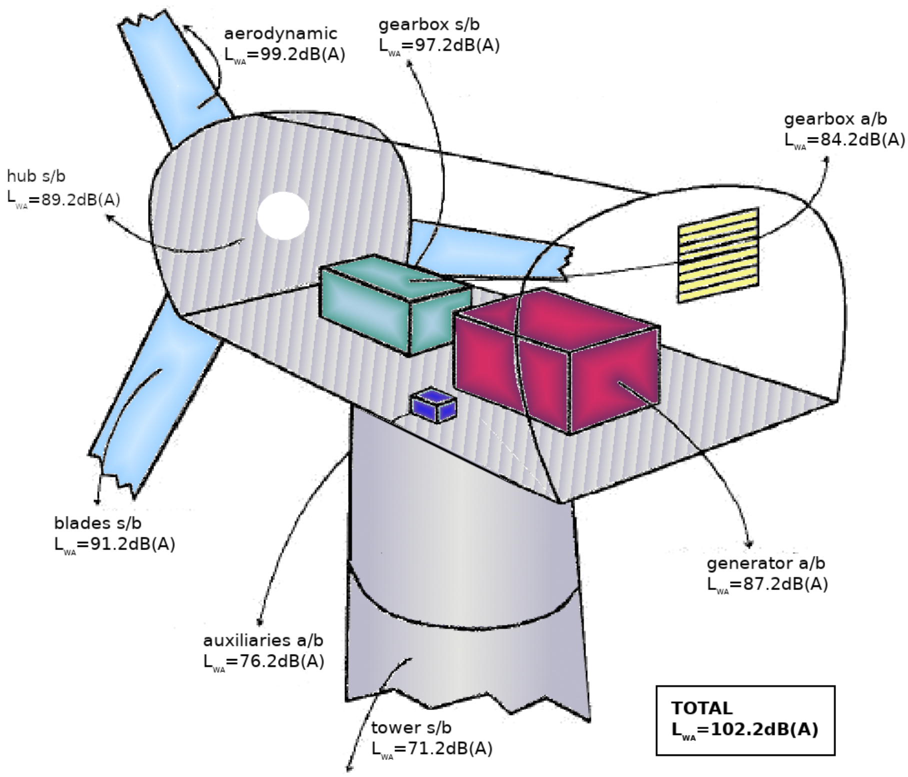

Figure 2.1 Contribution of individual components to the total sound power level of a Wind turbine (Pinder, 1992).

By the other hand aerodynamic noise classified as *self-noise* or *interaction noise* (Blake, 1986 II) it is more dominating than other sources and is a great challenge to find ways for it mitigation, it is radiated from the blades, from the wake in the near-field region (the airfoil self-noise), and from the interaction of the rotor with inflow turbulence and tower wake (the interaction noise).

Despite the many design configurations available for wind turbines, the most profitable and with greater capacity of energy production, bulk of the installed capacity in U.S., Europe and Brazil, is the HAWT. For this turbines the form of large-size is essentially fixed nowadays, but rotor diameter is continuously increasing as a way of harvesting more wind power (Burton, Sharpe, Jenkins, & Bossanyi, 2008), as predicted by the equation of the available mechanical power for turbo machinery (Hansen, 2008):

$$P_{mech} = \tfrac{1}{2} C_p \, \rho_0 \, \pi R^2 \, U_\infty{}^3 \quad [W] \tag{Eq. 1}$$

where C_p is the power coefficient, limited to 0.59 for unducted WT, the Betz Limit and R is the radius of the rotor. A typical modern, large-size WT, characteristic value for C_p is around 0.40 (Ragheb & Ragheb, 2011). The available mechanical power is plotted in Figure 2.2, for a range of rotor diameter and wind speeds, for illustration purposes.

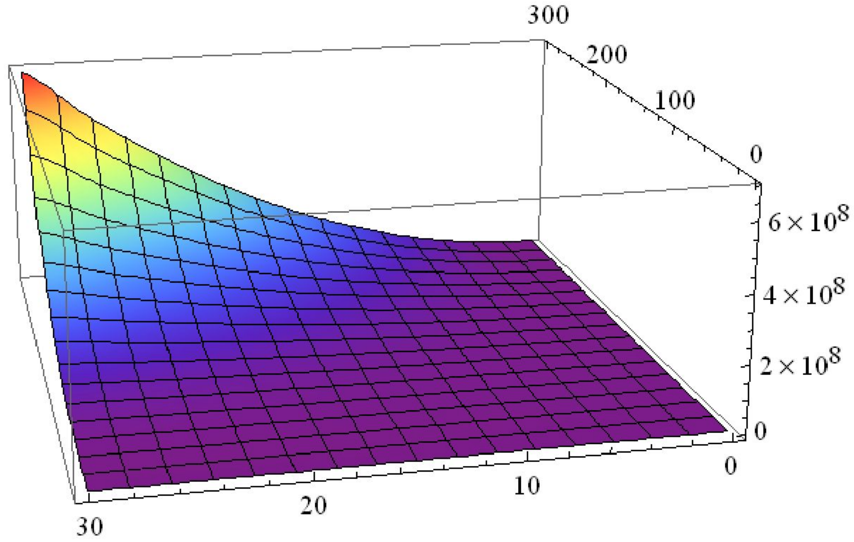

Figure 2.2 3-D plot of the available mechanical power P_{mec} for a WT, Eq. (1), for wind speeds from 0 to 30 m/s and rotor diameters from 0 to 300 m. Theoretical Betz limit used for C_p and sea-level, standard day density.

