



 TCAA - BANCIIIc3 - NACA 0012- Benchmark

Computational Aero-Acoustics Methodology for Airfoils
Project Summary

January 31, 2024



KEYWORDS:

Computational Aero-Acoustics, CAA, BANCIIIc3, Benchmark, NACA 0012, Airfoil, 3D, 10% span, Acoustic Analogy, Ffowcs Williams-Hawkings, Farassat1A, Finite Volume, transient 1s, CFD, Cell-centered, SnappyHexMesh, 8 inflation layers, TCAE environment, OpenFOAM, compressible, *k- ω -SST DES*, U=53 m/s, Re=70000, AOA 6 degrees, SPL, Polar plots, Sound reconstruction

Authors:

Radek M \acute{a} ca, radek.maca@cfdsupport.com

Vojtěch Kubáč, vojtech.kubac@cfdsupport.com

Luboš Pirkel, lubos.pirkl@cfdsupport.com

Matthieu Bernard Roger Gelot, mtege@vestas.com

TCAE interface

The screenshot displays the TCAE software interface, which is used for computational fluid dynamics (CFD) simulations. The interface is divided into several panels:

- Left Panel (Simulation Settings):** Contains various configuration options for the simulation, including:
 - SIMULATION:** CAE source (CFD simulation), Adaptive strategy (Pressure-based), Physical formulation (Acoustic), Custom time range (0 to 0.5), Time step (0.001), and Time end (0.5).
 - Observers:** observer group 1, observer group 2, observer group name (AcousticObserver), Location (Single observer position), Position (0.0, 0.0, 0.0), and Add virtual observers.
 - Probes:** probe 1, probe 2, probe 3, probe 4, Probe location (0.3556, 0.001182, 0.0), and Mesh (map.359237000021).
 - PHYSICAL CONSTANTS:** Physical constants (Speed of sound: 331.5, Reference sound pressure: 200.0).
 - SIGNAL PROCESSING:** DC filter (Butterworth), Filter order (3), Cutoff frequency (30), AA filter (Butterworth), Filter order (4), Cutoff frequency (0.4), Signal source (Wave), Number of 1/3 bands (3), Output (0.5), and Use 1/3 banding.
 - POST PROCESSING:** Breakout (enabled), Observer summary (enabled), Observer location (enabled), Observer position (enabled), Observer radius (0.0), and Observer color (red).
- Top Center Panel:** A 3D visualization of a turbine blade, colored red, with a color scale legend on the right labeled "ComponentColors" ranging from 0 to 11.
- Bottom Center Panel:** A 3D visualization of a turbine blade, colored green, with a color scale legend on the right labeled "ComponentColors" ranging from 0 to 11.
- Right Panel (Analysis Results):** Contains several plots and tables:
 - Frequency [Hz]:** A plot showing the frequency spectrum of the simulation results.
 - Probes:** A table listing the positions of five probes:

Probe Nr.	Position
1	(0.3556 0.001182 0.02)
2	(0.4 0 0.02)
3	(0.4 0 0)
4	(0.4 0 0.04)
5	(0 0 0.02)
 - Power spectral density of surface pressure:** A plot showing the pressure spectral density (PSD) of the surface pressure, with Pressure [dB/Hz] on the y-axis and Frequency [Hz] on the x-axis.
 - Polar plots:** A plot showing the polar sound pressure level, with Circular Observers-Distribution-Im-TE - 1000 Hz on the y-axis and Polar sound pressure level on the x-axis.
 - Velocity Magnitude:** A plot showing the velocity magnitude (m/s) over iterations, with Velocity Magnitude [m/s] on the y-axis and Iterations [-] on the x-axis.
 - Residuals:** A plot showing the residuals (log scale) over iterations, with Residuals [-] on the y-axis and Iterations [-] on the x-axis.
- Bottom Right Panel (Simulation Stats):** A table providing summary statistics for the simulation:

Test Case Name	BANCII-case3-final-case
Number of Points [-]	1
Machine Type	virtualTunnel
Number of Components [-]	2
	(topology)
Mesh Size [cells]	Co1 : 124600
	(details)
	Co2 : 3100429
	Total : 3225029
Simulation score [-]	defaults
Average y+ at walls [-]	defaults
Wall-clock time [h:mm:ss]	00:03:50 (meshing)
	10:25:10 (calculation)
Parallel Processors [-]	32
Fluid Name	air
Physical Model	compressible
Numerical model	second
Turbulence model	kOmegaSSTDES

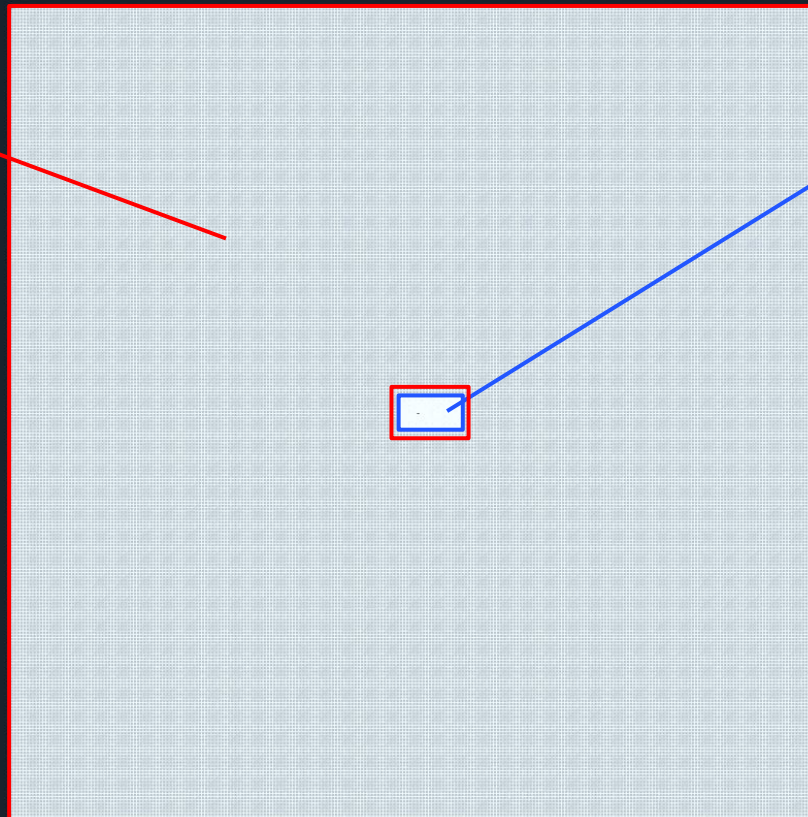
Mesh Topology

- blockMesh

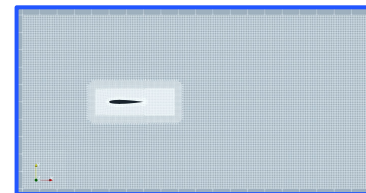
```
13 X0max 25.0;  
14 X0min -25.0;  
15  
16 Y0max 25.0;  
17 Y0min -25.0;  
18  
19 Z0max 0.04;  
20 Z0min 0.00;  
21  
22 XImax 3.0;  
23 XImin -1.0;  
24  
25 YImax 1.0;  
26 YImin -1.0;  
27  
28 xSize 0.2;  
29 ySize 0.2;  
30 zSize 0.02;  
31
```

Span (z-thickness) = 0.04cm
(10% of chord length)

/mnt/users_share/Projects/Vestas/TCAE-
NACA0012-Chord0,4-3DSnappy-Span0,04-Ai
rfoilRefLev55-15nCBL-lesDeltae-4-Eule
r-zubr1234



- snappyHexMesh



name	type	reference frame	min refinement	max refinement	layers
airfoil	wall	static	3	5	8
interface	freestreamInterface	static	0	0	-
zMax	symmetry	static	0	0	-
zMin	symmetry	static	0	0	-

