Towards the understanding of

Mechanisms of noise reduction from porous/permeable materials

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Noise Reduction Technologies with Meta-Materials
Lorentz Center@Snellius, Leiden, NL
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Outline

- **Intro**
  - Test setups
  - Material specification

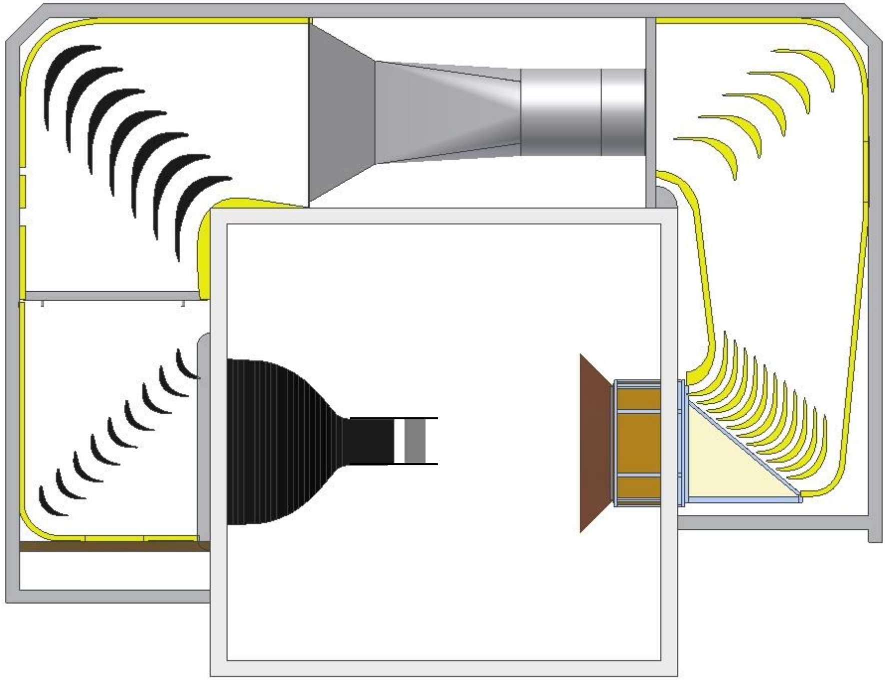
- **General findings**
  - Requirements for broadband noise reduction
  - Driving parameters

- **Technology challenges in application**
  - Production of tailored materials?
  - Potential show-stoppers, design details…

Focus: Turbulent boundary-layer trailing-edge noise reduction (TEN)

INTRO

Acoustic Wind Tunnel Braunschweig AWB

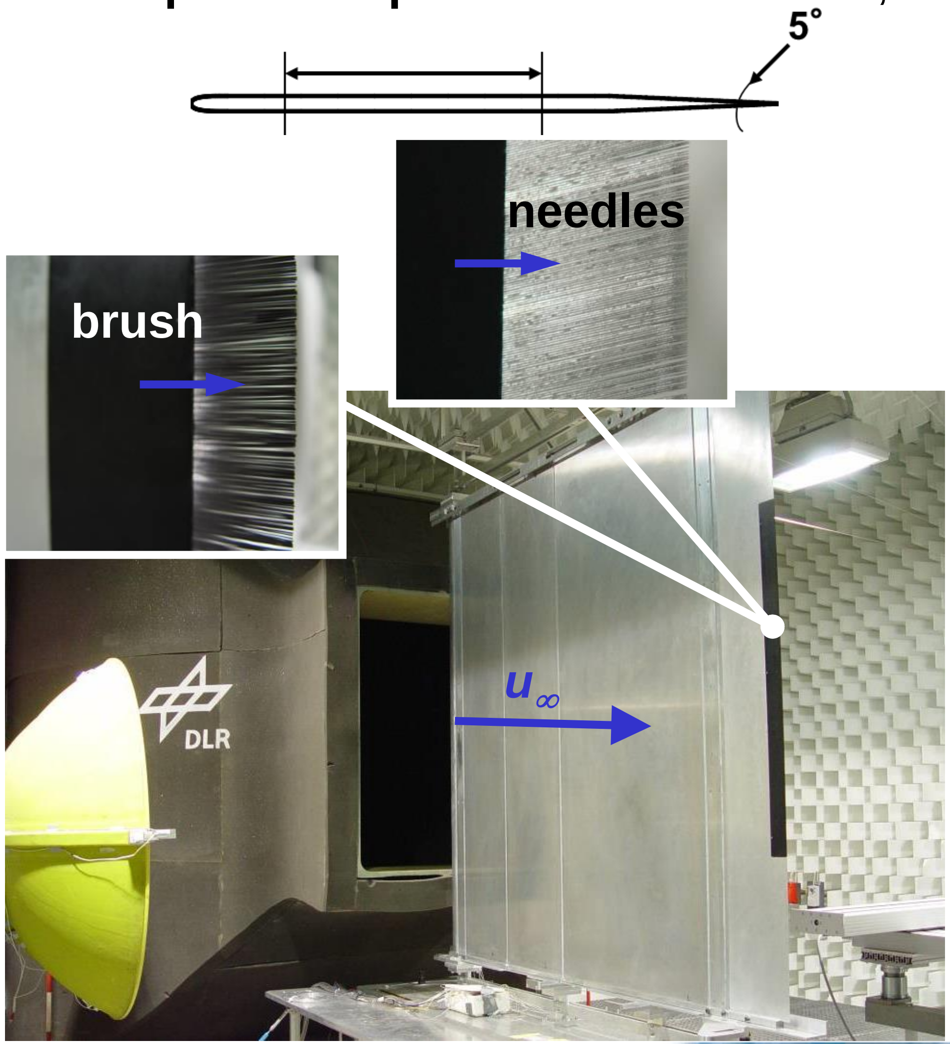


operational Data:

- Nozzle: 0.8 m x 1.2 m
- Max speed: 65 m/s
- Tu < 0.3 % @ 60 m/s

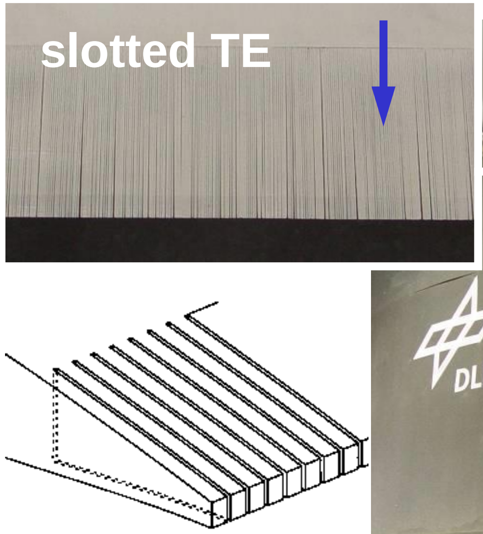
Technical realizations of porous devices in AWB

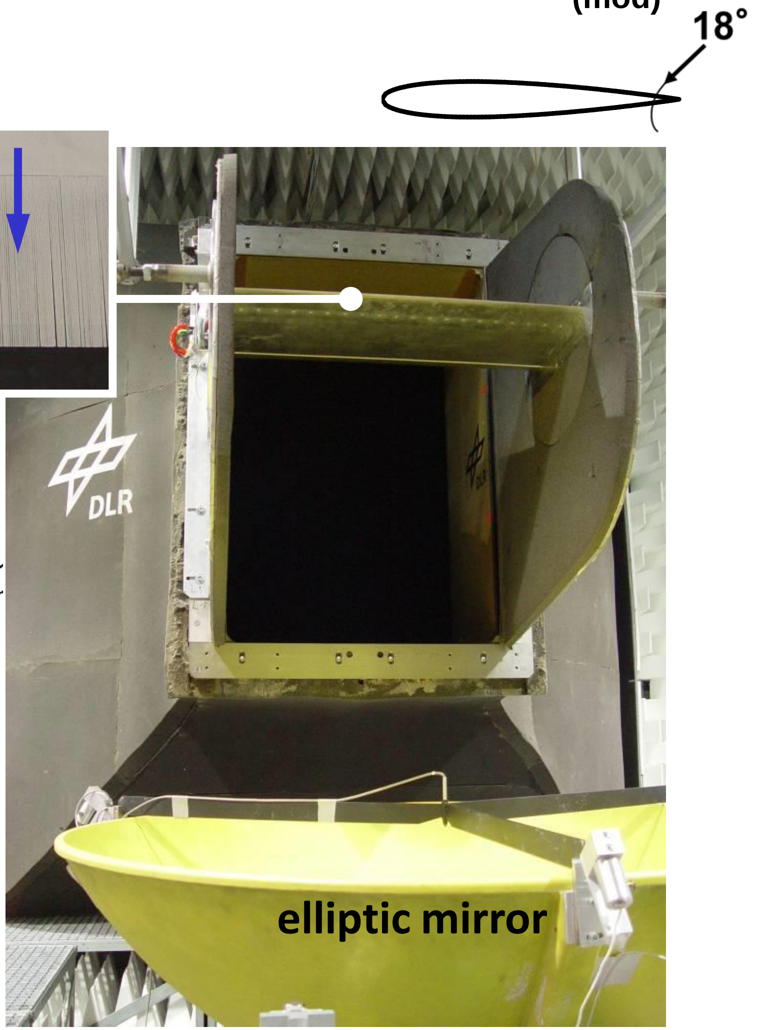
- parametric investigations of effect of **brushes** / **slotted TEs** on TEN
- **modular plate setup** with 0.8–2.0 m chord; 1.2 m wetted span



References: Herr & Dobrzynski, AIAA 2004-2804, AIAA Journal, Vol. 43, No. 6, June 2005

- 0.4 m chord **NACA0012**$_{\text{(mod)}}$

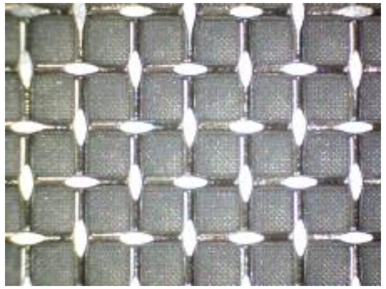
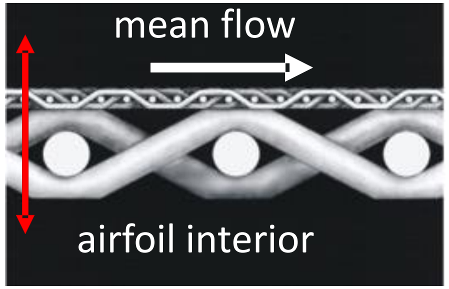


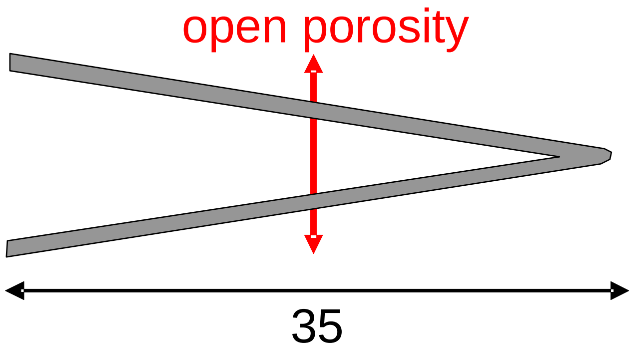


Reference: Herr & Dobrzynski, AIAA 2007-3470

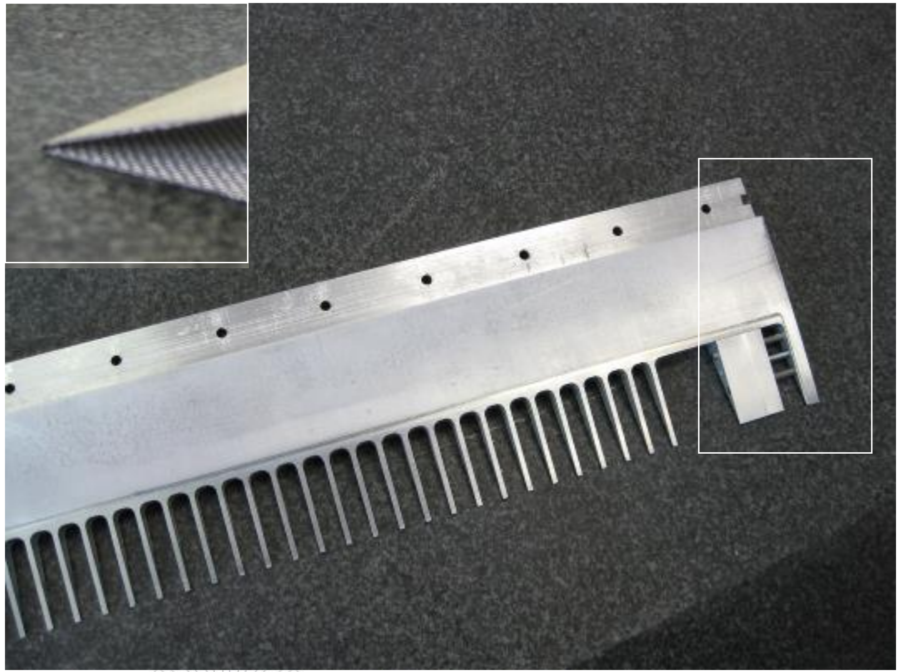
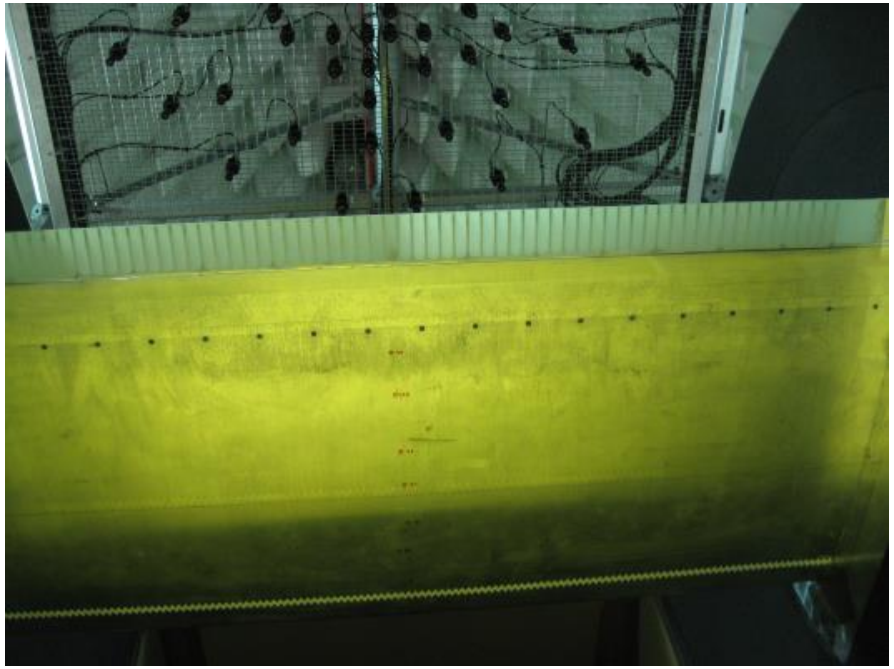
Technical realizations of porous devices in AWB

- 0.4 m chord **NACA0012$_{\mathbf{(mod)}}$**

- porous devices: 100% span, 8.75% chord

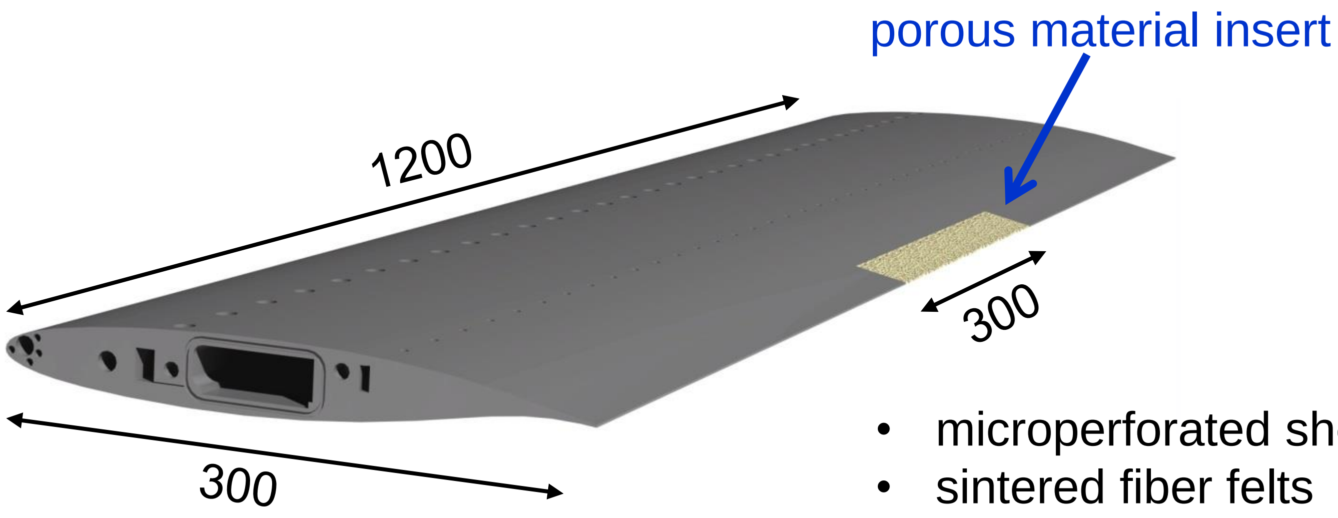
- Kevlar-type woven fabrics
- duo-layer metal mesh
- microperforated sheets

- brushes
- slotted TE

Reference: Herr & Reichenberger, AIAA 2011-2780

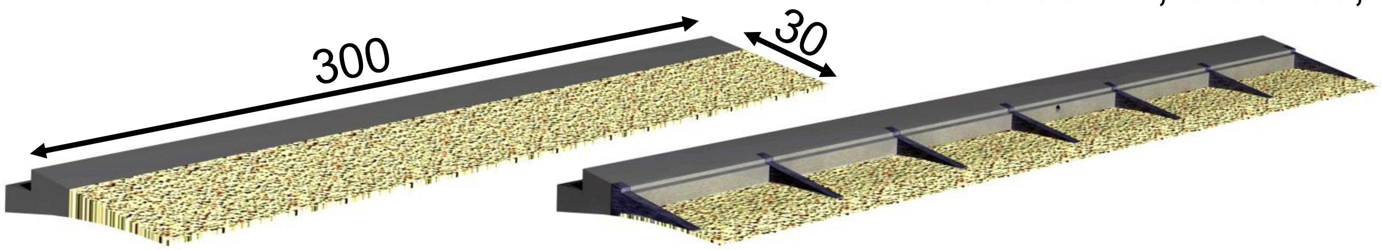
Technical realizations of porous devices in AWB

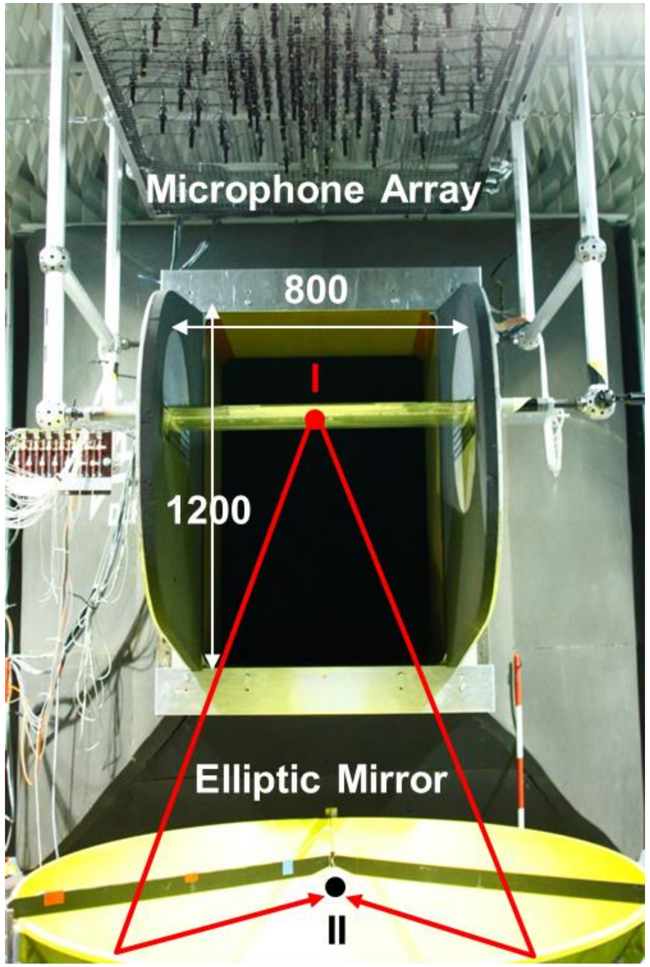
- parametric investigations of effect of porous materials on TEN
- 0.3-m-chord **DLR F16 2D-airfoil**
- porous devices: 37.5% span, 10% chord



- microperforated sheets
- sintered fiber felts
- porous aluminum
- slotted TE, brushes, …

example porous material inserts:



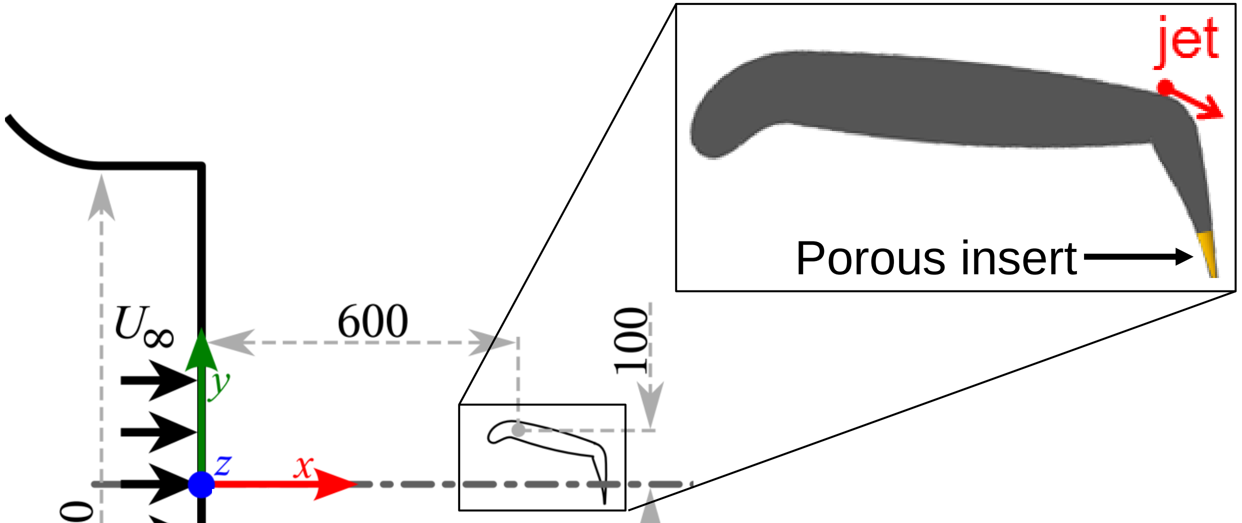


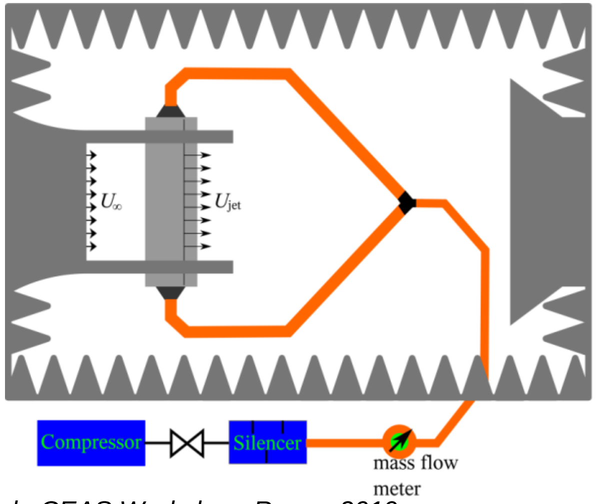
(dimensions in mm)

Reference: Herr et al., AIAA 2014-3041

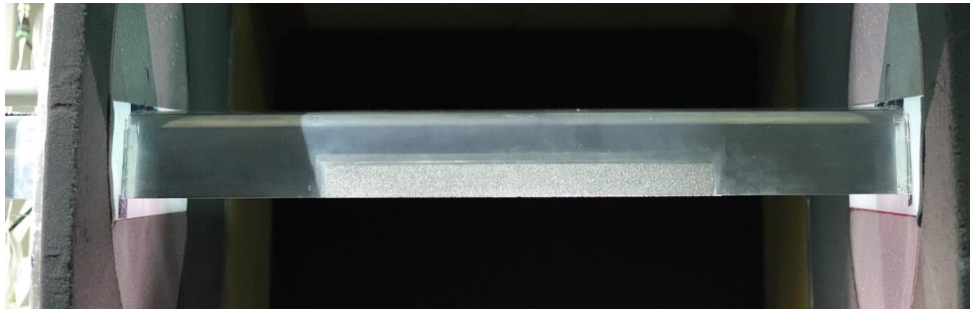
Technical realizations of porous devices in AWB

- DLR F16 based high-lift system with active flow control with droop nose and Coanda flap

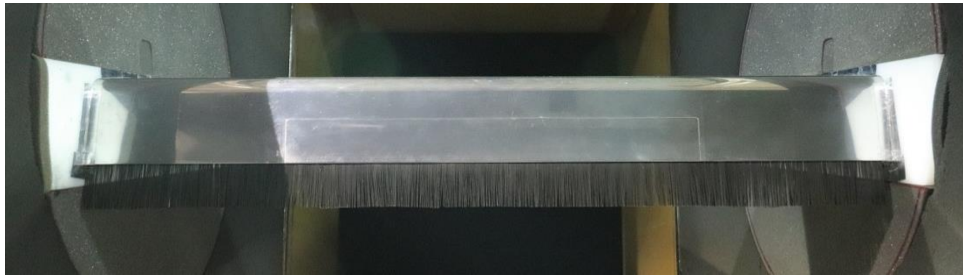




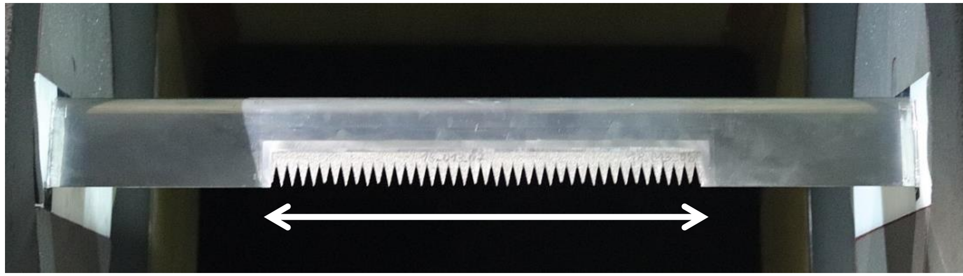
Reference:: Rossignol et al., CEAS Workshop, Rome, 2019



porous devices: 50% span, 10% chord



brush devices: 50-100% span, 10% chord



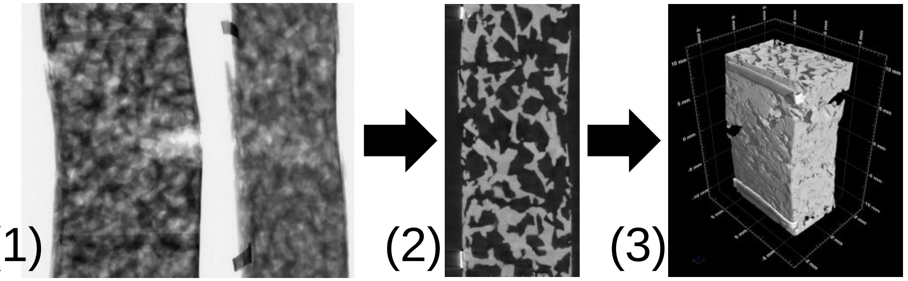
400 mm

Material characterization

Computertomography (CT) for porosity, pore morphology (and damage behavior)