Therefore the increase in the size of turbines come with the multitude of benefits, in particular helping to drive down the cost of wind energy because wind speeds increase with altitude, thus the taller the turbine the faster it spins and the more energy it can generate. Furthermore, the wind is generally steadier higher up, easing power peaks and troughs and increasing reliability. The trend is to increase the size of the turbines and not the wind farms, reducing maintenance and operation costs. Figure 2.3 further illustrate the tendency for larger rotor diameter in modern equipment.

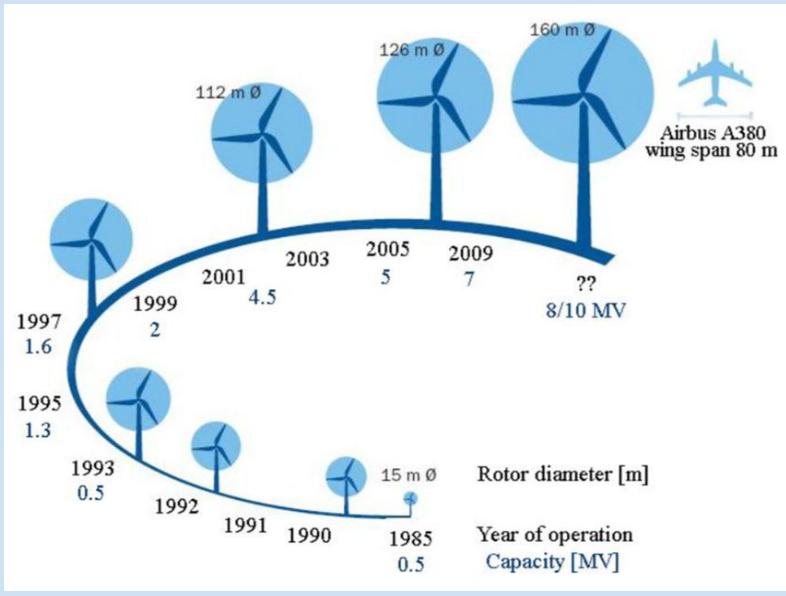

Figure 2.3 Utility-grade blade length growth over time (Sánchez *et al*).

For the sake of the argument it will be assumed that the aerodynamic self-noise sources of a WT may be represented by dipole-type sources, by employing a semi-infinite flat plate approximation for the WT blade airfoil, it can be shown analytically[5] that the acoustic power, which is proportional to the square of the acoustic pressure, p, scales with the sixth power of the flow velocity: $p^2 \tilde{} U^6$. Then, while the power increases with the third power of the wind velocity, the aerodynamic noise will increase with the sixth power of the local wind velocity, bringing the technology to a stall.

For the modern lift-type WT, the ratio between the tangential velocity of the blade tip and the velocity of the approaching wind is in the range of 6 to 8 (Ragheb & Ragheb, 2011). This dimensionless ratio is a very important performance parameter, of which the power coefficient depends upon and is called *Tip Speed Ratio*, (TSR, λ).

$$TSR = \lambda = \frac{blade\ tip\ tangential\ velocity}{wind\ velocity} = \frac{\omega R}{U_\infty} \qquad \text{(Eq. 2)}$$

For a 15 m/s approaching wind a WT with a TSR of 6 would operate with a tangential velocity close to 90 m/s at the tip of the blades. Because of this trend, blades sized only for performance will produce ever stronger sound power levels

[5] Assumed dipole source model, see (Norton & Karczub, 2003), p. 154.

(SPW) and will demand ever growing sites (and related investments) for operating within acceptable noise levels measured at the households closest to the wind farm.

3 Relevance of Subject for the Industry

Airfoil self-noise is the total noise produced when an airfoil encounters smooth, non-turbulent inflow. It results from the interaction between the airfoil blade and the turbulence produced inside its own boundary layer and near wake (Brooks, Pope, & Marcolini, 1989). The noise spectrum associated with airfoil self-noise is typically of broadband nature, but tonal components may arise due to laminar separation bubbles, blunt trailing edges or flow over slits and holes (Wagner, Bareiß, & Guidati, 1996).

There are many self-noise producing mechanisms and a sizeable effort has been devoted to studying this subject[6] that aim at identifying noise source location; quantifying emission power levels associated with the source in the near field; quantifying immission pressure levels associated with the observer position in the far field; and trying to identify noise abatement techniques for use in the emission, transmission or immission phases.

When the WT airfoil is large compared to the turbulent eddies typical length scale, the sound from the eddies will be scattered at the edges of the airfoil, producing “leading edge noise” due to inflow turbulence and “Trailing Edge (TE) noise” by to its own turbulent boundary layer (Oerlemans, 2011). Among the several airfoil self-noise emitting mechanisms identified to date, this noise mechanism has been found to display a dipole nature[7] (Brooks & Hodgson, 1981), and has been considered the main source of high-frequency noise (750 Hz < f < 2 kHz) for an airfoil in low angle-of-attach (AOA), low Mach number, smooth inflow regime (Brooks, Pope, & Marcolini, 1989) and (Wagner, Bareiß, & Guidati, 1996).

