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Selection of a leading edge noise prediction method for PNoise

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Abstract. Wind energy expansion is worldwide followed by various limitations, i.e. land availability, the NIMBY (not in my backyard) attitude, interference on birds migration routes and so on. This undeniable expansion is pushing wind farms near populated areas throughout the years, where noise regulation is more stringent. That demands solutions for the wind turbine (WT) industry, in order to produce quieter WT units. Focusing in the subject of airfoil noise prediction, it can help the assessment and design of quieter wind turbine blades. Considering the airfoil noise as a composition of many sound sources, and in light of the fact that the main noise production mechanisms are the airfoil self-noise and the turbulent inflow (TI) noise, this work is concentrated on the latter. TI noise is classified as an interaction noise, produced by the turbulent inflow, incident on the airfoil leading edge (LE). Theoretical and semi-empirical methods for the TI noise prediction are already available, based on Amiet's broadband noise theory. Analysis of many TI noise prediction methods is provided by this work in the literature review, as well as the turbulence energy spectrum modeling. This is then followed by comparison of the most reliable TI noise methodologies, qualitatively and quantitatively, with the error estimation, compared to the Ffowcs Williams-Hawkings solution for computational aeroacoustics. Basis for integration of airfoil inflow noise prediction into a wind turbine noise prediction code is the final goal of this work.

Keywords. *Wind turbine noise, airfoil leading edge noise, PNoise, Amiet broadband noise theory, QBlade.*

Introduction. Characterization and prediction of leading edge noise is part of an effort to have a complete 2-D airfoil noise analysis on the preliminary wind turbine blade design phase, since the annoyance potential due to wind turbine noise is a main concern when it comes to windfarm planning. The LE noise, also referred to as turbulent inflow noise, is identified as a low-frequency noise produced by the scattering of inflow turbulence at the leading edge of the airfoil.

Many authors have formulated methods in order to provide accurate airfoil noise prediction, by combining turbulence modeling, mean flow conditions and the airfoil geometric characteristics. Amiet (1) has presented an analytical methodology, as well as a semi-empirical method, being both based on an acoustic tunnel experiment. Further discussion around Amiet's methodology and modifications are provided by other authors. Lowson (2) has presented a semi-empirical method that contains corrections to Amiet's semi empirical model, considering a low-frequency correction factor and the compressible Sears function. Other authors, such as Sinayoko and Hurault (3) and Santana (10), have revisited Amiet's analytical formulation, and have presented and discussed corrections and improvements to this method, in order to ensure greater reliability.

Parallel to the semi-empirical and analytical formulations, Ffowcs Williams-Hawkings have developed an integration method based on Lighthill's acoustic analogy through numerical methods, in order to compute the sound pressure level (SPL) in the far field. This methodology has been validated against experimental data and is part of many commercial computational fluid dynamics (CFD) solvers (4).

Leading edge 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 (5). 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 (6).

The two noise generation mechanisms coexist, however for certain flow conditions, i.e. when the incoming turbulence intensity is large enough, so the pressure fluctuations caused by the boundary layer eddies is smaller compared to the pressure fluctuations due the turbulent inflow, and the so-called leading edge noise mechanism is predominant over the self-noise.

Studies conducted by Paterson and Amiet (7), Oerlemans and Migliore (8) and Moreau (9) have shown that the leading-edge noise is confined to lower frequencies, where the turbulent structures responsible for the inflow noise generation are the larger structures. It is common that the quantity given for most of the studies of turbulent noise is based on the longitudinal integral length scale, the largest turbulent structure (5).

Since the inflow noise is the second most important noise source to be analyzed, this work discusses a method to be implemented, in order to predict the amount of noise produced.

Amiet's method. Two different formulations were presented by Amiet (1). The first formulation, illustrated by Figure 1, corresponds to the theoretical approach that computes the aeroacoustic 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. The source and observer positions are of extremely importance to the noise prediction, given its dipole characteristic.

