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

The Quasi-3D TE Rotor Noise Prediction Tool of the PNoise Code

Joseph Youssif Saab Junior, Maua Institute of Technology (IMT).
Poli-Wind Research Group: saab@maua.br

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

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

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

Summary

A 2D airfoil trailing-edge (TE) noise prediction module, *PNoise*, was developed in 2016 under a Poli-USP - TU-Berlin collaboration project and integrated into the *QBlade* wind turbine (WT) design platform, available under General Public License (GPL). Owing to the continued user interest and a large number of downloads of the host platform, a quasi-3D method was planned as follow-on for implementation which should return to the user the approximate, full blade and full rotor noise prediction. Also, the PNoise code is gradually receiving upgrades for inflow noise and other self-noise sources that will gradually benefit the quasi-3D method. Because the quasi-3D variation resorts iteratively to local 2D solutions, it also depends on the same underlying boundary layer thickness hybrid calculation and induced flow calculation methods of the 2D algorithm, with resulting accuracy affected by the errors inherent in each method plus the error deriving from the use of a finite number of blade sections in the blade and a discrete number of angular positions of the blade along the azimuthal plane to model the effect of the wind field, distance to observer and directivity function. Although the Poli-Wind group also research higher-order, longer-response time noise prediction methods (theoretical, CFD and Lattice-Boltzmann formulations) the PNoise code was developed with the early wind turbine (WT) rotor design task in mind and remains true to its original purpose with the addition of a quick turn-around-time quasi-3D tool. Provisions are made in the expanded blade noise method for the calculation of the overall sound pressure level (SPL) perceived by an observer (i) at a fixed location behind one single rotating blade or (ii) fixed in space, at any user-specified location in relation to the full rotor. Atmospheric and terrain propagation effects are not added at this time, only the distance between the observer and the many aeroacoustic sources, along with the respective directivity function suitable for each type of source. The opportunities for further developments include the addition

of minor self-noise sources, transient wind field inlet condition, blade aeroelastic deformation effect calculations and noise propagation models to the farfield.

LIST OF ABBREVIATIONS AND ACRONYMS

Abbreviation	Meaning
AOA	Angle of Attack
BEM	The Blade Element Momentum method
BL	Boundary Layer
BPM	Brooks, Pope, Marcolini, Airfoil Self Noise Prediction Model
CFD	Computational Fluid Dynamics
FP	Flat Plate
HAWT	Horizontal Axis Wind Turbine
LBL	Laminar Boundary Layer
LE	Leading Edge
OASPL	Overall Sound Pressure Level (dB)
Poli – USP	Politechnic School - São Paulo State University - Brasil
PNoise	Poli-USP TE noise prediction code.
QBlade	TU Berlin-developed, public domain, Wind Turbine Performance and Structural analysis software.
Quasi-3D	Quasi Three Dimensional (method)
SPL	Sound Pressure Level (dB)
$SPL_{1/3}$	Sound Pressure Level for each 1/3 octave band (dB)
SPL_W	Weighted Sound Pressure Level (dB)
TBL	Turbulent Boundary Layer
TBL-FP	Turbulent Boundary Layer, Flat Plate model
TBL-TE	Turbulent Boundary Layer at the Trailing Edge
TE	Trailing Edge
TSR	Tip-Speed Ratio
VS	Vortex Shedding (Frequency) (Hz)
WT	Wind Turbine
WTN	Wind Turbine Noise
XFLR5	The XFOIL software with graphic user interface.
XFOIL	Hybrid, Potential Flow and Integral Boundary Layer Solver.
2D	Two-Dimensional (method)

LIST OF SYMBOLS

Letter	Meaning	Disambiguation, (section)	units
$\boldsymbol{a}$	Axial induction factor		
$\boldsymbol{a}$	Angle between $Y_B Z_B$plane and local segment mid-section chord line.		^{0}
$\boldsymbol{a'}$	Tangential induction factor		
$\boldsymbol{AOA}$	Angle of Attack		^{0}
$\boldsymbol{b}$	Geometric angle	Table 3, 20	^{0}
$\boldsymbol{c}, \boldsymbol{c_i}$	Airfoil chord		m
$\boldsymbol{c_{r,i+1}}$	Cord at the outboard section of the blade segment considered		m
$\boldsymbol{c_{r,i}}$	Cord at the inboard section of the blade segment considered		m
$\boldsymbol{csv}$	Comma-separated value (text file format)		

$\mathbf{D*}$	Displacement thickness (notation inside XFLR5 code)	m
$\boldsymbol{HR}$	Hub radius	m
$\boldsymbol{N/A}$	Not Available	
$\boldsymbol{N/S}$	Not Selected	
$\boldsymbol{N_s}$	Number of spanwise blade segments	
$\boldsymbol{N_\beta}$	Number of blade angular positions in the azimuthal plane	
$\boldsymbol{N_f}$	Number of frequencies in the spectrum	
$\boldsymbol{n_b}$	Number of blades	
$\boldsymbol{n}$	Number of blade segments	
$\boldsymbol{Re}$	Reynolds Number	
$\boldsymbol{Re_c}$	Reynolds Number, chord-based	
$\boldsymbol{r_o}$	Outer radius for each blade segment	m
$\boldsymbol{r_i}$	Inner radius for each blade segment	m
$\boldsymbol{r}$	Rotor, blade radial position	m
$\boldsymbol{r_{i+1}}$	Blade radius at the outboard section of the blade segment considered	m
$\boldsymbol{r_i}$	Blade radius at the inboard section of the blade segment considered	m
$\boldsymbol{T}$	Air temperature	$°C$
$\boldsymbol{V_0}$	Velocity, freestream	m/s
$\boldsymbol{V_{rel}}$	Velocity, wind relative	m/s
$(\boldsymbol{X_e}, \boldsymbol{Y_e}, \boldsymbol{Z_e})$	Observer coordinates at the far field (retarded coordinate system)	m
$(\boldsymbol{X_B}, \boldsymbol{Y_B}, \boldsymbol{Z_B})$	Blade Coordinate System	m
$(\boldsymbol{X_{RT}}, \boldsymbol{Y_{RT}}, \boldsymbol{Z_{RT}})$	Rotated Trailing-Edge Coordinate System	m