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[6] Bibliographic research covering the 1975-2012 timeframe on the HighTech (Proquest) database revealed 1,424 papers under “trailing edge noise” keywords. Nevertheless the number of trailing edge noise papers further associated with the “numerical methods” keywords is down to 47 papers only.

[7] Under certain conditions, i.e., when the airfoil may be considered a compact source.

The problem of TE noise emission is relevant for aircraft[8] industry but mainly it is of growing importance to the thriving Wind Turbine industry (Bowdler & Leventhall, 2011). The economy of scale brought about by larger rotor diameters, the advancement of this important renewable energy source in the world energy matrix and the concept of *distributed generation*[9] in the wind energy industry, they all depend upon tools that will allow designing more efficient, quieter and larger WT Blades, in an affordable manner.

Since the airfoil self-noise acoustic pressure scales with the fifth or sixth power of the flow speed[10], and stronger winds and larger area rotors both lead to increased local flow speed on the outboard section of the blades, one might expect a growing concern with the wind turbine noise as the equipment grows in size and wind energy increases its share in the world energy matrix. Therefore, that two of the largest issues the WT manufacturers are currently facing are the WTN and the wear (abrasion) of the blade composite material Leading Edge (LE) (Sloth, 2011)[11]. Both problems derive from the high tangential velocities attained at the blade outboard sections, even in mild wind conditions.

Designing for low noise for the WT industry, different from aircraft area (Da Silva, 2011; Orselli, 2011), is a new requirement and challenge, since most efforts have been historically aimed at improving aerodynamic performance since the first oil crisis. An insight of the WT industry point of view concerning noise was obtained through a field research carried out by the authors during a Wind Energy Conference event (AWEA 2012[12]), when ten important WT industry players[13] completed a survey designed to understand the importance of WTN to their companies, the methods

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[8] As an example, between 2009 and 2011 an extensive research concerning all aspects of passenger acoustic cabin comfort was conducted at Poli-USP, funded by FAPESP and Embraer.

[9] As of January 2013, 57% of the work-in-progress for the expansion of the electricity grid is behind schedule in Brazil (Domingos, 2013). This represents 238 lines and relay stations with problems, and at least 644 MW of hydraulic-generated electricity and 293 MW of wind-generated electricity that cannot be delivered to the grid.

[10] Depending upon the source being compact or non-compact.

[11] Two teleconferences were held between the author and Dr. Erik Sloth, Senior Specialist on Noise and Vibration for Suzlon Blade Tech., Denmark, in 2011.

[12] American Wind Energy Association annual Conference, held in Atlanta, Ga.

[13] Including five large companies that altogether manufactured 55% of all U.S. installed wind power capacity as of the end of 2011.

used for WTN prediction and also how soon in the product development cycle they considered the noise problem. Some of the most relevant conclusions drawn from the survey are:

- The subject “Wind Turbine Noise” was considered relevant by all respondents;
- Although eight out of ten mentioned that they tried to predict WTN in the early design phase, six out of eight explained that they only assessed WTN through scale model testing or prototype testing, later in the design phase.
- Two of them still did not consider WTN during the development cycle, leaving the problem for siting experts.
- Seven out of ten manufacturers felt the need for better noise prediction methods to be employed at the early design stages.
- One of the participants pointed out that more accurate prediction in the early design phase depends upon performance parameters that usually will be available only later in the development process, so that predictive methods that could be used with more accuracy in the early design phase would be most welcome.

This means that, although acknowledged, the noise problem is not always dealt with at the source level and will have eventually to be dealt with later and in a more expensive way, in the propagation phase. The trend for WT manufacturers is to have routines for estimating aero noise in the early phases, that could be later optimized via CFD in more advanced design phases and to guarantee quality for its customers of its product and added that the industry lacks better predictive methods and also better ideas to lessen WTN. Nowadays they still have many companies that do not consider the problem of WTN in their products, and consequently projects noisy WTs, still not integrated into their design processes at any level or don’t have acceptable guidelines for aero acoustic purposes.

The European based companies that participated seemed more sensitive to the WTN problem than their counterparts from other regions because of its stringent noise restrictions and greater population densities, because they are more tolerant in places WTs near communities. The US has greater availability of erratic territories so they can still site the turbines in no disturbance place. In developing countries, like Brazil, have much less stringent noise restrictions and lack specific WTN legislation.

At the AWEA 2012 industry forum, Mark Higgins, of the US Department of Energy, pointed out the need to increase rotor diameter and its benefits. Keith Longtin, also from GE, pointed out that, as rotors grow, the power produced by them also grow with the third power of the diameter, but the noise emitted growths with the fifth[14] power. GE was at the time developing two WT testing facilities in the USA since they consider validation of models of utmost importance in the engineering learning curve.