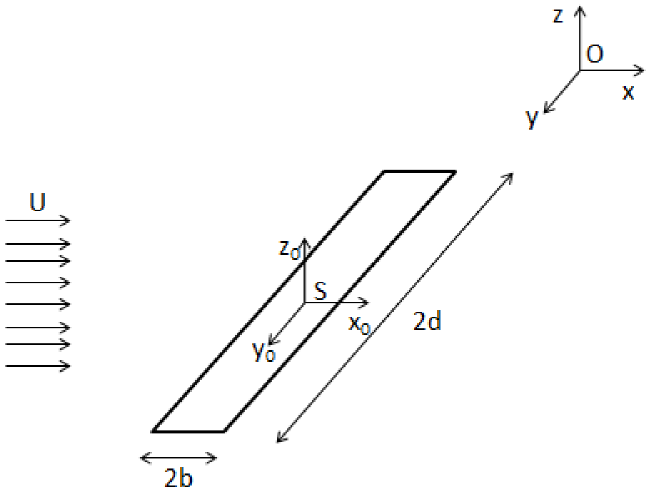

Figure 1. Amiet's problem representation

The second formulation 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.

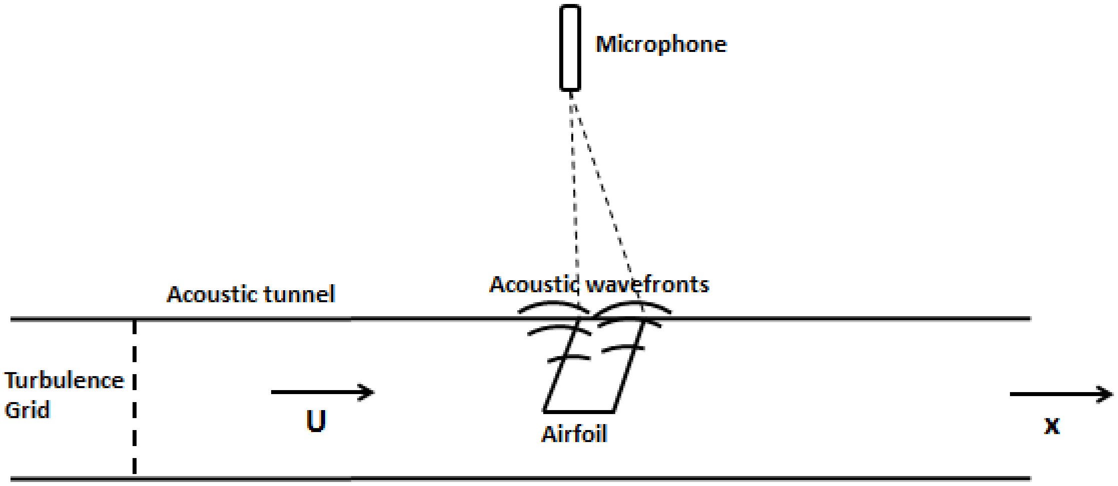

Figure 2. Airfoil in the free stream of an acoustic tunnel (adapted from R.K. Amiet, 1975).

Following Amiet's theoretical approach, the far-field power spectral density (PSD) is expressed, for the LE, as:

$$S_{pp} = \left(\frac{\rho_0 kzb}{\sigma^2}\right)^2 d\pi U \phi_{ww}\left(K_x, K_y\right)\left|\mathcal{L}\left(x, K_x, K_y\right)\right|^2 \tag{1}$$

Where ϕ_{ww} corresponds to the turbulent velocity energy spectrum, and $\mathcal{L}$ is the lift response function.

With respect to the acoustic tunnel experiment, the resultant semi-empirical expression for the sound power level (SPL) follows:

$$SPL = 10log_{10}\left[\frac{Ld}{z^2} M^5 \frac{\overline{u^2}}{U^2} \frac{\widehat{K}_x^2}{\left(1+\widehat{K}_x^2\right)^{7/3}}\right] + 181.3 \tag{2}$$

The SPL is calculated in dB relative to a reference pressure $p_{ref} = 2 \cdot 10^{-5}\ Pa$.

Turbulence spectrum and lift response function. Amiet considers the hypothesis of frozen turbulence and that the turbulence spectrum can be modeled after von Kármán isotropic turbulence model (1). More recent discussion and application of this turbulence modeling are presented by Sinayoko and Hurault (3). The von Kármán isotropic turbulence spectrum model follows:

$$\phi_{ww}\left(K_x, K_y\right) = \frac{4}{9\pi} \frac{{u'}^2}{k_e^2} \frac{(k_x/k_e)^2 + \left(k_y/k_e\right)^2}{\left(1 + (k_x/k_e)^2 + \left(k_y/k_e\right)^2\right)^{7/3}} \tag{3}$$

However, Santana (10) suggests that the turbulence spectrum should be modeled after the Batchelor rapid distortion theory (RDT) (11). 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. 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.

