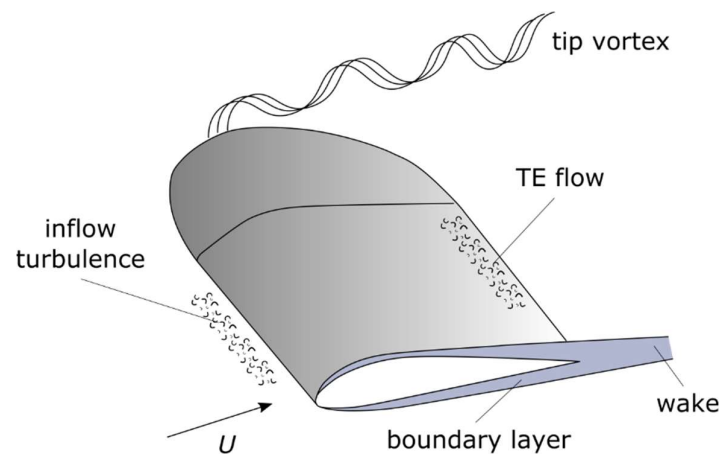


# Verification and Validation of the Airfoil Trailing-Edge Noise Prediction Module (PNoise) inside QBlade V0.95



Poli-USP - TU-Berlin Collaboration



**POLI USP**

**Technische  
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## 1 Introduction

The airfoil TE noise module *PNoise* was developed under a Poli-USP and TU-Berlin collaboration project.

The TE noise module is based on a modified BPM TE noise model (Brooks, et al., 1989) with turbulent boundary layer data provided by XFLR5 (Drela, et al., 2009), both integrated inside the unique wind-turbine-design, graphical interface and user-friendly environment provided by the QBlade software (Pechlivanoglou, et al., 2009), (Marten, 2010), (Marten & Wendler, 2013), (Marten, 2014).

Other self-noise sources as well as inflow noise models will be added in the future as part of the collaboration scope. Also a “quasi-3D rotor” noise prediction tool is planned.

The 2D TE noise module was developed and integrated in an alpha version into QBlade V0.8, when it was thoroughly verified and validated.

The module was later integrated into the newer QBlade V0.95 for public release. In this re-integration process, some improvements were made to the output graphs and files and also to the internal structure of the code. Despite the effort to keep the calculation routines intact, it was considered necessary once more to verify and validate the new integration prior to public release, which is the purpose of the present text.

This text is not a rigorous technical paper in format nor is it intended to be a detailed manual on the airfoil TE noise module inside QBlade v0.95.

## 2 Definitions

The following definitions were extracted from Oberkampf and Roy (Oberkampf & Roy, 2012) and applied throughout the verification and validation (V&V) procedure:

Prediction: use of a computational model to foretell the state of a physical system under conditions for which the computational model has not been validated.

Code verification: the process of determining that the numerical algorithms are correctly implemented in the computer code and of identifying errors in the software.

Solution verification: the process of determining the correctness of the input data, the numerical accuracy of the solution obtained and the correctness of output data for a particular simulation.

Model validation: quantification of the accuracy of the computational model results by comparing the computed system response quantities of interest with experimentally measured quantities of interest. It becomes a mathematical model validation only if code and solution verification were satisfactorily accomplished.

### 3 Verification and Validation range.

The code and solution verifications were accomplished within the original limitations of the BPM model (Brooks, et al., 1989).

The validation of the results was accomplished against the original BPM experimental spectra provided in the seminal BPM paper (Brooks, et al., 1989).

The use of the model for assessing the TE noise of a generic airfoil geometry at large Reynolds and Mach number flows has become a practical reality with the current integration of the BPM model to the XFLR5 and QBlade functionalities. As defined earlier, the use of model beyond the original validation scope is called a PREDICTION and, by definition, implies that it shall be made at the user own responsibility and risk, particularly in the case of absolute noise value assessment.

For improved performance, when using TBL displacement thickness reading over the TE from a XFLR5 output file, a recommendation is made for the data to be taken at 98% chord station (Saab Jr & Pimenta, 2016) as a *compromise station* among fully turbulent and transition flows, but the number is provided as a default value that may and should be altered at the discretion of the user. The same reasoning applies to the default eddy-convection Mach number ( $0.8 \cdot M$ ) and other default input data, like the observer distance from the source and the directivity angles, for instance.

## 4 Model validity range and scope.

The BPM model (Brooks, et al., 1989) is based on previous experimental work by (Brooks & Hodgson, 1981), (Brooks & Marcolini, 1985), (Brooks & Marcolini, 1986). The experimental cases which provided the database for the 2D TE noise are:

	Reference	Chord-Based Reynolds Number Range	Mach Number Range	AOA ( $\alpha$ )	TU	Type of flow	TE Type
1	(Brooks & Hodgson, 1981)	$9.5 \times 10^5 < Re_C < 2.5 \times 10^6$	$M < 0.19$	$0^\circ, 5^\circ, 10^\circ$	N/A	Tripped	From blunt to sharp variations
2	(Brooks & Marcolini, 1985)	$4.8 \times 10^4 < Re_C < 2.5 \times 10^6$	$M \leq 0.208$	$0^\circ$	$< 0.05\%$	Tripped and untripped	Very Sharp
3	(Brooks & Marcolini, 1986)	$Re_C < 3.0 \times 10^6$	$M \leq 0.208$	Up to $19.8^\circ$	$\sim 0.03\% / < 0.54\%$ Uniform flow / TE	Tripped and untripped	Very Sharp
4	(Brooks, et al., 1989)	$Re_C \leq 1.5 \times 10^6$	$M \leq 0.208$	Up to $19.8^\circ$	Low turbulence	Tripped and untripped	Very Sharp

In the seminal BPM paper (Brooks, et al., 1989), the TE noise model was introduced and validated for turbulent (tripped) flow up to  $Re_C \leq 1.5 \times 10^6$ ,  $M < 0.21$  and  $19.8^\circ$  AOA. All experiments and thus, the resulting model validation, were made for the NACA 0012 airfoil, based on the acoustic spectra measured in this range. For further details, see page 51 of the BPM report.

Also, the BPM authors, in page 99 of their report, state that:

*“For the turbulent-boundary-layer-trailing-edge noise and separation noise sources, an accurate and generally applicable predictive capability is demonstrated, especially for the important conditions of high Reynolds numbers and low to moderate angle of attack”*

*“The unique prediction capability presented should prove useful for the determination of broadband noise for helicopter rotors, wind turbines, airframe noise and other cases where airfoil shapes encounter low-to-moderate speed flow”*

A later NREL validation study for the BPM TE noise model (Moriarty & Migliore, 2003) showed good agreement of the BPM prediction model with data taken from a series of wind tunnel tests performed at the NLR, The Netherlands (Oerlemans, Wind Tunnel Aeroacoustic Tests of Six Airfoils for use in Small Wind Turbines. NREL SR-500-34470). The comparison was made at  $M=0.21$  and AOA ranging from  $0^\circ$  to  $13.1^\circ$ . The agreement was good for frequencies near 3 kHz but for lower frequencies ( $\sim 800$  Hz) the differences found were up to 6 dB. The study did not expand the validation range of the model.

More recently, Doolan and Moreau (Doolan & Moreau, 2013) have plotted SPL spectra as a function of Strouhal number for some experiments, against BPM predictions. For the case of the IAG Wind tunnel data (Herrig & Würz, 2008) at  $Re_C \sim 2.9 \times 10^6$  (graphic (d) of Fig. 3, at

page 6 of D&M), it is shown good agreement with BPM prediction at  $M=0.20$ , for peak Strouhal number and higher frequencies.

By verifying directly the IAG Wind Tunnel Data, on the other hand, it seems that the Reynolds number of the experiments tops at  $Re_c \sim 2.4 \times 10^6$  (see page 2 of (Herrig & Würz, 2008)).

Further attempts on extending the validation of the BPM-based tool integrated into QBlade are being made under the Poli-USP - TU-Berlin collaboration, using the research of (Devenport, et al., 2010) based on data from the Virginia Tech Aeroacoustic Tunnel, and will be published eventually.



## 5 Results

### 5.1 Displacement thickness data writing.

A preliminary modification had to be made to the XFLR5 output routines embedded into the QBlade, in order to save displacement thickness ( $D^*$ ) data along with each OpPoint (polar operational point object). This information was not previously stored, which became necessary since it is employed as the transversal turbulence scale at the TE noise model. It is also employed as a turbulence scale for other self-noise sources that are intended to be implemented in the future.

Table I below shows the results of the displacement thickness calculations made with some versions of the reference and QBlade software for the calculation procedure verification. All calculations are made for the NACA0012 airfoil modified with a sharp trailing edge, 300 panels and TE/LE point density ratio of 0.30, at a Reynolds number of 1,500,000, Mach number of 0.21 and tripping at 15% chord for upper and lower sides:

D* calculation Table					
Version	AOA	# of data points	D* at 1C, Upper	D* at 1C, Lower	symmetry
XFLR5 V6.06	0	188	0.00686	0.00689	acceptable
	10	213	0.02383	0.00297	N/A
	20	220	0.29850	0.00140	
QBlade V0.8	0	188	0.00686	0.00689	acceptable
	10	212	0.02383	0.00297	N/A
	20	220	0.29850	0.00140	
QBlade V0.95 32 bits	0	188	0.00686	0.00689	acceptable
	10	212	0.02383	0.00297	N/A
	20	220	0.29850	0.00140	

**Table I – Calculation procedure verification for the displacement thickness value returned by different codes, measured over the Trailing Edge (1C). N/A = non applicable.**

There are no differences among the values of  $D^*$  for the three versions tested. For a study of the impact of the quality of the  $D^*$  value assessment on a BPM-type TE noise prediction method, see (Saab Jr & Pimenta, 2016).

The path for exporting  $D^*$  calculated data for visual inspection, is:

*Operating Points -> Cp Graph -> Current XFoil Results -> Export Cur. XFoil Results.*

## 5.2 TE noise spectra generation procedure verification and validation.

### 5.2.1 Flow conditions and methodology.

Three different TE noise calculations procedures are provided for in the original BPM model:

- For zero angle-of-attack (AOA).
- For AOA below the switching angle.
- For AOA above the switching angle.

The specific switching angle, for AOA under  $12.5^\circ$ , is calculated as a function of the Mach number and describes the angle above which the noise contribution of the detached flow over the suction side of the airfoil becomes dominant. Below this angle, the attached flow over the pressure and the suction sides plus the unattached flow portion over the suction sides are all considered as contributive sources to the overall noise. For each of the mentioned cases, there are different calculation procedures and different displacement thickness correlations provided along with the original model.

However, since the implementation of the modified-BPM model allowed more flexibility, derived from the use of TBL data extracted from the XFLR5 calculations, the verification and validation process involved analyzing the results of six different situations, displayed in table II:

	NACA0012 Sharp TE airfoil	
	Transversal turbulence scale source	
Flow Angle	BPM correlations	XFLR5 data
Zero AOA	1	4
Below Switching angle	2	5
Above Switching angle	3	6

**Table II – Combinations (cases) of flow data sources and angles of attack for the verification and validation process.**

The calculation procedure verification for all six cases was accomplished against step-by-step calculations carried out in spreadsheets for each one of them. The verification cases requiring XFLR5 output data were run in a non-integrated fashion, with displacement thickness data calculated, exported to file, linearly interpolated to the desired chord station and then inputted in the spreadsheet for the remainder of the BPM calculation.

The verification and validation of the reference spreadsheets themselves was accomplished simultaneously against peak frequency, peak level and roll-off compared to graphical output (TE noise spectra), both experimental and calculated, provided in the original BPM paper (Brooks, et al., 1989).

An important description of the experimental spectra presented in the BPM paper is reproduced below:

*“The self-noise spectra for the 2D NACA 0012 airfoil models with sharp TE are presented in a 1/3-octave format in figures 11 to 74. Figures 11 to 43 are for airfoils*

*where the boundary layers have been tripped and figures 44 to 74 are for smooth surface airfoils where the boundary layers are untripped (natural transition). Each figure contains spectra for a model at a specific angle of attack for various tunnel speeds. Note that the spectra are truncated at upper and lower frequencies. This editing of the spectra was done because, as described in appendix A, a review of the narrow-band amplitude and phase for all cases revealed regions where extraneous noise affected the spectra in a significant way (2 dB or more). These regions were removed from the 1/3-octave presentations.*

*The spectra levels have been corrected for shear-layer diffraction and TE noise directivity effects, as detailed in appendix B. the noise should be that for an observer positioned perpendicular to, and 1.22 m from, the TE and the model midspan. In terms of the directivity definitions of appendix B,  $r_e = 1.22$  m,  $\theta_e = 90^\circ$  and  $\phi_e = 90^\circ$ ." (Brooks, et al., 1989), p. 17.*

Once verified and validated, the worksheets were used to generate detailed individual source contribution at each 1/3-octave frequency, which could be compared to the detailed output of the code.