The WT industry practice should include design requirements concerning WTN still in the conceptual and preliminary design phases of the blades because that most of the performance and operating costs in the first (conceptual) phase of the design[15] (Raymer, 2006). The subsequent phases (preliminary and detail design) will challenge the designer with decreasing degrees of freedom, increasing manpower needs and increasing costs. Any changes made in the later design phases will cost much more for retrofitting into the conceptual project. However the technology for designing, controlling and decreasing WTN seems to be still limited both in capacity and reach. According to Wagner et al. (Wagner, Bareiß, & Guidati, 1996), the industry is interested in how small modifications on airfoil geometry will influence in noise generation and most WT manufacturers employ no more than good manufacturing practices towards noise emission. Some of them will measure the noise emission *ex post* in order to provide the sound pressure level (SPL) value at a certain rotor distance (as per applicable standards), to provide as guidance for the purchasing customer or siting team.

[14] When the author refers generally to airfoil self-noise, the source model employed is the acoustic dipole and the scaling factor is $P \sim U6$ as mentioned earlier, but when the author refers to TE noise only, the edge-scatter theory predicts that the suitable scaling factor is $P \sim U5$, which is confirmed experimentally.
[15] By similarity with aircraft.

4 The impact of Wind Turbine Noise (WTN) on Humans and Fauna

Three negative impacts of the large scale HAWT equipment are frequently listed as the most relevant for the advancement of the technology: wildlife impacts, visual pollution and noise generation (Wagner, Bareiß, & Guidati, 1996).

Wildlife impact has been deemed low[16] (<1 of 30,000) compared to other human-erected structures and causes (NREL, 2005). In Brazil, there is a lack of studies quantifying the impact of wind farms on the bats and avian fauna (Instituto Chico Mendes de Conservação da Biodiversidade, 2014) however, the recommendation is to avoid siting wind farms where this fauna concentrates or in its migration routes. Out of the four main bird migration routes over Brazilian territory, the Atlantic Route[17] poses the major problem, because most of the country´s wind farms are located along the same shorelines.

The visual pollution problem may be minimized by careful site planning and also by repowering, which significantly reduces the total number of WT units deployed (Hansen, 2008).

The noise generation problem, on the other hand, remains a crucial challenge for the wind energy industry. A detailed survey made in the Netherlands concluded that noise is often cited as the most annoying aspect of Wind Energy (Bowdler & Leventhall, 2011). According to Gipe (2004), all WT create unwanted sound, or noise witch are typically foreign to the rural settings[18] and it can be very disturbing. Some recent noise complaints in Brazil confirm completely this argument:

"At the peaceful Icaraí, Ceará, the noise from the wind turbine blades has been annoying many citizens who live close to the wind farms. José Daniel lives close to

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[16] However, the recent deactivation of 800 WT units at the Californian desert, even after repowering[#] reduced the bird strike rate by 35% between 2006 and 2010, due to the risk of death of many avian species, including protected ones (Lawton, 2015) and bats, clearly shows the relevance and impact of this subject.

[17] Which extends from the Amapá State to the Rio Grande do Sul State shorelines.

[18] Where WT are most often used.

the towers and was waking up in the middle of the night due to the noise and could not sleep again: 'It´s been a complicated period but I am getting used to it'. Raimunda Martins dos Santos, 77, also suffered since the beginning of the wind turbines operation, some of which are at her backyard, among coconut, lemon and acerola trees: 'Although there is some rhythm to it the blades are noisy', complains Raimunda, who has a special daughter, deeply affected by the wind turbine blade noise, who kept everybody else restless in their home (Pereira, 19/June/2016).

Noise containing pure tones or impulsive sound is perceived as louder than broadband noise, which characterizes the flow around the turbine blades. Impulsive sounds were typical of the two-bladed, downwind early models installed at Palm Springs, Ca, and led to many complaints about WTN, this fact helps explains why modern WT have a three bladed, upwind basic design.

Broadband sound is arguably more tolerable than impulsive, but a WT generates broadband noise in a continuous fashion for days and this helps make this trait of wind energy more annoying than any other (GIPE, 2004). Modern noise regulations tend to specify maximum levels that must not be exceeded for a minimum determined fraction of the total time, called exceedance levels[19]. For the purpose of comparing with the exceedance levels the WTN is often measured in equivalent level, L_{eq}, the equivalent, steady level sound pressure that produces the same total acoustic energy of the original sound, over its duration. Gipe (GIPE, 2004) also explains that for a sound to be considered intrusive by an observer, the judgment will depend upon (i) the nature of the noise (broadband, tonal or impulsive); (ii) the perception of the noise source (e.g. whether or not the observer likes WT); (iii) the distance from the source, and (iv) the activity of the observer (sleeping, working, etc.).

In fact, according to Bistafa (Bistafa, 2011), studies have shown a significant correlation between community discomfort (intrusion) and noise levels. The *community reaction* (CR) and percentage of *highly annoyed people* (%HA) are the

[19] They must be met in the initial phase of WT projects, one observation is that an exceedance level of 45 dB(A) L_{90} is stricter than a standard of 45 dB(A) L_{10}, because 90% of the time the noise must be below 45 dB(A).

descriptive variables used in studies to show the correlation, plotted against day-and-night sound pressure levels (L_{dn})[20].

