8th International Conference
on
Wind Turbine Noise
Lisbon – June, 12-14th, 2019

Airfoil LE Noise prediction supplement for *PNoise* Code

Alexandre Martuscelli Faria, Polytechnic School, Sao Paulo State University (Poli-USP): martuscellifaria@usp.br

Joseph Youssif Saab Junior, Maua Institute of Technology (IMT): saab@maua.br

Sara Rodriguez, Polytechnic School, Sao Paulo State University (Poli-USP): sara.rodriguez@alumni.usp.br

Marcos de Mattos Pimenta, Polytechnic School, Sao Paulo State University (Poli-USP): marcos.pimenta@poli.usp.br

Summary

This work is part of an ongoing collaboration project between Poli-USP and TU-Berlin and aims to further improve the airfoil noise prediction module, *PNoise*, which is integrated into the wind turbine design environment, *QBlade*, available under General Public License. This paper discusses some of the aspects around selection, implementation and testing of an airfoil leading-edge (LE) noise prediction model to supplement the TE noise model of the *PNoise* code. The interaction of the LE with the turbulent inflow is an important source of wind turbine (WT) noise, especially in the case of small scale WT which behaves as non-compact noise sources. LE noise is usually confined to low frequencies (<1 kHz) and is strongly dependant on turbulence parameters, such as turbulence intensity and the turbulence integral length scale. Amiet's broadband noise theory and Lowson's semi-empirical method are discussed in the context of the model setup, along with the appropriate turbulence spectrum modelling. Results of the implemented model are then compared to experimental data from recent literature, in order to provide initial verification of the model. A discussion on compatibility with the current *PNoise* code is also presented.

1 Introduction

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) and Saab and Pimenta (Saab and Pimenta, 2016).

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.

Characterized as an interaction noise source, and perceived as a swishing noise, 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 atmospheric parameters, such as eddy size and turbulence intensity.

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

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 LE noise 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.

Estimation methods for quantifying LE noise should take into account parameters such as turbulence intensity, the longitudinal integral length scale, the largest turbulent structure, and the horizontal axis wind turbine (HAWT) geometric data, since turbulence depends on atmospheric conditions for specific height values (Staubs, 2008).

The main objective of this paper is to discuss the application of different methodologies for LE noise prediction and the respective turbulence spectrum modeling. First, a qualitative study of a full scale HAWT noise prediction is presented. Directly after that, a single airfoil LE noise prediction is compared to experimental measurements conducted on acoustic tunnel by Juknevicius and Chong (Juknevicius and Chong, 2018).

This work gives an overview of airfoil LE noise prediction, focusing on Amiet's theory (Amiet, 1976) and its extensions, such as inclusion of directivity proposed by Lowson (Lowson, 1992) and the more adequate turbulence spectrum model, proposed firstly by Simonich *et al.* (Simonich *et al.*, 1986) and further discussed by Santana (Santana, 2015).

Being this work part of *PNoise* code improvement, by Poli-Wind Research Group, compatibility with the current version is also discussed in this paper.

2 Methodologies for airfoil LE noise prediction

2.1 Amiet's broadband noise theory

A theoretical formulation and a semi-empirical methodology, for predicting the turbulent inflow noise, were introduced by Amiet with agreement to Kirchhoff and Curle theories, in order to ensure more reliability to the prediction against measurements. This methodology evaluates the far-field acoustic power spectral density 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 1, 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.

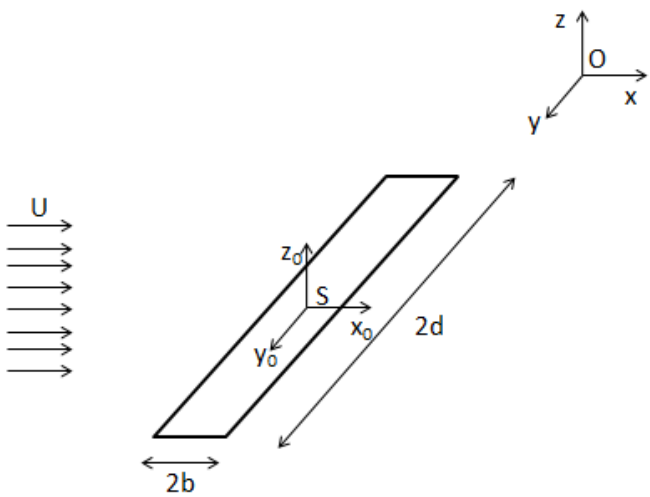

Figure 1: Amiet problem representation

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

$$S_{pp}(x, y, z, \omega) = \left(\frac{\omega z}{4\pi c_0 \sigma^2}\right)^2 U d\pi \Phi_{ww}(K_x, K_y) \left|\mathcal{L}(x, K_x, K_y)\right|^2 \tag{1}$$

where $\Phi_{ww}(K_x, K_y)$ is the turbulent velocity energy spectrum and $\mathcal{L}(x, K_x, K_y)$ corresponds to the acoustic lift response function.
Derivation of $\mathcal{L}(x, K_x, K_y)$ 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.