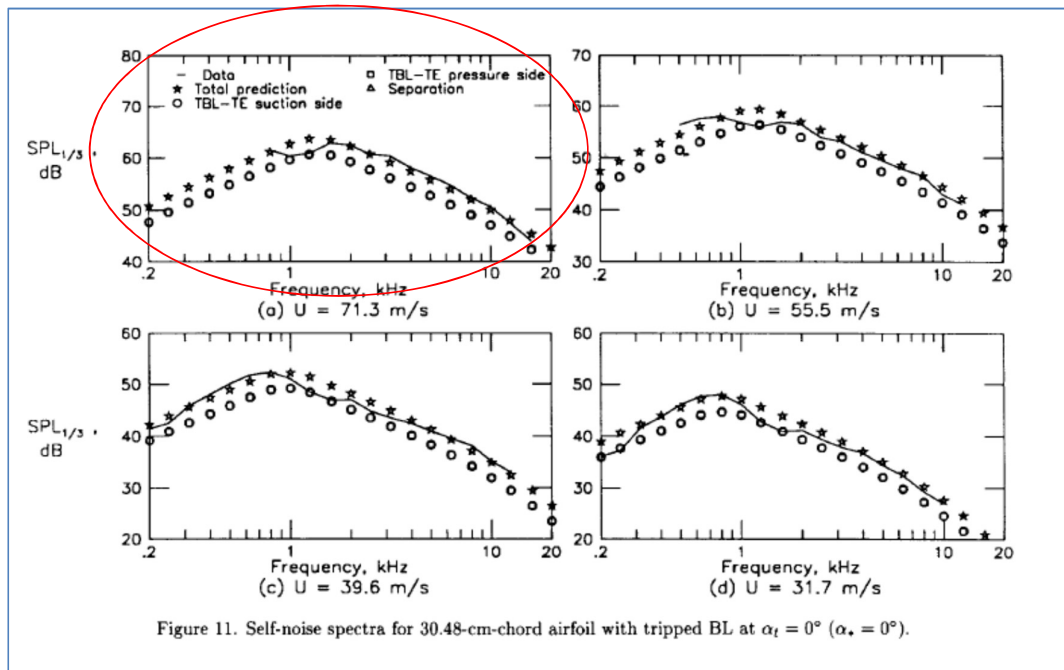
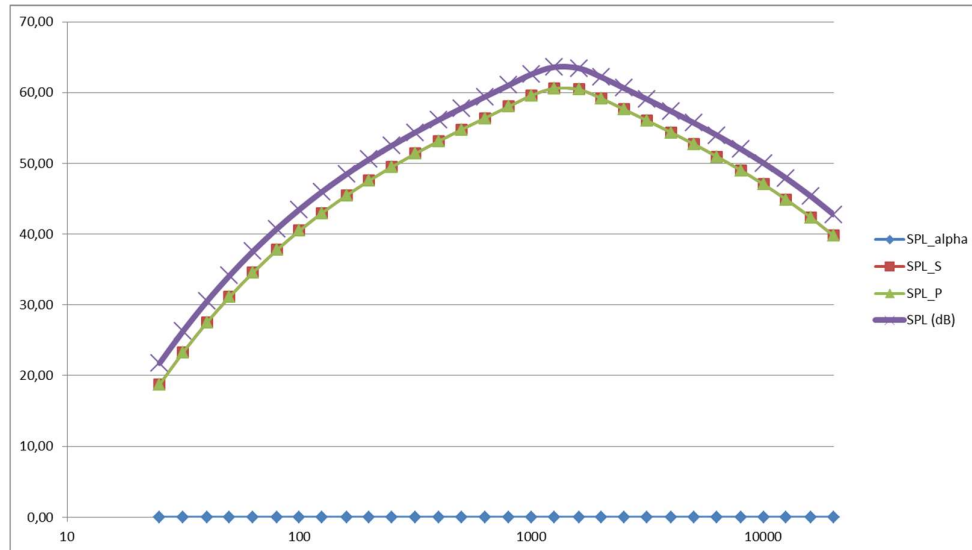
The spreadsheet-generated spectra were calculated and saved for the following key flow angles:

- Zero AOA flow, tripped BL.
- Flow below the switching angle ( $4^\circ$ ), tripped BL.
- Flow above the switching angle ( $17.4^\circ$ ), tripped BL.

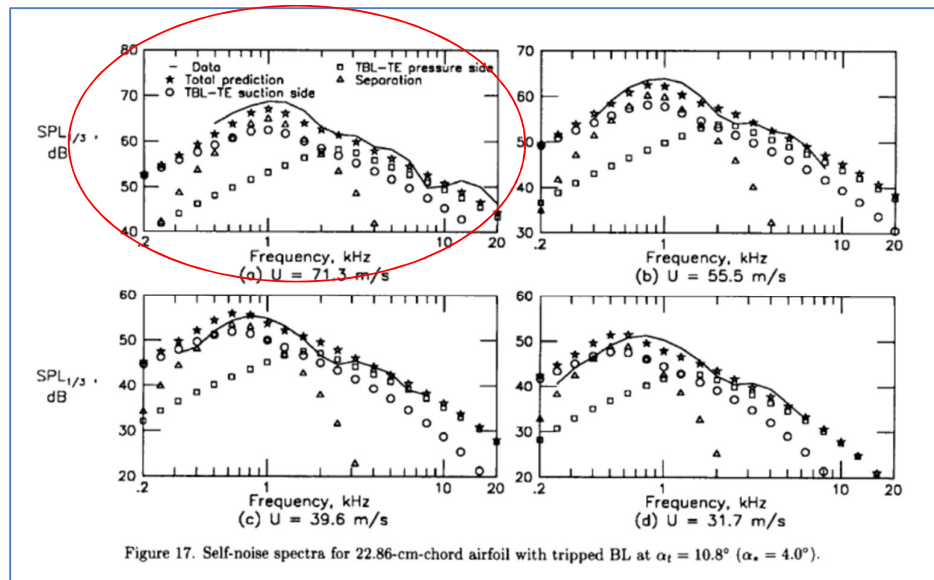
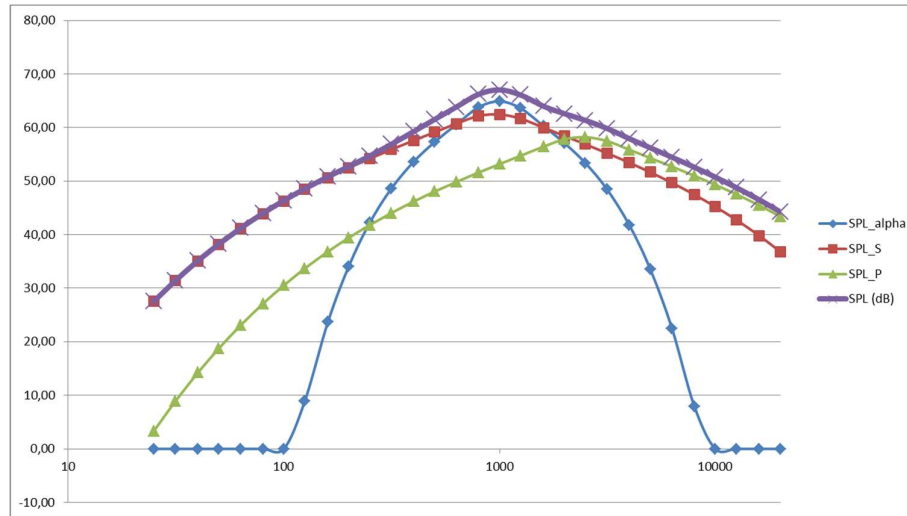
Examples of the spreadsheet-generated output spectra are shown below for 71.3 m/s flow, next to the original experimental measurements and the original BPM model calculations, all in graphical format.

### 5.2.2 Examples of the spreadsheet graphical output compared with original BPM output graphs:

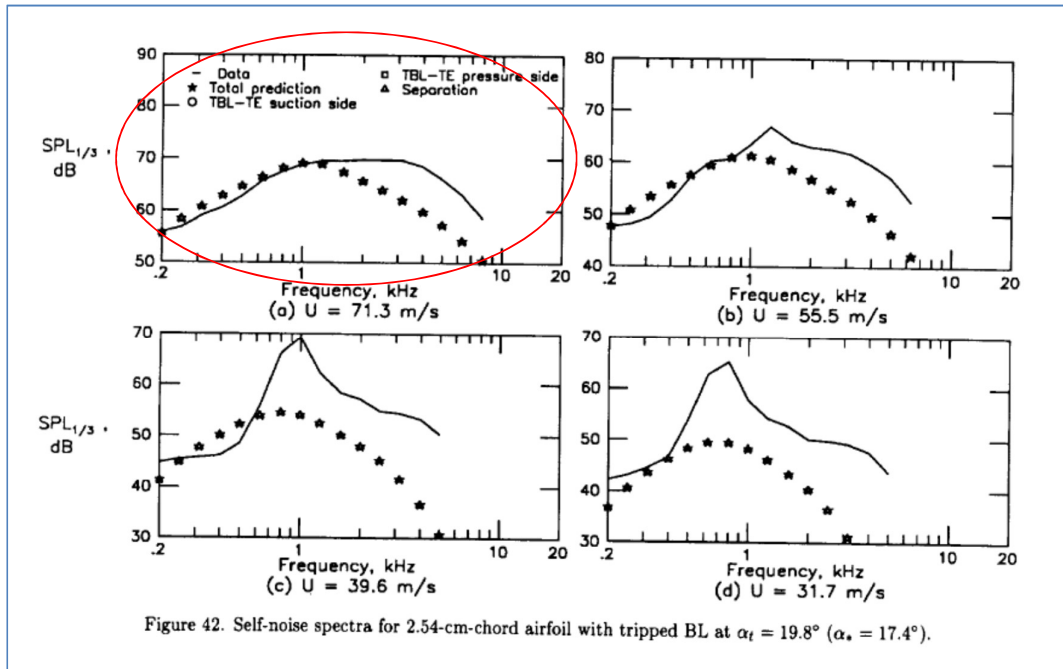
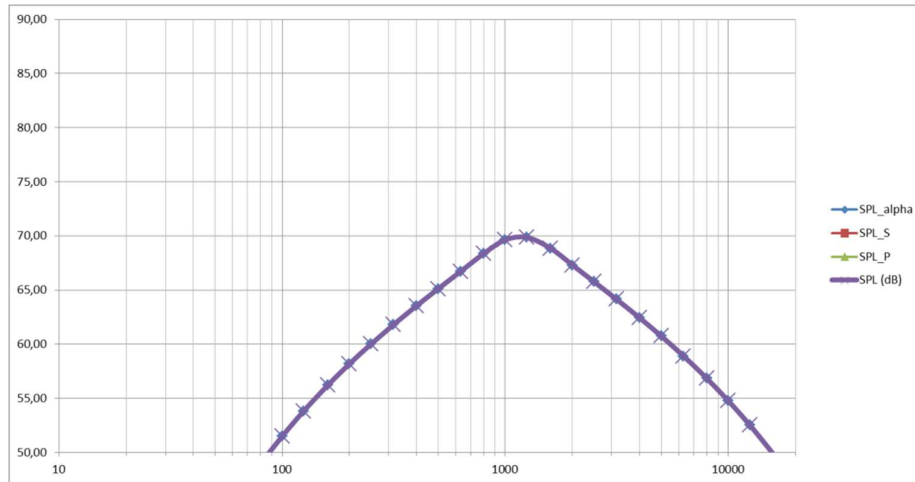
i) For zero AOA flow and same conditions as in figure 11, item (a) of BPM paper:



- ii) For  $\text{AOA}=4^\circ$  (below the switching angle) flow and same conditions as in figure 17, item (a) of BPM paper:



- iii) For  $\text{AOA}=17,4^\circ$  flow (above the switching angle) and same conditions as in figure 42, item (a) of BPM paper:



### 5.2.3 Working Procedure.

In the following pages, the procedure for using the new module will be described along the simulation for generating code verification data. For the 3 original BPM correlation cases considered (flow at zero AOA (i); below switching angle (ii) and; above switching angle (iii)), only case iii had a different angle from the previous validation plots. The reason is that, for a Reynolds Number of 284,000, the XFLR5 did not converge above  $14.5^\circ$  so the validation graph used earlier (@  $17.4^\circ$ ) had to be replaced by another validation chart at  $12.7^\circ$  geometrical AOA, still above the switching angle.

