Efficient and Airworthy Passive and Active Airframe Noise Control Strategies

Michaela Herr
DLR Institute of Aerodynamics and Flow Technology, Technical Acoustics

DLR

Outline

- Problem definition and overview

- Airframe noise reduction at the source:
  - Reduction of parasitic noise sources
  - Landing gear noise reduction
  - High-lift noise reduction
    - Basic principles: Edge noise reduction
    - Slat noise reduction
    - Flap side-edge noise reduction

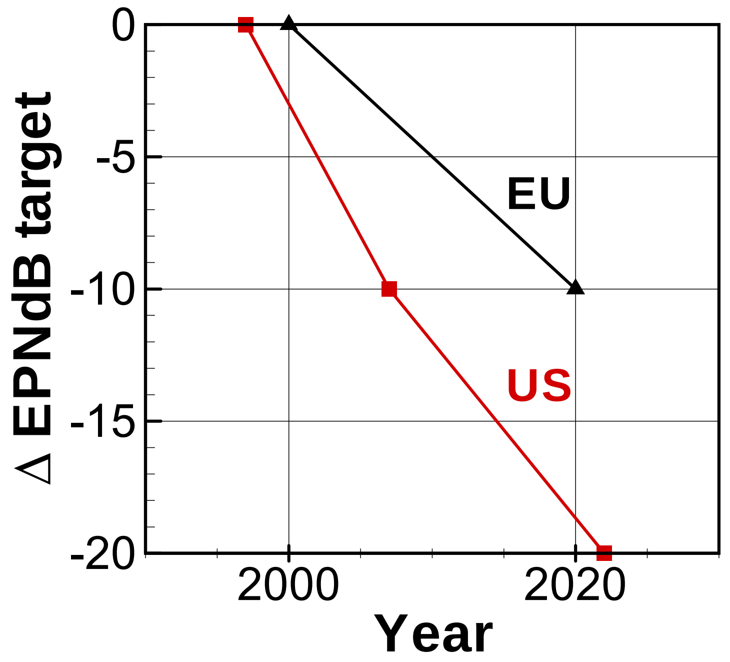
- Summary of achievements and future needs

This lecture focuses on <u>experimental and applied research</u> in airframe noise reduction and is an attempt to subsume related international activities without claiming to be complete.

Problem definition
EU and US strategic noise reduction targets

- EU ACARE "visions 2020":
  Reduce noise impact by <u>one half</u> per operation relative to <u>2000</u> technology.

- NASA "pillar goals":
  Reduce perceived noise impact of future aircraft by <u>one half</u> relative to <u>1997</u> technology within 10 years (AST and QAT program) and by <u>three quarters</u> (-20 dB) within 25 Years!

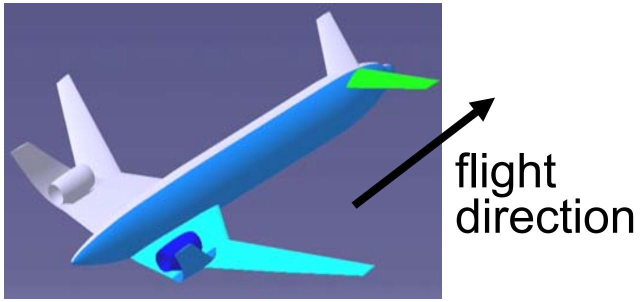


Reduction by <u>one half</u> "subjectively" corresponds to <u>-10 dB</u>, i.e. <u>-90 %</u> in sound power

Problem definition
EU and US strategic noise reduction targets

- EU ACARE "visions 2020":
  Reduce noise impact by <u>one half</u> per operation relative to <u>2000</u> technology.

- NASA "pillar goals":
  Reduce perceived noise impact of future aircraft by <u>one half</u> relative to <u>1997</u> technology within 10 years (AST and QAT program) and by <u>three quarters</u> (-20 dB) within 25 Years!

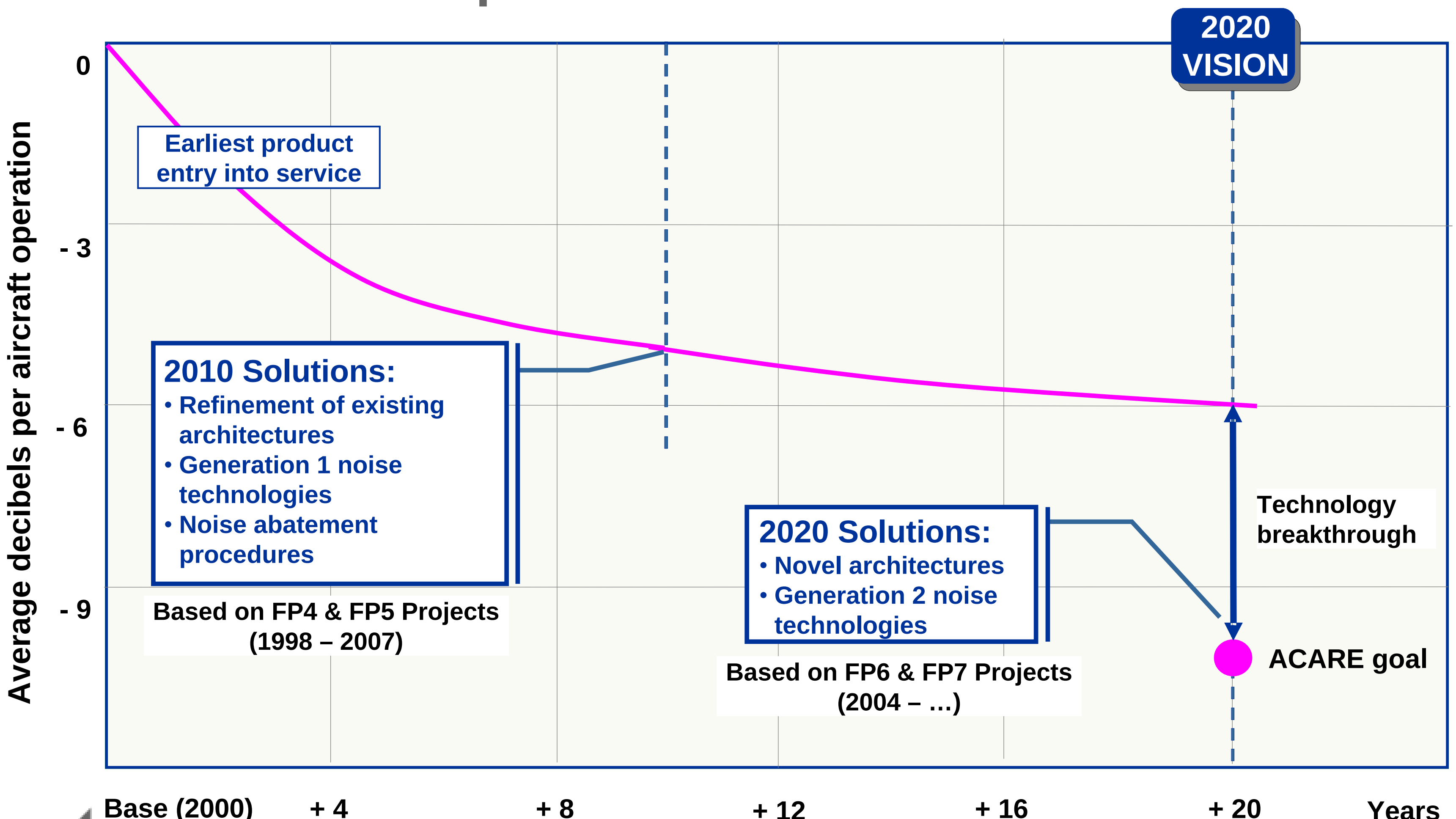


Source: DLR

Source: http://silentaircraft.org

- Silent Aircraft Initiative (MIT Cambridge, 2003): Develop a conceptual design for an aircraft whose noise would be almost imperceptible outside the perimeter of a daytime urban airport.

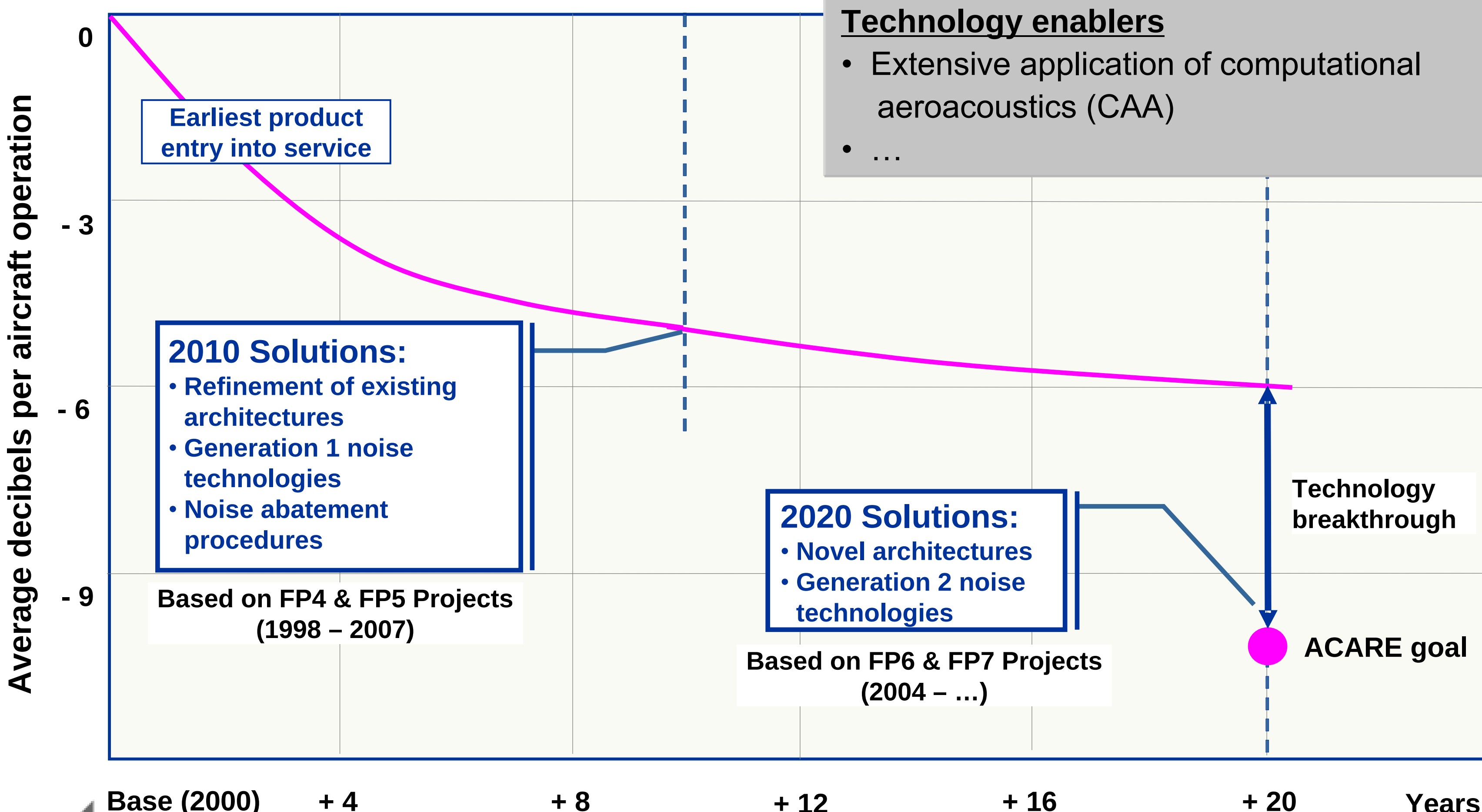
Problem definition
ACARE roadmap



Problem definition
ACARE roadmap

Noise reduction technology targets
- Engine components low-noise design
- Improved nacelle and nozzle liners
- Airframe components low-noise design (Landing gear, high-lift devices)

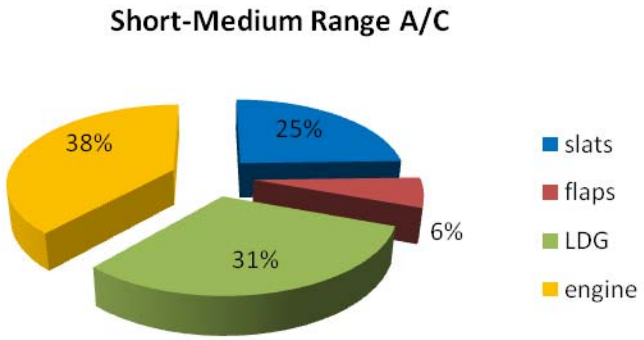
Technology enablers
- Extensive application of computational aeroacoustics (CAA)
- …

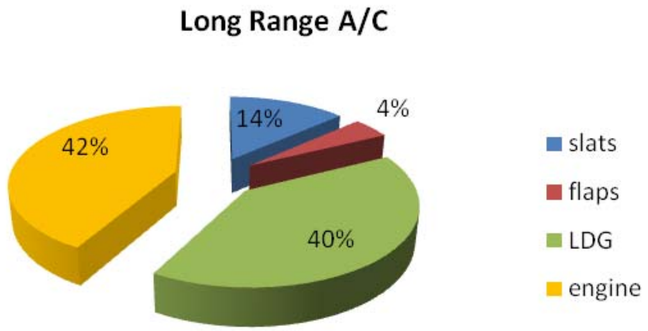


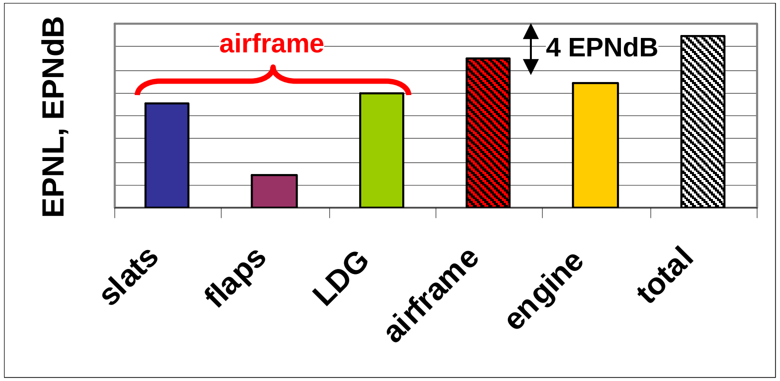
DLR

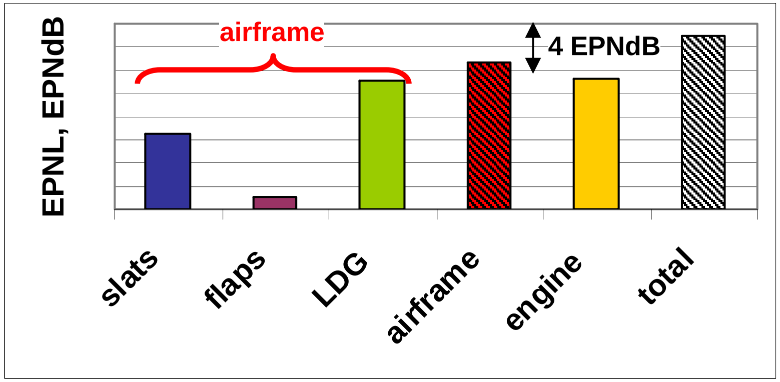
Problem definition

➢ Reminder: aircraft noise source ranking at approach (typical tube + wing configuration)









Source: AIRBUS Operations S.A.S. (data from SILENCE® project)

Problem definition

- This lecture focuses at efforts which directly address the noise reduction at the source, i.e. retrofit solutions for the existing aircraft fleet

- These are generally complex manipulations of flow/surface interactions i.e.
  - manipulations of the sound generation mechanism itself or
  - of relevant input parameters in the source area (local flow velocities, TKE)

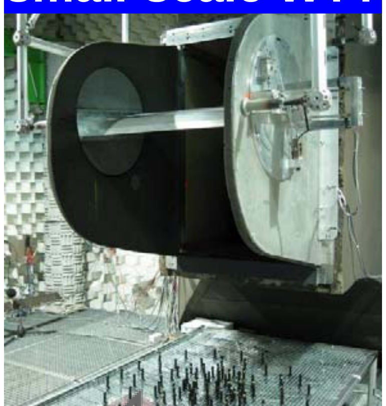
This is in contrast to acoustic absorbers that reduce the noise once generated!

Used methodology

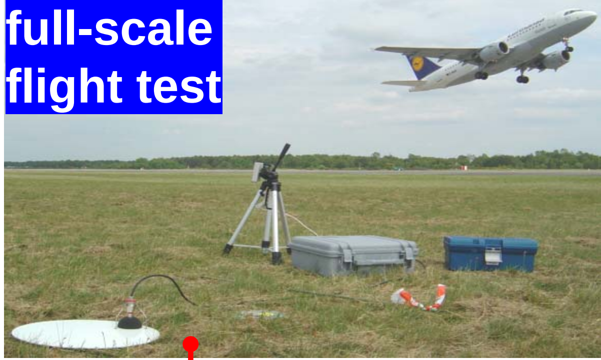
- Technology readiness levels and related scaling issues

	Technology programs							Commercial programs	
TRL	1	2	3	4	5	6	7	8	9
Description (source: SILENCE® project)	**Basic principles** observed and reported	Technology concept and/or application formulated	Analytical and experimental proof-of - concept	Component laboratory validation	Component validation in relevant environment	Acoustic system prototype validation in a relevant environment	Complete system prototype validation in operational environment	Production system flight qualified by demonstration	Production system **flight proven** by successful operation
Activity			Sample/ small scale testing		Large scale testing			Noise certification	In service
Maturity Phase	Discover		Understand	Adapt		Validate	Refine		

small-scale WTT



large-scale WTT (DNW-LLF)



Used methodology

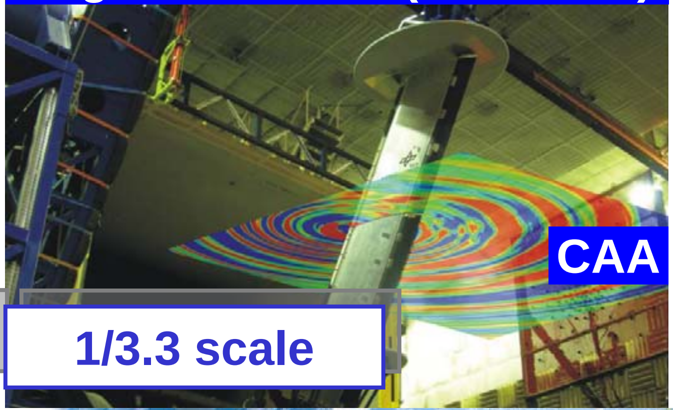
➢ Technology readiness levels and related scaling issues

Technology programs | Commercial programs

TRL	1	2	3	4	5	6	7	8	9
Description (source: SILENCE® project)	**Basic principles** observed and reported	Technology concept and/or application formulated	Analytical and experimental proof-of - concept	Component laboratory validation	Component validation in relevant environment	Acoustic system prototype validation in a relevant environment	Complete system prototype validation in operational environment	Production system flight qualified by demonstration	Production system **flight proven** by successful operation
Activity			Sample/ small scale testing		Large scale testing		Full scale testing	Noise certification	In service
Maturity Phase	Discover		Understand	Adapt		Validate	Refine		

small-scale WTT

large-scale WTT (DNW-LLF)