SnappyHexMesh parameters

Background mesh
cell size: 0.02 Use cube cell

Show background mesh wireframe

Internal point: 1.258 0 0.005

Show internal point as sphere with radius: 10

Cylindrical background mesh

Rotate background mesh

Use gap refinement

refinementRegion 1

Type: Box

Max: 0.75 0.15 0.1

Min: -0.15 -0.15 -0.1

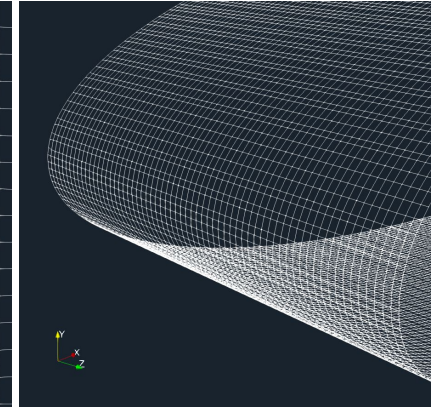
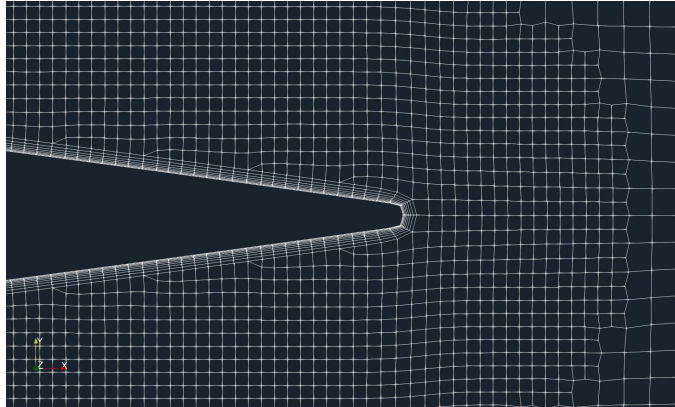
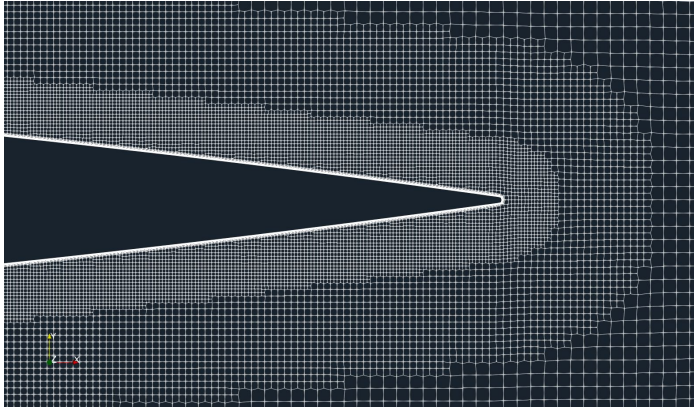
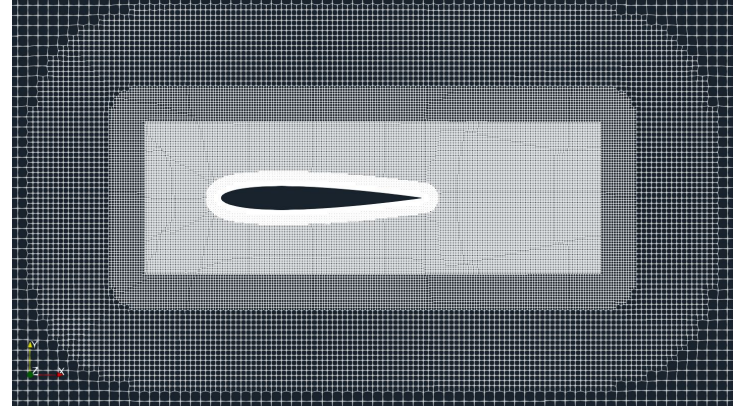
Show refinement region

Mode: Inside

Level: 2

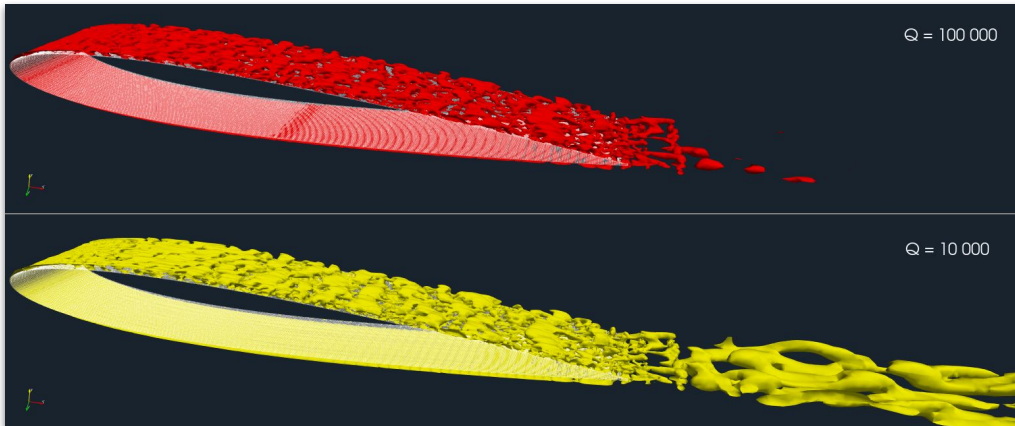
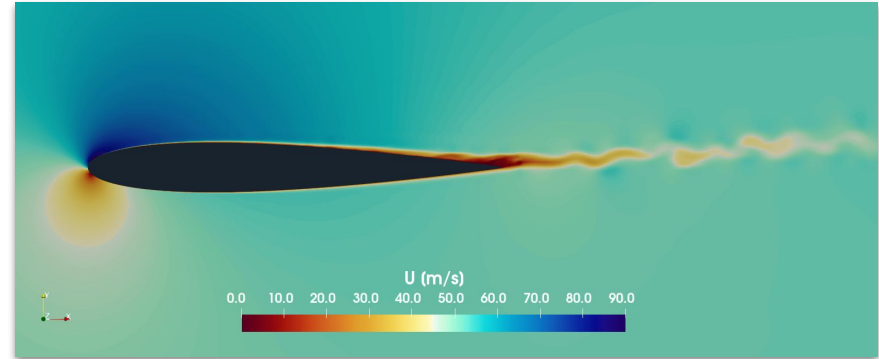
Mesh Statistics

- Hexahedra-dominant mesh
 - Cell size in the refined block: 2.5 mm
 - Cell size near the airfoil: 0.625mm
 - First inflation layer thickness: 0.032mm
 - Inflation layers: 15
 - 64 cells in spanwise direction (span = 40mm ~ 10% chord)
 - Overall cell count: 3 800 000 cells



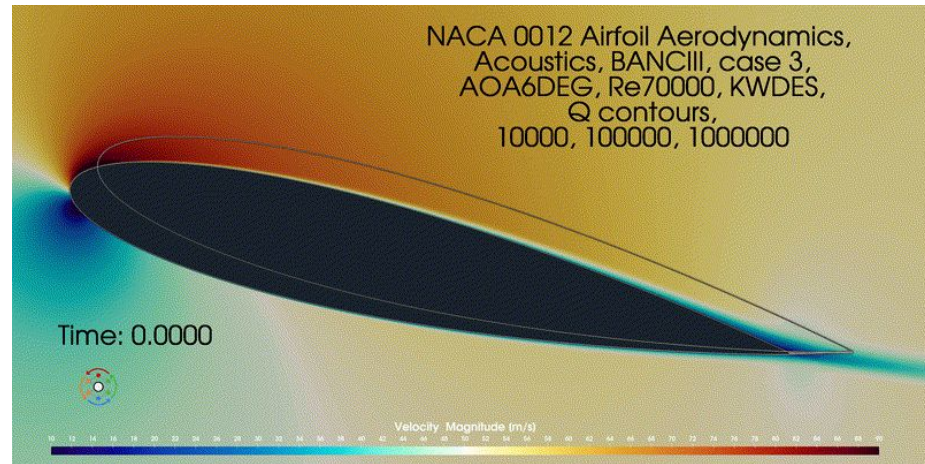
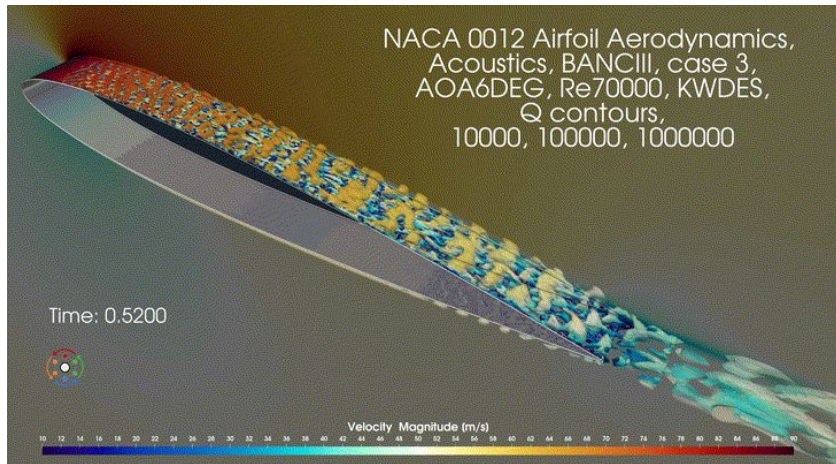
CFD Simulation Setup

- *Transient, compressible solver*
 - Physical run-time: $T=1s$
 - Time step: $5e-5s$
 - Acoustic data sampling: $T=0.5-1s$
 - Sampling the airfoil surface pressure
 - *steady-state (k- ω)* solution initialization



- *BANC III, case 3*
- $U=53$ m/s
- AOA 6 degrees
- Turbulence: *k- ω -SST DES*
- CPU time: ~ 600 core hours (one day with good PC)
- TCAA module (based on libAcoustics)