#### Step 1

Open the QBlade with the 2D TE noise module.

Open your working airfoil profile.

Globally refine your airfoil from 160 to 300 panels and set the TE/LE panel density to 0.30. Normalize and de-rotate the airfoil, then save it.

It is recommended that the  $V_{Accel}$  parameter in XFLR5 be set to 0.0001 value or less, when using the QBlade v0.95 64 bit version, before generating TBL data associated with TE noise calculations (path: Analysis->XFoil Advanced Settings->  $V_{Accel}$ ).

Define an XFOIL analysis by the Reynolds and Mach numbers, plus transition details to simulate the experimental case the user wants to replicate.

Analysis parameters for NACA 0012\_160\_panels\_STE

Analysis Name

☒ Automatic ☐ User Defined

T1\_Re1.500\_M0.21\_N9.0

Reynolds and Mach Numbers

Reynolds = 1500000 Mach = 0.21

Transition settings

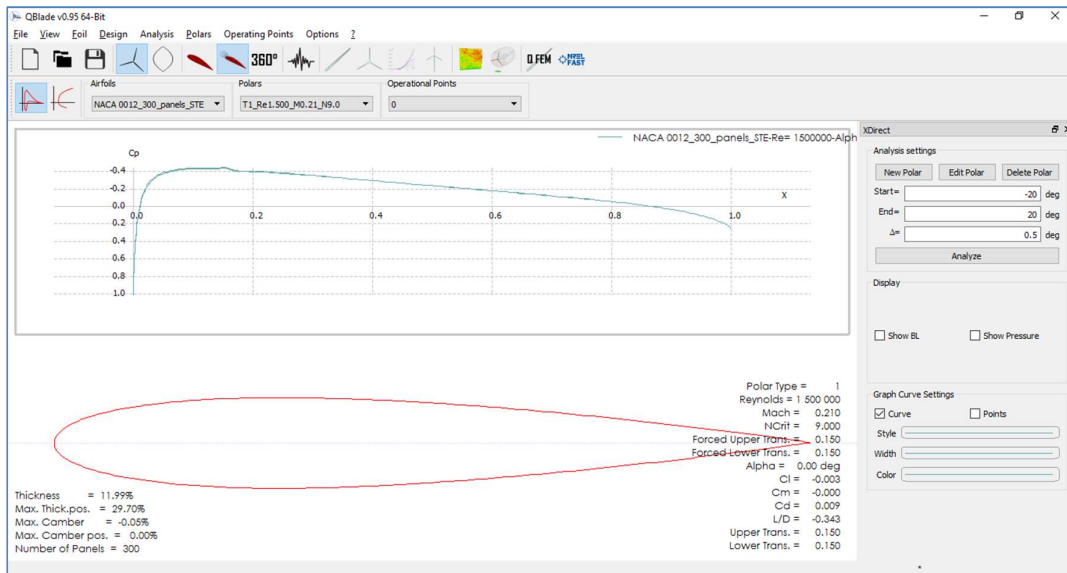
Free transitions ( $e^n$ ) method NCrit= 9

Forced transition: TripLocation (top) 0.15

TripLocation (bot) 0.15

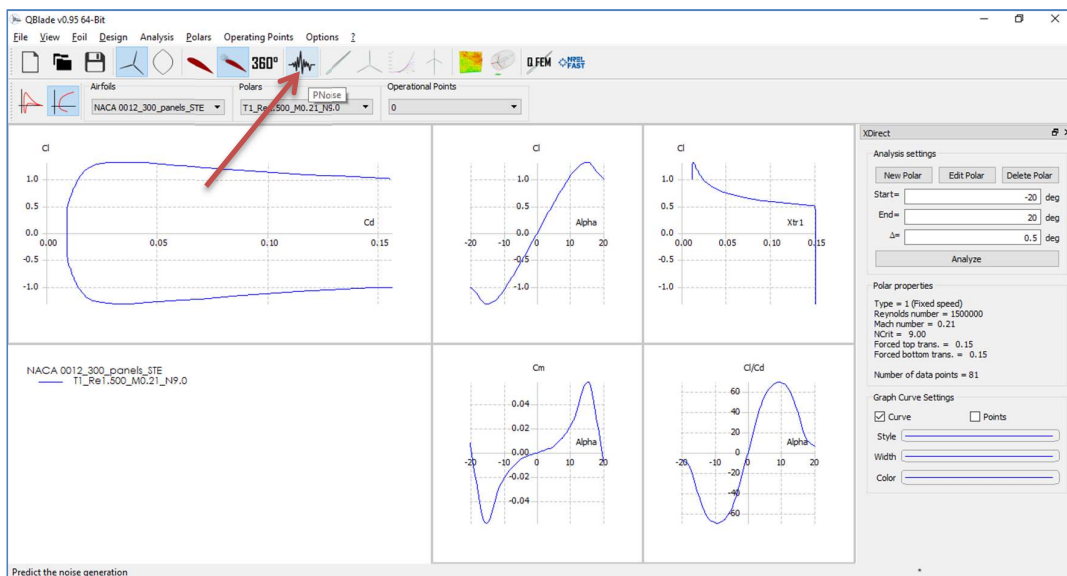
OK Cancel

Run the analysis along an AOA or angle range to meet the user specific needs, generating one or more Operational Points.



## Step 2

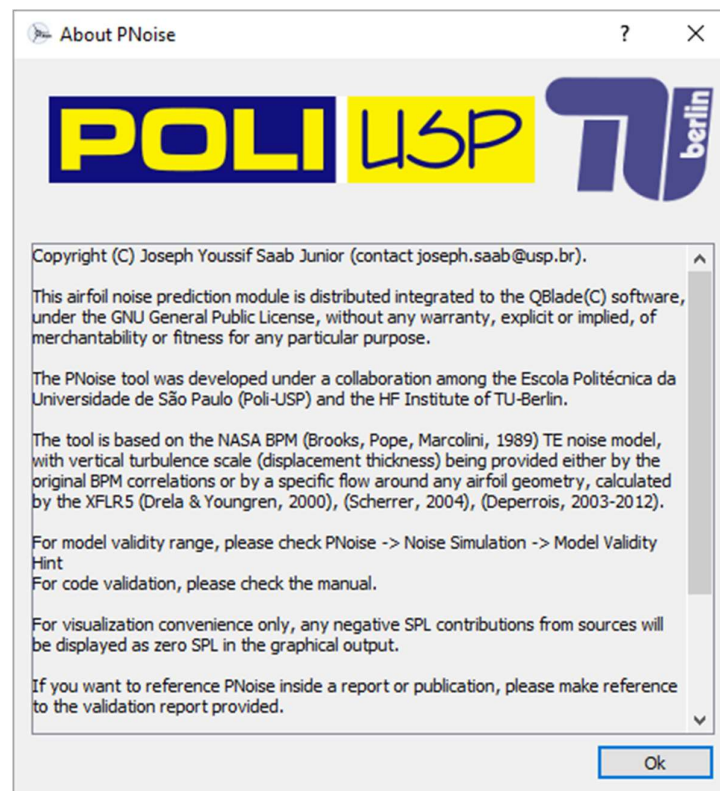
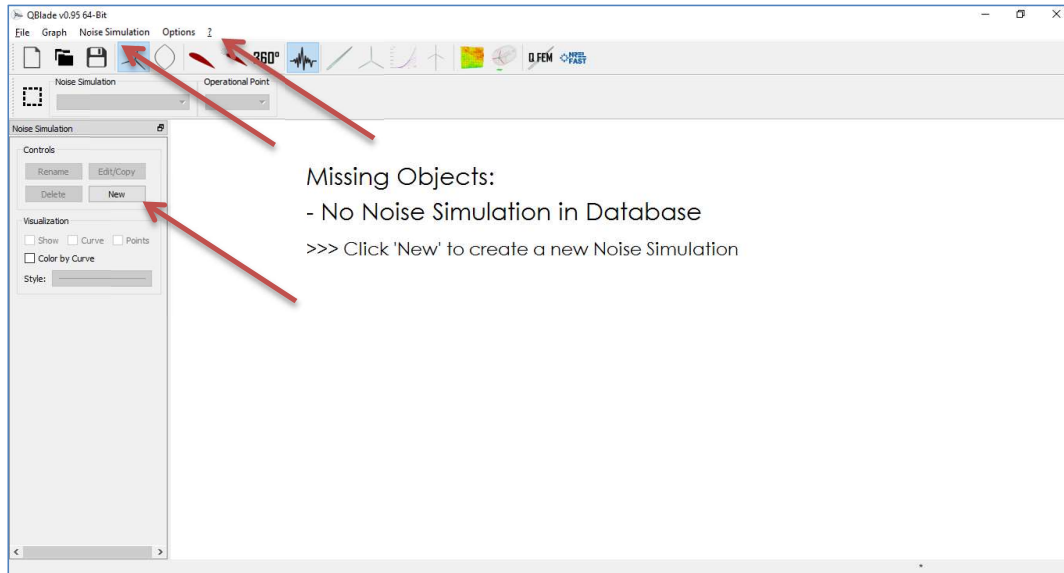
Click in the NOISE module icon (indicated by the red arrow in the picture below), to open the TE noise module:

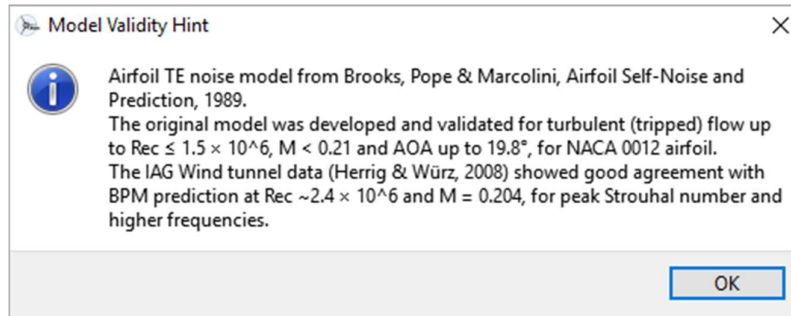




### Step 3

For important information on the model and the validity range, please check the “?” menu, option “About Qnoise” and also “Noise Simulation” menu, option “Model Validity Hint”.



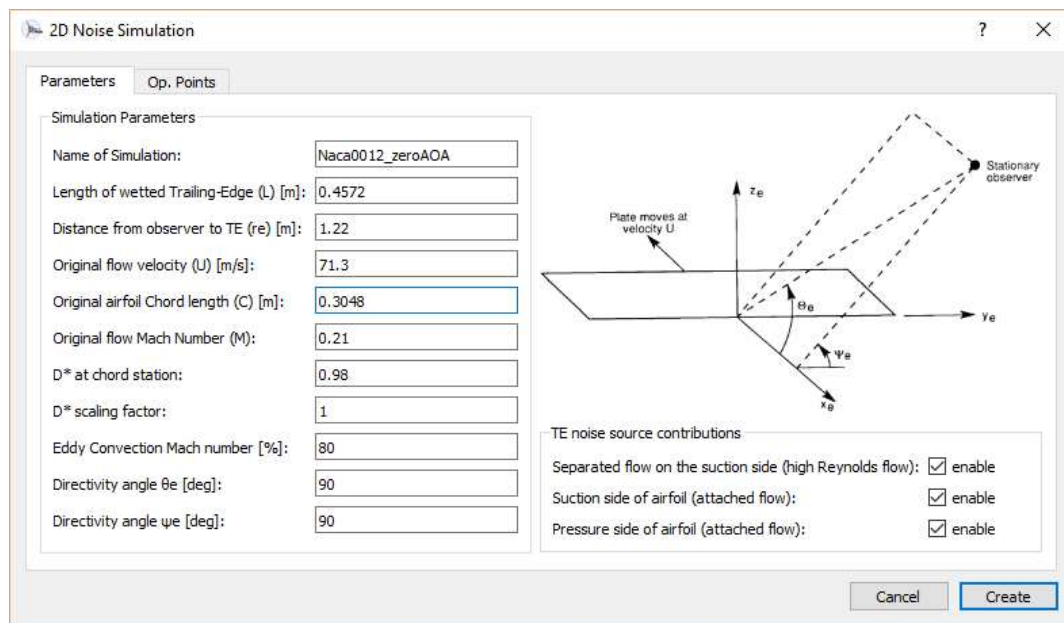


The user should read it carefully and review the definition of PREDICTION presented earlier. The result of any prediction should be declared alongside the limitations of the model employed.