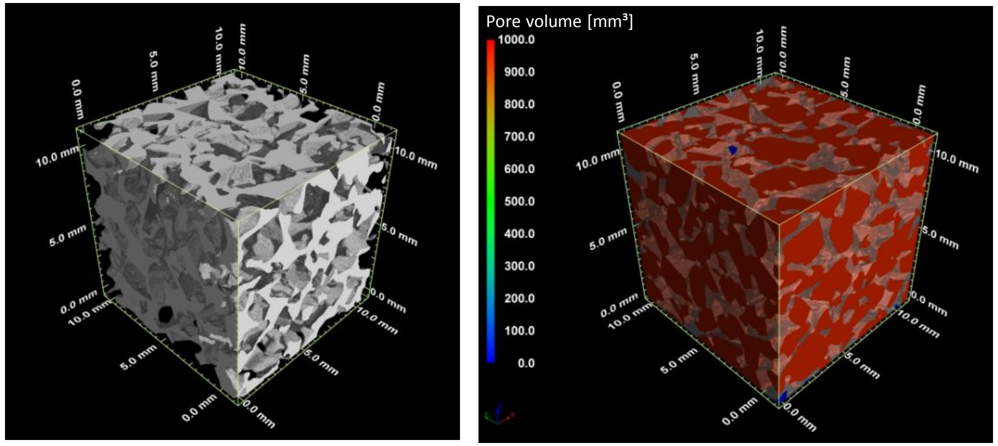
(1) Measurement: Image stacks of radiographic images 0-360°
(2) Reconstruction of sample 2D planes (grey scale)
(3) 3D volume with detected surface

(1) (2) (3)

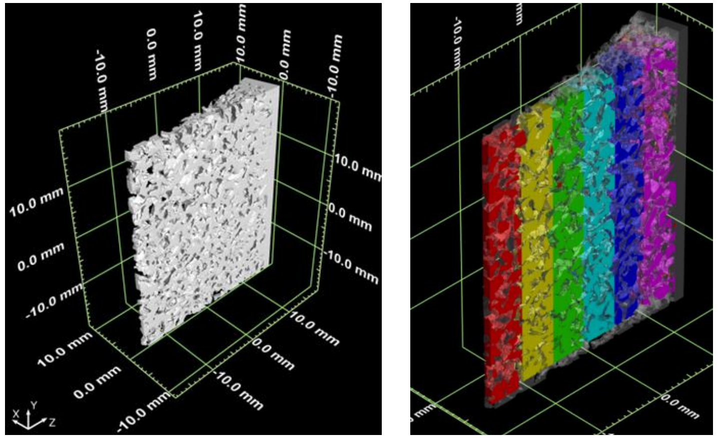


PA200-250: Sample for tensile testing

- Measurement of structures and porosity with defect detection for regions of interest (ROI)
- 2D cross-sections of volume for line segmentation technique → segment lengths



CT reconstruction of PA 200-250
(left: material; right: porosity color coded)



CT reconstruction of TE of PA 200-250
(left: material; right: ROI 1-6 for porosity analysis)

Reference: J. Tychsen, N. Lippitz, J. Rösler, Metals, 8, 598 (2018)

Hochauftrieb künftiger Verkehrsflugzeuge SFB 880

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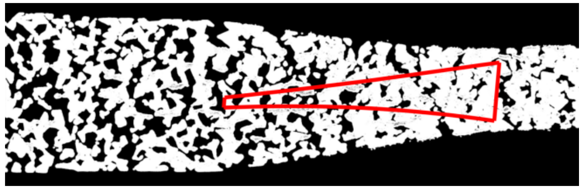
Technische Universität Braunschweig

Material characterization

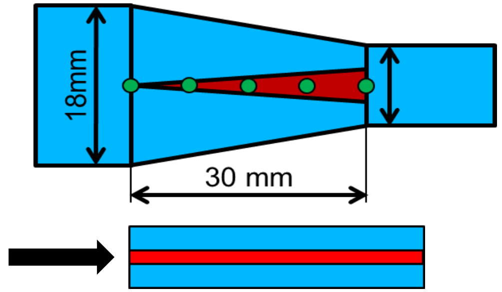
Specific airflow resistivity (and acoustic absorption) measurements with the challenge that TE inserts cannot be directly analyzed!

- samples with ø100 mm ideally needed
- thin areas of TEs do not have representative amount of volume (pores may directly connect upper and lower side)

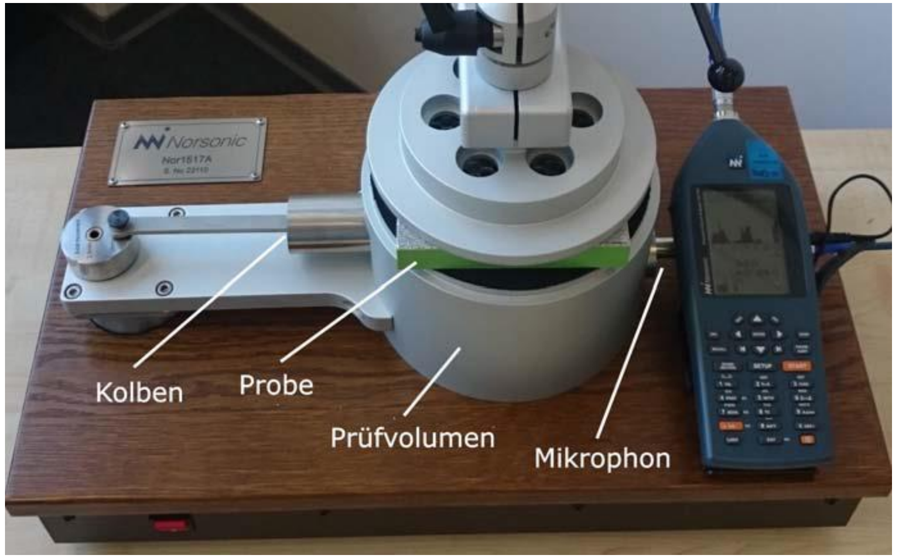
→ comparative samples needed



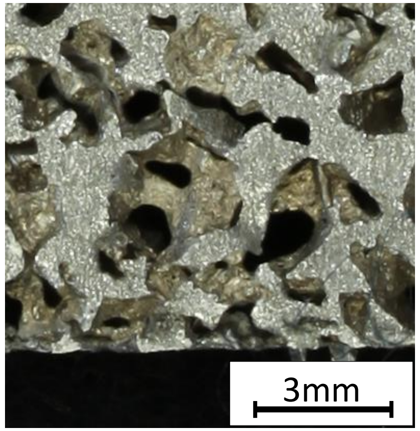
Cross-section of graded PA200-250, shape of TE highlighted

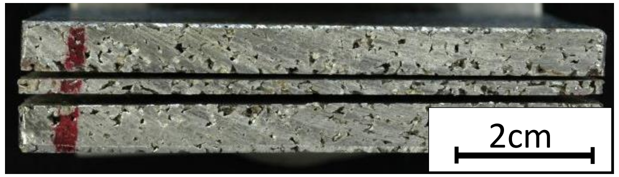


Schematic diagram showing graded material with five positions that are to be measured



Setup for measuring flow resistance with the air-flow process (process B) according to DIN EN 29 053





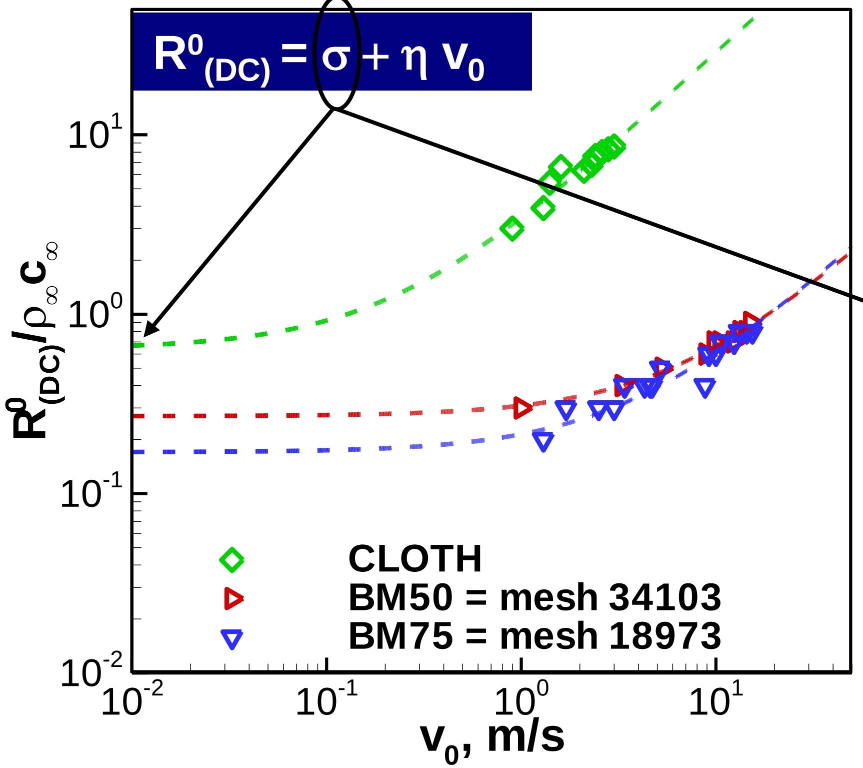
2-mm-sample separated by electrical discharge machining
left: surface (pores directly connecting upper and lower side)
right: original sample (thickness: 16 mm) with eroded disc (2 mm)

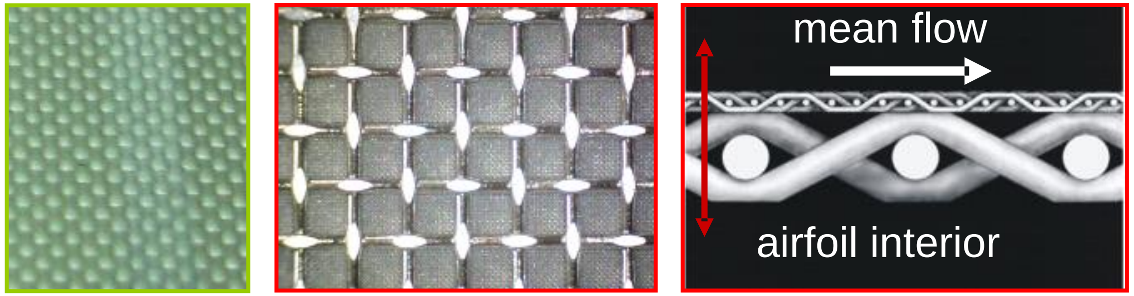
Reference: J. Tychsen, N. Lippitz, TU Bs

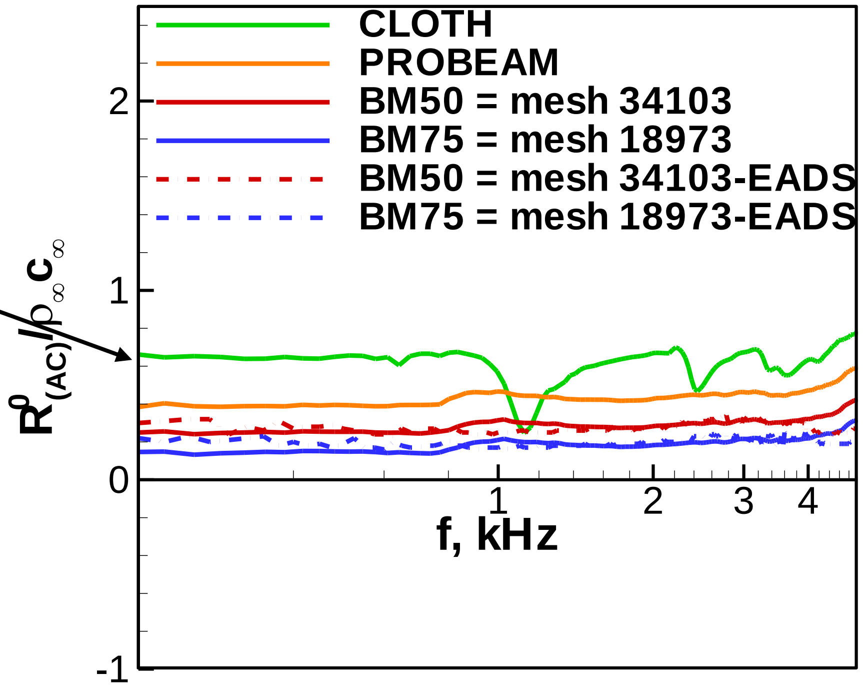
Material characterization

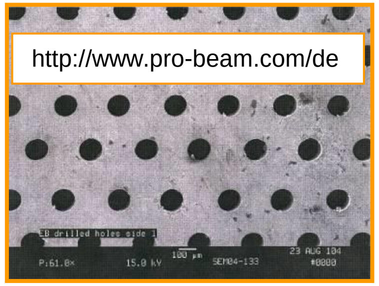
Specific airflow resistivity: $R^0 = \Delta p / v$

~Flow resistance value according to DIN EN 29 053: alternating airflow @ 2 Hz and 0.5 mm/s









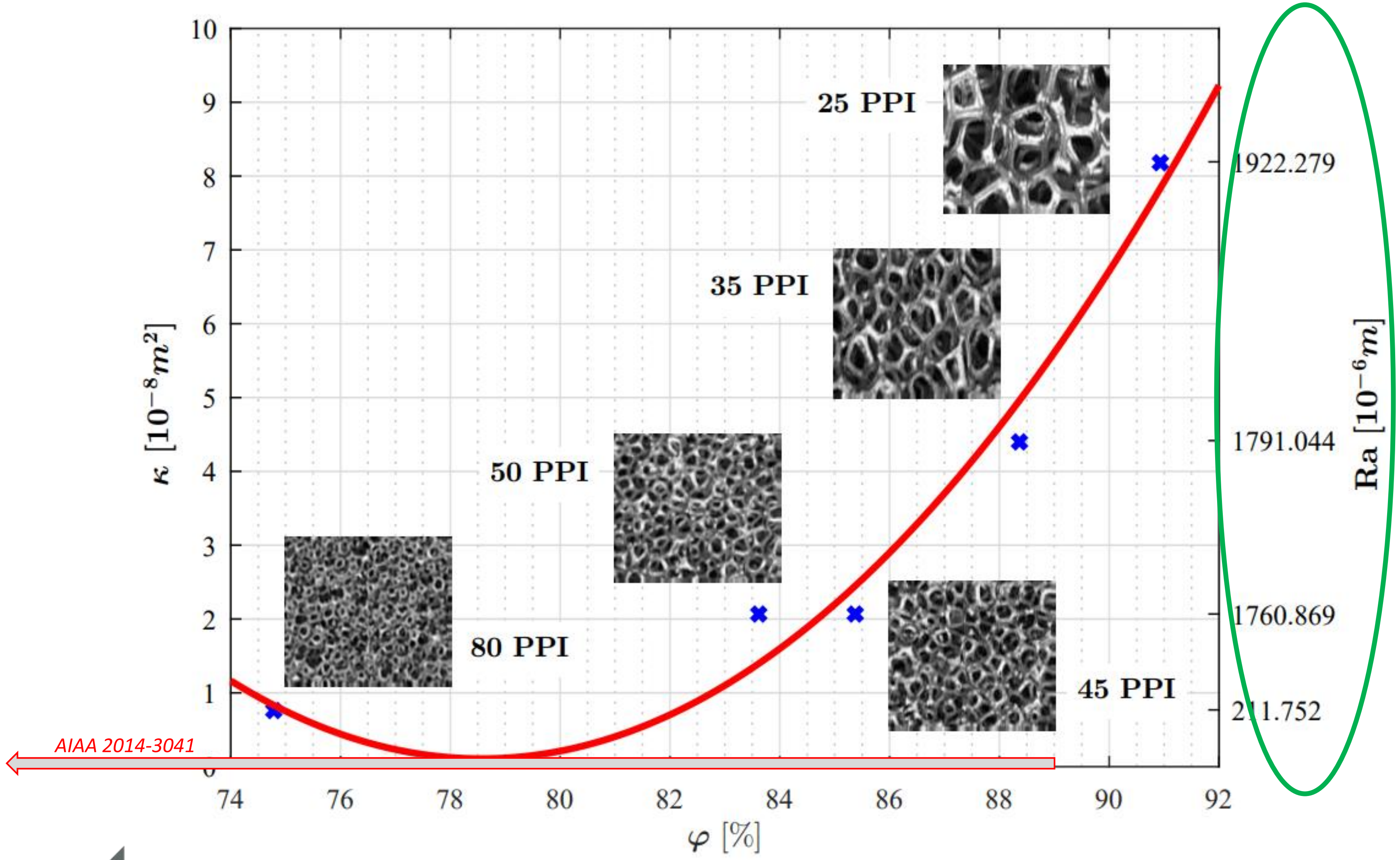
desired resistance behavior:

- open for wall-normal fluctuations, but
- no leakage flow through TE region

Reference: Herr & Reichenberger, AIAA 2011-2780

Material characterization

Porosity-permeability-roughness plot



Classical methods to determine surface roughness will fail when pores directly connect upper and lower side…

Open question:
How to quantify approx. “pore size” to investigate flow disturbance effects due to pores, e.g. excess noise generation at mid- to high frequencies?

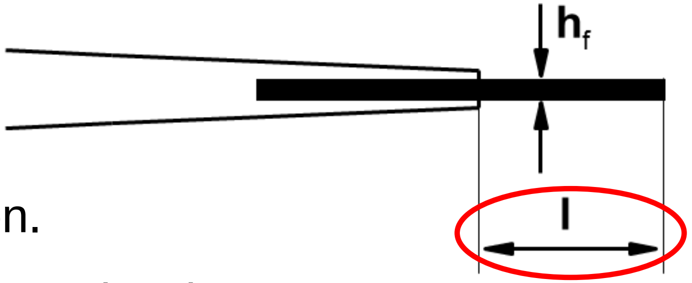
Ho to realize large permea-bility with small pore size?

Reference: Azarpeyvand, SFB 880 Final Symposium, 2019

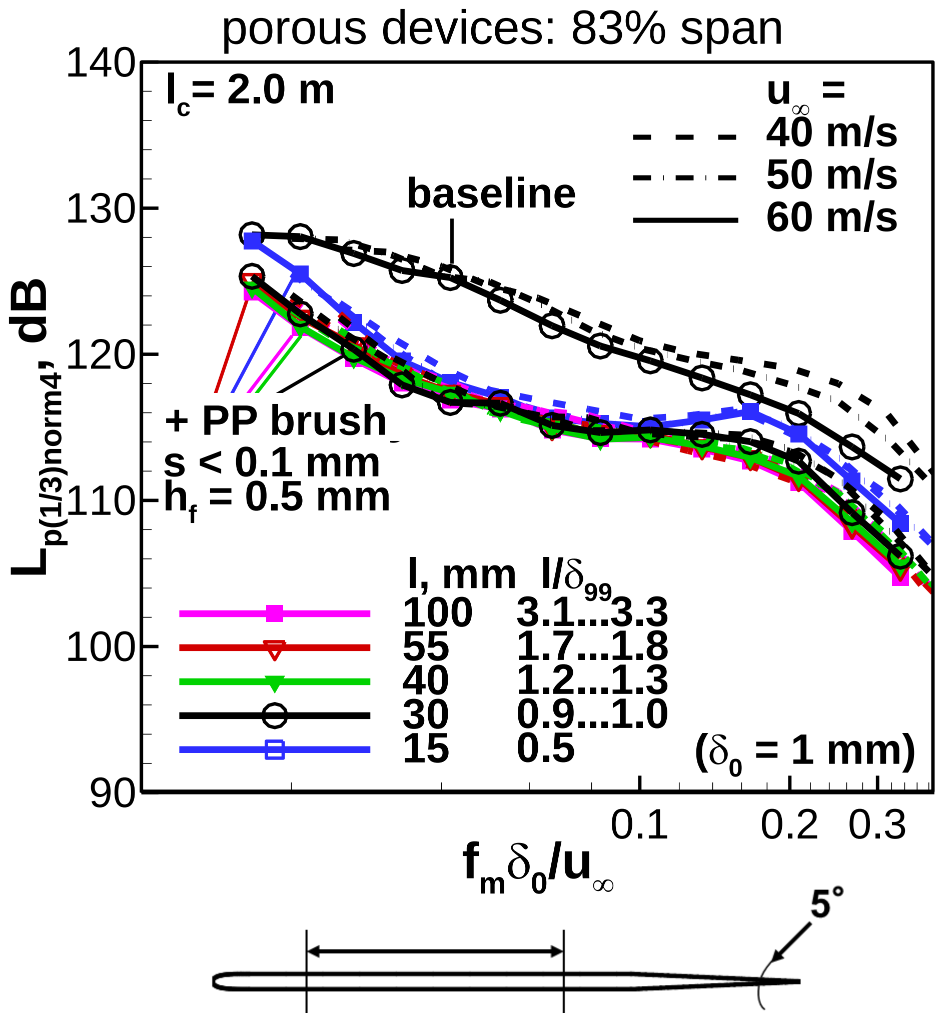
GENERAL FINDINGS

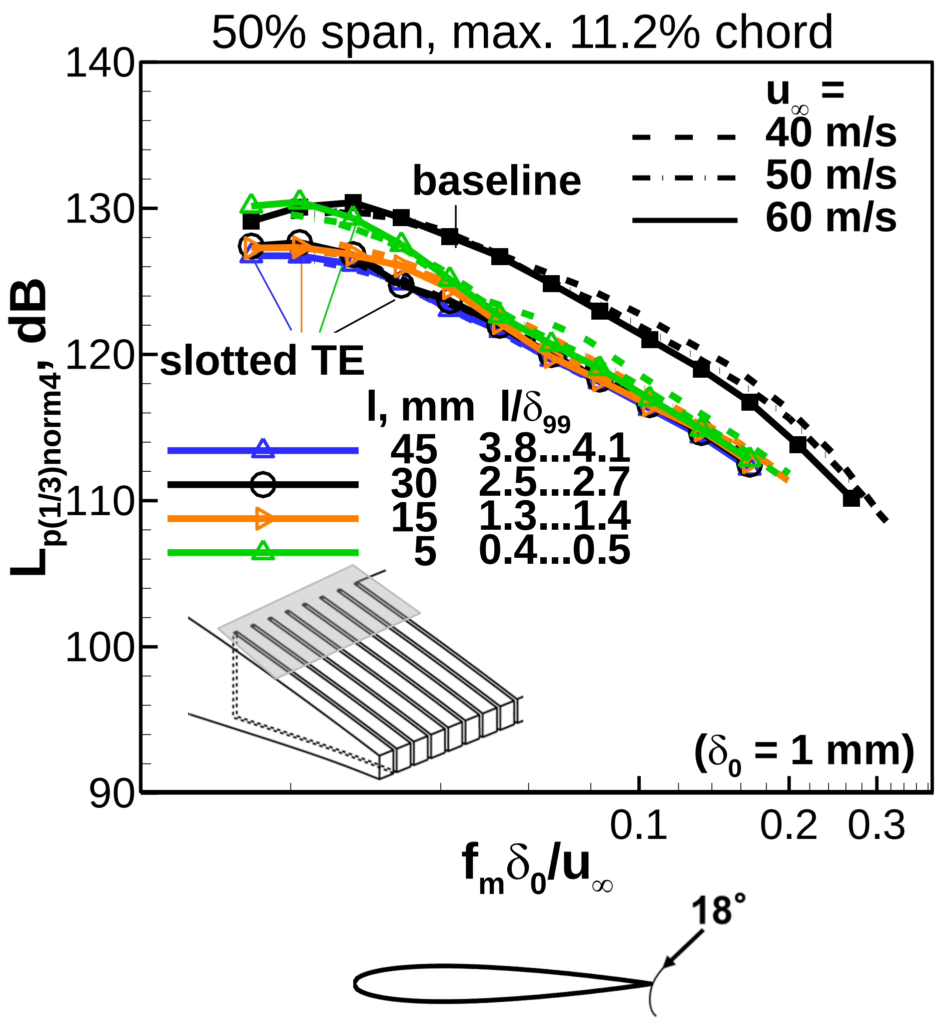
General findings

$$\langle p'^2 \rangle \propto u_\infty^5 \delta_0; \; \delta_0 = \mathrm{const}$$



1) A minimum device length of ~1–2 δ_{99} is required for maximum TEN reduction.