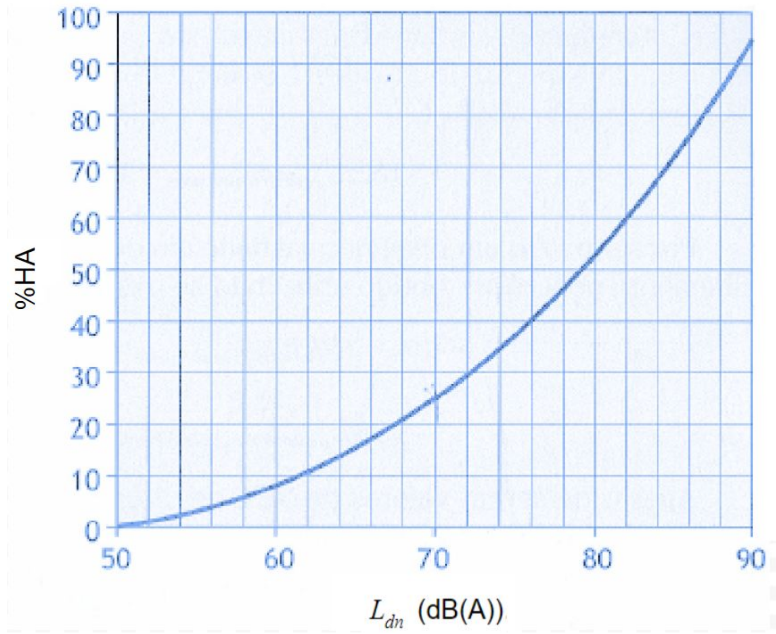

Figure 4.1 Percentage of highly annoyed (%HA) people by vehicle and aircraft traffic as a function of L_{dn} (dB(A)). Source: adapted by Bistafa (Bistafa, 2011), reproduced with permission.

Figure 4.1 above shows that a 60 dB(A) L_{dn} noise will heavily affect less than 10% of the community. In fact, another reaction study (Bistafa, 2011) shows that a 10 dB(A) increase in L_{dn} will elicit strong community change in reaction, from periodic complaints to generalized complaints and threats of law suit, because a 10 dB(A) increase in a noise source can be perceived as a doubling of loudness[21]. Also, Stankovic et al. (Stankovic, Campbell, & Harries, 2009), claim that a 5 dB(A) sound level change would probably be perceived by most people under normal listening

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[20] L_{dn} is a sound level introduced by the EPA for the evaluation of noise in communities. It is similar to a L_{eq} over a 24 hours period, except that the equivalent level measured overnight has a 10 dB penalty increase.

[21] Loudness (audibilidade in Portuguese), is the psychoacoustic value associated by the humans with the sound pressure level, which is a physical value. Loudness is a subjective sensation that depends upon the frequency of the noise and is (subjectively) measured in *phons*. A *phon* unit does not keep the same relation to *dB* for all frequencies. For an observer to perceive a doubling of the sound pressure, the loudness has to increase by 10 *phons* to his perception, which translates into 10 *dB* in the 700 *Hz* to 2 *KHz* range of frequencies, approximately. For details, please see (Bistafa, 2011) pp 68-73.

conditions. These observations will help us later define and propose a quality criteria for scaling variables employed in noise prediction methods.

As the background noise increases with wind speed, so does the WTN, making noise masking[22] generally not possible, a fact clearly illustrated in Figure 4.2.

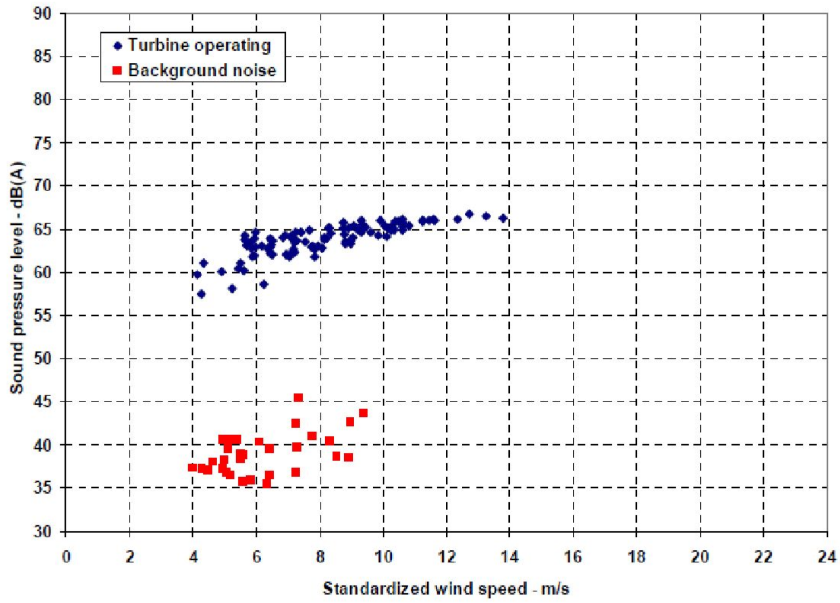

Figure 4.2 Sound Pressure levels (1 minute averages) as a function of wind speed, for background noise and a small size WT (Migliore, van Dam, & Huskey, 2003).