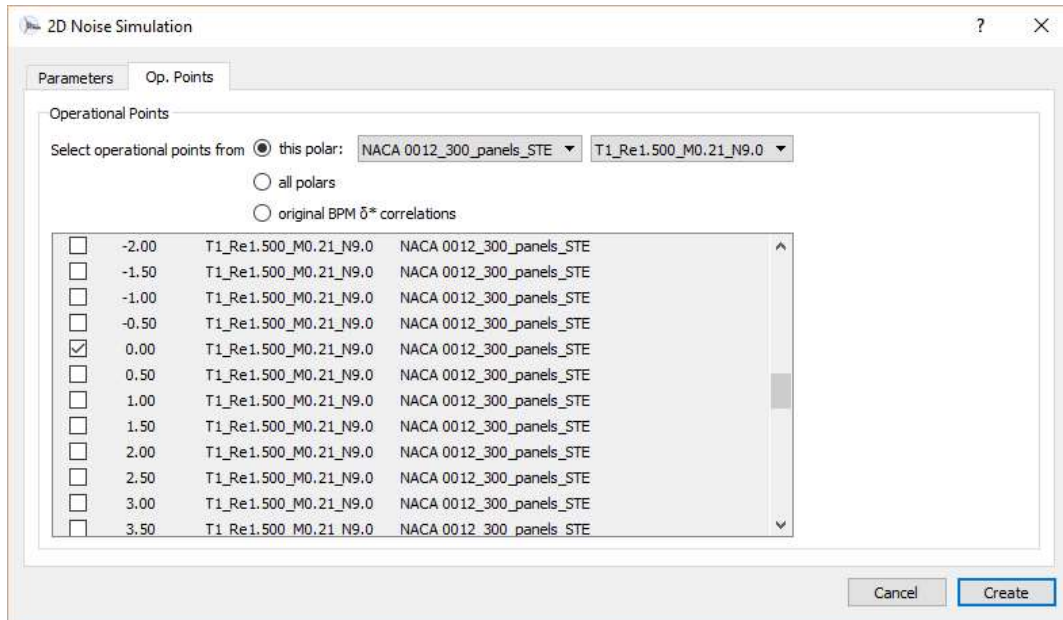
#### Step 4

Click the NEW simulation button.

The input screen will appear. The screen below shows the input screen that must be completed prior to any airfoil TE noise simulation. The snapshot is displayed with zero AOA data employed both in the MS Excel spreadsheet for that angle and also in the original BPM graph of Fig. 11, case a.



The next step is to open the second tab **Op.Points** and select the model (modified or original BPM TE noise models) and the angle of attack for the calculation.



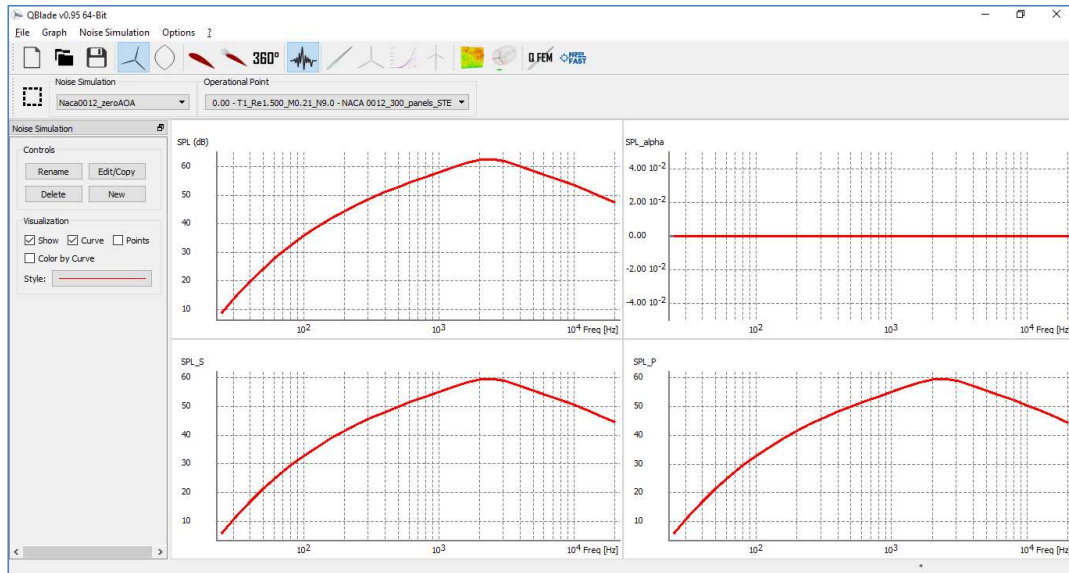
The user may select more than one angle for direct comparison of results.

Notice that the default option is to use boundary layer data (displacement thickness) calculated by the XFLR5, by selection a specific airfoil + polar combination. The user should select the “*original BPM  $\delta^*$  correlations*” option to run the unmodified BPM model.

Click **Create**.

## Step 5

The individual contributions of each source and the total SPL are displayed in different quadrants of the screen.



The original BPM model calculates the SPL\_alpha contribution (unattached flow on the suction side) for zero AOA as a negative value. Since the negative values have no overall contribution to the OASPL and their absolute number is large and distorts the graph scale making it difficult to read other curves (for other angles) in the same set of axis, it was decided that negative SPL contributions of the model would be plotted as zero values (see RH upper graph).

Also notice that, at zero AOA, the TE noise contributions should be the same for the pressure and the suction sides of the airfoil, which is confirmed above, and also, the logarithmic sum of two uncorrelated sources of the same strength should increase the total SPL by 3 dB, which can also be visually verified above and numerically confirmed in the “save to file” output option described next.

## STEP 6

The TE noise overall data may be saved to file by selecting the “Noise Simulation” menu, “Export Current Noise Simulation” option.

Example of file output (file NACA0012\_zeroAOA\_noise.txt)

```
Noise prediction file export

Alpha: 0.00, Re = 1500000
OASPL: 70.82949 dB
OASPL (A): 71.35975 dB(A)
OASPL (B): 70.30961 dB(B)
OASPL (C): 70.26860 dB(C)
SPL_a: -931.90020
SPL_s: 67.80969
SPL_p: 67.82868
```

Freq [Hz]	SPL (dB)	SPLa	SPLs	SPLp	SPL (dB(A))	SPL (dB(B))	SPL (dB(C))
25	8.81529	-1456.96154	5.74057	5.86847	-35.88471	-11.58471	4.41529
31.5	14.32465	-1380.62597	11.25446	11.37343	-25.07535	-2.77535	11.32465
40	19.53943	-1310.34594	16.47362	16.58393	-15.06057	5.33943	17.53943
50	23.99696	-1252.14763	20.93499	21.03772	-6.20304	12.39696	22.69696
63	28.22047	-1198.97585	25.16220	25.25762	2.02047	18.92047	27.42047
80	32.19540	-1151.09917	29.14067	29.22908	9.69540	24.79540	31.69540
100	35.57681	-1112.41303	32.52512	32.60752	16.47681	29.97681	35.27681
125	38.66414	-1079.10545	35.61523	35.69210	22.56414	34.46414	38.46414
160	41.76772	-1047.99372	38.72160	38.79294	28.36772	38.76772	41.66772
200	44.31901	-1024.57624	41.27514	41.34202	33.41901	42.31901	44.31901
250	46.65542	-1005.17122	43.61354	43.67646	38.05542	45.35542	46.65542
315	48.87591	-988.83409	45.83584	45.89517	42.27591	48.07591	48.87591
400	50.98772	-975.45574	47.94923	48.00542	46.18772	50.48772	50.98772
500	52.81920	-965.70980	49.78193	49.83571	49.61920	52.51920	52.81920
630	54.60024	-957.93649	51.56396	51.61577	52.70024	54.50024	54.60024
800	56.34709	-951.87004	53.31155	53.36189	55.54709	56.34709	56.34709
1000	57.91968	-947.53966	54.88456	54.93405	57.91968	57.91968	57.91968
1250	59.46311	-944.04976	56.42812	56.47737	60.06311	59.46311	59.46311
1600	61.16785	-942.92492	58.13285	58.18210	62.16785	61.16785	61.06785
2000	62.42217	-937.87515	59.39355	59.42832	63.62217	62.32217	62.22217
2500	62.60944	-937.45596	59.59281	59.60545	63.90944	62.40944	62.30944
3150	61.67233	-940.11304	58.66764	58.65642	62.87233	61.27233	61.17233
4000	60.02262	-942.84396	57.01793	57.00671	61.02262	59.32262	59.22262
5000	58.48165	-946.12855	55.47698	55.46572	58.98165	57.28165	57.18165
6300	56.86691	-950.24452	53.86259	53.85061	56.76691	54.96691	54.86691
8000	55.14318	-955.77619	52.13951	52.12623	54.04318	52.24318	52.14318
10000	53.45559	-962.58736	50.45279	50.43778	50.95559	49.15559	49.05559
12500	51.66706	-971.43678	48.66537	48.64814	47.36706	45.56706	45.46706
16000	49.54008	-984.13200	46.53991	46.51963	42.94008	41.14008	41.04008
20000	47.45553	-998.71325	44.45700	44.43343	38.15553	36.35553	36.25553

Also, any of the individual plots may be exported by pressing RMC, “Export Graph” option over the selected graph.

#### 5.2.4 Code verification with TBL data calculated by XFLR5 (inside QBlade) for zero AOA (Case 1).

For all cases, the procedure will be to verify the calculation output for three specific frequencies, including the peak one, and then the overall Sound Pressure Levels.

VV project file name: QbladeV095\_32b\_validation.wpa

Baseline case: Figure 11 of BPM original paper.

NACA 0012, Sharp Trailing Edge.

Reynolds: 1,500,000

Mach: 0.21

Tripping: @15% chord, both sides

Chord: 0.3048 m

Wetted TE span: 0.4572 m

Reference Spreadsheet output data:

Chord Station for D\* measurement: 0.98C

See the working procedure figures for illustration on this case input and output files.

The results for zero AOA are shown in table III below:

Frequency(Hz)	Source	SPL_alpha(dB)	SPL_S (dB)	SPL_P (dB)	SPL (dB)	Diff.(dB)
50	Spreadsheet	-1252.71	19.64	19.74	22.70	+1.2
	Code	-1252.15	20.93	21.04	24.00	
1,000	Spreadsheet	-948.83	53.60	53.65	56.64	+1.3
	Code	-947.54	54.88	54.93	57.92	
2,500	Spreadsheet	-938.72	58.32	58.33	61.34	+1.3
	Code	-937.46	59.59	59.61	62.60	

**Table III – Results from QBlade v0.95 code calculation against verification spreadsheet, for zero AOA.**

The differences are systemic and around 1.3 dB, which was considered acceptable. The peak frequency is within the 2,500 Hz band for both spectra.

The overall unweighted sound pressure level is 69.6 dB for the Spreadsheet and 70.8 dB for the Code, a 1.2 dB difference over prediction by the code.

### 5.2.5 Code verification with TBL data calculated by XFLR5 (inside QBlade) for AOA other than zero.

The BPM model has different calculation procedures for AOA below and above the “switching angle”. The switching angle calculated to match the experimental conditions for the 22.86 cm–chord BPM airfoil at a Reynolds number flow of 1,120 Million, is  $9.5^\circ$ . Thus, one verification shall be made below the switching angle ( $4^\circ$ ) and another one above it ( $12.5^\circ$ ).

#### 5.2.5.1 Code verification with TBL data calculated by XFLR5 (inside QBlade) for AOA below the switching angle ( $4^\circ$ - Case 2).