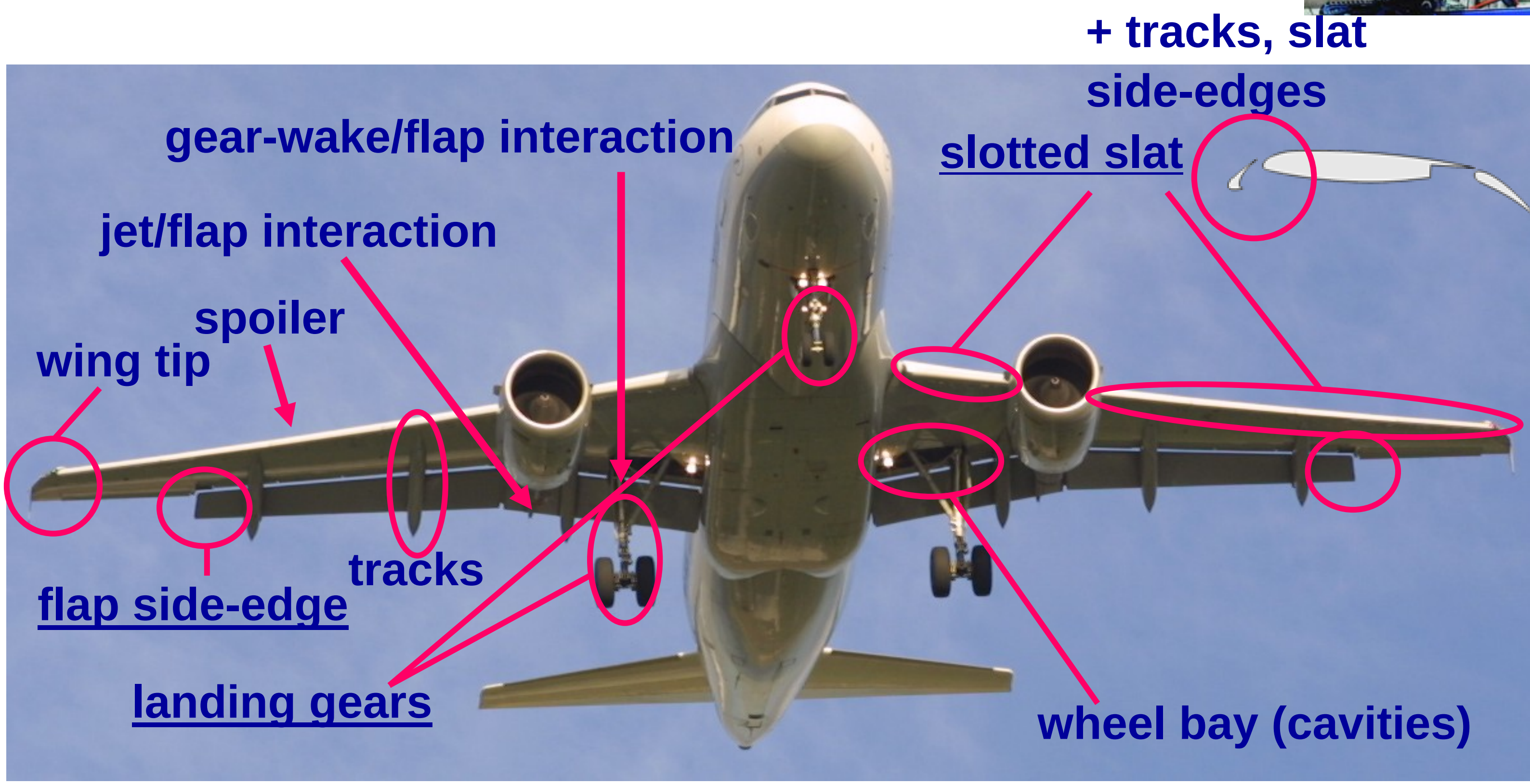


full-scale WTT

DLR

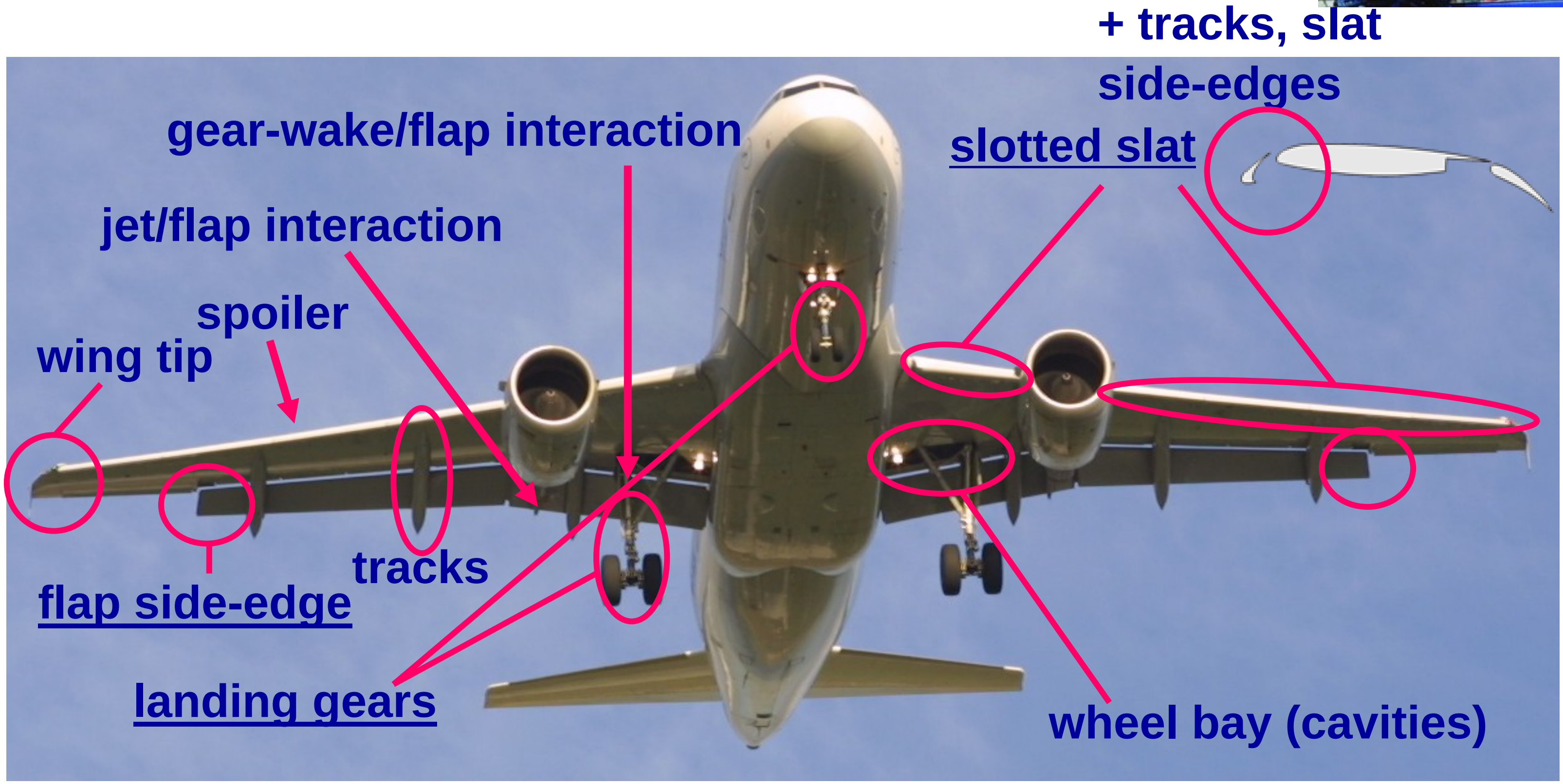
Airframe noise reduction at the source

- Reminder: classical airframe noise sources



Airframe noise reduction at the source

- Reminder: classical airframe noise sources

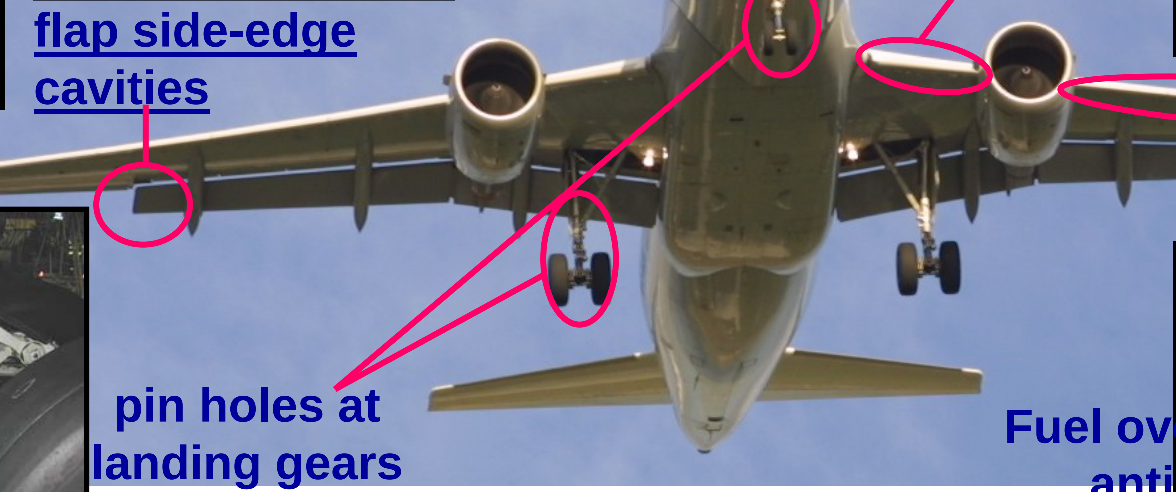


→ **In addition to these classical sources, on real aircraft structures numerous parasitic sources of excess noise can be detected.**

Reduction of excess noise sources

+ slat-side edge cavities

- Noise due to design details at original components, generally not resolved at small-scale WT models or in CAA simulations



Slat track cutouts

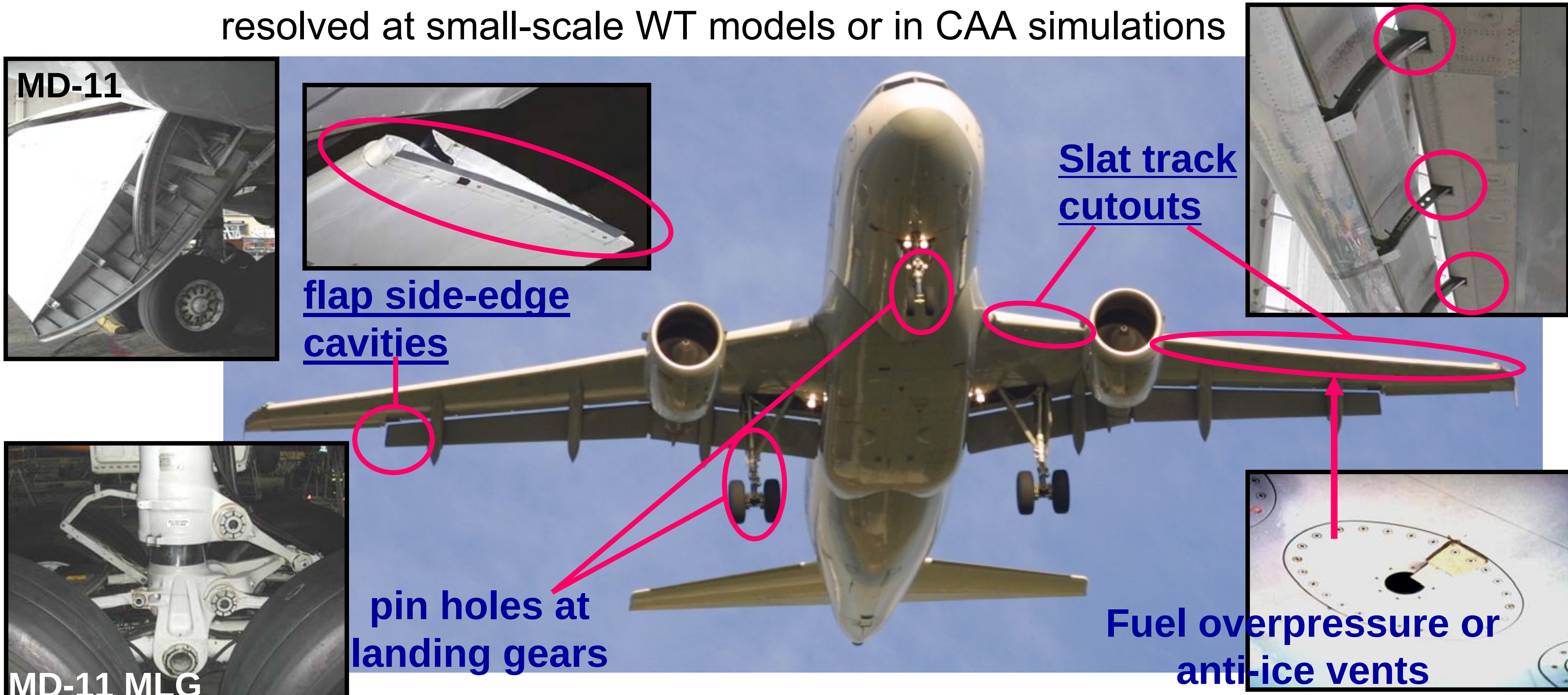
flap side-edge cavities

pin holes at landing gears

Fuel overpressure or anti-ice vents

Reduction of excess noise sources

- Noise due to design details at original components, generally not resolved at small-scale WT models or in CAA simulations



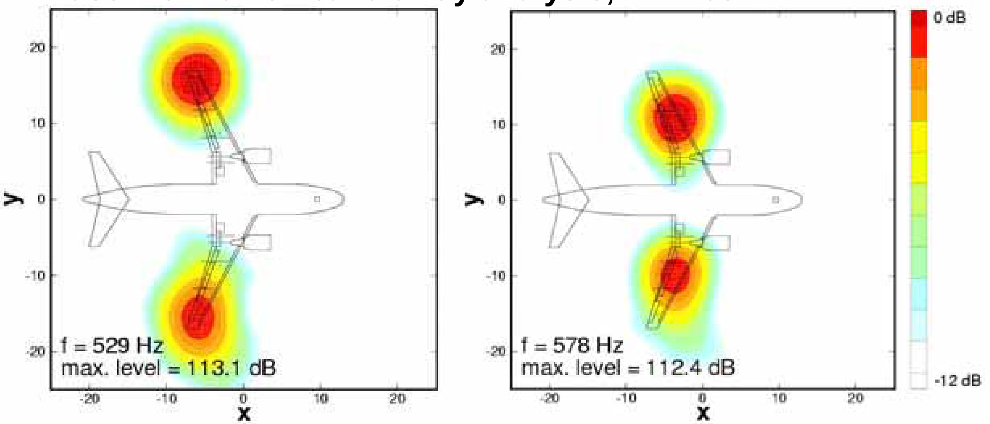
→ **Such components (tonal or <u>broadband</u>) could be often easily avoided.**

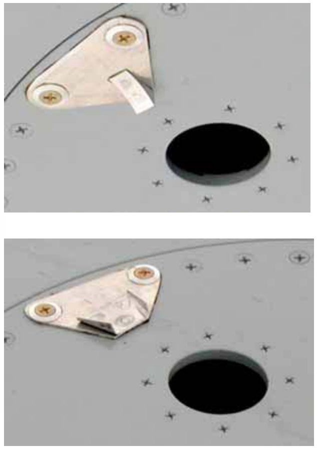
→ **Overall source ranking unclear; only limited measurement information available**

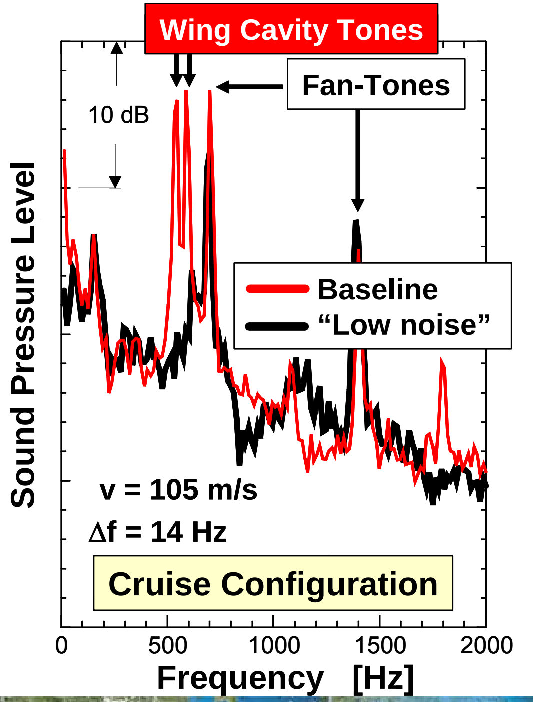
Reduction of excess noise sources

- Tonal parasitic noise:
  - Landing gear: elimination of 'pipe' resonance by pin-hole covers, but such means are not popular due to <u>water condensation problems</u>.
  - Wing: elimination of shear-layer induced Helmholtz resonance by vortex generators <u>→ flightworthy solution</u>

Baseline: Narrowband array analysis, R = 268 m





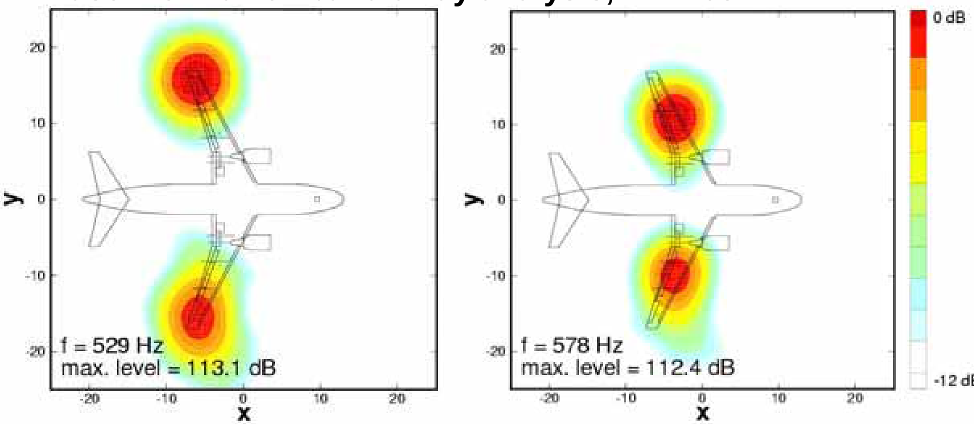


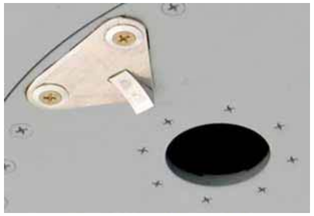
Loudest sound sources during approach to landing until full flaps are extended

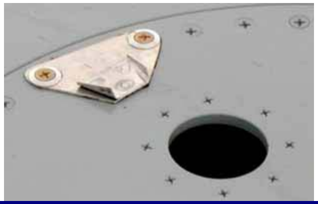
Reduction of excess noise sources

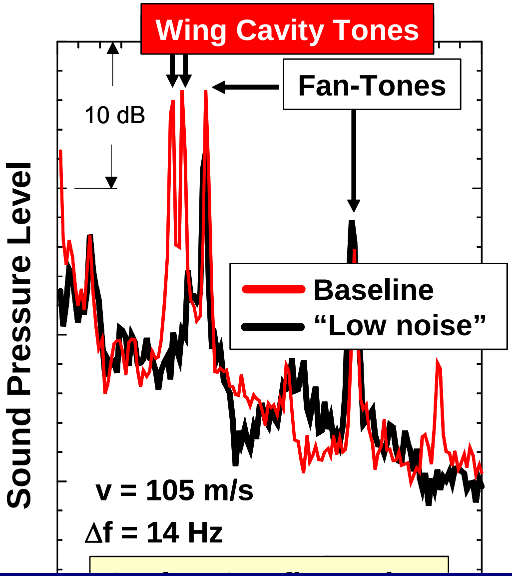
- Tonal parasitic noise:
  - Landing gear: elimination of 'pipe' resonance by pin-hole covers, but such means are not popular due to <u>water condensation problems</u>.
  - Wing: elimination of shear-layer induced Helmholtz resonance by vortex generators <u>→ flightworthy solution</u>

Baseline: Narrowband array analysis, R = 268 m









→ **Up to 6 dB(A) during approach at noise monitoring positions; <u>but:</u> not at certification point when flaps are fully extended**

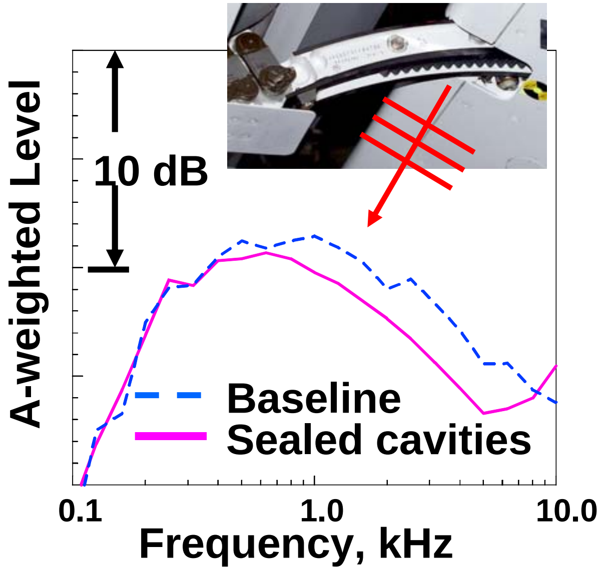
→ **During departure at noise monitoring points 0.6 dB(A), on take-off certification point 0.2 dB(A)**

full-scale WTT

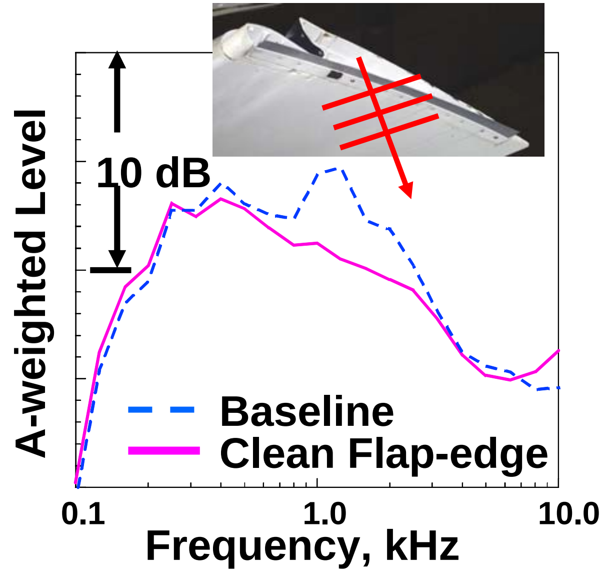
Reduction of excess noise sources

- Broadband parasitic noise: reduction potential by sealing

A320 Slat-track cut-outs



A320 Flap edge cavity



full-scale WTT

Reduction of excess noise sources

- Broadband parasitic noise: reduction potential by sealing

A320 Slat-track cut-outs

Tape sealing

A320 Flap edge cavity

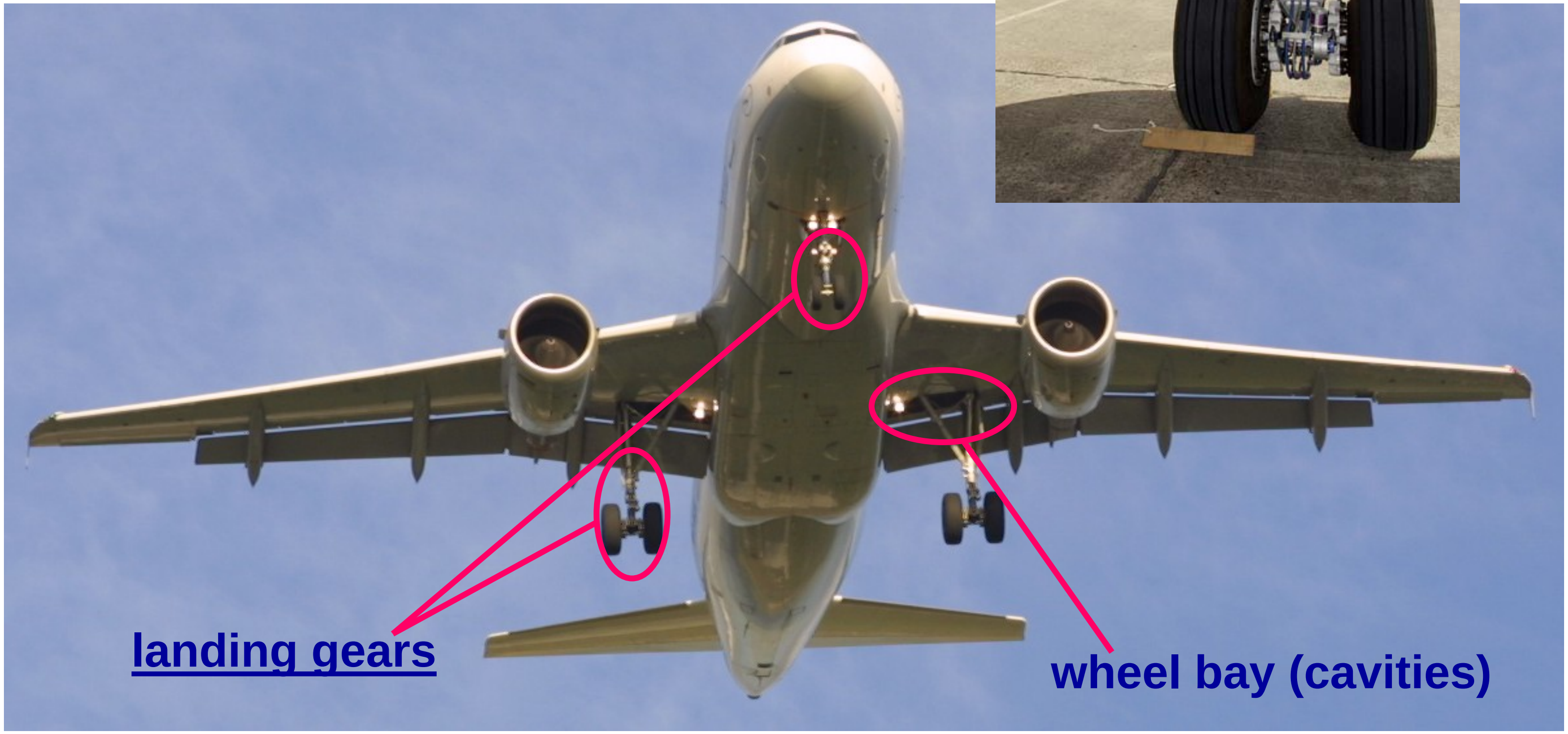
Foam filler

→ **Lufthansa initial flight test showed ~2 dB broadband noise reduction (for frequencies from 0.5 to 1.5 kHz).**

Reduction of excess noise sources
Synopsis

- Full scale (component and flyover) testing at revealed sources of excess noise:
  - Tone noise from flow over holes in wing surface or hollow pins at landing gear components
  - Broadband noise from flow over cavities in wing leading-edge and flap side-edge
- These contributions could be easily avoided <u>in the early design phase</u> (technical solutions trivial), retrofits are costly → transfer to the existing fleet rather unlikely
- Note: Quantification of source ranking is only available for selected A/C (limited full-scale test data including source localization); these sources could dominate the overall component noise which limits current prediction capability
- From the researcher's standpoint the classical sources are much more interesting → reduction is more challenging

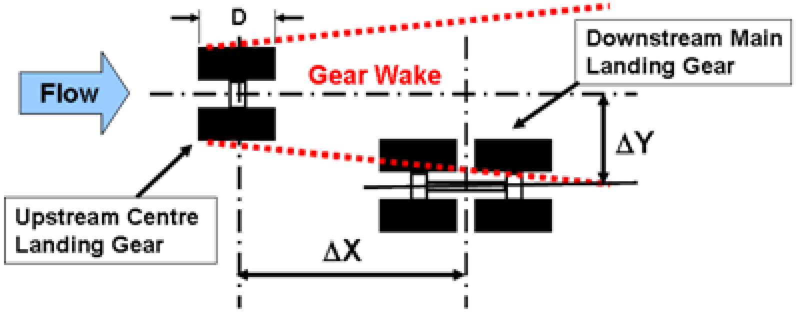
Landing gear noise reduction



Landing gear (LG) noise reduction

- For current short and long range aircraft (not for typical business jets) the undercarriages are the primary sources of airframe noise.

- Possible noise reduction efforts:
  - Avoidance of flow separation of the various bluff-body/rim elements and hence, prevention of wake/solid-body interaction (single elements of individual LG but also interaction noise between the LGs of an A/C)



Landing gear (LG) noise reduction

- For current short and long range aircraft (not for typical business jets) the undercarriages are the primary sources of airframe noise.

- Possible noise reduction efforts:
  - Avoidance of flow separation of the various bluff-body/rim elements and hence, prevention of wake/solid-body interaction (single elements of individual LG but also interaction noise between the LGs of an A/C)
  - Lowering the complexity and/or number of individual LG components
  - Reduction of the local flow speeds at the installation position of protruding parts

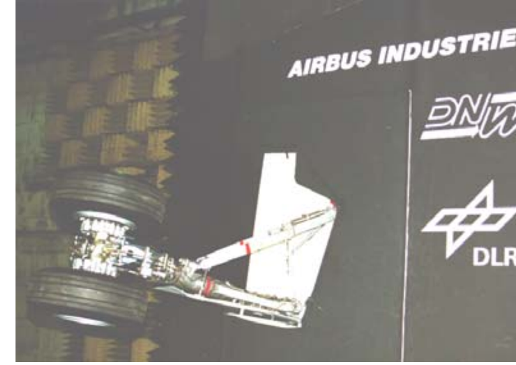
Reminder: $\langle p^2 \rangle \sim u_\infty^6$,
i.e. a 3-dB noise reduction could be achieved by reducing u_∞ by only 11%!

Landing gear (LG) noise reduction

- For current short and long range aircraft (not for typical business jets) the undercarriages are the primary sources of airframe noise.