CFD Simulation Setup

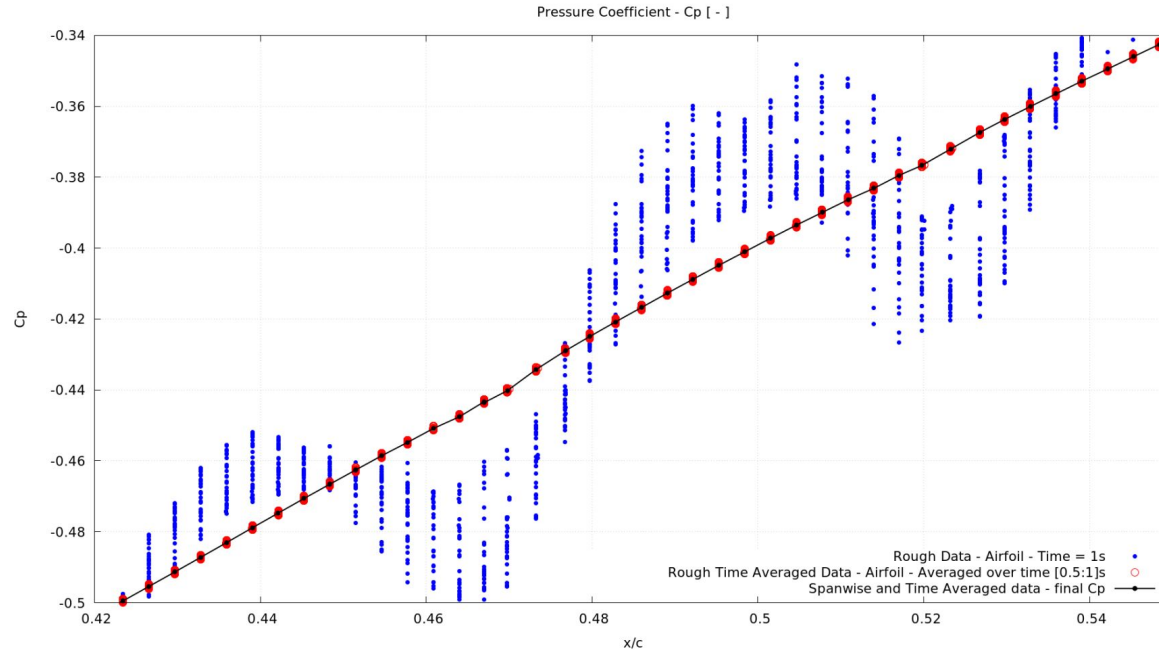


- <https://www.cfdsupport.com/download/NACA0012-BANCIII-CASE3-Q-contours-zoom1-30.gif>
- <https://www.cfdsupport.com/download/NACA0012-BANCIII-CASE3-Q-contours-zoom2-20.gif>
- <https://youtu.be/6mKSCT1-wK4>

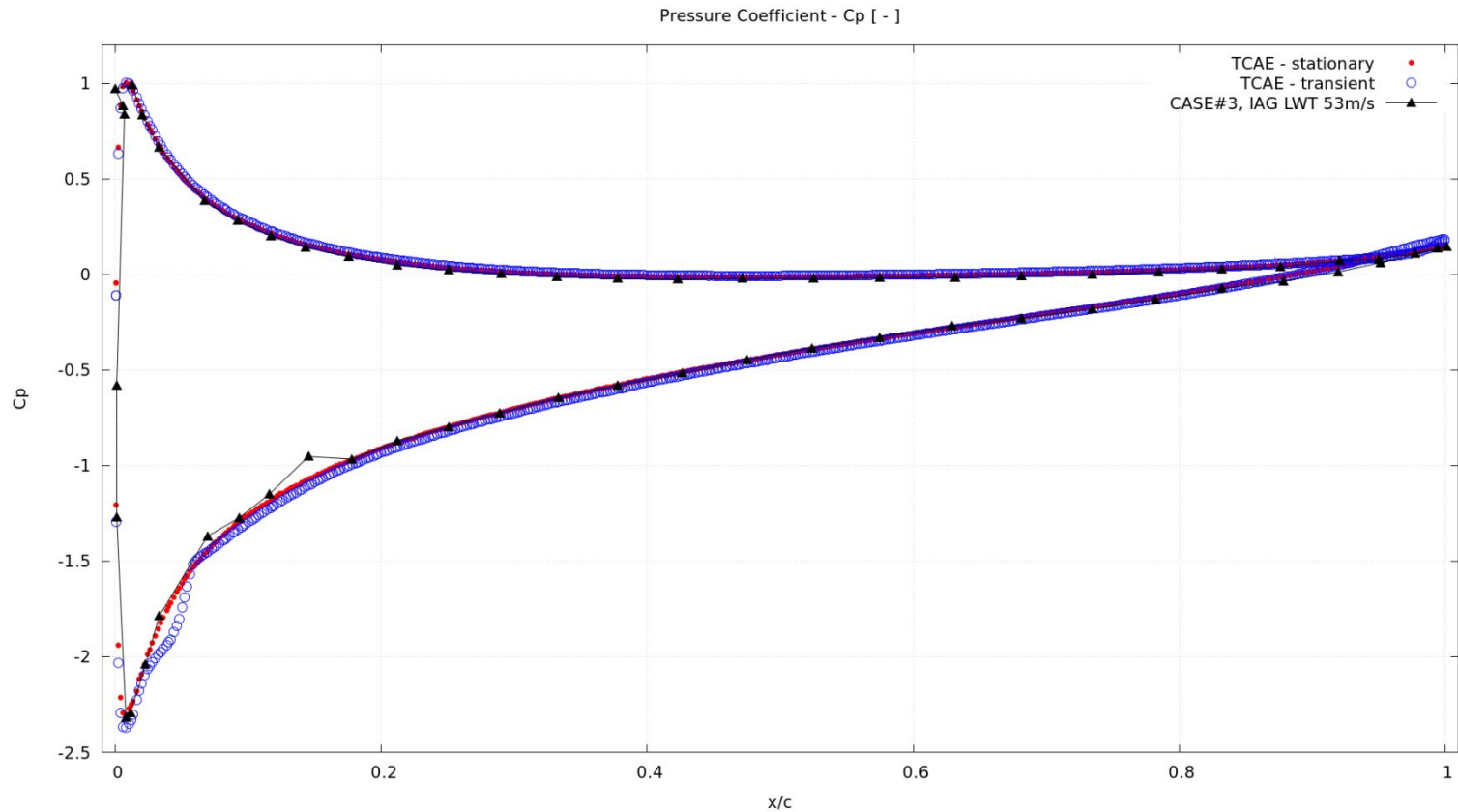
CFD Evaluation

Cp Evaluation

- C_p coefficient is evaluated from *transient* results as a *time* and *spanwise average*
 - Automated processing implemented

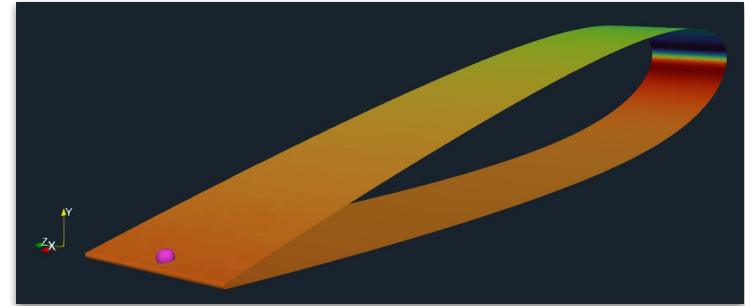


Cp Evaluation

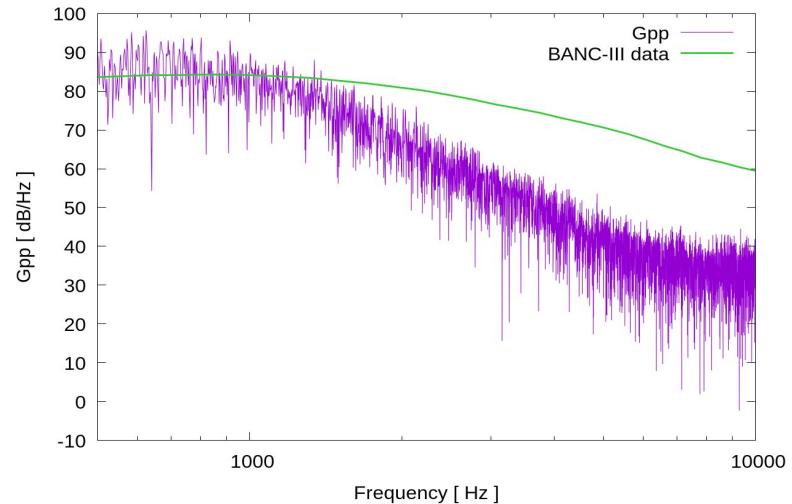
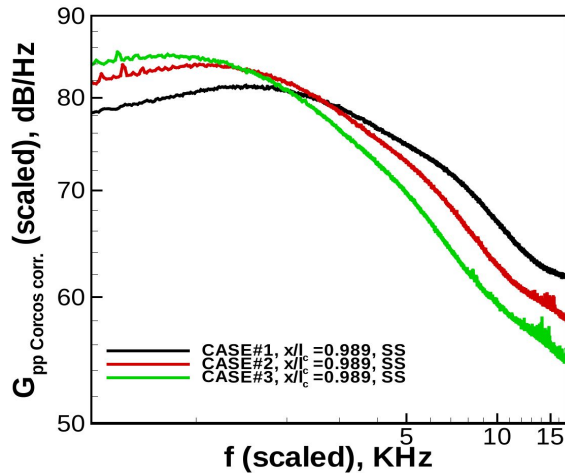