2D Noise Simulation

Parameters Op. Points

Simulation Parameters

Name of Simulation: Naca0012\_4AOA\_noise

Length of wetted Trailing-Edge (L) [m]: 0.4572

Distance from observer to TE (re) [m]: 1.22

Original flow velocity (U) [m/s]: 71.3

Original airfoil Chord length (C) [m]: 0.2286

Original flow Mach Number (M): 0.21

D\* at chord station: 0.98

D\* scaling factor: 1

Eddy Convection Mach number [%]: 80

Directivity angle  $\theta_e$  [deg]: 90

Directivity angle  $\psi_e$  [deg]: 90

TE noise source contributions

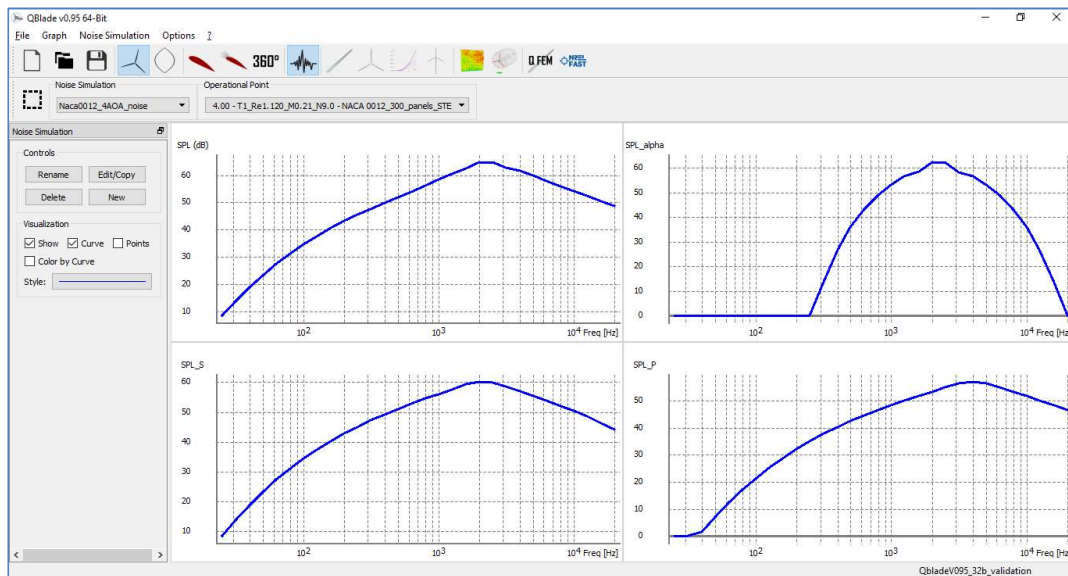
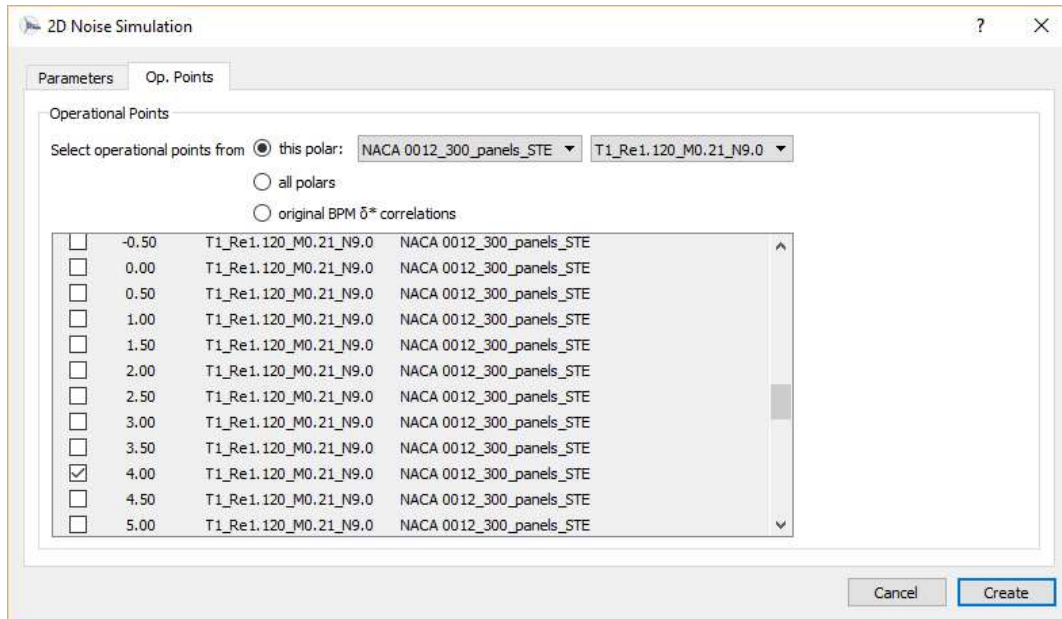
Separated flow on the suction side (high Reynolds flow): ☒ enable

Suction side of airfoil (attached flow): ☒ enable

Pressure side of airfoil (attached flow): ☒ enable

Cancel Create





The results for some frequencies at 4° AOA (below the switching angle), are shown in table IV below:

Frequency (Hz)	Source	SPL_alpha (dB)	SPL_S (dB)	SPL_P (dB)	SPL (dB)	Diff.(dB)
50	SpreadSheet	-243.38	21.83	5.67	21.93	+1.3
	Code	-241.81	23.12	6.97	23.23	
1,000	SpreadSheet	51.88	54.77	47.13	57.04	+1.3
	Code	53.18	56.05	48.42	58.33	
2,500	SpreadSheet	61.10	58.89	52.10	63.47	+1.4
	Code	62.38	59.96	54.92	64.82	

Table IV – Results from QBlade v0.95 code calculation against verification spreadsheet, for 4° AOA.

The differences are systemic and of the order of 1.3 dB, which was considered acceptable. The peak frequency is contained within the 2,500 Hz band for both spectra.

Also the OASPL is 71.1 dB for the Spreadsheet and 72.2 dB for the code or a 1.1 dB difference.

The user should be warned that for negative AOA, the upper surface, initially a suction side, becomes a pressure side and the lower surface, initially a pressure side, becomes a suction side. Since the graphs are labelled “pressure” and “suction” sides, not “upper” and “lower” sides of the airfoil, the output will appear overlapped in such cases as symmetrical angles (e.g.,  $+4^\circ$  and  $-4^\circ$  AOA) are simultaneously selected.

#### 5.2.5.2 Code verification with TBL data calculated by XFLR5 (inside QBlade) for AOA above the switching angle (12.5° - Case 3).

2D Noise Simulation

Parameters Op. Points

Simulation Parameters

Name of Simulation: Naca0012\_12\_5AOA\_noise

Length of wetted Trailing-Edge (L) [m]: 0.4572

Distance from observer to TE (r<sub>e</sub>) [m]: 1.22

Original flow velocity (U) [m/s]: 71.3

Original airfoil Chord length (C) [m]: 0.0254

Original flow Mach Number (M): 0.21

D\* at chord station: 0.98

D\* scaling factor: 1

Eddy Convection Mach number [%]: 80

Directivity angle  $\theta_e$  [deg]: 90

Directivity angle  $\psi_e$  [deg]: 90

TE noise source contributions

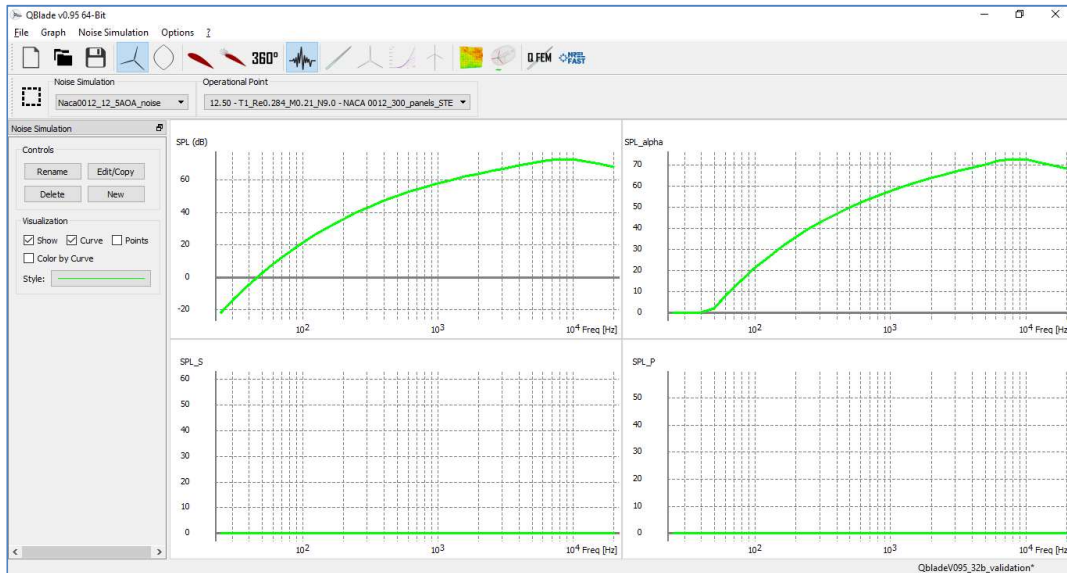
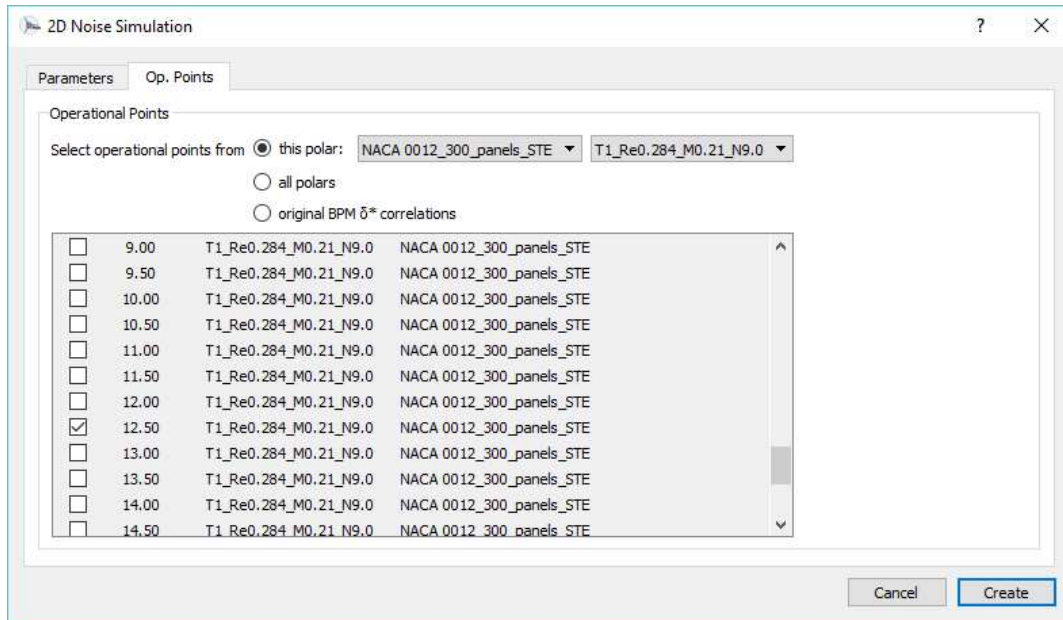
Separated flow on the suction side (high Reynolds flow): ☒ enable

Suction side of airfoil (attached flow): ☒ enable

Pressure side of airfoil (attached flow): ☒ enable

Cancel Create





The results for some frequencies at 12.5° AOA (above the switching angle), are shown in table V below:

Frequency (Hz)	Source	SPL_alpha (dB)	SPL_S (dB)	SPL_P (dB)	SPL (dB)	Diff.(dB)
50	SpreadSheet	1.78	-∞	-∞	1.78	+0.3
	Code	2.03	-2.1E+9	-2.1E+9	2.03	
1,000	SpreadSheet	57.67	-∞	-∞	57.67	0.0
	Code	57.67	-2.1E+9	-2.1E+9	57.67	
8,000	SpreadSheet	72.92	-∞	-∞	72.92	-0.1
	Code	72.82	-2.1E+9	-2.1E+9	72.82	

Table V – Results from QBlade v0.95 code calculation against verification spreadsheet, for 12.5° AOA.

SPL\_Alpha should be the sole positive noise source contributor for an angle above the switching angle, which is exactly the behavior displayed.

The OASPL is 80.7 dB for the Spreadsheet and 80.6 dB for the code or a 0.1 dB difference.

### 5.2.6 Code verification with TBL displacement thickness calculated with the original BPM correlations (Cases 4, 5 and 6):

The same three conditions of cases 1, 2 and 3 will be verified in this section, with the original BPM displacement thickness correlations applied instead of the XFLR5 calculation results, i.e., the original BPM procedure, without modification shall be applied.