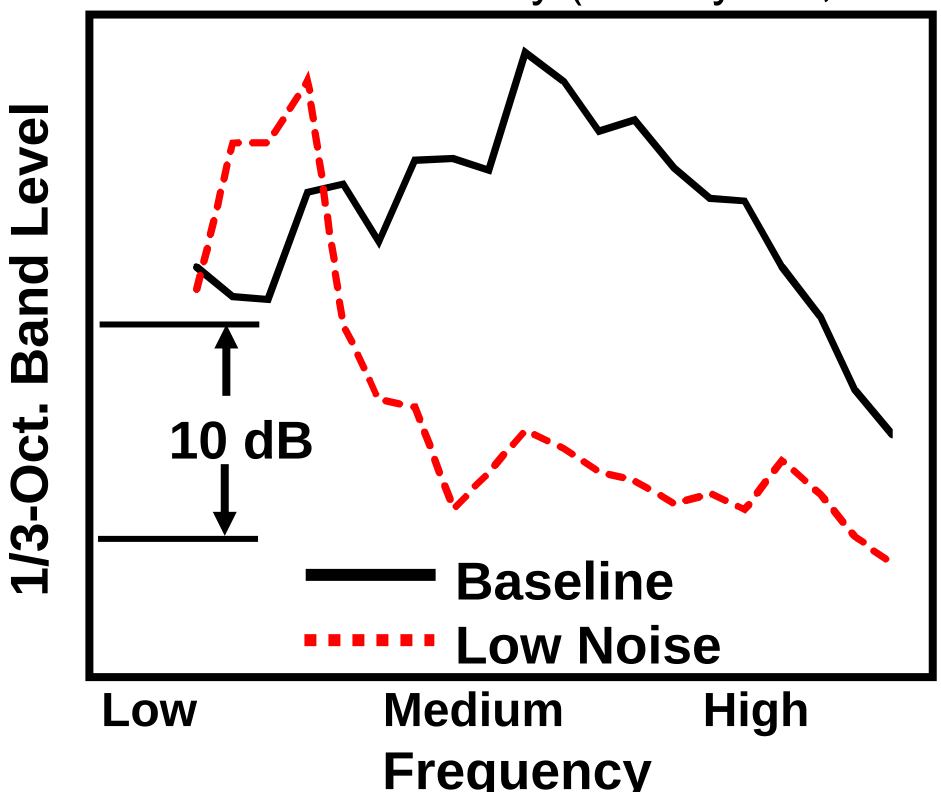
- Possible noise reduction efforts:
  - Avoidance of flow separation of the various bluff-body/rim elements and hence, prevention of wake/solid-body interaction (single elements of individual LG but also interaction noise between the LGs of an A/C)
  - Lowering the complexity and/or number of individual LG components
  - Reduction of the local flow speeds at the installation position of protruding parts

- Low-noise LG solutions:
  - Add-on LG noise reduction technologies → streamlined fairings
  - New architectures
  - Optimized LG installation



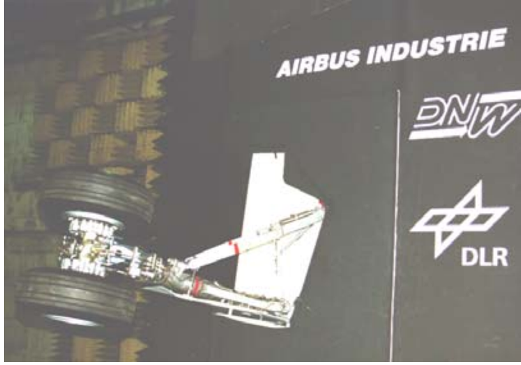
LG noise reduction
Maximum noise reduction potential

- Straightforward approach: unrealistic complete fairing installed in fundamental LG study (Dobrzynski, 1995)

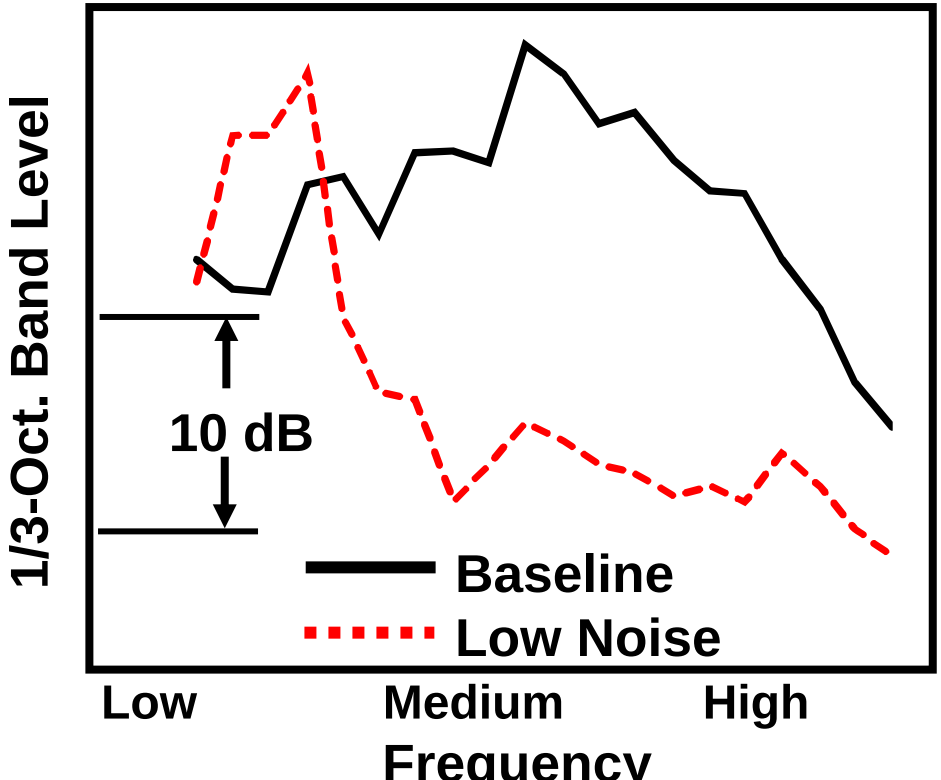


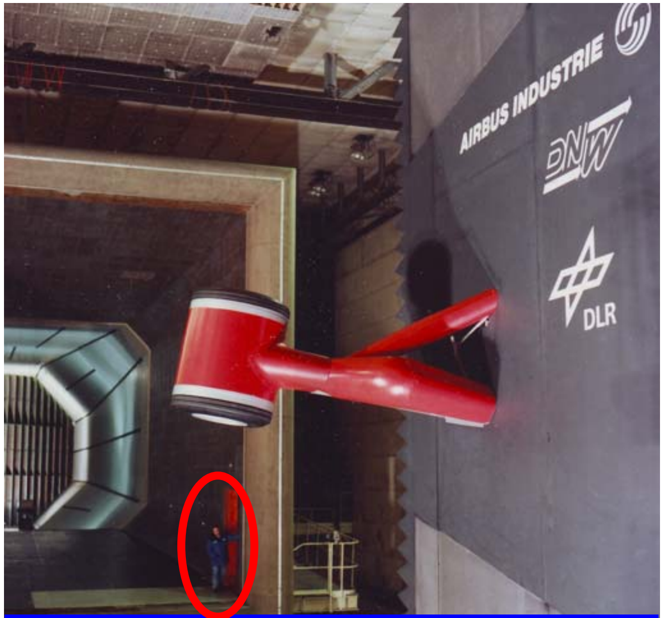
full-scale WTT (DNW-LLF)

LG noise reduction
Maximum noise reduction potential



- Straightforward approach: unrealistic complete fairing installed in fundamental LG study (Dobrzynski, 1995)

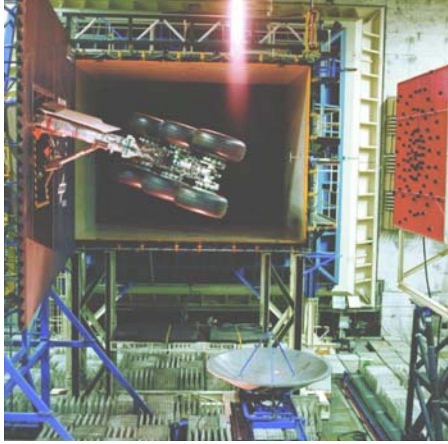




full-scale WTT (DNW-LLF)

→ Aim: Provide noise reduction of similar order for realistic treatment

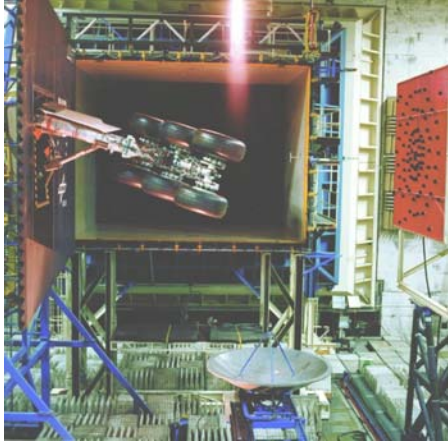
→ Huge basic noise reduction potential of > 10 dB for not practicable solution!



Landing gear noise reduction
Airworthiness requirements 1/2

- Operational aspects:
  - Runway loads restrictions define number and spacing of wheels
  - Gear locations are defined by lateral aircraft stability and rotation before liftoff
  - Brake heating dissipation requirement (fairings which would delay cooling increase the turnaround time on airport)

- Security aspects:
  - Emergency extension requirement:
    - Mechanical free-fall system which disengages the uplocks and allows the landing gear to fall due to gravity
    - Mechanical gear downlock → affects MLG side-stay design
  - Tire burst requirements → affects location of hydraulical/electrical dressings and enforces redundancy, equipment located in the landing gear bay should be protected

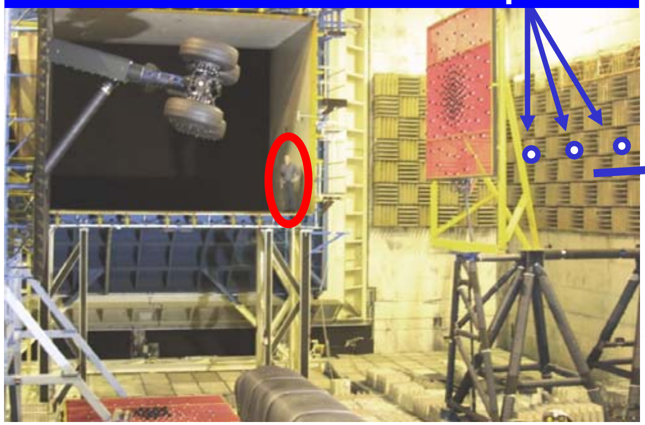


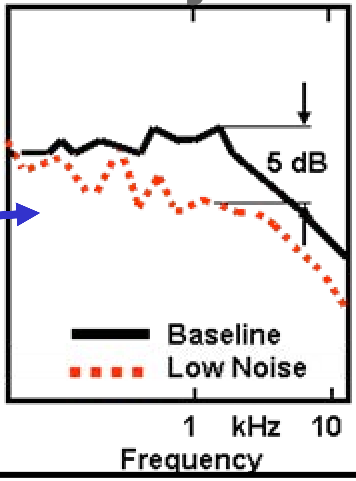
Landing gear noise reduction
Airworthiness requirements 2/2

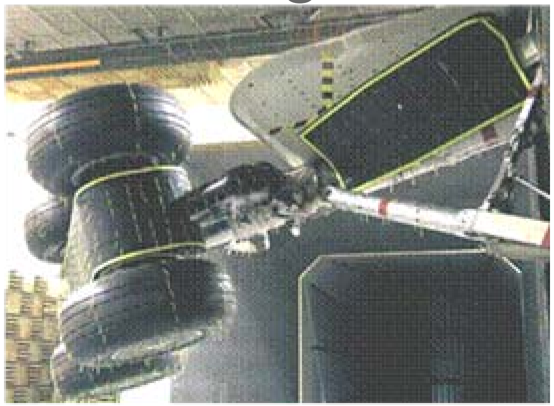
- Cost aspects:
  - Effects on the airframe should be minimized (minimum bay size for stowing)
  - System complexity must be as low as possible (articulated components should be avoided)
  - Viability of fairing materials and maintenance access: Potential add-on fairings must not obstruct quick routine inspection and should be easily maintainable (contamination)

Landing gear noise reduction
Noise reduction potential by realistic fairings

Farfield wall-mounted microphones







Source: RAIN project

NASA QTD 2 Boeing 777 MLG fairings

Source: Herkes, et. al. (AIAA 2006-2720)

Flight testing of LG fairings:

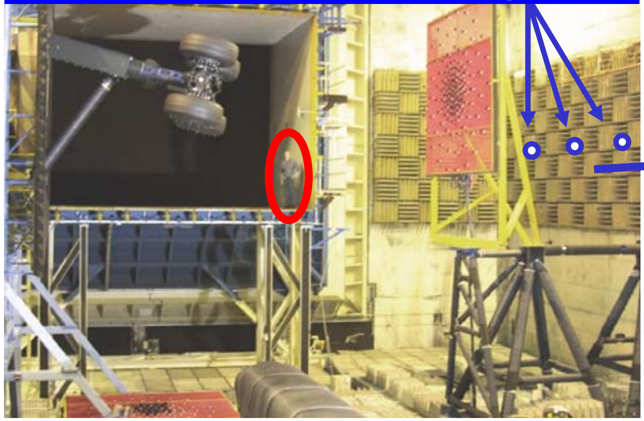
all devices manufactured w.r.t. airworthiness requirements

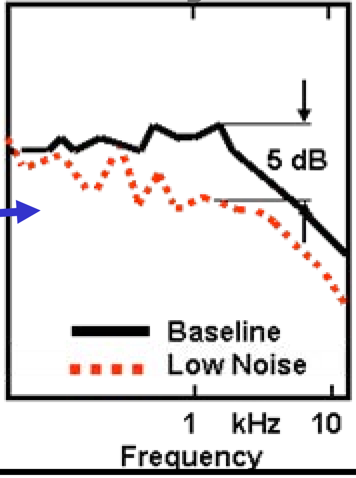
Airbus 320 NLG and MLG Fairings

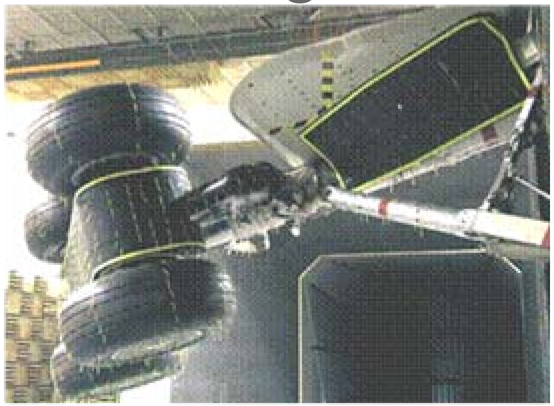
Source: SILENCE® project

Landing gear noise reduction
Noise reduction potential by realistic fairings

Farfield wall-mounted microphones







Source: RAIN project

Source: Herkes, et. al. (AIAA 2006-2720)

Flight testing of LG fairings:

all devices manufactured w.r.t. airworthiness requirements

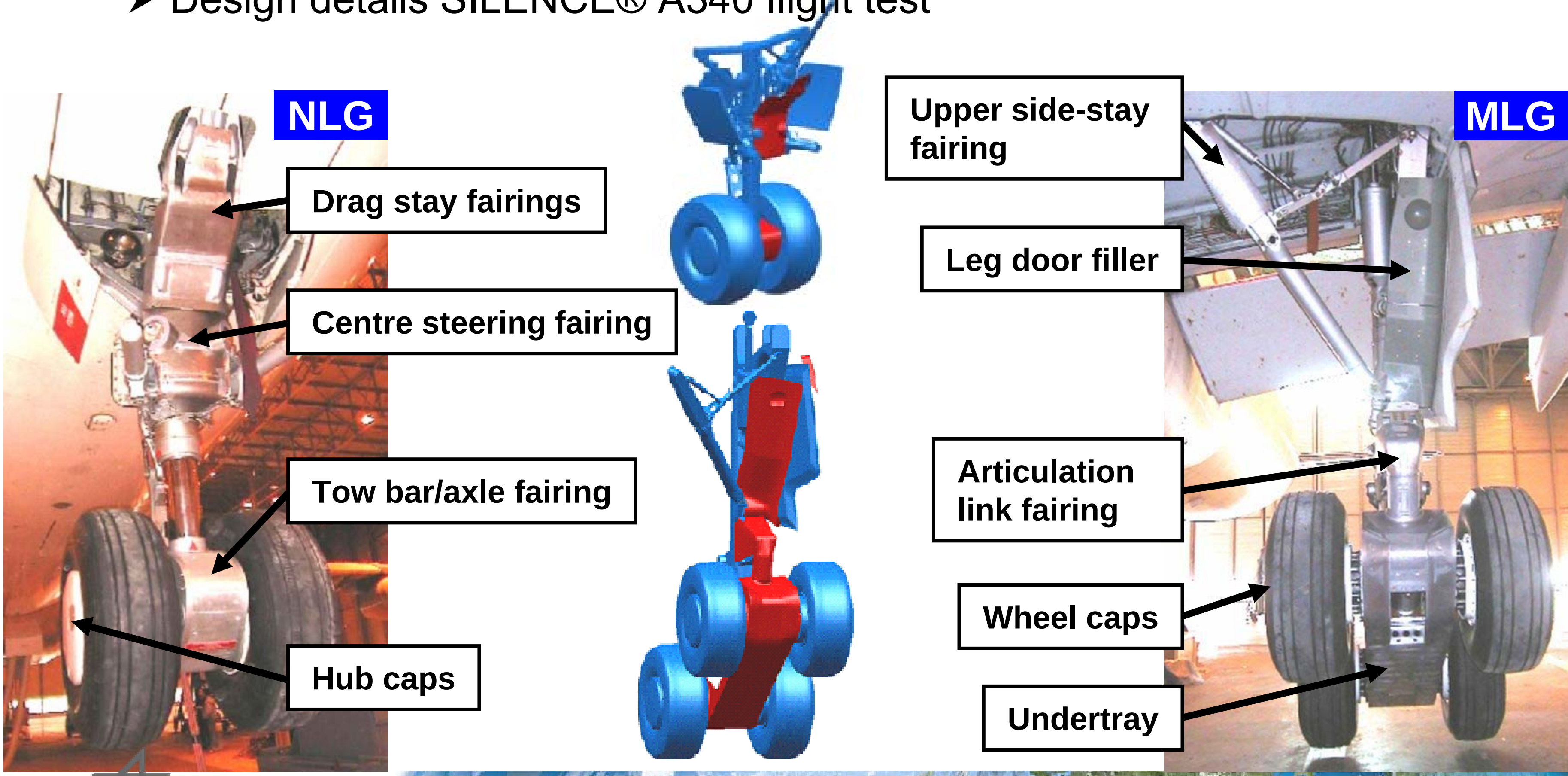
Airbus 320 NLG and MLG Fairings

Source: SILENCE® project

→ - 2 EPNdB achieved on total A340 landing gear source noise,
→ - 0.4 EPNdB on A/C level (approach certification noise; LG + HLD)

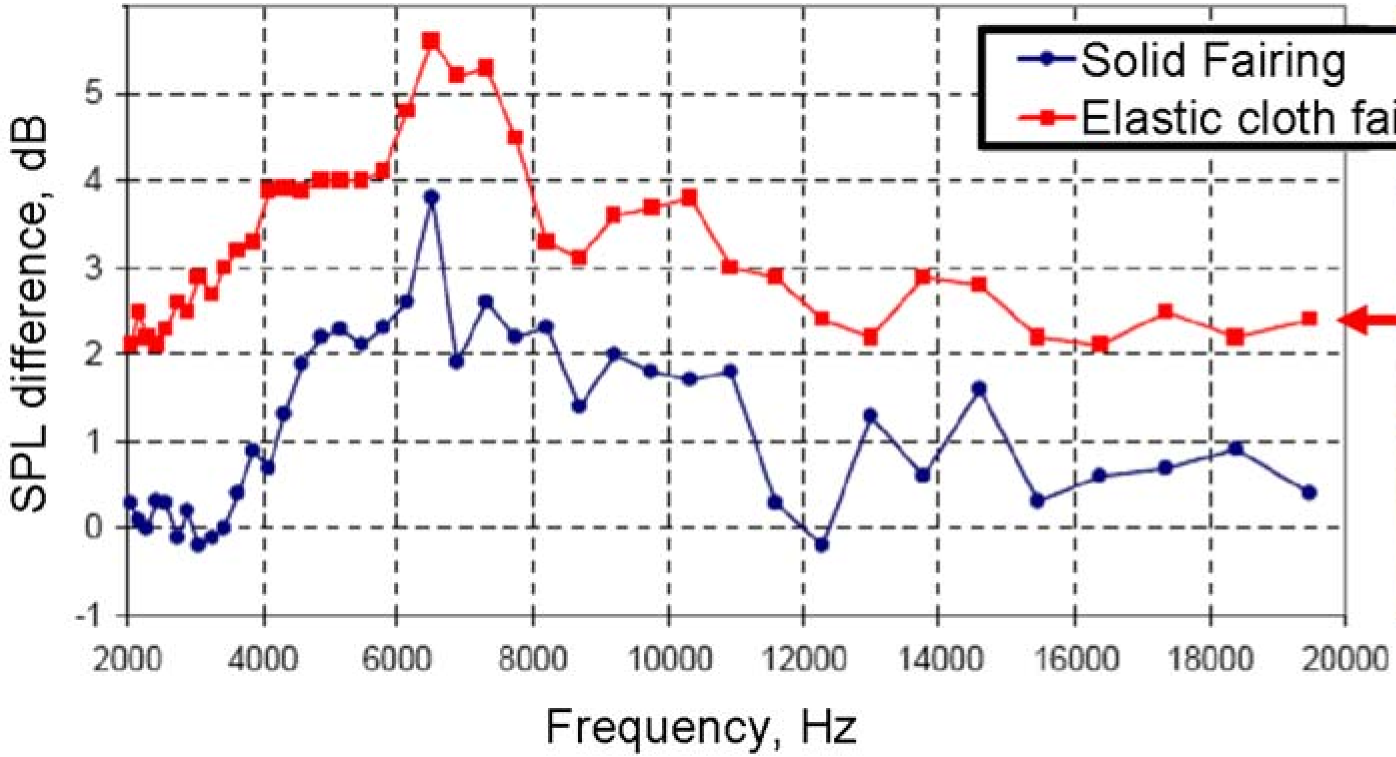
Landing gear noise reduction
Noise reduction potential by realistic fairings

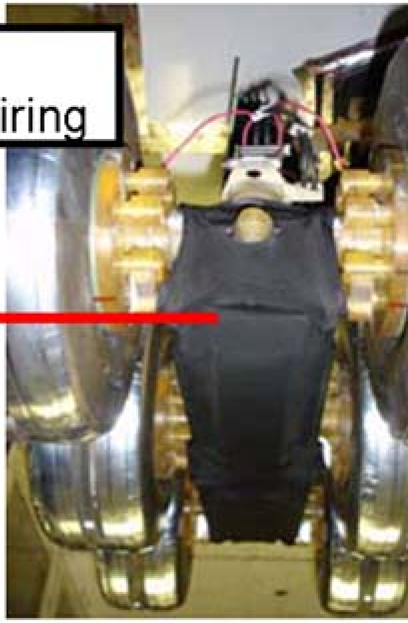
- Design details SILENCE® A340 flight test



Landing gear noise reduction
Technologies under development: elastic fairings

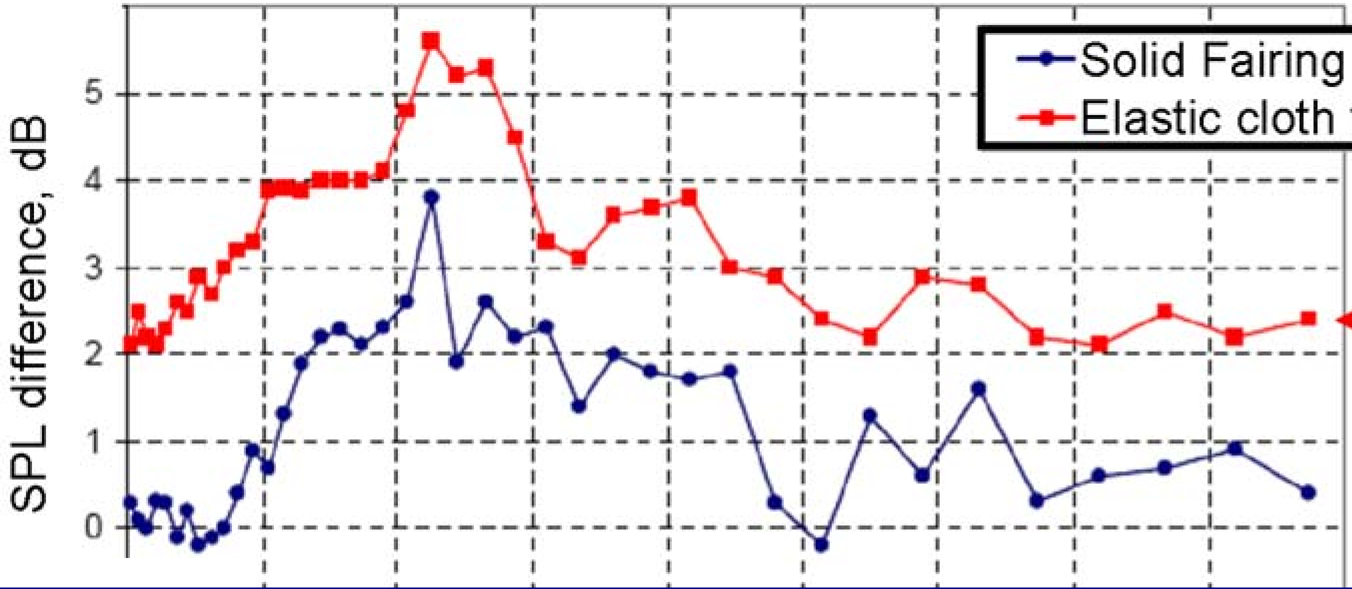
- Ravetta, et. al. (AIAA 2007-3466): Initial study at ¼ scale B777 gear