In addition to Batchelor Rapid Distortion Theory, other authors also have proposed modifications to the distorted turbulence energy spectra, such as the work from Hunt (12), that discusses a change in the decay of the turbulence energy spectra, when the small scales of turbulence approximates to the wall. Another contribution is the one presented by Christophe (13) that modifies the turbulence energy spectrum, from the undistorted isotropic case to the anisotropic distorted case. The correspondent modified turbulent energy spectrum is written as follows:

$$\phi_{ww}\left(K_x, K_y\right) = \frac{91}{36\pi}\frac{u'^2}{k_e^2}\frac{(k_x/k_e)^2+\left(k_y/k_e\right)^2}{\left(1+(k_x/k_e)^2+\left(k_y/k_e\right)^2\right)^{19/6}} \tag{4}$$

With respect to the lift response function corrections, Santana (10) provides such a complete discussion that may not be treated as a central subject of this work. Its methodology is validated against several experimental data and follows that:

$$\mathcal{L}\left(x, K_x, K_y\right) = \int_{-1}^{1} g\left(\xi, K_x, K_y\right) e^{-i\mu(M-x/\sigma)\xi} d\xi \tag{5}$$

where:

$$g\left(x, K_x, K_y\right) = \frac{p(x,y,0,t)e^{ik_y y}e^{-i\omega t}}{\pi\rho U w_0} \tag{6}$$

Lowson's method. An alternative semi-empirical method was then introduced by Lowson (2), based on Amiet's semi-empirical formulation. 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.

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.

$$SPL = SPL_H + 10log_{10}\left[\frac{LFC}{1+LFC}\right] \tag{7}$$

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

$$SPL_H = 10log_{10}\left(\frac{\rho_0 c_0^2 sL}{2r_e^2} M^3 U^2 I^2 \frac{K^3}{(1+K^2)^{7/3}} \overline{D}_L\right) + 58.4 \tag{8}$$

$$LFC = 10S^2 M K^2 \beta^{-2} \tag{9}$$

$$S^2 = \left(\frac{2\pi K}{\beta^2} + \left(1 + 2.4\frac{K}{\beta^2}\right)^{-1}\right)^{-1} ;\ \beta = \sqrt{1-M^2}; K = \frac{\pi f c}{U} \tag{10}$$

Units of measure are not provided by Lowson, what can lead to misunderstandings. However, as Paterson and Amiet (7) method has presented a constant value of 58.4 utilizing the CGS system of units, it can be assumed that Lowson also adopted that system.

Ffowcs Williams-Hawkings analogy. In order to have a consistent comparison between Amiet's theoretical approach and Lowson's method, by introducing the use of computational fluid dynamics (CFD) through Ffowcs Williams-Hawkings (FW-H) analogy. The FW-H analogy is an integration method, based on Lighthill's acoustic analogy, which considers the source as a limited dimensionally stable control surface, which moves with velocity v_i through a fluid. The solution presented by the FW-H analogy can be used directly to calculate the noise emission. If the flow is characterized as low Mach number around a solid and impermeable fixed body, the contribution of other sources out of the control surface limits to the sound pressure level are not significant (4).

Methodology. In face of Santana's considerations on turbulence velocity energy spectra modeling (10), both Amiet's method and Lowson's method are tested under adoption of von Kármán turbulent energy spectrum and Batchelor's rapid distortion theory turbulent energy spectrum. This should introduce a modified version of Lowson's method. Equation 8 can be rewritten, for a RDT turbulence modeling:

$$SPL_H = 10log_{10}\left(\frac{\rho_0 c_0^2 sL}{2r_e^2} M^3 U^2 I^2 \frac{\hat{K}_x^3}{\left(1+\hat{K}_x^2\right)^{19/6}} \overline{D}_L\right) + 58.4 \quad (8)$$

A closer investigation of the applicability range of each turbulent energy spectrum model is also proposed, in light of the fact that turbulent inflow noise is produced by the interaction of large scale turbulent eddies with the airfoil, and many of the studies consider the integral length scale of turbulence to be much smaller than the airfoil chord, instead of having at least the same order of magnitude of the airfoil chord, as the definition of the turbulent inflow noise states.