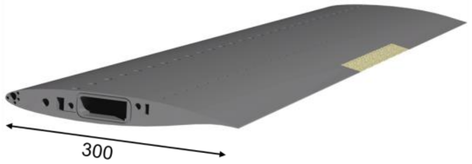




Reference: Herr, PhD thesis, 2013

General findings

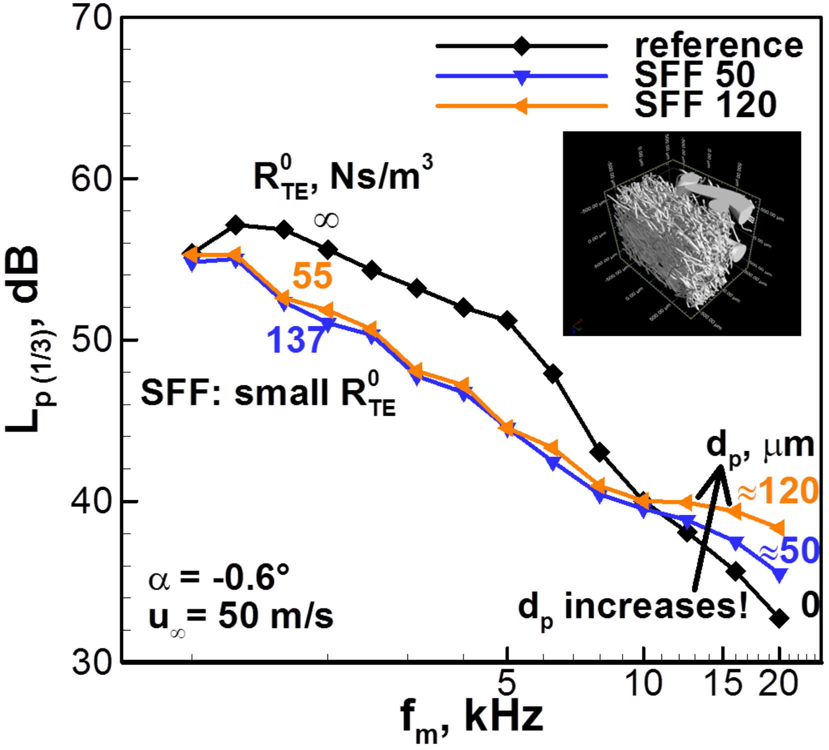
DLR F16, 50 m/s (Re = 1 Mio.), α = -0.6°
TE thickness h = 1.12 mm (or h = 2 t)

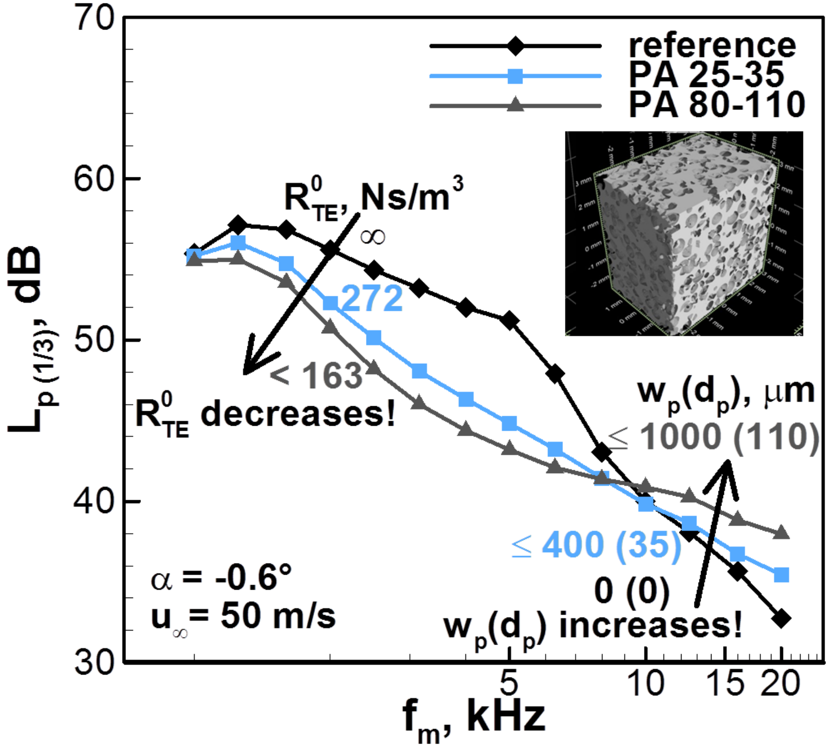


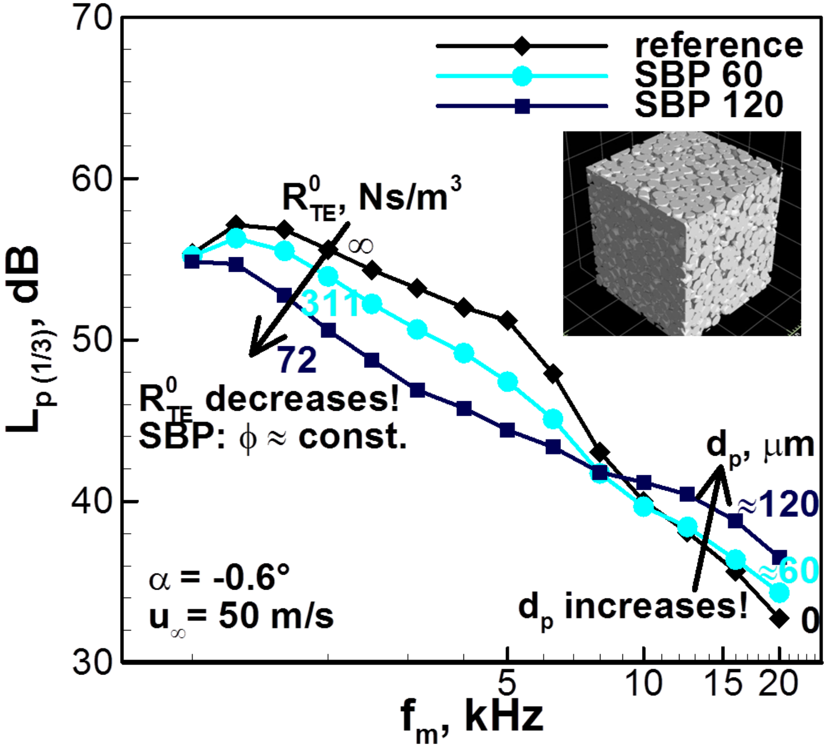
2) Flow airflow specific resistivity at TE is key parameter for TEN reduction at low frequencies!

$R = \Delta p / t\,v$

$R^0_{TE} \approx R\,h$







3) "pore size" (~ surface roughness) is key parameter for TEN noise increase at high frequencies

Reference: Herr et al. AIAA 2014-3041

recommendations from AIAA 2014-3041 to be revisited!

$$R^0_{TE} < 100\,Ns/m^3$$

$$w_p \leq 160\,\mu m$$

Hochauftrieb
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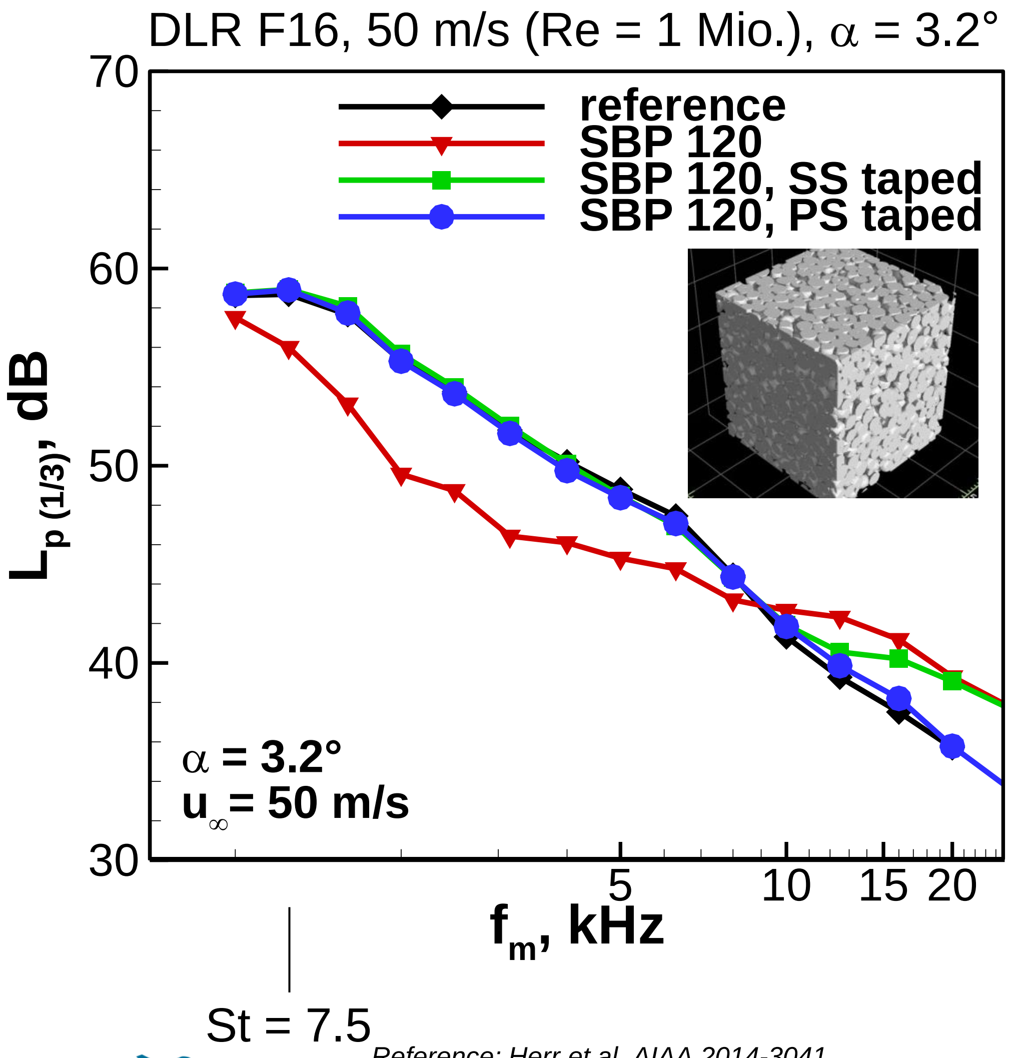
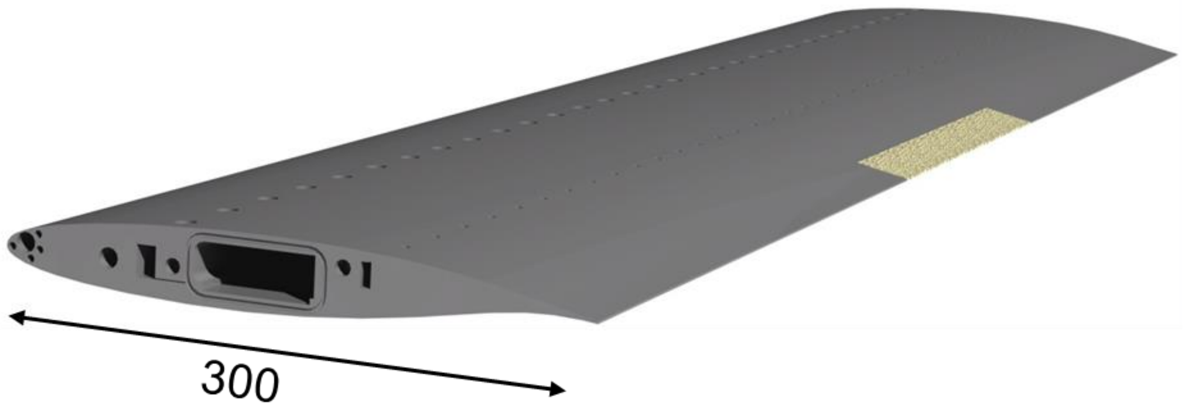
General findings

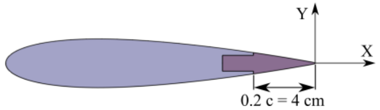
4) Pressure communication across TE is necessary requirement!





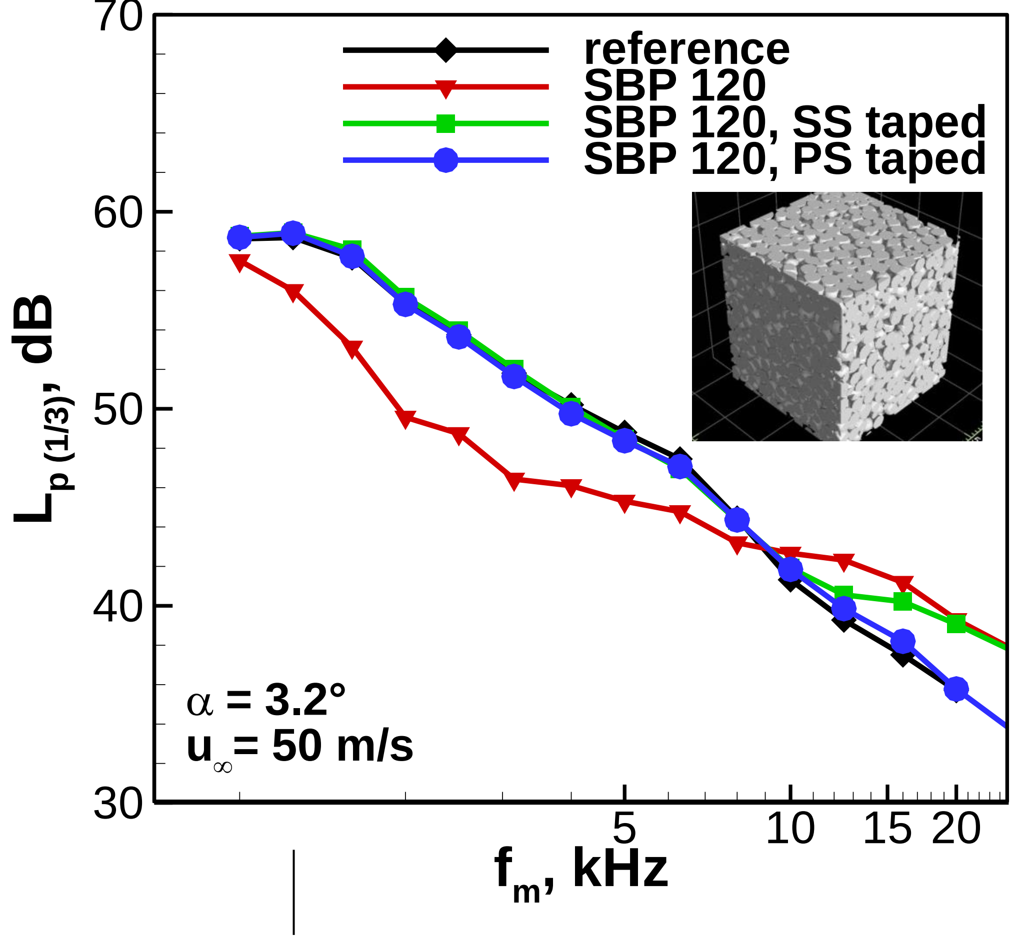
Reference: Herr et al. AIAA 2014-3041

General findings



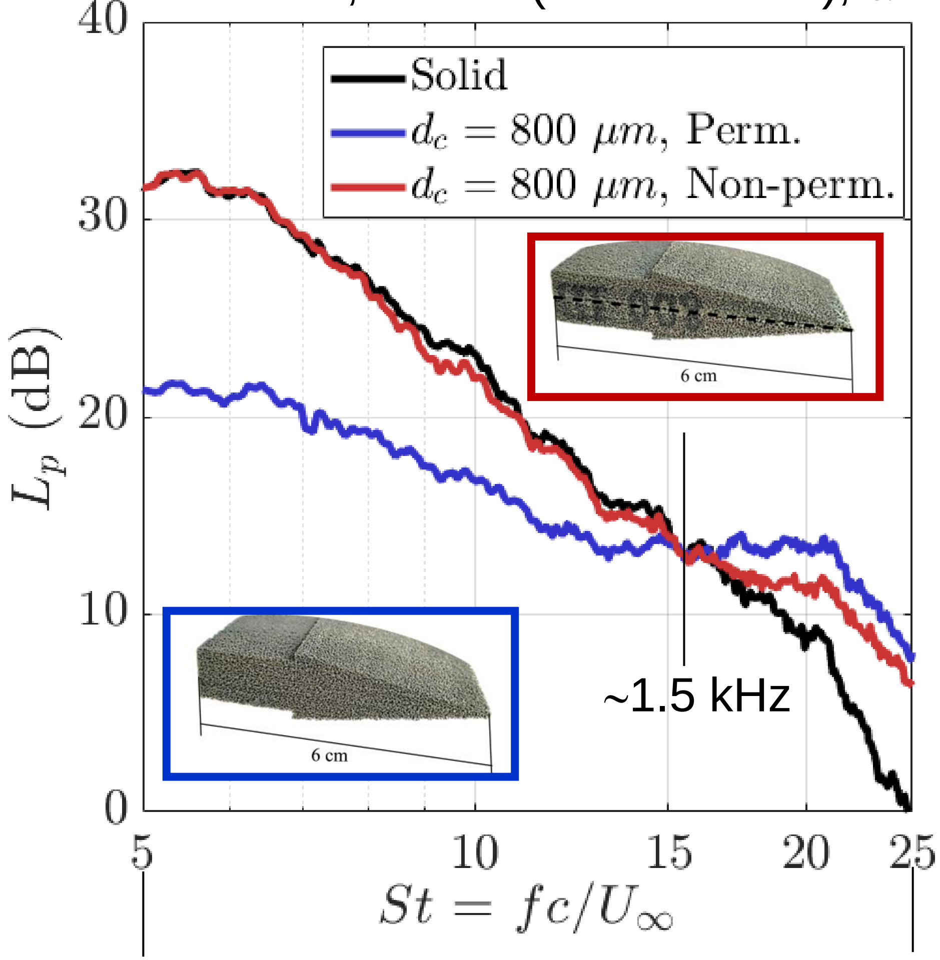
4) Pressure communication across TE is necessary requirement!

DLR F16, 50 m/s (Re = 1 Mio.), α = 3.2°



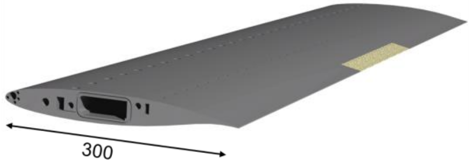
Reference: Herr et al. AIAA 2014-3041

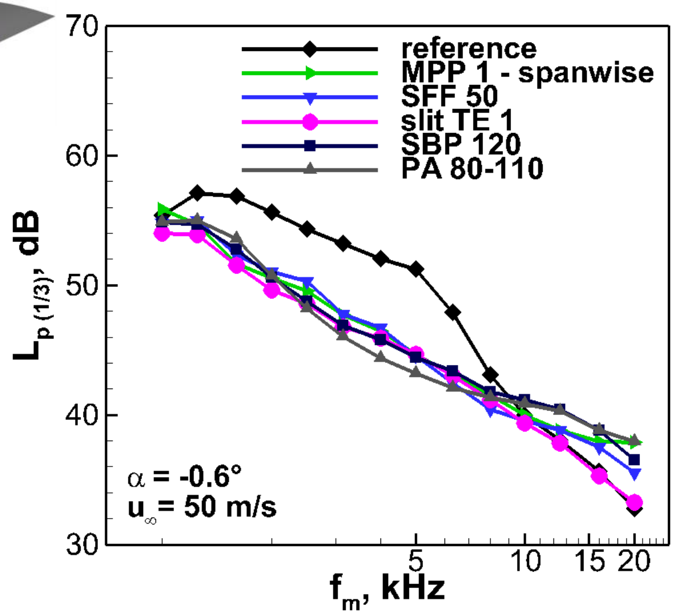
NACA 0018, 20 m/s (Re = 263000), α = 0°



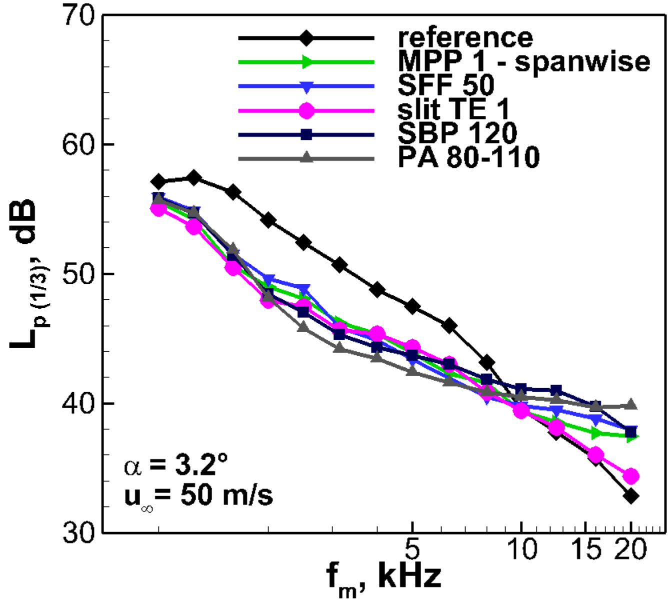
Reference: Carpio et al. AIAA 2018-2964

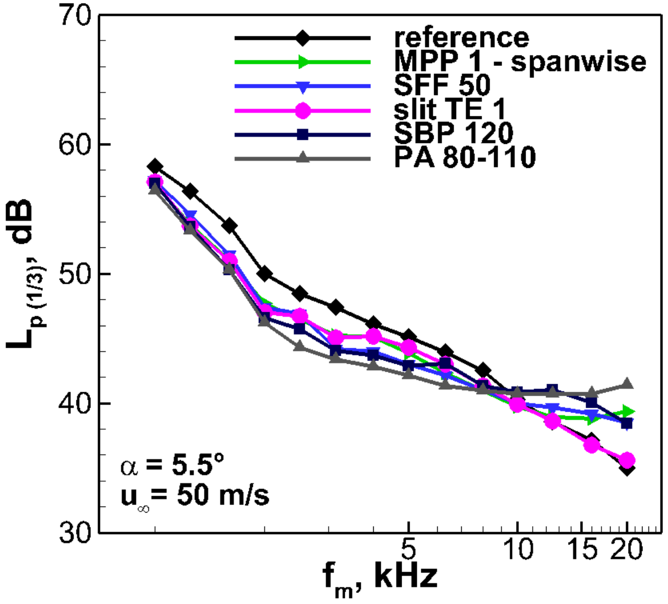
General findings

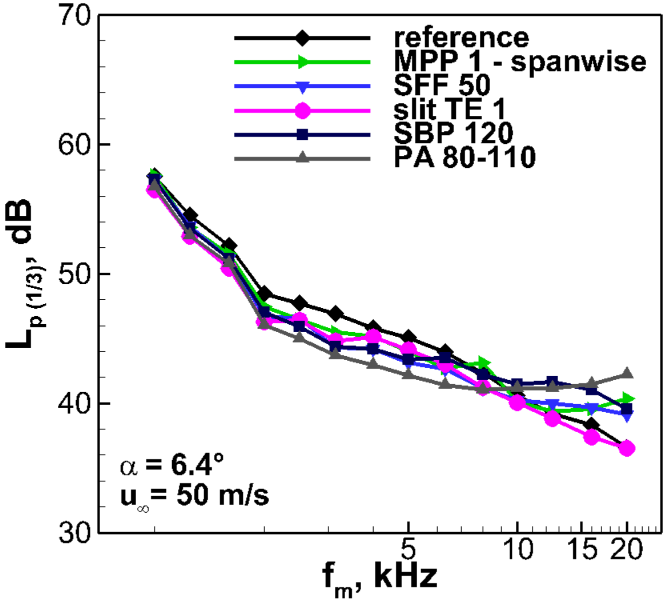




5) TEN noise reduction diminishes with increasing angle-of-attack

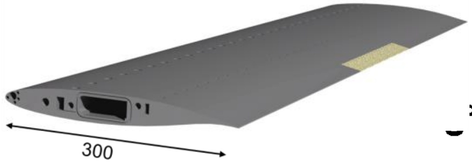


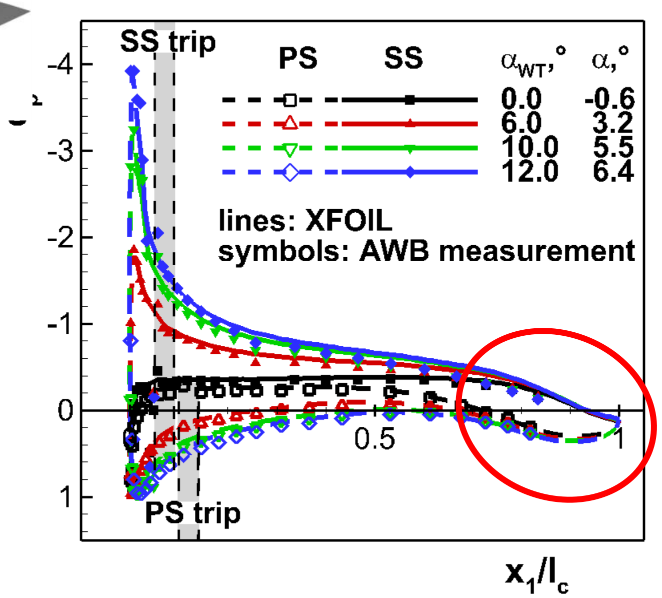




Reference: Herr et al. AIAA 2014-3041

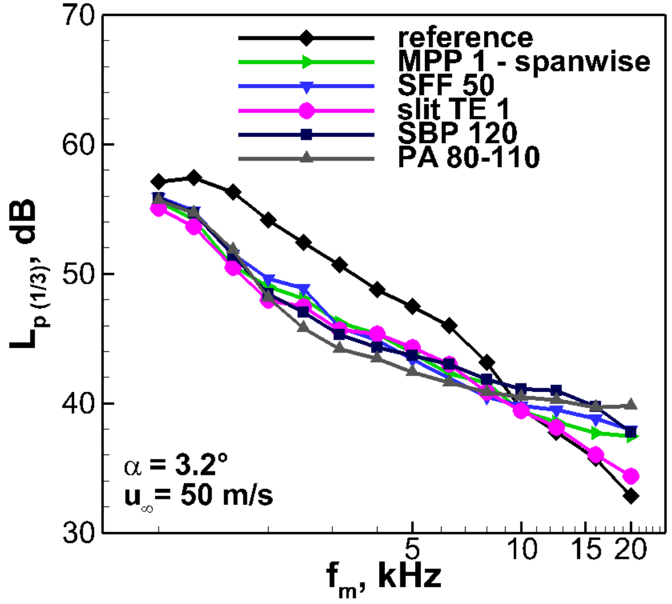
General findings

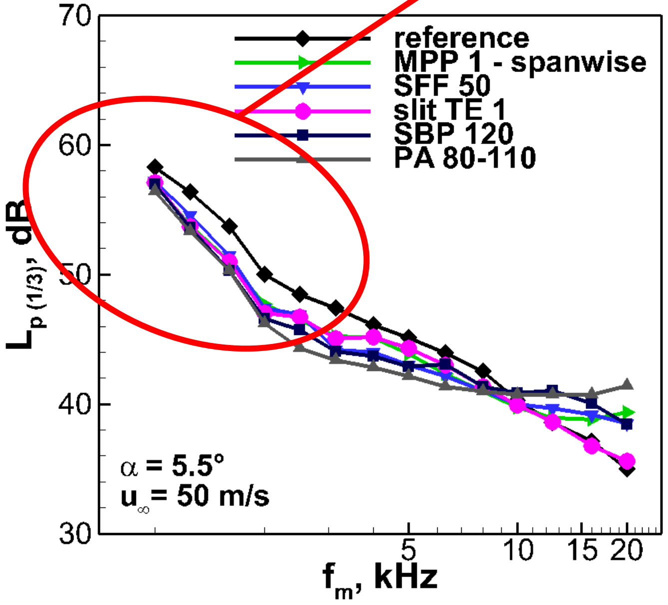


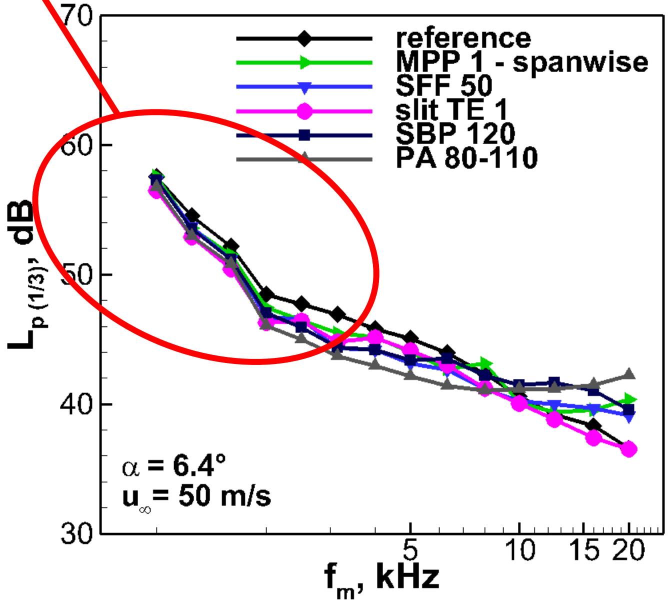


5) TEN noise reduction diminishes with increasing angle-of-attack

onset of separation?