In order to illustrate the consequences of the perceived noise by a nearby community, Gipe (GIPE, 2004) describes two interesting cases. Dan Win, a Danish WT manufacturer spent US$ 750,000 to fix the noise levels coming from a 21-unit, 180 kW (each) wind farm near Kynby, Denmark. Despite many siting precautions and reducing operational speed below ideal, the noise at the nearest residence, a farm 220 m away, exceeded permissible levels and included a pure tone component[23]. After four years of correction rework the WTN emissions were reduced from 102 dB(A) to 95 dB(A), resulting in an acceptable noise level at the dwellings. Curiously,

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[22] Noise masking is a phenomena derived from the human ear physiology. Sound actuating the oval window of the inner ear, results in standing waves being set up on the basilar membrane. The amplitude peak changes position for different frequencies (Everest & Pohlmann, 2009). Because of the continuous nature of the membrane and of the fact that low frequency tones generate activity over a larger area of the membrane, its displacement in response for low frequency tones also displace the hearing threshold, “masking” sounds of nearby frequencies (Bistafa, 2011).
[23] A pure tone component penalizes the measured *Lp* in a further 5 or 10 *dB(A)*.

"The engineers found that they could gain 4 dB(A) simply by sharpening the trailing edge of each blade, providing one of the most convincing demonstrations that trailing edge thickness is a significant factor in aerodynamic noise" (GIPE, 2004).

The other report is about the Wisconsin Public Service (WPS), which began receiving noise complaints after installing 14 Vestas V47 WTs in 1999. The WPS conducted a series of noise studies and ultimately had to make proposals to buy six homes to fix the problem, but only two owners accepted the offer. The initial project cost investment was overrun and the problem was not solved. These examples help to make the point that WTN should be dealt with in the beginning of the development phase of a new design, not later, in the field.

Figure 4.3 shows typical spectra diagram for a WTN, analyzed with different frequency resolutions.

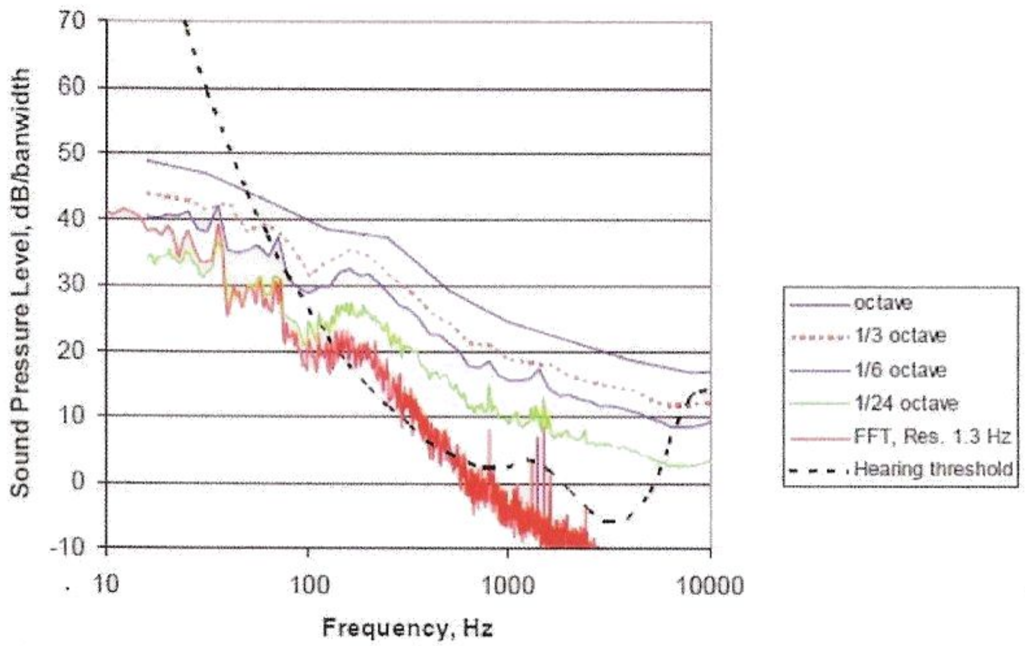

Figure 4.3 Typical spectral signature for a WT, overlaid in a standard human hearing threshold line, adapted from the work of T.H. Pedersen (Bowdler & Leventhall, 2011). Reproduced under permission.

The spectra are overlaid in a hearing threshold curve and it may be seen that, although the human being is not capable of hearing frequencies below 100 Hz, the amount of noise energy produced in that range looks significant at a first glance[24], in the overall noise signature for this type of equipment, it can impact on human health.

A measurement of the apparent A-weighted and C-weighted sound power spectra, down to 4 Hz in some cases, for 78 wind turbines ranging in capacity from 75 kW to 3.6 MW was performed by Hessler (Hessler, 2011), who concluded that the C-A (C minus A) level difference was in the range of 11 dB. He further developed pressure spectra for the largest WT at “suitable” distance and compared to annoyance thresholds developed specifically for Low Frequency Noise (LFN), concluding that the spectra was 20 to 40 dB below the perception threshold but Figure 4.3 shows that the highest noise levels are present in the lower bands of the spectrum.