The problem setup consists of a NACA 0012 airfoil of 0.15 m chord and 0.45 m span under a low Mach number stream. The sound pressure level is calculated for an observer placed at 1.22 m directly above the airfoil leading edge. The test cases consist of varying the flow mean velocity, turbulence intensity, and the integral length scale of the turbulent eddies. The FW-H solutions are performed at the environment of a commercial finite volume code.

Table presents the simulations' setup. Each simulation is performed for each turbulent inflow noise prediction method discussed in this section. The results are then plotted in independent frequency-SPL charts for each setup, in order to be compared to the FW-H solution.

Table 1 - Simulations setup

	Flow Mach number ***M***	**Turbulece intensity** ***I*** **(%)**	**Turbulence integral length scale** ***L*** **(m)**
SPL 1 (dB)	0.0804	2.06	0.005
SPL 2 (dB)	0.0804	4.00	0.10
SPL 3 (dB)	0.10	4.00	0.10

Results and discussion. The first case of the sound pressure level (SPL) evaluation for the turbulent inflow noise, represented by **Erro! Fonte de referência não encontrada.**, considers the airfoil subjected to a flow with Mach number $M = 0.0804$, turbulence intensity $I = 2.06\%$ and turbulence integral length scale $L = 0.005\ m$.

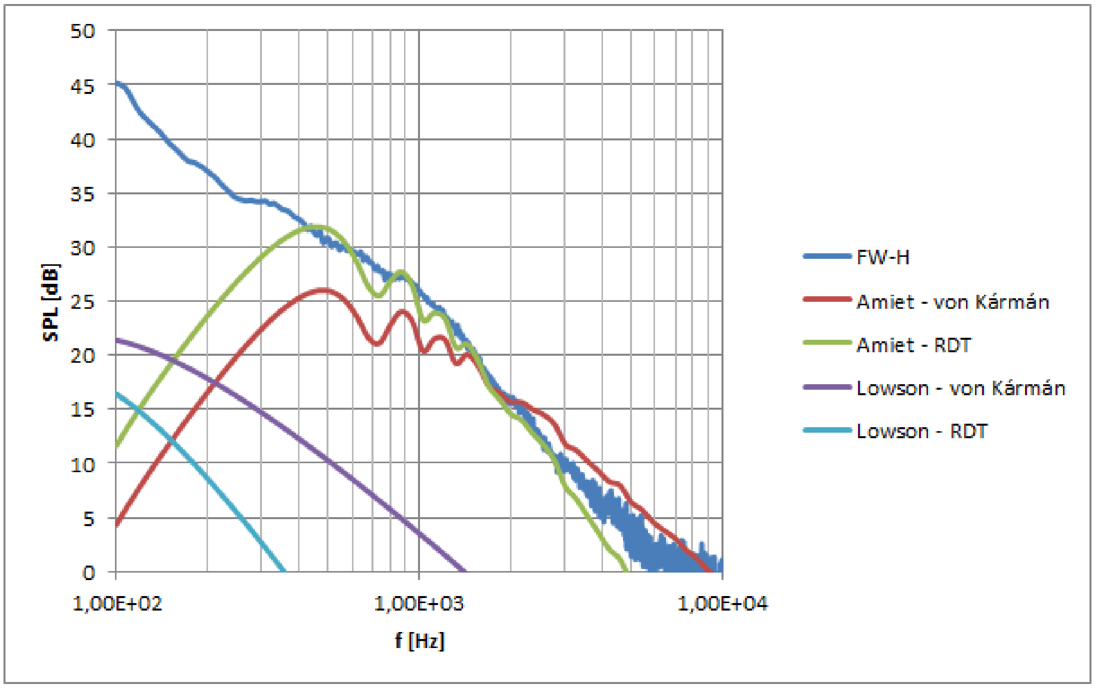

Figure 3. Case 1: Sound pressure levels for von Kármán and RDT Amiet methods versus Lowson method versus Ffowcs Williams-Hawkings method. The integral length scale is 0.005 m, the turbulence intensity is set to 2.06% and the Mach number is 0.0804.