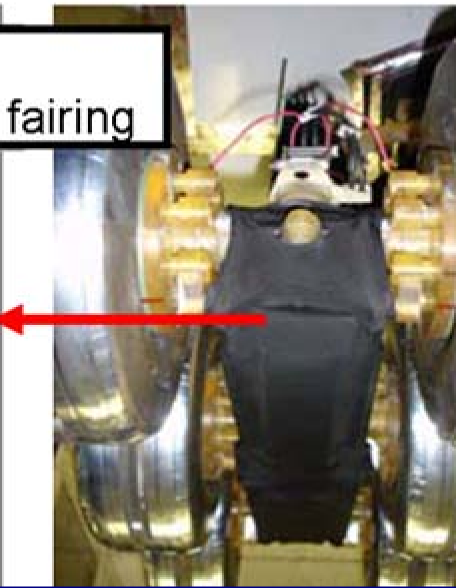




Landing gear noise reduction
Technologies under development: elastic fairings

➢ Ravetta, et. al. (AIAA 2007-3466): Initial study at ¼ scale B777 gear



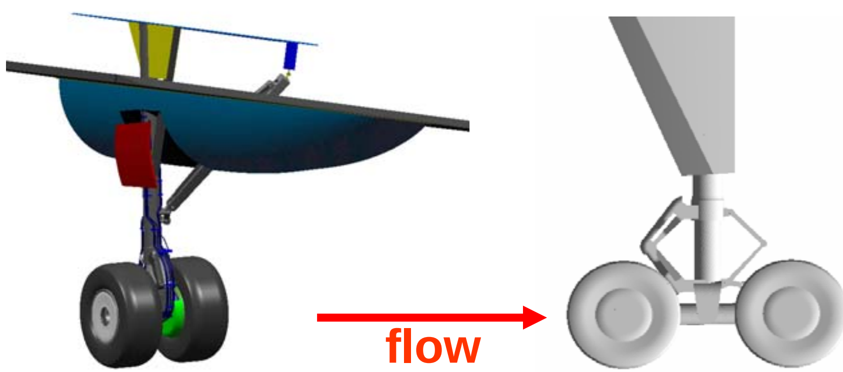


→ **Cloth fairings promise an additional 2-dB noise reduction compared to solid fairings (solid fairings cause flow deflection that might lead to noise increase in adjacent areas with increased flow velocity).**

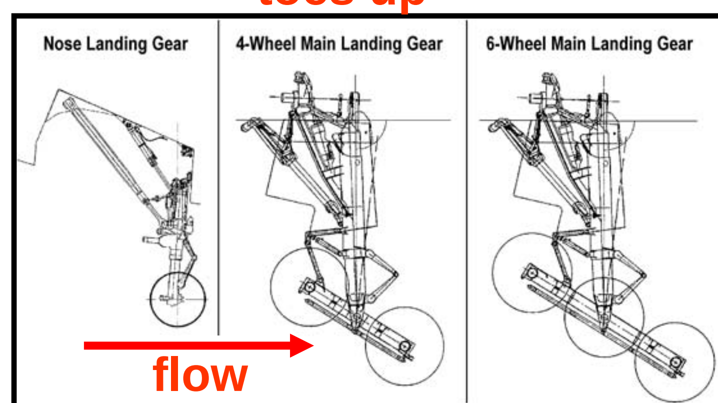
→ **Challenge: Flow resistance should be low enough to reduce deflection effect, but high enough to limit the wake flow velocity (mesh fairings induce high-frequency excess noise that has to be shifted to low-weighted frequencies)…**

Landing gear noise reduction
Noise reduction potential by new architectures

- Current design efforts involve iterative loops based on experimental experience, supported by CFD calculations
- General remarks:
  - Belly mounted landing gears are beneficial (2-3 dB quieter than wing mounted equivalent) → parts of the legs and side stay are hidden in the bay/belly fairing
  - Bogie aligned with airflow during approach is beneficial to typical ‘toes up’ position

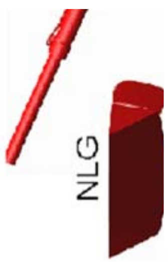


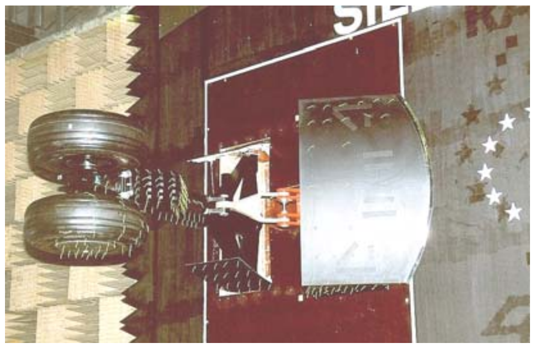
‘toes up’

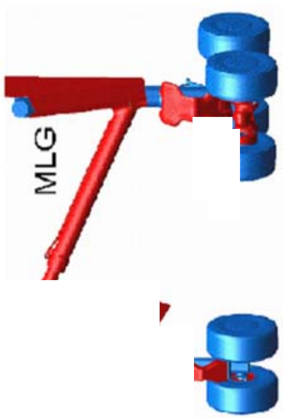


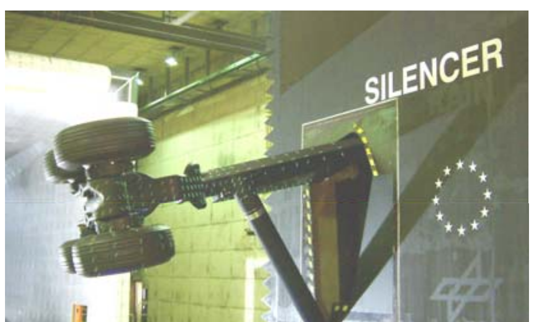
Landing gear noise reduction
Noise reduction potential by new architectures

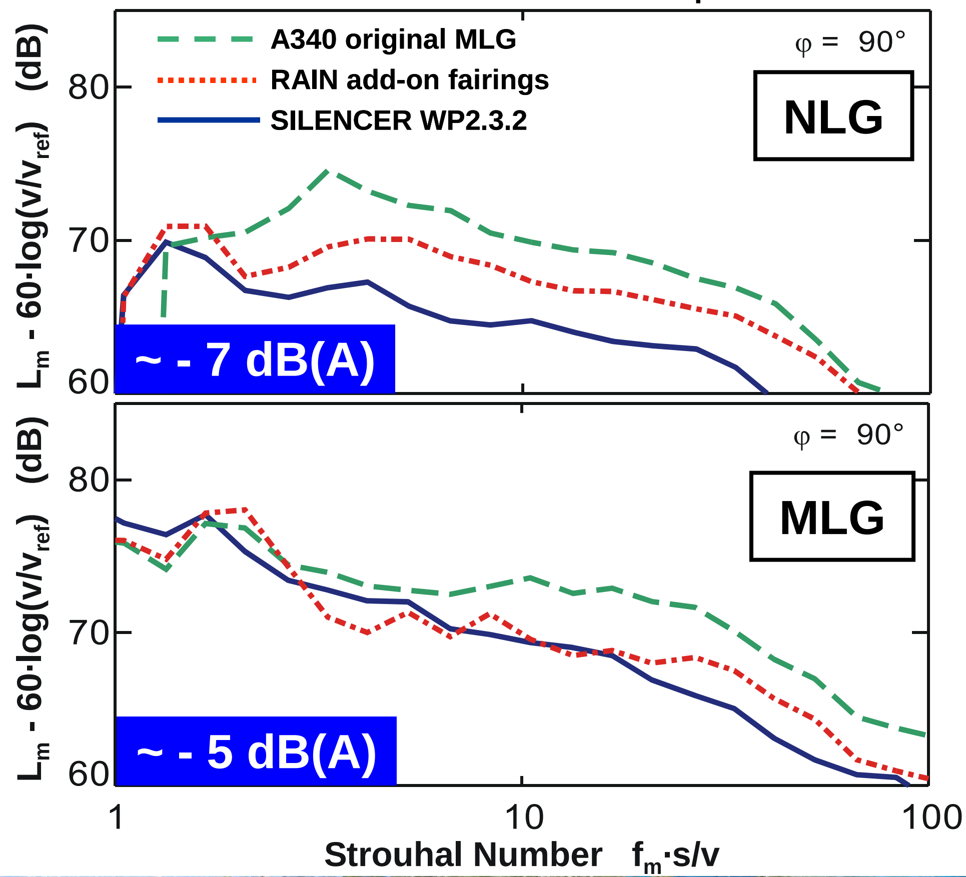
➢ Example: SILENCE® DNW-LLF test results at full-scale mock-up





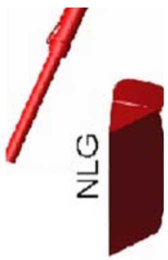


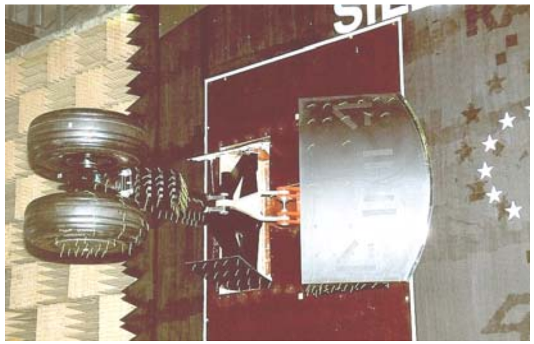


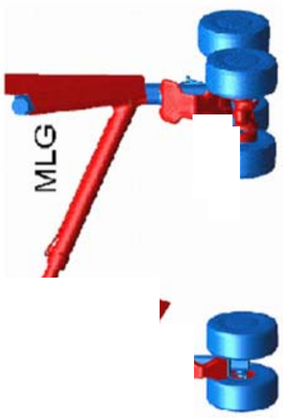


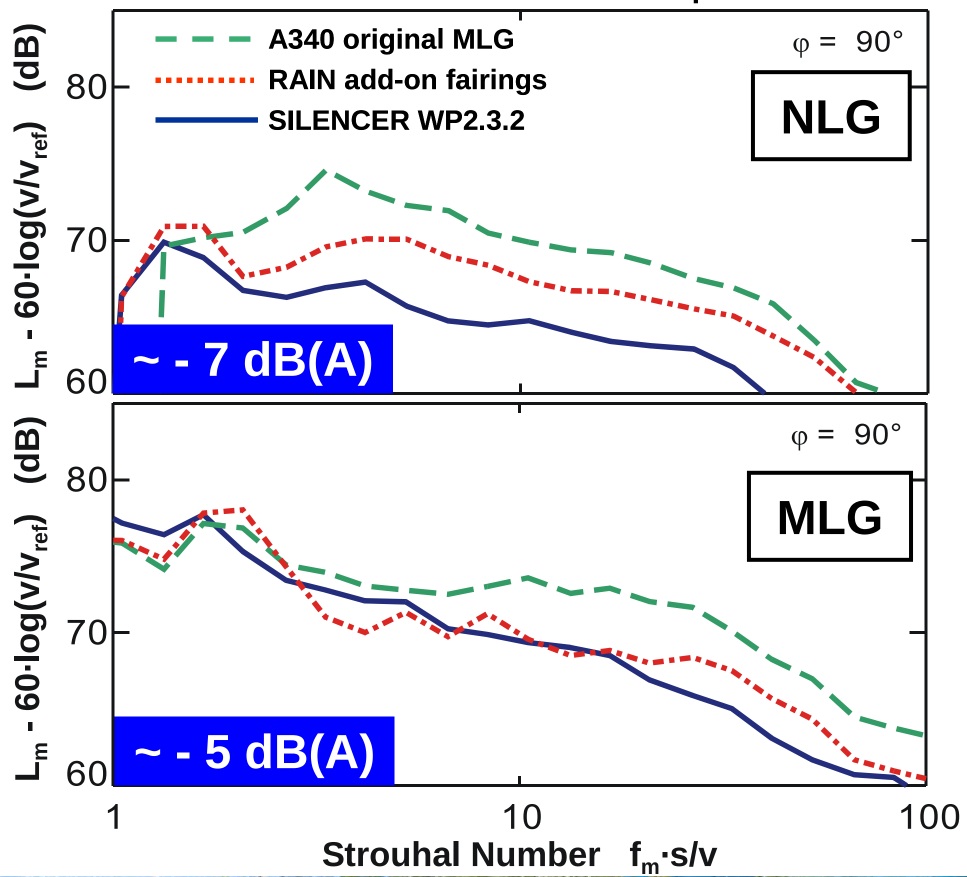
Landing gear noise reduction
Noise reduction potential by new architectures

- Example: SILENCE® DNW-LLF test results at full-scale mock-up









→ Corresponding in-flight prediction: -4.1 EPNdB on LG level

Landing gear noise reduction
Synopsis

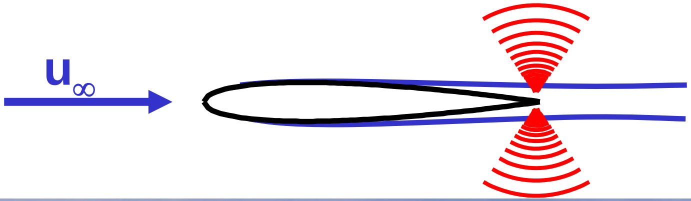
- Mid- to long-term LG noise reduction potential on component level:
  - ~ 5 EPNdB to be realized by realistic fairing solutions
    (estimate based on WTT, flight test: ~2 EPNdB); high TRL
    main implementation issue: weight, heat dissipation, maintenance access, system complexity
  - ~ 5 EPNdB to be realized by future architectures; medium TRL
    main implementation issue: structural and system integration

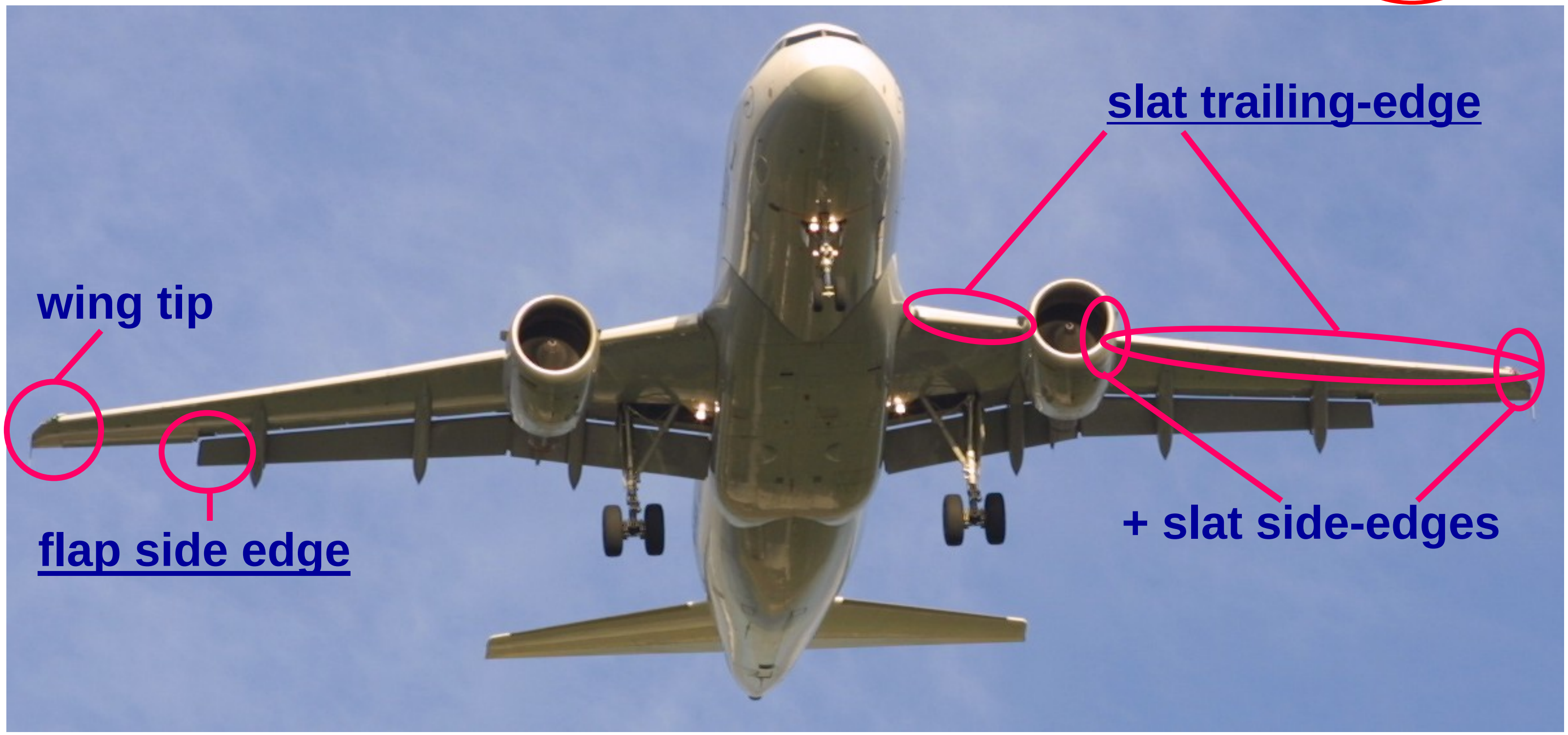
- LG noise reduction efforts are on a good track w.r.t the 2020 goal; further efforts are needed to eliminate the remaining drawbacks and to further increase the achieved noise reduction potential

- Note: Active flow control devices (blowing/suction, plasma actuation) are at very low TRL: basic studies promise ~1 EPNdB LG noise reduction on top of low-noise design; main implementation issue: weight, structural and system integration, air/energy supply, complexity vs. passive devices

High-lift noise reduction

- Basic principles: edge noise reduction

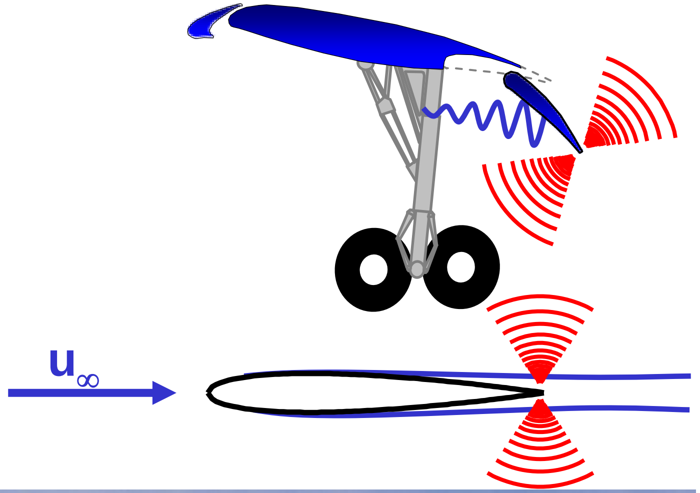


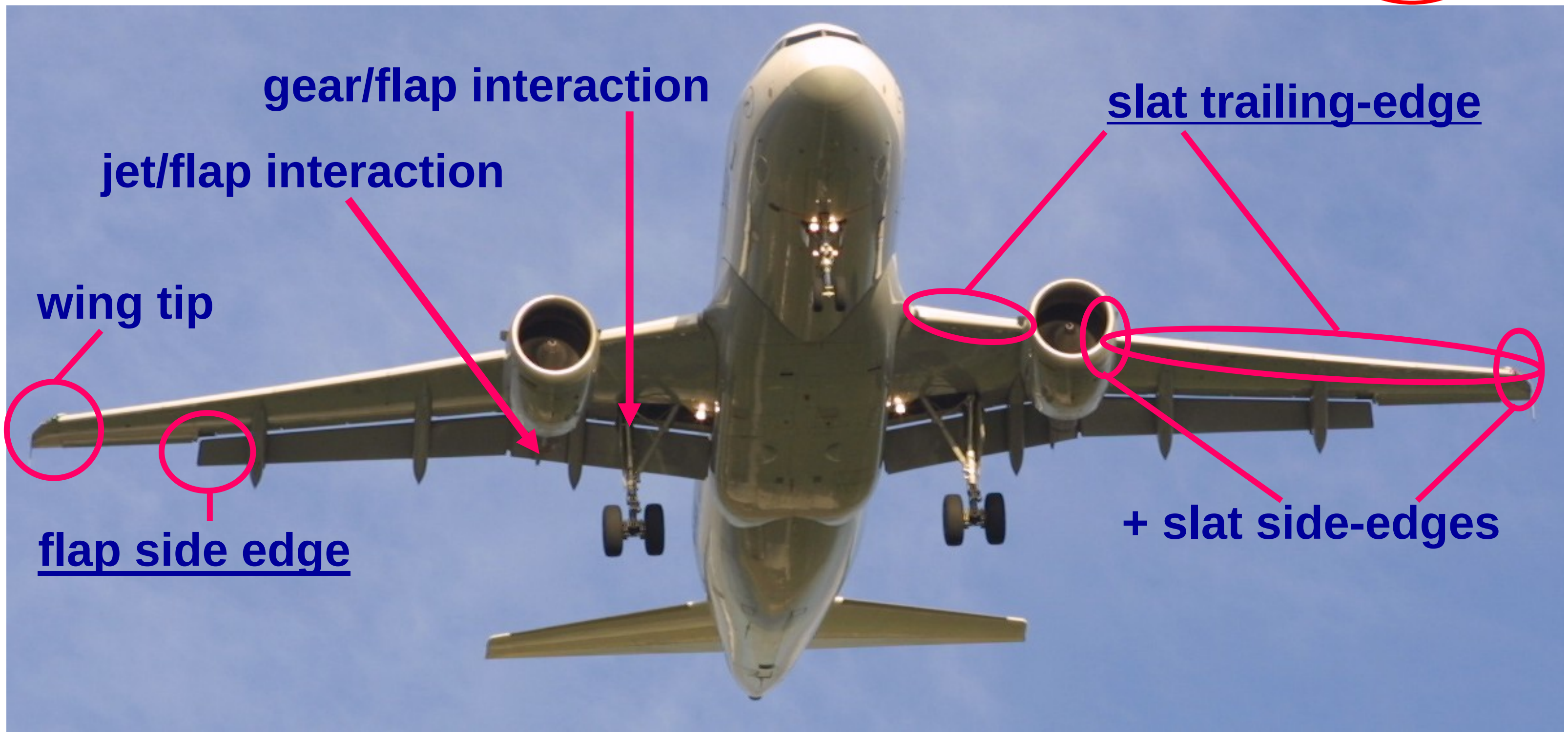


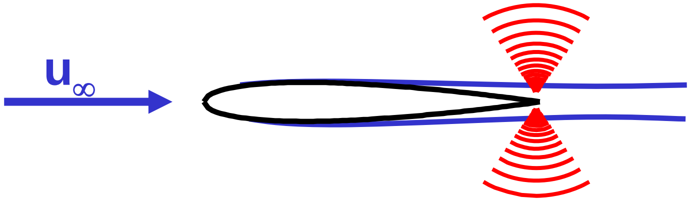
DLR

High-lift noise reduction

- Basic principles: edge noise reduction







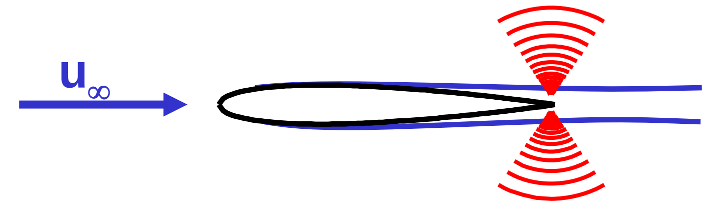
Basic principles: trailing-edge (TE) noise reduction

- First airframe noise reduction approaches go back to the 1970ies, mainly dedicated to edge noise reduction

- Possible TE noise reduction mechanisms are:
  - Modification of the edge enhancement factor by matching of the edge boundary conditions to free air ('impedance adjustment')/ or modification of the 'scattering center' (geometric break up of the edge contour)
  - Acoustic absorption
  - Hydrodynamic absorption

- These could be realized by means of
  - Serrated edges (note: $<p^2> \sim \cos^3\beta$)
  - Porous material application
  - Slotted and brush-type edges

→ Reminder: Not a mechanism but also successful: changes of the governing parameters, e.g. reduction of the incoming flow velocity because $<p^2> \sim u_\infty^5$