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

$$\varphi(\bar{x},0)=0, \qquad \bar{x}\leq 0 \tag{3}$$

$$\frac{\partial\varphi}{\partial\bar{z}}(\bar{x},0)=\frac{-w_0 b}{\beta}e^{\overline{k_x}^*\bar{x}}, \qquad 0\leq\bar{x}\leq 2 \tag{4}$$

$$\left(i\overline{k_x}^*+\frac{\partial}{\partial\bar{x}}\right)\varphi(\bar{x},0)=0, \qquad \bar{x}>2 \tag{5}$$

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

$$\Phi_{ww}(k_x,k_y)=\frac{4}{9\pi}\frac{\overline{u^2}}{k_e^2}\frac{(k_x/k_e)^2+\left(k_y/k_e\right)^2}{\left(1+(k_x/k_e)^2+\left(k_y/k_e\right)^2\right)^{7/3}} \tag{6}$$

where $\overline{u^2}=(IMc_0)^2$ and $k_e=\frac{\sqrt{\pi}}{L}\left(\frac{\Gamma(5/6)}{\Gamma(1/3)}\right)$.
Simonitch *et al.*, 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 (Simonitch *et al.,* 1986). Experimental evidences of rapid distortion were also reported by Santana (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, the turbulence spectrum can be written as:

$$\Phi_{ww}(k_x,k_y)=\frac{91}{36\pi}\frac{\overline{u^2}}{k_e^2}\frac{(k_x/k_e)^2+\left(k_y/k_e\right)^2}{\left(1+(k_x/k_e)^2+\left(k_y/k_e\right)^2\right)^{19/6}} \tag{7}$$

2.2 Amiet's semi-empirical method

A second formulation presented by Amiet is a semi-empirical method, based on the acoustic tunnel experiment. An airfoil of $2b$ chord and $2d$ span is placed in a turbulent flow with mean velocity U in the x direction, as Figure 2 illustrates. The y coordinate extends in the spanwise direction and the origin of the coordinate system is placed at the center of the airfoil. The observer is located at the far-field, directly overhead the airfoil, represented as a microphone. This procedure is used to neglect the retarded time differences, what allows one to formulate the far-field sound in terms of the total fluctuating lift of the airfoil.

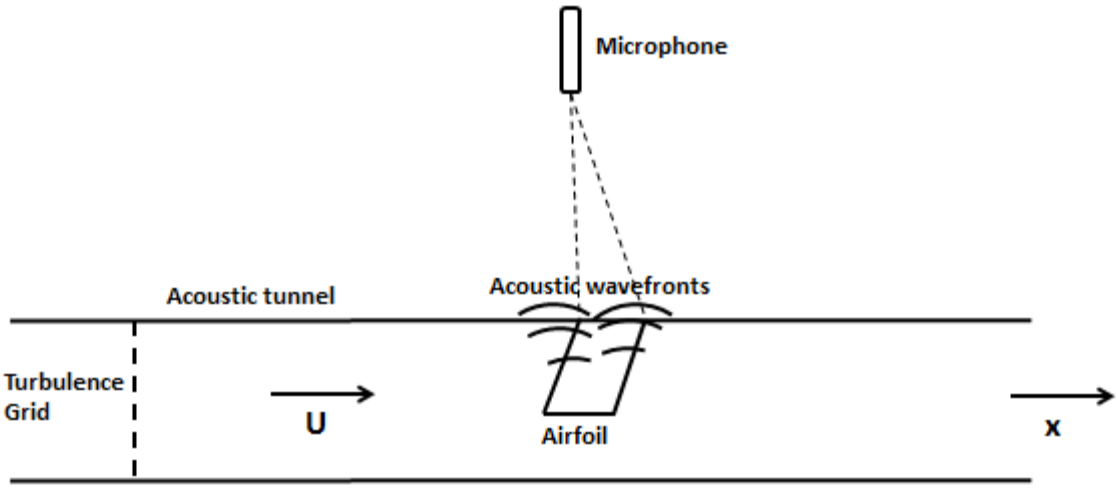

Figure 2: Airfoil in the free stream of an acoustic tunnel (adapted from R.K. Amiet, 1975).

