Almost 40 Years of Airframe Noise Research – What did we achieve?

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This informative talk focuses on experimental and applied research in airframe noise and is an attempt to subsume related activities worldwide without claiming to be complete.

European “Visions 2020”:
Reduce noise impact by one half per operation relative to 2000 technology.

United States Noise Reduction Goals:
Reduce perceived noise impact of future aircraft by one half relative to 1997 technology within 10 years (AST and QAT Program) and by three quarters (-20 dB) within 25 Years!

Note: Reduction by one half is -10 dB “subjectively”, corresponds to -90% in sound power.
Why are we Interested in Airframe Noise?

Airframe noise is generated through the interaction of turbulent flows with solid bodies, e.g. landing gears and lifting surfaces.

- With the introduction of high-bypass ratio engines around 1970 (for fuel saving!) a significant reduction in jet noise was achieved.
- As a result airframe noise became relevant in the approach phase, where engines are throttled down.
- Substantial research efforts into airframe noise started after 1970.

1st generation engines

B707

A380

2nd generation engines
Overall Aircraft Noise Ranking at Approach

Aircraft Noise Source Breakdown:

**APPROACH (long range aircraft)**

- Slats
- Flaps
- Landing Gear
- Airframe
- Engine
- Total

**APPROACH (short range aircraft)**

- Slats
- Flaps
- Landing Gear
- Airframe
- Engine
- Total

Source: Airbus
Airframe noise was first identified as a lower “aircraft noise barrier” in the early 70ies.

Main objectives were to quantify airframe noise levels through dedicated flyover noise tests ranging from gliders to the Galaxy aircraft.

Fink developed a first “Airframe noise prediction method” essentially based on this data (1977).

Already at that time fundamental noise reduction concepts were invented and wind tunnel tested on generic models.

Between about 1980 to 1990 the interest in airframe noise temporarily decreased (due to the first fuel crisis).

From 1990 up to now airframe noise reduction again is a matter of prime interest.
History of Noise Reduction Technologies

Based on theoretical work in aeroacoustics in the 60ies, already from 1975 on most of the basic noise reduction technologies were invented:

- **Trailing edge/ slat noise**
  - porous edge extensions (Bohn, 1976)
  - perforated edge extensions and edge serrations (Grosche, 1979 and Fink, et. al 1980)

- **Flap noise**
  - porous leading edge inserts (Fink, et. al 1980)

- **Side-edge noise**
  - porous edge replacements (Fink, et. al 1980, and later Revell, et. al 1997)

More current developments are:

- **Trailing edge/ slat noise**
  - TE-brushes
  - slat cove cover; -filler; -liner

- **Flap side-edge noise**
  - side-edge fences, -brushes, -porous inserts

- **Landing gear noise**
  - application of streamlined fairings
Major Sources of Airframe Noise

Dominating sources at current aircraft:
- Landing gears
- Slotted slat
- Flap side-edges and slat side-edges including cavities
- Flap/slat tracks and slat track cut-outs
- Spoilers
- Gear-wake/flap interaction

In addition to “classical” edge noise sources, on real aircraft structures numerous parasitic sources of excess noise can be detected.
Parasitic Airframe Noise Sources – Landing Gears

Tone noise from pin-holes:

Tones originate from flow excited resonances in different pin holes.

Parasitic tone noise can easily be avoided by pin-hole covers, but such means are not popular due to water condensation problems.
Parasitic Airframe Noise Sources – Wing Systems

- Tone noise from fuel vents or anti-ice vents
- Broadband noise from slat track cut-outs
- Broadband noise from flap side-edge cavities

A320 Slat-track cut-outs:

A320 Flap edge cavity

Example: MD-11
Second Order Airframe Noise Sources

Airframe noise sources of minor importance:

- **Wing tip noise** *(seldom identified in source location plots due to other prominent sources)*

- Noise from “infinitely extended” surfaces (e.g. fuselage) is expected to be more than 10 dB below current high-lift noise levels (i.e. below clean aircraft trailing edge noise), this is
  - boundary layer noise including roughness effects
  - **noise from surface vibration** *(low radiation efficiency due to impedance mismatch between wall material and air)*

- **Free wake turbulence** *(quadrupole noise is insignificant for M < 0.2)*

- **Tonal vortex shedding noise from smooth circular landing gear struts** *(seldom observed for high flight Reynolds numbers)*
Landing Gear Noise – Problem Definition

- More than 10 dB reduction demonstrated for **not practical** complete aerodynamic fairing
- Future efforts needed to realise noise reduction of similar order of magnitude under practical constraints

First full scale LG test in 1995:
A320 Main Gear in German-Dutch Wind Tunnel
Landing Gear Noise - Source Mechanisms

Landing gears represent a 3D cluster of noise sources:

- Broadband noise from turbulent vortex shedding off struts
- Turbulent wake-flow / solid body interaction between components
- Broadband noise from gear bay free shear layer interaction with downstream bay rim

