

Aeroacoustic characterization of a NACA 63(3)-018 airfoil with trailing-edge serrations: a benchmarking study across facilities over a wide Reynolds number range

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Outline

- Benchmark history and goals
- Airfoil models and wind-tunnel facilities
- Set-ups and experimental techniques
- Results
- Dataset summary
- Conclusions and next steps

Benchmark history and goals



History:

- Extension of the Benchmarking problems for Airframe Noise Computations (BANC) in the AIAA/CEAS framework
- Facilitated by the IEA Wind TCP Task 39 corporative framework, aiming at consolidating knowledge on wind turbine noise for quiet wind turbine technologies

Goals: create verified experimental data on trailing-edge noise sources and noise reduction devices (trailing-edge serrations) with applications for the wind turbine industry:

- Several research facilities;
- Different Reynolds numbers and AoA conditions;
- Baseline and serrated trailing edge configurations.



Benchmark goals
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2D NACA 63(3)-018 airfoil models

- Symmetric airfoil;
- Favorable pressure gradient up to 30% of the chord;
- Thickness-to-chord ratio 18%, Trailing-edge thickness = 0.15%;
- Small trailing-edge angle (3.2 degrees).

Small model

- 0.2 m chord;
- 0.4, 0.6 or 0.8 m span;
- Embedded pressure taps;
- Removable TE inserts;
- Re_c up to 1×10^6 .



Large model

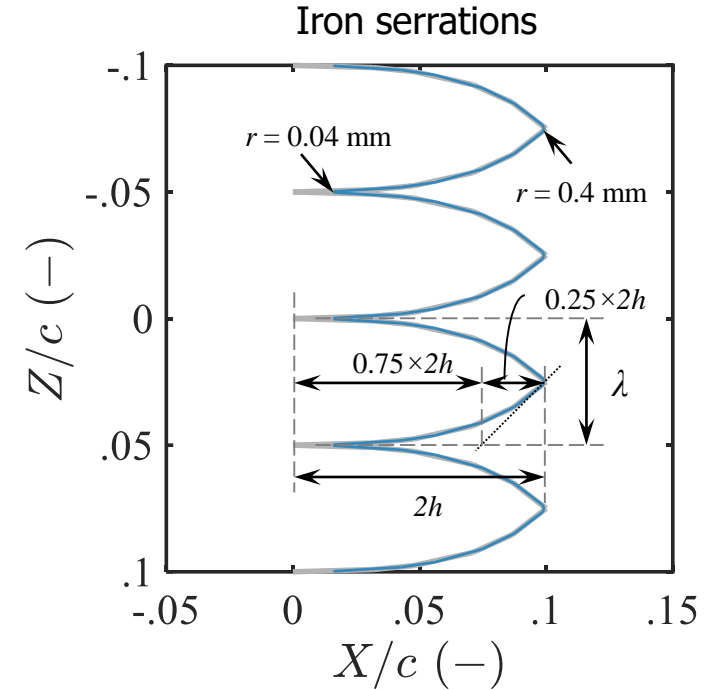
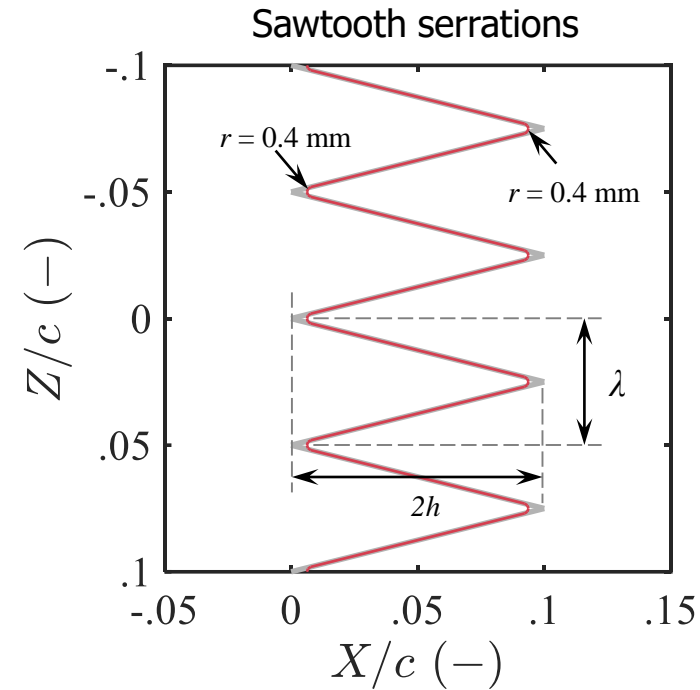
- 0.9 m chord;
- 2.0 m span;
- Embedded pressure taps;
- Re_c up to 4.3×10^6 .



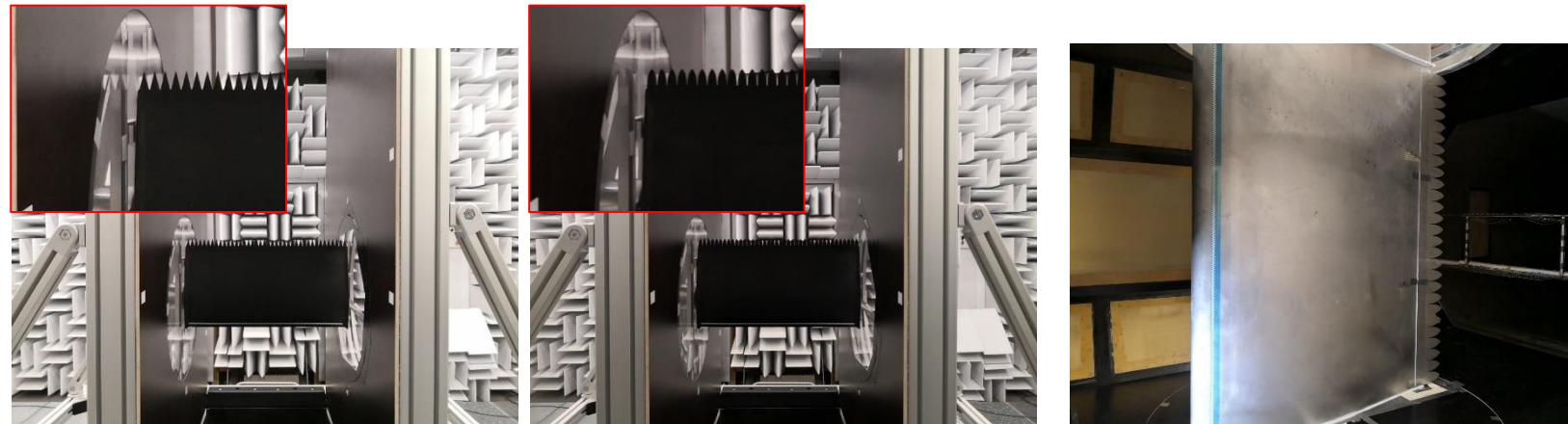
c : chord
 h : serrations amplitude
 r : fillet radius
 λ : serrations wavelength

Trailing edge serration cases

— Geometry in Avallone et al.
 — Present geometry

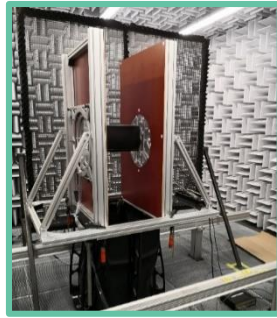


$2h = 0.1c$
 $\lambda = 0.05c$

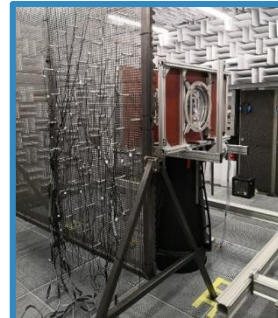


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Covering a broad Reynolds number range using multiple models and facilities



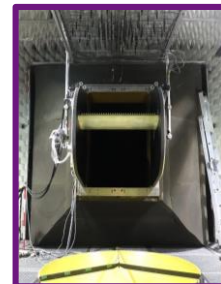
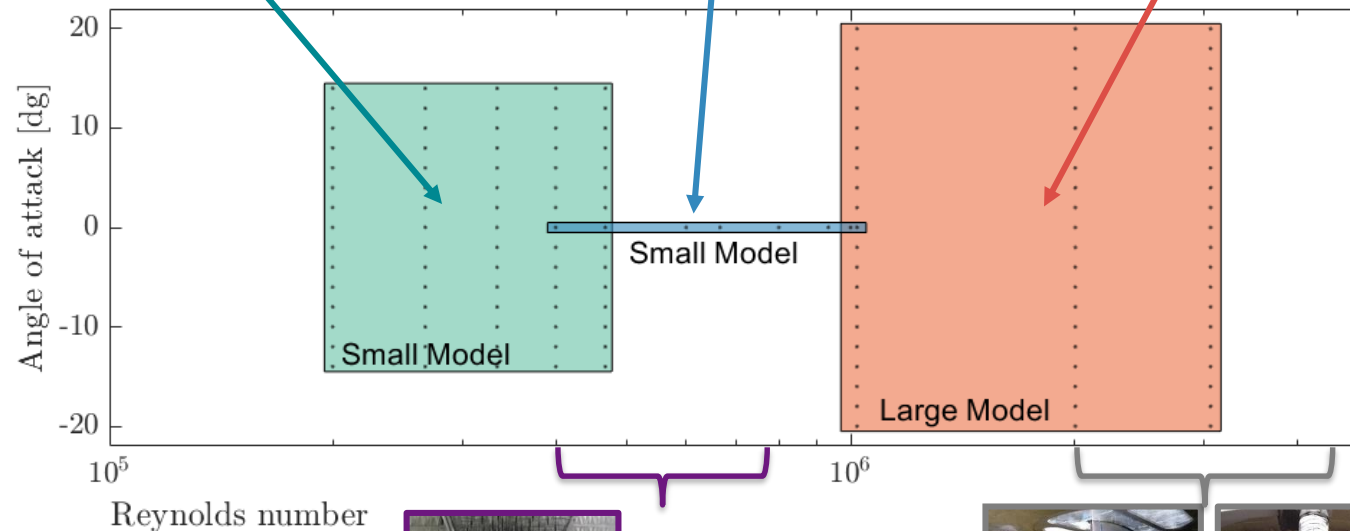
A-Tunnel (nozzle 40 x 70 cm)



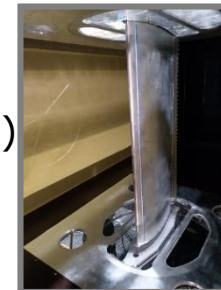
A-Tunnel (nozzle 40 x 25 cm)



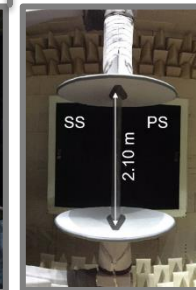
LTT (125 x 180 cm)



AWB
(nozzle 80 x 120 cm)