GREEK LETTERS

Letter	Meaning	Disambiguation, (section)	units
α	Local angle of attack (AOA)		^{0}
β	Twist (angle) of the blade or local segment	Table 3, step 5	^{0}
β	Blade step angle on the azimuthal plane	Table 2	^{0}
δ^*	Boundary Layer Displacement thickness		m
θ_e	Directivity angle. Angle between the observer position and the chordwise airfoil plane, retarded coordination system.		
θ_p	Variable pitch angle of the blade	Table 3, steps 5, 20	^{0}
ϕ	Angle between the plane of rotation and the relative velocity.	Table 3, step 12	^{0}
ϕ	Angle, directivity, between the observer and the edge plane, projected in the plane perpendicular to the edge.	See Fig 1	^{0}
$\boldsymbol{\phi_e}$	Angle, directivity, between the observer and the edge plane, projected in the plane perpendicular to the edge, retarded coordinate system.	See Fig 1	
ω	Frequency, angular or rotational speed		$1/s$

1. Introduction

Since most airfoil self-noise prediction methods based on semi-empirical or simplified theoretical models are applicable to an airfoil section interacting with the flow, their application to a WT rotor must follow a procedure generally referred to as a *quasi-3D* method. This procedure has been applied, with some variations, in many researches (Glegg, 1987), (Brooks, Pope, & Marcolini, 1989), (Moriarty & Migliore, 2003), (Fuglsang & Bak, 2004), (Zhu, 2004), (Vargas, 2008), and (Kamruzzaman, Lutz, Nübler, & Krämer, 2011), among others.

In the current implementation scheme, the quasi-3D extension envisioned for the PNoise code (Saab Jr & Pimenta, Displacement Thickness Evaluation for BPM-Type Airfoil-TE Noise Prediction Model, 2015), (Saab Jr J. Y., Trailing-Edge Noise – Development and Application of a Noise Prediction Tool for the Assessment and design of Wind Turbine Airfoils, 2016), (Saab Jr & Pimenta, 2016), (Saab Jr., et al., 2016), (Saab Jr & Pimenta, Verification and Validation of the "PNoise" Airfoil Trailing-Edge Noise Prediction Module inside "QBlade"., 2017), (Saab Jr J. Y., Pimenta, Faria, & Rodriguez, 2018) intends to offer the user, whether a WT manufacturing enterprise or a researcher, with a unique set of features:

- Overall and spectral sound pressure level quick estimates, suitable for comparison and refinement of design.
- Flexibility for any airfoil, blade and rotor geometry.
- Flexibility for flow conditions specification and calculation, within noise models validity range.
- Flexibility on the source of the vertical turbulent scale to be employed in some of the noise models.
- Selection of airfoils self-noise sources to be modeled.
- Inflow noise source selection.
- A table for warning the user on all model validity limitations.
- User-defined number of blade segments and blade azimuthal positions for the quasi-3D noise estimation.
- Arbitrary, user-defined observer position at the farfield (for rotor noise estimation).
- Open-source, free software download, under GPL.

2. Methodology Overview

In the quasi-3D procedure, the generic steps listed on Table 1 are followed.

Table 1 – The steps of a generic quasi-3D noise calculation procedure for wind turbine rotors.

Step	*Description*
1	The blade is divided into N_S spanwise segments.
2	By determining iteratively, the axial and radial induction factors with the aid of a Blade Element Momentum (BEM) method (Hansen, 2008) the relative speed, Reynolds number, Mach number and AOA are calculated. The tip correction method and other corrections elected are applied.
3	One TBL 2-D calculation process (e.g. TBL-FP correlation, XFOIL, CFD, Experiment) provides the data necessary to calculate the source parameters of the model.

4	The TE source spectrum in 1/3 octave bands is obtained for each radial blade segment, at a fixed observer position with respect to the blade segment (i.e. an observer rotating with the blade and positioned at $(\theta = 90°, \phi = 90°)$, according to the reference frame of Figure 1.
5	A more physical situation of a rotating blade but with the observer fixed relative to the ground is then introduced with the aid of a coordinate systems transformation and use of a directivity function.
6	The total spectrum and OASPL can then be calculated from the logarithmic sum of all contributions at the observer position, fixed relative to the ground.
7	Propagation models may or may not be employed to the farfield

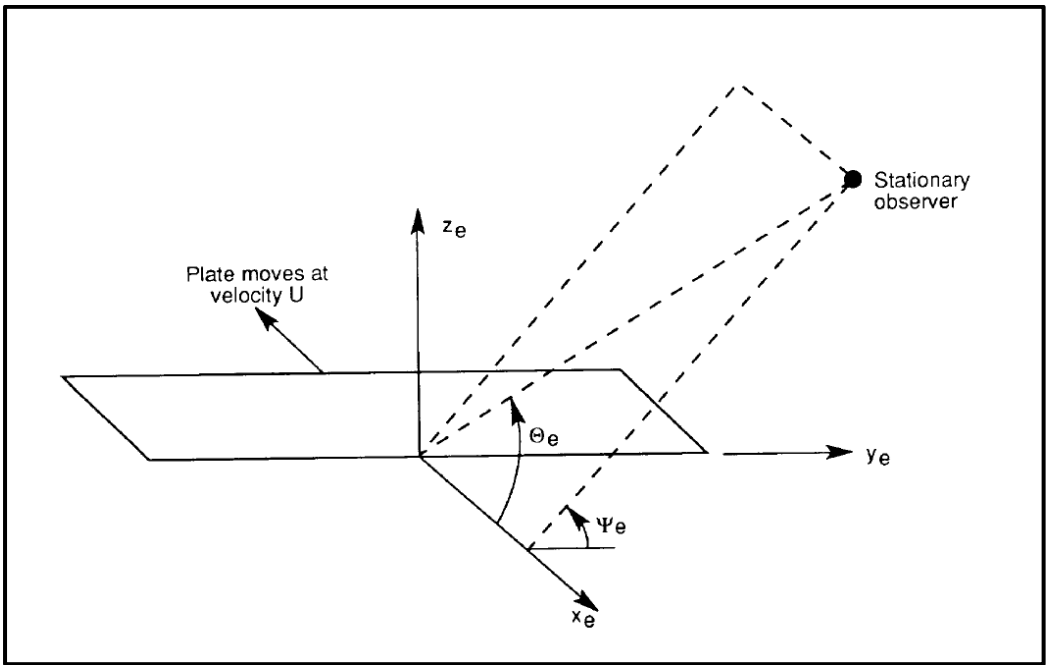


Figure 1 - The 3D retarded coordinate system with origin at the TE of a thin plate representing the airfoil moving in rectilinear motion of velocity U in negative x_e axis direction. $\Theta \rightarrow \theta$; $\Psi \rightarrow \phi$. Source: (Brooks, Pope, & Marcolini, 1989)

