DISCUSSION ON TURBULENT INFLOW NOISE PREDICTION

Alexandre Martuscelli Faria[1], Joseph Youssif Saab Jr.[2], Sara Rodriguez[3], Marcos de Mattos Pimenta[4]

ABSTRACT

Wind farm planning is increasingly bounded by land availability. That means that wind turbine (WT) sittings are being pushed near to populated areas, where the annoyance potential due to noise generation might become an impediment. The main objective of Poli-Wind research group is to provide the WT industry with a low cost wind turbine blade noise prediction code, PNoise, which allows a detailed assessment of many WTN sources in the preliminary design phase. This work is specifically focused on turbulent inflow noise, also referred to as leading-edge noise (LEN), and discusses the implementation of semi-empirical correlations based on Amiet's broadband noise theory and Lowson's method, and the more appropriate turbulence spectrum modeling. The LEN is classified as an interaction noise, produced by the turbulent inflow, which is incident to the WT blade leading-edge. Turbulent inflow noise is usually predominant at lower frequencies (<1 kHz), with a minimal contribution to the higher frequencies sound pressure level (SPL).

Keywords

Wind Turbine Noise · Airfoil Leading-Edge Noise · Turbulent Inflow Noise · Amiet's Method · Lowson's Method

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1. TURBULENT INFLOW NOISE CHARACTERIZATION

An airfoil in a turbulent flow experiences a fluctuating lift which radiates noise to the far-field. This fluctuating lift is a result of the unsteady pressure field produced by the airfoil in response to turbulence (Staubs, 2008). The turbulent flow field can be either produced upstream the airfoil, by the presence of inflow distortions and other aerodynamic elements, or it can be also consequence of the development of a turbulent boundary layer over the airfoil surface, in case of a steady inflow. The upstream mechanism is linked with the noise produced close to the airfoil leading edge, while the mechanism related to the turbulent boundary layer is a self-noise mechanism, discussed in details by Saab (Saab, 2016).

As Figure 1 illustrates, the two noise generation mechanisms coexist and are responsible for the overall noise spectra. Normally, for WT applications, airfoil self-noise constitutes the dominant noise source. For certain flow conditions, however, i.e. when the incoming turbulence intensity and the integral length scale of the inflow eddies are large enough, the pressure fluctuations caused by the boundary layer eddies is smaller compared to the pressure fluctuations due the turbulent inflow, and the turbulent inflow noise mechanism is predominant over the self-noise.

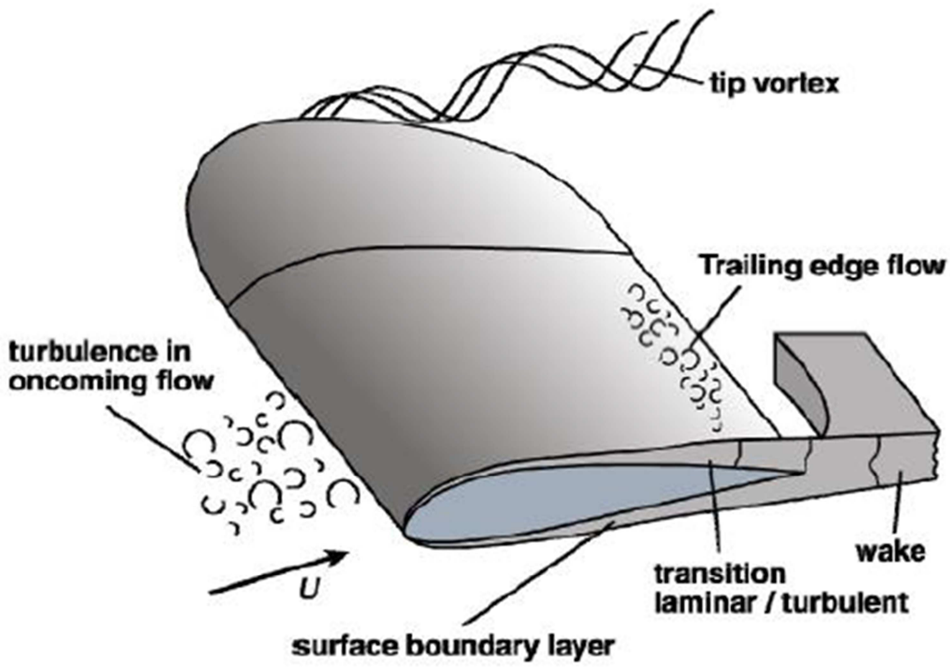

Figure 1 - Flow around a WT rotor blade (Wagner, Bareiß and Guidati, 1996).