#### *AOA=0° (Case 4)*

Input screen for the case where the original BPM correlations will be used for displacement thickness evaluation:

**2D Noise Simulation**

Parameters Op. Points

Simulation Parameters

Name of Simulation: Naca0012\_zeroAOA\_BPM

Length of wetted Trailing-Edge (L) [m]: 0.4572

Distance from observer to TE (r<sub>e</sub>) [m]: 1.22

Original flow velocity (U) [m/s]: 71.3

Original airfoil Chord length (C) [m]: 0.3048

Original flow Mach Number (M): 0.21

D\* at chord station: 0.98

D\* scaling factor: 1

Eddy Convection Mach number [%]: 80

Directivity angle  $\theta_e$  [deg]: 90

Directivity angle  $\psi_e$  [deg]: 90

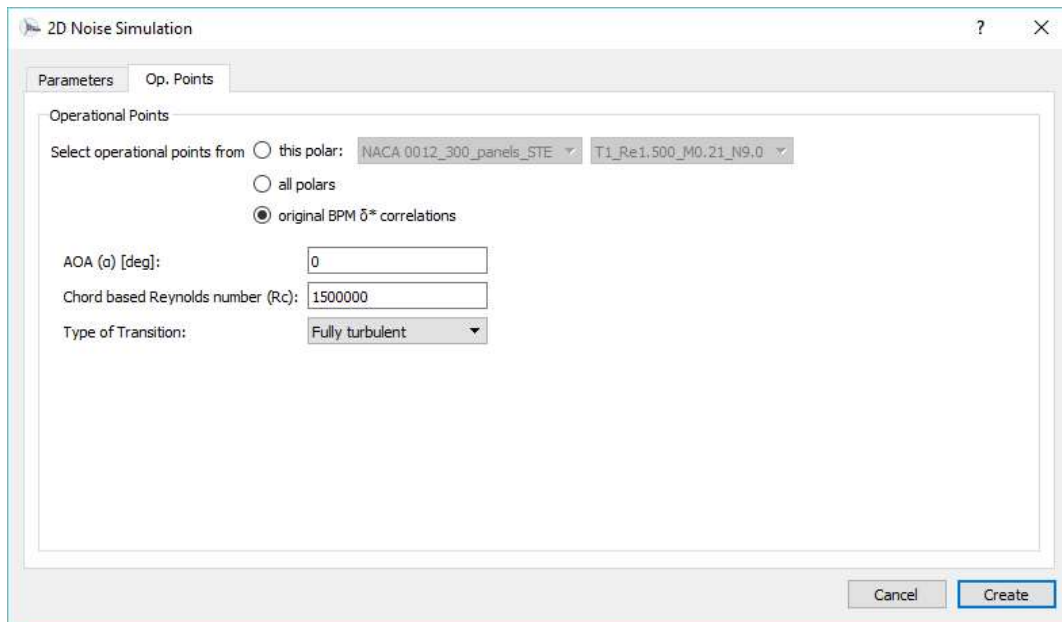
TE noise source contributions

Separated flow on the suction side (high Reynolds flow): ☒ enable

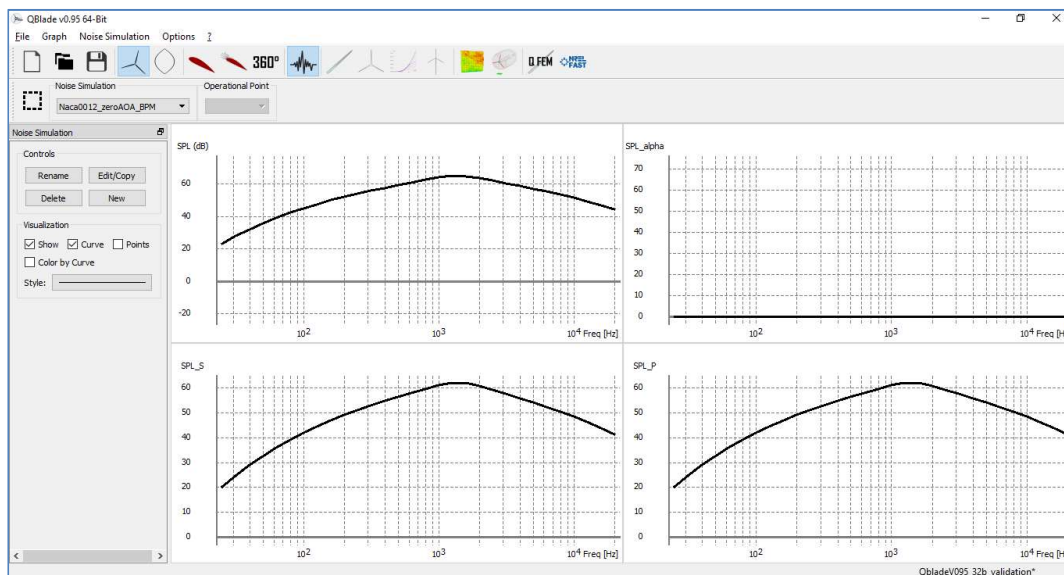
Suction side of airfoil (attached flow): ☒ enable

Pressure side of airfoil (attached flow): ☒ enable

Cancel Create



When the Original BPM correlations for displacement thickness are selected, the dialog opens three new fields for the user to enter AOA data, chord-based Reynolds Number and Transition of Fully Turbulent Flow.



The verification was once again made with the aid of a calculation spreadsheet, fed with the BPM  $D^*$  correlations ( $D = 2.66E-3$  m is this particular case), in order to reproduce the original model intended spectrum.

Frequency (Hz)	Source	SPL_alpha (dB)	SPL_S (dB)	SPL_P (dB)	SPL (dB)	Diff.(dB)
50	SpreadSheet	-1138.39	31.19	31.19	34.20	+1.29
	Code	-1136.90	32.48	32.48	35.49	
1,000	SpreadSheet	-938.72	59.63	59.63	62.64	+1.28
	Code	-938.24	60.91	60.91	63.92	
1,250	SpreadSheet	-936.48	60.61	60.61	63.62	+1.27
	Code	-935.20	61.88	61.88	64.89	

The peak frequency of 1,250 is correctly predicted by the code and the overall SPL is 73.2 dB against 71.9 dB for the spreadsheet, a difference of 1.25 dB. The same kind of systemic difference is seen on the 3 frequencies compared.

### *AOA=4° (case 5)*

2D Noise Simulation

Parameters
Op. Points

Simulation Parameters

Name of Simulation: Naca0012\_4AOA\_noise\_BPM

Length of wetted Trailing-Edge (L) [m]: 0.4572

Distance from observer to TE (re) [m]: 1.22

Original flow velocity (U) [m/s]: 71.3

Original airfoil Chord length (C) [m]: 0.2286

Original flow Mach Number (M): 0.21

D\* at chord station: 0.98

D\* scaling factor: 1

Eddy Convection Mach number [%]: 80

Directivity angle  $\theta_e$  [deg]: 90

Directivity angle  $\psi_e$  [deg]: 90

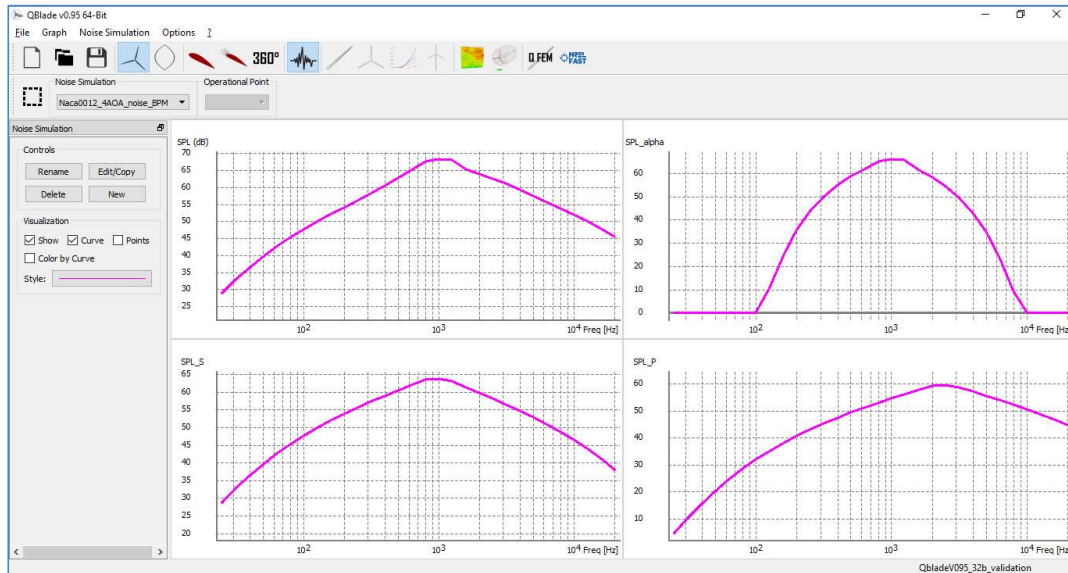
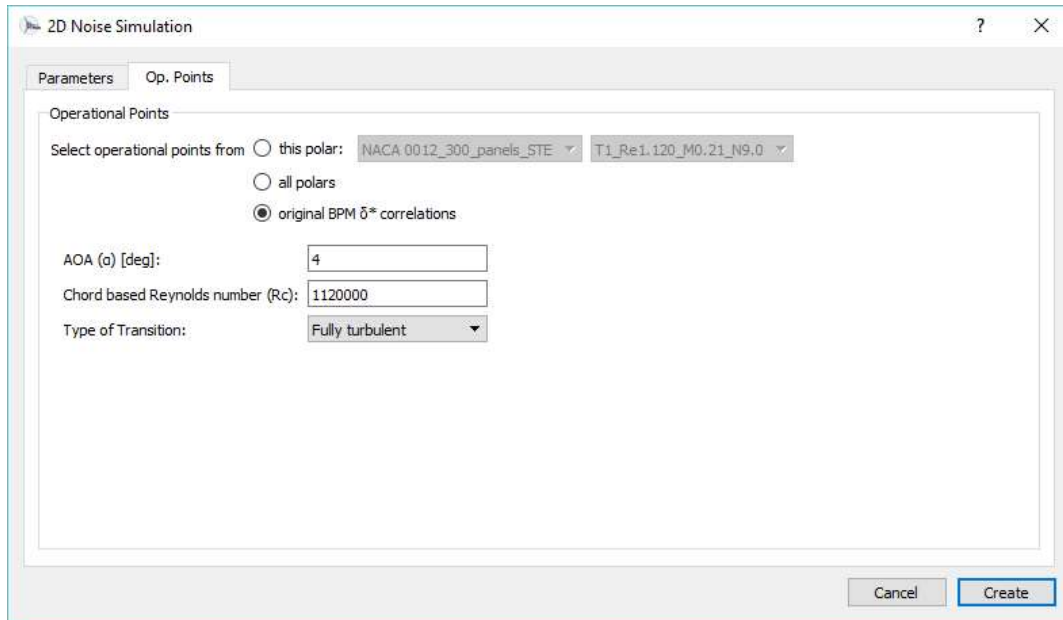
TE noise source contributions

Separated flow on the suction side (high Reynolds flow): ☒ enable

Suction side of airfoil (attached flow): ☒ enable

Pressure side of airfoil (attached flow): ☒ enable

Cancel Create



Frequency (Hz)	Source	SPL_alpha (dB)	SPL_S (dB)	SPL_P (dB)	SPL (dB)	Diff.(dB)
50	SpreadSheet	-85.55	38.20	18.76	38.25	+1.29
	Code	-84.10	39.49	20.06	39.54	
1,000	SpreadSheet	64.90	62.44	53.18	67.03	+1.28
	Code	66.17	63.72	54.46	68.31	

The peak frequency of 1,000 is correctly predicted by the code and the overall SPL is 75.8 dB against 74.4 dB for the spreadsheet, a difference of 1.4 dB. A systemic difference close to +1.3 dB is seen for both frequencies compared.