In section 3, the most important definitions for the PNoise quasi-3D extension are briefly discussed. In section 4 the specific flow diagram developed for the blade noise prediction method only is presented.

3. PNoise quasi-3D Method definitions

Noise calculation for a wide range of wind speeds, rotational speeds and pitch angles does not seem practical. A combination of 10 values for each of those parameters would result in a thousand different flow and geometry input combinations for analysis. Now suppose each blade of a 3-blade rotor would be split in 50 sections for the BEM calculations and each noise source would be calculated for each blade segment, for 8 different angular positions along the azimuthal plane and for 33 center frequencies. If only the TE noise model is selected for the calculation (which comprises 3 different sub sources as in the BPM model (Brooks, Pope, & Marcolini, 1989)), the algorithm would produce almost 12 million noise contributions, from a single source, to be log-summed at the observer location! Apart from complexity and output screen and file clutter, the computation time would become impractical for the purpose of preliminary design analysis.

This simple exercise suggests that the noise calculation for a specific wind condition and one (at a time) tip speed ratio (TSR) selected by the user would be more plausible, at first. This section discusses the minimum number of noise sources, i.e., blade segments and blade angular positions along the azimuthal plane necessary to render OASPL and noise spectrum representative at the observer position in the farfield.

3.1 Number of blade segments.

The blade discretization is accomplished in spanwise segments with specific chord length, twist angle and airfoil geometry, all considered in the calculations of the PNoise quasi-3D extension.
The discretization step is considered by some authors (Kamruzzaman, Lutz, Nübler, & Krämer, 2011) to be the most sensitive and difficult part to adjust in a quasi-3D extension of a blade noise method.
Glegg (Glegg, 1987), employed 5 radial positions, for each blade, in his application of the method, while Zhu (Zhu, 2004) employed 8 segments for the blades, like Kamruzzaman et al. (Kamruzzaman, Lutz, Nübler, & Krämer, 2011).
However, Vargas (Vargas, 2008) accomplished a sensitivity study (see Table 2) that indicates 13 segments for each blade as a number below which SPL variation is still significant at the farfield. Thus, in the PNoise quasi-3D method, the user is warned if less than 13 segments are adopted for the blade discretization process. As the QBlade embedded BEM method uses 40 blade segments as a default minimum, for high precision, the user might select the same discretization number used in the BEM method, in order to avoid a second discretization/interpolation process with associated error propagation.

3.2 Number of azimuthal positions for each blade.

For practical application purposes, Glegg (Glegg, 1987) suggested the average of 20 azimuthal angles for each blade, in the application of the quasi-3D method. However, Vargas (Vargas, 2008) also accomplished a sensitivity study on the number of optimal positions of the blade in the azimuthal plane N_β, versus the OASPL predicted. For this purpose, the blade was split in $N_S = 13$ segments and the frequency spectrum was divided in $N_f = 29$ centre frequencies. The sensitivity analysis result is displayed in Table 2. It shows that OASPL evaluation for more than 8 blade positions (equivalent to a step of 45°) on the azimuthal plane is not necessary. Also, Vargas found that this number of positions also kept the calculation time very low.
For this reason, the default number of steps for each blade along the azimuthal plane is kept in 8 for the current model.

Table 2 - Sensitivity studies of $\boldsymbol{SPL_W}$ (A-Weighted SPL) as a function of the number of positions of the blade in the azimuthal plane. The total number of computed pressure values is $\boldsymbol{N_p = N_\beta \cdot N_S \cdot N_f}$. Source: (Vargas, 2008).

β step (°):	360	320	250	130	80	60	45	20	1
N_β:	1	2	2	3	5	6	8	18	360
N_p:	377	754	754	1131	1885	2262	3016	6786	135720
processing time (s):	0	0	0	0	1	1	1	3	59
SPL_W (dBA):	94.31	93.82	94.72	98.43	97.93	98.30	98.29	98.30	98.29

3.3 Definition of the reference system.

After analyzing the reference systems adopted by some authors (Zhu, 2004), (Broux, 2008), (Vargas, 2008), it was considered that all adopted coordinate systems had aspects that could be improved upon. After further conference with some Industry experts in the field[1] a decision was made to adapt the local reference frames suggested in the German Guideline for Certification of Wind Turbines, (Germanisher Lloyd and German Wind Energy Committee, 2010).

In the selected base-system, the WT geometry representation is simplified by the absence of rotor axis tilt and cone angles, but the main advantage of this system is that the blade and chord coordinate frames have one axis aligned with the pitch axis of the blade, while for the other frames studied some unusual spanwise axis were adopted, passing through “the middle of the blade” or “the middle of the chord”, for instance, which are neither precisely described nor relevant geometrical points for calculations.

However, the improvement of the representation obtained by taking the pitch axis as part of reference system also brings about another simplifying assumption, i.e., the pitch axis is assumed to intersect the chord line of all sections at 25% of its length, from the TE. With this assumption it is the authors´ goal to make the pitch axis intersect the thickest section of each airfoil (or close to it), the region where the center of pressure and structural spar should be preferably located and often the axis through which different airfoil sections are stacked in order to assemble a blade.