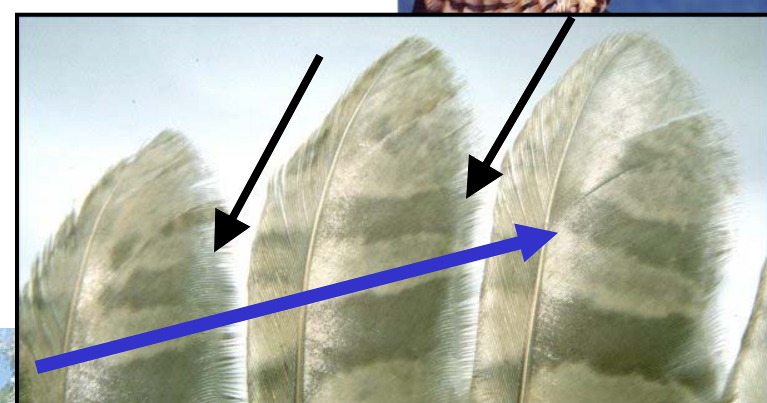


Basic principles: trailing-edge (TE) noise reduction

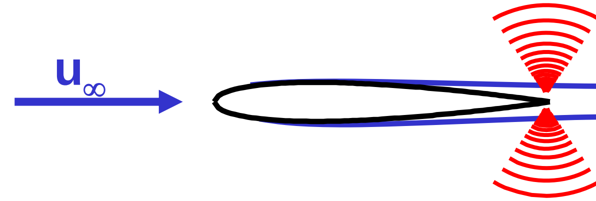
- First airframe noise reduction approaches go back to the 1970ies, mainly dedicated to edge noise reduction

- Possible TE noise reduction mechanisms are:
  - Modification of the edge enhancement factor by matching of the edge boundary conditions to free air (‘impedance adjustment’)/ or modification of the ‘scattering center’ (geometric break up of the edge contour)
  - Acoustic absorption
  - Hydrodynamic absorption

- These could be realized by means of
  - Serrated edges (note: $\langle p^2 \rangle \sim \cos^3\beta$)
  - Porous material application
  - Slotted and brush-type edges

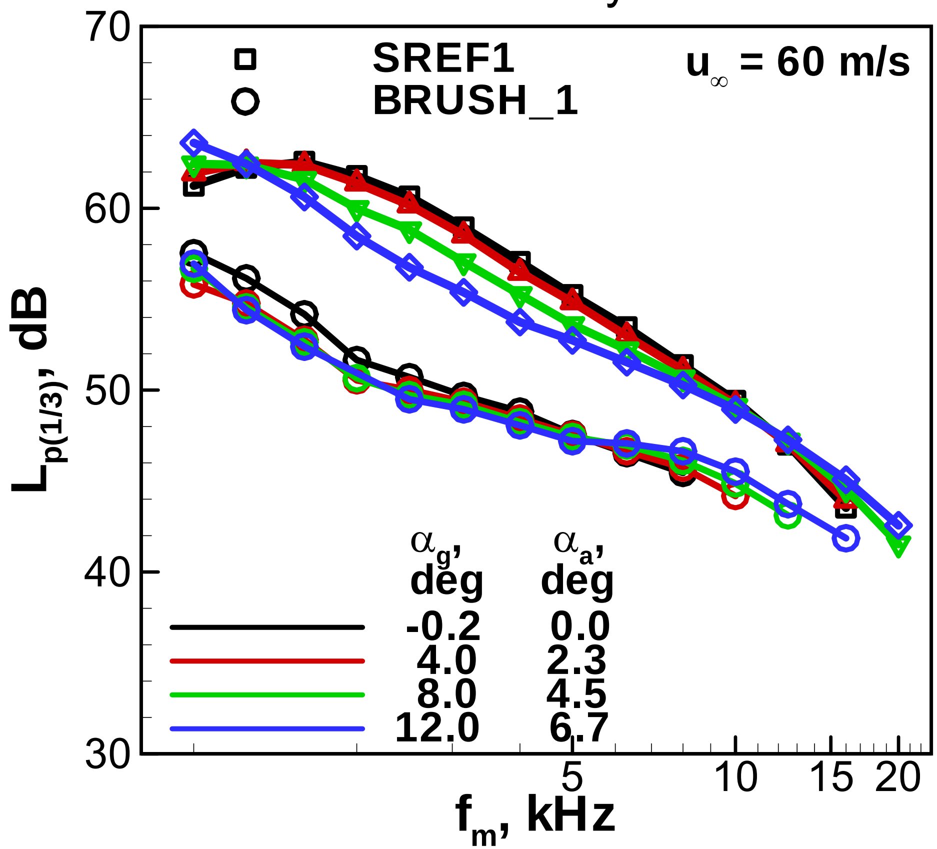


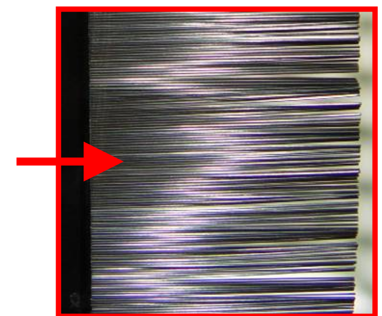
http://www.earthlife.net/birds/images/anatomy/owl-feather.jpg

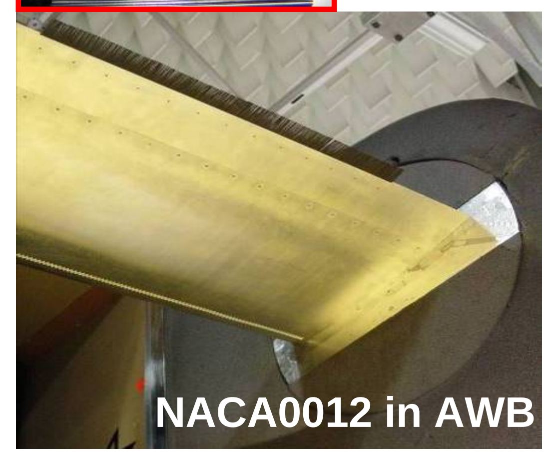


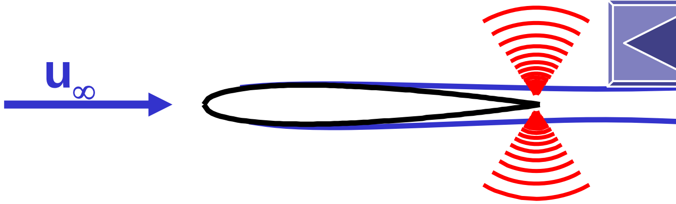
Basic principles: TE noise reduction
Brush-type TE extensions

- Parametric AWB study on TE brushes



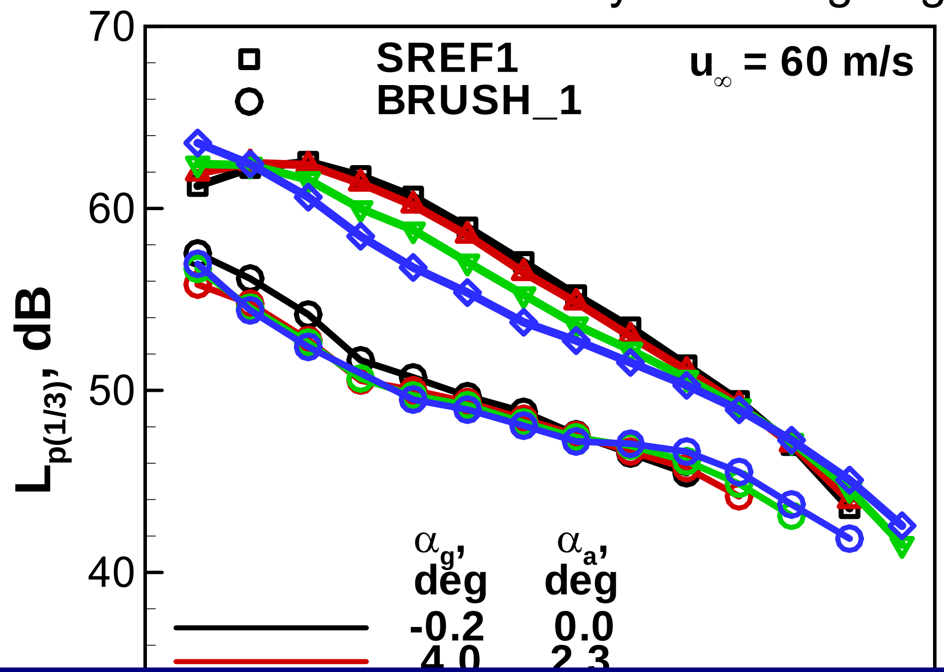


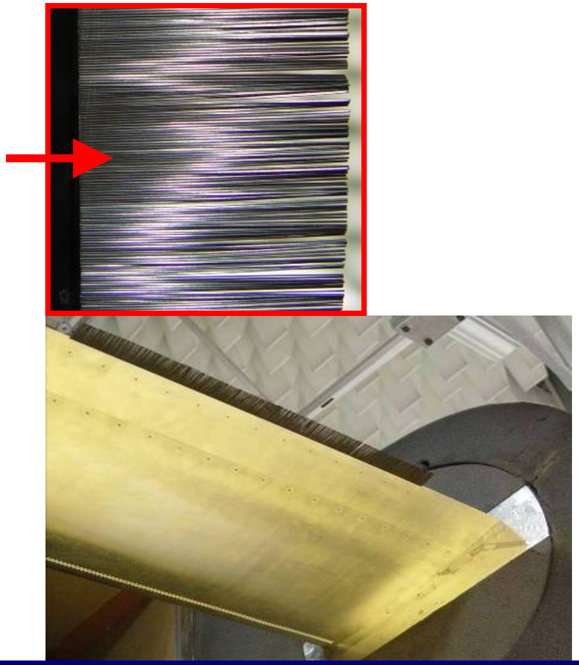




Basic principles: TE noise reduction
Brush-type TE extensions

- Parametric AWB study on trailing edge brushes

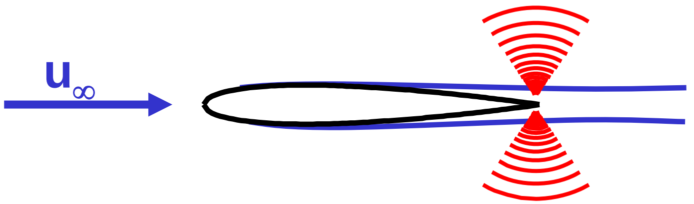




→ **Basic design criteria (fiber diameter, slit width, length) and scaling laws available**

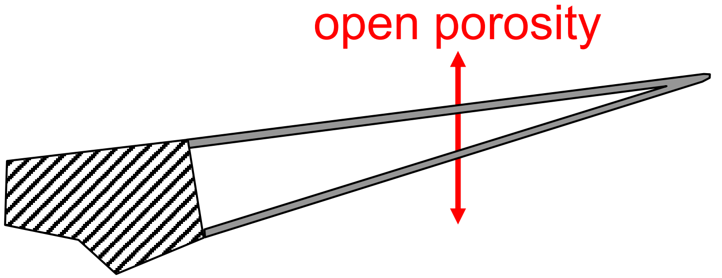
→ **Largest noise reduction potential among all previously tested TE devices**

Note: Non-flexible brushes made of steel needles provided a comparable noise reduction effect like flexible devices!

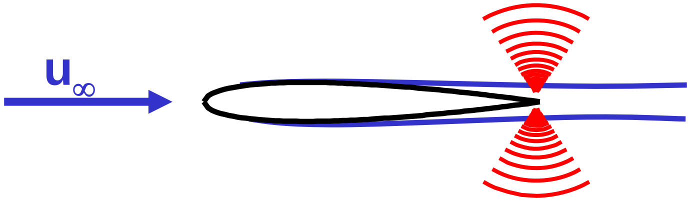


Basic principles: TE noise reduction Material airworthiness requirements

- No deviations from basic geometrical definition
- Operational temperature range
- UV-stability/ chemical resistance/ aeronautical fluids compatibility/ humidity – wet ageing/ ice accretion/ corrosion – salt spray test
- Sand and dust contamination
- Mechanical/ abrasion resistance/ stiffness
- Weight and balance requirements
- System integration aspects
- No impact on aerodynamical performance
- Noise requirements

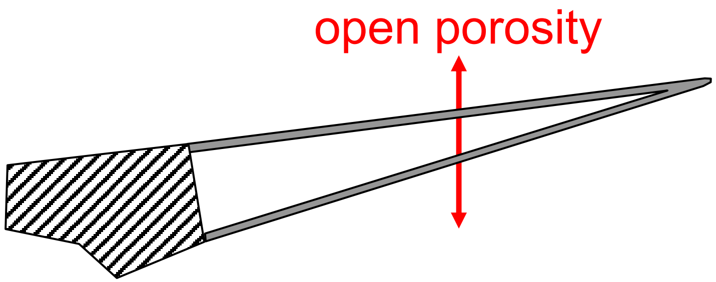


→ Material selection according to nonlinear resistance behavior:
  - Transparent to the acoustically relevant wall-normal velocity fluctuations but
  - Impermeable to typical mean flow velocities (no mean leakage flow through TE region)



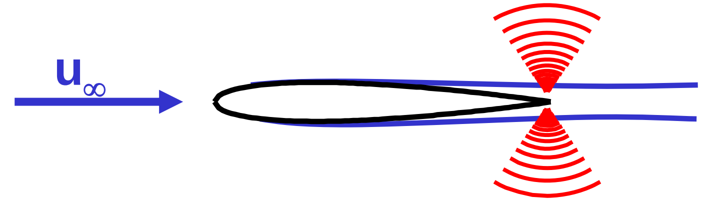
Basic principles: TE noise reduction
Material airworthiness requirements

- ➢ No deviations from basic geometrical definition
- ➢ Operational temperature range
- ➢ UV-stability/ chemical resistance/ aeronautical fluids compatibility/ humidity – wet ageing/ ice accretion/ corrosion – salt spray test
- ➢ Sand and dust contamination
- ➢ Mechanical/ abrasion resistance/ stiffness
- ➢ Weight and balance requirements
- ➢ System integration aspects
- ➢ No impact on aerodynamical performance
- ➢ Noise requirements



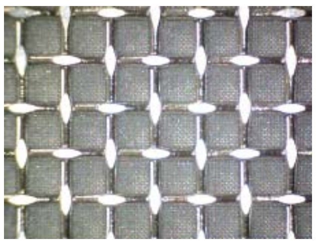
→ Material selection according to nonlinear resistance behavior:
- Transparent to the acoustically relevant wall-normal velocity fluctuations but
- Impermeable to typical mean flow velocities (no mean leakage flow through TE region)

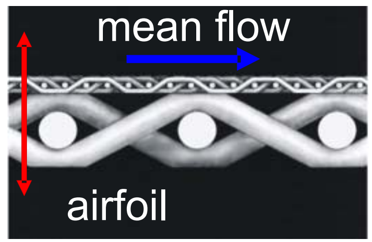
→ Critical hurdle: coming up with a design that does not create extra drag at cruise

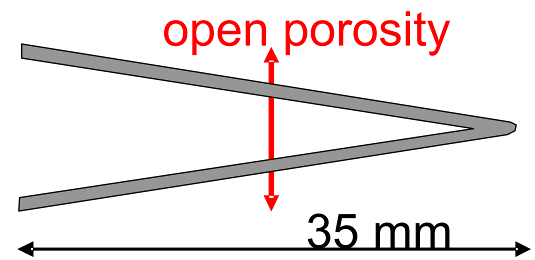


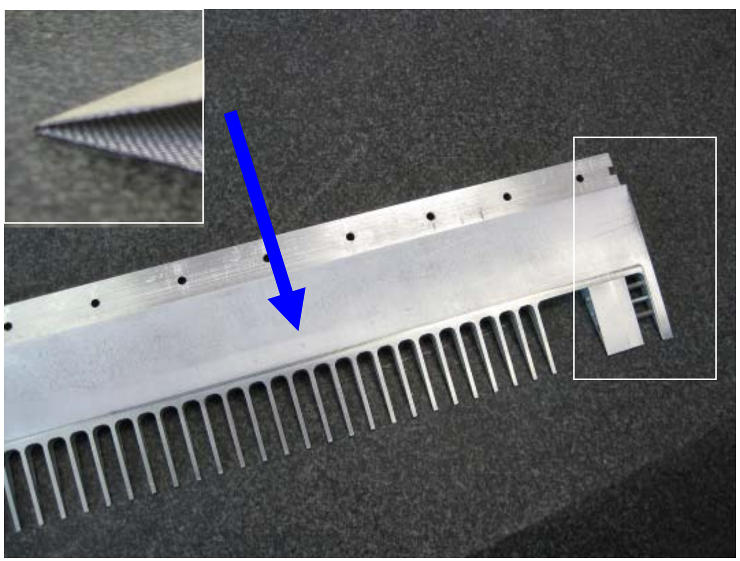
Basic principles: TE noise reduction
Porous material application

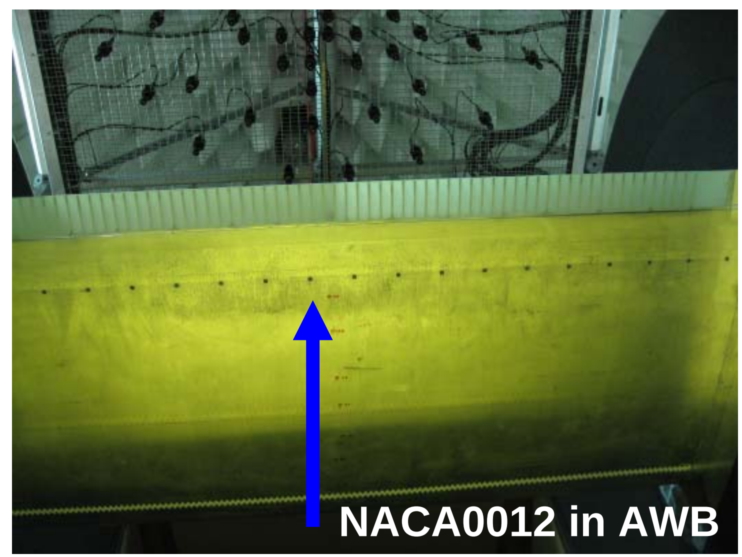
- Parametric <u>small-scale</u> AWB study on porous trailing edges

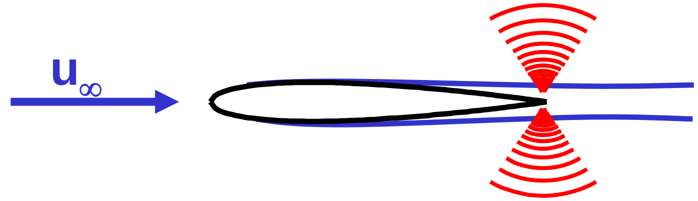






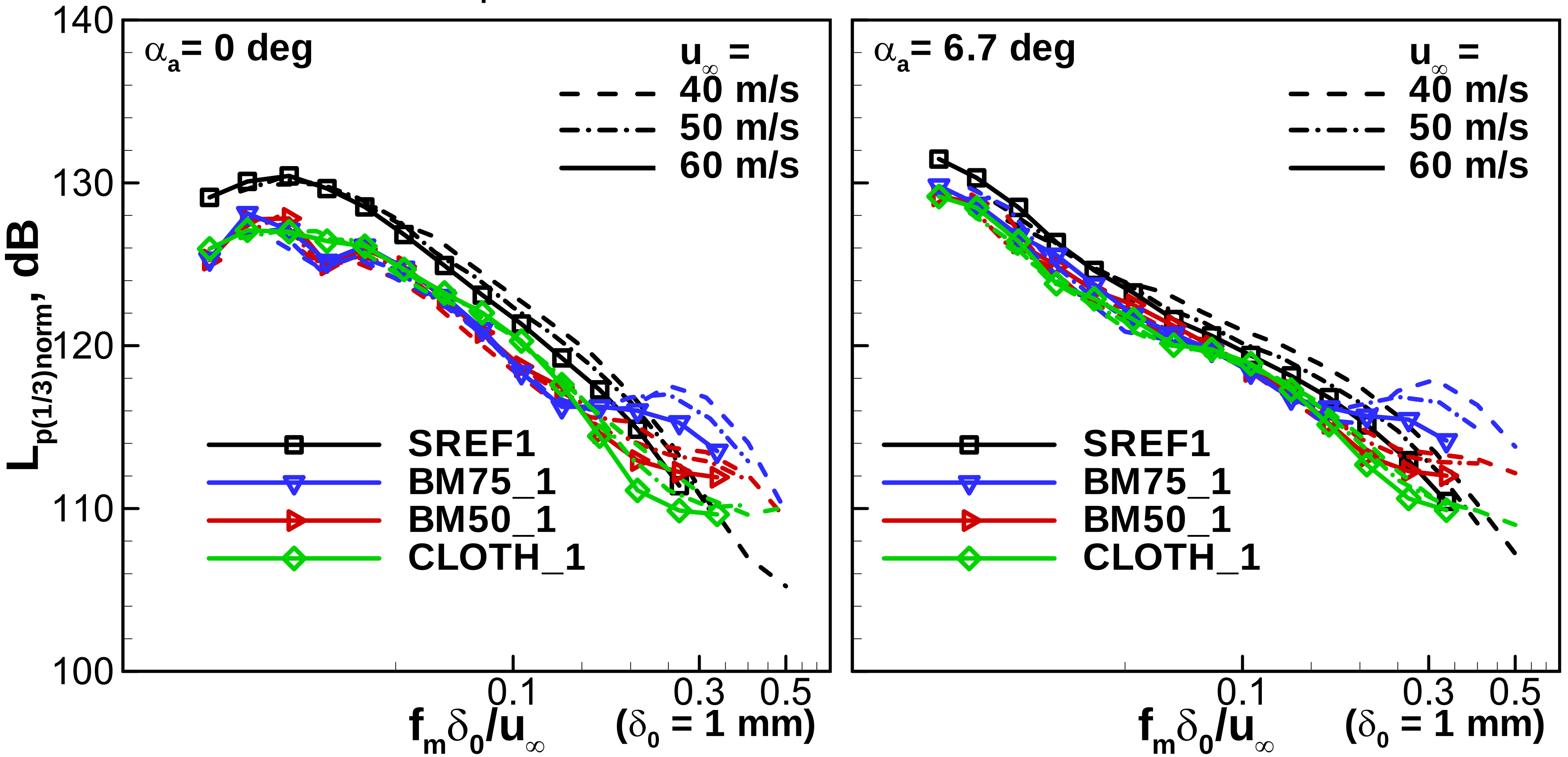


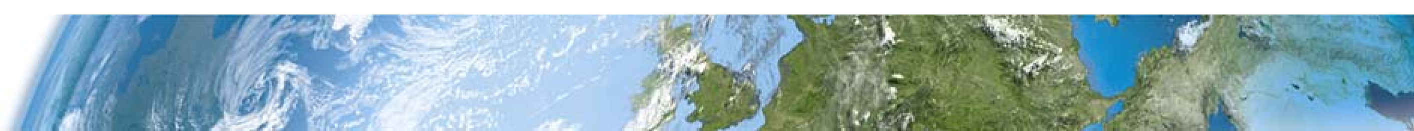


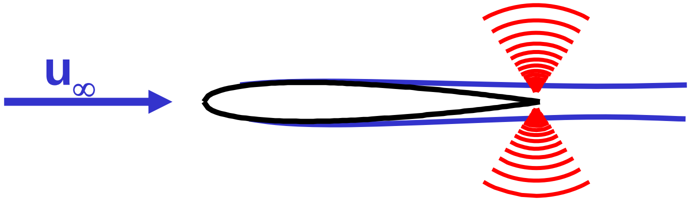


Basic principles: TE noise reduction
Porous material application

- Noise reduction potential

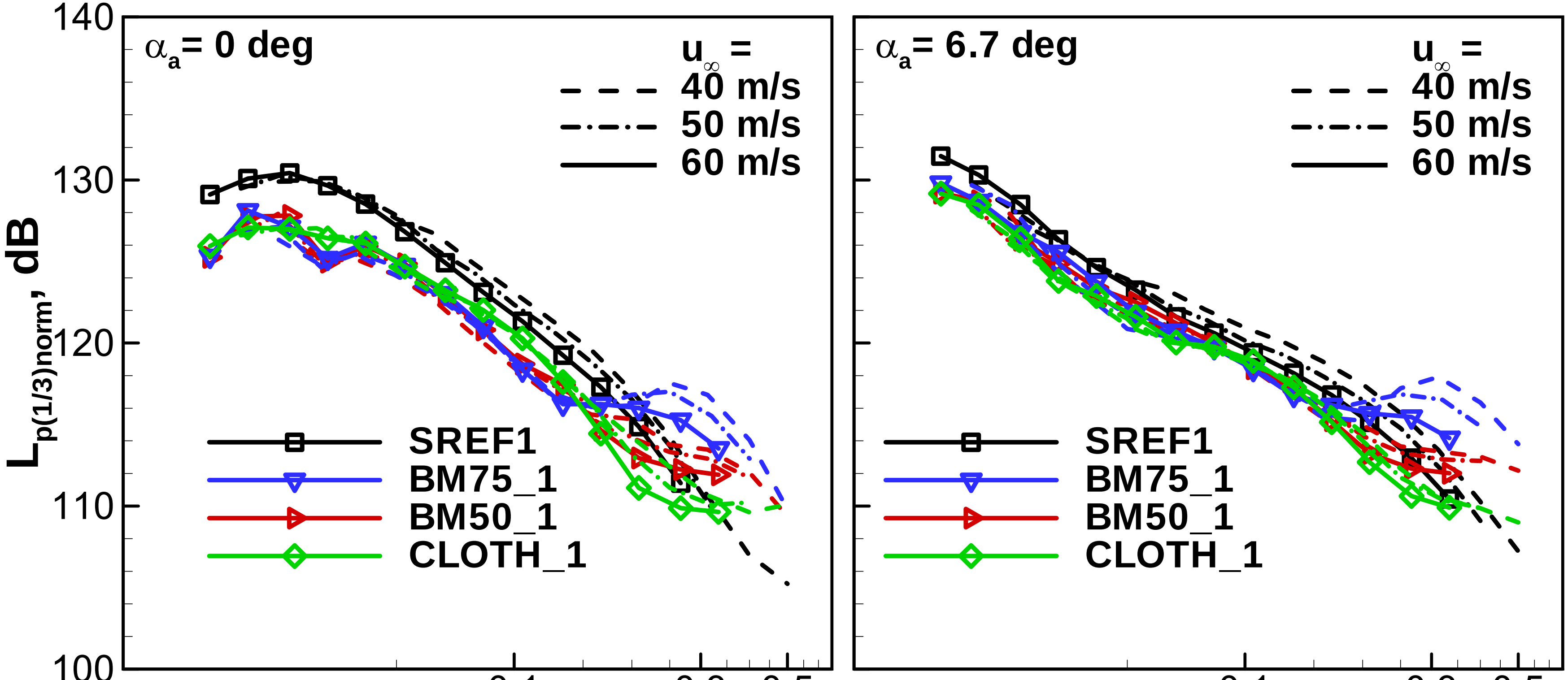






Basic principles: TE noise reduction
Porous material application

- Noise reduction potential

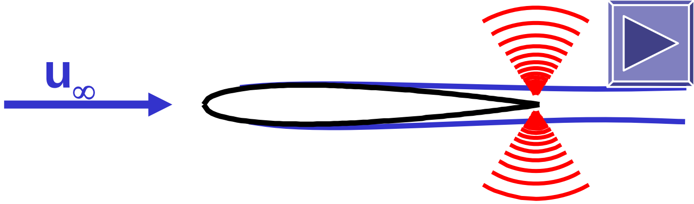


→ **Materials provide noise reduction (dependence on a-o-a and flow resistance)**