As it can be seen, for the first case, none of the four prediction methods fit the curve in its entirety. Lowson's method, for example, underestimates substantially the SPL for the whole frequency spectrum, for both turbulence spectrum models. On the other hand, when it comes to Amiet's turbulent inflow noise prediction method, it is observed that, above certain frequencies, the curves fit. Modeling the turbulence spectrum as von Kármán isotropic turbulence, the prediction begins to present suitability above 1500 Hz. For the Batchelor RDT turbulence spectrum model, curves begin to fit for frequencies above 400 Hz. Nevertheless, turbulent inflow noise is confined to low frequencies, and its SPL should decrease while increasing the frequency. Case 1 presents no good agreement.

The second case of SPL evaluation for the turbulent inflow noise, represented by **Erro! Fonte de referência não encontrada.**, the airfoil was subjected to a flow with the same Mach number

$M = 0.0804$, turbulence intensity was increased to $I = 4.00\%$ and the turbulence integral length scale was 20 times greater than the first case, $L = 0.1\ m$.

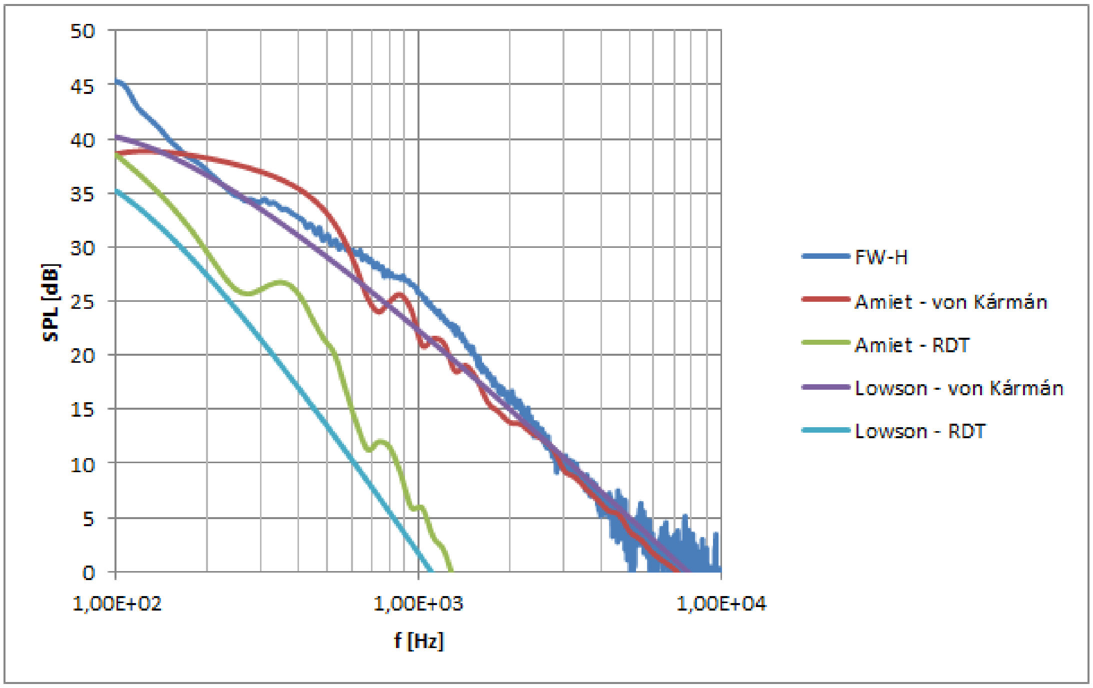

Figure 4. Case 2: Sound pressure levels for von Kármán and RDT Amiet methods versus Lowson method versus Ffowcs Williams-Hawkings method. The integral length scale is 0.1 m, the turbulence intensity is set to 4.0% and the Mach number is 0.0804.