Pressure Evaluation

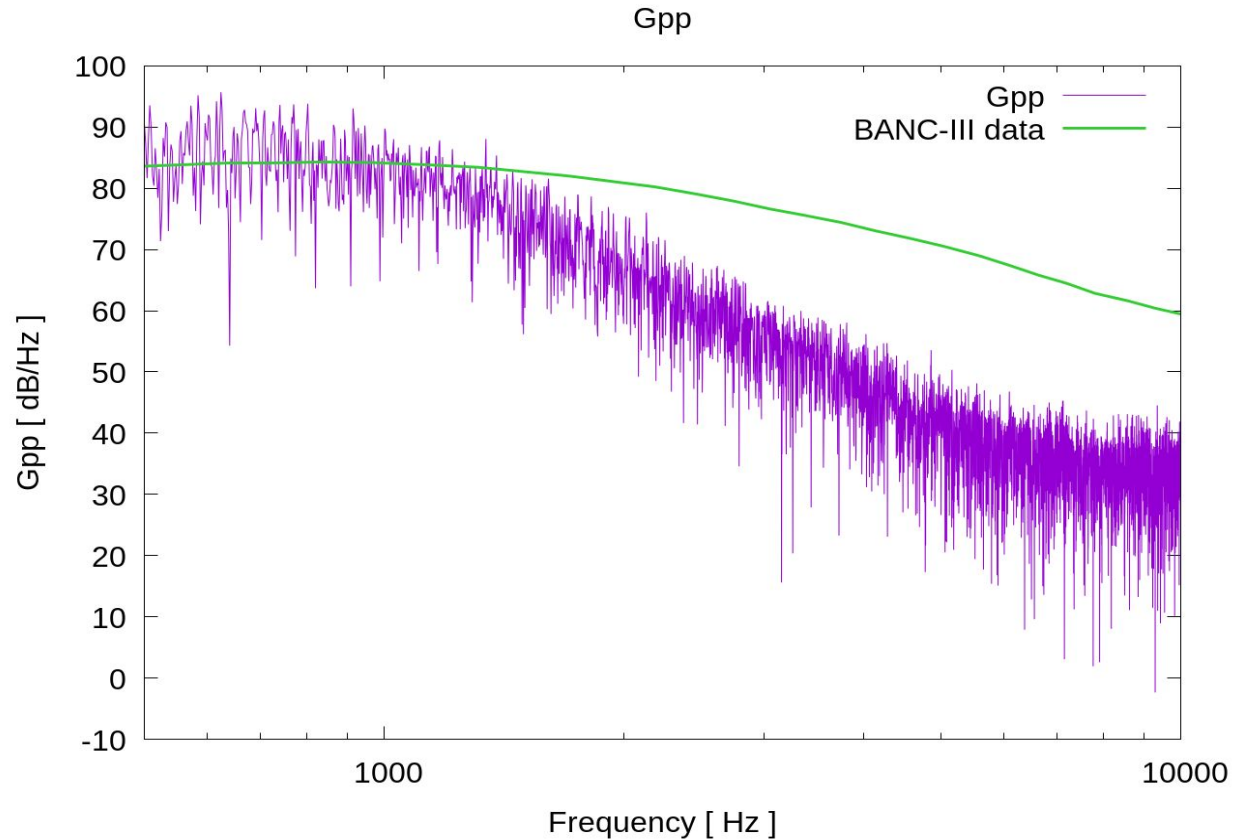
- Power spectral density: BANC-III Report, fig. 10
 - Suction side point [0.3956, 0.0011182, 0.02]
 - Single point close to the trailing edge
 - Surface *pressure* evaluation



Gpp



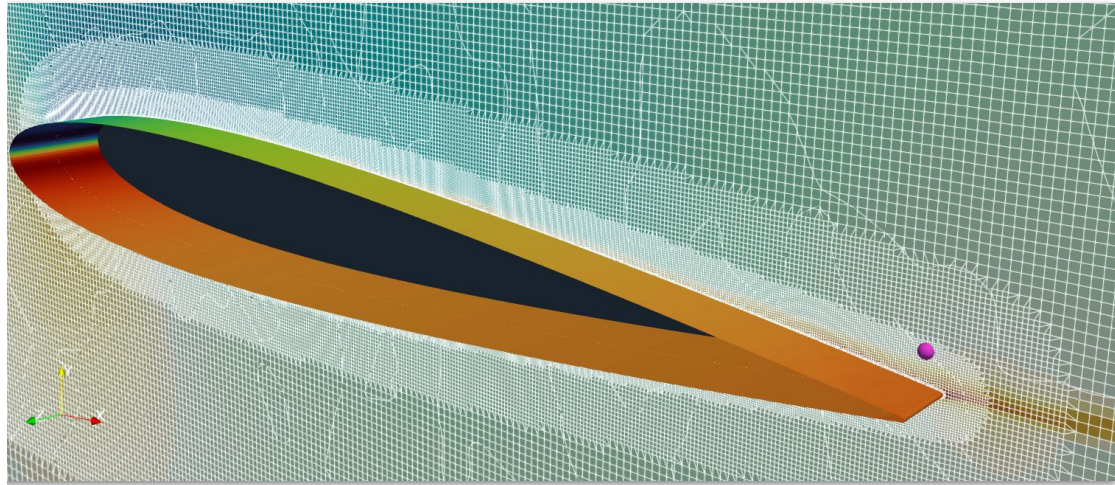
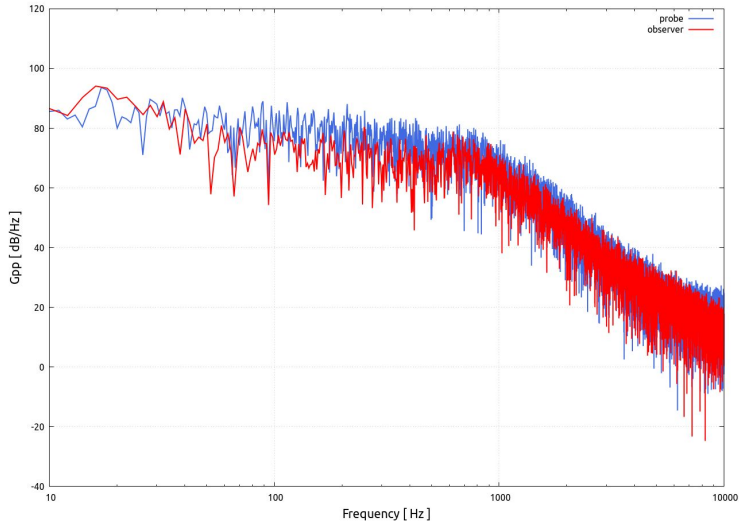
Pressure Evaluation