Factually, there is no current definitive evidence that, at normal WT noise emission levels, the infrasound part of the noise spectrum has a significant impact over the population (Leventhall, 2013), although there is a theory concerning the physiological effects of infrasound produced by wind farm sites (Schomer, Erdreich, Boyle, & Pamidighatam, 2013). Also, Wagner et al. (Wagner, Bareiß, & Guidati, 1996), p. 77, show that the SPL at lower frequencies may couple with natural vibration frequencies of building windows, which might resonate in a broader spectrum.

The UK Government published a research in 2007 (Bowdler & Leventhall, 2011) showing that noise complaints had been received for 20% of all regional wind farms, the majority of these had a description of a sound with a regular variation in level, or amplitude modulation (AM) witch is related by the Blade Passing Frequency (BPF), three times the rotation frequency for a common rotor, and the typical modulation depth[25] measured was up to 7 dB[26].

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[24] In order to evaluate the importance of the Low Frequency Noise from a source, usually a C-weighting measurement is made and compared with an A-weighting measurement. If the reading is close for both filters, then there is little energy in the low frequencies. When the C reading is larger than the A reading by a significant amount (say 15-20 dB level difference) the spectrum is said to be dominated by the low frequency range (Bistafa, 2011).

[25] Difference between the highest and lowest level.

[26] More usually about 3 dB.

5 Regulations on Wind Turbine Noise

WTN regulations appears in the form of noise-limiting ordinances and acceptable standards for measuring and evaluating WTN. While in countries with a well-developed wind energy industry there are specific regulations concerning WTN, in some others, general noise regulations and limitations apply. Noise limitations, regardless of general or specific types, exist in order to protect people health and well-being and they may have strong economic impact whether in a stand-alone WT siting or large farm siting projects. The noise levels that WT enterprises must meet in Europe and USA are similar, differing mostly in the *exceedance levels*[27] (GIPE, 2004), as can be seen in Table 1.

Table 1 - Selected Noise Limits for different Countries, SPL [dB] (GIPE, 2004). Reproduced under permission.

Selected Noise Limits, Sound Pressure Levels in dBA

		Commercial	Mixed	Residential	Rural
Germany					
Day		65	60	55	50
Night		50	45	40	35
Netherlands					
Day	L_{eq}		50	45	40
Night			40	35	30
Denmark[1]	L_{eq}			40	45
England[2]					
High speed	L_{50}				45
Low speed	L_{50}				40
Minnesota					
Day	L_{50}	75	65	60	60
Night	L_{50}	75	65	50	50
Minnesota					
Day	L_{10}	80	70	65	65
Night	L_{10}	80	70	55	55
Kern County, Calif.[3]	$L_{8.3}$			45	45
Riverside County, Calif.	L_{90}			45	
Palm Springs, Calif.[4]	L_{90}			50	60

Notes: [1] Not to exceed 45 dBA beyond 400 m from wind turbine.
[2] L_{50} approx. 350 m from the nearest turbine.
[3] $L_{8.3}$, not to exceed 50 dBA.
[4] 50 dBA if lot is actually used as residential.

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[27] The L_{10} WTN limit, means that the dB(A) limit must be observed 10% of the time, while L_{90} means that the dB(A) level cannot be exceeded for over 90% of the observed time. The, exceedance levels also may be expressed as equivalent levels, L_{eq}.

Most community noise standards incorporate a penalty for pure tones, typically 5 *dB*. In Brazil there is currently no specific regulations concerning WTN and, like in many other countries, general noise regulations apply in that case. The maximum noise levels allowed are regulated by the Associação Brasileira de Normas Técnicas (ABNT), NBR 10151 Standard (Acústica - Avaliação do Ruído em Áreas Habitadas, Visando o Conforto da Comunidade), (NBR10151, 2000), Ilustrated in the table below.

Table 2 - Criteria level for external environment evaluation, dB(A).

Type of area	Criteria Level dB(A)	
	Day	Night
Farms and Countryland	40	35
Strictly residential urban area or hospital or school area	50	45
Mixed use, predominantly residential.	55	50
Mixed use, commercial and service prone.	60	55
Mixed use, recreational prone.	65	55
Industrial area (mostly)	70	60

For the purpose of illustrating in a quantitative manner the impact of the regulations on the cost of a WT siting project, let us consider the simple van der Borg one parameter, linear model[28] for WT Sound Power Level (SPW) noise production, (GIPE, 2004) p. 295:

$$SPW = 22.log\ D + 65 \quad dBA \qquad \text{(Eq. 3)}$$

Since every increase of 3 dB means doubling the source power, growing the WT diameter from 38 to 150 m roughly increases the source power level sixteen times by this model and the sound pressure level at a fixed observer location, would increase four times.

The divergence of the SPL, from an omnidirectional noise source, far from the ground or reflective surfaces, propagating spherically without attenuation to distance r from the source, is (Bistafa, 2011):

$$SPL = SPW - 20.log\ r - 11 \quad dB \qquad \text{(Eq. 4)}$$

[28] Van der Borg introduced two different correlations for L_W, this one being the one for second generation, quieter, WT.