Characterized as an interaction noise source, turbulent inflow noise is caused by the flow-surface interaction, when the atmospheric turbulence encounters the rotor blades. Since turbulence is not a uniform phenomenon, its characteristics depend on local parameters, such as eddy size and turbulence intensity.

The eddy size is the most important parameter for determining the LEN (Zhu, 2004). Due to the turbulence structure and the atmospheric stability, eddies of a wide range of sizes interact with the blade, as Figure 2 points out.

Studies conducted by Paterson and Amiet, Oerlemans and Migliore and Moreau, Roger and Jurdic have shown that the turbulent inflow noise is usually confined to the lower frequencies (<1 kHz), where the turbulent structures responsible for the LEN generation are the larger structures (Paterson and Amiet, 1976) (Oerlemans and Migliore, 2004) (Moreau, Roger and Jurdic 2005). Therefore, the blade can be simplified as an acoustic dipole, which source strength is equal to the total fluctuating lift on the blade surface.

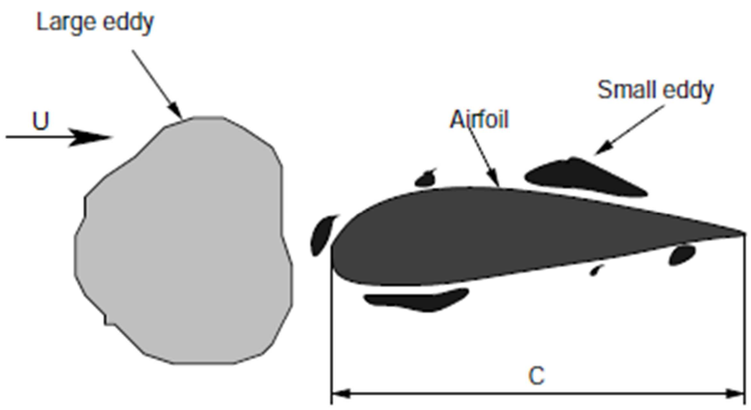

Figure 2 - Turbulent eddies of different sizes (Adapted from Zhu, 2004).

Estimation methods for quantifying the LEN should take into account parameters such as the turbulence intensity, the longitudinal integral length scale and the WT geometric data, since turbulence depends on atmospheric conditions for specific height values (Staubs, 2008).

2. TURBULENCE ANALYSIS

Discussion around the turbulent integral length scale (L) modeling is presented by many authors. The approach proposed by Moriarty and Migliore sets it as a function of distance from the ground up to a specific height, where is it then set constant (Moriarty and Migliore, 2003). For WT applications, the specific height is the hub height. This modeling follows:

$$L = \begin{cases} 0.7h, 0 \leq h \leq 60 \\ 42\ m, h > 60 \end{cases} \tag{1}$$

On the other hand, Zhu *et al.* has proposed an empirical expression, which presents L as a function of the hub height h, but also the surface roughness z_0, for different terrain types (Zhu *et al.*, 2005):

$$L = 25h^{0.35}z_0^{-0.063} \tag{2}$$

Boorsma and Schepers have also presented a third correlation to evaluate the integral length scale L (Boorsma and Schepers, 2011):

$$L = 2h\big(0.5 + 0.316(3 + \log_{10} z_0)\big) \tag{3}$$

Values to surface roughness z_0 are provided by Table 1.

At the same manner, the turbulence intensity is presented by Zhu *et al.* and Boorsma and Schepers as function of the WT hub height and surface roughness (Zhu *et al.*, 2005), (Boorsma and Schepers, 2011). The correlation provided by Zhu *et al.* follows:

$$I = \gamma \frac{\log_{10}(30/z_0)}{\log_{10}(h/z_0)} \tag{4}$$

where γ is a power law factor, which gives the amount of shear between the flow mean velocity and the turbulence velocity fluctuations. The factor γ is estimated empirically by Couniham, with respect to Figure 3 (Couniham, 1967).