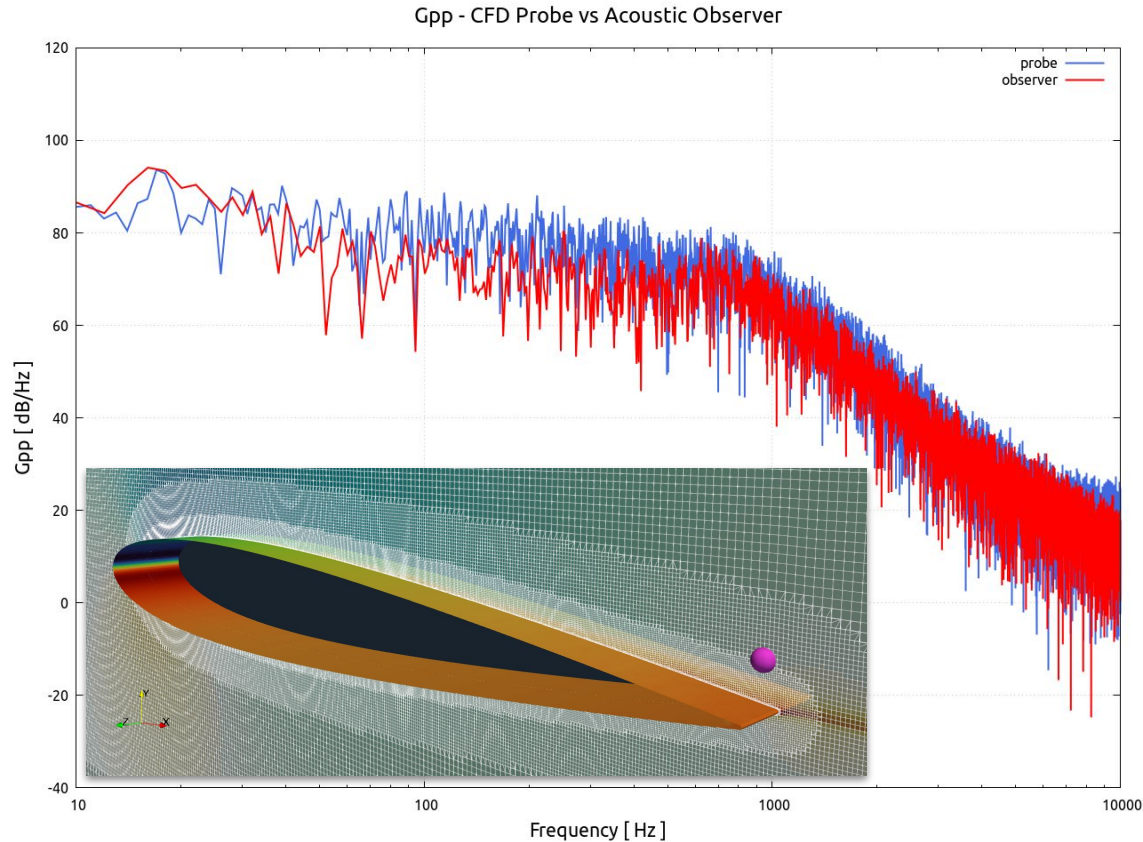
CFD Probe vs Acoustic Observer

- Comparison of power spectral density evaluated from
 - CFD results pressure fluctuations - **Probe**
 - Acoustics pressure fluctuation (Acoustic analogy - FWH) - **Observer**