By equating the SPL for the two different diameters and estimating the ratio of distances where the SPL will be the same for both sources, we will find a distance ratio of 1:4.5, which suggests that the larger diameter equipment will need 20 times more ground area for siting than the smaller diameter machine. In Brazil, the daytime Criteria Level (maximum limit) acceptable as per current standard (NBR10151, 2000), for acoustic comfort criteria in farmlands and fields, is 40 dB(A). By replacing this upper limit for SPL in the expression (4) one can obtain the linear distance r required from the closest dwelling in this simplified propagation model[29].

It becomes quite clear that the larger the WT, the farthest away it must be sited from dwellings in order to fulfill legal noise requirements. That translates into increased cost of acquisition of the real state, maintenance, access roads and also precludes the large size WT to come closer to the electricity end-user.

CONCLUSION

Wind energy is one of the most important renewable energy sources today, and has been used more and more in the world. However, it needs prerequisites for sitting WTs, since it must be in a strong wind weather, be able to support the installation of these large turbines (100m high for example, HAWT type) and environmental impacts should also be considered due to the installation of a wind farm, mainly the noise emitted by the turbines.

This work presented the importance of evaluating using appropriate software to predict the noise of wind turbines in the initial phase of WTs project and, thus, to avoid large future costs and problems in relation to the vicinity of wind farms. which are increasingly approaching areas with human occupation.

This work also presented the lack in specific brazilian regulations about WTN, that is not appropriated for wind farms near populated areas, and the future problems that this can cause. It was made a comparison with north american and european

[29] For 38 m diameter WT: $40=100-20.\log r-11 \ \ \text{dB} \ => r=102.45 \cong 282 \text{ m}$ and for 150 m diameter WT: $40=113-20.\log r-11 \ \ \text{dB} \ => r=103.10 \cong 1,259 \text{ m}$.

legislations about WTN and its particularities that are very stricts in terms of noise emitted.

The research area of WTN still has a lot to be developed, however the current technology allows us, even with a simplified noise prediction model in helping the siting planners to evaluate the information provided by the WT manufacturers regarding allowable distance from households and avoid problems of sound emission in the surroundings of wind farms according the considerations presented above.

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APPENDIX A – CONSIDERATIONS ON DESIGNING-FOR-NOISE AND SUGGESTIONS FOR LOCAL NOISE-REGULATIONS IMPROVEMENTS.

It was shown in Eq. (1), that *WT* mechanical power output scales with the approaching wind speed cubed, $P_{mec} \approx U_{\infty}^{3}$, and we have also that the acoustic power for a dipole-type source, for instance, scales with the sixth power of the local flow velocity $P \approx U^{6}$.

The monotonic increase in local flow velocity and Mach number found from root to tip in the Wind Turbines confirms the concentration of stronger noise sources towards the tip of the blades.

Similarly to the design challenge on the performance side, one very important aspect of designing for noise is that there is no single operating point for a WT.

Because the Rayleigh distribution is positively skewed, the wind may attain very high velocity values associated with low probability and it was shown that the modern WT has mechanisms to prevent it from going outside an acceptable operating range (over speeding), from the standpoints of performance and structural integrity, such as the *pitch control*. Power regulation can be achieved either by pitching to promote stalling or pitching to feather which reduces the lift force on the blades by reducing the angle of attack (Burton, Sharpe, Jenkins, & Bossanyi, 2008), p. 181.

While designing-for-noise, pitch control by stalling is certainly not desirable, since it may worsen the noise problem, and there are currently no applicable noise models for stalled flows over airfoils.

For an efficient design-to-noise it is also necessary that the local noise regulations are efficiently designed. Although the WT must be safely operated at wind cut-out speed, it will be operating most of the time in speeds below that limit. As an example, suppose that modal value of the wind speed, σ, is $10\ m/s$, at a site and that the wind follows a Rayleigh distribution. The average wind speed may be calculated from:

$$\mu(v) = \sigma.\sqrt{\frac{\pi}{2}} = 12.5\frac{m}{s} \qquad \text{(Eq. A-1)}$$

The time the WT would spend subjected to 25 m/s winds, above which the equipment is cut-out, would be only 1% of the time. Also the total cumulative time spend above cut-out would be:

$$F\,(v > 25m/s) =- e^{-\frac{v^2}{2\sigma^2}} = 0.0436 \; or \; 4.36\% \qquad \text{(Eq. A-2)}$$

Even then, speeds above cut-out-speed would not be attained due to the WT pitch control mechanism. It may be seen that designing the equipment for noise emissions at the extreme condition, i.e., the 1% time it will be facing a 25m/s wind, may prove uneconomical.

This is probably the reason why most countries where the Wind Energy Industry is more developed have migrated from peak-maximum noise (sound pressure level) allowable limits to equivalent levels allowable limits (e.g. in Denmark, Netherlands), expressed as L_{eq} , or exceedance levels (e.g. California), expressed as L_{60}, L_{90} , etc. The issuing of a specific noise standard concerning WTN would be also desirable in Brazil, and the noise limits should be stated in energy equivalence methods as those described above, not absolute maximum levels.