### *AOA=12,5° (Case6)*

2D Noise Simulation

Parameters Op. Points

Simulation Parameters

Name of Simulation:

Length of wetted Trailing-Edge (L) [m]:

Distance from observer to TE (re) [m]:

Original flow velocity (U) [m/s]:

Original airfoil Chord length (C) [m]:

Original flow Mach Number (M):

D\* at chord station:

D\* scaling factor:

Eddy Convection Mach number [%]:

Directivity angle  $\theta_e$  [deg]:

Directivity angle  $\psi_e$  [deg]:

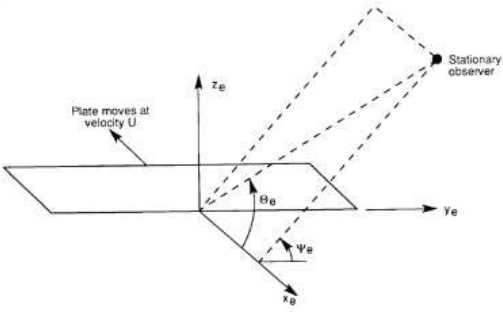
TE noise source contributions

Separated flow on the suction side (high Reynolds flow): ☒ enable

Suction side of airfoil (attached flow): ☒ enable

Pressure side of airfoil (attached flow): ☒ enable

Cancel Create



2D Noise Simulation

Parameters Op. Points

Operational Points

Select operational points from ☐ this polar:

☐ all polars

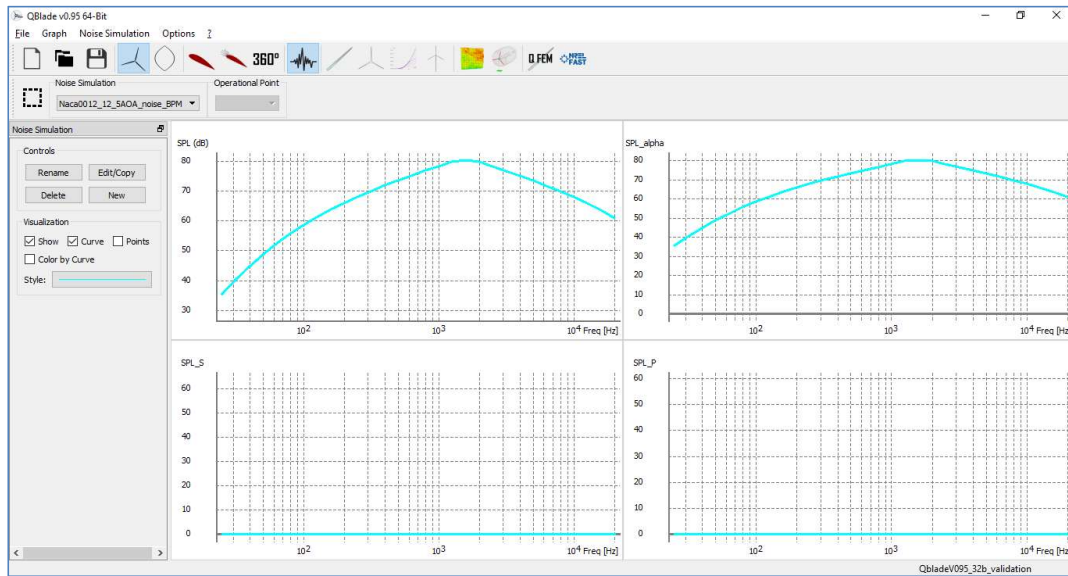
☒ original BPM  $\delta^*$  correlations

AOA ( $\alpha$ ) [deg]:

Chord based Reynolds number (Rc):

Type of Transition:

Cancel Create



Frequency (Hz)	Source	SPL_alpha (dB)	SPL_S (dB)	SPL_P (dB)	SPL (dB)	Diff.(dB)
50	SpreadSheet	48.75	-∞	-∞	48.75	-0.22
	Code	48.53	-2.1E+9	-2.1E+9	48.53	
1,000	SpreadSheet	78.41	-∞	-∞	78.41	-0.20
	Code	78.21	-2.1E+9	-2.1E+9	78.21	
1,600	SpreadSheet	80.42	-∞	-∞	80.42	-0.18
	Code	80.24	-2.1E+9	-2.1E+9	80.24	

The OASPL is 88.6 dB for the spreadsheet and 88.4 dB for the code calculation, a -0.2 dB difference and the peak frequency in in the band of the 1,600 Hz central frequency for both calculations.



## 6 Conclusions

The calculation procedure verification for the code was made for 6 cases, covering the zero, below and above the switching angle conditions, with turbulent boundary layer data provided by the XFLR5 or by the original BPM correlations, depending on the case.

The code calculation verification procedure was made for all cases against spreadsheet (manual) calculation, prepared as per the original model and previously verified against the original BPM-calculated spectra.

The code calculations displayed a systemic, positive overprediction of about 1.3 dB for the cases below the switching angle ( $0^\circ$ ,  $4^\circ$ ). This applies to sample frequencies selected for comparison, which included the peak frequency for each case and also to the overall SPL.

The code calculations displayed a closer adhesion to manual calculation in the cases for AOA above the switching angle ( $12.5^\circ$ ), where the differences ranged in the  $[-0.2, +0.1]$  dB interval, for selected frequencies and for the overall SPL.

The +1.3 dB systemic difference perceived in some of the cases was considered acceptable for the first release of the PNoise module, but improvements in calculation accuracy will be made for follow-up releases.

All correspondence and suggestions for improvements are welcome and should be addressed to the corresponding author, which is the sole responsible for any bugs and mistakes found.



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## Appendix A - Original BPM displacement thickness correlations calculation procedure.

In the model correlations (Brooks, et al., 1989), the displacement thickness is calculated for zero alpha and for the type of flow (turbulent or transition) and for both the pressure and suction sides, as a function of Chord-based Reynolds number ( $R_c$ ). When the alpha is other than zero, a scaling factor is calculated for each side of the airfoil (pressure and suction) and multiplies the original displacement thickness calculated for zero alpha.

- For turbulent flows (FT selected in the menu):

For  $R_c \leq 0,3 \times 10^6$

$$\delta_0^* = C * 0,0601 \cdot R_c^{-0,114}$$

For  $R_c > 0,3 \times 10^6$

$$\delta_0^* = C * 10^{[3,411 - 0,5397 \cdot \log(R_c) + 0,1059(\log R_c)^2]}$$

The log function referred above is the LOG10 function of MS Excel (base 10 logarithm).

For zero AOA flows,  $\delta_0^* = \delta^*$  (above result is final and the same for the pressure and suction sides)

- For the transition flows (NT selected in the menu):

For all Reynolds number based on chord:

$$\delta_0^* = C * 10^{[3,0187 - 0,5397 \cdot \log(R_c) + 0,1059(\log R_c)^2]}$$

- The correction for non-zero AOA, applicable for the pressure side only and for NT flows is made with the expression below, for all AOA:

$$\delta_p^* = \delta_0^* * 10^{[-0,0432 \cdot \alpha + 0,00113 \cdot \alpha^2]}$$

- The correction for non-zero AOA, applicable for the suction side depends upon the AOA and the type of flow, and is made with the expressions below:

For FT type of flows:

For  $0^\circ \leq |\alpha| \leq 5^\circ$  (absolute value of alpha should be used, remembering the pressure and suction side definition depends upon the signal of  $\alpha$ ).

$$\delta_s^* = \delta_0^* * 10^{0,0679.\alpha}$$

For  $5^\circ \leq |\alpha| \leq 12,5^\circ$

$$\delta_s^* = \delta_0^* * 0,381 (10^{0,1516.\alpha})$$

For  $12,5^\circ \leq |\alpha| \leq 25^\circ$

$$\delta_s^* = \delta_0^* * 14,296 (10^{0,0258.\alpha})$$

For NT type of flows:

For  $0^\circ \leq |\alpha| \leq 7,5^\circ$

$$\delta_s^* = \delta_0^* * 10^{0,0679.\alpha}$$

For  $7,5^\circ \leq |\alpha| \leq 12,5^\circ$

$$\delta_s^* = \delta_0^* * 0,0162 (10^{0,3066.\alpha})$$

For  $12,5^\circ \leq |\alpha| \leq 25^\circ$

$$\delta_s^* = \delta_0^* * 52,42 (10^{0,0258.\alpha})$$

#### Calculation routine for $SPL_\alpha$ .

At this point, only AOA specified in the XFoil Analysis may be specified for TE noise calculation. No interpolation will be made between available AOA. Example: if XFoil Analysis was run from 0 to 10 AOA, with step of 1 degree, the user may not, at this point, specify the noise calculation at 4.5 AOA, unless he does again the XFoil Analysis with step 0.5 degree.

Calculate only if  $SPL_\alpha$  source is selected in the menu.

If  $D^*$  station = default, use 0.98 station as a reference, else, read desired reference station.

For each OpPoint selected, locate the XFoil TBL output table and recover  $D^*$  data at a number of upstream and downstream stations of specified chord station, as necessary per the interpolation scheme to be used. For linear interpolation scheme, only one upstream and one downstream value will be needed. Linear interpolation scheme will be the only one available at this time.

Linearly interpolate data to find the  $D^*$  value at 0.98 chord station or else, at specified station.

Linear interpolation example:

Location	Chord Station	D*
Upstream (*)	0,979	0,000381
Specified Station	0,98	Interp. Value
Downstream (#)	0,981	0,000383
Interp. value=		0,000382

$$\text{Interp. Value} = [(0.000381 - 0.000383) \times (0.98 - 0.981) / (0.979 - 0.981)] + 0.000383$$

$$D^*_{\text{final}} = D^*_{\text{interpolated}} \times D^*_{\text{scaling factor (default = 1)}}$$

Take the Mach number specified in the input. If velocity is also provided in the input, use it, else, calculate the flow velocity based on the Mach number and Standard conditions:

$$\text{Velocity} = \text{Mach number (M)} / (\text{SQRT}(1.4 \times 286.9 \text{ [J/kg.K]} \times (273.15 + 15)))$$

If Eddy Convection Mach number ( $M_c$ ) = default,

$$\text{Eddy Convection Mach number} = \text{Mach number} \times 0.8$$

Else

$$\text{Eddy Convection Mach number} = \text{Mach number} \times \text{specified factor.}$$

Calculate Switching Angle ( $\alpha$ )<sub>0</sub> and compare to alpha ( $\alpha$ ) of OpPoint:

$$\text{Switching Angle}_1 = \text{Gamma\_zero}$$

$$\text{Gamma\_zero} = 23.43 \times M + 4.651$$

$$\text{Switching Angle}_2 = 12.5 [^\circ]$$

If Switching Angle<sub>1</sub> < Switching Angle<sub>2</sub>,

$$\text{then Switching Angle} = \text{Switching Angle}_1$$

$$\text{Else, Switching Angle} = \text{Switching Angle}_2$$

Compare Alpha and the Switching Angle:

If Alpha (Angle of Attack of the OpPoint) is larger than the Switching Angle,

Set  $\text{SPL}_s = -\infty$  (and skip  $\text{SPL}_s$  calculation routine)

Set  $\text{SPL}_p = -\infty$  (and skip  $\text{SPL}_p$  calculation routine)

Calculate  $\text{SPL}_\alpha$  :

General expression:

If angle is smaller than the switching Angle:

$$SPL_{\alpha,1/3} = 10 \cdot \log \left[ M^5 \frac{L \delta_s^* \bar{D}_h}{r_e^2} \right] + B \left( \frac{St_s}{St_2} \right) + K_2$$

If angle is larger than the switching Angle:

$$SPL_{\alpha,1/3} = 10 \cdot \log \left[ M^5 \frac{L \delta_s^* \bar{D}_l}{r_e^2} \right] + A' \left( \frac{St_s}{St_2} \right) + K_2$$

Available Data:

$M$  = Mach number (input or modified input or calculated from above).

$L$  = length of TE (input).

$\delta_s^*$  = displacement thickness (D\*) linearly interpolated value on specified station, FROM THE SUCTION SIDE OF THE AIRFOIL. If  $\alpha > 0$ , the SUCTION SIDE is the UPPER side. If  $\alpha < 0$ , the SUCTION SIDE is the LOWER side of the airfoil as drawn in the Xfoil monitor screen, with the TE to the left of the user. Alpha is positive when airfoil is turned clockwise from chord resting in horizontal position.

$r_e$  = distance from observer to TE (specified or default input).

Data to be calculated before  $SPL_\alpha$  can be evaluated for each 1/3 octave frequency:

$\bar{D}_h = 1$  if default options were selected. Else, calculate  $\bar{D}_h$  from:

$$\bar{D}_h(\theta_e, \phi_e) \approx \frac{2 \sin^2 \left( \frac{\theta_e}{2} \right) \sin^2 \phi_e}{(1 + M \cos \theta_e) [1 + (M - M_c) \cos \phi_e]^2}$$

$\bar{D}_l = 1$  if default options were selected. Else, calculate  $\bar{D}_l$  from:

$$\bar{D}_l(\theta_e, \phi_e) \approx \frac{2 \sin^2 \theta_e \sin^2 \phi_e}{(1 + M \cos \theta_e)^4}$$

All data are available for this calculation, from Mach and Eddy Convection Mach numbers, to the inputted angles for directivity function,  $\theta_e, \phi_e$ .