In Amiet's experimental setup, an airfoil with a chord of 18 inches and a span of 21 inches was mounted between sideplates at zero angle of attack (AOA) in the UARL 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 one-third octave sound measurements with a microphone placed at 7 feet directly above the airfoil. Under the assumption that the mean flow is an one-dimensional flow, this simplified semi-empirical relation is obtained, for the one third octave sound pressure level, $SPL_{1/3}$, in dB relative to a pressure of $2 \cdot 10^{-4} \mu bar$:

$$SPL_{1/3} = 10 \log_{10} \left[\frac{Ld}{z^2} M^5 \frac{\overline{u^2}}{U^2} \frac{K^3}{(1+K^2)^{7/3}} \rho_0^2 c_0^4 \right] + 181.3 \tag{8}$$

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 not calculated in S.I. Paterson and Amiet have presented the same formulation but for the CGS unit system (Paterson and Amiet, 1976):

$$SPL_{1/3} = 10 \log_{10} \left[\frac{Ld}{z^2} M^5 \frac{\overline{u^2}}{U^2} \frac{K^3}{(1+K^2)^{7/3}} \rho_0^2 c_0^4 \right] + 58.4 \tag{9}$$

Another question that one could point out is the influence of the airfoil AOA on LE noise. Measurements from Juknevicius and Chong evidence that, for symmetrical airfoils, only self-noise mechanism is influenced by AOA, while it does not play a significant role on turbulent inflow noise (Juknevicius and Chong, 2018).

2.3 Lowson's semi-empirical method

An alternative semi-empirical method for LE noise prediction was introduced by Lowson (Lowson, 1992), by modifying Amiet's semi-empirical method. 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 TBL-TE (Brooks, Pope and Marcolini Turbulent Boundary Layer Trailing-Edge) noise prediction method (Brooks, Pope and Marcolini, 1989) (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:

$$SPL_{1/3} = SPL_H + 10log_{10}\left[\frac{LFC}{1+LFC}\right] \tag{10}$$

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

$$SPL_H = 10log_{10}\left[\frac{\rho_0^2 c_0^2 sL}{2r_e^2} M^3 U^2 I^2 \frac{K^3}{(1+K^2)^{7/3}} \overline{D}_L\right] + 58.4 \tag{11}$$

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:

$$\overline{D}_L = \frac{\sin^2\theta \cos^2\varphi}{(1+M\cos\theta)^4} \tag{12}$$

where θ and φ are the directivity angles.

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

$$LFC = 10S^2 M K^2 \beta^{-2} \tag{13}$$

where S is the compressible Sears function that relates K and β^2 which can be written in the following form:

$$S^2 = \left(\frac{2\pi K}{\beta^2} + \left(1 + 2.4\frac{K}{\beta^2}\right)^{-1}\right)^{-1} \tag{14}$$

Units of measure are not provided by Lowson, what can lead to misunderstandings. However, as showed at the last sub-section, Paterson and Amiet method has already presented a constant value of 58.4 utilizing the CGS system of units (Paterson and Amiet, 1976), it can be assumed that Lowson also adopted that same system.

2.4 Modified RDT-Lowson's semi-empirical method

In face of Simonitch *et al.* and Santana's considerations on turbulence velocity energy spectrum modeling (Simonitch *et al.*, 1986) (Santana, 2015), one can follow a similar procedure to derive a modified Lowson's method, in order to model turbulence after the RDT spectrum.

This happens to change the constant value to 65.95 and the turbulence spectrum exponent to $19/6$. The result is an expression similar to Equation 11:

$$SPL_H = 10log_{10}\left(\frac{\rho_0^2 c_0^2 sL}{2r_e^2} M^3 U^2 I^2 \frac{K^3}{(1+K^2)^{19/6}} \overline{D}_L\right) + 65.95 \tag{15}$$

3 Methodology

Given that this work discusses LE noise prediction methods to be implemented in *PNoise*, and that the current version presents a modified BPM TBL-TE noise prediction method, let us consider Lowson's semi-empirical method the more suitable, because of taking into account spherical directivity. This reduces the comparison to terms of turbulence spectrum modeling, by considering turbulence being modeled after von Kármán isotropic turbulence or by Batchelor's rapid distortion theory.