DTU-PLCT
(nozzle 200 x 300 cm),
Re up to 4×10^6

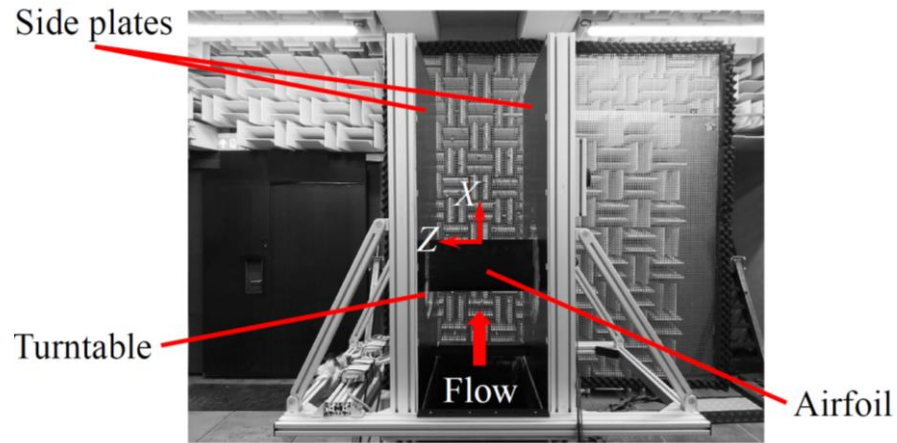


DNW-NWB
(nozzle 325 x 280 cm),
Re up to 4.3×10^6

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Wind-tunnel facilities involved (1/2)

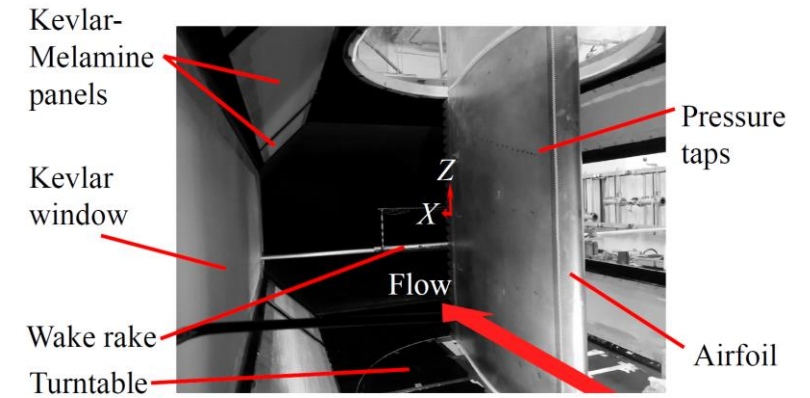
Small model → A-Tunnel (TU Delft)



- Anechoic tunnel (A-Tunnel);
- Open test section, different nozzles.

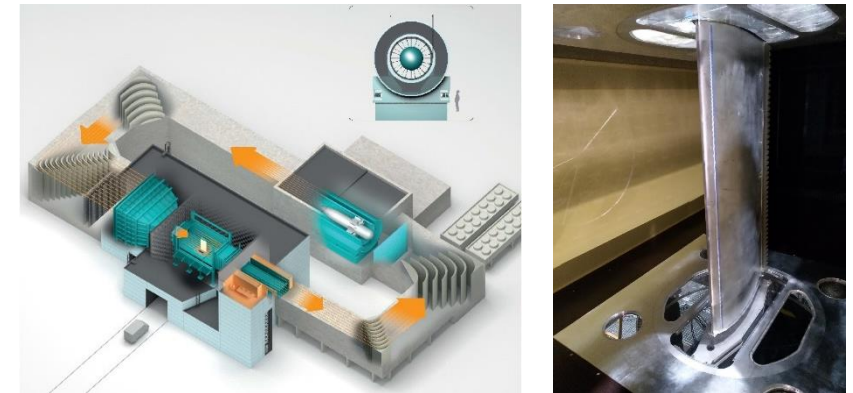
Small model → AWB (DLR) (next slide)

Large model → LTT (TU Delft)



- Low Turbulence Tunnel (LTT);
- Kevlar test section.

Large model → PLCT (DTU)

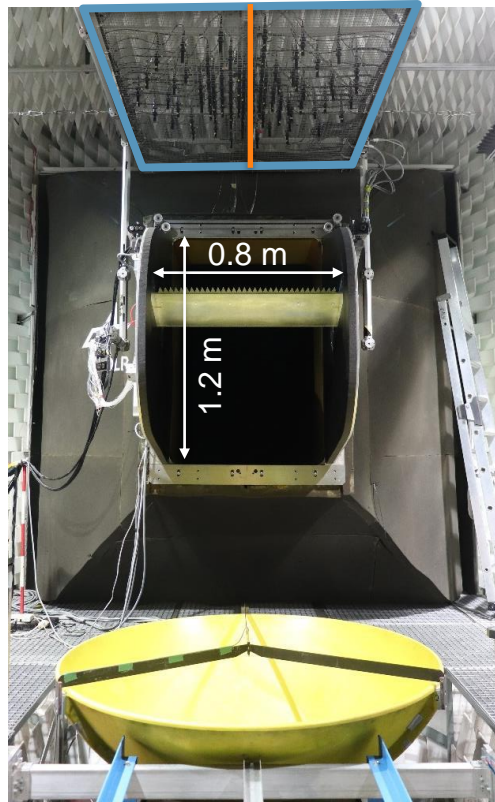


Large model → NWB (DLR) (next slide)

Wind-tunnel facilities involved (2/2)

Small model → AWB

Acoustic Wind-Tunnel Braunschweig



1-m-diameter array
(96 mics.)

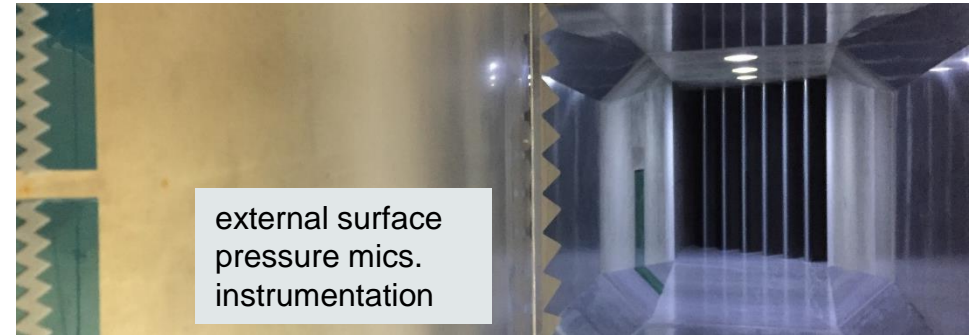
line array of free
field mics.

1.4-m-diameter
elliptical mirror

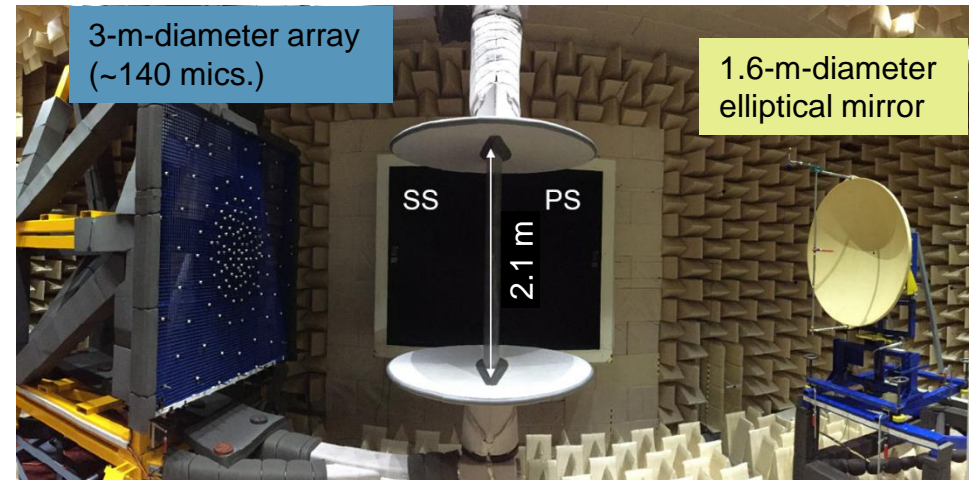
- Anechoic facility with open test section;
- Nozzle 80x120 cm (up to 60 m/s)

Large model → DNW-NWB

Low-Speed Wind-Tunnel Braunschweig



external surface
pressure mics.
instrumentation



3-m-diameter array
(~140 mics.)

1.6-m-diameter
elliptical mirror

SS

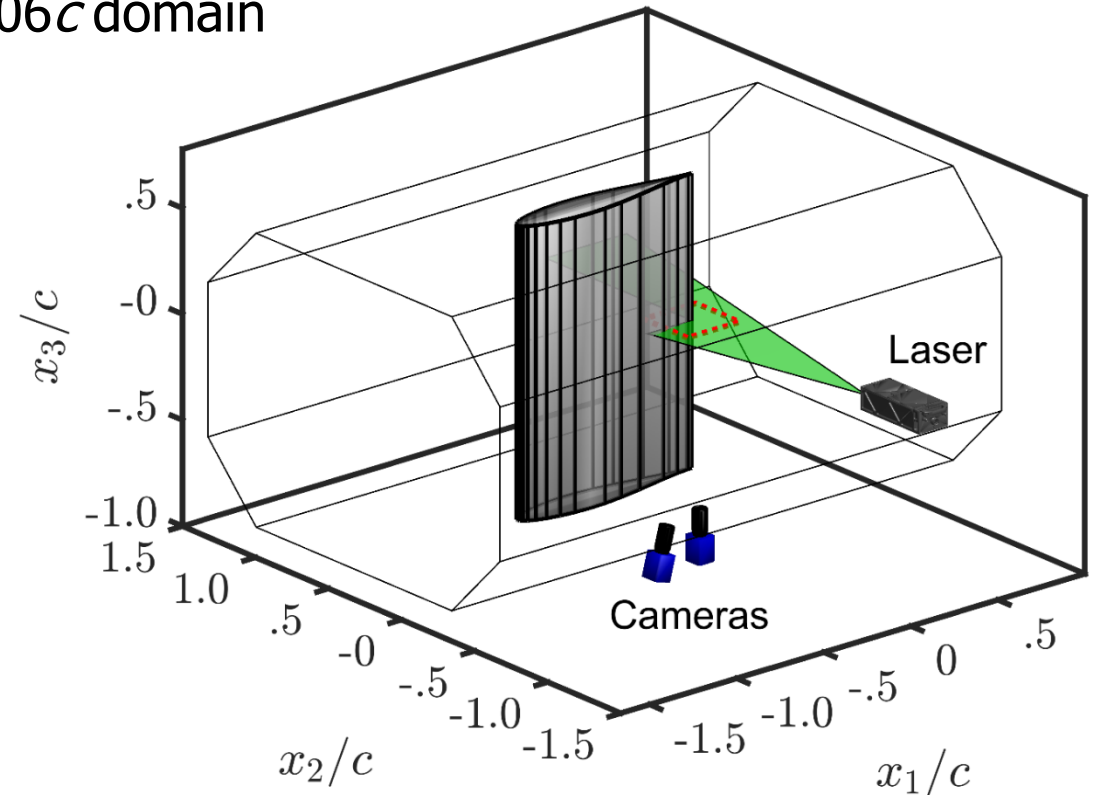
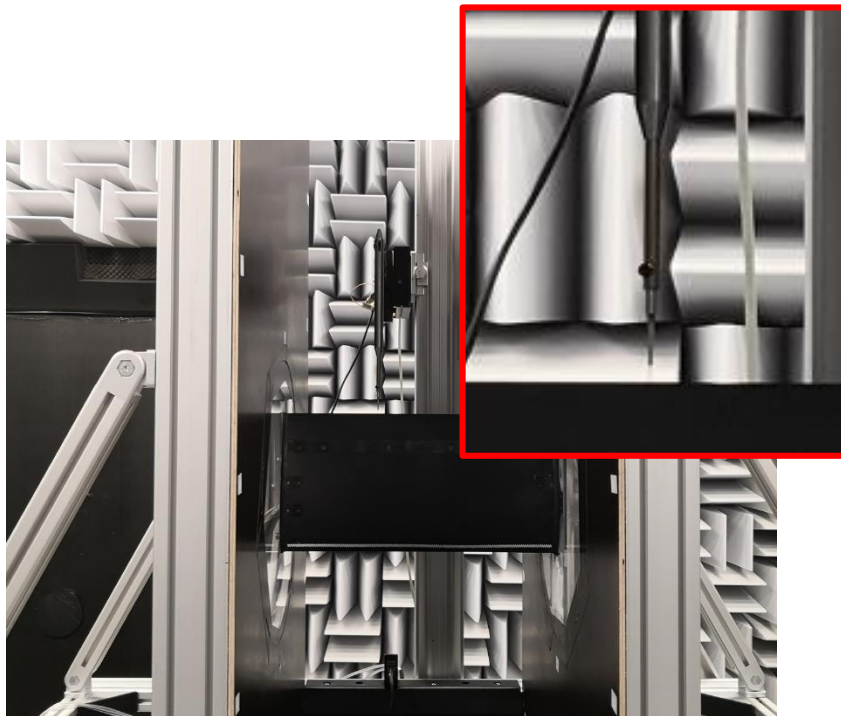
PS