The set of reference systems adopted do not affect the aerodynamic or structural routines of QBlade (Pechlivanoglou, Marten, G., N., & Wendler, 2009), (Marten D. , Extension of an Aerodynamic Simulator for Wind Turbine Blade Design and Performance Analysis, 2010), (Marten D. , Qblade Short Manual V0.8, 2014), (Marten D. , 2016).

For the quasi-3D rotor noise prediction calculation, five reference frames were adopted, among inertial and non-inertial systems. For details on all the reference systems and final coordinate transformation matrix, please refer to (Saab Jr J. Y., Trailing-Edge Noise – Development and Application of a Noise Prediction Tool for the Assessment and design of Wind Turbine Airfoils, 2016).

4. The resulting implementation plans.

Figure 2 displays one of the flow diagrams developed for integration of the PNoise quasi-3D code into the QBlade code, more specifically the flow diagram for the estimation of the full-blade noise, with the observer in a solidary, rotational movement at constant specified distance and directivity angles from the TE mid-point.

[1] Dr. George Pechlivanoglou, from SmartBlade and Dr. Erik Sloth, from Vestas Wind Systems.

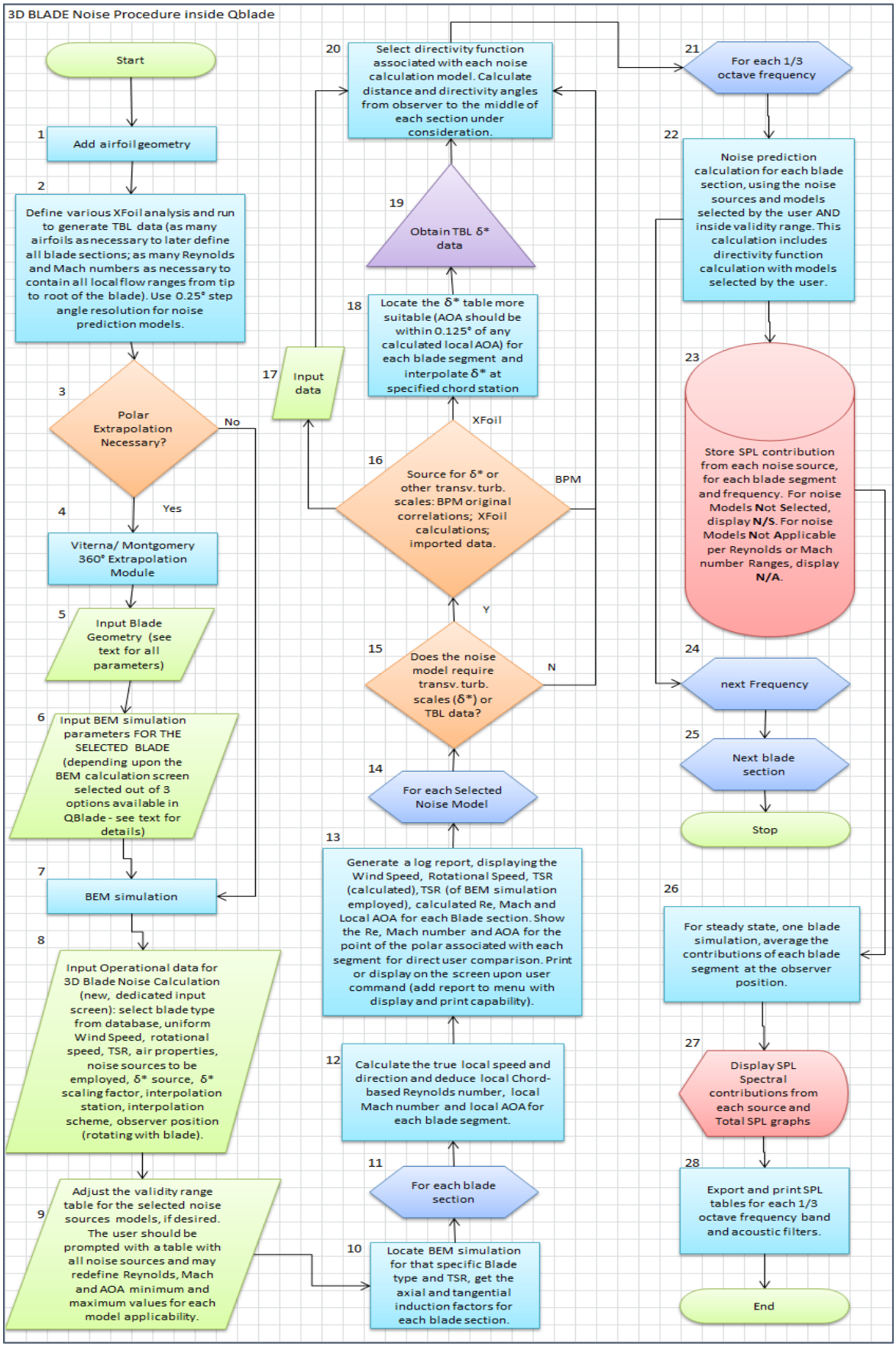


Figure 2 – Flow diagram for the PNoise quasi-3D extension for a single, full blade noise calculation.