First, as a qualitative example, the influence of turbulence modeling on Lowson's method is analyzed. The blade geometry chosen is the one presented in the DAN-AERO report (Madsen *et al.*, 2010) and flow conditions are the ones provided by Sinayoko and Hurault (2015). In this case, the blade has 0.9 m chord, total length of 38.8 m. The observer is placed at 104.5 m downstream of the turbine and 60 m below the hub. Turbulence integral length scale is set to 40 m and the incoming turbulence intensity is set to 12.5%. The flow Mach number is set to $M = 0.11$. The chord-based Reynolds number is $Re = 3.08 \cdot 10^6$. The respective TBL-TE noise prediction is also obtained from the *PNoise* noise prediction module, inside *QBlade* environment (Marten, 2016), at zero angle of attack.

The second part consists of validating the methods against experimental data. Juknevicius and Chong have conducted LE noise measurements for a NACA 0008 airfoil with 0.15 m chord and 0.498 m span subjected to a turbulent flow with mean velocity 50 m/s ($Re = 5 \cdot 10^5$), turbulence intensity 3.7% and turbulence integral length scale of 6.5 mm. Two other measurements were conducted with flow mean velocity of 30 m/s ($Re = 3 \cdot 10^5$) and 60 m/s ($Re = 6 \cdot 10^5$). The microphone was positioned 1 m directly overhead the airfoil LE (Juknevicius and Chong, 2018).

4 Results and discussion

4.1 Qualitative analysis – DAN-AERO WT

Figure 3 shows the predicted LE noise source by implementation of the modified Lowson-RDT-LE noise prediction method for the DAN-AERO WT, as well as the predicted TBL-TE noise source. The modified Lowson-RDT-LE appears to attend the low-frequency noise nature of the LE noise. For this prediction, TE noise becomes and is kept the dominant source for frequencies above 63 Hz, which is expected for a large HAWT.

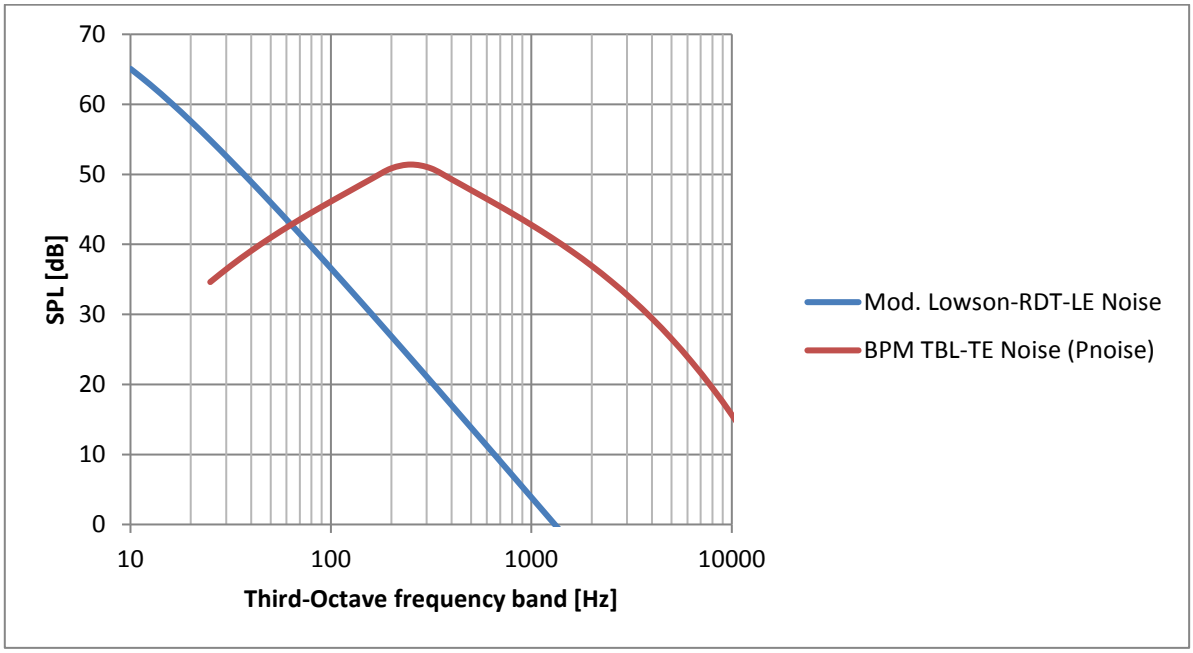

Figure 3: Predicted sound pressure levels for TE and LE noise by implementation of the PNoise BPM TBL-TE noise prediction method (red line) and the Modified Lowson-RDT LE noise prediction method (blue line) for the DAN-AERO wind turbine.