2.1 m

- Closed and open (anechoic) test sections
- Nozzle 325x280 cm (up to 80 m/s in open test section)

Measurement techniques: Steady aerodynamic data

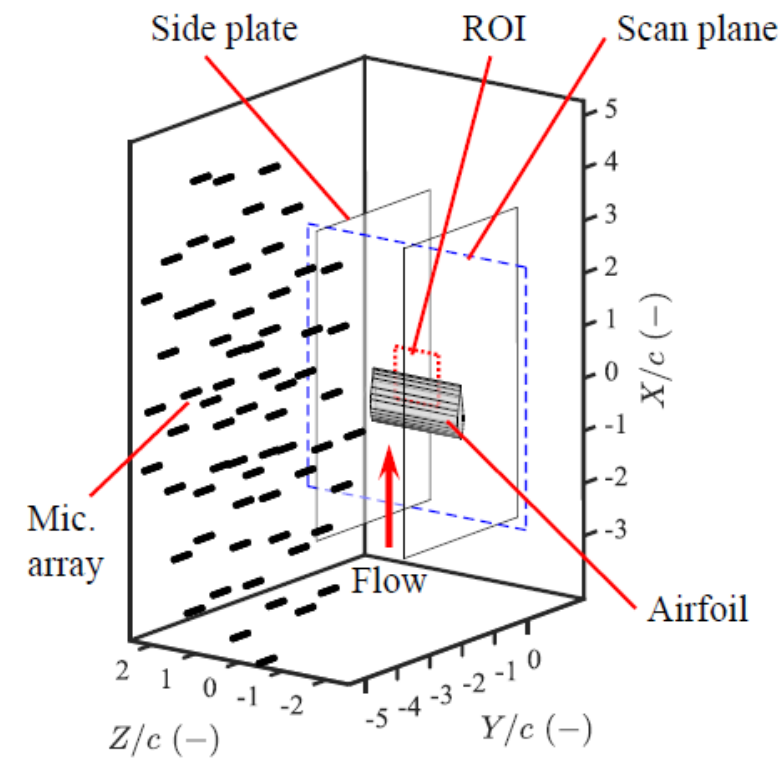
- Lift and drag:
 - Built-in pressure taps;
 - Wake rake.
- Boundary-layer profiles:
 - A-Tunnel: hot-wire anemometry, 98% chord;
 - LTT: Stereo-PIV, $0.15c \times 0.06c$ domain



c : chord
 f_s : sampling frequency
 t_{samp} : sampling time

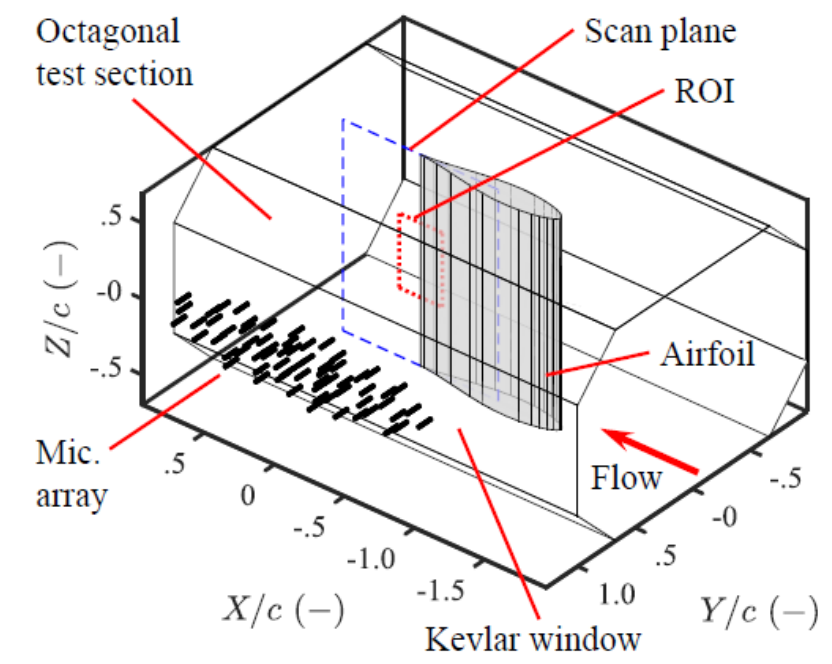
Measurement techniques: Acoustics

Small model → A-Tunnel



- Array of 64 GRAS 40PH microphones;
- $f_s = 51.2 \text{ kHz}$, $t_{\text{samp}} = 30 \text{ s}$;
- Source Power Integration (SPI) beamforming;
- Integration area = $c \times c$ centered at the trailing edge.

Large model → LTT

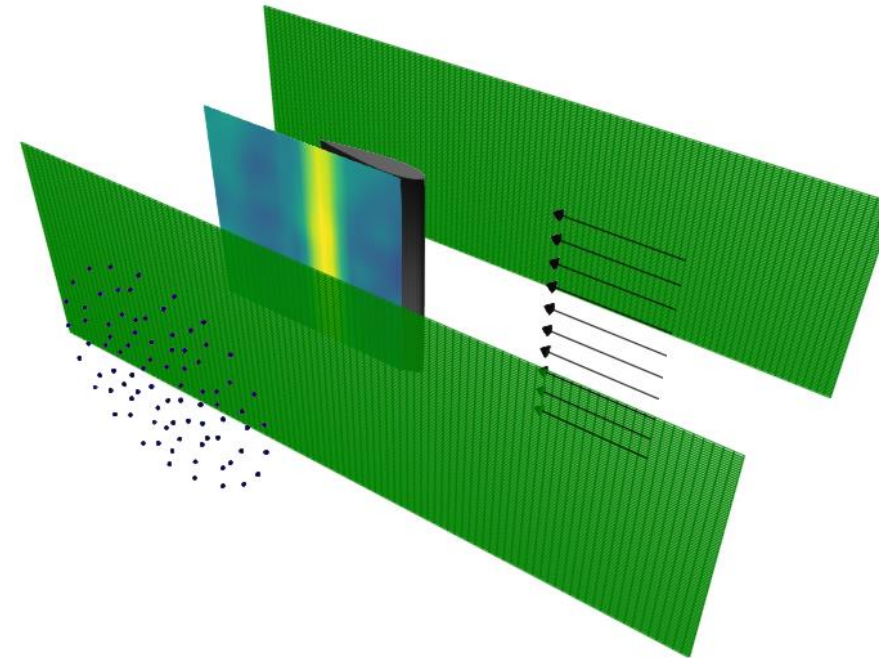


- Array of 64 PUI Audio 665-POM microphones;
- $f_s = 50 \text{ kHz}$, $t_{\text{samp}} = 30 \text{ s}$;
- Source Power Integration (SPI) beamforming;
- Integration area = $0.28c \times 0.22c$ centered at the trailing edge.

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Measurement techniques: Acoustics

- 84 B&K microphone array, circular pseudo random pattern, 2 m diameter
- Delay And Sum (DAS) beamforming with diagonal removal
- Shear layer correction according to 3D Amiet correction
- Clean SC to remove contamination of trailing edge source by floor/ceiling junction and Pitot tube
- Empirical corrections of the integrated spectra for Kevlar and turbulent boundary layer losses