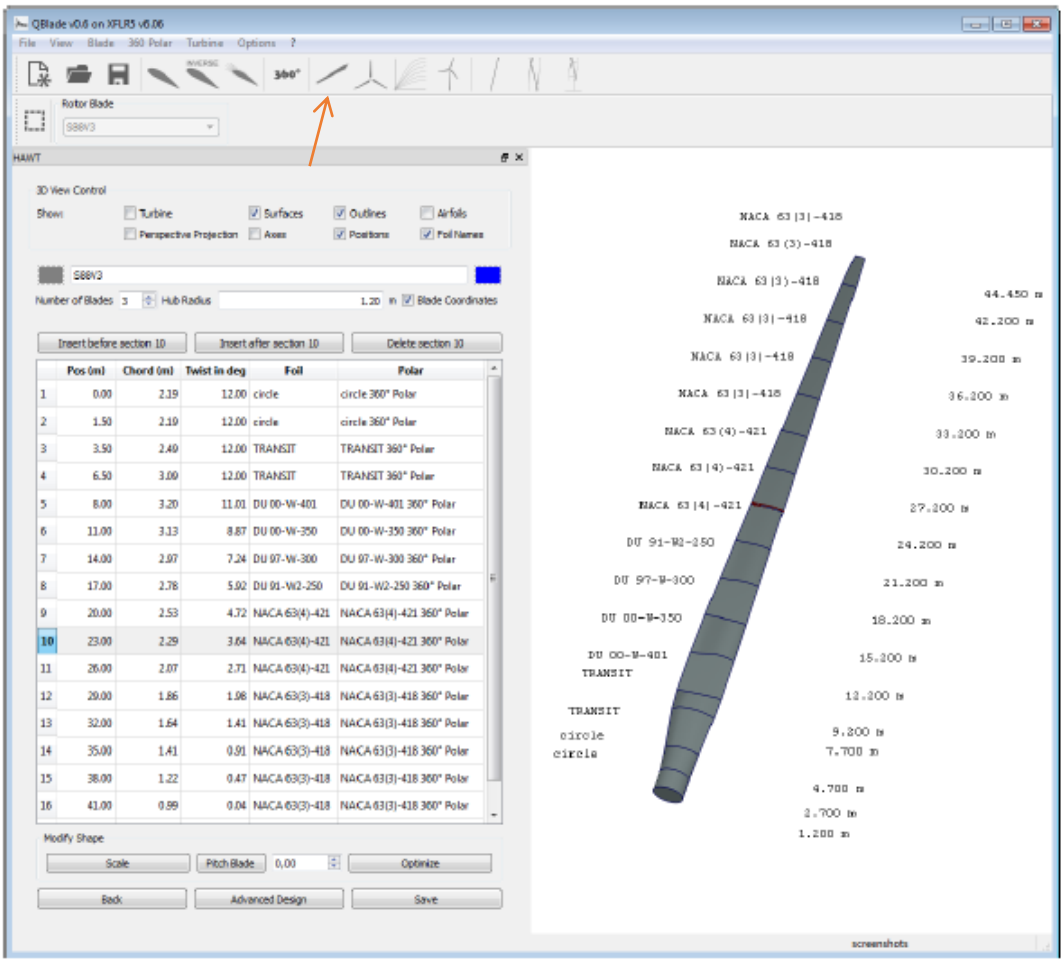
4.1 Step by step description of the calculation procedure.

The description in Table 3 follows the same flow-chart element numbers shown in Figure 2.

Table 3 – Step by step description of the quasi 3D blade noise estimation procedure in PNoise code.

STEP	DESCRIPTION
1	• Airfoil geometry imported into XFoil/XFLR5 (Drela, X-FOIL, 2000), (Drela, Youngren, & Deperrois, XFOIL/XFLR5, 2009) module. All the airfoils to be employed later in the blade definition screen must be either generated or imported at this time.
2	• XFoil analysis for all airfoils to be employed in the blade construction shall be defined and run for Reynolds, Mach and AOA ranges that may occur during the blade operation. The outputs are necessary in the form of Polar Objects (for BEM method calculations) and D* tables (for noise calculations). One Polar Object shall be associated with each blade section later in the blade geometry definition routine.
3	• As of the development of this code, there is no noise model (TE or other source) applicable to angles of attack beyond stall, although there has been steady progress toward it (Bertagnolio, Madsen, Fischer, & Bak, 2015). However, WT blades are subject to this kind of flow during transient operation. Since there are some ongoing efforts pursuing modeling of the noise beyond the stall, there should be provisions for the Polar object calculated by the XFoil to be replaced by the 360° Polar object calculated by the QBlade 360° Polar module, which employs either the Viterna (Viterna & Janetzke, 1982) or Montgomery (Montgomerie, 2004) models.
4	• 360° Polar generation, if necessary, as a substitute for the XFoil polar.

5	• Input blade geometry @ HAWT ROTORBLADE DESIGN Module:
	  ○ Rotor name.
	  ○ Number of blades, *nb.*
	  ○ Hub diameter (m) (divide by 2 to obtain HR, Hub radius).
	  ○ Index number for each segment, *i.*
	  ○ Outer Radius for each segment (m), r_o.
	  ○ Inner Radius for each segment (m), r_i.
	  ○ Chord (m) for each segment, c_i.
	  ○ Twist angle (β°) for each segment, β_i.
	  ○ Airfoil Object attributed to each segment.
	  ○ Polar Object attributed to each segment.
	  ○ Pitch angle ($\theta_p{}^{\circ}$) for the blade (when entered, will add a constant value to the twist at every segment of the blade).
	
	• When "Blade coordinates" checkbox is checked, the distance to each segment is measured from the blade root, i.e. the reference is at the hub radius (HR) obtained from the hub diameter informed. If it is not checked, the distance to each segment is measured in absolute coordinates, with reference at the hub axis. The finished geometry can be exported in the ".stl" format.
	• In case the user has made use of the blade optimization and/or blade scaling features of the QBlade code, the optimized/scaled blade geometry should replace the original entered geometry for all future calculations, including noise prediction modules.
	• The modifications that can be made to the blade with the Advanced Design menu options are made in the export drawing only and do not affect the BEM calculations. Also, the modifications implemented with this optimization/scaling tool is not the geometrical baseline used by the noise calculation routines.



Screen shot from the (Marten & Wendler, Qblade Guidelines v0.6, 2013) manual.

6

- The next step it to input the BEM information in one of the modules that perform that calculation (Rotor BEM Simulation, Multiparameter BEM Simulation and Turbine BEM simulation).

7

- Calculation of the aerodynamic local features with the aid of the BEM method.

8

In this step, many groups of data are loaded for the 3D steady Blade noise calculation routine:

a) Geometry selection and flow conditions.

- Choose blade type in the database (with pitch angle).
- Wind Speed [m/s]
- Rotational Speed [RPM]
- TSR [ ]

Notice: only two of the 3 last parameters above should be informed, since their calculation is interdependent.

b) Air properties

- Air Density (default = 1.225 kg/m^3)
- Air Dynamic Viscosity (default = 1.78 E-5 Pa.s)

c) Selection/activation of noise sources (both available and planned sources shown).