Figure 4 shows the predicted LE noise source by implementation of the standard Lowson LE noise prediction method for the DAN-AERO WT, as well as the predicted TBL-TE noise source. In this case, on the other hand, LE noise plays a significant role on the overall sound pressure level for the whole frequency spectrum, being also predicted as the dominant source for frequencies above 5 kHz, which does not represent the low-frequency noise nature of the LE source of a large scale WT.

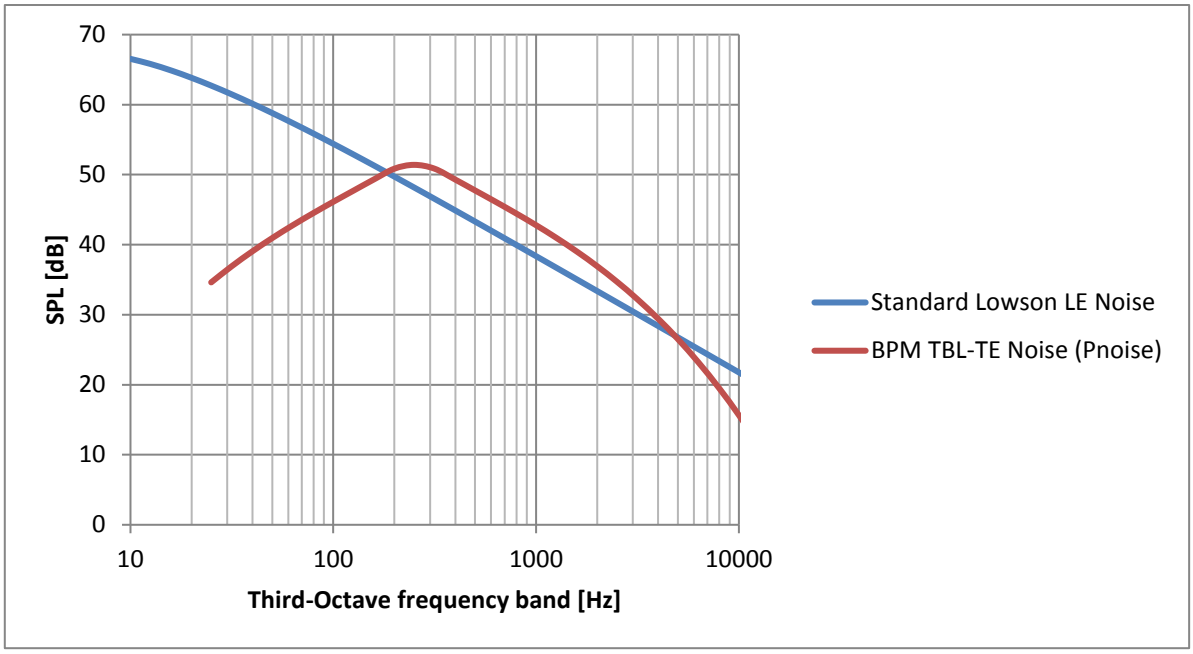

Figure 4: Predicted sound pressure levels for TE and LE noise by implementation of the PNoise BPM TBL-TE noise prediction method (red line) and the Standard Lowson LE noise prediction method (blue line) for the DAN-AERO wind turbine.

4.2 Quantitative analysis – validation against experimental data

As it can be seen in Figure 5, Figure 6 and Figure 7, the modified Lowson-RDT-LE noise prediction method provides a great approximation for the measured data, at the three different flow regimes, while the standard Lowson LE noise prediction method produces overestimations up to 33 dB at frequencies higher than 1 kHz. These overestimations were already noticed at the qualitative analysis, and yet confirmed in this validation. One should notice, however, that the experiment conducted by Juknevicius and Chong has only provided data for a NACA 0008 airfoil profile under low Re numbers ($< 10^6$).

Another noticeable fact is that all models based on Amiet's broadband noise theory begin assume the airfoil to be thin, so it does not take into account the real airfoil thickness. As already shown by Roger and Moreau and Devenport *et al.*, LE noise is strongly dependent on the airfoil thickness, and it decreases for thicker airfoils. An empirical expression for the airfoil thickness correction is proposed by Tian and Cotté, referenced from a NACA 0012 airfoil. This correction, however, does not contain the effects of camber and the nose radius (Tian and Cotté, 2016).