$$\gamma = 0.24 + 0.096\log_{10}(z_0) + 0.016(\log_{10}(z_0))^2 \tag{5}$$

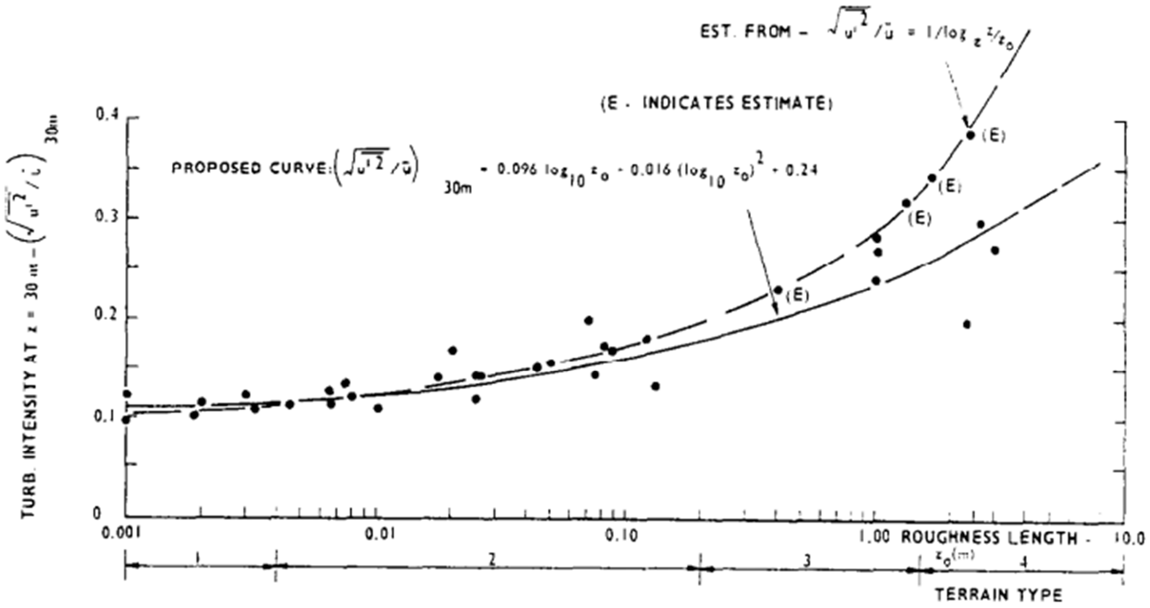

Figure 3 - Variation of turbulence intensity with roughness length (Couniham, 1975).

Table 1 – Surface roughness for various terrain types

Terrain type	$z_0\ (m)$
Very smooth, ice or mud	0.00001
Calm open sea	0.00020
Blown sea	0.00050
Snow surface	0.0030
Lawn grass	0.0080
Rough pasture	0.010
Fallow field	0.030
Crops	0.050
Few trees	0.100
Many trees, hedges	0.250
Forests and woodlands	0.500
Suburbs	1.500
Centers of cities with tall buildings	3.000

Boorsma and Schepers have provided a methodology based on ESDU standards (Boorsma and Schepers, 2011):

$$I = \frac{0.286 + 0.187\log_{10} h - 0.81(\log_{10} h)^2}{{z_0}^{0.07}\log_{10} h/z_0} \tag{6}$$

Comparisons between different estimation methodologies for turbulence integral length scale and turbulence intensity are displayed respectively at Figure 4 and Figure 5.

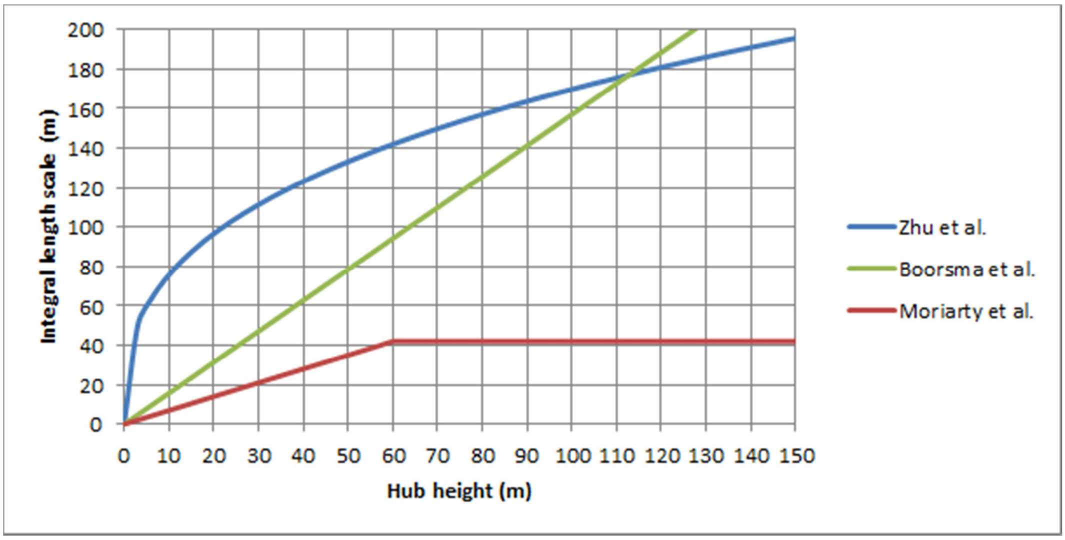

Figure 4 - Comparison of three integral length scale estimation methods for lawn grass terrain