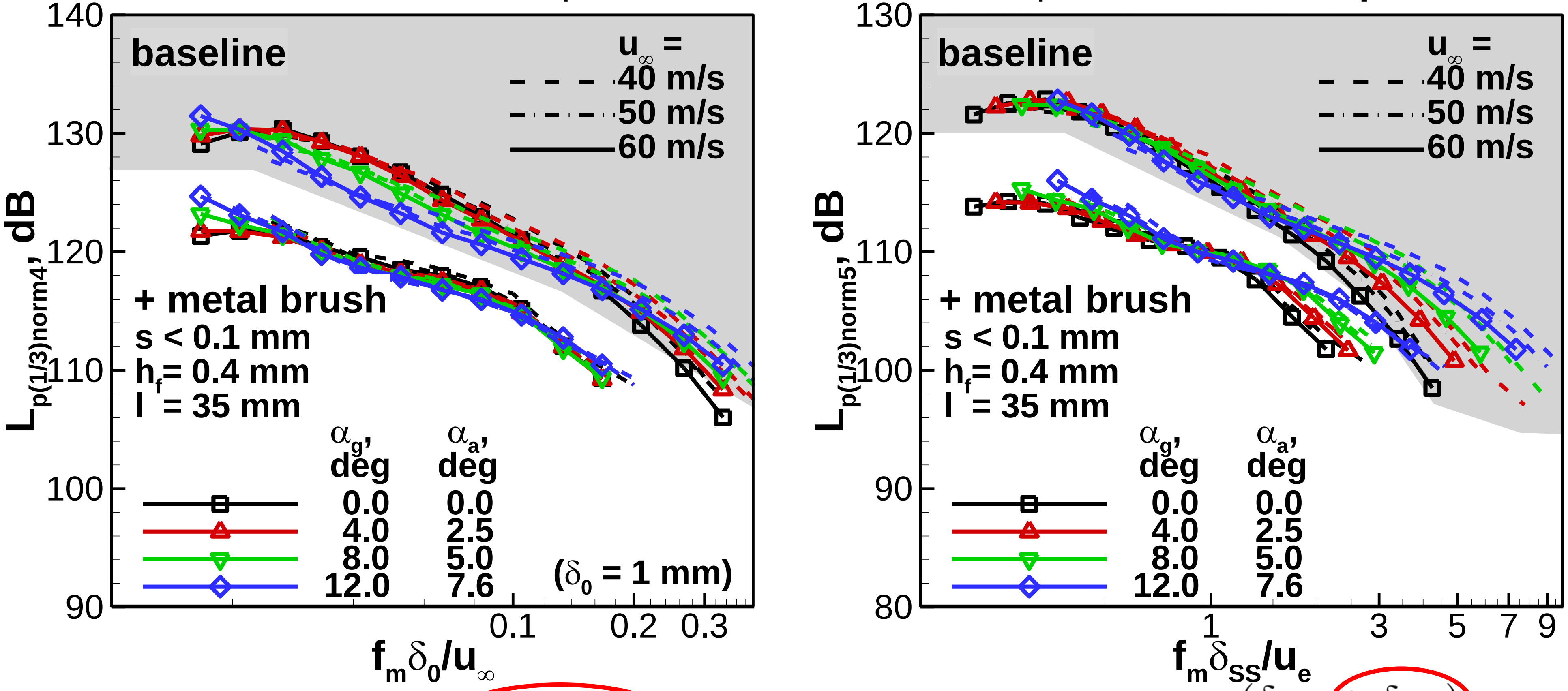


Reference: Herr et al. AIAA 2014-3041

General findings

5) TEN noise reduction diminishes with increasing angle-of-attack

- Generally better overall performance (& perfect TEN scaling behavior!) observed for flow-permeable **TE extensions** instead of porous block material TE replacements; **example: metal brush extension**



$$\langle p'^2 \rangle \propto u_\infty^5 \delta_0; \; \delta_0 = \text{const}$$

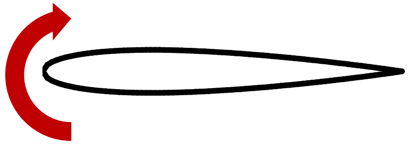
$$\langle p'^2 \rangle \propto u_e^5 \frac{(\delta_{PS} + \delta_{SS})}{2}$$

NACA0012$_{(mod)}$
0.4 m chord
Re = 1.1–1.6 Mio.

Reference: Herr, PhD thesis 2013

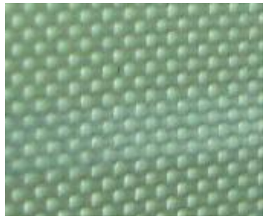
General findings

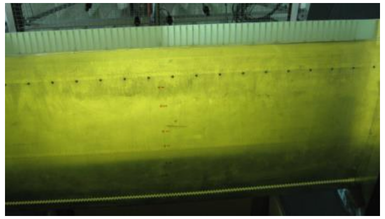
NACA0012$_{(mod)}$
0.4 m chord
Re = 1.6 Mio.

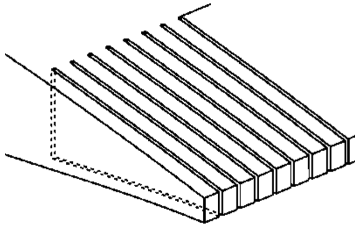


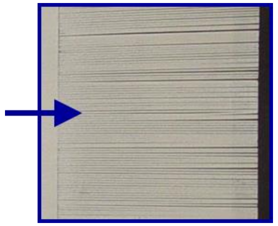
5) TEN noise reduction diminishes with increasing angle-of-attack

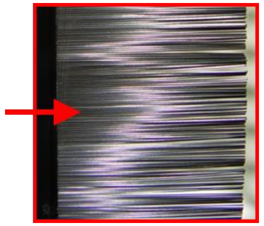
- Generally better overall performance observed for flow-permeable **TE extensions** instead of TE replacements**; examples: PP brush extension vs. cloth covers vs. slotted TE**

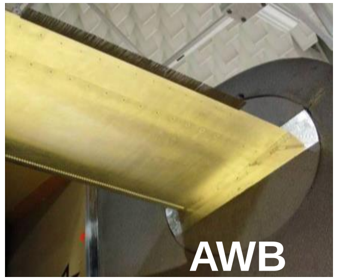


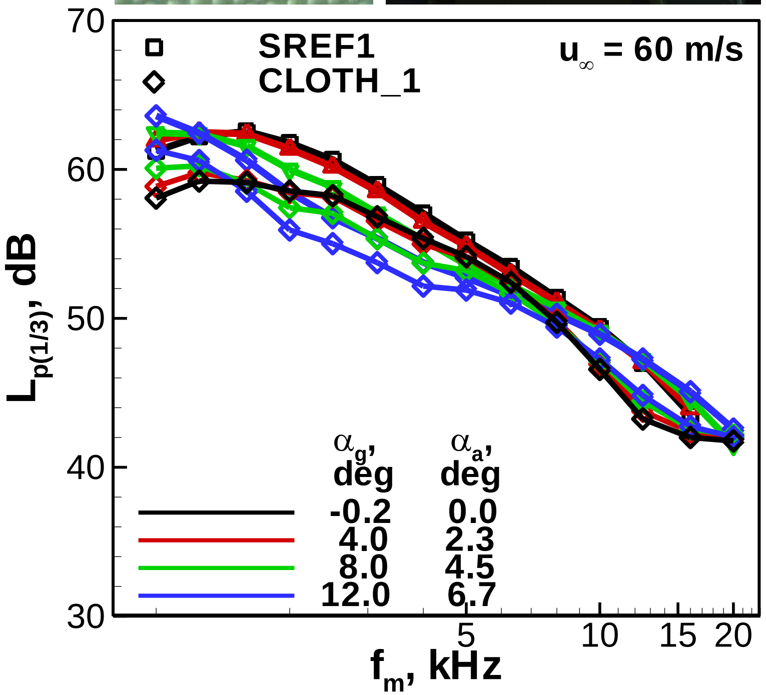


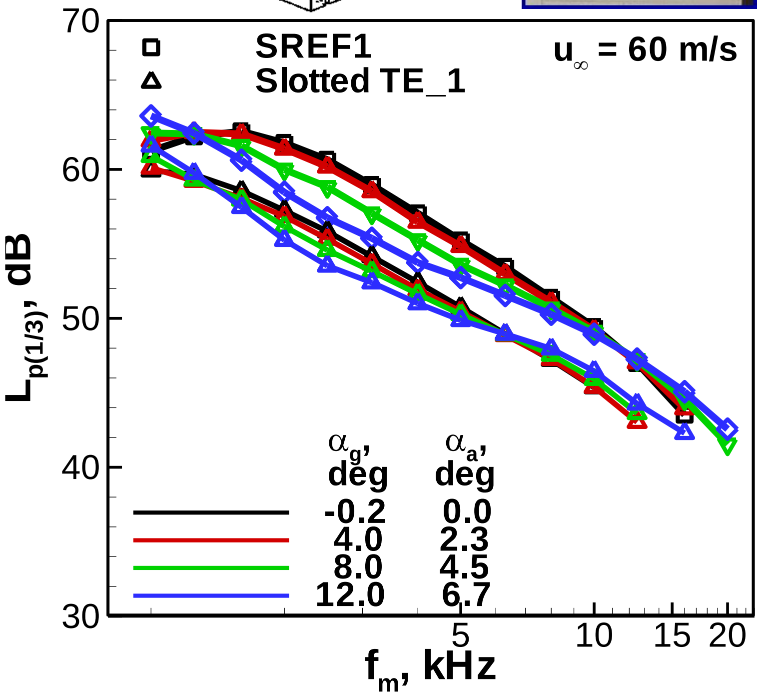


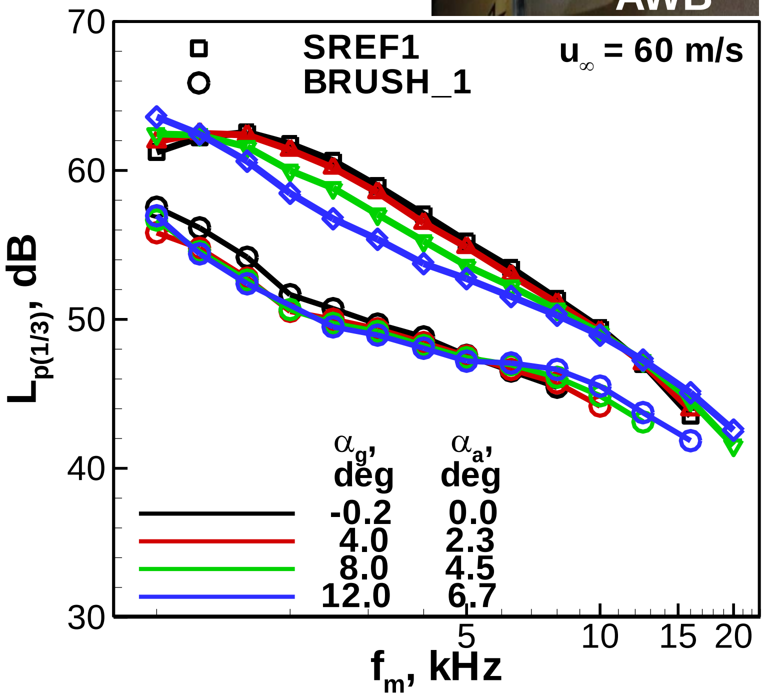












Reference: Herr & Reichenberger, AIAA 2011-2780

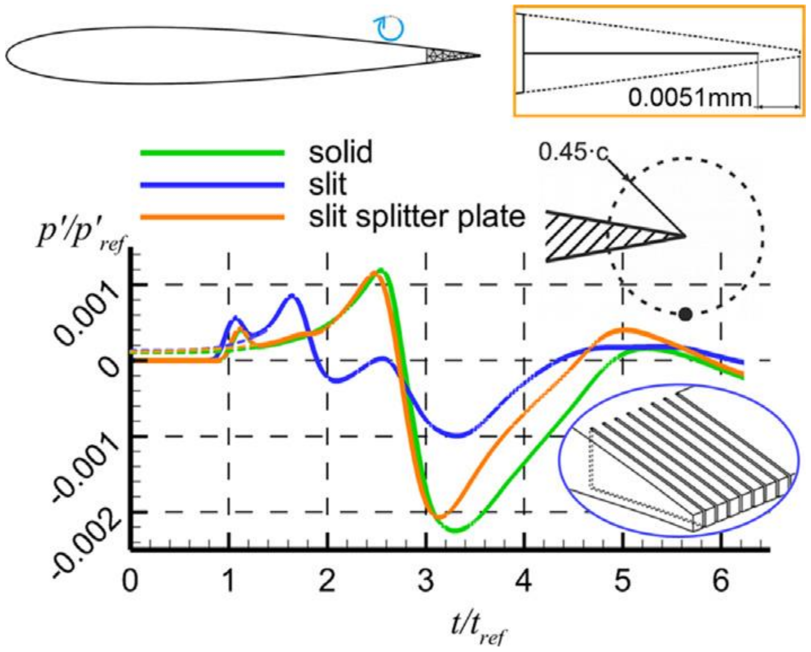
Hypothesis on noise reduction mechanism

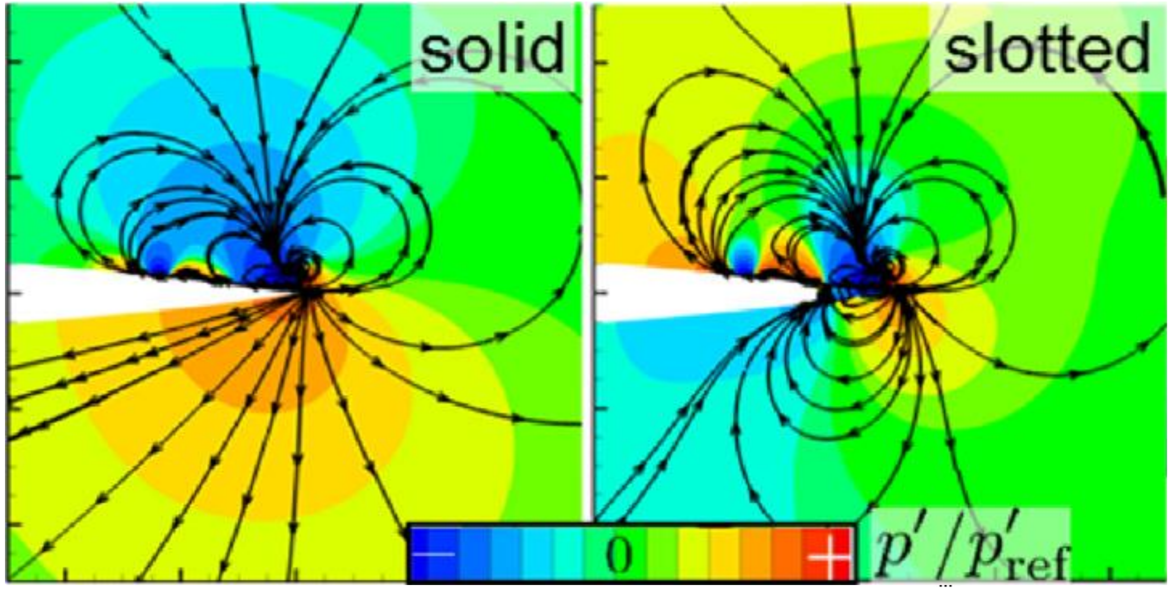
Assumed primary mechanisms to be related to a **reduced scattering efficiency of the TE**

- **pressure release in the acoustic nearfield by impedance matching**
- **(geometric break up of the edge contour)**

Experimental indicators: **Pressure communication across TE is necessary requirement!**

Numerical indicators: **Simple inviscid perturbation simulations lead to comparable noise reduction as in measurement!** → mechanism not driven by viscosity





References: Delfs et al., JSV 357 (2015)

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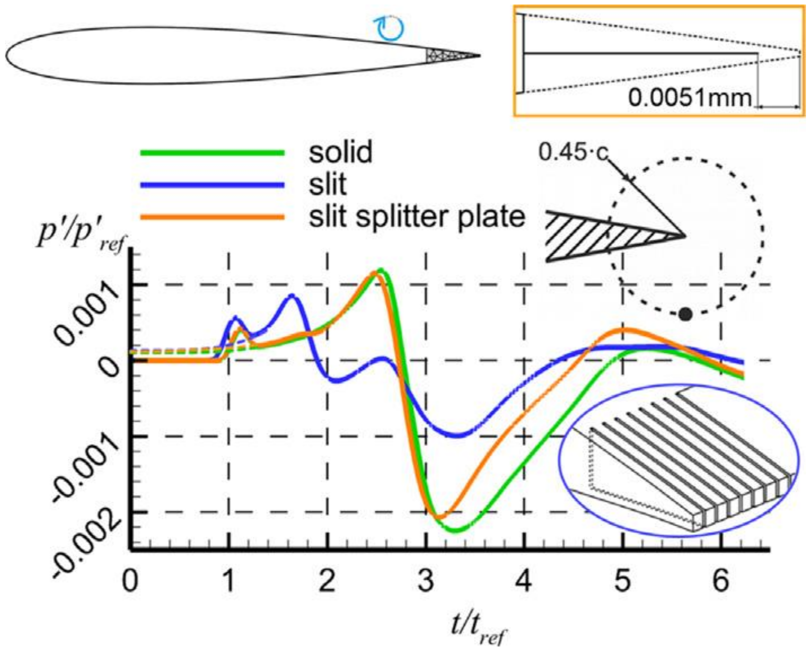
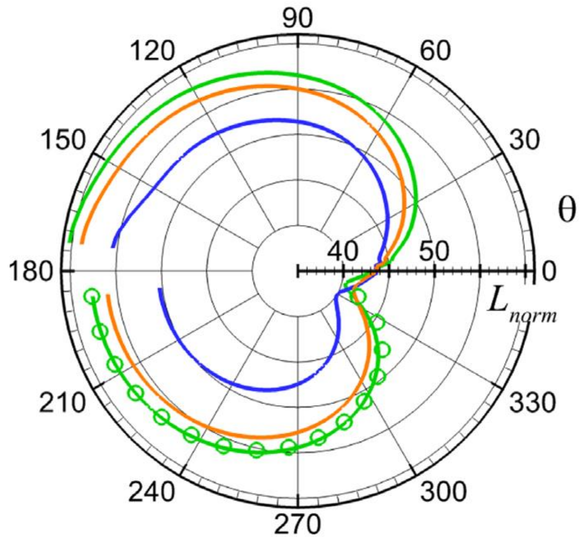
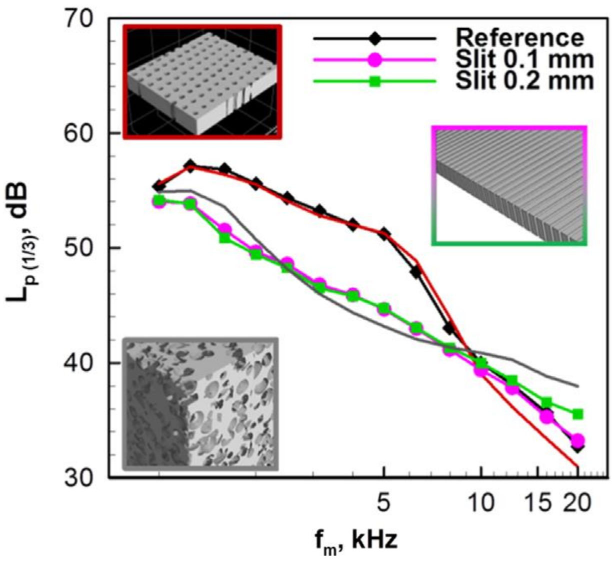






References: *Delfs et al., JSV 357 (2015), Herr et al. AIAA 2014-3041*

Hypothesis on noise reduction mechanism

Assumed secondary mechanisms with further modifications of the overall performance in direction of

more noise reduction:

- reduction of spanwise correlation lengths of turbulence
- reduction of convection velocities in TE area
- hydrodynamic absorption, i.e. viscous damping of velocity fluctuations
- acoustic absorption (rather not for these tiny sizes!)

less noise reduction:

- excess noise production due to cross-flow, surface roughness, installation details
- thickening of turbulent boundary-layers & increase of TKE due to cross-flow, surface roughness, …
- mutual Interaction of separate acoustic sources?

Major take-aways (w.r.t. requirements for technical application)

- The major determining material parameter for OASPL reduction is the flow resistance, but
  - design optimization will likely have to account for its velocity- and frequency dependence
  - acoustic requirement: open for wall-normal fluctuations and pressure but minimal mean leakage-flow through TE region (aero performance!)
- Only limited empirical relationships between TEN reduction effect, well-defined material characteristics and flow properties have been identified, resulting in a rather arbitrary pre-selection of materials (based on available manufacturing capabilities for "airworthy" materials)

- Noise reduction results from reported studies in literature cannot be easily compared to derive conclusive answers due to
  - largely varying setups (zero a-o-a vs. loaded test cases, low vs. high Re numbers, BGN in facilities, …)
  - different measurement methods used for material characterization and their respective inherent errors (material properties provided by manufacturers vs. measurements performed by material specialists)
  - limitations to determine the "true" resistivity values of the tested TE inserts

- Potential high-frequency excess noise contributions will have to be shifted towards low-weighted frequencies @ full scale
- Full elimination of high-frequency excess noise and/or artificial thickening of the TBL will require a hydraulically smooth surface

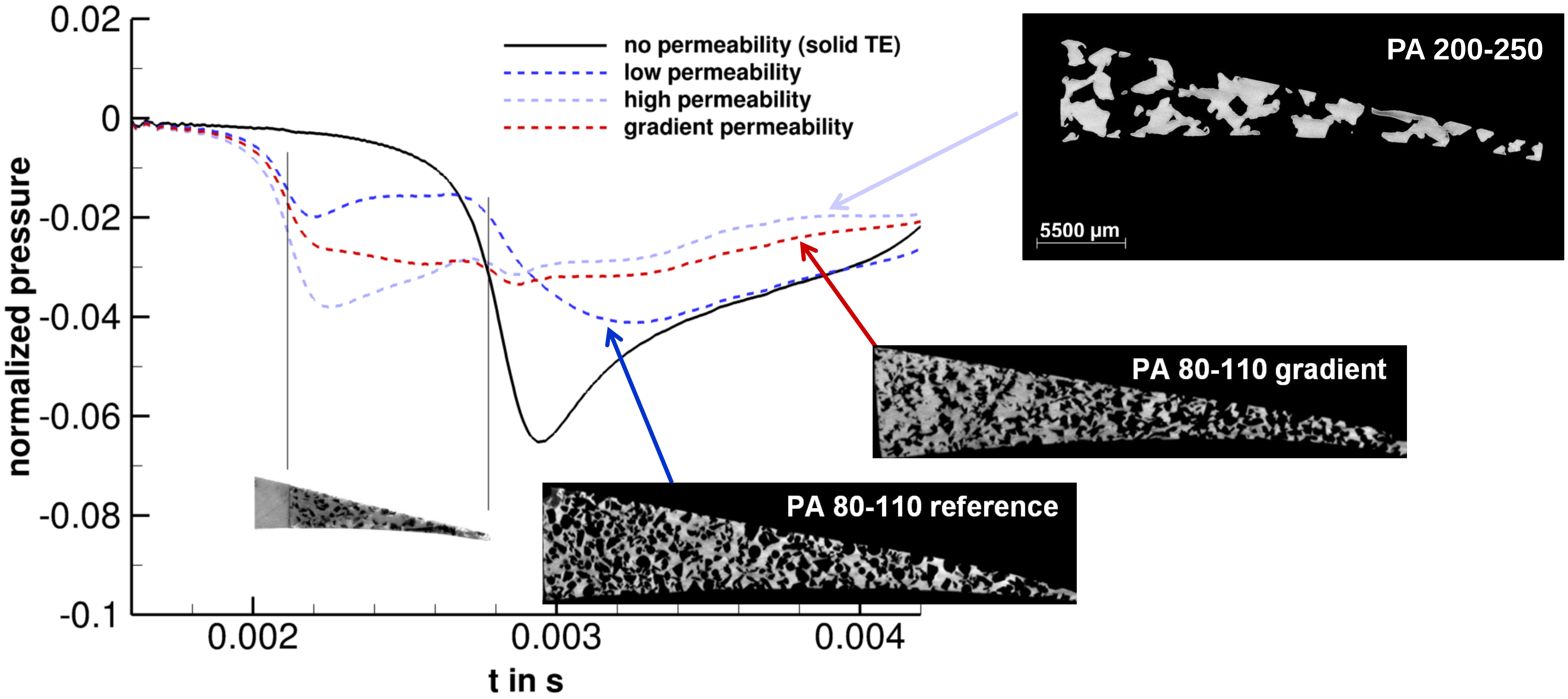
TECHNOLOGY CHALLENGES

PART 1: Tailored materials?

- Technical realization of design targets
- Repeatability of desired material properties
- Accuracy of material specification

Tailored materials?

Hypothesis: material with **gradient permeability** will increase acoustic & aerodynamic performance!