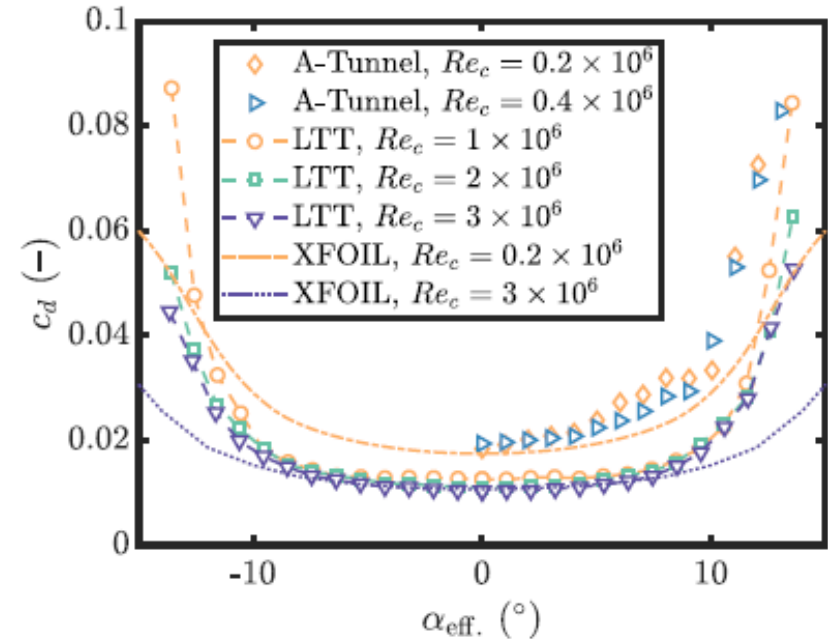
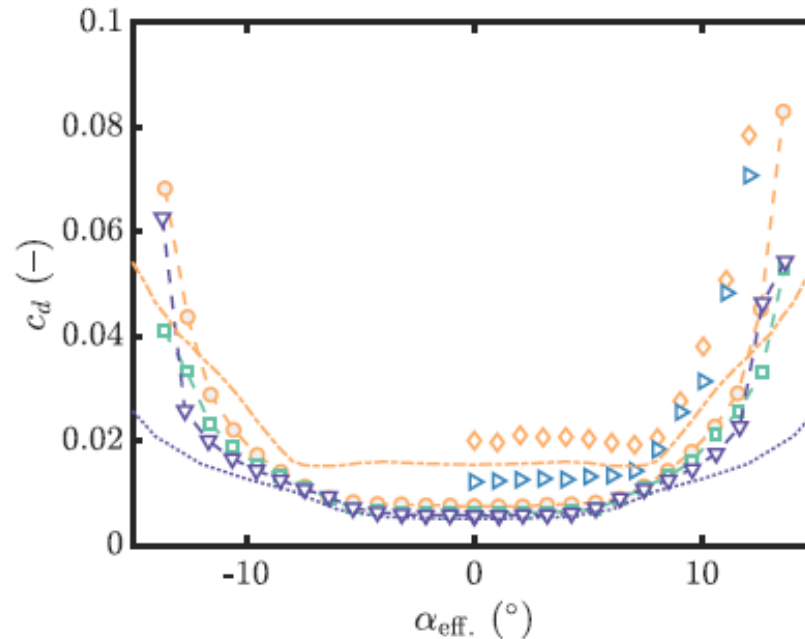
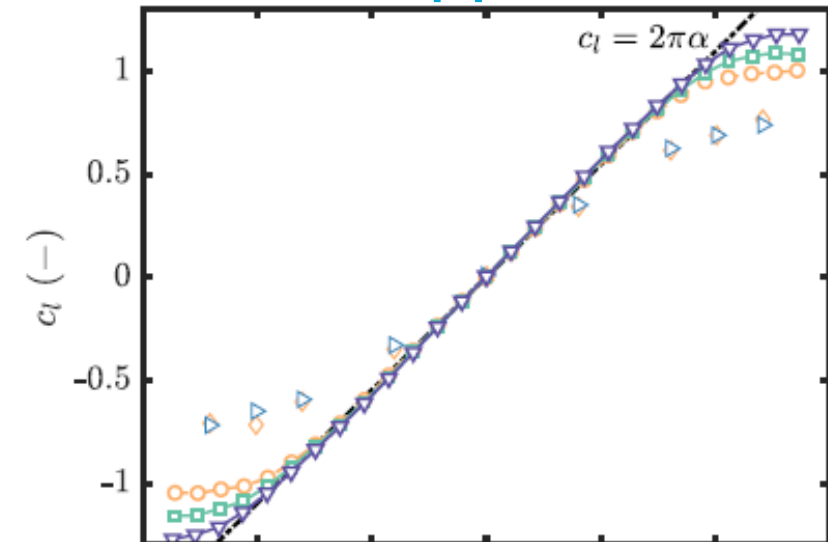
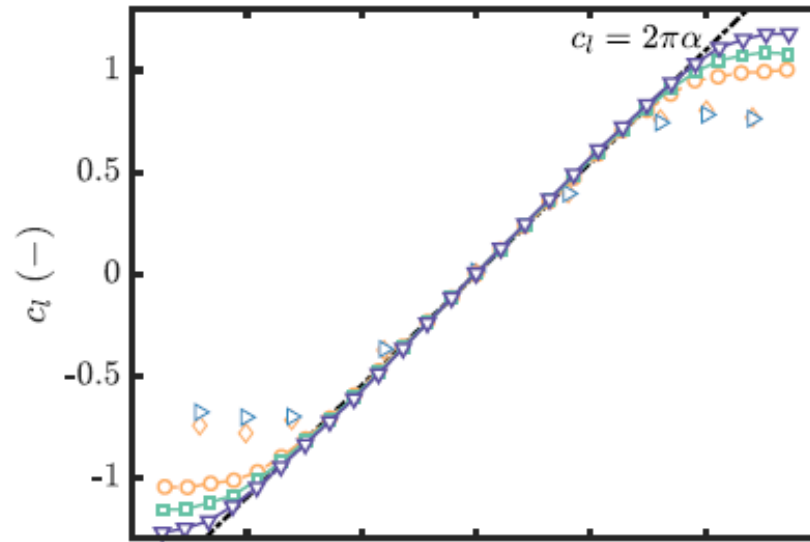


α : angle of attack
 c_l : lift coefficient
 c_d : drag coefficient
 Re_c : chord-based Reynolds No.

Results: aerodynamic coefficients overview

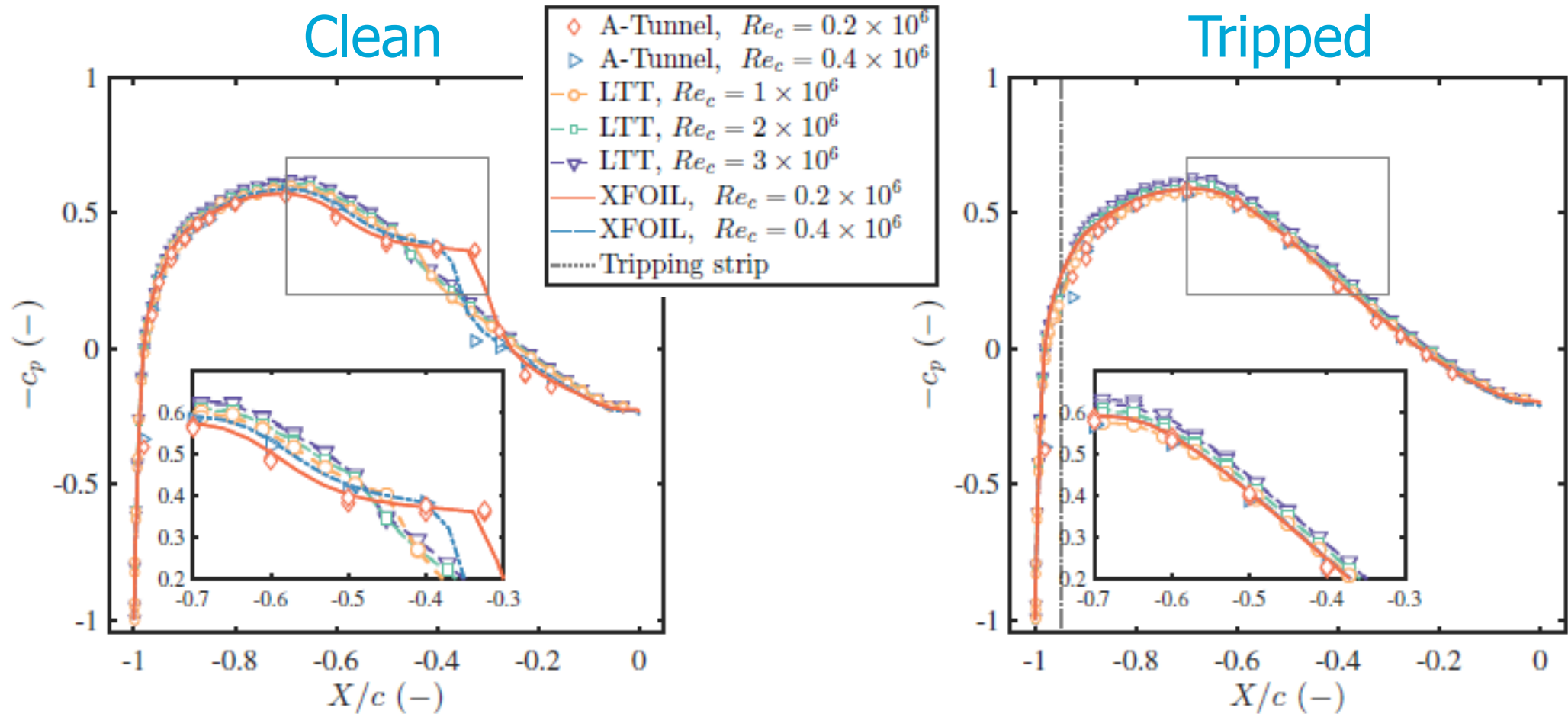
Clean

Tripped



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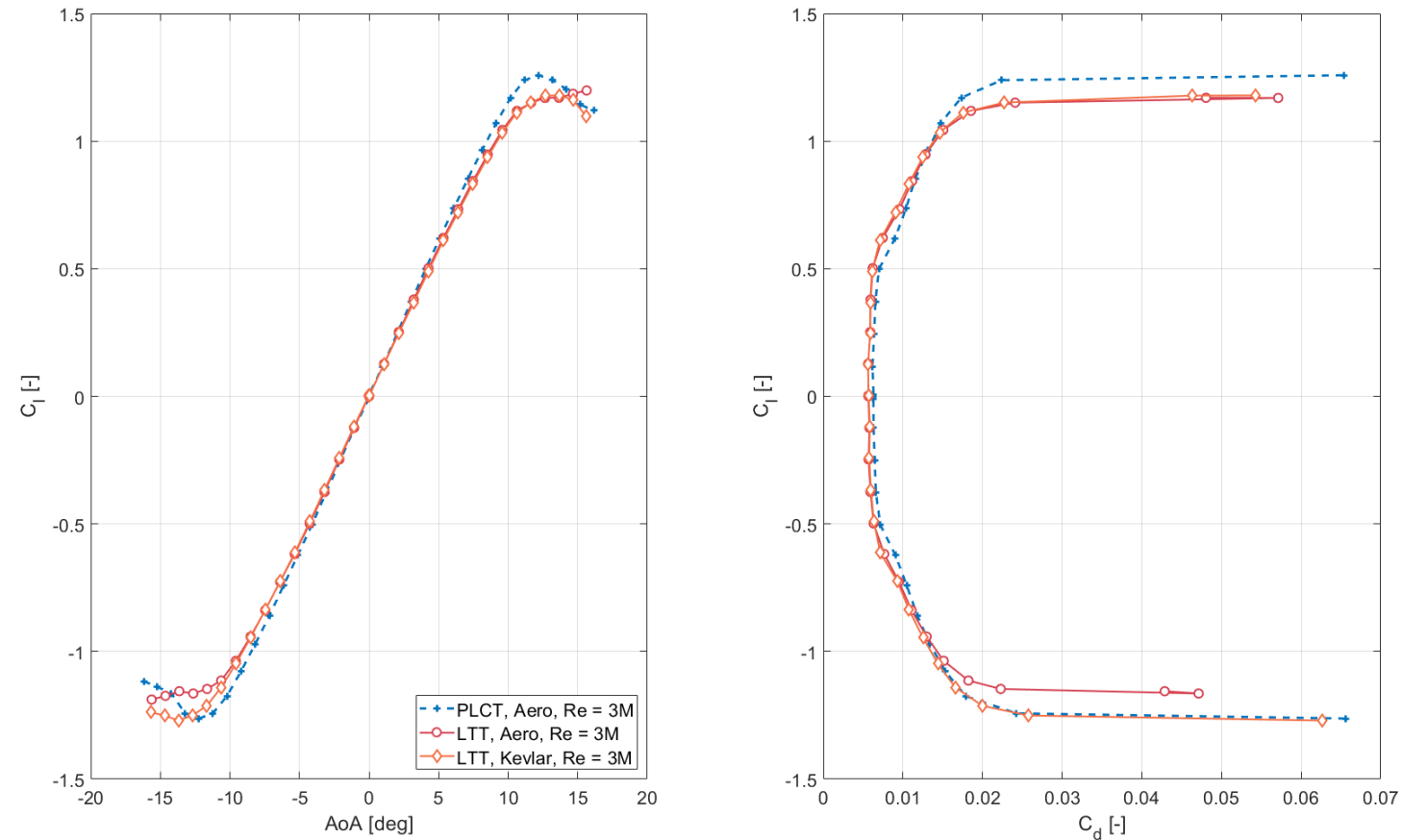
Results: pressure distribution



- Comparison between pressure distribution of the two models;
- Reynolds influence on the laminar separation bubble.