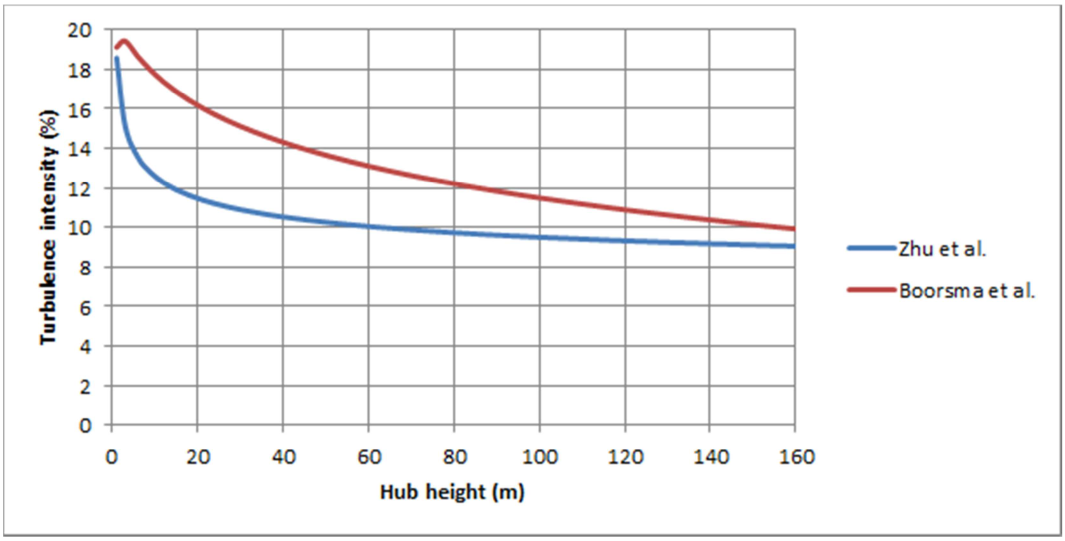

Figure 5 - Comparison of two turbulence intensity estimation methods for lawn grass terrain

Figure 4 illustrates the trend of increasing the integral length scale while increasing the WT hub height. That means, for higher hub height WT, more low frequency noise is expected to be produced due to the interaction between blades and eddies.

On the other hand, Figure 5 shows that turbulence intensity decays to a minimum level around 9% when increasing the hub height.

3. TURBULENT INFLOW NOISE PREDICTION

3.1. Amiet's problem and theoretical approach

A theoretical formulation for predicting the turbulent inflow noise was firstly introduced by Amiet with agreement to Curle (Curle, 1955) theory. His methodology evaluates the far-field acoustic power spectral density (PSD) produced by an airfoil in a subsonic turbulent stream, given in terms of characteristic quantities of the turbulence (Amiet, 1975).
The theoretical approach, illustrated by Figure 6, corresponds to the compute the acoustic response of an airfoil of $2b$ chord and $2d$ span subjected to a turbulent flow with mean velocity U in the x direction. The noise source S is placed at the center of the airfoil, at the (x_0, y_0, z_0) coordinate system and the observer O is placed at the far-field, represented by the (x, y, z) coordinate system. This is a more general case, since it considers the observer placed at an arbitrary position of the far-field, with the free stream extending to infinity, what suggests suitability for WT noise prediction.

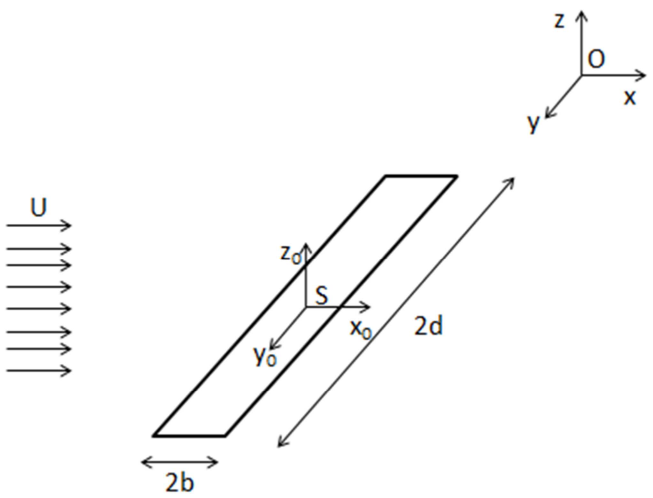

Figure 6 - Amiet problem representation

The far-field PSD is described by Amiet's formulation as:

$$S_{pp}(x,y,z,\omega)=\left(\frac{\omega z}{4\pi c_0\sigma^2}\right)^2 Ud\pi\Phi_{ww}(K_x,K_y)\left|\mathcal{L}(x,K_x,K_y)\right|^2 \tag{7}$$