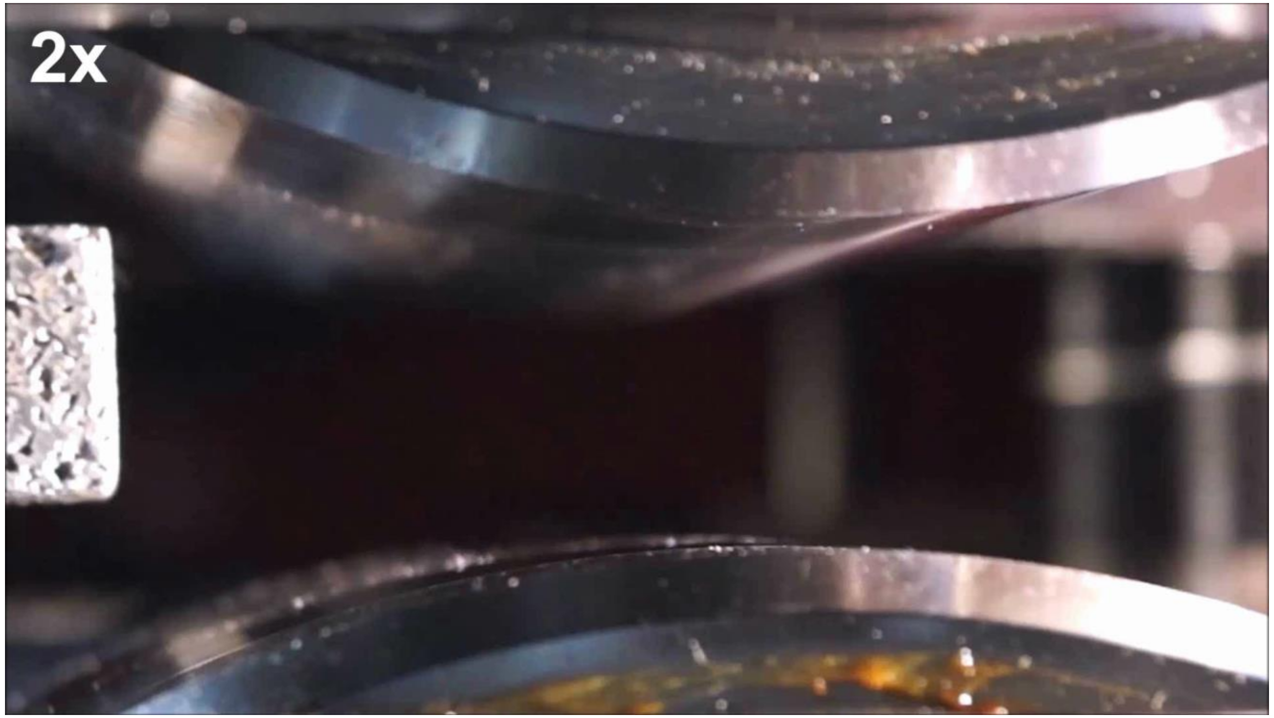


Reference: Rossian, DLR, 2017

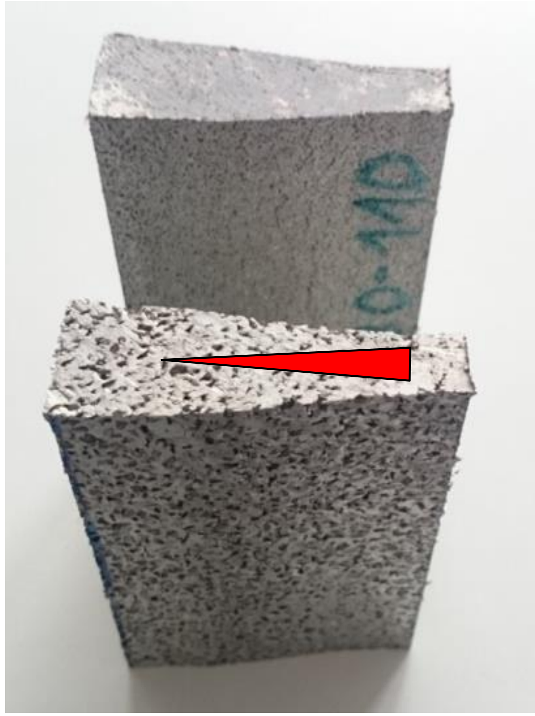
Tailored materials? → realisation by gradient rolling

Technical challenges: material characterization & repeatability of achieved properties

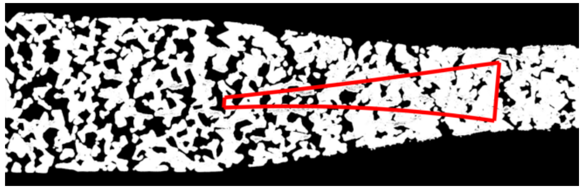
- comparative samples needed (made of constant rolled material) for material characterization!
- repeatability of material characteristics OK for rolling procedure; **but: overall result is dependent on delivered starting material by manufacturers (be careful!)**



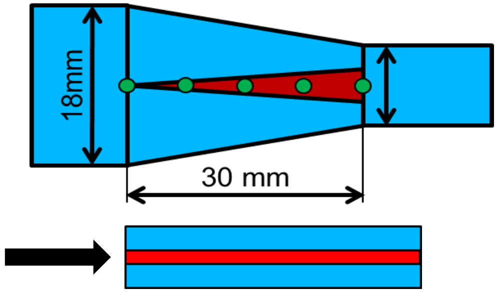
gradient rolling of PA 120-150: $\Delta t/t_0$ = 0–50 % over a length of 30 mm in one rolling pass



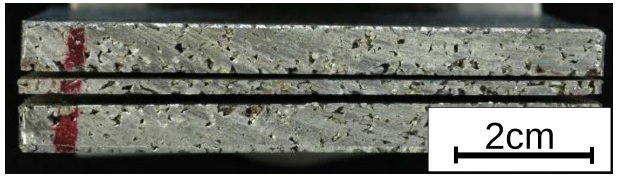
gradient PA 80-110 (top) and gradient PA 200-250 (bottom)



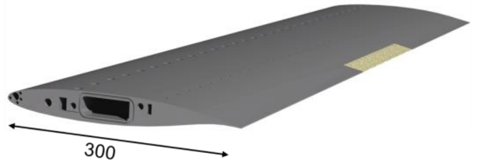
Cross-section of graded PA200-250, shape of TE highlighted



Schematic diagram showing graded material with five positions that are to be measured

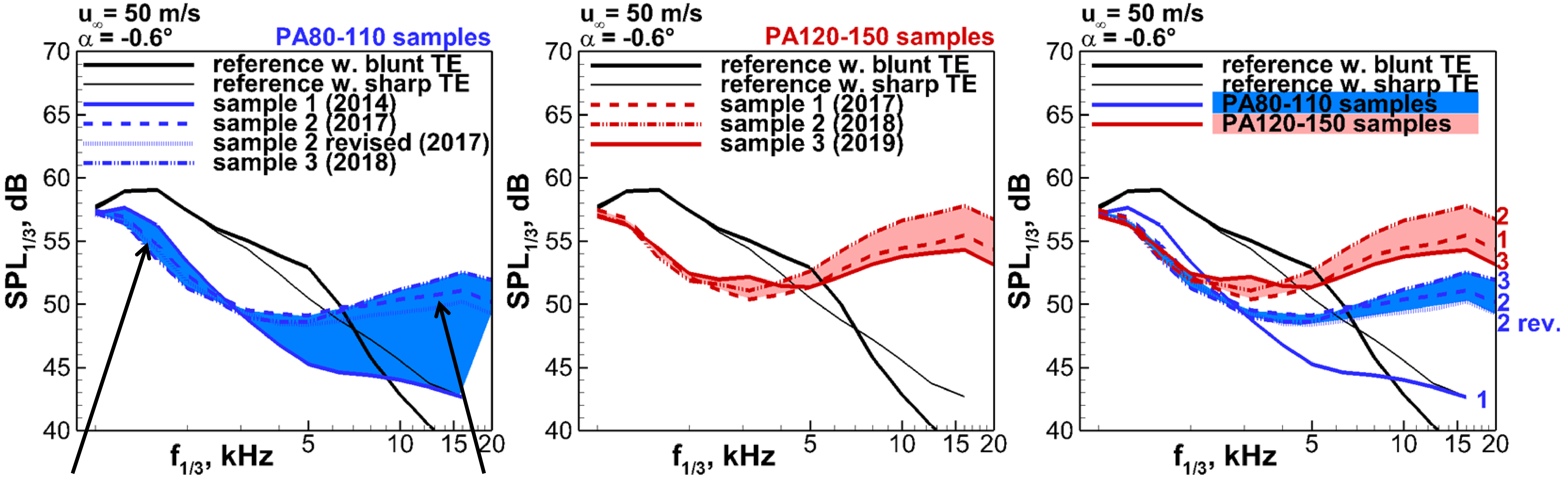


Technical challenge: Repeatability of material characteristics



Technical challenge: repeatability of material characteristics
Overall result is dependent on delivered starting material by manufactures (be careful!)

Acoustic results for ordered PA materials with supposedly identical nominal effective pore size:



variations in flow resistivity? variations in pore size?

Detailed assessment of “true” material characteristics ongoing…

Technical challenge: Repeatability of material characteristics

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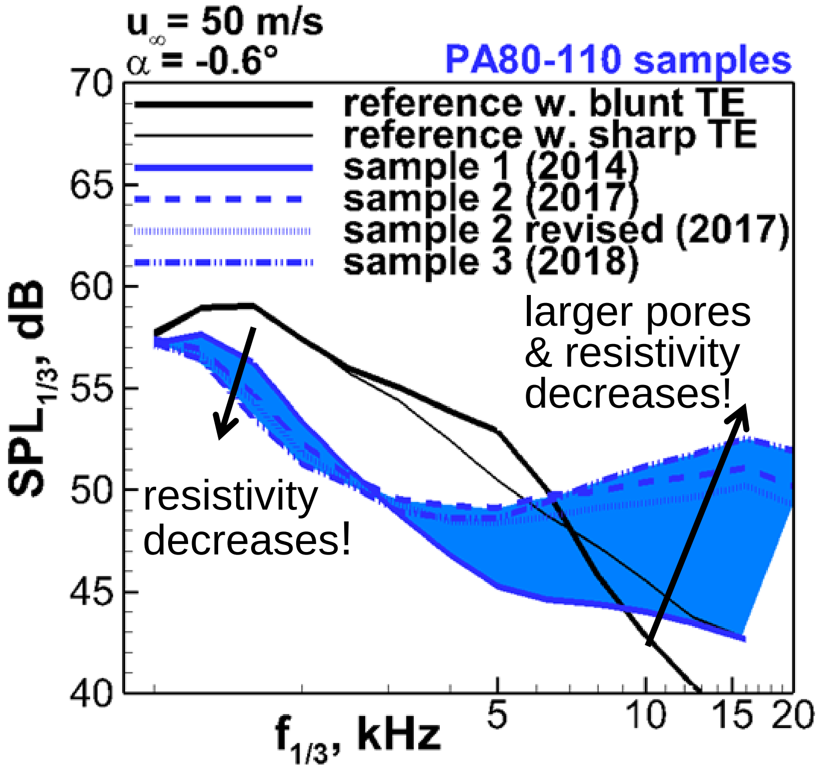
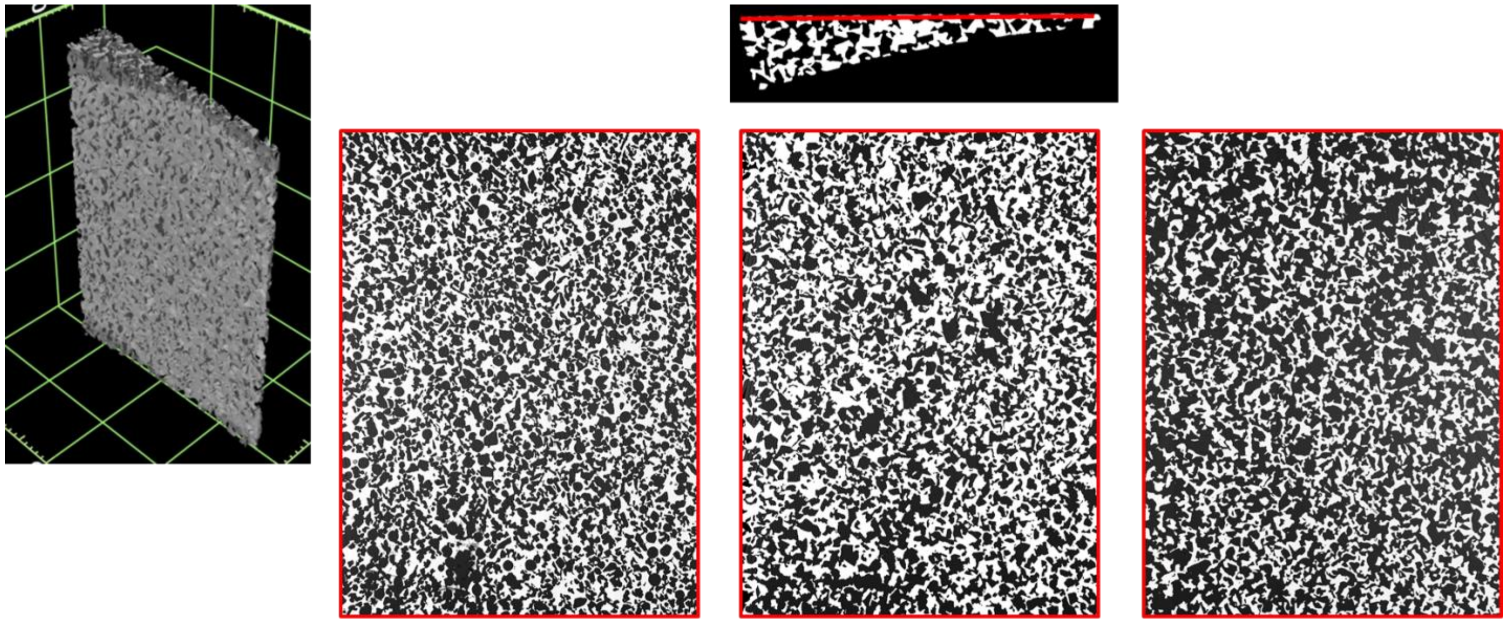
Technical challenge: repeatability of material characteristics
Overall result is dependent on delivered starting material by manufactures (be careful!)

Measured material characteristics PA80-110: flow resistivity





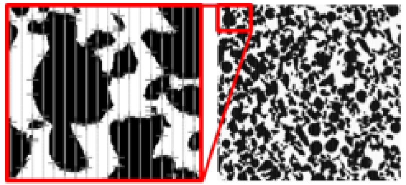
PA80-110 sample No.	1	2	3
R, kNs/m^4	145.5	30.7	25.3

Detailed assessment of "true" material characteristics ongoing…

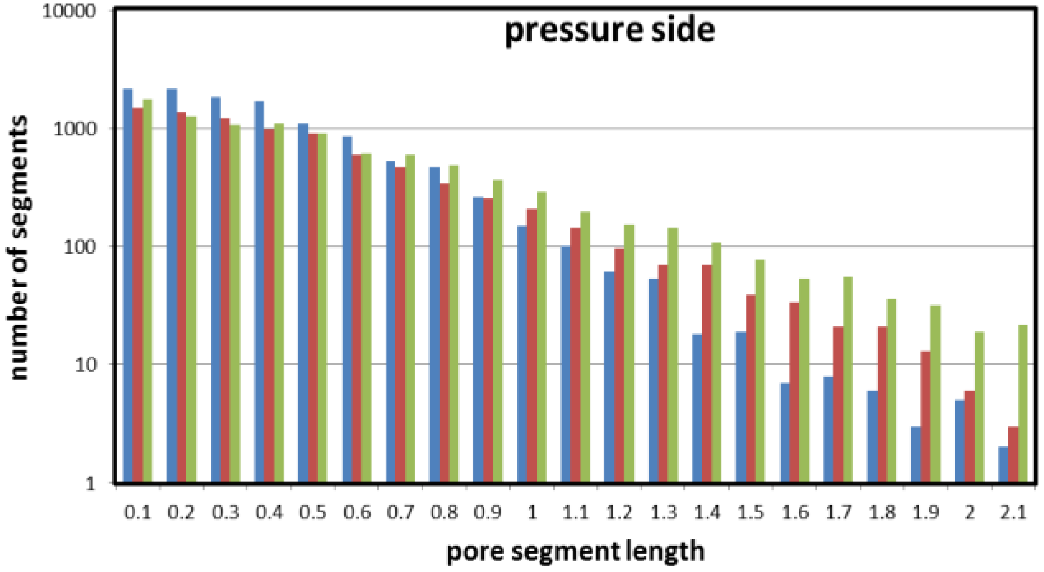
Technical challenge: Repeatability of material characteristics

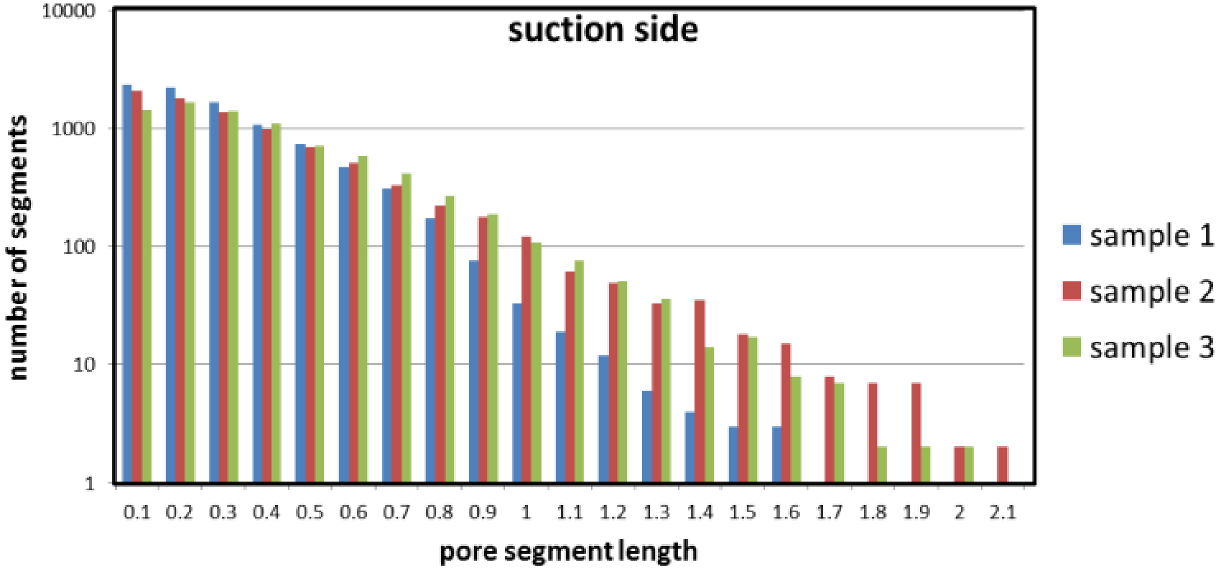
Technical challenge: repeatability of material characteristics
Overall result is dependent on delivered starting material by manufactures (be careful!)

Measured material characteristics PA80-110: pore size distribution derived from **streamwise** line cuts, resolution: 5 px



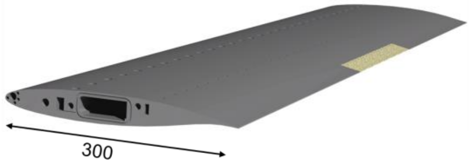
Direct comparisons gradient vs. segmented vs. non-gradient are only possible for test samples originating from same batch!



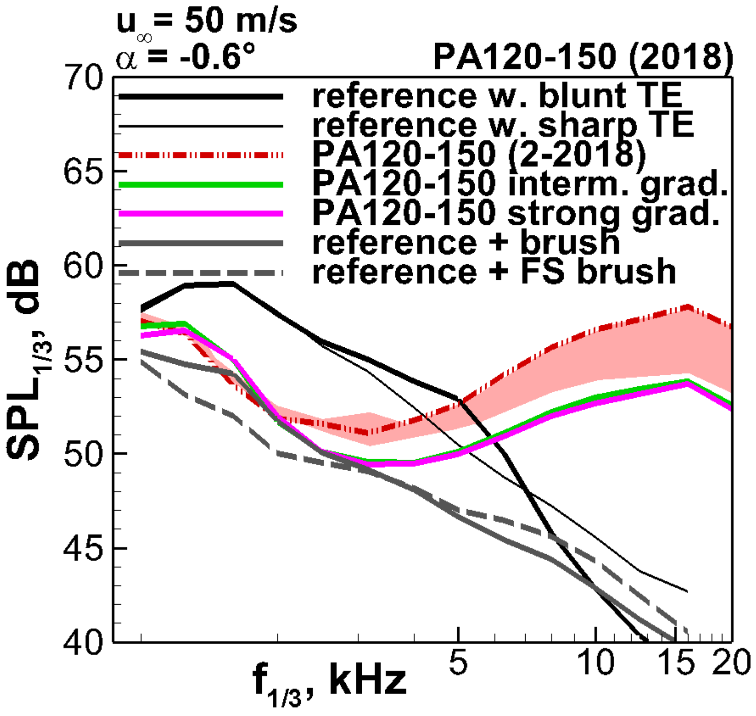


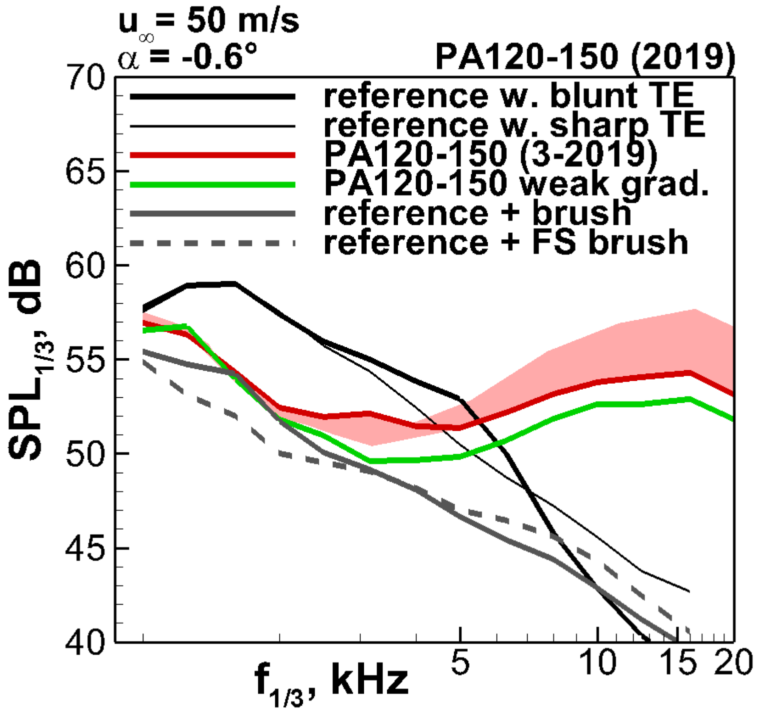
Detailed assessment of "true" material characteristics ongoing…

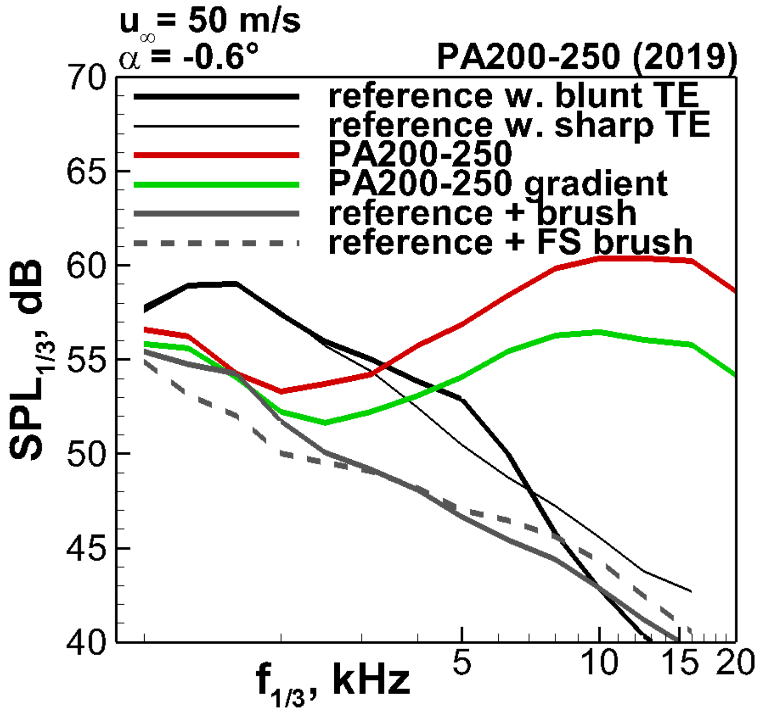
Tailored materials? → realisation by gradient rolling



First (promising!) acoustic results for TE with gradient resistivity



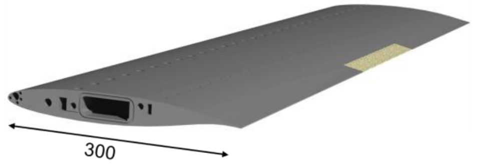




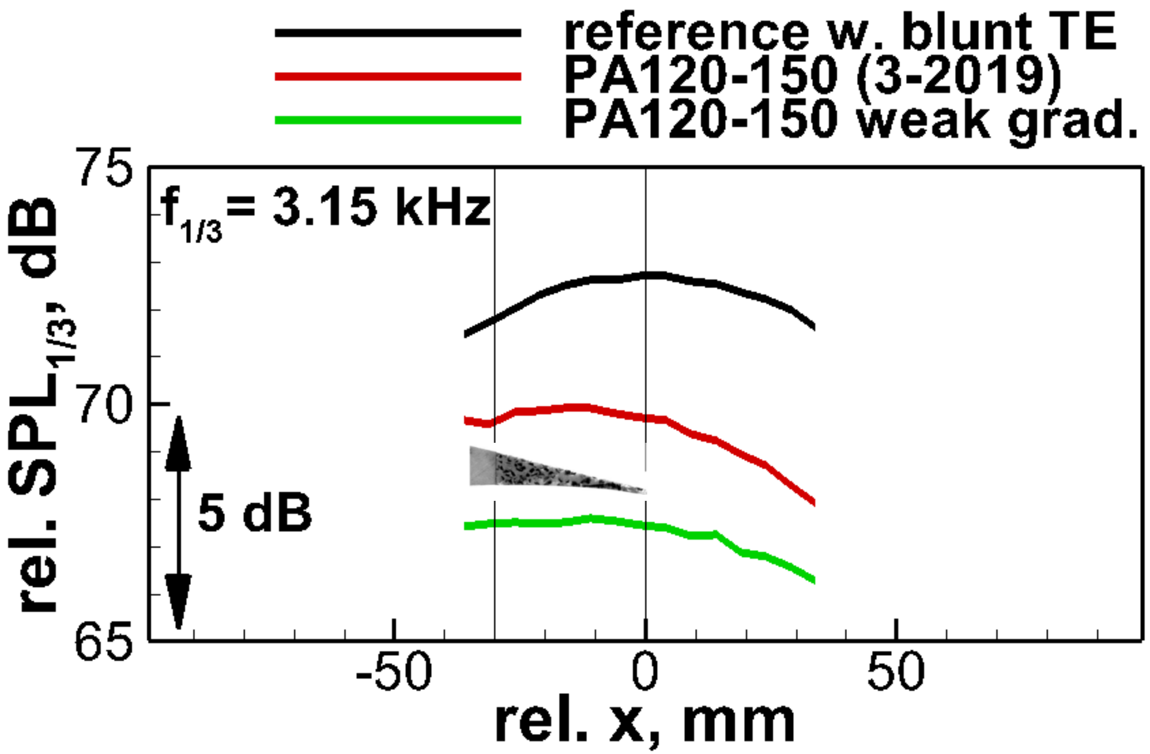
Current limitations:

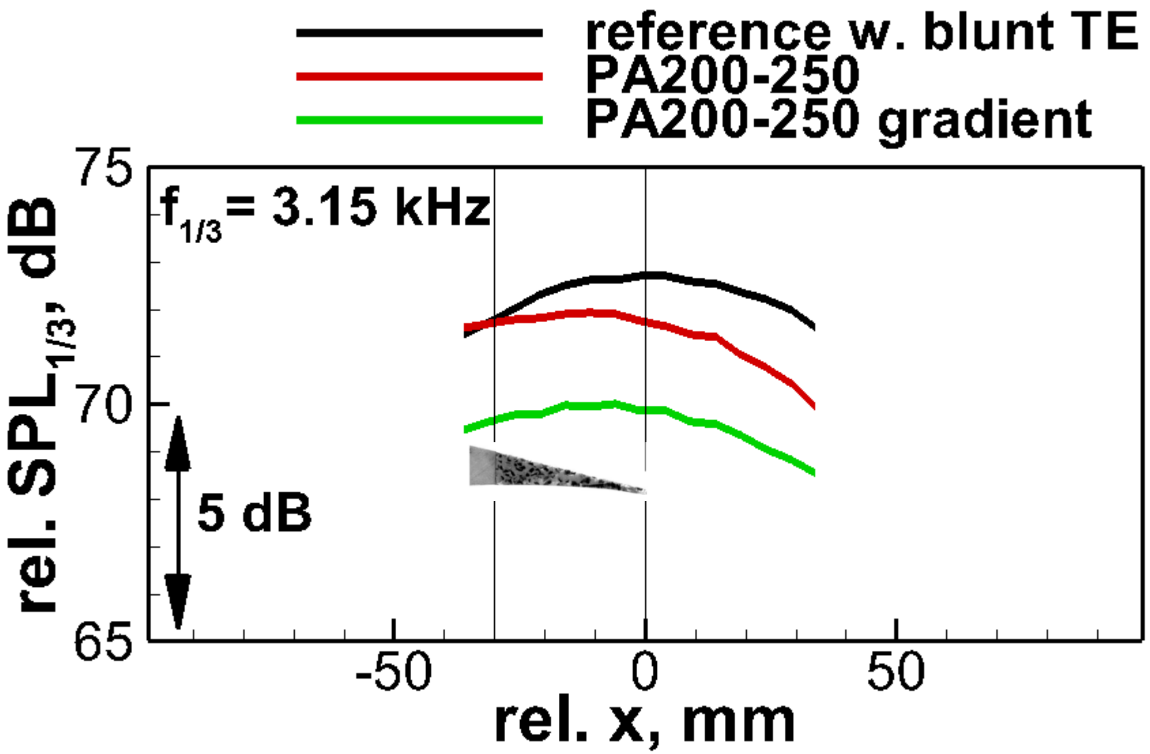
- Further decreasing of resistivity for starting PA material (i.e. resulting resistivity at TE) not possible with the current manufacturer!
- Use of coarser starting material will induce excess noise at relevant frequencies!
- Overall device length might now be too short to achieve the full noise reduction potential (< ~1–2 δ_{99})
- Limited (30 cm) spanwise extent of porous region vs. resolution of focusing measurement technos.