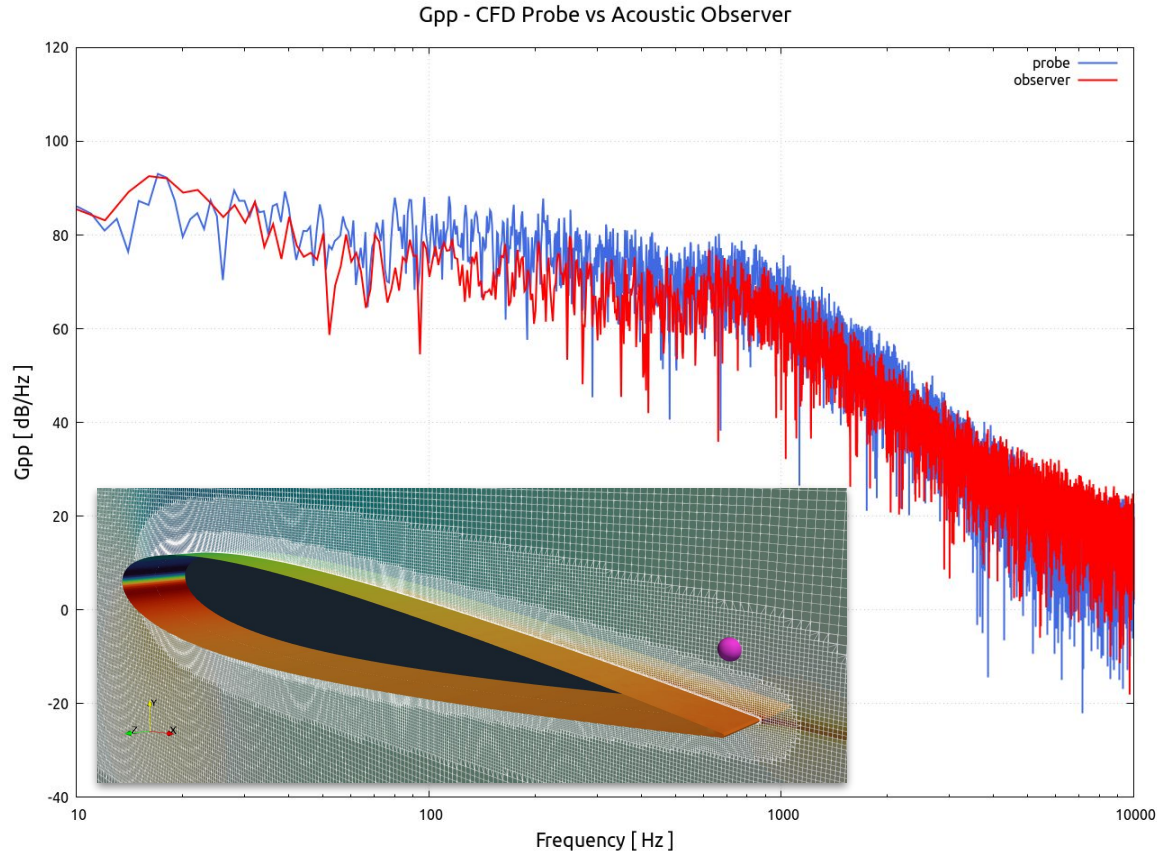
Gpp - CFD Probe vs Acoustic Observer



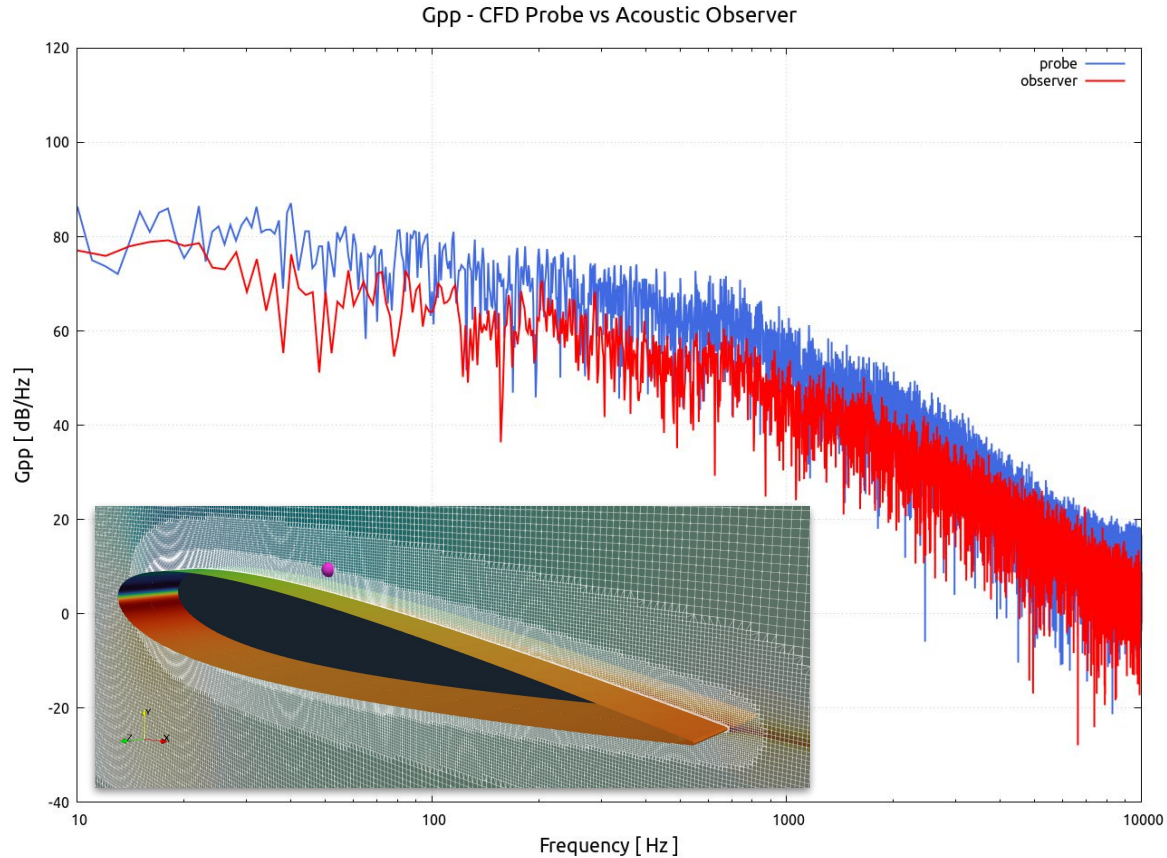
CFD Probe vs Acoustic Observer



CFD Probe vs Acoustic Observer



CFD Probe vs Acoustic Observer



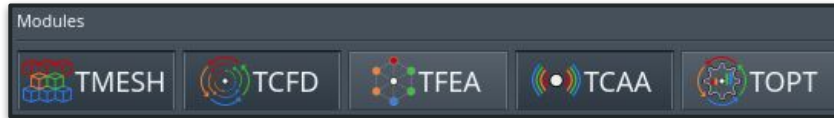
Signal Processing

Signal Processing Setup

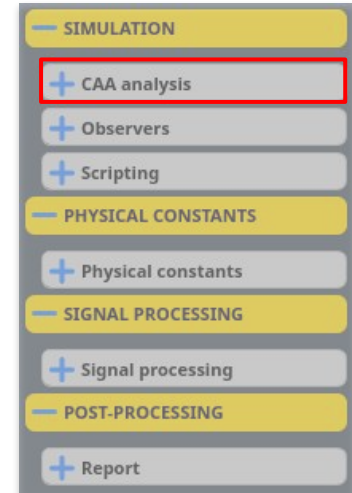
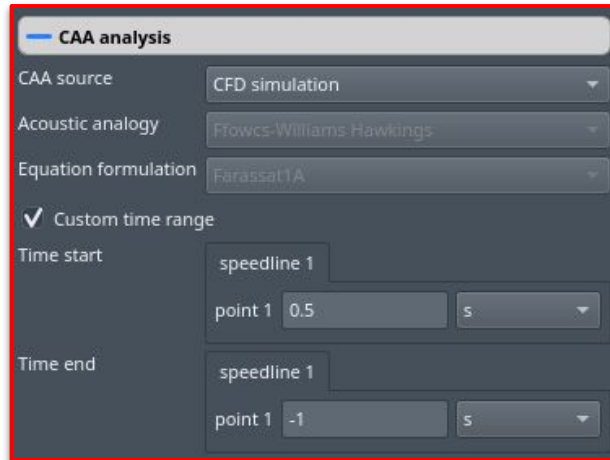
- TCAA module
- Raw signal is centered to origin and Butterworth filters are applied
- Welch method is used to transfer the signal to frequency spectrum
 - Signal is divided into three overlapping segments
 - On each segment Hann window is applied and Fourier transform is executed
 - Transformed segments are reassembled
- PSD and SPL are evaluated from the final signal in frequency domain

TCAA

- The whole workflow is implemented in TCAA module



- Current implementation uses *Farassat1A* equation formulation of *Ffowcs-Williams Hawkings* acoustic analogy

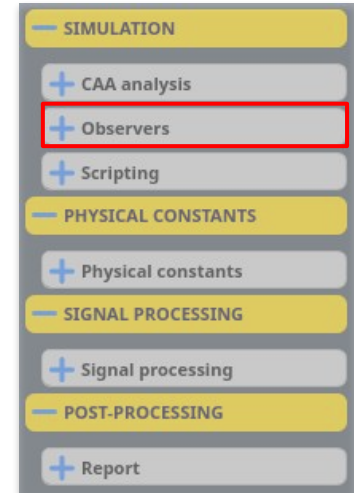


- The source data are taken directly from CFD simulation
- User can defined a custom time range for processing the source data

TCAA

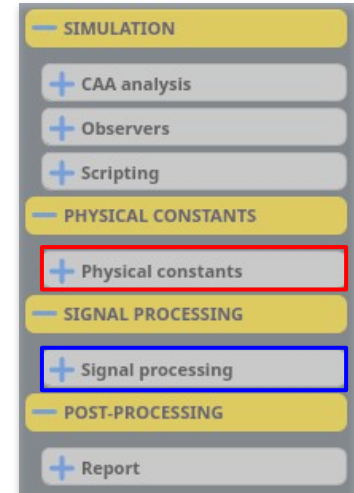
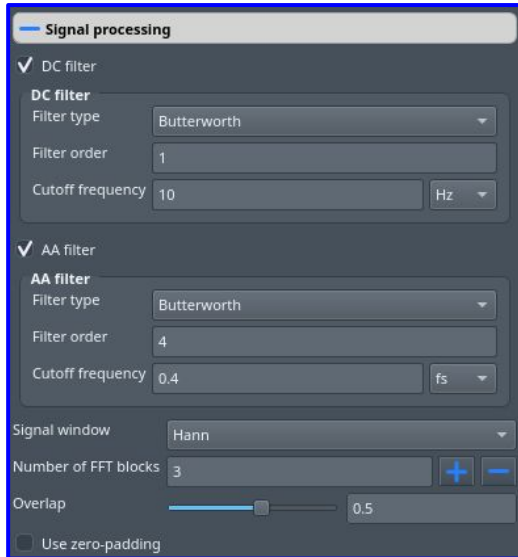
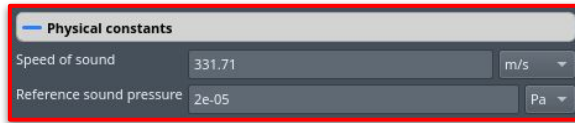
- Observer is a point in the far field where the acoustic pressure is evaluated by acoustic analogy
- Add virtual observers allows to scale the source (CFD) span to a general scale, typically 1m
- Observers location can be also imported from file to define more general distribution

The screenshot shows the 'Observers' configuration panel. At the top, there are two existing observers: 'observer 1' and 'observer 2', each with a red 'x' icon for removal. A blue '+' icon is in the top right corner. Below this, the 'Observer name' field is set to 'observer2'. The 'Import Coordinate file' section includes '+ Import', 'Create', 'Remove', and 'No file' buttons. The 'Position' is defined by three input fields with values 0.4, 1, and 0.02. A checked checkbox 'Add virtual observers' is followed by a 'Virtual observers' section with fields for 'Axis' (0, 0, 1), 'Number of virtual observers' (24), and 'Spacing' (0.04). A checked checkbox 'Symmetrical distribution' is at the bottom.



TCAA

- Physical constants define reference speed of sound and pressure level for 0 dB

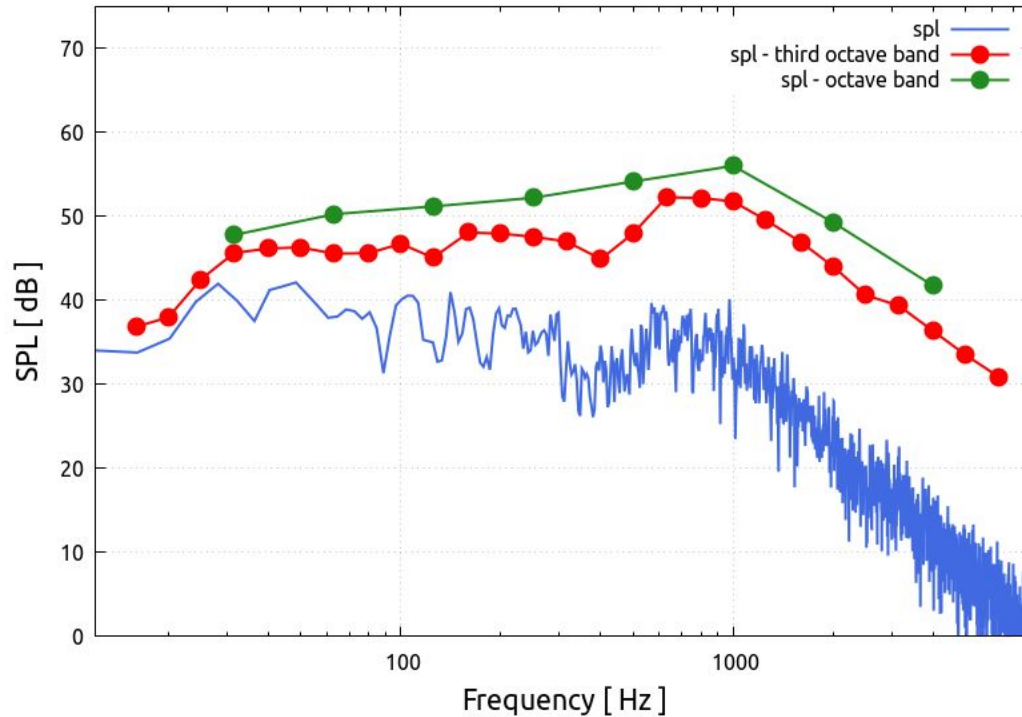


- Signal processing can be applied to clear the input data from unwanted noise, oscillation or data extremes

SPL Evaluation

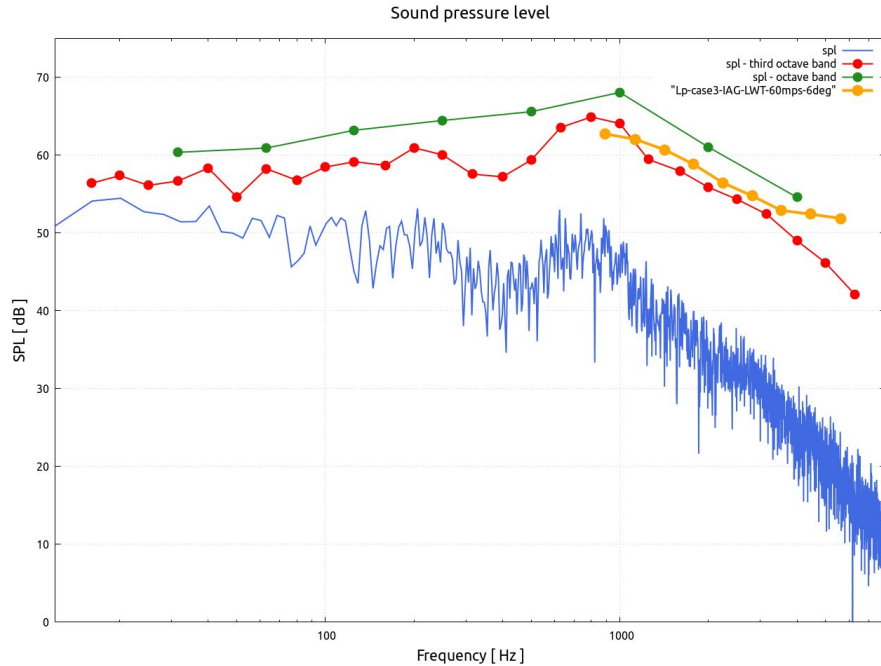
Fundamental Results - SPL - span 0.04m - single observer