→ **Two of the shown materials have passed preliminary airworthiness checks**

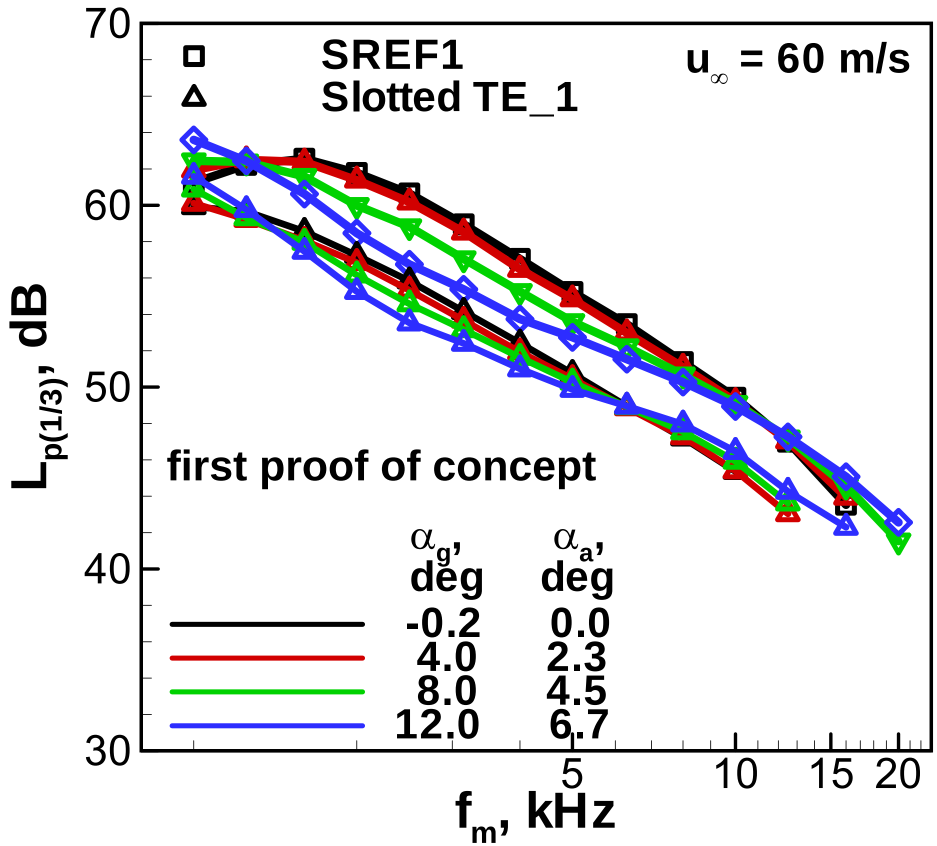
→ **Kickback: adverse a-o-a dependence**

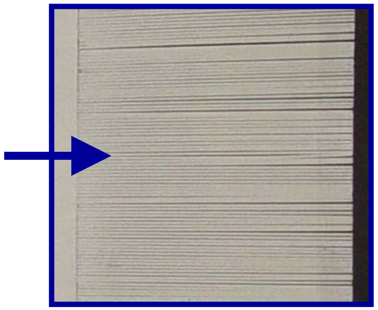
→ **Not by far the noise reduction as achieved for brushes!**

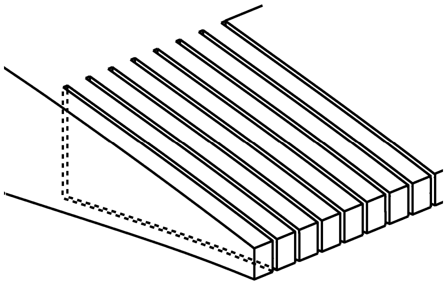


Basic principles: TE noise reduction
Slotted TEs

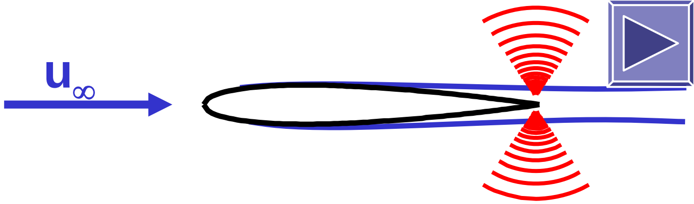
- Transfer solution: slotted TEs (anisotropic porosities)





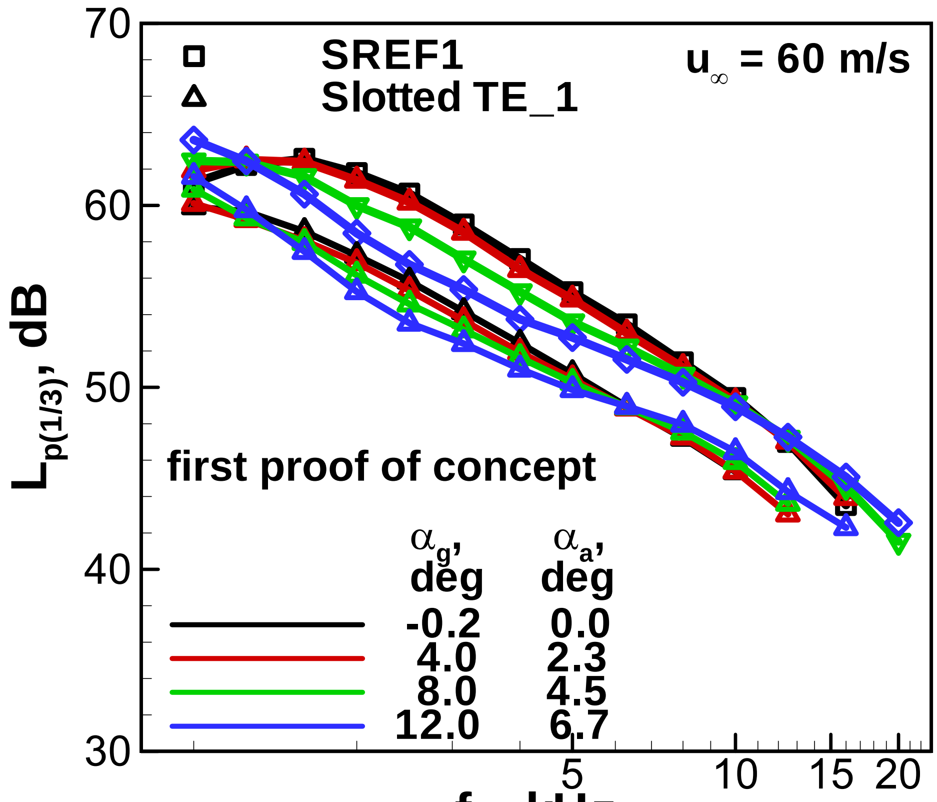


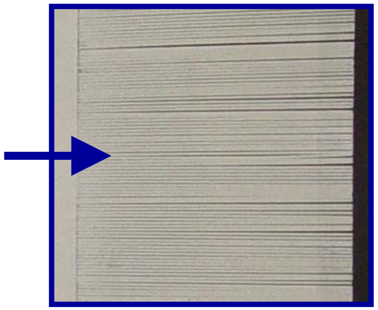
NACA0012 in AWB

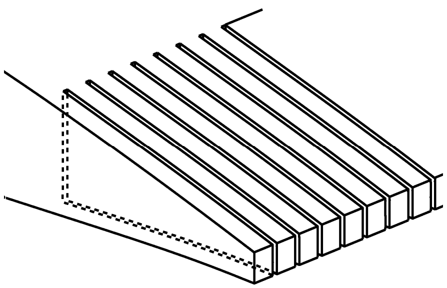


Basic principles: TE noise reduction
Slotted TEs

- ➢ Transfer solution: slotted TEs (anisotropic porosities)



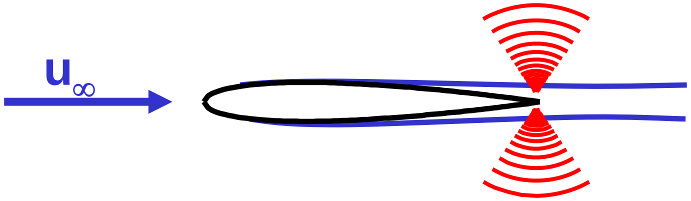




NACA0012 in AWB

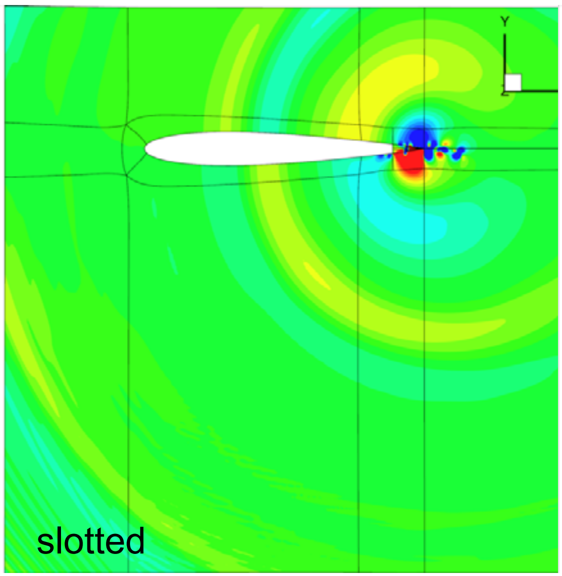
→ **Significant noise reduction achieved; further optimization potential? → CAA**

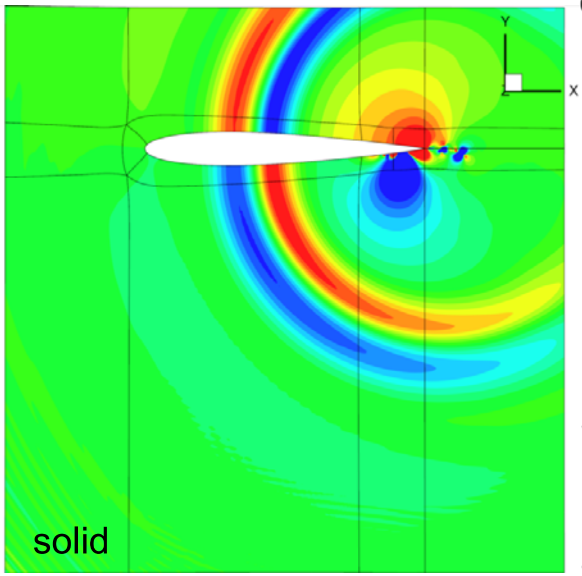
→ **Related CFD Study has shown that detrimental effect on HLD aerodynamic performance vanishes for slotted configuration.** **(Ortmann & Wild, Journal of Aircraft, 44(4), 2007)**

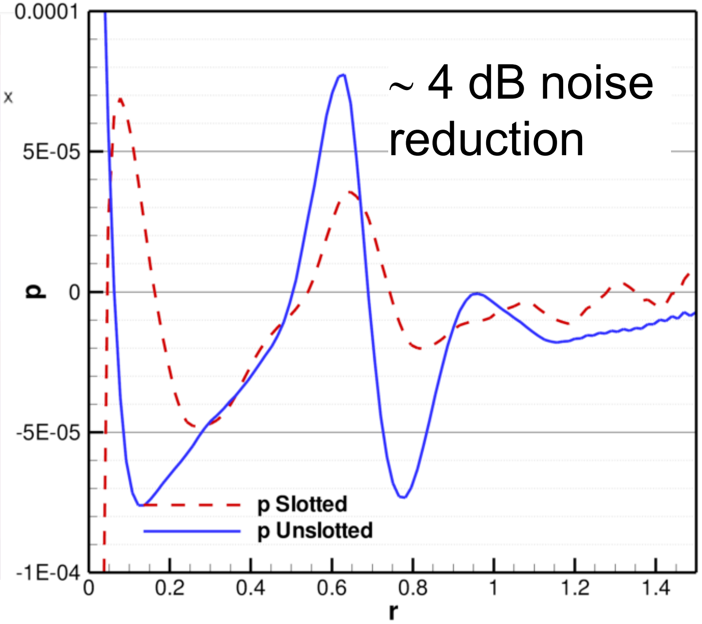


Basic principles: TE noise reduction
Slotted TEs

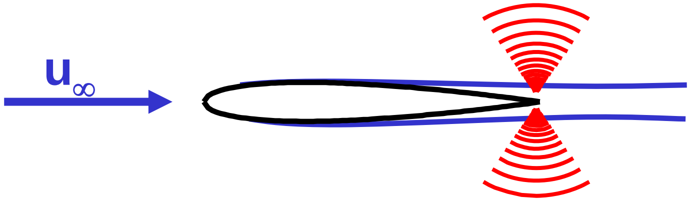
- CAA study on slotted TEs at a NACA0012:
  - Isolation of the edge enhancement contribution to noise/noise reduction





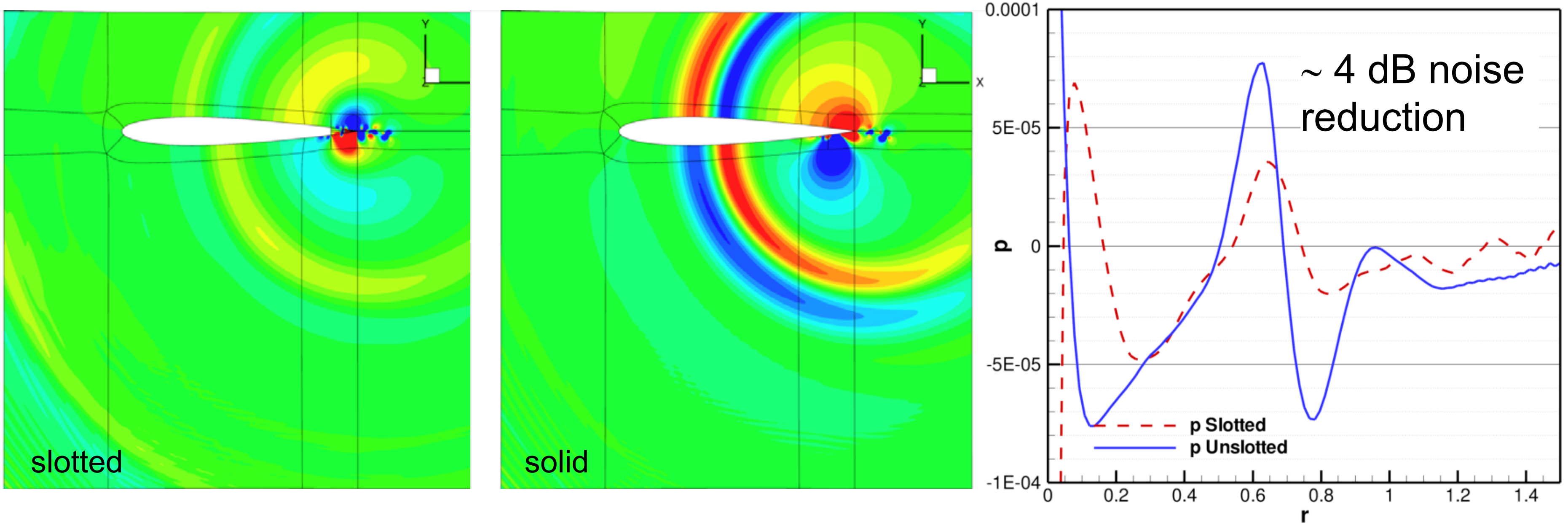


Source: Fassmann et al., DLR



Basic principles: TE noise reduction
Slotted TEs

- CAA study on slotted TEs at a NACA0012:
  - Isolation of the edge enhancement contribution to noise/noise reduction



Source: Fassmann et al., DLR

→ According to CFD results: modification of inflow turbulence (hydrodynamical absorption) not major mechanism

→ Currently under investigation: effect of acoustic absorption

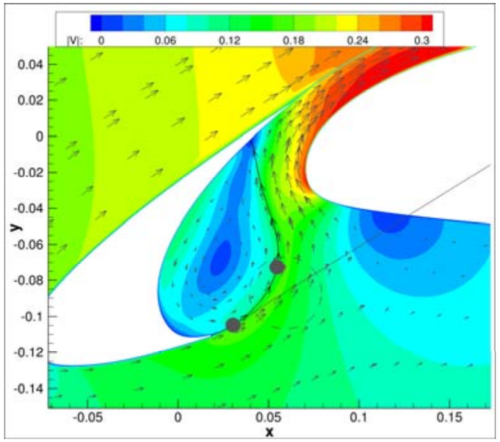
Basic principles: TE noise reduction
Synopsis

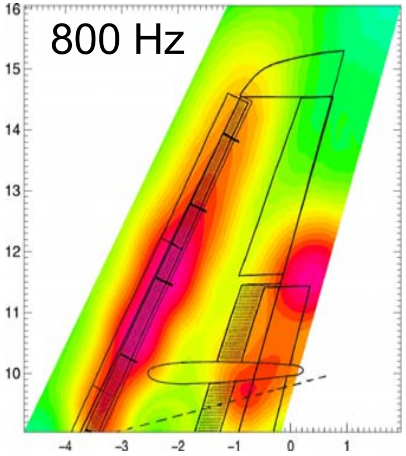
- A large noise reduction potential can be provided by flow-permeable TE modifications

- Main implementation issues: structural and system integration (retraction), material airworthiness and fixture, transfer of the gained knowledge (design rules and scaling laws for brushes) from generic test configurations to realistic HLD components (all relevant parameters included in empirical descriptions?)

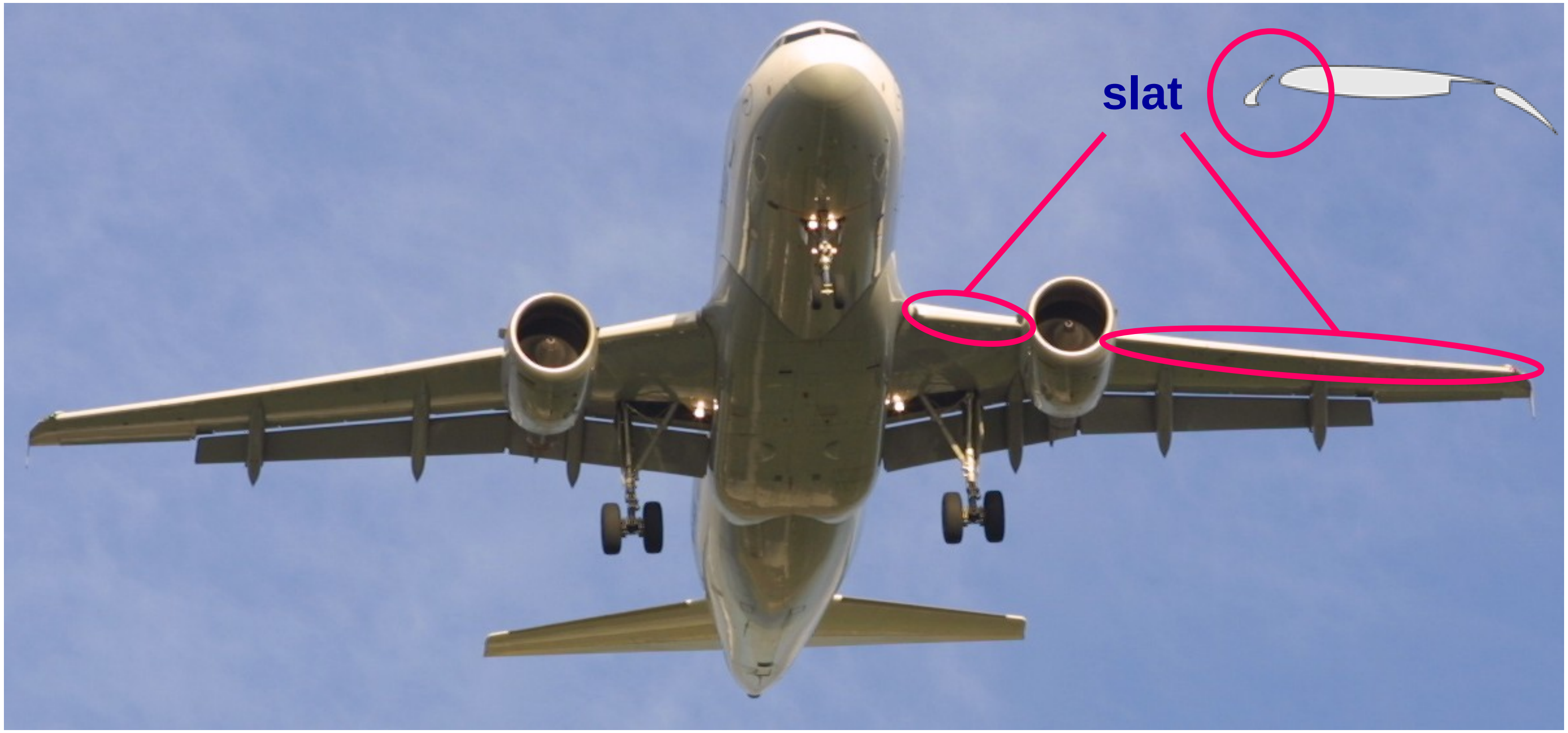
- Evaluation of airworthy & aeroacoustically efficient materials is subject of ongoing projects, in particular the further development of devices with anisotropic porosities

High-lift noise reduction

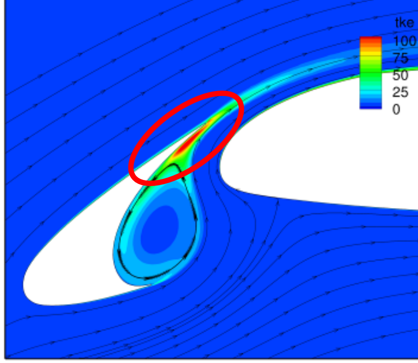




- ➢ Slat noise reduction



DLR



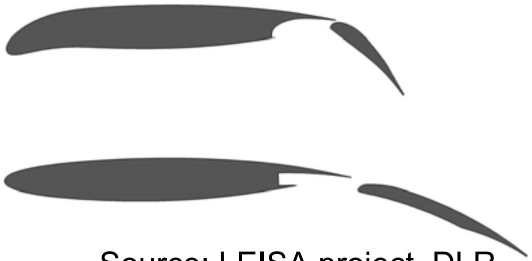
Slat noise reduction

- Slat noise dominates the total high-lift noise spectrum (this is known since 1995)

- Possible noise reduction mechanisms are:
    - Manipulations of the various slat noise generation mechanisms (e.g. of the TE noise/ flow impingement noise sources, …) with the following governing parameters:
        - TKE of slat cove shear layer flow
        - TE local flow speed/ mean pressure gradient
        - TE/ reattachment location boundary conditions
    - Provision of local sound attenuation (acoustic absorption)