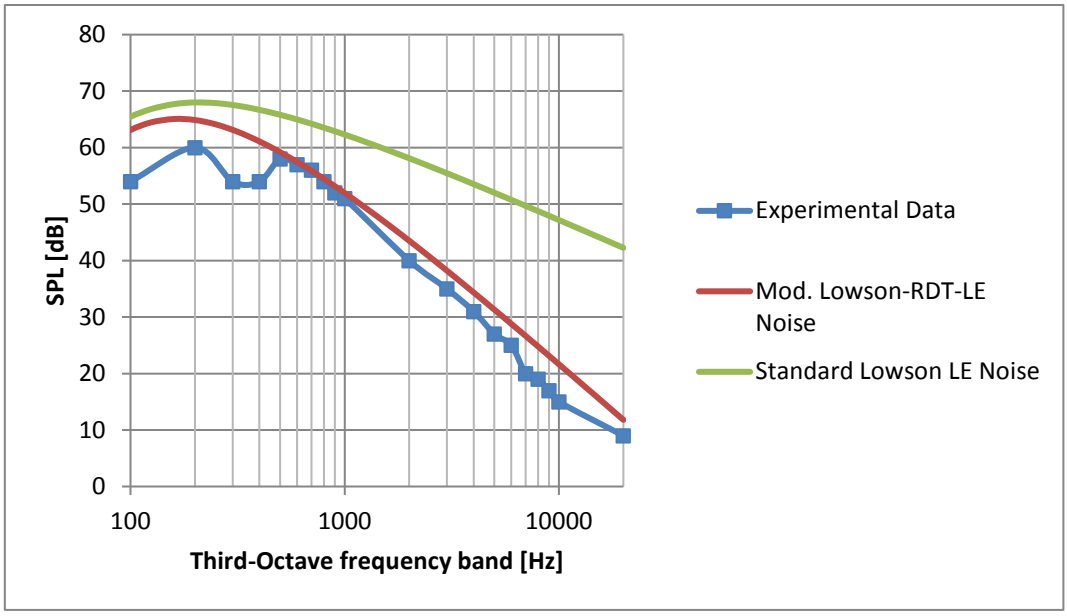

Figure 5: Measured LE noise of a NACA 0008 airfoil under a $Re = 5 \cdot 10^5$ flow (blue squares) against the predicted sound pressure levels: Standard Lowson LE noise prediction method (green line) and the Modified Lowson-RDT LE noise prediction method (red line) for the NACA 0008 airfoil.