In a more convenient form, it can be rewritten as:

$$S_{pp}(x,y,z,\omega)=A(x,y,z,\omega)\Phi_{ww}(K_x,K_y)\left|\mathcal{L}(x,K_x,K_y)\right|^2 \tag{8}$$

Where $A(x,y,z,\omega)$ represents the mean flow and geometric aspects of the problem, $\Phi_{ww}(K_x,K_y)$ is the turbulence energy spectrum and $\mathcal{L}(x,K_x,K_y)$ is the aeroacoustics transfer function, which represents the lift response of the airfoil.

Derivation of the lift response of the airfoil is discussed in details by Santana (Santana, 2015), where the flow field is described as a partial differential equation (PDE) problem, which consists of a canonical Helmholtz equation subjected to the boundary conditions of zero velocity potential upstream the airfoil leading-edge; zero airfoil surface normal velocity (non-penetration condition) and zero pressure jump at the airfoil trailing-edge (Kutta condition) and downstream.

$$\frac{\partial^2\varphi}{\partial\bar{x}^2}+\frac{\partial^2\varphi}{\partial\bar{z}^2}+\kappa^2\varphi=0 \tag{9}$$

$$\varphi(\bar{x},0)=0,\qquad \bar{x}\le 0 \tag{10}$$

$$\frac{\partial\varphi}{\partial\bar{z}}(\bar{x},0)=\frac{-w_0 b}{\beta}e^{\overline{k_x}^*\bar{x}},\qquad 0\le\bar{x}\le 2 \tag{11}$$

$$\left(i\overline{k_x}^*+\frac{\partial}{\partial\bar{x}}\right)\varphi(\bar{x},0)=0,\qquad \bar{x}>2 \tag{12}$$

The turbulent velocity energy spectrum, $\Phi_{ww}(K_x,K_y)$, on the other hand, can be modeled after von Kármán energy spectrum (Amiet, 1975) (Sinayoko and Hurault, 2015):

$$\Phi_{ww}(k_x,k_y)=\frac{4}{9\pi}\frac{\overline{u^2}}{k_e^2}\frac{(k_x/k_e)^2+\left(k_y/k_e\right)^2}{\left(1+(k_x/k_e)^2+\left(k_y/k_e\right)^2\right)^{7/3}} \tag{13}$$

where . $\overline{u^2}$ is evaluated by taking the root mean square of the turbulence fluctuations and can be represented in terms of the turbulence intensity I and the mean flow velocity U:

$$\overline{u^2}=(IU)^2 \tag{14}$$

The average wavenumber of the energy containing eddies, k_e, is defined in terms of the integral length scale of turbulence, L, and the gamma functions $\Gamma(5/6)$ and $\Gamma(1/3)$:

$$k_e = \frac{\sqrt{\pi}}{L}\frac{\Gamma(5/6)}{\Gamma(1/3)} \tag{15}$$

Santana, however, suggests that the turbulence spectrum should be modeled after Batchelor's Rapid Distortion Theory (RDT), because turbulence rapid distortion takes place when a variation in the mean velocity field occurs due to change in the boundary conditions, e.g. turbulent flow approaching an airfoil (Santana, 2015). It is also necessary that the turbulence distortion occurs so rapidly that the contribution to the change in relative positions of the fluid particles from the turbulence is negligible (Batchelor and Proudman, 1954). In this case, one can write:

$$\Phi_{ww}(k_x, k_y) = \frac{91}{36\pi}\frac{\overline{u^2}}{k_e^2}\frac{(k_x/k_e)^2 + \left(k_y/k_e\right)^2}{\left(1 + (k_x/k_e)^2 + \left(k_y/k_e\right)^2\right)^{19/6}} \tag{16}$$

3.2. Amiet's semi-empirical method

A semi-empirical method was also developed by Amiet, by coupling his theoretical method with an acoustic tunnel experiment, which is represented at Figure 7 (Amiet, 1975).