Landing gear noise

- Scales on a Strouhal number basis
- Increases with velocity to the 6th power (dipole type source) and
- Features an almost omnidirectional radiation characteristic
Landing Gear Low Noise Design - Constraints

- **Operation**
  - Limitation of runway loads defines number of wheels and spacing
  - Gear locations defined by lateral stability and rotation before lift-off (local velocity at gear position for under wing installation)
  - Brake cooling (fairings which would delay cooling increase the turn around time on airport)

- **Safety**
  - Free fall requirement (MLG leg door can not be used as spoiler)
  - Tyre burst (location and redundancy of dressings)

- **Cost**
  - Weight
  - Effect on airframe (minimum bay size for stowing)
  - Systems complexity (articulated components)
  - Maintenance (fairings obstruct quick inspection, contamination)
Landing Gear Noise – **Baseline WT-Studies**

Baseline full scale or close to full scale LG tests

**Boeing Low Speed Aeroacoustic Facility**

**NASA Langley Quiet Flow Facility**
Landing Gear Noise – Add-on Fairing Design

Flight testing of landing gear fairings:
- 2 EPNdB achieved on total A340 landing gear source noise

Farfield wall mounted microphones

A340 fairings manufactured to airworthiness requirements

Airbus NLG and MLG Fairings

Herkes, et. al. / AIAA 2006-2720

Flight testing of landing gear fairings:
- 2 EPNdB achieved on total A340 landing gear source noise

Boeing MLG Fairings
Cloth fairings promised an additional 2 dB in noise reduction compared to solid fairings.

Source: Ravetta, et. al. / AIAA 2007-3466
Landing Gear Noise – **Advanced Low Noise Design**

Iterative design process for low noise gears based on experimental experience with support from CFD calculations:

- Design with support from CFD computation
- Full scale mock-up wind tunnel test
- Test result: 5 to 7 dB(A) noise reduction
- In-flight prediction: - 4.1 EPNdB on LG-level
Landing Gear Noise - Prediction Tools

Empirical and Semi Empirical Tools:

- **Fink (NASA ANNOP)** (empirical tool scaled from early DLR scale model data)
- **DLR** (empirical tool re full scale wind tunnel data by Dobrzynski)
- **ISVR** (semi empirical tool by Smith)
- **Boeing** (semi empirical tool by Guo)

Semi empirical tool concepts:

- Superposition of noise contribution from individual components
- Account for small details through “complexity” or “dressing” factor (governs high frequency levels)

CFD/CAA approaches with design to noise capabilities:

- LES/ DES calculations and FW-H for **simplified gear geometries** only (not really convincing results yet)
Challenges in HLD noise testing in comparison with LG experiments:

- Testing of complete wing systems mostly performed at small scale (i.e. 1/4 up to 1/11) due to lack of sufficiently large anechoic facilities.

- Accordingly results suffer from:
  - Reynolds number effects (tone noise)
  - Components can not always be manufactured to scale (trailing edge thickness, track design)

- Basic investigations in 2D (i.e. no sweep) need validation in 3D (cross flow)

- Wing downwash causes inaccurate aerodynamic conditions in open test sections for measurement of farfield noise directivity
High-Lift Devices Noise Sources

For the same speed (!) noise from high-lift devices in landing configuration is about 10 dB higher compared to the same aircraft in “clean” conf. (cruise).

Major HLD noise sources are:
- Slotted slats
- Slat tracks (oblique to inflow)
- Slat horn
- Flap side-edges
- Flap tracks

Source: Oerlemans / NLR
High-Lift Slotted Slats - Noise Mechanisms

Source: Choudhari, et.al. / NASA Langley

Potential source mechanisms:
- Free shear layer vortex flow reattachment
- Trailing edge (bluntness tone noise only relevant at model scale !)
- Unsteadiness of vortex core

Analytical and CFD/CAA studies provided insight in major slat noise mechanisms.

PIV Measurements:
Vorticity field

Potential source mechanisms:
- Vorticity field
- Trailing edge
- Free shear layer vortex flow reattachment
- Unsteadiness of vortex core
High-Lift Slat Noise – Sources of Tone Noise

Tone phenomena for scale model testing:

- Low frequency tone effects due to “cavity resonances” (Rossiter modes?) (to be reduced by tripping on pressure side)
- High frequency tone effects due to Tollmien-Schlichting instability (to be avoided by tripping on suction side)

Source: Oerlemans / NLR
Farfield noise test results at a 1/7.5 scaled A320 model and a full scale A320 wing section indicate that

- **Slat noise** dominates the total high lift noise spectrum
- **Slat noise scales with the 4.5th power of flight speed** and wetted span (SF) vs a Strouhal number, based on slat dimension
- **Slat noise slightly decreases** with increased angle-of-attack (low $\alpha$-range)
- **Slat noise radiation is highest in the rear arc.**
High-Lift Devices - Slat Noise $\rightarrow \alpha$ - Effect