- Inflow noise
  - Lowson´s model

- Amiet´s model
- Poli-Wind Modified Lowson model

- Self-noise sources
  - BPM TE Noise Model (select all here or individual sub-sources below)
  - Suction side of airfoil (attached flow).
  - Pressure side of airfoil (attached flow).
  - Separated flow on suction side (high Reynolds flow).

  OR
  - TNO-Blake TE Noise Model.

  OR
  - Amiet´s TE Noise Model.

- Separation-Stall Model
  - BPM Separation-Stall Model

- Laminar Boundary Layer Vortex Shedding Noise Model
  - BPM LBL-VS Model

- Tip Vortex Formation Noise Model
  - BPM Tip Vortex formation Model

  Trailing-Edge Bluntness Vortex Shedding Noise
  - BPM TE Bluntness VS Noise Model

d) δ* (displacement thickness) source
- XFoil calculation
- Station for reading or interpolating δ* value (default = 0.98c).
- Original BPM correlations
- Import data
- δ* scaling factor (default = 1)
- Eddy Convection velocity as a fraction of the Mach number (default = 0.8*M)

e) Select directivity functions to be employed.

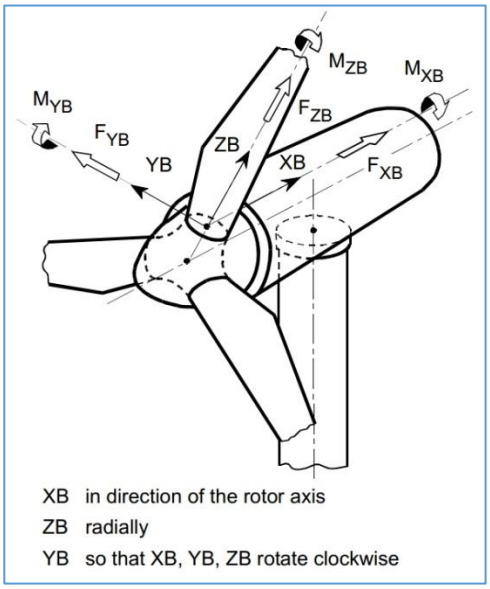
- Same options for high and low frequency sources of the 2D input screen apply here.

f) Define the observer position.

- In this option (single blade noise calculation routine), the observer rotates with the blade, at the fixed distance and angles specified by the user, the angular speed will be the same for the blade and the observer, both in non-inertial frames. The observer position should be determined in relation to the Blade Coordinate System (Germanisher Lloyd and German Wind Energy Committee, 2010). Its origin is at the Blade root (at hub radius) and rotates with the rotor. Its orientation to the hub is fixed. X_B in direction of rotor axis; Z_B radially; Y_B is set so that the system rotates clockwise:

  - X_B = +10 [m] (default)
  - Y_B = +10 [m] (default)
  - Z_B = blade radius/2 [m] (default value)

- The default position is 10 m downstream of the rotor plane, 10 m downstream of the blade in the rotation plane and in the mid-span of the blade. The following figure is provided in the input menu in order to help the user define the observer location:



- The following warning notice is to be included in the code and displayed for the user at this screen: "Notice: The BPM directivity expression for High Frequency noise is not suitable for shallow angles ($\Theta \rightarrow 180°$). For details, see page 105 of (BPM, 1989)."

9

- Display for acceptance or adjustment, the table with validity range known for each selected noise source models. If the informed limits are deleted, the models will be applied regardless of validity. If the user inputs new validity ranges based in his/her experience, the values are stored and displayed as future default values, unless the INITIAL SYSTEM DEFAULT VALUES box is checked. For each noise source and model combination, the user will be able to set upper and lower limits for Reynolds Number, Mach Number and Angle of attack.

10

- For blade segments 1 to n, locate the BEM simulation results associated with the selected blade, for the same or closer TSR for which calculation is available. Save the Calculated TSR and BEM TSR values on the log.

11

- For blade segments 1 to n (root to tip; n was specified in the Blade input screen):

12

- Obtain the axial (a') and tangential (a) induction factors for each blade segment.
- Calculate the local tangential and local axial speed for the middle of each blade segment, employing the following relations:

$$tangential\ speed = \omega . r(1 + a')$$

Where:

$\omega = 2.\pi.\frac{n}{60}\ (\frac{rad}{s})$, where

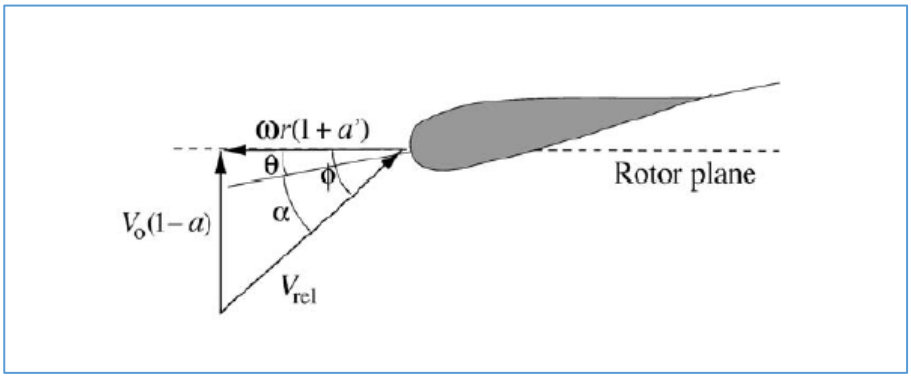
n=rotational speed in rpm
r = radius of the segment mid-section, from the rotation axis (if absolute coordinates are in use) or from the hub radius (if root coordinates are in use), in meters.

$$axial\ speed = V_0.(1 - a)$$

Where:

$V_0 = wind\ speed\ (\frac{m}{s})$.