Slat noise reduction
Technologies under development

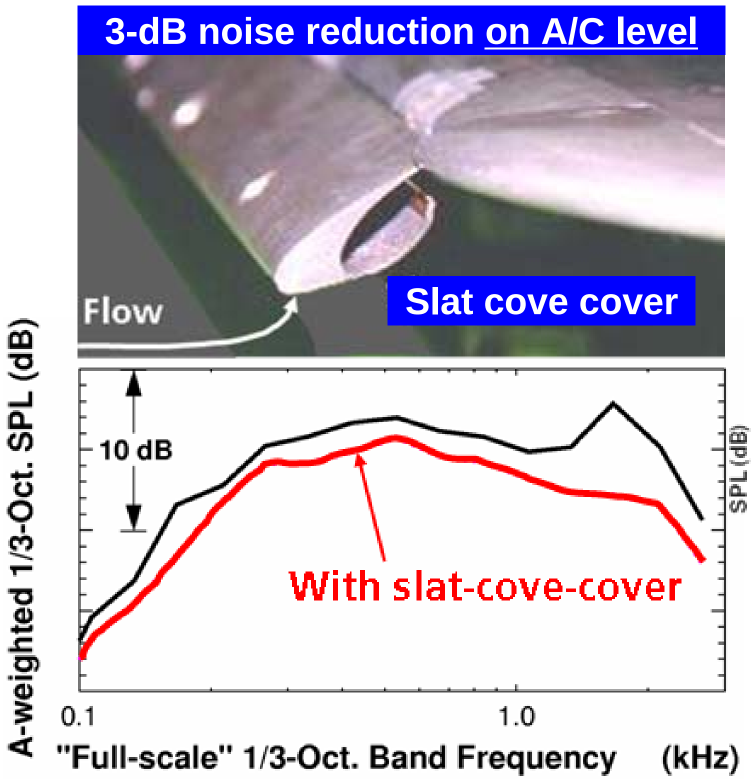
- Add-on treatments
  - Flow-permeable TE treatment: adaptation of aforementioned TE noise reduction technologies successfully tested at 2D profiles
  - Cusp treatment/alternative cusp designs → cove filler etc.
  - Slat cove liner technology
- Optimized slat gap/overlap settings and derivative technologies
  - Adaptive slat
  - Very long chord slat
- Alternative high-lift system architectures (extreme case: slot-/slatless configurations, droop nose devices) → new A/C architectures

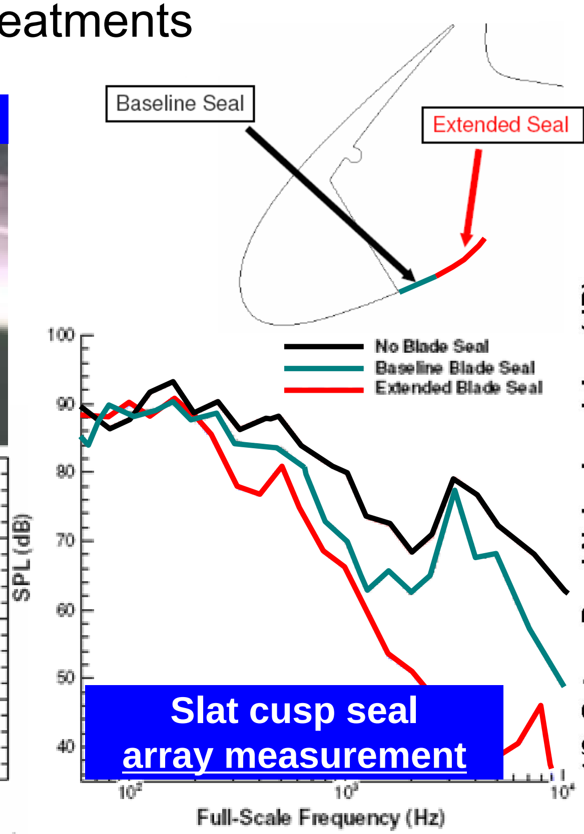


Source: LEISA project, DLR

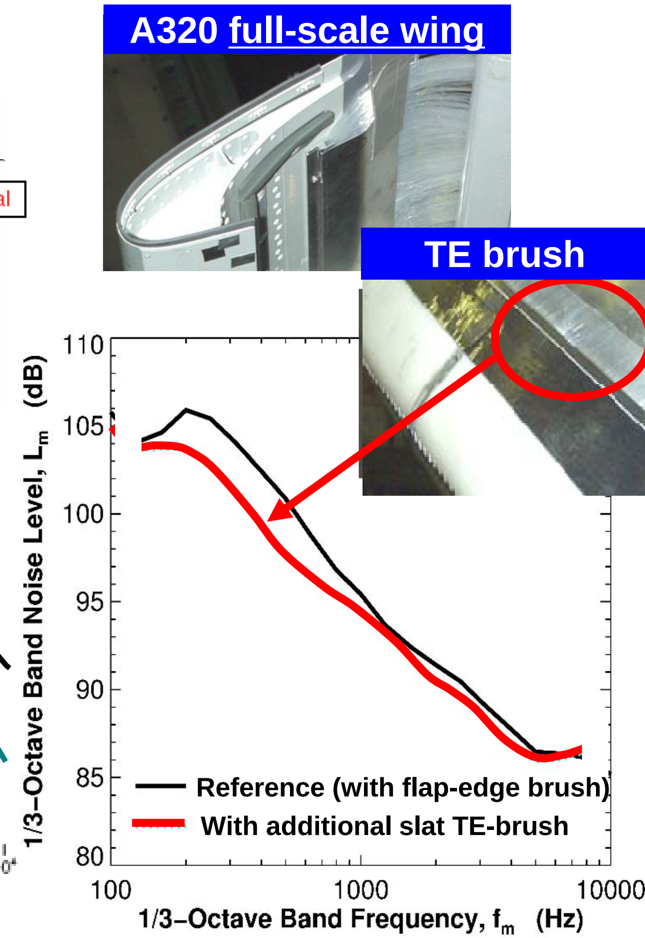
Slat noise reduction
Technologies under development

- Survey on add-on treatments



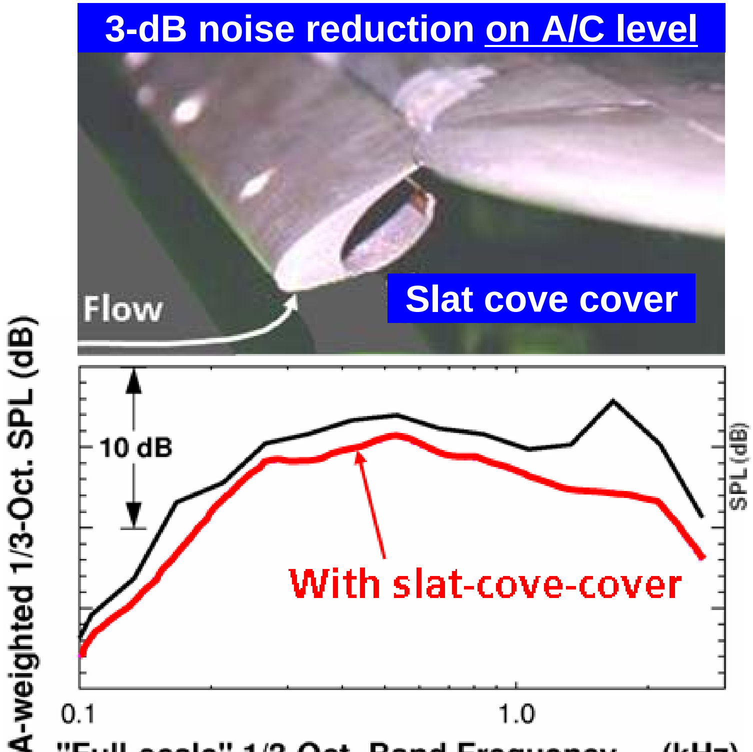


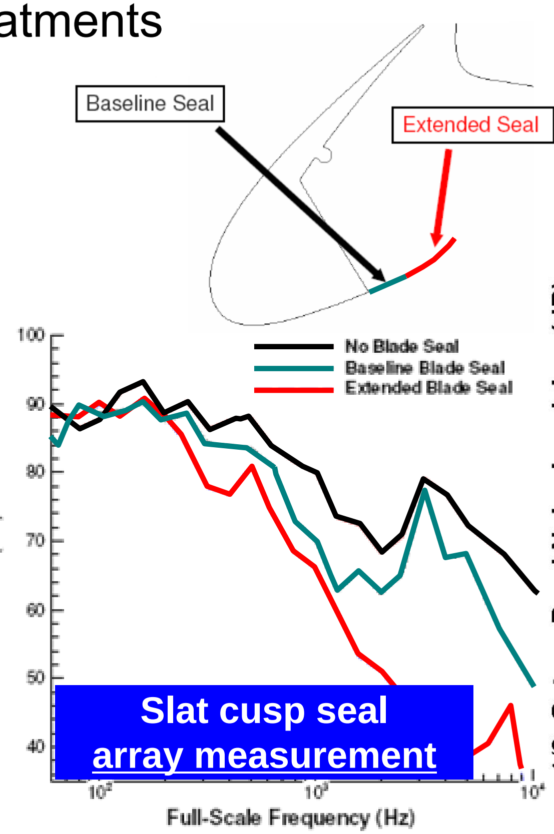
Source: Khorrami et al., NASA

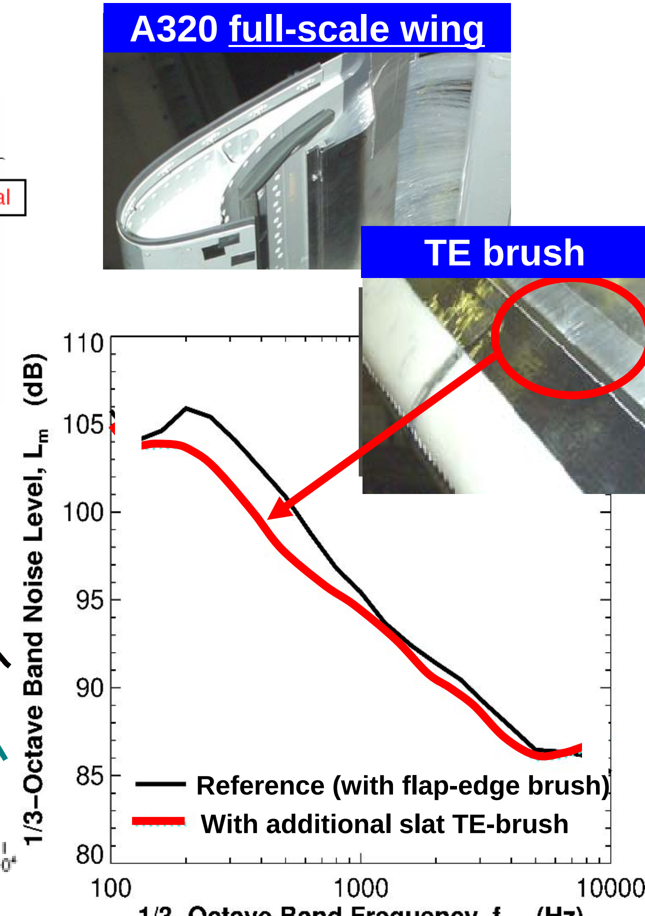


Slat noise reduction
Technologies under development

➢ Survey on add-on treatments





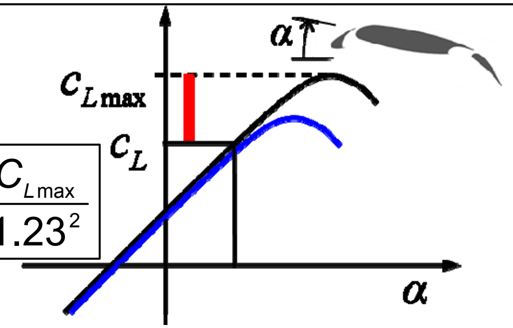


→ **Degradation of aerodynamical performance might be a 'show-stopper' for many ideas; certification requirement: C_{Lmax} determines lowest selectable approach speed, i.e. C_{Lmax} degradation might counterbalance achieved noise benefit…**

$$v_{(approach)} = 1.23\, v_{stall} = 1.23\sqrt{\frac{2mg}{\rho A C_{L\max}}}$$

Slat noise reduction
Airworthiness requirements

$$C_{L(approach)} = \frac{C_{L\max}}{1.23^2}$$

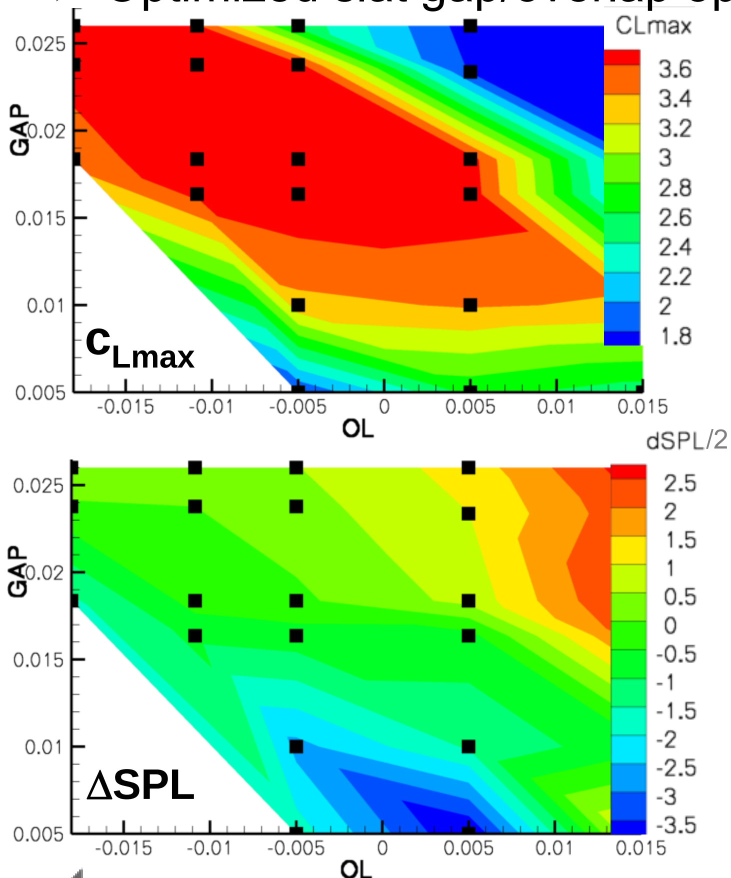


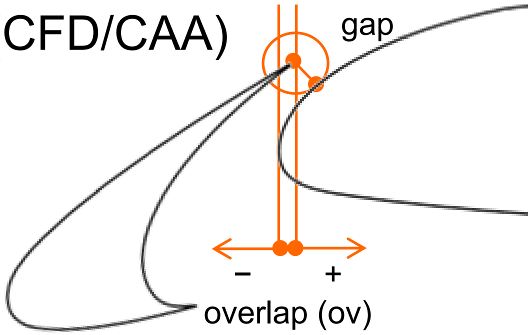
- Operational aspects:
  - Maximum lift determines landing speed
  - Sufficient lift for <u>moderate</u> angles-of-attack to prevent tail-strike for take-off
  - Low noise treatments must not affect cruise performance if not operational (retraction)
- Security aspects:
  - Reliability
  - No sudden lift/ moment changes through activation of control device
- Cost aspects:
  - Weight
  - Structural constraints (slat tracks affect front spar position, etc.)
  - Systems complexity (e.g. bleed air for flow control, etc.)
  - Maintenance (contamination, icing of noise red. treatments)

$u_\infty \sim C_{L\max}^{-1/2}$ with assumption: $\langle p^2 \rangle \sim u_\infty^5$:
→ 10 % less $C_{L\max}$ is about 5.4 % increase in landing speed = 1.1 dB noise increase!
→ Cost function: $\langle p^2 \rangle \sim C_{L\max}^{-5/2}$

Slat noise reduction
Technologies under development

➢ Optimized slat gap/overlap optimization (CFD/CAA)

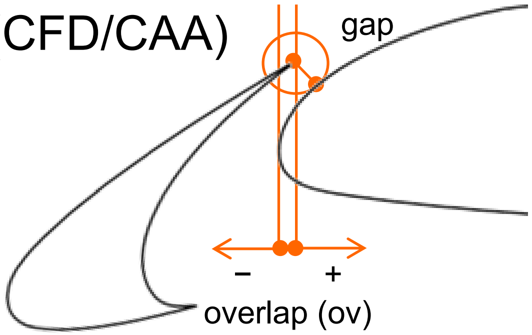




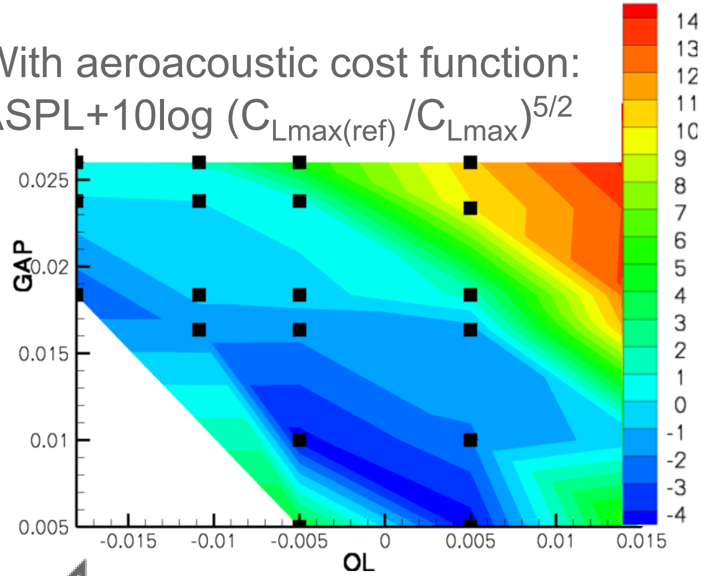
Source: TIMPAN project

Slat noise reduction
Technologies under development

- Optimized slat gap/overlap optimization (CFD/CAA)



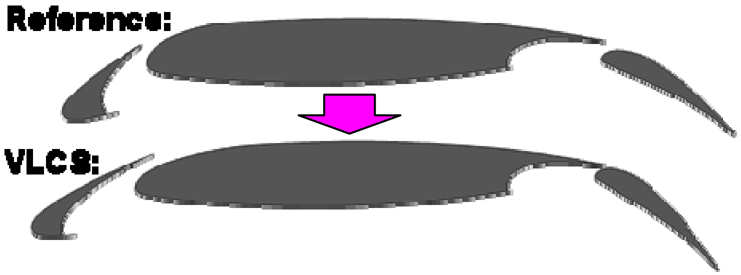
With aeroacoustic cost function:
$\Delta SPL + 10\log\left(C_{Lmax(ref)} / C_{Lmax}\right)^{5/2}$

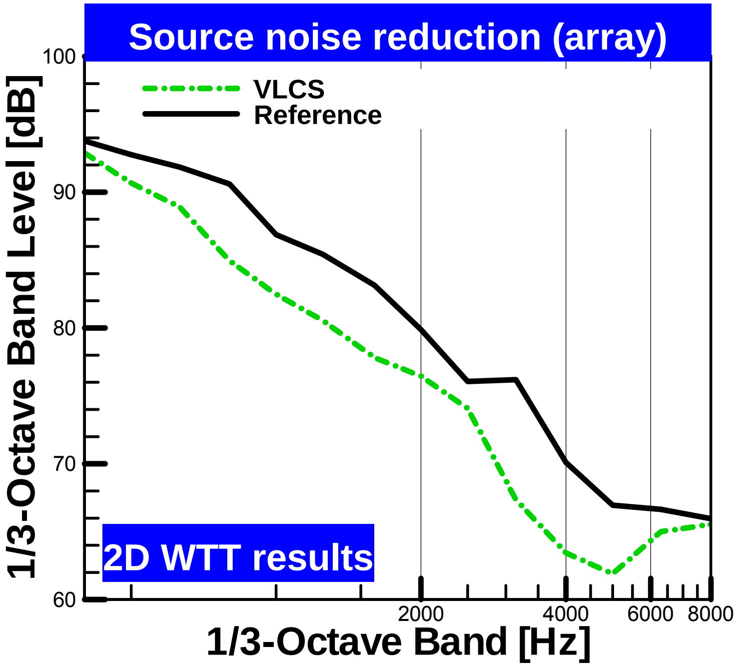


Source: TIMPAN project

Slat noise reduction
Technologies under development

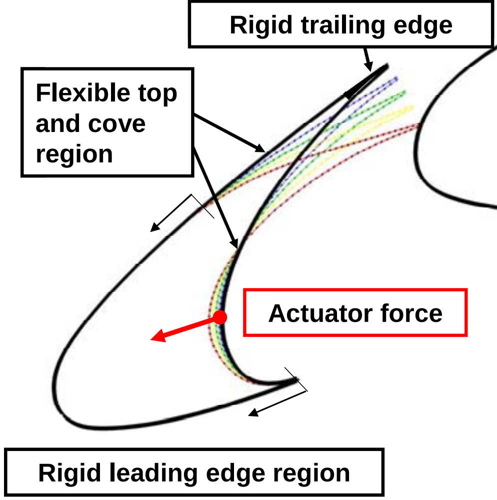
- Derivative 1: Very long chord slat (VLCS):
  - Reduced gap size and increased overlap
  - Reduced slat deflection angle with adapted flap deflection for constant aerodynamical performance



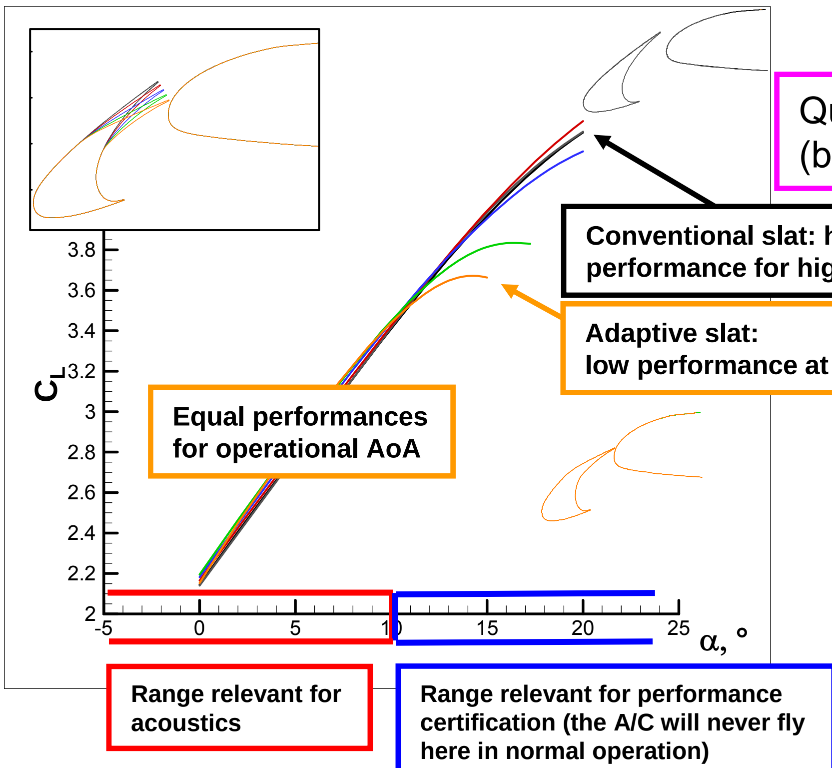


Source: LEISA project, DLR

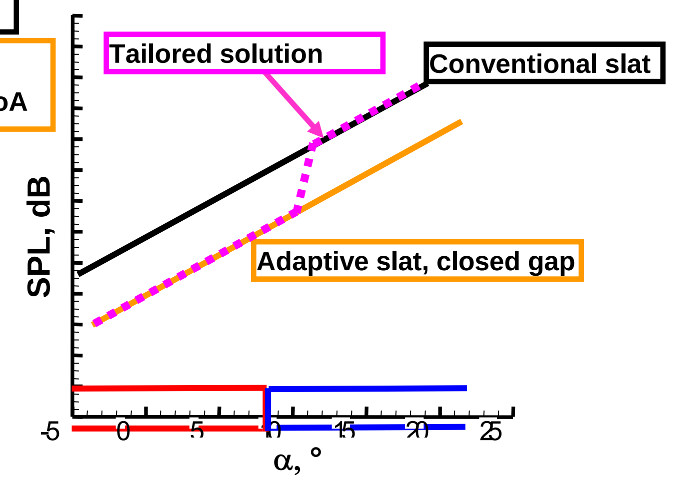
Slat noise reduction
Technologies under development



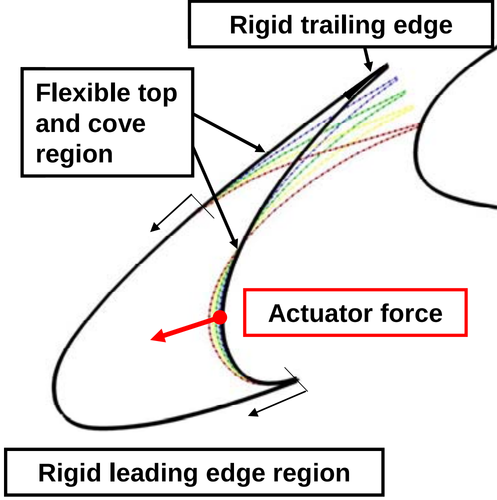
- Derivative 2: Adaptive slat
- Full elimination of slat noise for closed gap variation



Quiet for small α, high aerodynamic performance (but loud) where needed = tailored solution!