Sound pressure level - Single observer

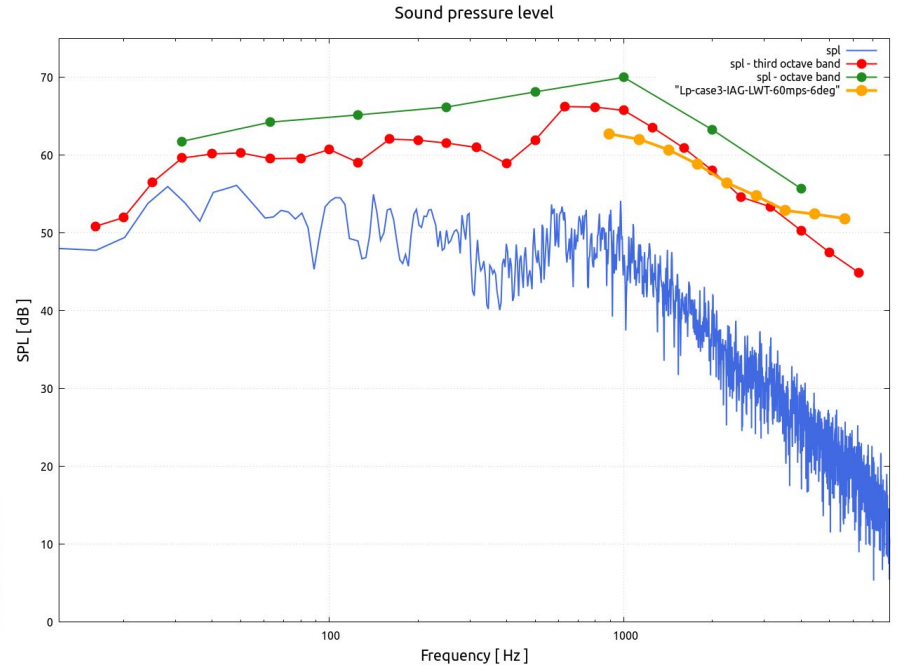


Mesh Convergence Test

Original Mesh, 8IL, 3.2 MCells

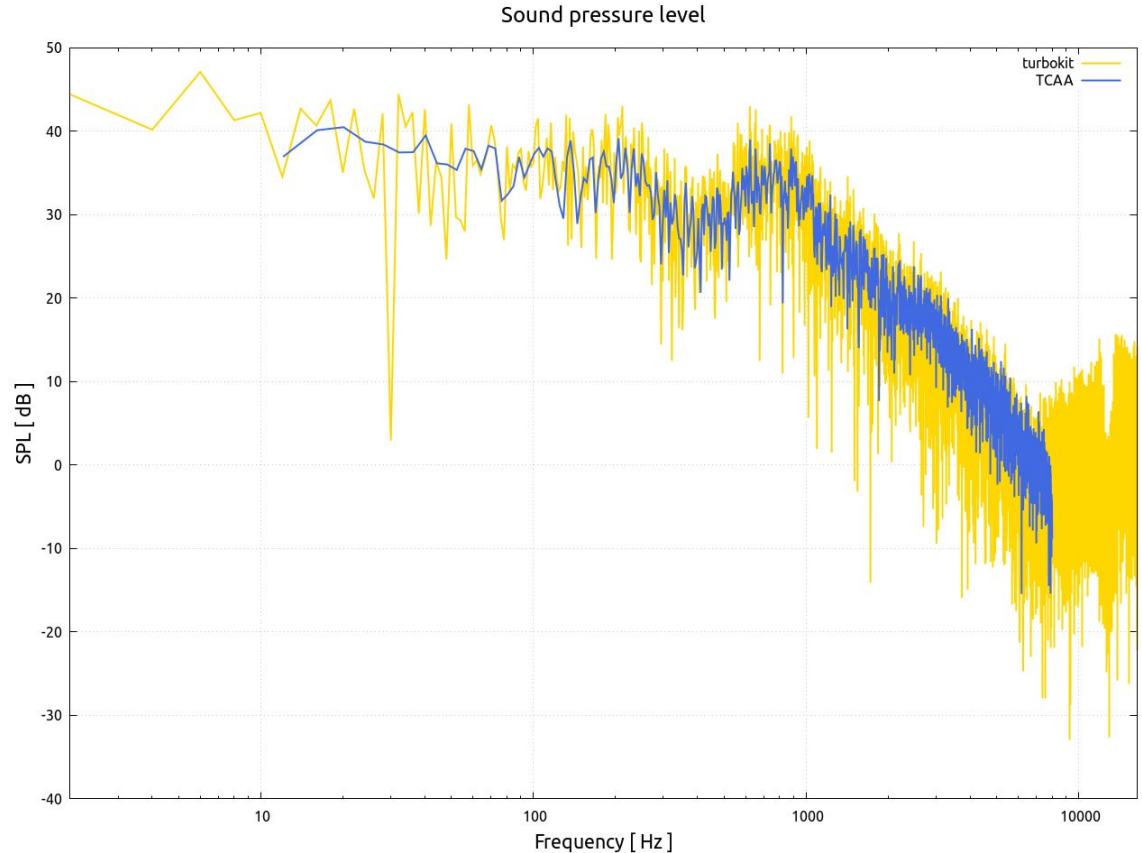


Original Mesh, 15IL, 3.8 MCells

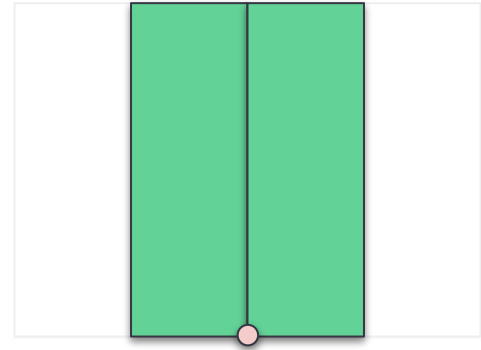
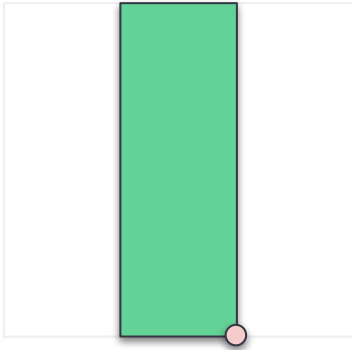


Signal Processing - TCAA vs. Turbokit

- Comparison to other CAA code - Turbokit
- To check possible implementation mistake
- Turbokit is a CAA (FWH-based) code developed by Prof. Sofiane KHELLADI, Ecole Nationale Supérieure d'Arts et Métiers, Paris