AoA : angle of attack
 c_l : lift coefficient
 c_d : drag coefficient
 Re_c : chord-based Reynolds No.

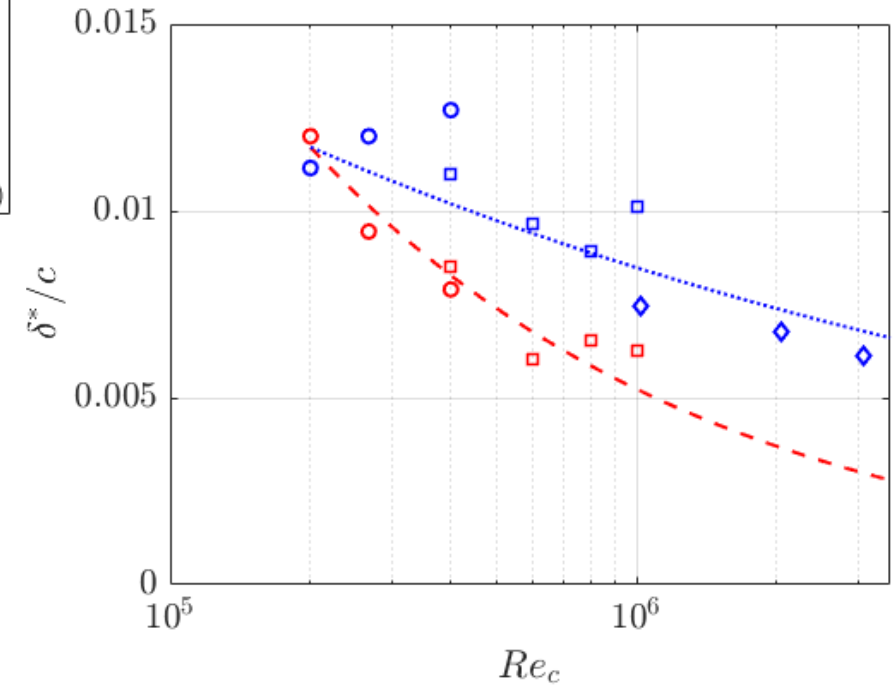
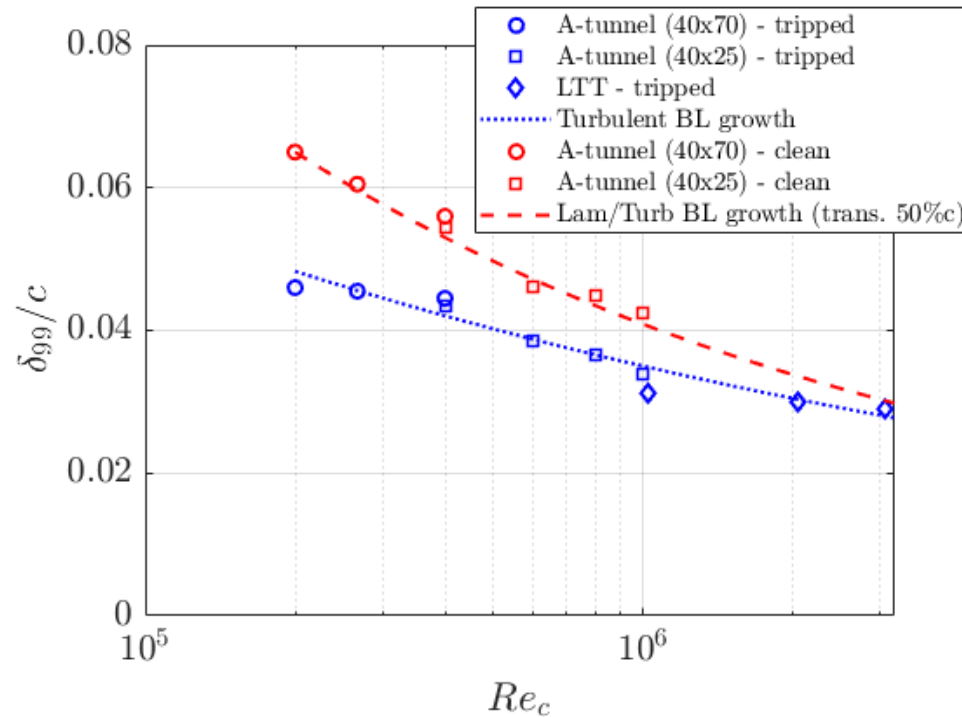
Results: aerodynamic coefficients, comparison TU Delft vs DTU, Clean



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- At high angles of attack, the model is affected by three-dimensional flow effect in the LTT

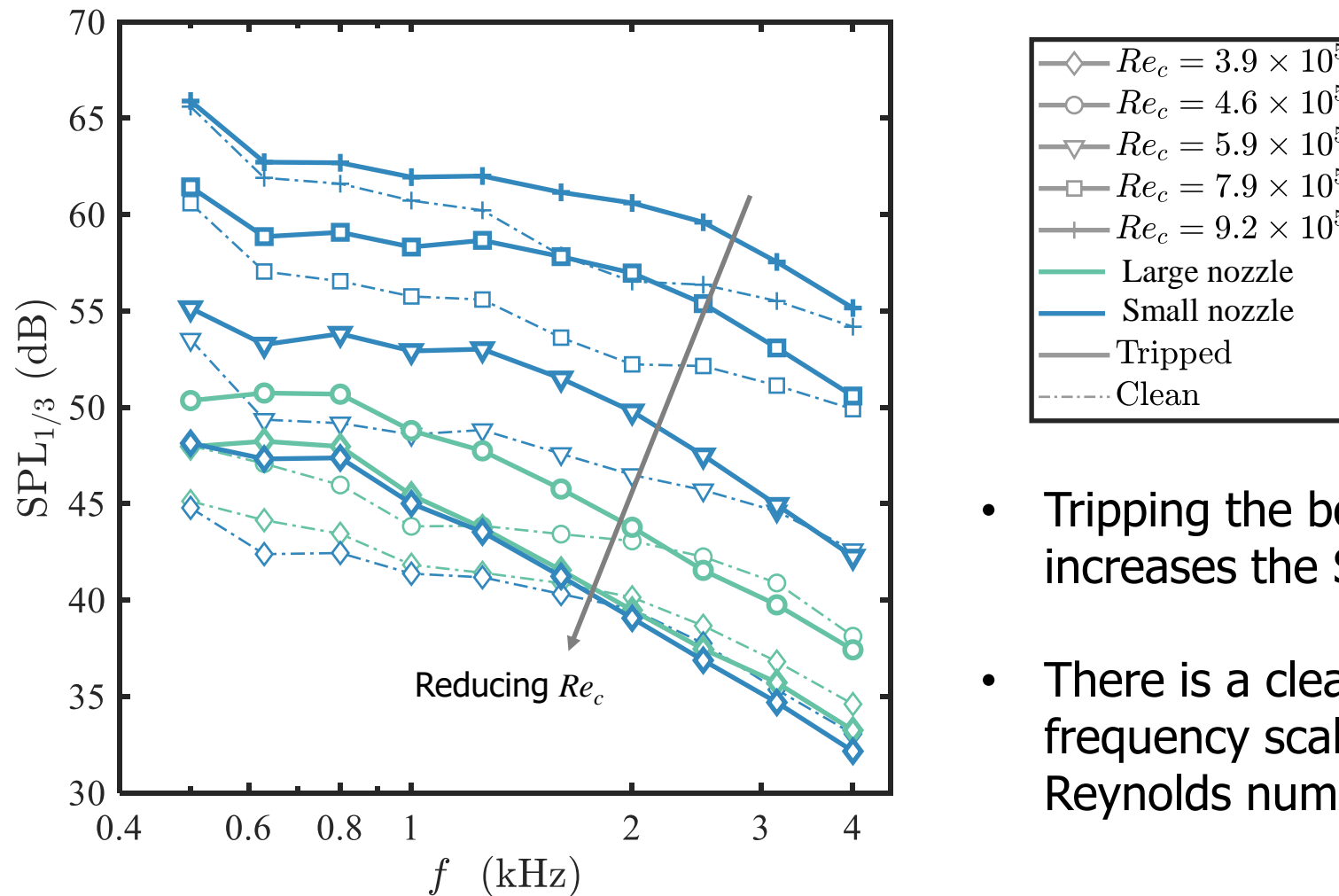
Results: boundary layer parameters vs Reynolds number



- Observable scaling trend across the different facilities
- Tripped boundary layer follows the Reynolds number scaling (power of 1/5)
- Clean airfoil, assuming the natural transition at 50% chord

Results: Effects of Reynolds number and tripping

f : frequency
 Re_c : chord-based Reynolds No.
 $SPL_{1/3}$: 1/3-octave band sound pressure Level