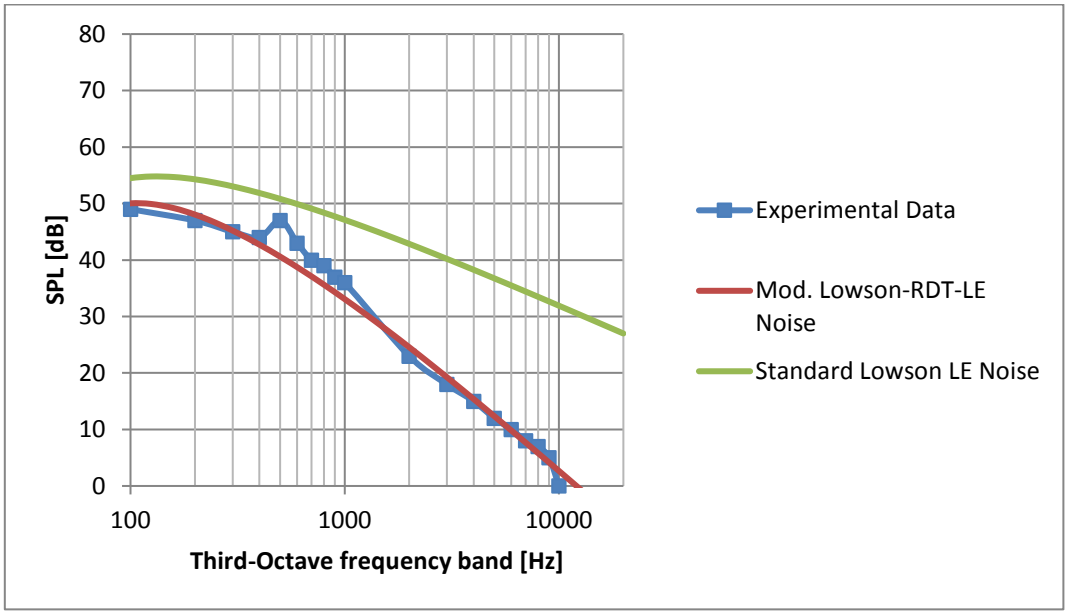

Figure 6: Measured LE noise of a NACA 0008 airfoil under a $Re = 3 \cdot 10^5$ flow (blue squares) against the predicted sound pressure levels: Standard Lowson LE noise prediction method (green line) and the Modified Lowson-RDT LE noise prediction method (red line) for the NACA 0008 airfoil.

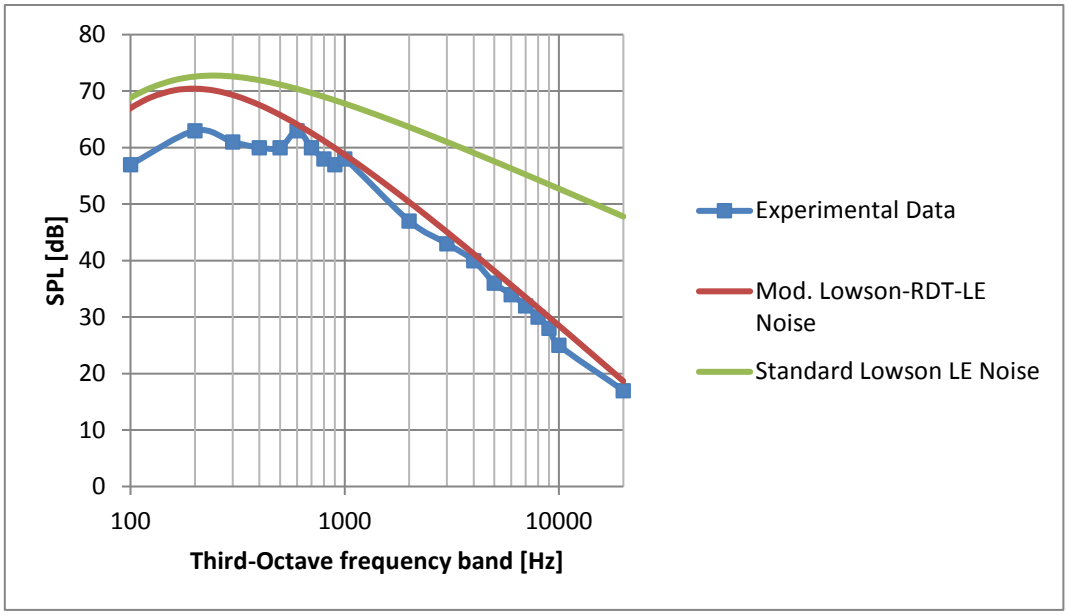

Figure 7: Measured LE noise of a NACA 0008 airfoil under a $Re = 6 \cdot 10^5$ flow (blue squares) against the predicted sound pressure levels: Standard Lowson LE noise prediction method (green line) and the Modified Lowson-RDT LE noise prediction method (red line) for the NACA 0008 airfoil.

5 Conclusions

This paper has presented an overview on turbulent inflow noise and its respective theoretical and semi-empirical prediction methods. As Lowson's method appeared to be more suitable for implementation on *PNoise* due to similarities with the BPM TBL-TE noise prediction method. The model was then discussed along with the turbulence spectrum modeling.

A modified Lowson's method was introduced with the turbulence spectrum modeled after Batchelor's rapid distortion theory. It was derived after Amiet's broadband noise theory analogously to the standard Lowson's method, with the von Kármán isotropic turbulence model.

Qualitative and quantitative analysis were then performed, respectively for a large scale WT ($Re = 2 \cdot 10^6$) and also for a NACA 0008 airfoil under a lower Re flow ($< 10^6$). The qualitative analysis has shown that RDT turbulence spectrum produces on the SPL curves a behavior closer to expectations, with the LE noise confined to lower frequencies (< 1 kHz), and with limited influence on the overall SPL. The quantitative analysis confirmed the qualitative analysis, displaying a curve fitting for the modified Lowson's method much closer to measured datathan the standard Lowson's method, and avoiding overestimations of up to 35 dB at higher frequencies. However, it demands further verification and validation for higher Reynolds numbers ($> 10^6$) and for airfoil geometries other than the NACA 0008.