- Obtain the relative wind speed direction, ϕ, experienced by the rotating blade segment:



- Obtain the local blade AOA, α, by subtracting from the angle φ, the twist angle for that section:

$$\alpha = \phi - \theta$$

- Calculate the local Reynolds and Mach numbers, based on the relative wind speed $V_{rel.}$ and air properties supplied in the selected BEM module input:

Local Reynolds number = Air Density [kg/m^3] * Vrel [m/s] * Chord at mid span of the segment [m] / Air Dynamic Viscosity [Pa.s]

Local Mach number = Vrel [m/s]/ SQRT (1.4*286.9* (T+273.15)),

Where T = atmospheric air temperature, [˚C]. Default = 15 ˚C

13 Generate a log report, displaying:

- Calculated x used TSR data for the blade.

For each blade segment:

- Calculated x Re number data on the Polar Object associated with that blade segment.
- Calculated x used Mach number data on the Polar Object associated with that blade segment.
- Calculated local AOA x closer AOA angle available in the Polar Object associated with that blade segment.

The log is to be printed or displayed onscreen depending upon user selection on the menu (add report to menu with display and print capability).

14
- For each Selected Noise Model:

15
- Check if the noise model requires transversal turbulence length scales (δ*) or other Turbulent Boundary Layer data.

16
- Check user source option for δ* or other transversal turbulence length scales: BPM original correlations; XFoil calculations; imported data.

17
- Input data (in .csv format), if applicable.

18
- If the information is to be provided by the XFoil TBL calculation, locate the δ* table more suitable (AOA should be within 0.125° of any calculated local AOA) for each blade segment….

19 ….and interpolate δ* at the chord-station specified by the user (or default station of 0.98C, if not specified). Interpolate δ* data for one or both airfoil sides (pressure and suction sides), depending upon TE noise source selection in the input dialog.

20
- Locate the directivity function associated with each noise calculation model selected.

- Calculate distance and directivity angles from observer to the mid-span of the segment under consideration using the reference frame transformation matrices provided (different set for 3D blade and 3D rotor calculations).
- Save information for the noise calculation routine.
- Store the Mach and Reynolds information for the calculation.
- If original BPM correlation is to be employed, identification of the closest polar is not necessary.
- Get the δ* data for each applicable airfoil side.
- Transform the observer position in relation to all intermediate reference systems, until the observer position is obtained in relation to the TE Coordinate System and obtain the values for the BPM coordinates (r, θ, ϕ)

  - Input X_e , Y_e, Z_e
  - Attribute their respective values to X_B , Y_B, Z_B
  - For the blade, get the Pitch angle, θ_p
  - For each blade segment, get: $c_{r_{i+1}}, c_{r_i}, r_{i+1}, r_i, \beta$
  - Calculate $angle\ a, angle\ b, Z_B - (r_{i+1} - r_i)/2$
  - Calculate $\begin{bmatrix} X_{RS} \\ Y_{RS} \\ Z_{RS} \end{bmatrix}$
  - Calculate $Y_{RS} - 0.75 * (c_{r_{i+1}} - c_{r_i})/2$
  - Calculate $\begin{bmatrix} X_{RT} \\ Y_{RT} \\ Z_{RT} \end{bmatrix}$
  - Calculate (r_e, θ_e, ϕ_e)

  The whole process may be summarized in the following matrix operations:

$$\begin{bmatrix} X_{RT} \\ Y_{RT} \\ Z_{RT} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos b & \sin b \\ 0 & -sin\ b & \cos b \end{bmatrix} \cdot \begin{bmatrix} X_{RS} \\ Y_{RS} - 0.75 * (c_{r_{i+1}} - c_{r_i})/2 \\ Z_{RS} \end{bmatrix}$$

$$\begin{bmatrix} X_{RS} \\ Y_{RS} \\ Z_{RS} \end{bmatrix} = \begin{bmatrix} \cos a & sin\ a & 0 \\ -sin\ a & \cos a & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} X_B \\ Y_B \\ Z_B - (r_{i+1} - r_i)/2 \end{bmatrix}$$

Where,

the angle *a* is the total angle between the Y_BZ_B blade reference system plane and the local midsection chord line. If the Y_BZ_B plane is set equal to the rotation plane, then the angle *a* is the equivalent to the θ angle in QBlade manual (Marten D. , Qblade Short Manual V0.8, 2014), p.34:

$$\theta = \theta_p + \beta$$

θ_p = pitch angle; β = the local twist angle.

$$b = \text{atan}\left(\frac{c_{r_{i+1}} - c_{r_i}}{r_{i+1} - r_i}\right)$$

$$r_e \equiv r_{RT} = \sqrt{X_{RT}^2 + Y_{RT}^2 + Z_{RT}^2}$$

$$\theta_e = \pm\,\text{atan}\left(\frac{Z_{RT}}{Y_{RT}}\right)$$

$$\phi_e = \pm\,\text{atan}\left(\frac{X_{RT}}{Z_{RT}}\right)$$

21

- For each 1/3 octave frequency, using δ* information interpolated from XFoil or from original BPM correlations, or read from file, as selected by the user.

22	• Call the noise prediction calculation routine for each blade segment, for each noise source selected by the user AND inside validity range. This calculation includes directivity function calculation with models associated with each source.
23	• Store SPL contribution from each noise source, for each blade segment and frequency. For noise Models **N**ot **S**elected, display **N/S**. For noise Models **N**ot **A**pplicable per Reynolds, Mach number or AOA Ranges, display **N/A**.
24	• Next Frequency.
25	• Next blade Section.
26	• Since this is a steady-state, one blade simulation, average the contributions of each blade segment at the observer position. For *n* blade segments, calculate the average SPL as follows: $$SPL_{Blade_Total} = 10.log\left(\frac{1}{n}\left(\sum_{i=1}^{n} 10^{SPL_i/10}\right)\right)$$
27	• Display SPL Spectral contributions from each source and Total SPL graphs (output analog to the existing 2D noise module).
28	• Export and print SPL tables for each 1/3 octave frequency band, per source, and acoustic filters (A, B, C), as selected by the user on the menu.