1/10.6 scaled A340 Model in DNW-LLF: $\varphi = \varphi_m + \alpha = 103^\circ$

- Only little effect on slat noise of moderate “landing” angles-of-attack, i.e. $\alpha < 10^\circ$
- Significant noise increase for $\alpha > 13^\circ$
Stochastic broadband approach
“Low cost CAA”

- CFD: Steady RANS
- Mean-flow
- CAA based Sound Propagation (time domain)
- Acoustic farfield
- RPM(*): Stochastic model for turbulent fluctuations (time domain)

(*) RPM: Random Particle-Mesh method, in press Comp. & Fluids

APE = Acoustic Perturbation Equation
TKE = Turbulence kinetic energy
RPM = Random particle mesh

TKE RANS target
Turbulence source terms
TKE from RPM Reconstruction

Local length scale / turb. kinetic energy / anisotropy

Stochastic model
Unsteady vortex/entropy sound sources

Time averaged turbulent flow problem
Stationary turbulent properties:

Frequency
Sound Pressure Level / dB
5 kHz 10

Narrow Band Spectra

Simulation (PIANO)
Exp. (EADS-IW AWB)
High-Lift Devices Low Noise Design – Constraints

- **Operation**
  - Maximum lift *(determines landing speed)* → 10 % less $C_{L_{\text{max}}}$ is about 5.4 % increase in landing speed = 1.4 dB noise increase !
  - Sufficient lift for moderate angles-of-attack to prevent tail-strike for take-off

- **Safety**
  - Reliability *(low noise treatments must not affect performance if not operational)*
  - No sudden lift/ moment changes through activation of control device

- **Cost**
  - 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)*
High-Lift Devices – Slat Noise Reduction

3 dB noise reduction through slat-cove-cover

Flow

Slat-cove-cover

Source: Khorrami, et.al. / NASA Langley

With extended blade seal
High-Lift Devices – Slat Noise Reduction

Slat noise reduction through cove filler:

- Predicted with CFD/CAA
- Validated by experiments of different research groups (i.e. DLR, EADS-IW, NASA and JAXA),
- But noise reduction found to be extremely sensitive re filler contour.

Source: Horne, et.al. / NASA Ames
High-Lift Devices – Slat Noise Reduction

A320 Full Scale and Model Scale Tests:

- Slat trailing edge brushes are effective for noise reduction but installation is sensitive re $C_{L_{\text{max}}}$ degradation (!)
- In contrast slat trailing edge serrations showed a slight noise increase
High-Lift Devices – Low Noise Slat Design

Noise reduction to be achieved through

- reduced gap size and increased overlap
- reduced slat deflection angle with adapted flap deflection
- for constant aerodynamic performance

Source noise reduction (array):

\[ \Delta C_L \approx 4 \text{ dB} \]
High-Lift Devices – Flap Side-edge Noise Reduction

Source: Choudhari, et. al., NASA Langley

Side-edge Fences:

Fences provide some 2-3 dB source noise reduction

A340

Baffled Flap Side-Edge

Brush- or porous edge:

Full wing noise reduction

Local source noise reduction

Moldline Techno. for hinged or Fowler flap

Source: NASA
Spoilers can be applied to enable steep noise abatement approach procedures and to contribute to wake vortex alleviation.

- Conventional spoilers are sources of low frequency noise, but spoiler source noise mechanisms are still not known in detail (edge noise, wake flap interaction noise?)

- Note: Spoiler deflection affects wing circulation and in turn slat noise!!
Interaction Noise Sources – Gear wake/ Flap

Problem:

Parametric wind tunnel study on 1/10 scaled wing-gear model:

- Wake flow measurements
- Interaction noise measurements
- Result: up to 10 dB source noise increase at low frequencies
- 2 dB high-lift devices noise reduction through porous flap LE liner

![Diagram showing noise reduction](image-url)
To answer the question: What did we achieve?

- Detailed insight in noise source mechanisms but still no sound knowledge of all noise generation parameters for complex 3D sources
- Computational Aeroacoustics (CAA) methods have developed rapidly and promise to enable a design-to-noise of airframe components in the future
- Landing gear source noise reduction of up to 5 EPNdB has been demonstrated for future low noise gear designs
- High-lift devices source noise reduction is still limited to less than 1 EPNdB (through add-on means for conventional slats) and often suffers from a degradation in maximum lift
- Low noise slat designs (for constant aerod. performance !) were identified but need validation in 3D
- Flap side-edge low noise modifications were identified and validated
Status and Future Needs

Status of Airframe noise reduction:

- Airframe noise reduction achievements still need further improvement to cope with the European “Vision 2020” and the even more stringent US noise reduction goals.
- While LG noise reduction is on a good track high-lift devices noise reduction needs more attention in particular with respect to maintain aerodynamic performance.

Future needs:

- Focussed efforts to develop CAA tools for 3D application in the industrial design chain.
- Flow separation control technologies must be developed for both gear structures and slat-less high-lift devices.

In long terms new aircraft configurations are needed, which feature short landing gears and enhanced lift capabilities for reduced approach speed.
Thank you for your attention!