Another future improvement is to include airfoil thickness effects along with the modified Lowson's method.

Acknowledgements

The authors would like to acknowledge National Council for the Improvement of Higher Education (CAPES) for the financial support.

References

Amiet RK. (1975). Acoustic radiation from an airfoil in a turbulent stream. Journal of Sound and Vibration: Vol. 41(Pt. 4):407-20.

Batchelor GK, Proudman, I. (1954). The effect of rapid distortion of a fluid in turbulent motion. The Quarterly Journal of Mechanics and Applied Mathematics; Vol. 7(Pt. 1):83-103.

Brooks TF., Pope DS., Marcolini MA. (1989). Airfoil Self-Noise and Prediction. NASA Reference Publication 1218.

Devenport W, Staubs J, Glegg S. (2010). Sound radiation from real airfoils in turbulence. Journal of Sound and Vibration 329 (2010) 3470–3483.

Juknevicius A., Chong TP. (2018). On the leading edge noise and aerodynamics of thin airfoil subjected to straight and curved serrations. Journal of Sound and Vibration: Vol. 425:324-43.

Lowson MV. (1992). Assessment and prediction of wind turbine noise. Flow Solutions Report. Bristol (England). Report No.: ETSU W/13/00284/REP.

Madsen HA, Bak C, Paulsen US, Gaunaa M, Dtu R, Fuglsang P, Glasfiber LM. (2010) The DAN-AERO MW Experiments Final Report Risø-R-Report. Vol. 1726.

Marten, D. (2016). PNoise Guidelines, Berlin: TU Berlin.

Moreau S, Roger M, Jurdic V. (2005). Effect of angle of attack and airfoil shape on turbulence interaction noise. Proceedings of the 11th AIAA/CEAS Aeroacoustics Conference Meeting and Exhibit; May 23-25, Monterey (CA). NASA.

Moriarty P, Migliore P. (2003). Semi-empirical aeroacoustic noise prediction code for wind turbines. NREL Technical Report. Golden, Colorado (US), Report No.: NREL/TP- 500-34478.

Oerlemans S, Migliore P. (2004). Wind tunnel aeroacoustic tests of six airfoils for use on small wind turbines. NREL Scientific Report. Golden, Colorado (US), Report No.: NREL/SR-500-35339.

Paterson RW, Amiet RK. (1976). Acoustic radiation and surface pressure characteristics of an airfoil due to incident turbulence. Proceedings of the 3rd AIAA Aero-Acoustics Conference; Palo Alto (CA). NASA.

Roger M, Moreau S. (2010). Extensions and limitations of analytical airfoil broadband noise models. International Journal of Acoustics 9 (2010) 273–305.

Saab Jr. JY. (2016). Trailing-Edge Noise - Development and Application of a Noise Prediction Tool for the Assessment and Design of Wind Turbine Airfoils [dissertation]. Escola Politécnica, Universidade de Sao Paulo (Brazil).

Saab Jr JY, Pimenta, MM. (2016). Displacement Thickness Evaluation for Semi-Empirical Airfol Trailing-Edge Noise Prediction Model. Journal of the Brazilian Society of Mechanical Sciences and Engineering, V.38, N.2, pp. 385-394.

Santana LD. (2015). Semi-Analytical Methodologies for Airfoil Noise Prediction [dissertation]. Katholieke Universiteit Leuven (Belgium).

Sinayoko S, Hurault J. (2015). On predicting wind turbine noise and amplitude modulation using Amiet's theory. Proceedings of the 6th Wind Turbine Noise Conference; 2015 Apr 20-23; Glasgow, Scotland. New Brighton: INCE Europe.

Simonich JC, Amiet RK, Schlinker RH, Greitzer EM. (1986). Helicopter Rotor Noise Due to Ingestion of Atmospheric Turbulence. NASA Contractor Report 3973, Langley Research Center, Hampton, Virginia.

Staubs JK. (2008). Real Airfoil Effects on Leading Edge Noise [dissertation]. Virginia Polytechnic Institute and State University, Blacksburg (VA).

Tian Y, Cotté B. (2016). Wind Turbine Noise Modeling Based on Amiet's Theory: Effects of Wind Shear and Atmospheric Turbulence. Acta Acustica united with Acustica vol. 102, 626-639.

Zhu WJ, Heilskov N, Shen WZ, and Sörensen JN. (2005). Modeling of aerodynamically generated noise from wind turbines. Journal of Solar Energy Engineering, vol. 127, no. 4, pp. 517-528.