5. Conclusions

A quasi-3D method was devised for rotor and blade noise prediction and the latter is described in detail in this paper. The method is intended to extend the current PNoise 2D TE noise prediction capabilities inside QBlade, due to significant user acceptance of that open-source, GPL code. The method is not new in essence, but combines the best practices recommended by many authors for various parameters with a more straightforward coordinate system and is optimized for the environment, the main goal of which is delivering a quick turn-around-time user experience for the preliminary, relative noise performance evaluation at the early design phase of WT equipment. Although conceived for preliminary design, the tool is also formal in a sense that it communicates clearly all model validity conditions and generate a detailed log of all calculations accomplished. The 3D extension was designed to draw as much synergy as possible from existing and tested features, like the boundary-layer code, the BEM code and 2D noise method previously implemented in QBlade or PNoise. The implementation and validation will be the objects of a future report, since coding is undergoing progress and a new model for inflow noise will be also included (Faria, Pimenta, Saab Jr, & Rodriguez, 2018), which is receiving the final analysis. The implementation has provisions for other noise sources (both in the 2D and 3D algorithms) and it is the authors' intent to add a complete menu of self-noise and inflow noise prediction sources and models to the QBlade platform, in order to complement its already comprehensive aerodynamic, structural and aeroelastic features.

References

Bertagnolio, F., Madsen, H. A., Fischer, A., & Bak, C. (2015). Experimental characterization of stall noise toward its modelling. *Wind Turbine Noise 2015* (pp. 1-12). Glasgow: INCE Europe.

Brooks, T. F., Pope, S., & Marcolini, M. A. (1989). *Airfoil Self-Noise and Prediction.* NASA. Langley: NASA.

Broux, F. (2008). *3D Extension of Wind Turbine Noise Prediction Tool IAGNOISE.* Stuttgart: IAG.

Drela, M. (2000). X-FOIL. http://web.mit.edu/drela/Public/web/xfoil/: MIT.

Drela, M., Youngren, H., & Deperrois, A. (2009). *XFOIL/XFLR5.* MIT, Cambridge, Ma.

Faria, A., Pimenta, M. M., Saab Jr, J. Y., & Rodriguez, S. (2018). Selection for a Leading-Edge Noise Model for PNoise. *Terceiro Congresso de Engenharia e Ciências das Três Fronteiras*, (pp. 1-15). Foz do Iguaçu, BR.

Fuglsang, P., & Bak, C. (2004). *Development of the Risø Wind Turbine Airfoils.* Risø, Roskilde.

Germanisher Lloyd and German Wind Energy Committee. (2010). *Guideline for the Certification of Wind Turbines.* Hamburg: Germanisher Lloyd.

Glegg, S. (1987, June). Significance of Unsteady Thickness Noise Sources. *AIAA Journal V. 25 (6)*, pp. 839-844.

Hansen, M. (2008). *Aerodynamics of Wind Turbines* (Second Edition ed.). London: Earthscan.

Kamruzzaman, M., Lutz, T., Nübler, K., & Krämer, E. (2011). Implementation and Verification of an Aeroacoustc Wind Turbine Blade Analysis Tool. *WTN 2011 Proceedings* (pp. 1-16). Rome: INCE Europe.

Marten, D. (2010). *Extension of an Aerodynamic Simulator for Wind Turbine Blade Design and Performance Analysis.* Technischen Universität Berlin. Berlin: TU Berlin.

Marten, D. (2014). *Qblade Short Manual V0.8.* Berlin: TU Berlin.

Marten, D. (2016). *QBlade v0.95 - Guidelines for Lifting Line Free Vortex Wake Simulations.* Berlin: TU Berlin.

Marten, D., & Wendler, J. (2013). *Qblade Guidelines v0.6.* Berlin: TU Berlin.

Montgomerie, B. (2004). *Methods for Root Effects, Tip Effects and Extending the Angle of Attack to 360 degrees with Application to Aerodynamics for Blades on Wind Turbines and Propellers.* Kista: Swedish Defense Research Agency Scientific Report FOI R 1305 SE.

Moriarty, P., & Migliore, P. (2003). *Semi-Empirical Aeroacoustic Noise Prediction Code for Wind Turbines.* NREL, Golden, CO.

Pechlivanoglou, G., Marten, D., G., W., N., M., & Wendler, J. (2009). *QBlade.* Technische Universität Berlin, Berlin.

Saab Jr, J. Y. (2016). *Trailing-Edge Noise – Development and Application of a Noise Prediction Tool for the Assessment and design of Wind Turbine Airfoils.* Retrieved 07 19, 2017, from USP Digital Library - Thesis and Dissertations: http://www.teses.usp.br/teses/disponiveis/3/3150/tde-14032017-140101/pt-br.php

Saab Jr, J. Y., & Pimenta, M. M. (2015). Displacement Thickness Evaluation for BPM-Type Airfoil-TE Noise Prediction Model. *6th International Conference on Wind Turbine Noise* (pp. 1-15). Glasgow: INCE Europe.

Saab Jr, J. Y., & Pimenta, M. M. (2017). Verification and Validation of the “PNoise” Airfoil Trailing-Edge Noise Prediction Module inside “QBlade”. *7th International Conference on Wind Turbine Noise* (pp. 1-11). Rotterdam: INCE Europe.

Saab Jr, J. Y., Pimenta, M. M., Faria, A. M., & Rodriguez, S. (2018, Sept 28). Determination of local fow conditions and preliminary investigation on the validity of the PNoise code for large-size wind turbine. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, pp. 493-504.

Saab Jr, J., & Pimenta, M. (2016, Feb). 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.

Saab Jr., J. Y., Pimenta, M. M., Piqueira, J. R., Marten, D., Pechlivanoglou, G., Nayeri, C. N., & Paschereit, C. O. (2016). *Verification and Validation of the Airfoil Trailing-Edge Noise Prediction Module (PNoise) inside QBlade v0.95.* São Paulo: POLI-USP.

Vargas, L. d. (2008). *Wind Turbine Noise Prediction.* Instituto Superior Técnico, Lisboa.

Viterna, L. A., & Janetzke, D. C. (1982). *Theoretical and Experimental Power From Large Horizontal-Axis Wind Turbines.* Cleveland, OH: NASA Lewis Research Center Technical Report TM-82944.

Zhu, W. (2004). *Modelling of Noise From Wind Turbines.* DTU, Lyngby, DK.