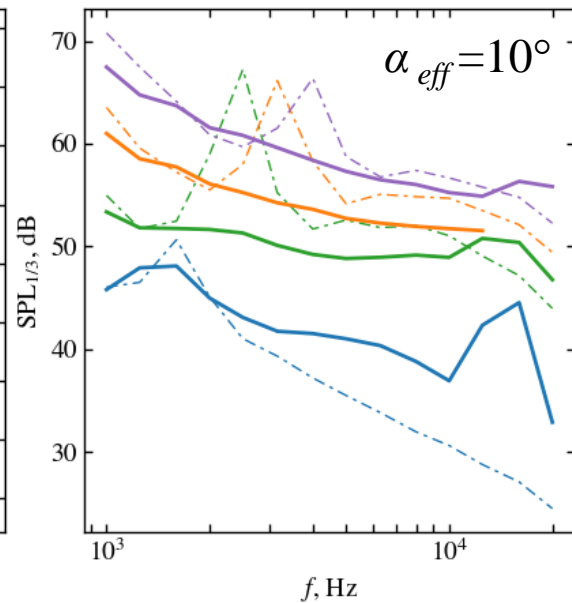
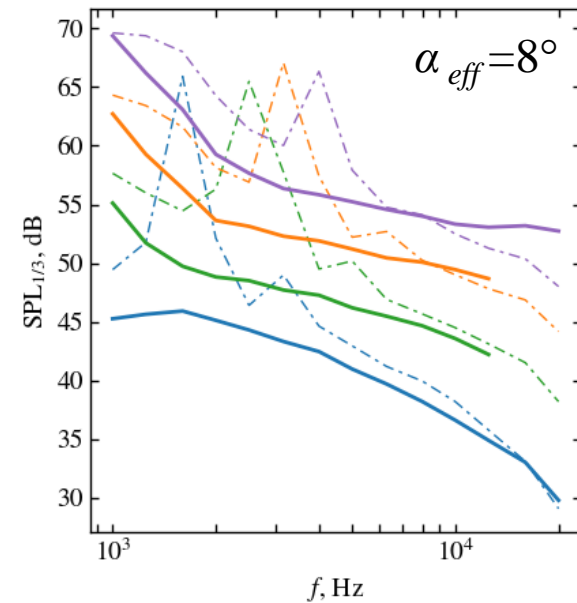
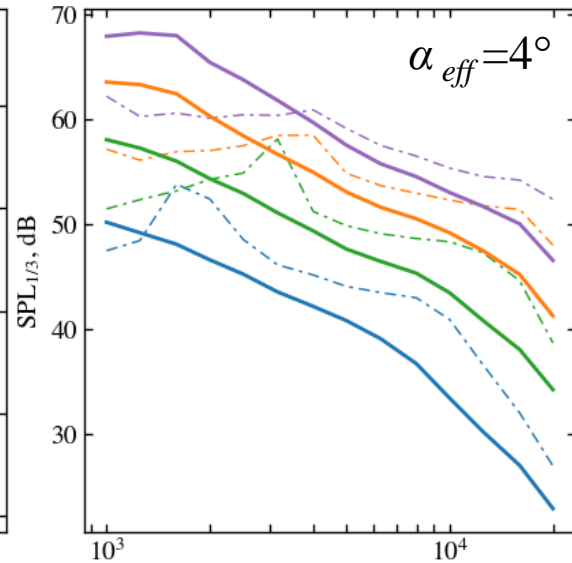
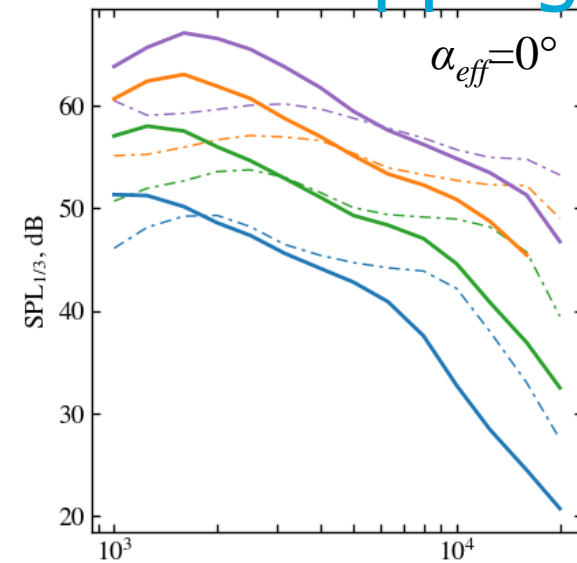
- Tripping the boundary layer increases the SPL up to 5 dB;
- There is a clear amplitude and frequency scaling with the Reynolds number.

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Results from AWB (small model): effects of Reynolds number and tripping

α_{eff} : effective aerodynamic angle of attack
 f : 1/3-octave band center frequency
 Re_c : chord-based Reynolds No.
 $SPL_{1/3}$: 1/3-octave band sound pressure Level

- Clean, $Re_c = 3.8 \times 10^5$
- Clean, $Re_c = 5.1 \times 10^5$
- Clean, $Re_c = 6.4 \times 10^5$
- Clean, $Re_c = 7.7 \times 10^5$
- Tripped, $Re_c = 3.8 \times 10^5$
- Tripped, $Re_c = 5.1 \times 10^5$
- Tripped, $Re_c = 6.4 \times 10^5$
- Tripped, $Re_c = 7.7 \times 10^5$

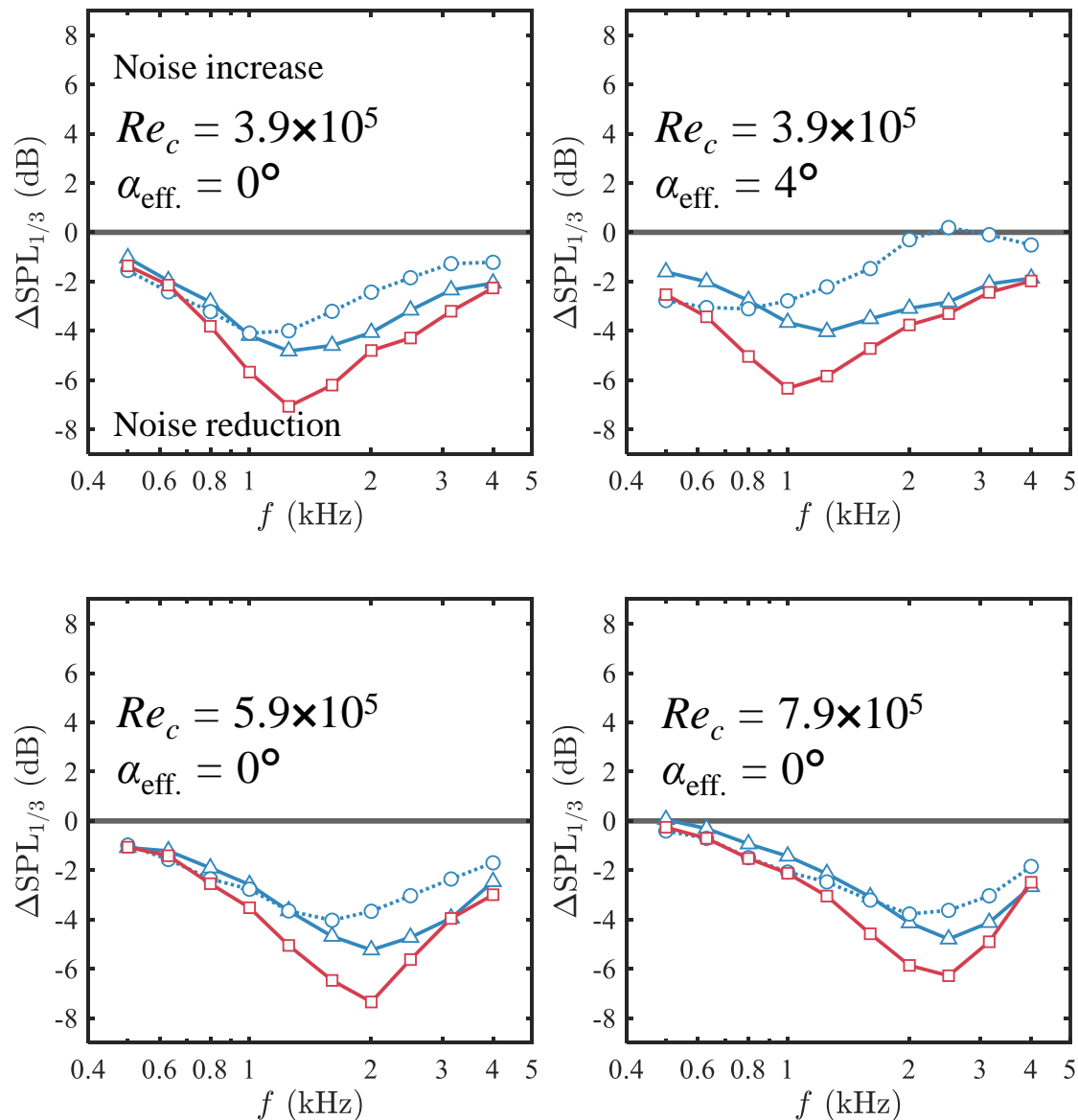


- Spectra are obtained by the directional microphones
- Clean (naturally transitioning BL):
 - Laminar vortex-shedding feedback tonal contributions at non-zero α_{eff} (2-4 kHz) as effect of low Re
- Tripped:
 - Re effect to SPL; spectral slope changes at $Re_c = 3.8 \times 10^5$, $\alpha_{eff} = 8^\circ$ & 10° and $Re_c = 5.1 \times 10^5$, $\alpha_{eff} = 10^\circ$ due to increased flow separation effects

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Results: Noise reduction by TE serrations

α : angle of attack
 f : frequency
 Re_c : chord-based Reynolds No.
 $\Delta SPL_{1/3}$: 1/3-octave band sound pressure level difference
 φ : flap angle



- At low angles of attack, the iron serrations give the highest noise reduction, approximately 7 dB.
- The flapped serrations show the highest noise variability with angle of attack.

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Results from AWB (small model): Noise reduction by TE serrations