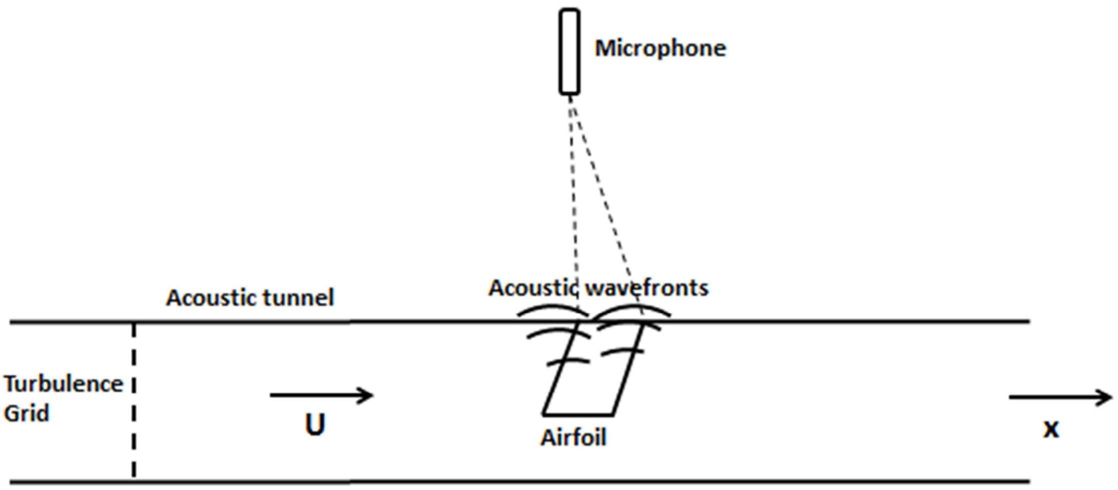

Figure 7 - Airfoil in the free stream of an acoustic tunnel (adapted from R.K. Amiet, 1975).

In Amiet's experiment, an airfoil with a chord of 18 inches and a span of 21 inches was mounted between sideplates at zero AOA in an acoustic tunnel, and a turbulence generating grid was placed upstream the airfoil. The turbulence measurements indicated at the test section that turbulence properties were approximated by an isotropic homogeneous turbulence model. The integral length scale, L, of the turbulence was 1.25 inches. The streamwise turbulence intensity, I, was set to 4.4% for $U = 103$ ft/s.

Amiet have conducted third octave sound measurements with a microphone placed at 7 feet directly above the airfoil and obtained a semi empirical relation for the one third octave level, $SPL_{1/3}$, in dB relative to a pressure of $2 \cdot 10^{-4} \mu bar$:

$$SPL_{1/3} = 10 \log_{10} \left[\frac{Ld}{z^2} M^5 \frac{\overline{u^2}}{U^2} \frac{\hat{K}_x^3}{\left(1 + \hat{K}_x^2\right)^{7/3}} \rho_0^2 c_0^4 \right] + 181.3 \quad (17)$$

It is important to draw attention here for the units of measure, that may influence the total SPL, because of the 181.3 constant, which is calculated in the English system of units.

Although showing good agreement to a range of frequencies, which extended from 200 Hz up to 2500 Hz, the experiment was not conducted for frequencies lower than 200 Hz because of limitations of the test chamber. Characterized as a low frequency noise, LE noise prediction methods should be effectual for a wider range of frequencies.

3.3. Lowson's semi-empirical method

An alternative semi-empirical method was then introduced by Lowson. Intended to be more suitable for WT applications, it presents modifications in order to provide a correction for the lower frequencies of the spectrum, and has introduced the concept of spherical directivity to turbulent inflow noise prediction, as already seen in the contemporary BPM turbulent boundary layer trailing-edge noise (more details in Brooks, Pope and Marcolini, 1989) prediction method (Lowson, 1992) (Moriarty and Migliore, 2003).

In Lowson's formulation, the total $SPL_{1/3}$ is firstly decomposed in terms of the high frequencies sound pressure level and the low frequency correction factor, LFC.

$$SPL_{1/3} = SPL_H + 10 log_{10} \left[\frac{LFC}{1 + LFC} \right] \quad (18)$$

For the high frequency domain, the evaluation of the sound pressure level follows:

$$SPL_H = 10log_{10}\left(\frac{\rho_0 c_0^2 sL}{2r_e^2} M^3 U^2 I^2 \frac{\widehat{K}_x^3}{\left(1+\widehat{K}_x^2\right)^{7/3}} \overline{D}_L\right) + 58.4 \quad (19)$$

where r_e is the total distance between source and observer, and $\overline{D}_L$ is the spherical directivity factor.

The directivity can be obtained by:

$$\overline{D}_L = \frac{\sin^2\theta\cos^2\varphi}{(1+M\cos\theta)^4} \quad (20)$$

where θ and φ are the directivity angles.