$St_s = \frac{f \delta_s^*}{U}$  This peak Strouhal Number shall be calculated for each 1/3 octave frequency band,  $f$ .  $U$  is the reference flow velocity and should be calculated from:

$$\text{Velocity} = (\text{Reynolds number} \times 1.78 \text{ E-5 [Pa.s]}) / (1.225 [\text{kg/m}^3] \times 1 [\text{m}])$$

$\delta_s^*$  = displacement thickness (D\*) linearly interpolated value on specified station, FROM THE SUCTION SIDE OF THE AIRFOIL (see above, the value is already available from linear interpolation).

Calculate the peak Strouhal number:

$$St_2 = St_1 \times \begin{cases} 1 & (\alpha < 1.33^\circ) \\ 10^{0.0054(\alpha-1.33)^2} & (1.33 \leq \alpha \leq 12.5^\circ) \\ 4.72 & (\alpha > 12.5^\circ) \end{cases}$$

$$\text{Where, } St_1 = 0.02M^{-0.6}$$

$$B(b) = B_{min}(b) + B_R(b_0)[B_{max}(b) - B_{min}(b)]$$

Where

$$B_{min}(b) = \begin{cases} \sqrt{16.888 - 886.788b^2} - 4.109 & (b < 0.13) \\ -83.607b + 8.138 & (0.13 \leq b \leq 0.145) \\ -817.810b^3 + 335.210b^2 - 135.024b + 10.619 & (b > 0.145) \end{cases}$$

and

$$B_{max}(b) = \begin{cases} \sqrt{16.888 - 886.788b^2} - 4.109 & (b < 0.10) \\ -31.330b + 1.854 & (0.10 \leq b \leq 0.187) \\ -80.541b^3 + 44.174b^2 - 39.381b + 2.344 & (b > 0.187) \end{cases}$$

where

$$b = |\log(St_s/St_2)|$$

$$b_0(R_c) = \begin{cases} 0.30 & (R_c < 9.52 \times 10^4) \\ (-4.48 \times 10^{-13})(R_c - 8.57 \times 10^5)^2 + 0.56 & (9.52 \times 10^4 \leq R_c \leq 8.57 \times 10^5) \\ 0.56 & (R_c > 8.57 \times 10^5) \end{cases}$$

And the interpolation factor  $B_R(b_0)$  is determined from

$$B_R(b_0) = \frac{-20 - B_{min}(b_0)}{B_{max}(b_0) - B_{min}(b_0)}$$

The last variable needed for the calculation is the level correction  $K_2$ :

$$K_2 = K_1 + \begin{cases} -1000 & (\alpha < \gamma_0 - \gamma) \\ \sqrt{\beta^2 - (\beta/\gamma)^2(\alpha - \gamma_0)^2} & (\gamma_0 - \gamma \leq \alpha \leq \gamma_0 + \gamma) \\ -12 & (\alpha > \gamma_0 + \gamma) \end{cases}$$

where

$$\gamma = 27.094M + 3.32; \quad \gamma_0 = 23.43M + 4.651$$

$$\beta = 72.65M + 10.74; \quad \beta_0 = -34.19M - 13.82$$

All the angle definitions are in degrees, and:

$$K_1 = \begin{cases} -4.31 \log(R_c) + 156.3 & (R_c < 2.47 \times 10^5) \\ -9.0 \log(R_c) + 181.6 & (2.47 \times 10^5 \leq R_c \leq 8.0 \times 10^5) \\ 128.5 & (R_c > 8.0 \times 10^5) \end{cases}$$

In case the Angle is larger than the switching angle,  $A'$  shall be calculated in the following way:

$A'$  is the same function as  $A$ , except that the  $R_c$  value entered should be three times larger than actual  $R_c$  value.

Make  $R_c = 3 \times R_{c\_original}$

$$A(a) = A_{min}(a) + A_R(a_0)[A_{max}(a) - A_{min}(a)]$$

Where

$$A_{min}(a) = \begin{cases} \sqrt{67.552 - 886.788a^2} - 8.219 & (a < 0.204) \\ -32.665a + 3.981 & (0.204 \leq a \leq 0.244) \\ -142.795a^3 + 103.656a^2 - 57.757a + 6.006 & (a > 0.244) \end{cases}$$

and

$$A_{max}(a) = \begin{cases} \sqrt{67.552 - 886.788a^2} - 8.219 & (a < 0.13) \\ -15.901a + 1.098 & (0.13 \leq a \leq 0.321) \\ -4.669a^3 + 3.491a^2 - 16.699a + 1.149 & (a > 0.321) \end{cases}$$

where

$$a = |\log(St_s/St_2)|$$

Notice again that  $R_c$  below is the original  $R_c$  multiplied by 3:

$$a_0(R_c) = \begin{cases} 0.57 & (R_c < 9.52 \times 10^4) \\ (-9.57 \times 10^{-13})(R_c - 8.57 \times 10^5)^2 + 1.13 & (9.52 \times 10^4 \leq R_c \leq 8.57 \times 10^5) \\ 1.13 & (R_c > 8.57 \times 10^5) \end{cases}$$

And the interpolation factor  $A_R(a_0)$  is determined from

$$A_R(a_0) = \frac{-20 - A_{min}(a_0)}{A_{max}(a_0) - A_{min}(a_0)}$$

#### Calculation routine for SPL<sub>s</sub>.

Calculate only if SPL<sub>s</sub> source is selected in the menu AND the alpha angle ( $\alpha$ ) is smaller than the switching angle,  $(\alpha)_0$ .

General expression for each 1/3 frequency band:

$$SPL_{s,1/3} = 10. \log \left[ M^5 \frac{L \delta_s^* \bar{D}_h}{r_e^2} \right] + A \left( \frac{St_s}{St_1} \right) + (K_1 - 3)$$

If the  $SPL_\alpha$  (item 7) has not been selected by the user in the main Option Menu (and therefore has not been calculated) the calculations for the Mach number (M), TE Length (L), Displacement Thickness on the suction side ( $\delta_s^*$ ), the Directivity Function  $\bar{D}_h$ , and the observer distance are exactly the same as specified in item 7 above, ( $SPL_\alpha$  calculation).

Calculation of the remaining variables for the evaluation of the above expression:

Notice, if  $R_c$  was multiplied by a factor of 3 for the calculation of  $SPL_\alpha$ , then restore the original value for  $R_c$  before proceeding.

$St_s$ :  $St_s = \frac{f \delta_s^*}{U}$ . This Strouhal Number shall be calculated for each 1/3 octave frequency band,  $f$ .  $U$  is the reference flow velocity and should be calculated from:

$$\text{Velocity} = (\text{Reynolds number} \times 1.78 \text{ E-5 [Pa.s]}) / (1.225 [\text{kg/m}^3] \times 1 [\text{m}])$$

$$\overline{St_1}: \quad \overline{St_1} = \frac{St_1 + St_2}{2}.$$

Again:

$$St_1 = 0.02 M^{-0.6}$$

and

$$St_2 = St_1 \times \begin{cases} 1 & (\alpha < 1.33^\circ) \\ 10^{0.0054(\alpha - 1.33)^2} & (1.33 \leq \alpha \leq 12.5^\circ) \\ 4.72 & (\alpha > 12.5^\circ) \end{cases}$$

$A$ : The value for the 1/3 octave spectral shape function,  $A$ , is given by:

$$A(a) = A_{min}(a) + A_R(a_0)[A_{max}(a) - A_{min}(a)]$$

Where:

$$a = |\log(St_s / \overline{St_1})|$$

and,

$$a_0(R_c) = \begin{cases} 0.57 & (R_c < 9.52 \times 10^4) \\ (-9.57 \times 10^{-13})(R_c - 8.57 \times 10^5)^2 + 1.13 & (9.52 \times 10^4 \leq R_c \leq 8.57 \times 10^5) \\ 1.13 & (R_c > 8.57 \times 10^5) \end{cases}$$

and,

$$A_R(a_0) = \frac{-20 - A_{min}(a_0)}{A_{max}(a_0) - A_{min}(a_0)}$$



and,

$$A_{min}(a) = \begin{cases} \sqrt{67.552 - 886.788a^2} - 8.219 & (a < 0.204) \\ -32.665a + 3.981 & (0.204 \leq a \leq 0.244) \\ -142.795a^3 + 103.656a^2 - 57.757a + 6.006 & (a > 0.244) \end{cases}$$

and,

$$A_{max}(a) = \begin{cases} \sqrt{67.552 - 886.788a^2} - 8.219 & (a < 0.13) \\ -15.901a + 1.098 & (0.13 \leq a \leq 0.321) \\ -4.669a^3 + 3.491a^2 - 16.699a + 1.149 & (a > 0.321) \end{cases}$$

$K_1$ :

$$K_1 = \begin{cases} -4.31 \log(R_c) + 156.3 & (R_c < 2.47 \times 10^5) \\ -9.0 \log(R_c) + 181.6 & (2.47 \times 10^5 \leq R_c \leq 8.0 \times 10^5) \\ 128.5 & (R_c > 8.0 \times 10^5) \end{cases}$$

#### Calculation routine for SPL<sub>p</sub>.

Calculate only if SPL<sub>p</sub> source is selected in the menu AND the alpha angle ( $\alpha$ ) is smaller than the switching angle, ( $\alpha$ )<sub>0</sub>.

General expression for each 1/3 frequency band:

$$SPL_{p,1/3} = 10. \log \left[ M^5 \frac{L \delta_p^* \bar{D}_h}{r_e^2} \right] + A \left( \frac{St_p}{St_1} \right) + (K_1 - 3) + \Delta K_1$$

If the SPL <sub>$\alpha$</sub>  (item 7) has not been selected by the user in the main Option Menu (and therefore has not been calculated) the calculations for the Mach number (M), TE Length (L), the Directivity Function  $\bar{D}_h$ , and the observer distance are exactly the same as specified in item 7 above, (SPL <sub>$\alpha$</sub>  calculation). However, the Displacement Thickness, which has the same type of calculation, must be done based on the Turbulent Boundary Layer develop on the Pressure Side of the airfoil ( $\delta_p^*$ ).

Notice, if Rc was multiplied by a factor of 3 for the calculation of SPLalpha, then restore the original value for Rc before proceeding.

$\delta_p^*$  = displacement thickness ( $\delta^*$ ) linearly interpolated value on specified station, FROM THE PRESSURE SIDE OF THE AIRFOIL. If alpha > 0, the PRESSURE SIDE is the LOWER side. If alpha < 0, the PRESSURE SIDE is the UPEER side of the airfoil as drawn in the Xfoil monitor screen, with the TE to the left of the user. Alpha is positive when airfoil is turned clockwise from chord resting in horizontal position.

Calculation of the remaining variables for the evaluation of the above expression:

$St_p$ :  $St_p = \frac{f \delta_p^*}{U}$ . This Strouhal Number shall be calculated for each 1/3 octave frequency band,  $f$ .  $U$  is the reference flow velocity and should be calculated from:

$$\text{Velocity} = (\text{Reynolds number} \times 1.78 \text{ E-5 [Pa.s]}) / (1.225 [\text{kg/m}^3] \times 1 [\text{m}])$$

$$St_1: \quad St_1 = 0.02 M^{-0.6}$$

A: The calculation procedure is the same as for the suction side, above, except for the value of  $a$ , that should be calculated as:

$$a = |\log(St_p/St_1)|$$

$K_1$ : The same calculation procedure for the suction side applies.

$\Delta K_1$ : The level adjustment shall be calculated as per:

$$\Delta K_1 = \begin{cases} \alpha [1.43 (R_{\delta_p^*}) - 5.29] & (R_{\delta_p^*} \leq 5000) \\ 0 & (R_{\delta_p^*} > 5000) \end{cases}$$

Where:  $R_{\delta_p^*}$  is the Reynolds number based on the displacement thickness at the TE of the pressure side of the airfoil.

$$R_{\delta_p^*} = \frac{1.225 * U * \delta_p^*}{1.78 \text{ E} - 5}$$

Calculated data export options (saving should be automatic upon calculation).

- If EXPORT data selected (see item 2 above):

Display list of OpPoint for user to select the OpPoint(s) for data export.

Display option for SPL weighting (none, A, B or C filters) selection.

For each OpPoint selected:

Export Op Point header (airfoil, Re, AOA)

Export info on acoustic data header (Source and model; all options on step 4)

Export OASPL to header

Export table with 2 columns:

- (1) SPL 1/3 octave band center frequency
- (2) SPL for each 1/3 octave band