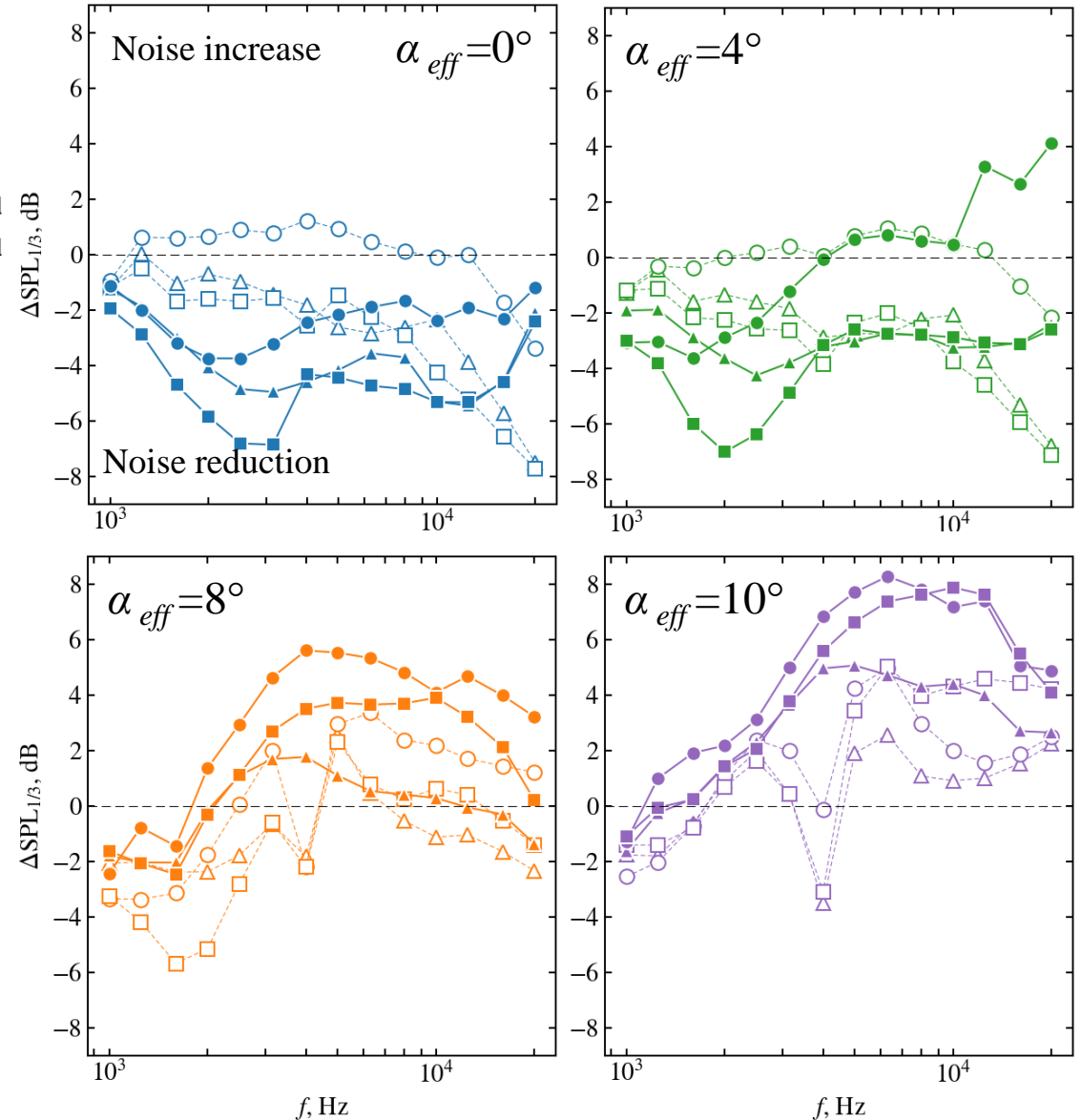
α_{eff} : effective aerodynamic angle of attack
 f : 1/3-octave band center frequency
 Re_c : chord-based Reynolds No.
 $\Delta SPL_{1/3}$: 1/3-octave band sound pressure level difference
 φ : flap angle

$Re_c = 7.7 \times 10^5$

- △-- Sawtooth $\varphi = 0^\circ$, Clean,
- Sawtooth $\varphi = 8^\circ$, Clean,
- Iron, Clean
- ▲— Sawtooth $\varphi = 0^\circ$, Tripped
- Sawtooth $\varphi = 8^\circ$, Tripped
- Iron, Tripped

Large model results from DNW-NWB are readily available (from both test sections – open and closed) and will be post-processed & published in the framework of IEA Wind TCP Task 39.

- Increased α_{eff} leads to decreased noise reduction
- With non-zero α_{eff} add-ons behave as flap, despite $\varphi = 0^\circ$

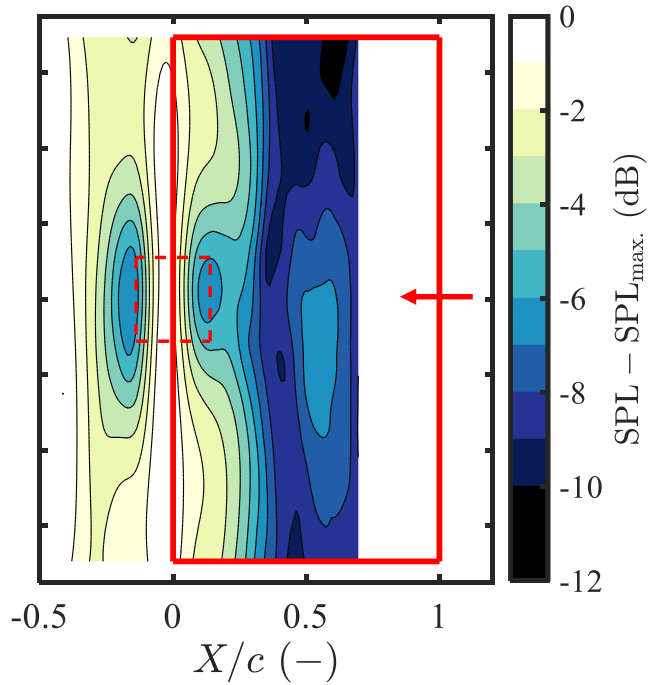


f : frequency
 Re_c : chord-based Reynolds No.
SPL : Sound Pressure Level

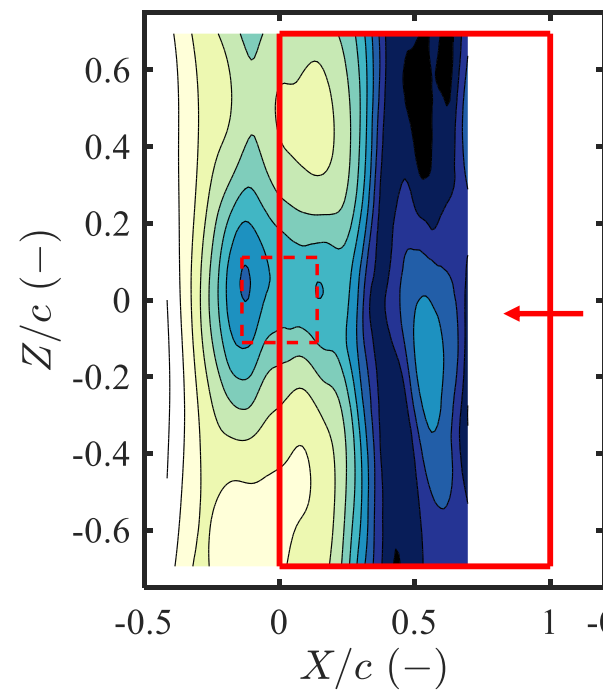
Results: Noise reduction by TE serrations, Large model \rightarrow LTT



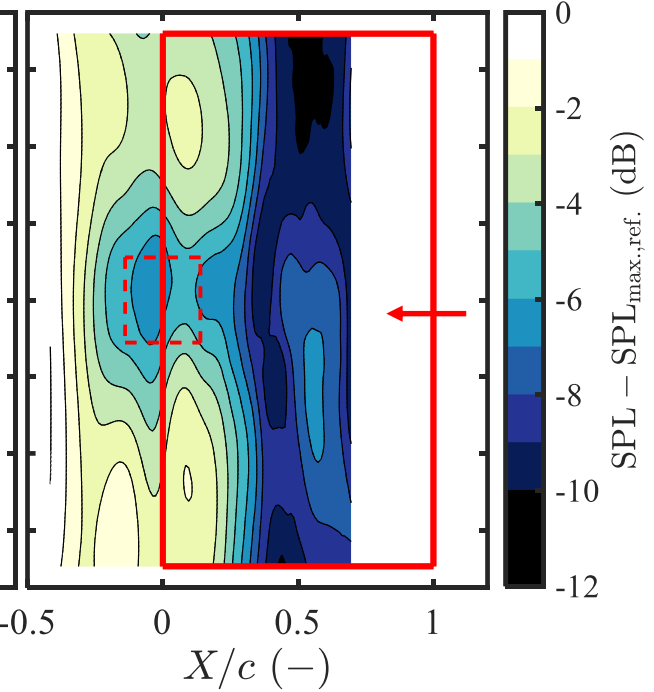
Tripped (ref.)
 $Re_c = 2 \times 10^6$,
 $f = 2000-3000$ Hz



Sawtooth serrations
 $Re_c = 2 \times 10^6$,
 $f = 2000-3000$ Hz



Iron serrations
 $Re_c = 2 \times 10^6$,
 $f = 2000-3000$ Hz



- Approximately 4-5 dB noise reduction is observed for the sawtooth and iron serrated TE cases in the usable frequency range (2-3 kHz)

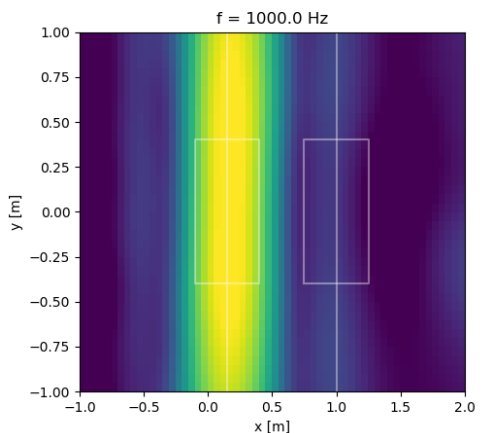
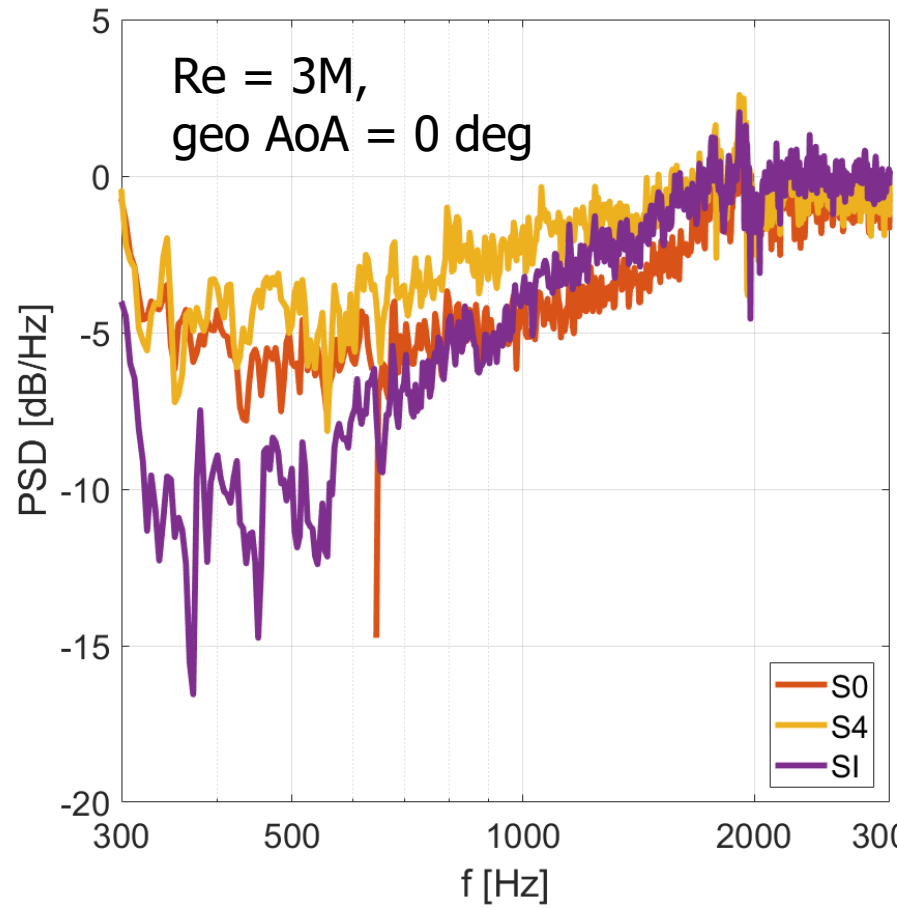
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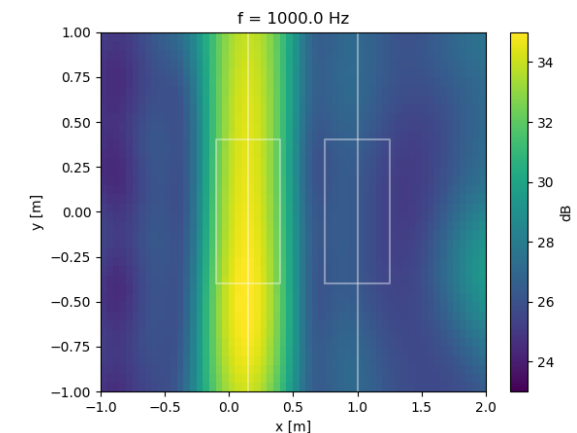
f : frequency
 Re_c : chord-based Reynolds No.
 PSD : Power Spectral Density