The low frequency correction factor is approximated by the following expression:

$$LFC = 10S^2MK^2\beta^{-2} \quad (21)$$

where S is the compressible Sears function that relates $\widehat{K}_x^3$ and β^2 can be written in the following form:

$$S^2 = \left(\frac{2\pi K}{\beta^2} + \left(1 + 2.4\frac{K}{\beta^2}\right)^{-1}\right)^{-1} \quad (22)$$

4. CASE STUDY – QUALITATIVE EXAMPLES

For didactic purposes, data from the DAN-AERO wind turbine are selected (Madsen *et al.*, 2010). The blade tip section chord length is 0.9 m, blade length is 38.8 m, the Mach number at the blade tip is M = 0.11, mean wind flow velocity is 8.5 m/s. The observer is placed 60 m below the hub and 104.5 m downstream the turbine. The prediction is performed using Amiet's theoretical method.

4.1. Sensitivity to turbulence intensity

In order to ensure consistence to this analysis, let us consider the observer as a microphone placed on the ground, so the hub height can be approximated to 60 m. Terrain is lawn grass; turbulence length scale is modeled after Moriarty *et al.* formulation (see Figure 4); turbulence spectrum is modeled after von Kármán isotropic turbulence. The turbulence intensity is then set as 5%, 10%, 15% and 20%.

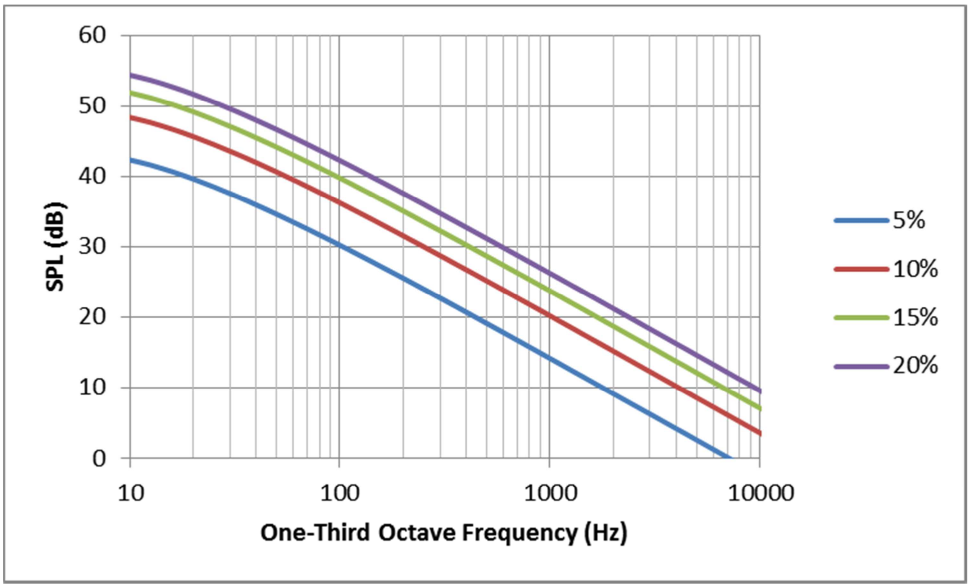

Figure 8 - Sensitivity to turbulence intensity

Figure 8 illustrates the behavior of sound pressure level in response to the turbulence intensity. The SPL increases while increasing the turbulence intensity. In other words, at the same integral length scale, at higher hub heights, the SPL may decrease.

4.2. Sensitivity to turbulence integral length scale

Analogously to the turbulence intensity analysis, here the turbulence intensity is set fixed at 12.5%. The turbulence integral length scale varies from 10 m to 100 m.