Tailored materials? → realisation by gradient rolling



Measured source locations for TE with gradient resistivity





Tailored materials? → realisation by gradient distribution of pores

Technical challenges: material characterization & repeatability of achieved properties

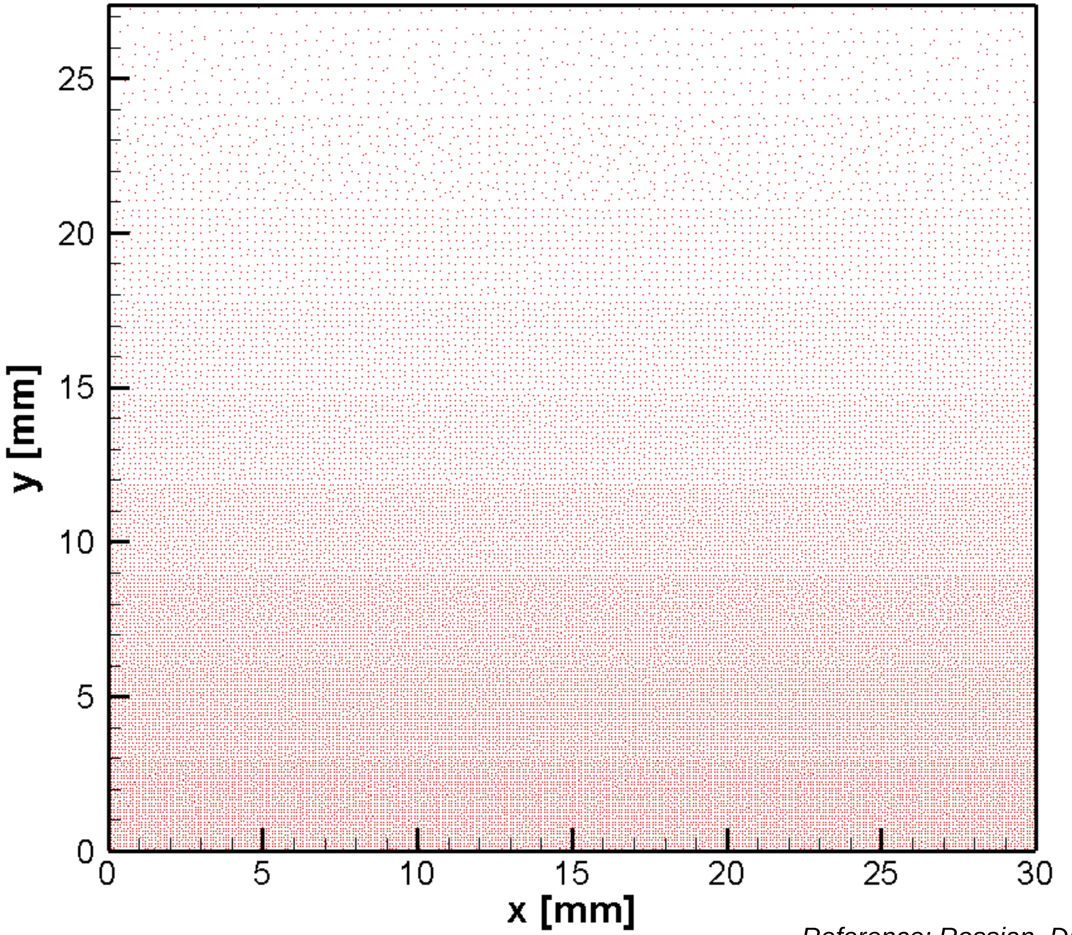
Design target: hydraulically smooth micro-perforated sheet with gradient resistivity

Realizable according to manufacturer:

- ø 40 µm pores
- @ minimum separation distance of 80 µm

Expected resulting maximum specific resistivity of sheet:

- $\boldsymbol{R^0 \approx 160\, Ns/m^3}$
  (comparable to PA 80-110 material sample from 2014 study (AIAA 2014-3041)



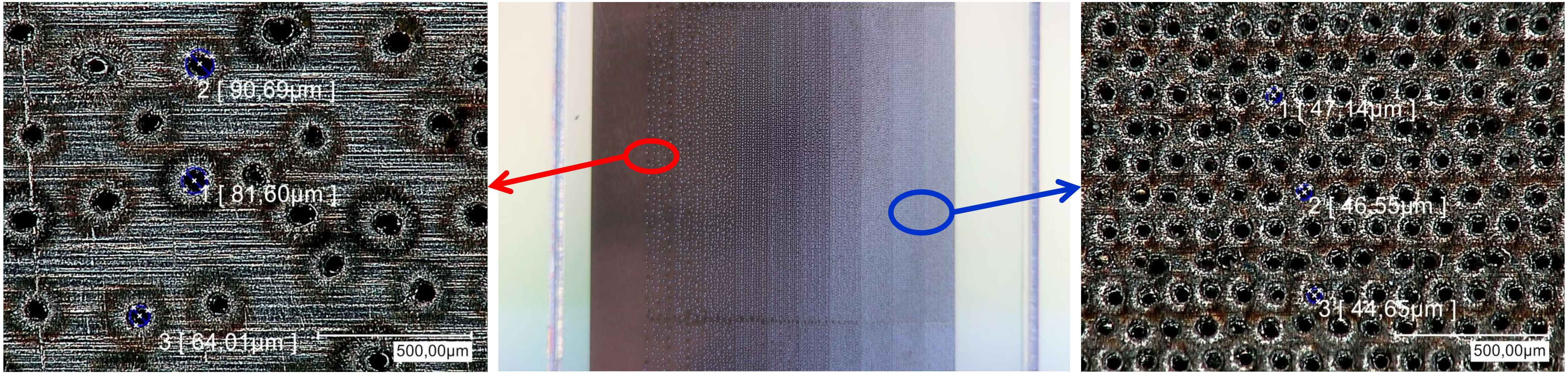
Reference: Rossian, DLR, 2019

Tailored materials? → realisation by gradient distribution of pores

Technical challenges: material characterization & repeatability of achieved properties

Design target: hydraulically smooth micro-perforated sheet with gradient resistivity

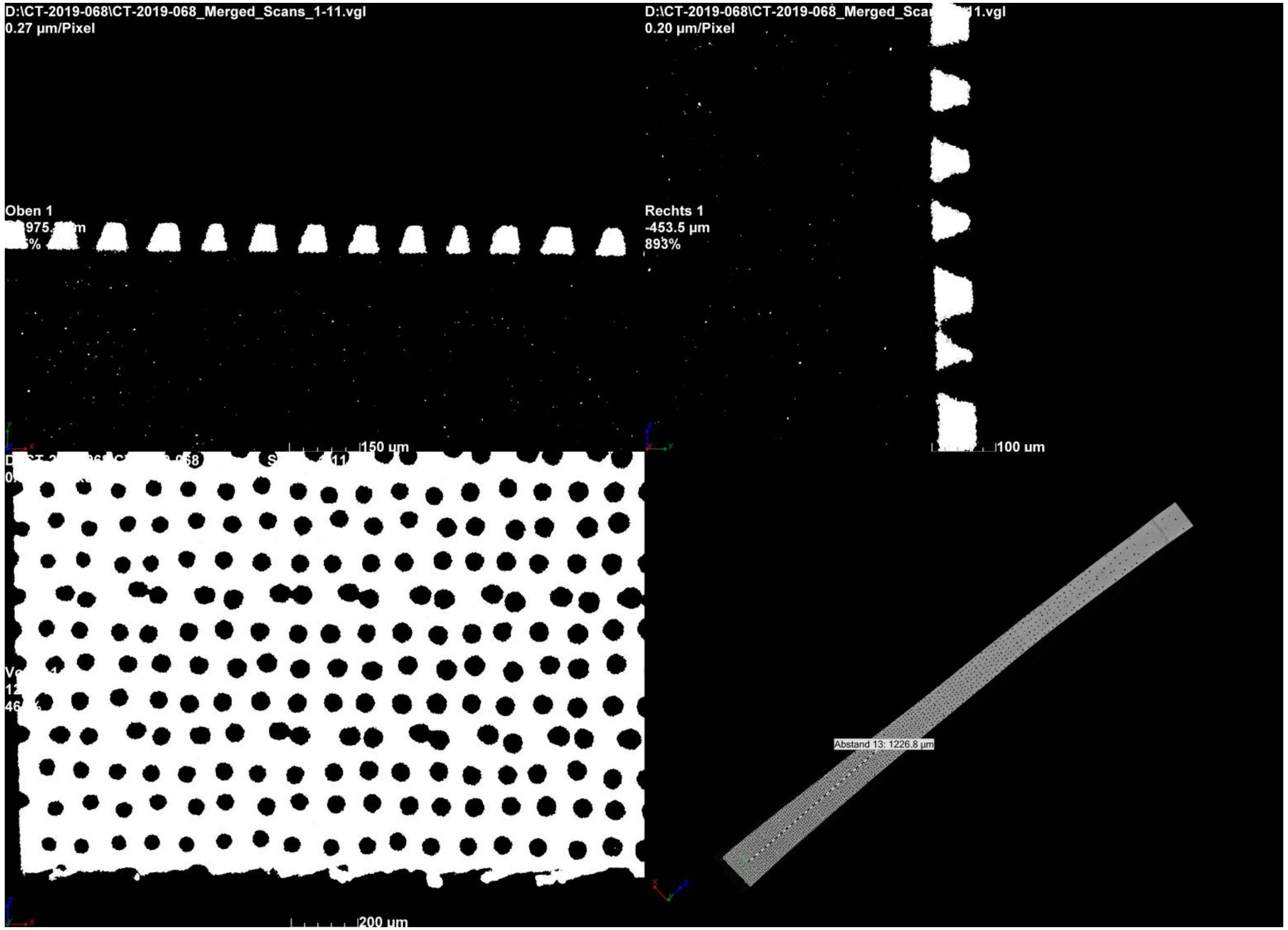
finally delivered realization with actual hole diameters of 45– 90

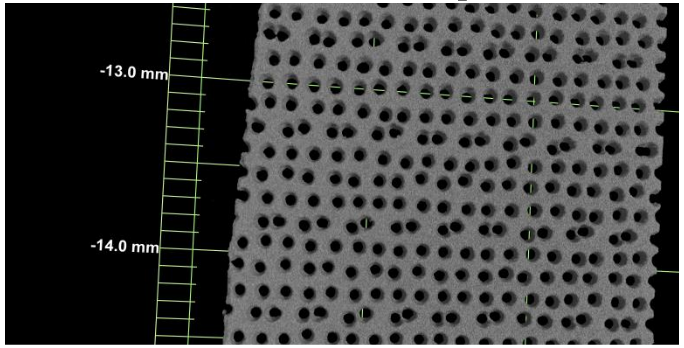


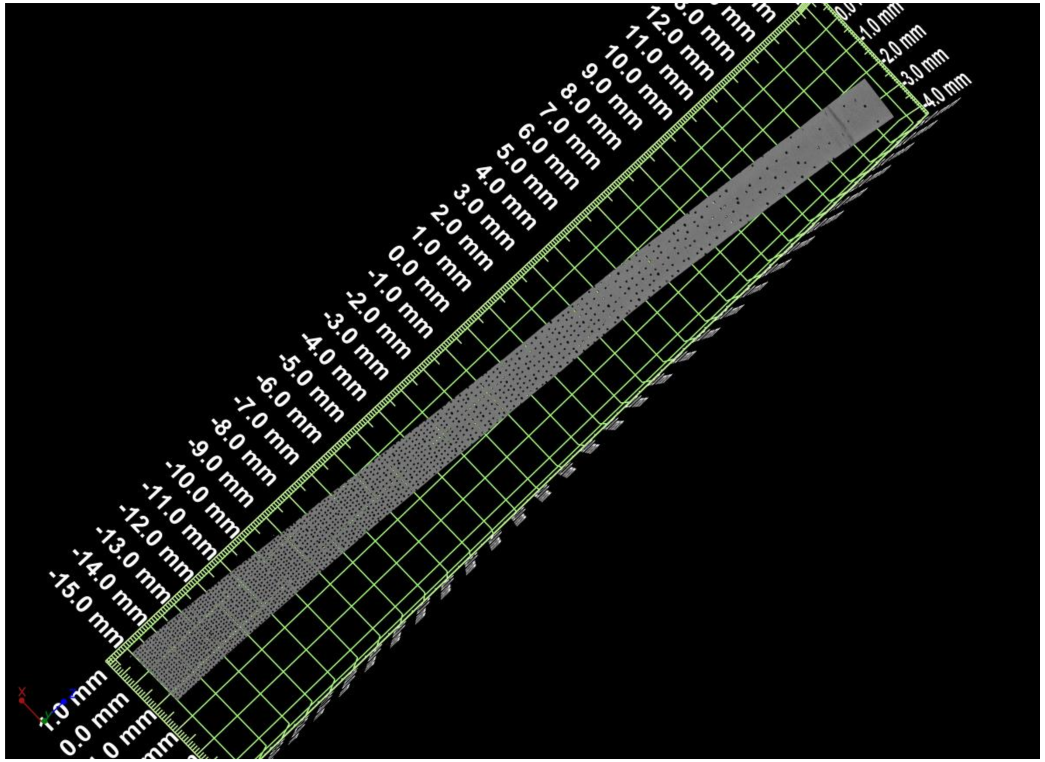
diameters larger than target! solid region TE diameters close to target

Tailored materials? → realisation by gradient distribution of pores

CT images of finally delivered realization…





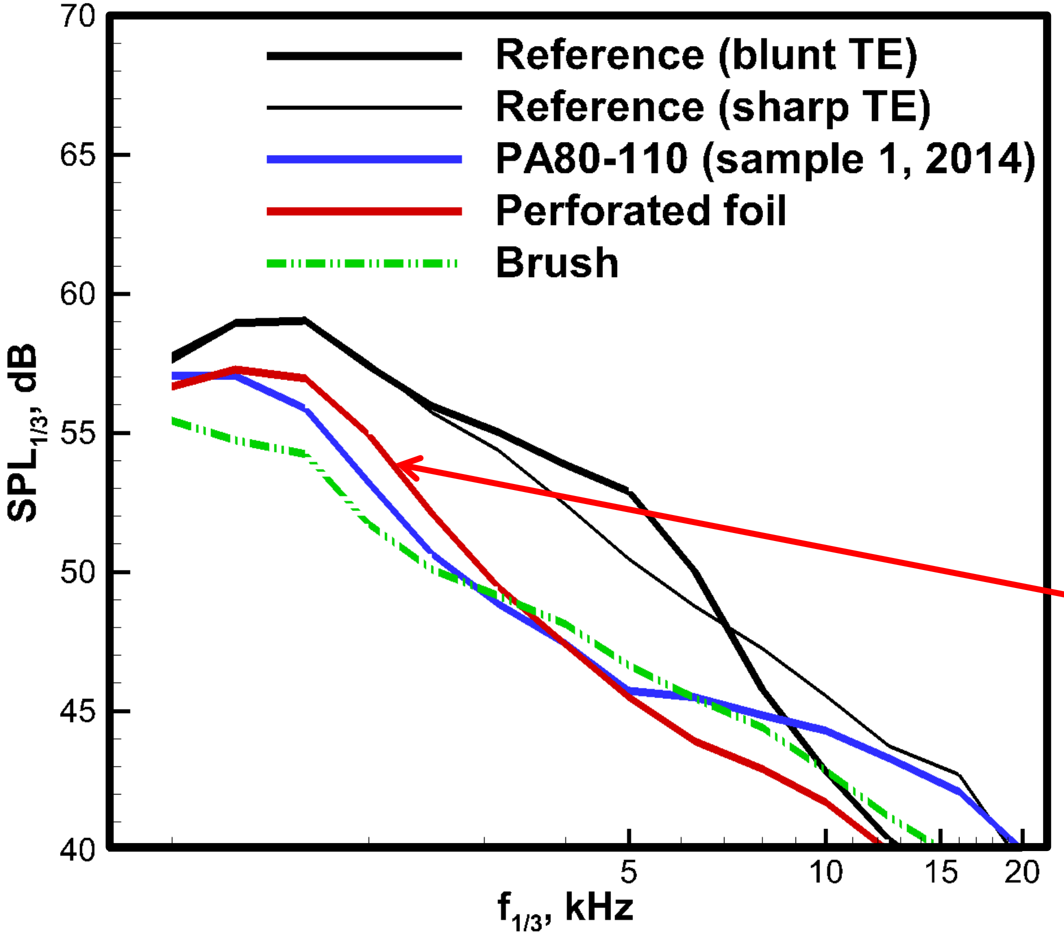


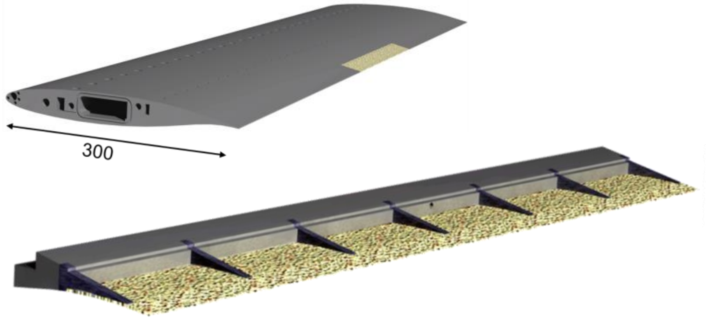
Tailored materials? → realisation by gradient distribution of pores

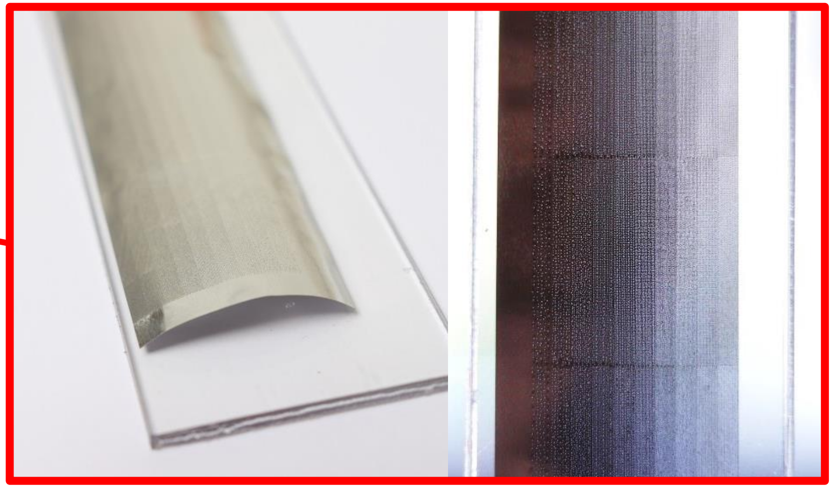
Technical challenges: material characterization & repeatability of achieved properties

Design target: hydraulically smooth micro-perforated sheet with gradient resistivity

Acoustic results:







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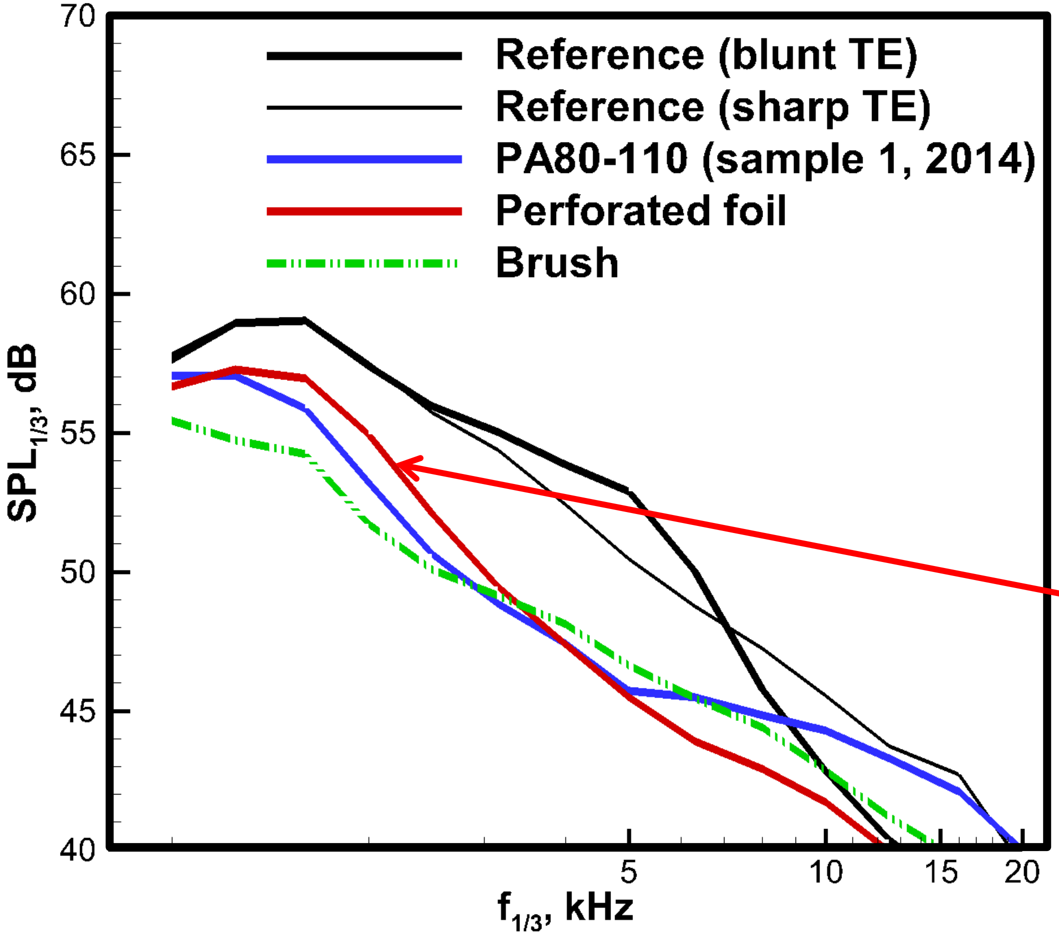


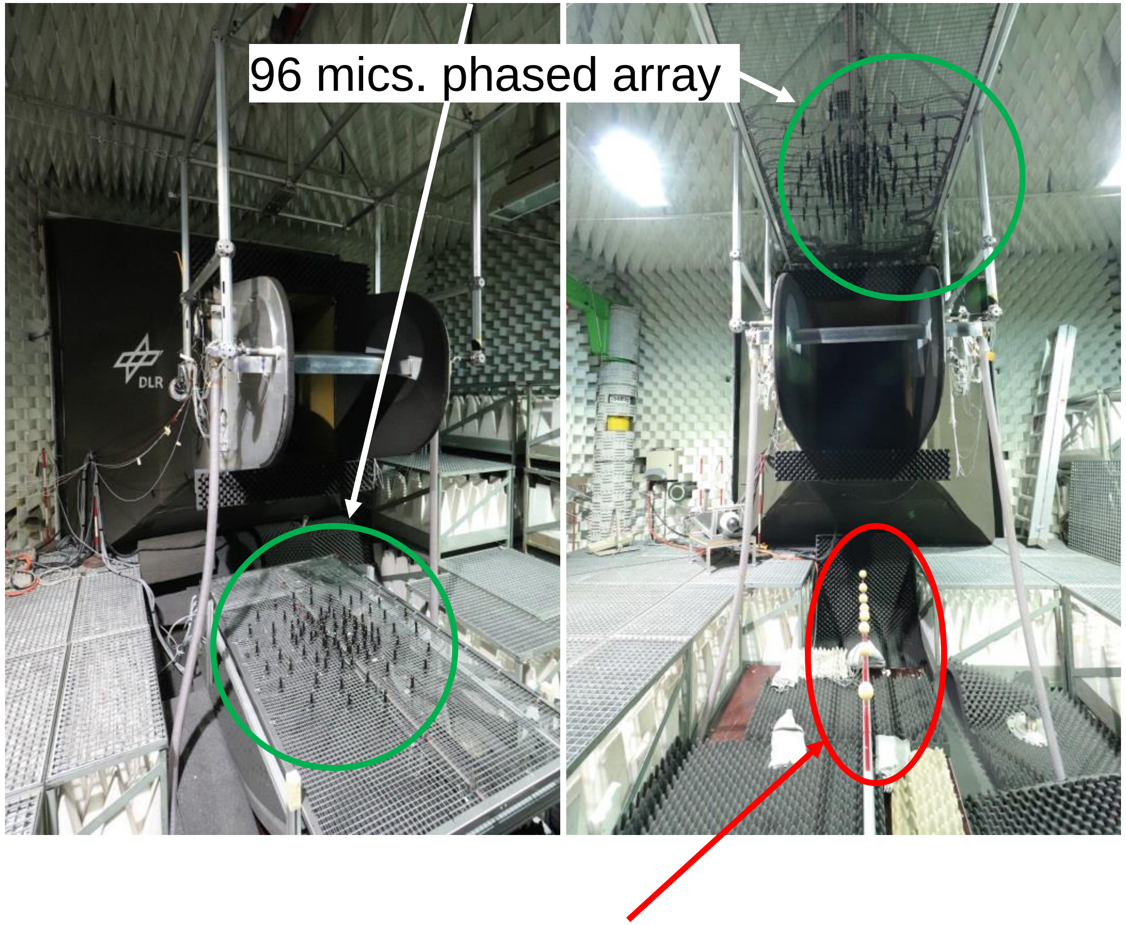
- Full mitigation of high-frequency excess noise!
- To ensure effective porous device lengths ~1–2 δ_{99} for maximum low-frequency TEN reduction, the overall device length might now be too short to achieve the full noise reduction potential
- Actually achieved resistivity values at TE are unknown, very likely too high (i.e. not according to design target; trustworthy measurements would require huge effort…)
  → to be continued…