In this case, one can notice the influence of order of magnitude of the turbulence integral length scale on the quality of the turbulence inflow SPL prediction methods. Both Amiet and Lowson methods, under the von Kármán isotropic turbulence assumption, present a better agreement for noise prediction for the whole frequency spectrum, with respect to FW-H solution. Although some fluctuations are noticeable (maximum +/- 4 dB), these two methods are representative for a first estimation. However, Batchelor RDT turbulence spectrum assumption does not produce any representative results, when compared to FW-H, producing underestimation for the whole frequency range. Case 2 points at the importance of an appropriated integral length scale selection.

Case 3 presents a flow Mach number increase, with respect to case 2. The direct effect of changing the Mach number to $M = 0.1$ is a shift of about 5 dB up, for all the curves, as it is shown at **Erro! Fonte de referência não encontrada.**. Increasing the Mach number represents also an increase on the turbulent velocity fluctuations.

With respect to the different turbulent inflow noise prediction methods, as it was expected, the same qualitative results from case 2 are obtained and the same discussion is applicable. Assumption of Batchelor RDT turbulence energy spectrum does not produce a reliable representation of the phenomenon of WT turbulent inflow noise generation.

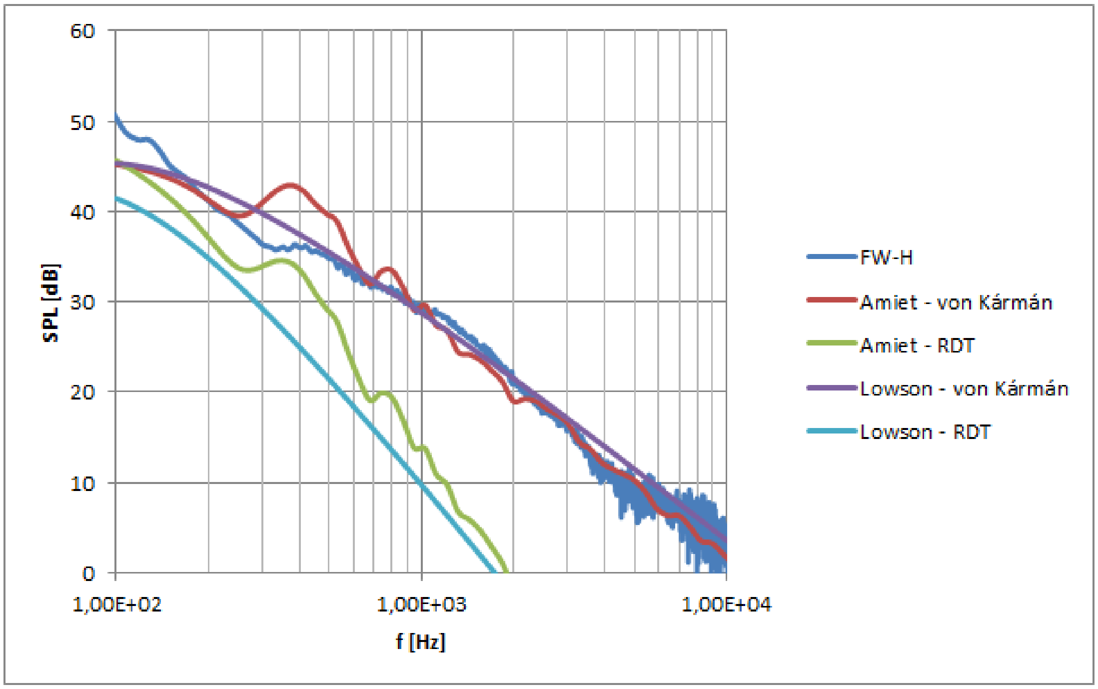

Figure 5. Case 3: Sound pressure levels for von Kármán and RDT Amiet methods versus Lowson method versus Ffowcs Williams-Hawkings method. The integral length scale is 0.1 m, the turbulence intensity is set to 4.0% and the Mach number is 0.1.

Conclusion. The results produced have returned that von Kármán isotropic turbulence model is the more adequate method for the case of interest, when compared to Batchelor's rapid distortion theory. Order of magnitude of the turbulence integral length scale has seemed to be the most important turbulence parameter, when predicting turbulent inflow noise. The integral length scale of turbulence should have at least the same order of magnitude of the airfoil chord length. Lowson's semi-empirical method has produced less over and underestimations and more stability than Amiet's theoretical methodology.

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