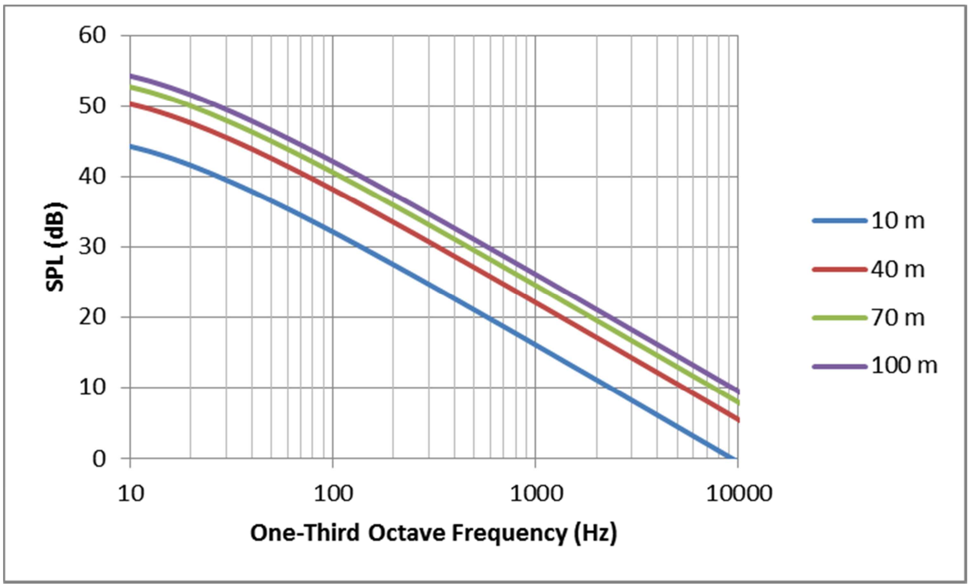

Figure 9 - Sensitivity to the turbulence integral length scale

As expected from Equations 13 to 16, the sound pressure level also increases while increasing the integral length scale, as it is seen at Figure 9. That means, increasing the hub height, the integral length scale is increased, and so does the SPL. This conclusion apparently conflicts with the conclusion of the previous subsection. However, turbulence is not an isolated phenomenon, and moreover turbulence intensity and integral length scale consist of a pair of factors associated simultaneously to the hub height.

4.3. Sensitivity to turbulence modeling

For this last sensitivity analysis, the turbulence intensity is set to 12.5% and the integral length scale is set to 40 m. The SPL is calculated considering both von Kármán isotropic turbulence model and Batchelor rapid distortion theory as the turbulence energy spectrum.

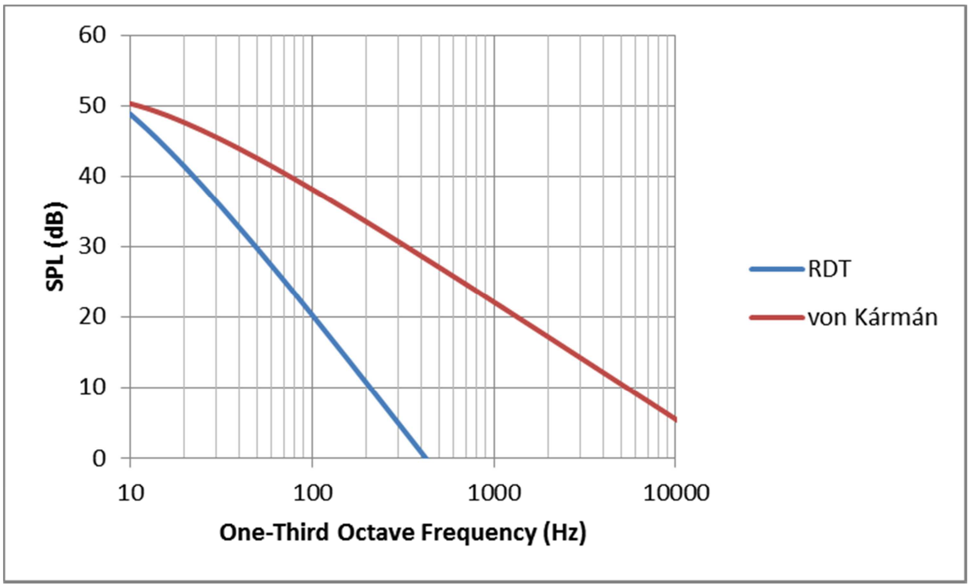

Figure 10 - Sensitivity to turbulence modeling

As shown in Figure 10, choosing the appropriate turbulence spectrum model might produce large under or overestimations to the turbulent inflow noise. Despite being more conservative, von Kármán isotropic turbulence spectrum modeling predicts a turbulent inflow noise SPL which extends to the whole frequency spectrum, even at frequencies above 1 kHz. The rapid distortion theory spectrum SPL curve, on the other hand, presents the expected behavior for LEN. However, this present study is yet qualitative, and the modeling requires experimental data in order to be validated.

5. Conclusions

Assessment of the turbulent inflow noise coupled with the self-noise sources should contribute to the design of quieter WT units and reduce the environmental impact to inhabited areas near wind farms.

This work has presented discussions about LEN particular characteristics, along its main causes. This includes how turbulence behaves at certain heights above ground, due to atmospheric conditions, but also how it can be related to the terrain surface roughness. These two factors play important roles on estimating local turbulence intensity and local turbulence integral length scale.

A review on the most usual LEN prediction methods was presented, in order to provide the reader conditions to understand how turbulence is associated to noise generation, and how attention should be dispensed in order to choose an appropriate turbulence modeling. Also a case study is developed, which discusses how the SPL is sensitive to turbulence parameters, and yet how these parameters are linked to geometric, atmospheric and field variables.

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