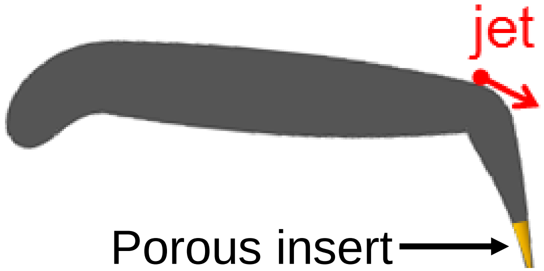
TECHNOLOGY CHALLENGES

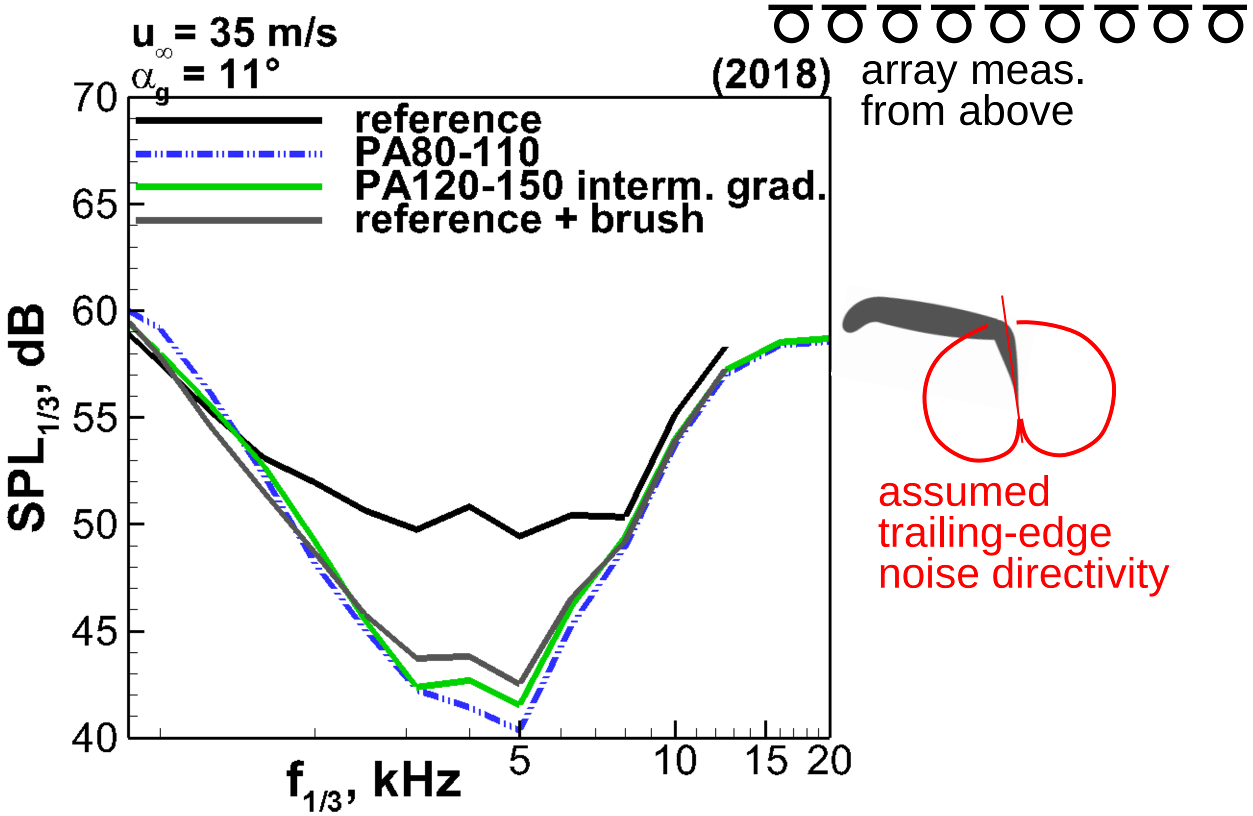
PART 2: Design details in technical application…

General transferability of results

Example: High-lift system with active flow control

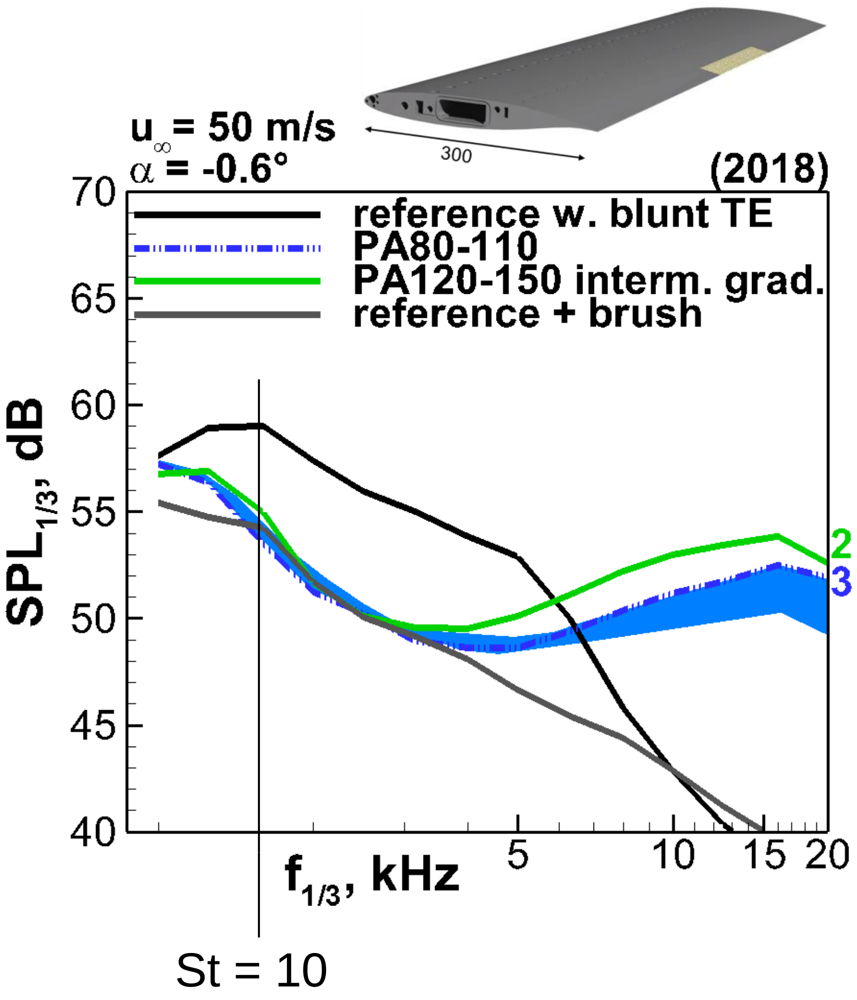


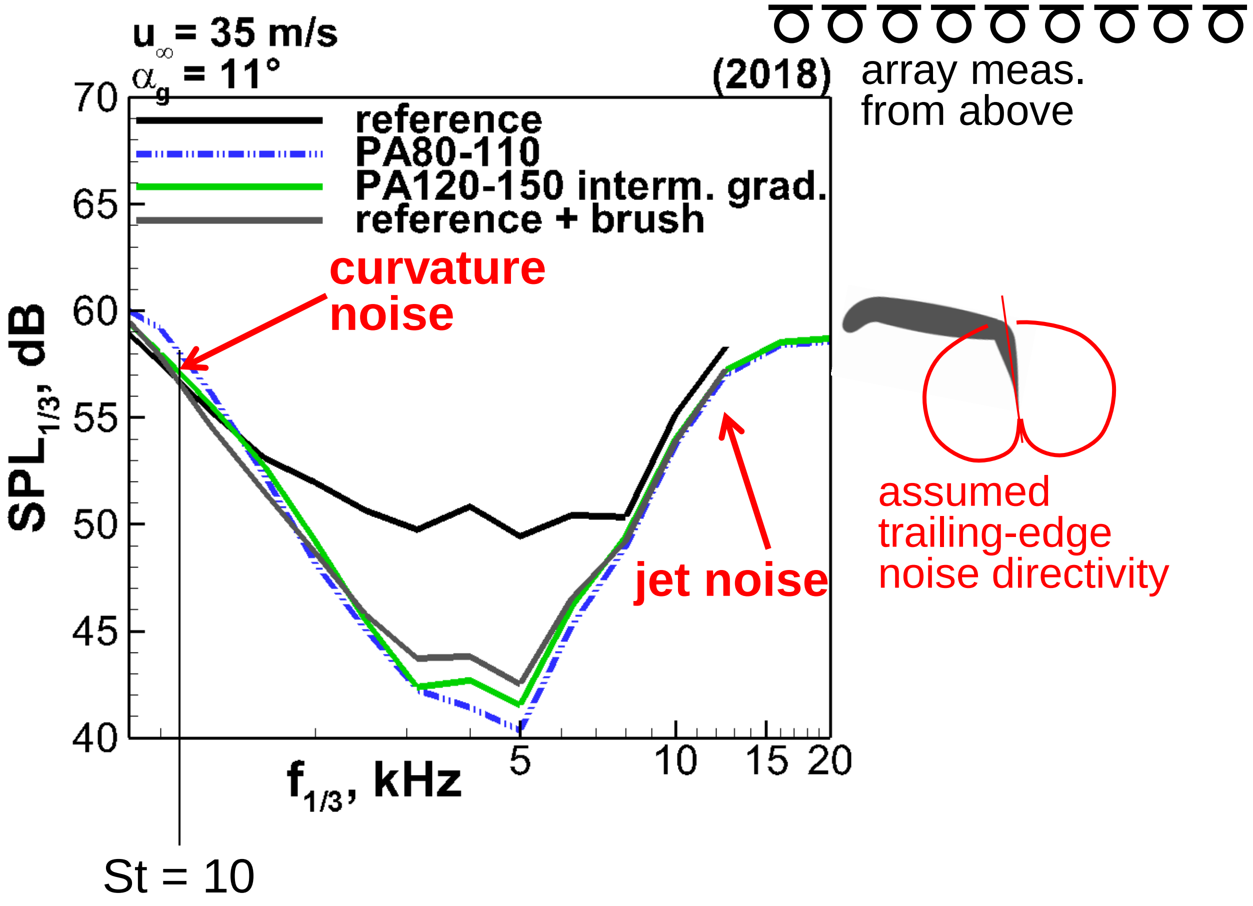




General transferability of results

Example: High-lift system with active flow control





General transferability of results

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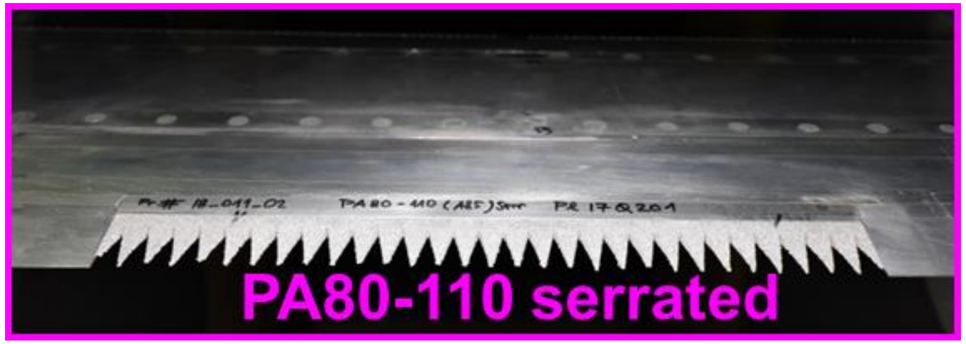
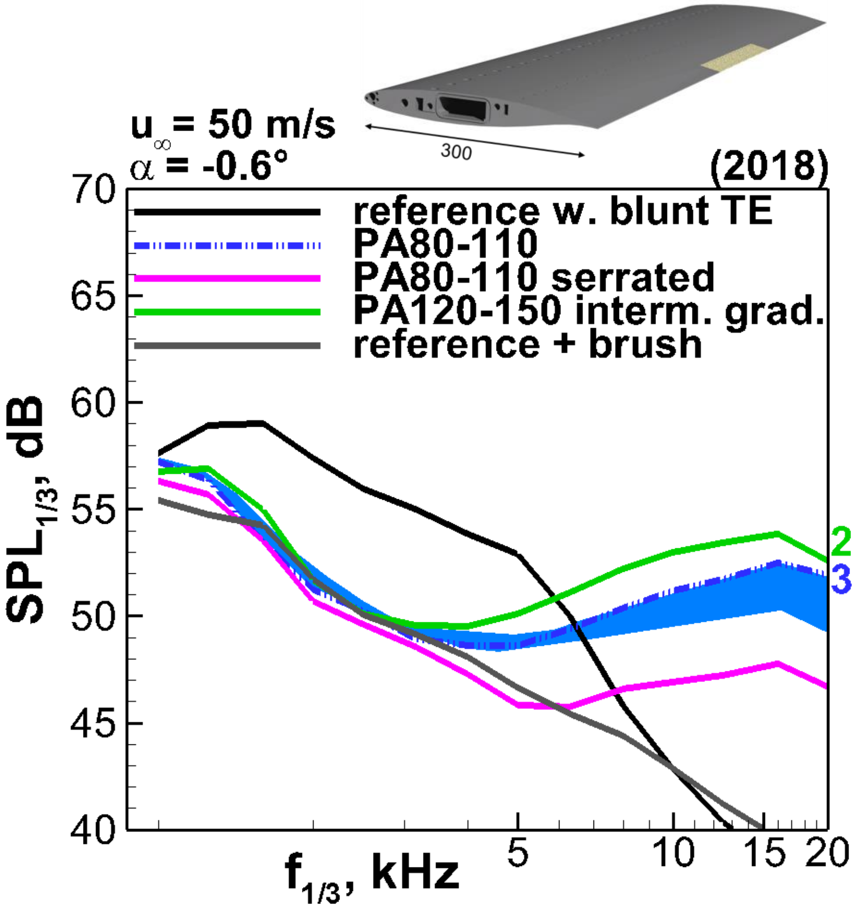
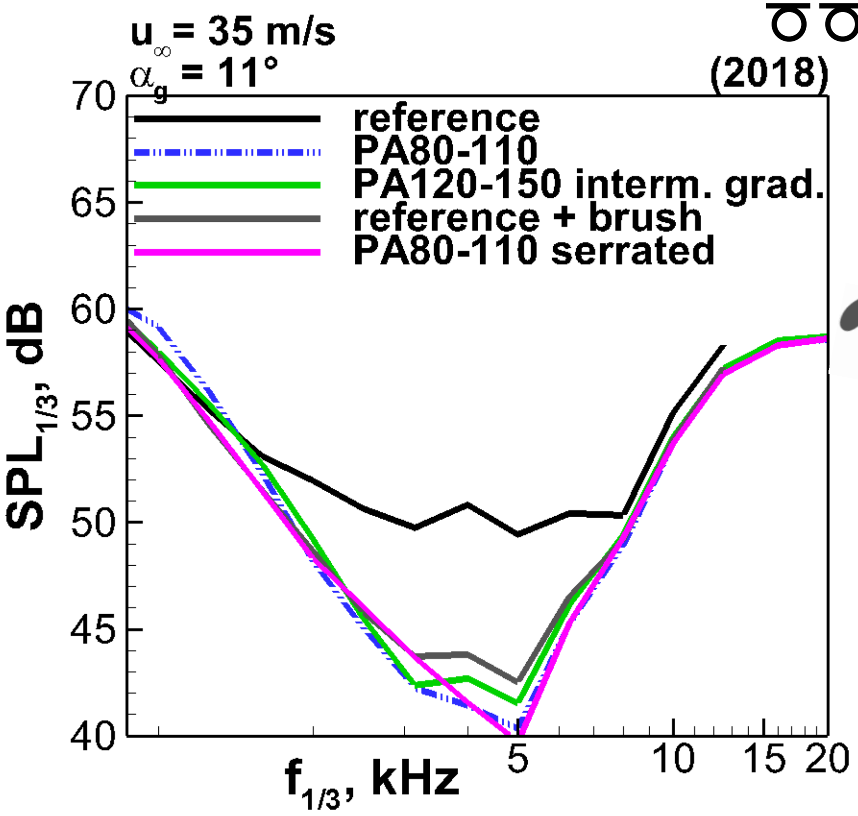
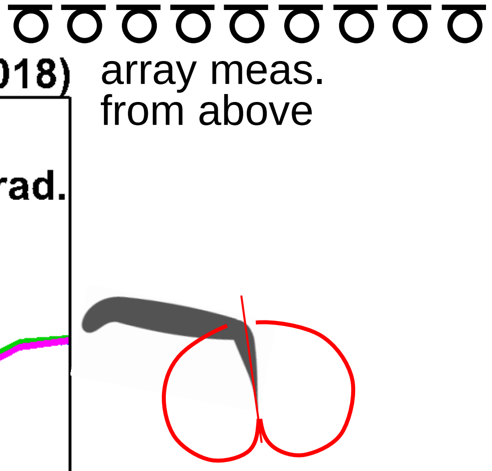