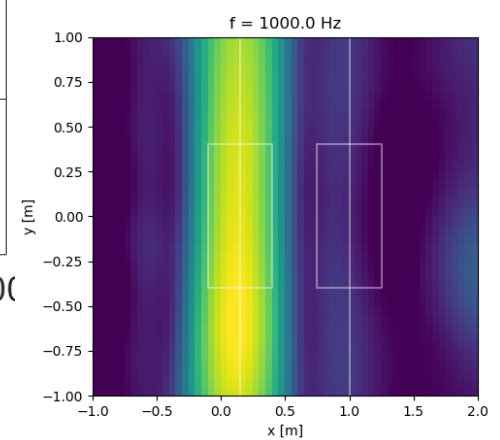
Results: Noise reduction by TE serrations, Large model \rightarrow PLCT



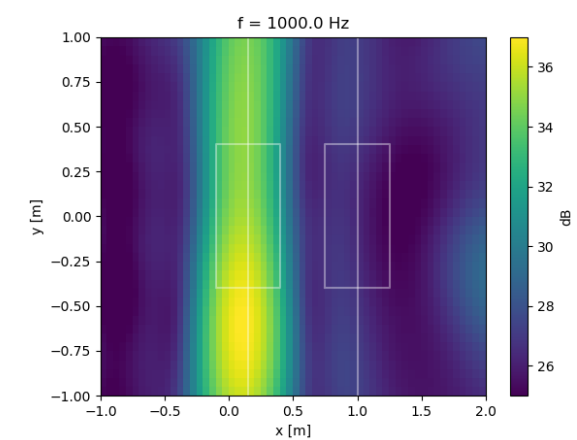
Baseline



S0 = Sawtooth



S4 = Sawtooth, flapped



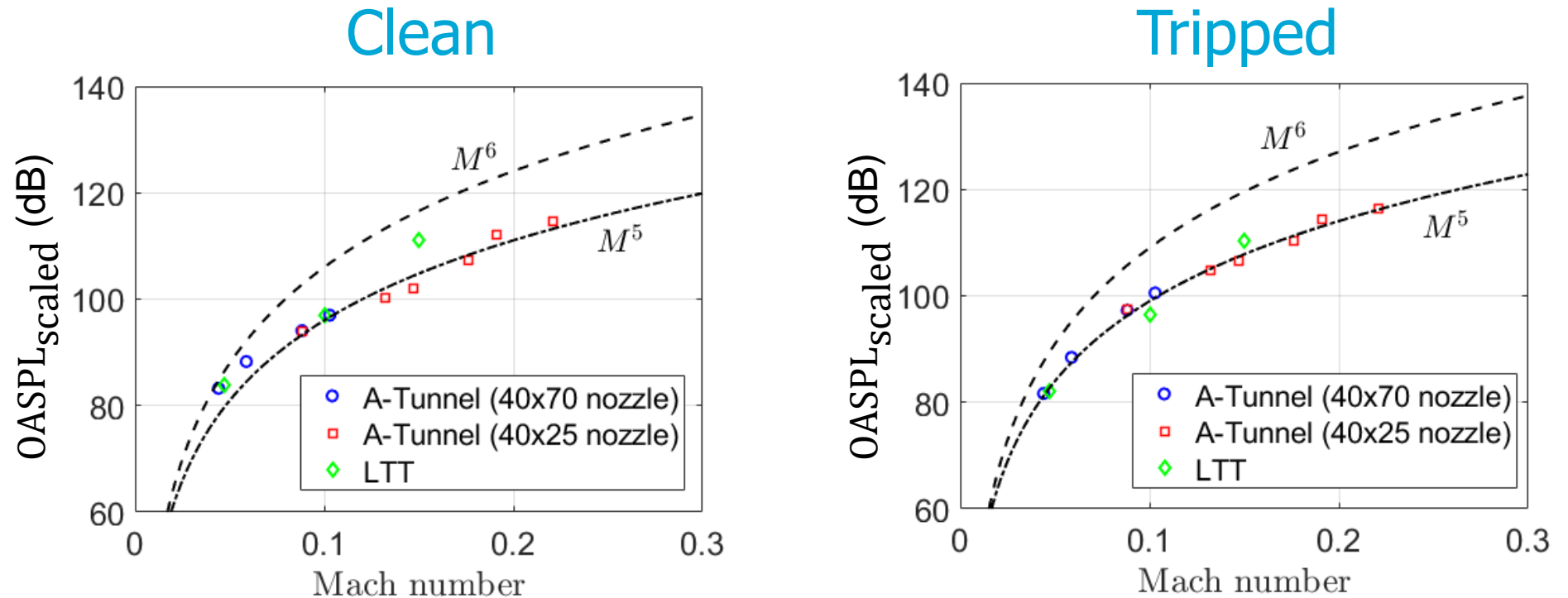
SI = Iron

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Results: Preliminary scaling with the Mach number

$$\text{OASPL}_{\text{scaled}} = \text{OASPL} - 10 \log_{10} b - 10 \log_{10} \delta^*$$



- Frequency range: 500 – 3000 Hz for both facilities
- Better agreement for the tripped boundary layer
- For the LTT and clean cases, deviation comes from the frequency range selected

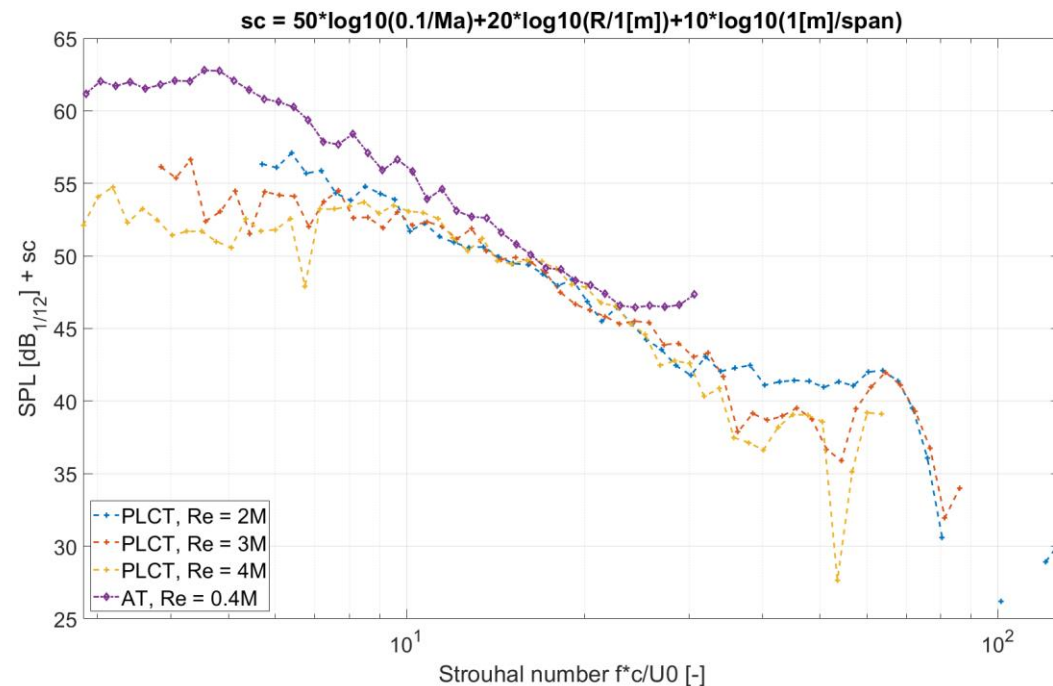
Dataset summary

Model and facility	Re_c ($\times 10^6$)	Available measurements				
		Aerodynamics		TBL profiles		Acoustics
		Pressure taps	Wake rake	Hot-wire ($0.98c$)	PIV	
Small model, A-Tunnel, $3.5\alpha 2c$ nozzle (Nozzle 1)	0.06	✓ (0°-15°)	✓ (0°-21°)	✗	✗	✓ (0°)
	0.20	✓ ±(0°-24°)	✓ (0°-21°)	✓ (0°)	✗	✓ ±(0°-18°)
	0.26	✓ ±(0°-18°)	✓ (0°-21°)	✓ (0°)	✗	✓ (0°-15°)
	0.39	✓ ±(0°-24°)	✓ (0°-21°)	✓ (0°)	✗	✓ ±(0°-18°)
	0.46	✓ ±(0°-18°)	✓ (0°-21°)	✗	✗	✓ (0°-15°)
Small model, A-Tunnel, $1.5\alpha 2c$ nozzle (Nozzle 2)	0.39	✓ (0°)	✗	✓ (0°)	✗	✓ (0°)
	0.59	✓ (0°)	✗	✓ (0°)	✗	✓ (0°)
	0.66	✓ (0°)	✗	✗	✗	✓ (0°)
	0.79	✓ (0°)	✗	✓ (0°)	✗	✓ (0°)
	0.92	✓ (0°)	✗	✗	✗	✓ (0°)
	1.00	✓ (0°)	✗	✓ (0°)	✗	✓ (0°)
Large model, LTT	1.00	✓ ±(0°-20°)	✓ ±(0°-20°)	✗	✓ (0°,4°)	✓ ±(0°-16°)
	2.00	✓ ±(0°-20°)	✓ ±(0°-20°)	✗	✓ (0°,4°)	✓ ±(0°-16°)
	3.00	✓ ±(0°-20°)	✓ ±(0°-20°)	✗	✓ (0°,4°)	✓ ±(0°-16°)

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Conclusions and next steps

- Aeroacoustics characterization of the NACA 63(3)-018 airfoil models has been performed in two wind tunnels of TU Delft, the PLCT at DTU, and the wind tunnels of DLR (AWB and NWB)
- Consistent aerodynamic results from the wind tunnels and scalable far-field acoustic results are found



c : chord
 f : frequency
 M : Mach No.
 R : observer distance
 sc : scaling term
SPL: Sound pressure level
 U_0 : free-stream velocity

- Next steps include comparison of the collected data across different institutions

Thank you for your attention.

Q&A