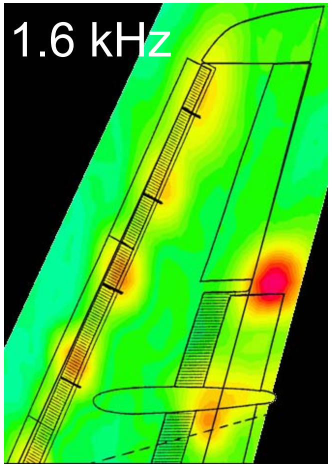
Source: OPENAIR project



Slat noise reduction
Technologies under development

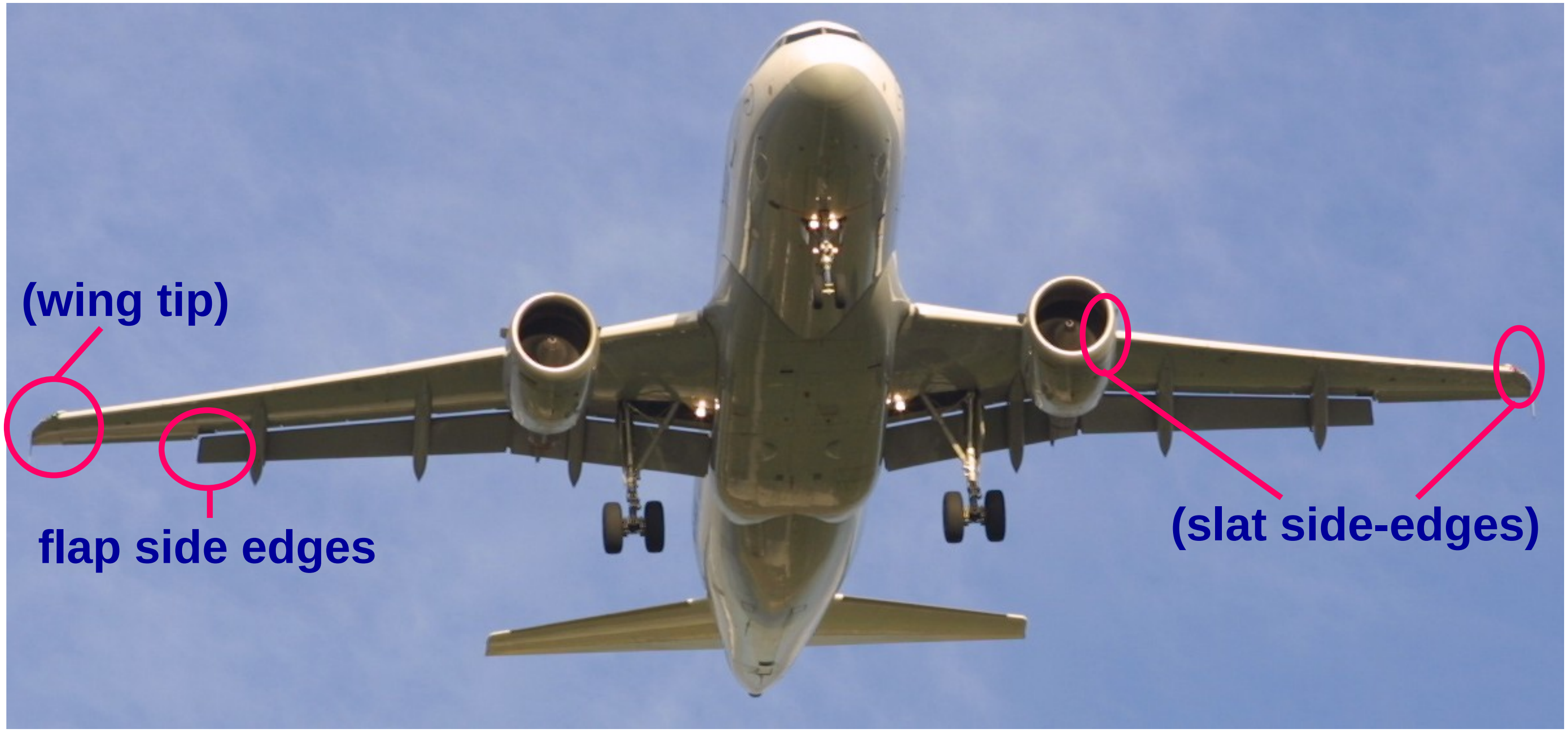
- Derivative 2: Adaptive slat
- Full elimination of slat noise for closed gap variation
- Specified airworthiness requirements
  - System must be safe: inactive system = original gap (C_{Lmax})
  - Must work for all possible load conditions
  - Limited impact on weight, complexity, flow
  - Extension time < 2 s

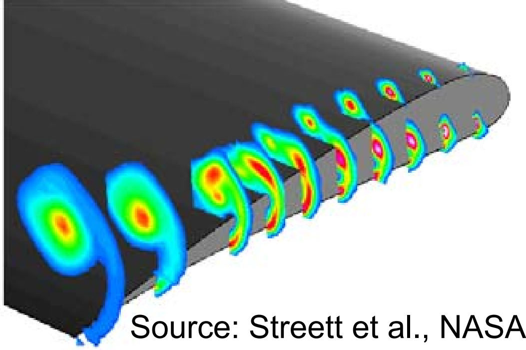
Source: OPENAIR project



High-lift noise reduction

- Flap side-edge noise reduction





Source: Streett et al., NASA

Flap side-edge (FSE) noise reduction

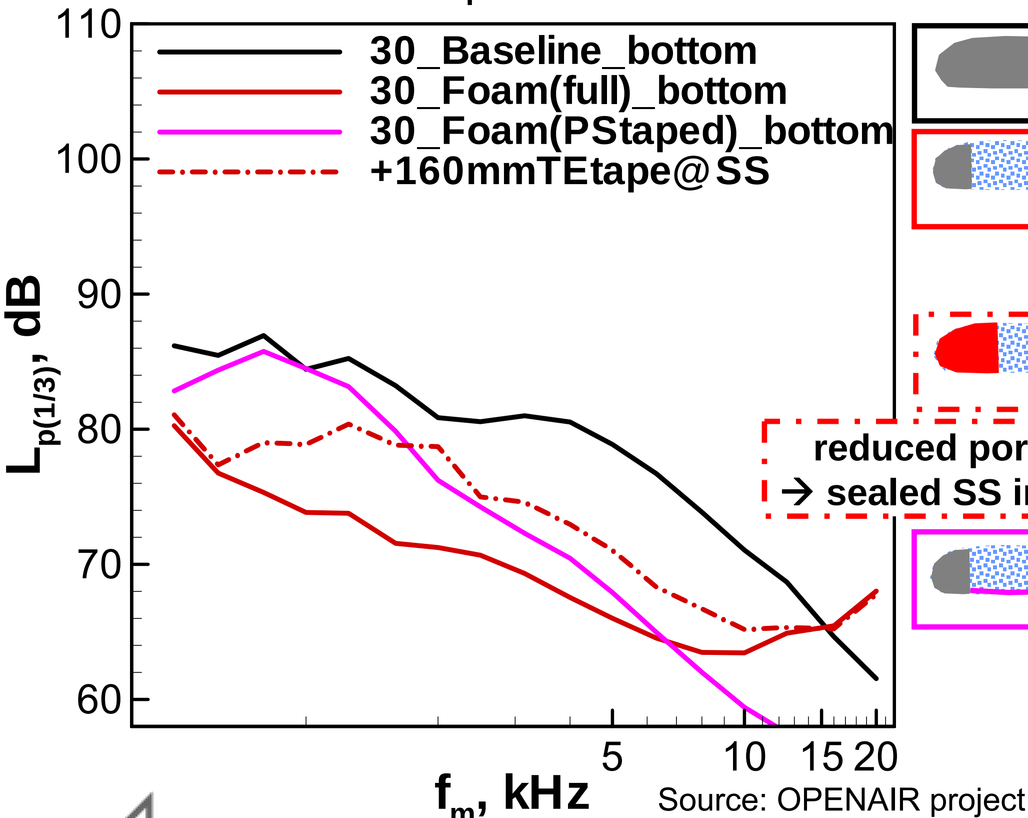
- For typical business jets the flaps + FSEs are the primary sources of airframe noise.

- Possible noise reduction approaches include:
  - Reduce vortex interaction with sharp edges
  - Remove/postpone vortex roll-up process at FSE, outboard/upwards shift of FSE vortex (enable more delocalized pressure release)
  - Reduction of the FSE cross flow velocity (increase of vortex diameter while keeping vortex strength)
  - Modification of the edge boundary condition

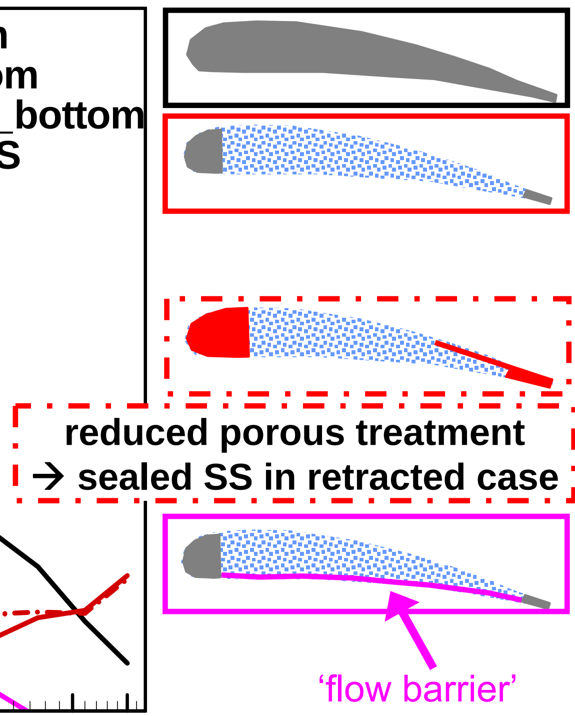
- Airworthiness requirements cf. slat

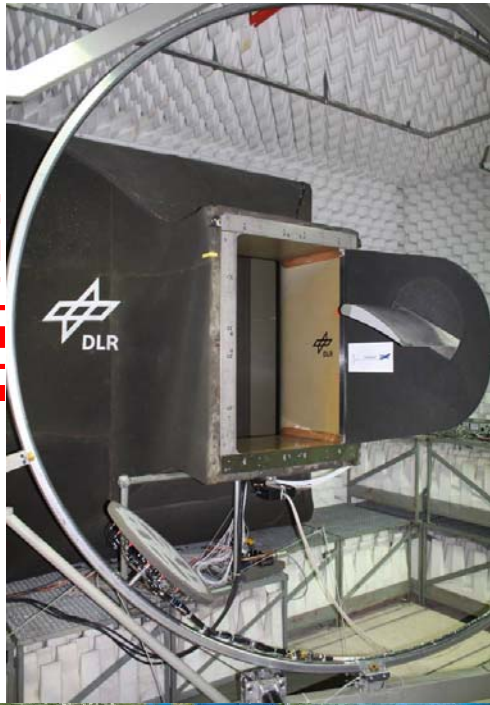
FSE noise reduction
Maximum noise reduction potential

- Basic side-edge noise reduction study in the AWB:
  - Extent of porous treatment vs. airworthiness



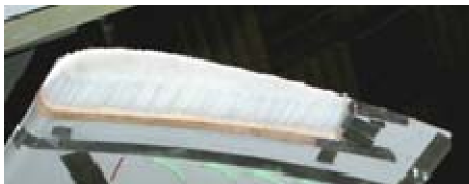
Source: OPENAIR project



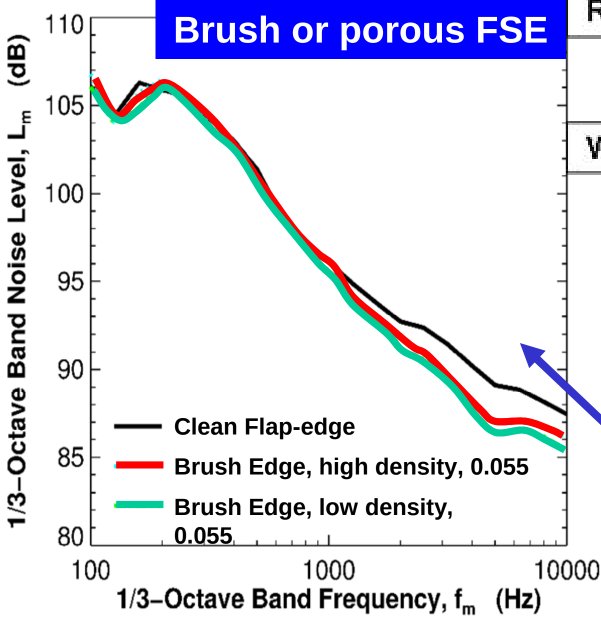


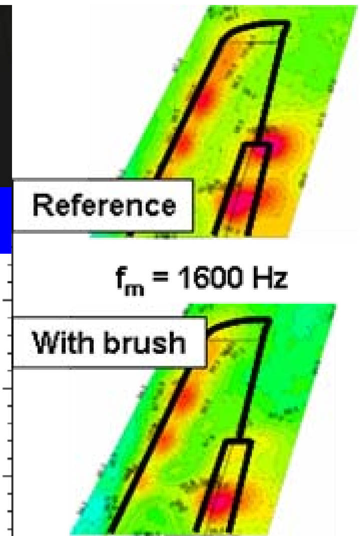
FSE noise reduction
Technologies under development

- Survey of different passive concepts:



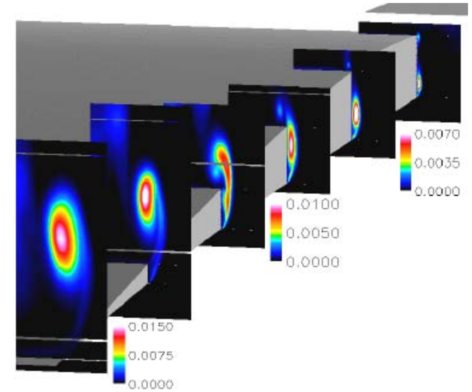
Brush or porous FSE



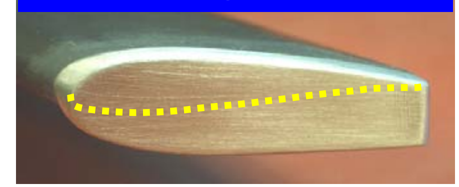


Full-scale A320 wing noise reduction (DNW-LLF)

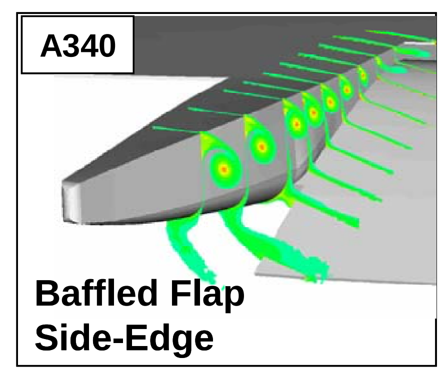
Source: Choudhari et. al., NASA



Side-edge fences



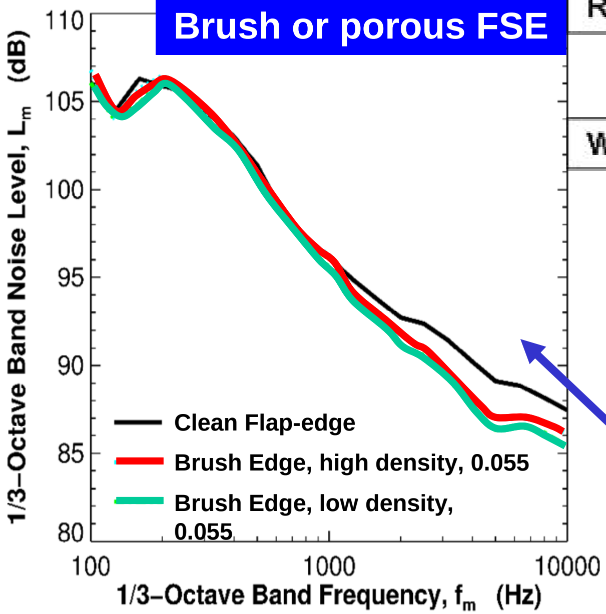
Fences provide some 2-3 dB source noise reduction

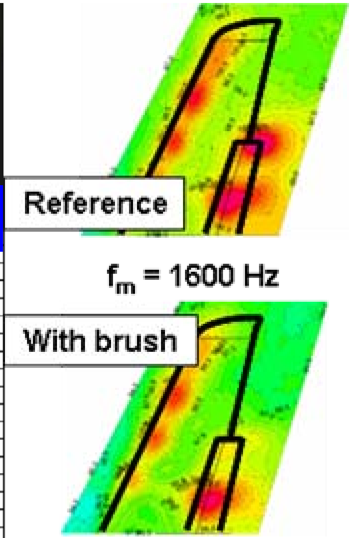


FSE noise reduction
Technologies under development

- Survey of different passive concepts:

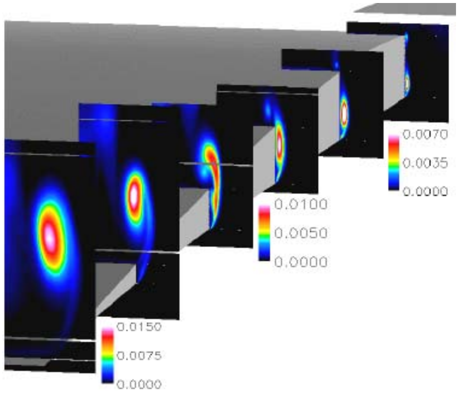
Brush or porous FSE



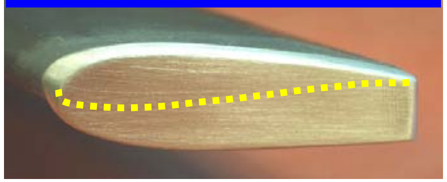


Full-scale A320 wing noise reduction (DNW-LLF)

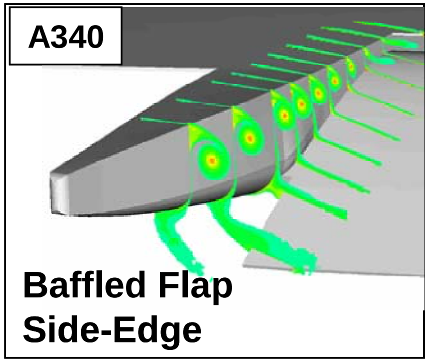
Source: Choudhari et. al., NASA



Side-edge fences



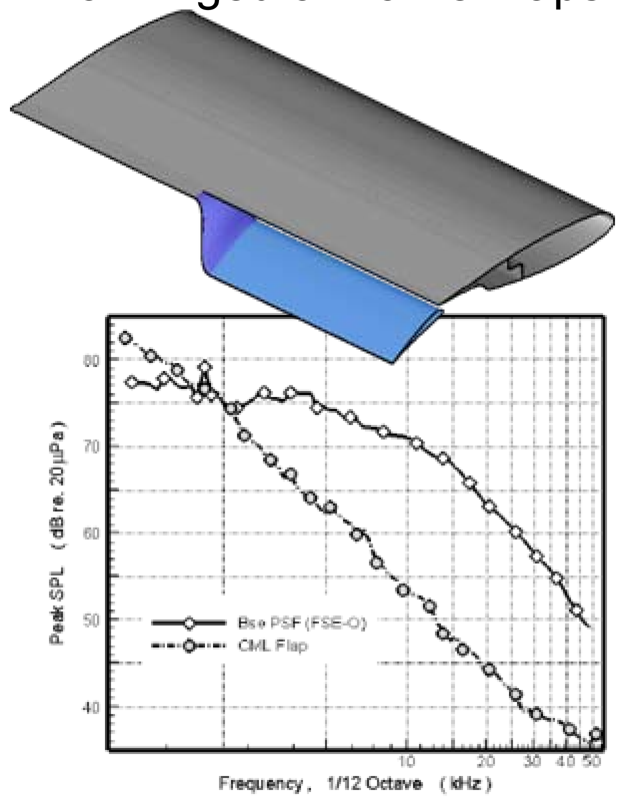
Fences provide some 2-3 dB source noise reduction



→ Airworthiness analysis of porous materials (foam and mesh) is subject of ongoing EC project OPENAIR.

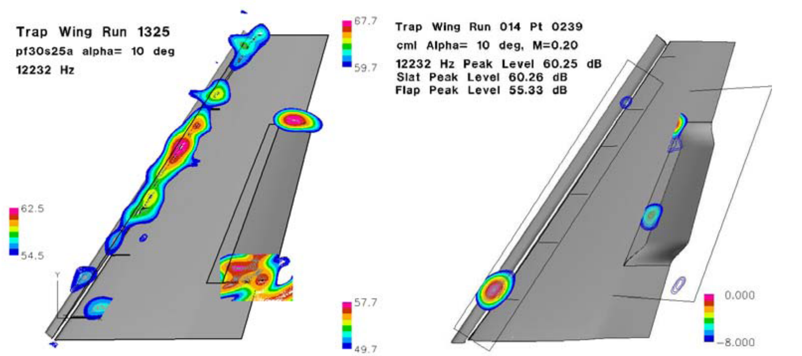
FSE noise reduction
Technologies under development

- ➢ Continuous mold-line links
  - for hinged or Fowler flaps



also applicable to slat side-edges

local source noise reduction: Baseline vs. moldline links + slat cove filler



Source: NASA

High-Lift Noise Reduction
Synopsis

- Compared to landing gears available HLD noise reduction technologies are on a much lower TRL; main implementation issues: potential effect on L/D, structural and system integration (retraction, mechanical links, materials), potential impact on stability and control.

- Promising noise reduction technologies have been identified and validated but need further analysis.

- Actually, HLD source noise reduction through add-on means for conventional slats or FSEs is still limited to < 1 EPNdB and often suffers from a degradation in maximum lift.

Note: New configuration design requires strong application of validated CFD and CAA tools.

Summary of achievements and future needs
State of the art

- Airframe noise reduction features on recent A/C products:
  - Novel component architectures:
    - High-lift systems: Implementation of <u>droop nose devices</u> as low-noise compromise to slotted slats on <u>inboard wing of A380</u> (development time ~1990-2005)

Source: AIRBUS Operations S.A.S.

Summary of achievements and future needs
State of the art

- Airframe noise reduction features on recent A/C products:
  - Novel component architectures:
    - High-lift systems: Implementation of <u>droop nose devices</u> as low-noise compromise to slotted slats on <u>inboard wing of A380</u> (development time ~1990-2005)
    - Landing gear design: optimization of gear/wheel number and size combination, bogie tilt angle, lower exposure of dressings to high speed flows
  - Prevention of parasitic noise sources
    - Hole covering/ re-design

Summary of achievements and future needs
State of the art

- Airframe noise reduction features on recent A/C products:
  - Novel component architectures:
    - High-lift systems: Implementation of droop nose devices as low-noise compromise to slotted slats on inboard wing of A380 (development time ~1990-2005)
    - Landing gear design: optimization of gear/wheel number and size combination, bogie tilt angle, lower exposure of dressings to high speed flows
  - Prevention of parasitic noise sources
    - Hole covering/ re-design

→ Noise consideration at overall airplane design level and some limited noise component design features

→ But: Most of the reported component noise reduction technologies are on a too low TRL or induce too significant penalties to be efficiently integrated on new A/C

Summary of achievements and future needs
Near- to mid-term realizable gains at component level

- Landing gear noise reduction
  - Fairings and caps (high TRL): ~5 EPNdB (based on WTT, flight test: ~2 EPNdB); main implementation issue: weight, heat dissipation, maintenance access
  - Low-noise design (medium TRL): ~5 EPNdB; main implementation issue: structural and system integration

- Slotted slat noise reduction
  - Low-noise design/treatment (low TRL): ??? (actually < 1 EPNdB); main implementation issue: potential impact on L/D, retraction, structural and system integration, airworthiness of materials

- Flap side-edge noise reduction
  - Low-noise design/treatment (low to medium TRL): ???; main implementation issue: potential impact on L/D, stability & control, airworthiness of materials

Summary of achievements and future needs
Future needs

- Implementation to future product (mid term) with full noise benefit will require further design optimization
  - development and validation of efficient evaluation and design tools (CFD-CAA)
  - significant integrated demonstration efforts

Acknowledgments

The author wishes to thank

- Dr. Roland Ewert, Michael Pott-Pollenske & Anton Rudenko, DLR
- Dr. Alexander Büscher, Hendrik Friedel, Eléonore Ammeux, Airbus Operations GmbH/S.A.S
- Dr. Johann Reichenberger, EADS Innovation Works
- Nicolas Réau, Dassault Aviation

for their valuable support in providing relevant picture and data material from past and ongoing projects.

Special thanks are due to my former (now retired) colleague and mentor

- Dr. Werner Dobrzynski, DLR

for leaving permission to use his comprehensive lecture and documentation material. A valuable set of information has been taken from the well-documented airframe noise survey in Dobrzynski, W. (2010): “Almost 40 Years of Airframe Noise Research – What Did we Achieve?”, Journal of the Acoustic Society of America, 47 (2): 353-367.

Thank you for your attention!