array meas. from above

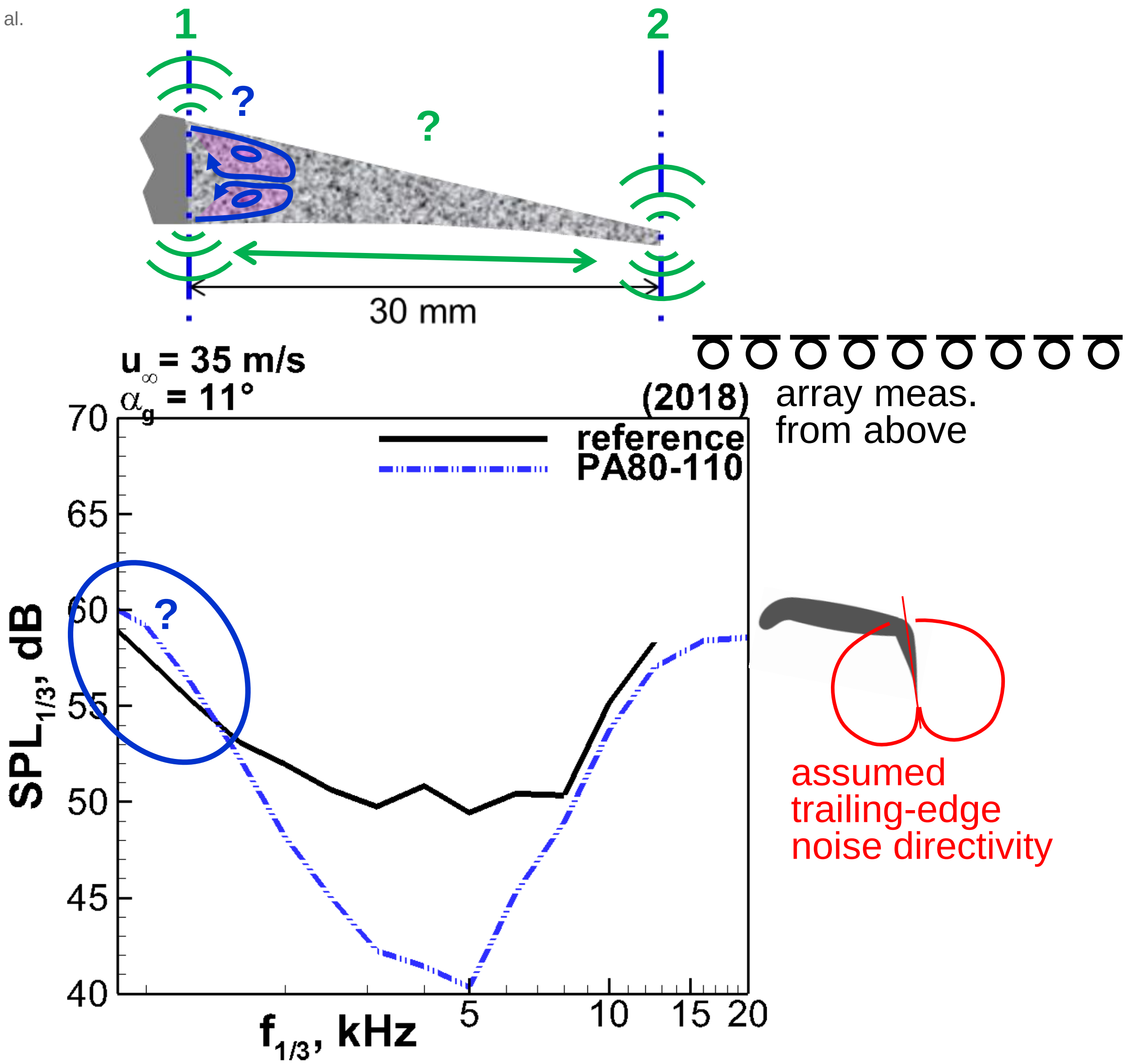


assumed trailing-edge noise directivity

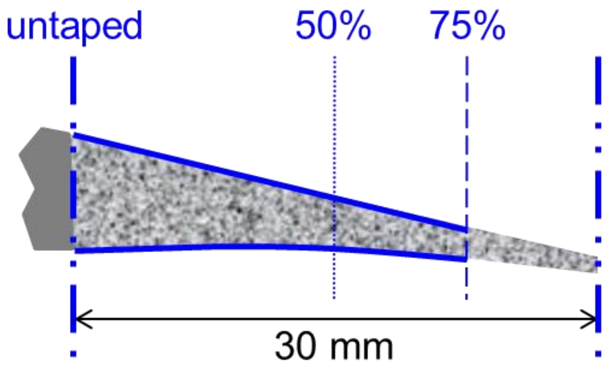
General transferability of results

Example: High-lift system with active flow control

- Excess noise due to installation details

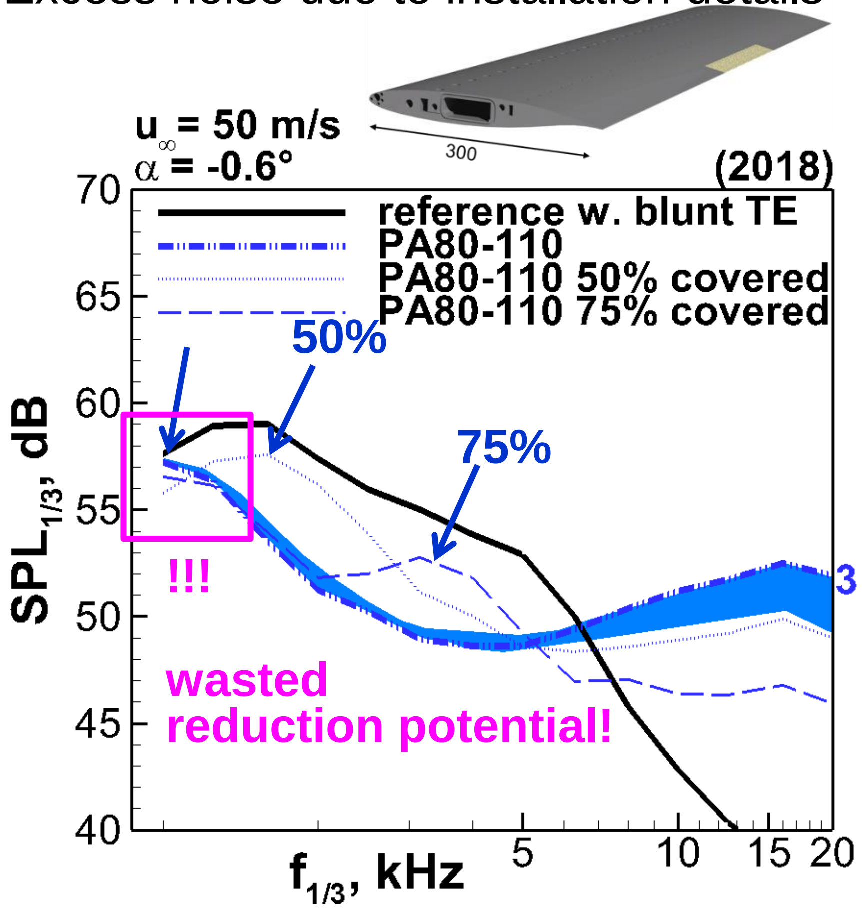


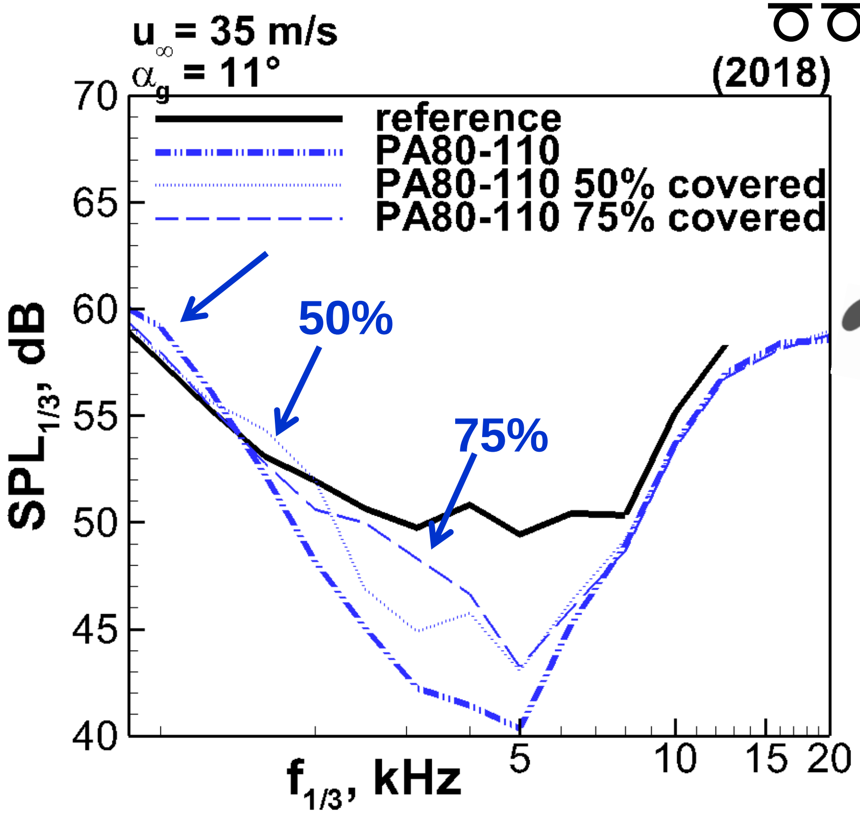
General transferability of results

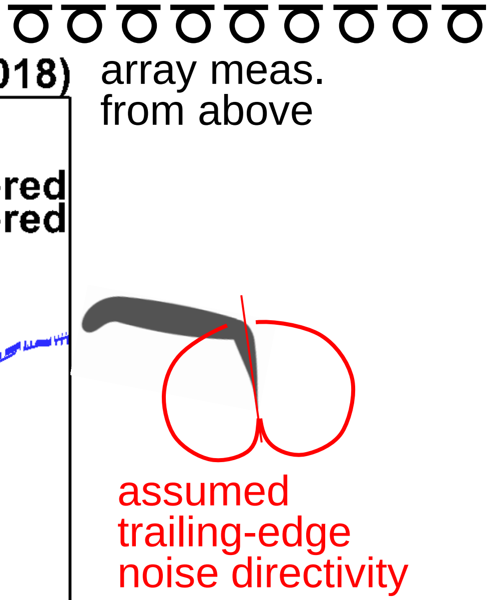


Example: High-lift system with active flow control

- Excess noise due to installation details





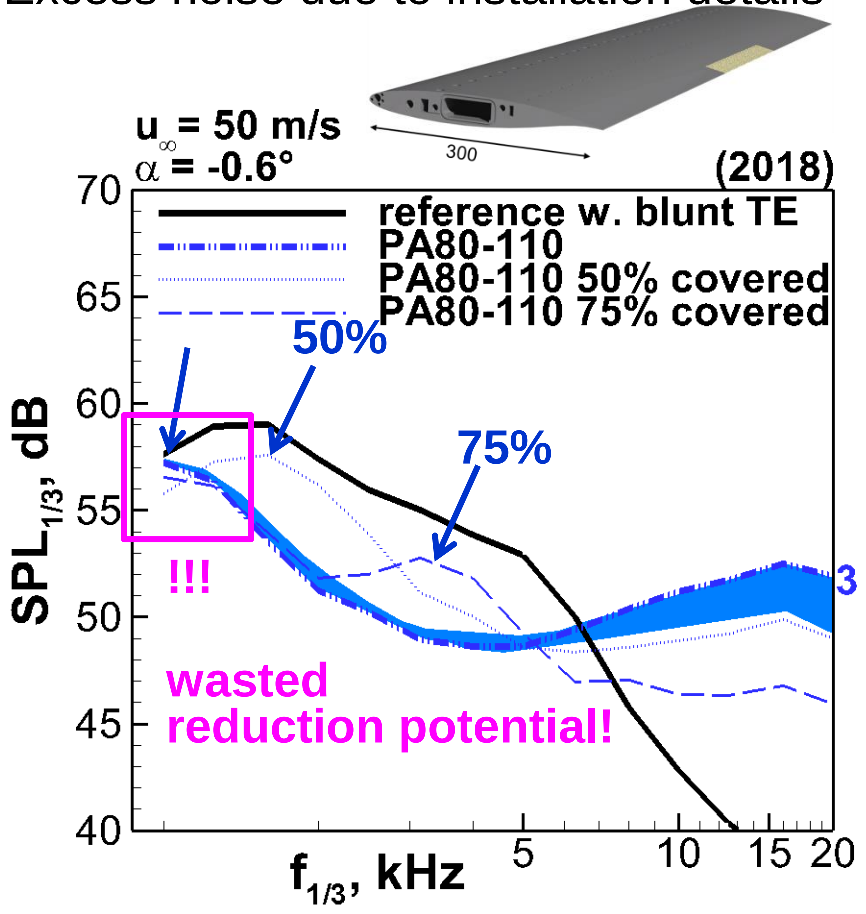


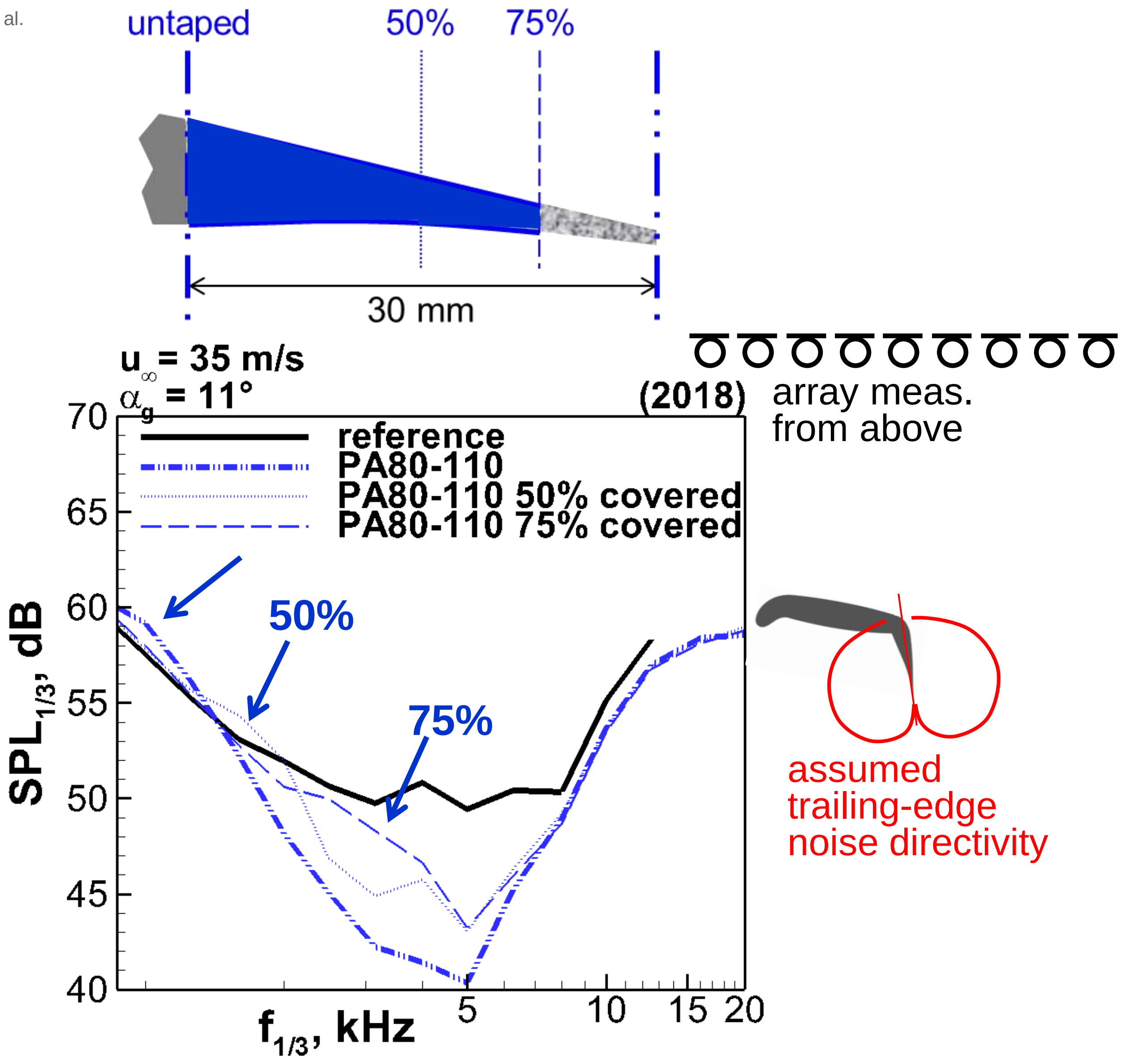
- Humps follow St number scaling based on **TE thickness <u>or</u> distance between two sources**

General transferability of results

Example: High-lift system with active flow control

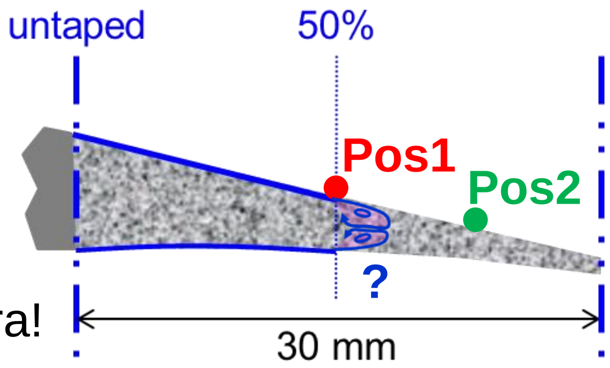
- Excess noise due to installation details

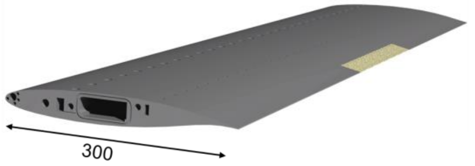




- Humps follow St number scaling based on **TE thickness <u>or</u> distance between two sources**
- 75% results are exactly reproduced for accordingly filled TE part (cavity between tape layers is not important!)

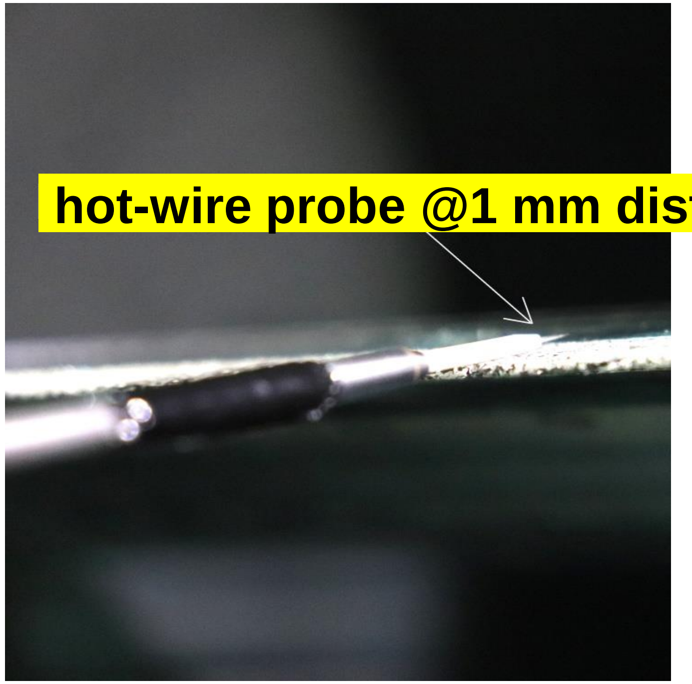
Installation details

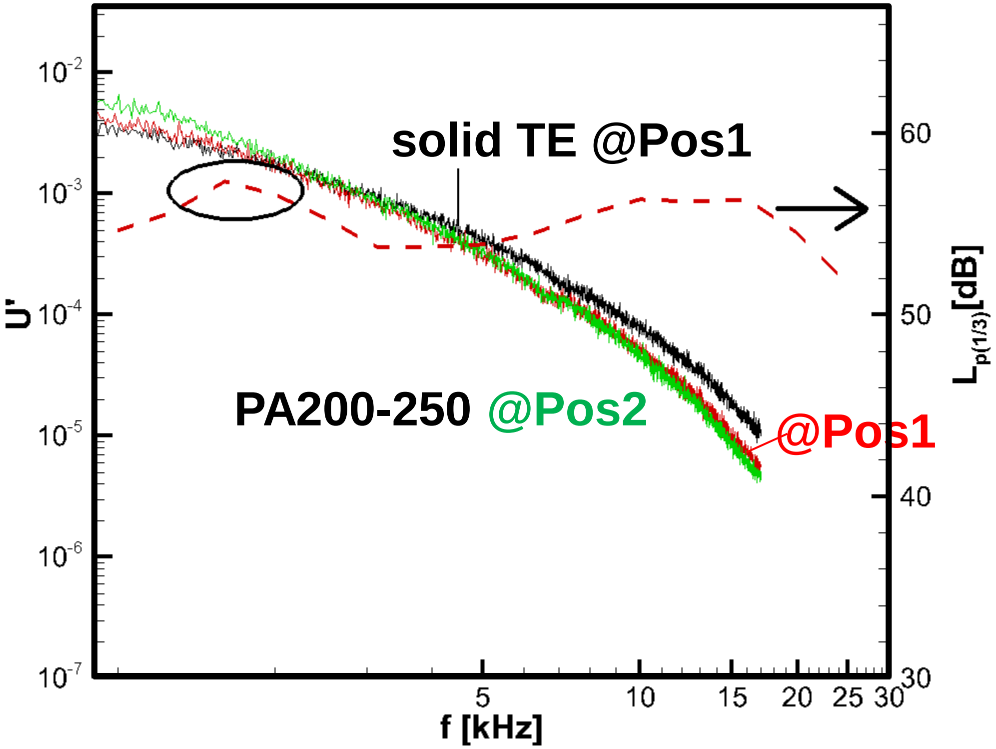




In search of the origin of the spectral humps…

- No indicators for “vortex shedding” found in hot-wire spectra!



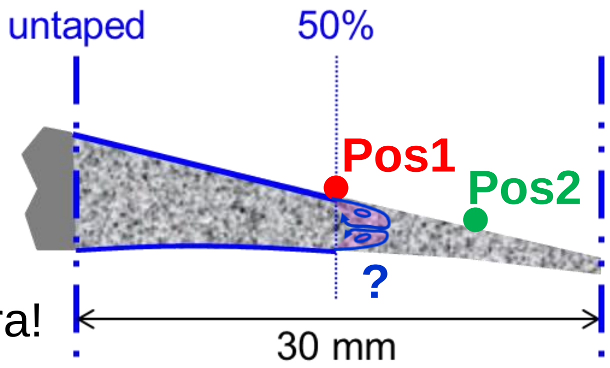


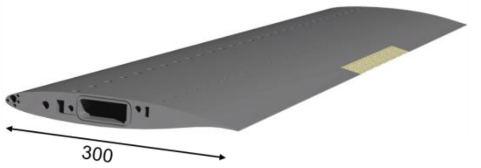
- Btw: no indicators for increased TKE at high-frequencies (to explain high frequency excess noise…)

DLR

Hochauftrieb künftiger Verkehrsflugzeuge
SFB 880

Installation details





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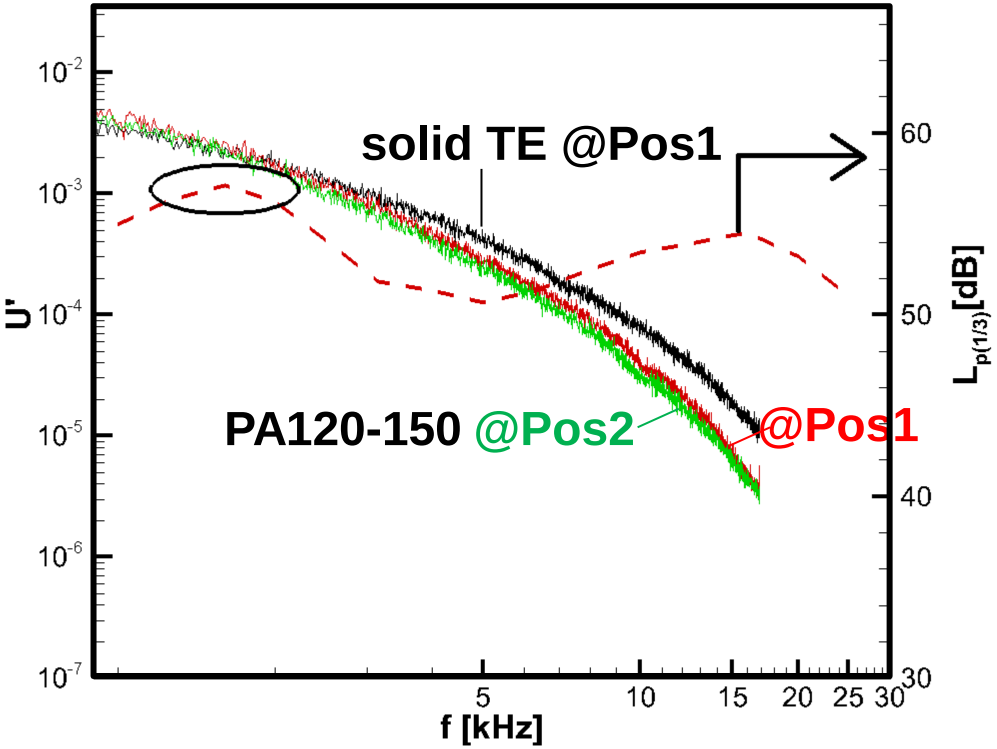

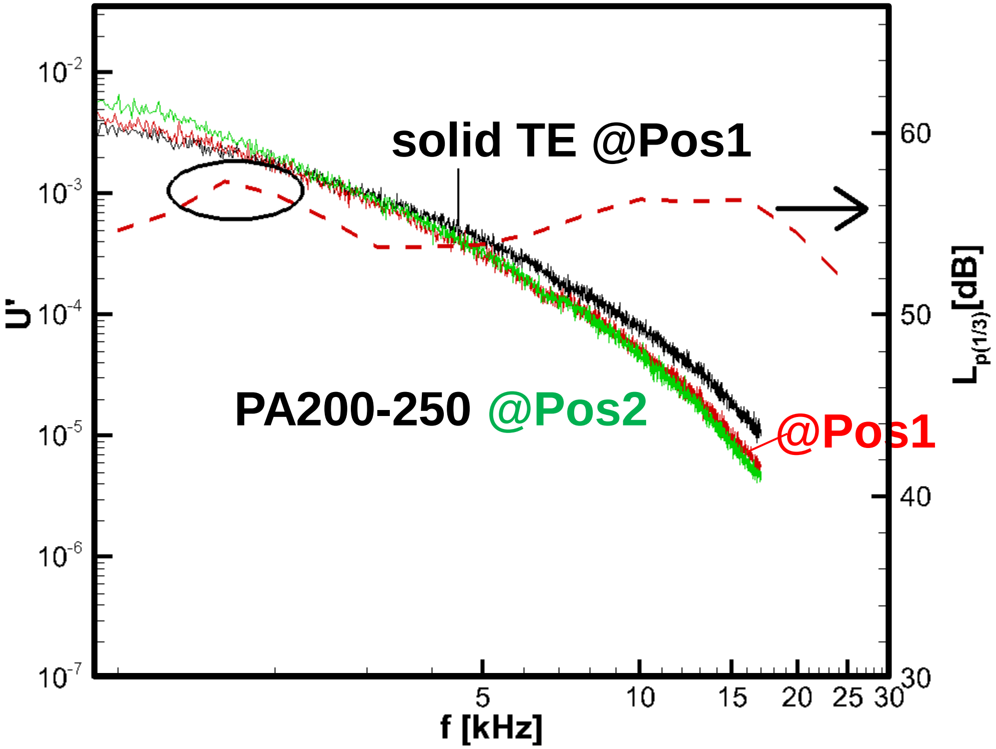

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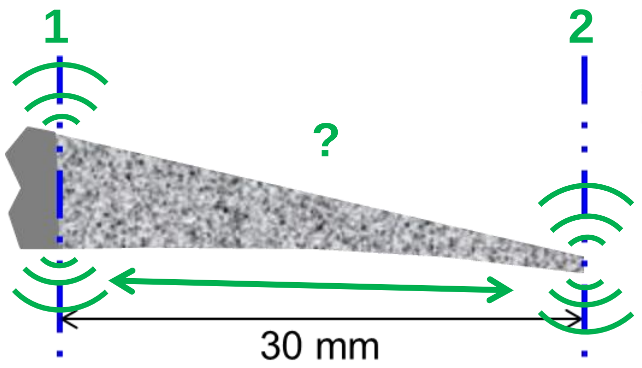
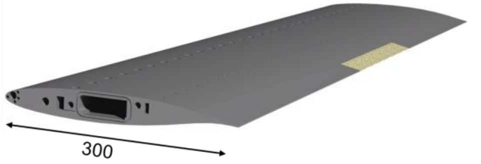
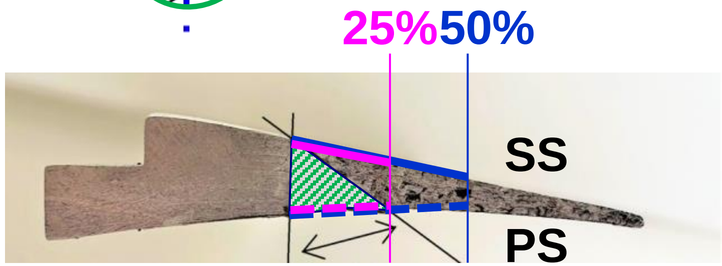
Installation details

In search of the origin of the spectral humps…

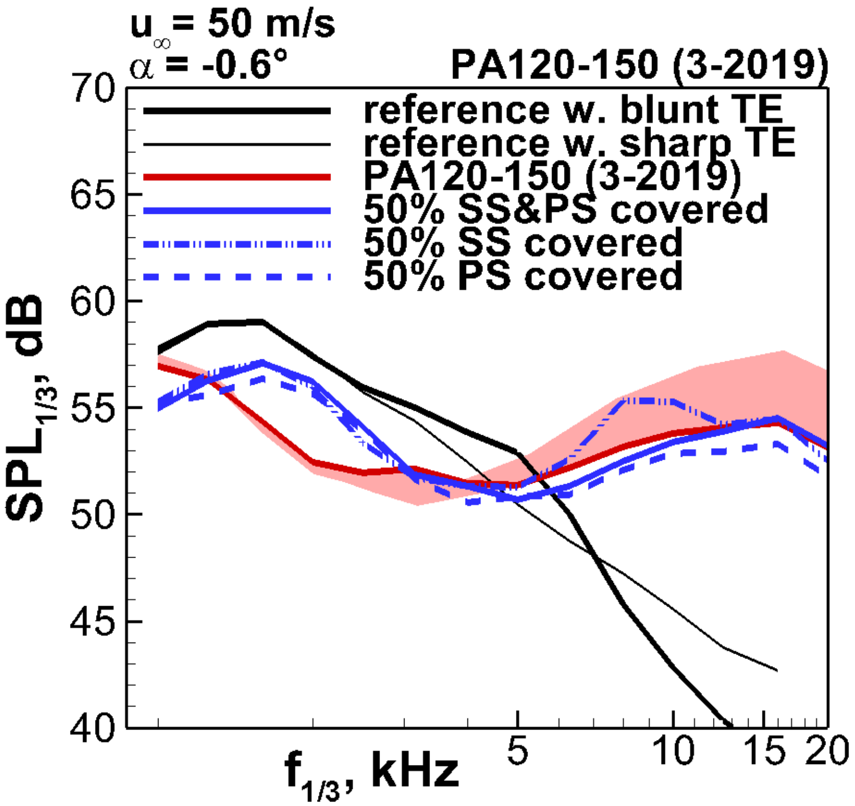
- …rather an acoustic phenomenon! → t.b.c.

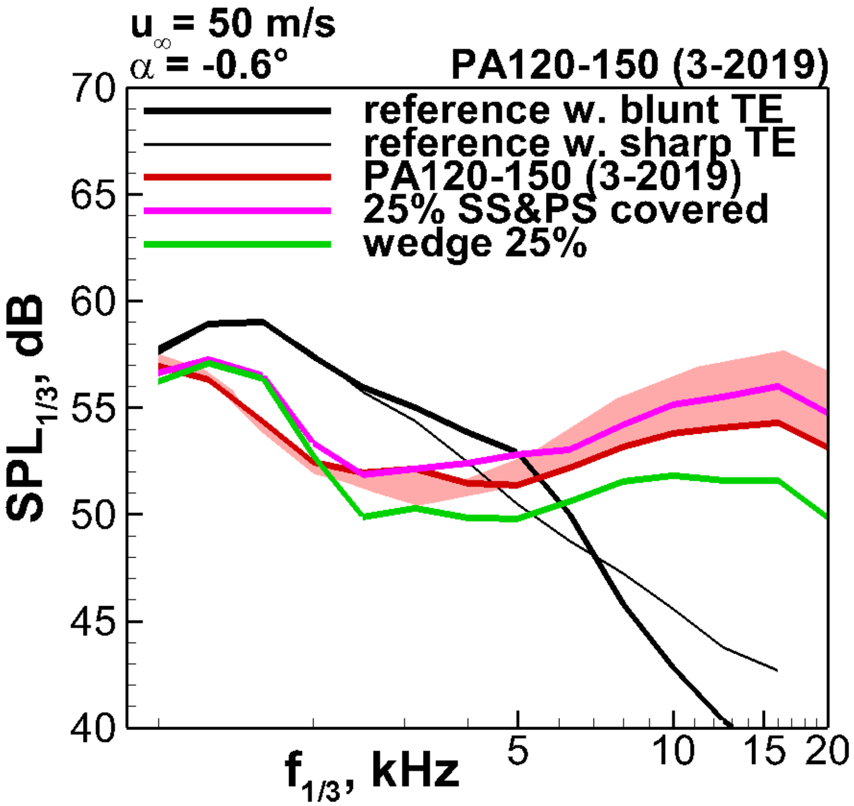






solid replacement





Any suggestions on the mechanism?

- Humps are maintained for asymmetric taping or asymmetric TE geometry!

Wrapping up…

- Pressure release across TE (with airflow resistivity being the key parameter) = prerequisite for TEN reduction
  → technical applications represent a compromise between aero & acoustic requirements, i.e. decrease of lift performance cannot fully be avoided for porous replacements *conflicting criterias!*
    → the device length should be reduced to the necessary minimum
    → mechanism behind "hump issue" needs to be clarified
    → depending on the application TE extensions might represent the better solution…
    → affordable high-frequency excess noise t.b.d depending on the application

- Mean leakage-flow through devices @nonzero a-o-a leads also to decreased acoustic performance

- Production of tailored TE devices suffer from *conflicting criterias!*
  - deficits in available technical capabilities (tiny pore size vs. low resistance!)
  - deficits at manufacturers to ensure consistency of manufacturing process, i.e. of material characteristics
  - uncertainties in material characterization; TE (as in the experiment) cannot be characterized
  - deficits in TEN measurement setups
    - spanwise extent of porous material (costs!) vs. resolution of focusing measurement technos.
    - excess noise contributions from wall/model junctions (increases for highly loaded airfoils)
    - line source assumption does not always hold for porous inserts → error estimates

Wrapping up… & future steps

(with some restrictions, but at least…)

- Porous insert integration details are considered important in defining largest noise reduction
- Results of the DLR F16 airfoil were successfully transposed to active flow control high-lift system (TE noise reduction on the order of ~10 dB)
- Future successful concepts are seen in porous TE inserts with streamwise gradient resistivity to continuously match the impedance to free air
- For a robust, better controllable set-up of the resistivity gradients porous sheets, covering a mainly hollow, flow-transparent TE region and porous sheet TE extensions should be revisited.
- Today’s manufacturing possibilities (defining better reproducible target hole diameters ≥ 100 µm) will likely violate the condition of hydaulically smothness of the surface which is acceptable as long as high-frequency excess noise contribution can be shifted towards low-weighted regions

- Meaningful collaborative activity
  - Cross-comparison of the currently applied material characterization methods for aeroacoustic applications (examples: measurement of flow resistance over frequency and AC/DC velocity, “roughness”)
    - → Which are the most adequate procedures?
    - → Are all published values comparable?
    - → Establish a common standard
  - Any volunteers to reproduce the presented TE tape study at other available test setups?

Thank you for your attention!