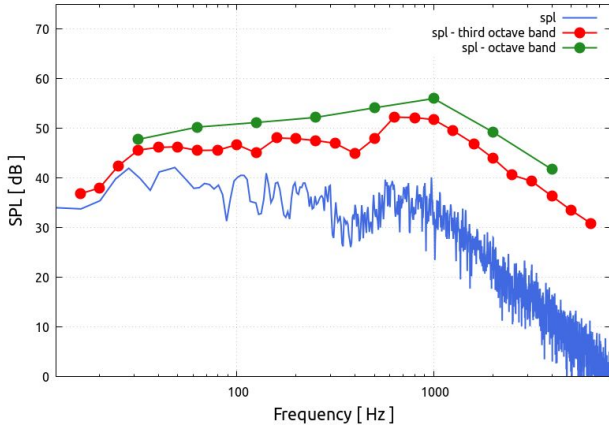
$10\log_{10}$ transformation



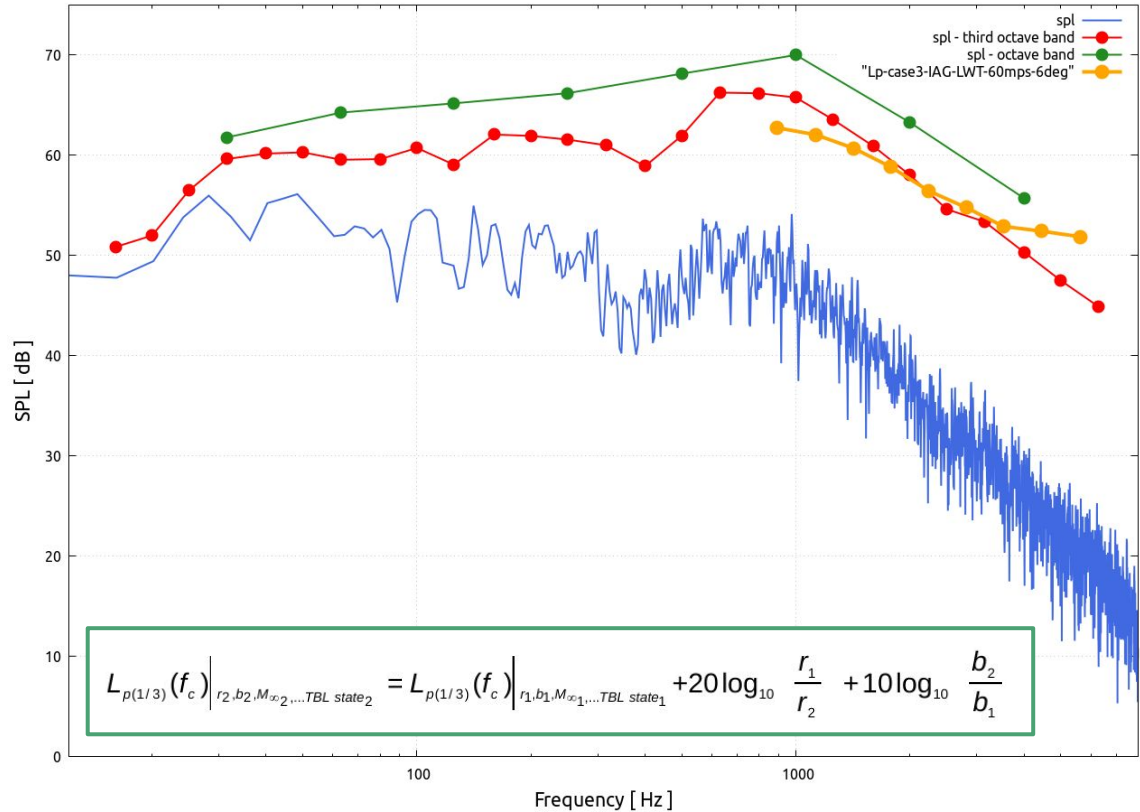
$$L_{p(1/3)}(f_c) \Big|_{r_2, b_2, M_{\infty 2}, \dots, TBL \text{ state}_2} = L_{p(1/3)}(f_c) \Big|_{r_1, b_1, M_{\infty 1}, \dots, TBL \text{ state}_1} + 20\log_{10} \frac{r_1}{r_2} + 10\log_{10} \frac{b_2}{b_1}$$

Scaling to 1m span by the orig. article - SPL - span 1.00m

Sound pressure level - Single observer



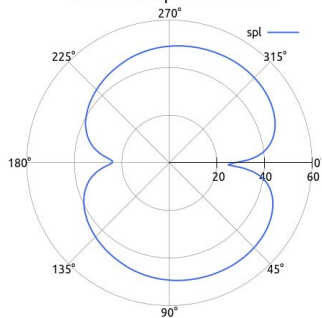
Sound pressure level - Scaled



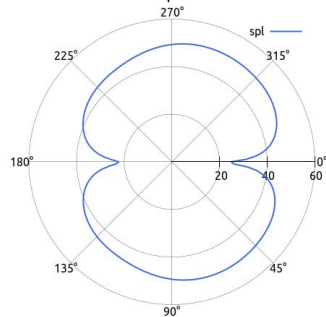
Polar Plots of SPL

500Hz, 800Hz, 1000Hz, 1250Hz, 1600Hz, 2000Hz, 2500Hz, 3150Hz, 4000Hz, 5000Hz

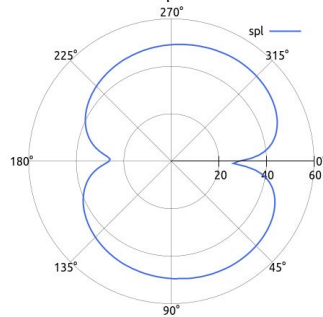
Polar sound pressure level



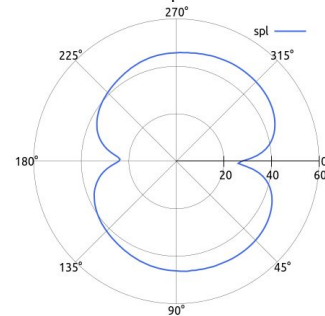
Polar sound pressure level



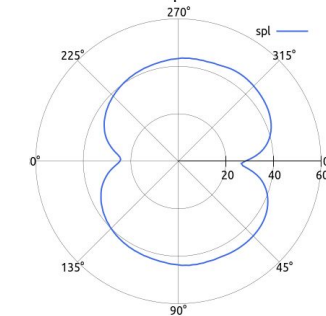
Polar sound pressure level



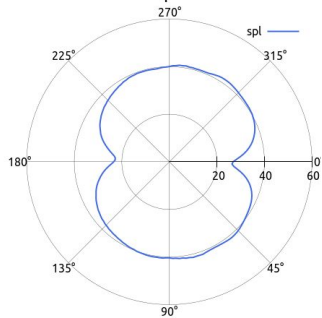
Polar sound pressure level



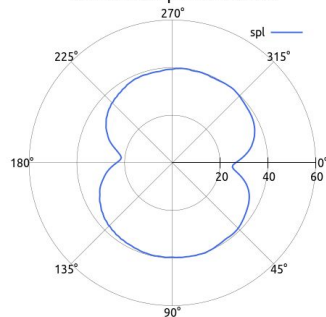
Polar sound pressure level



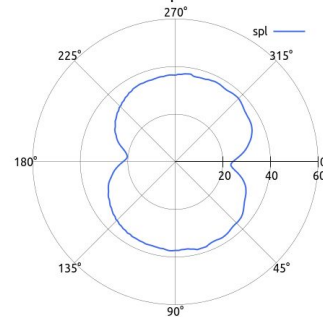
Polar sound pressure level



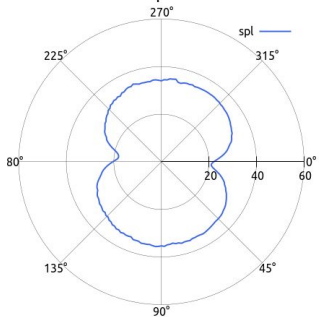
Polar sound pressure level



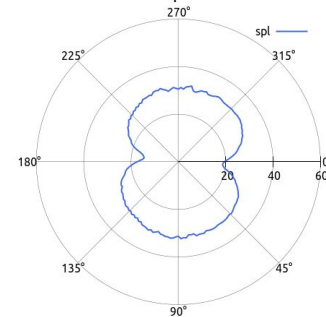
Polar sound pressure level



Polar sound pressure level



Polar sound pressure level



Conclusions

Conclusion

- The workflow is created and ready to use, The results pass the benchmark, Simulations are repeatable, All the data are available for further processing.
- The lesson has been taken, Project Work Hours: >400 [hours] (Research, Implementation, Setup & Simulation Runs, Evaluation).
- Total CPU time: >60 000 [core*hours].
- It has been shown how to make a comprehensive Computational Aeroacoustics analysis on an airfoil in a single automated workflow.
- The TCAE results were successfully compared to the measurement data and with other CFD simulation results.
- There was no special tuning used in the CFD simulation at all. There remains a lot of space for tuning CFD methodology, especially for mesh resolution, turbulence modeling, and numerical schemes.
- TCAE has shown to be a very effective tool for Computational Aero-Acoustics simulations.
- This benchmark was intentionally written so short not to overwhelm its reader with too many details. The original intention was to show the modern simulation workflow and its accuracy.
- The benchmark details are listed in the references below.
- All the technical details regarding CFD & FEA simulation are listed in the [TCAE Manual](#).
- The benchmark geometry and data are freely available for download on the CFDSUPPORT website <https://www.cfdsupport.com>.
- More information about [TCAE](#) can be found on CFD SUPPORT website: <https://www.cfdsupport.com/tcae.html>
- Questions will be happily answered via email info@cfdsupport.com.

References

- [1] [Herr](#), Michaela & Ewert, Roland & Rautmann, Christof & Kamruzzaman, M. & Bekiropoulos, Dimitrios & Iob, Andrea & Arina, Renzo & Batten, Paul & Chakravarthy, Sukumar & Bertagnolio, Franck. (2015). Broadband Trailing-Edge Noise Predictions-Overview of BANC-III Results. 10.2514/6.2015-2847.
- [2] TCAA simulation REPORT: <https://www.cfdsupport.com/download/report/naca0012-acoustics/TCAAREport.html>
- [3] Case study: <https://www.cfdsupport.com/naca-0012-acoustic-benchmark.html>
- [4] https://en.wikipedia.org/wiki/Sound_pressure
- [5] <http://www.sengpielaudio.com/calculator-leveladding.htm>
- [6] <https://www.linkwitzlab.com/faq.htm#Q21>
- [7] <http://physics.bu.edu/py231/db3.pdf>
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The END.