Airframe related aeroacoustics of transport aircraft
–research into prediction and reduction of sound radiation–

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Jan Delfs
DLR – German Aerospace Center
Institute of Aerodynamics and Flow Technology
Technical Acoustics – AS-TEA
Braunschweig, Germany
jan.delfs@dlr.de
DLR
German Aerospace Center

- Research Institution for Aeronautics, Space, Transport, Energy
- Space Agency
- Project Management Agency
**Tools**

**Prediction & Design**
- component sound generation & propagation:
  - TAU
  - FRPM
  - PIANO/DISCO++
  - APSIM+

- complete a/c acoustic installation: FM-BEM
- complete a/c airframe noise estimation: semi-empirical

**Testing & Validation**
- acoustic wind tunnels (AWB, NWB, LLF, …)
- flyover testing (A320 ATRA, G550 HALO, …)
Outline

- Introduction - definition of topic
- Airframe related aircraft noise
- conclusions
- outlook
Introduction
"Classical" sources of exterior noise at aircraft

- jet
- flap side edge
- main landing gears
- nose landing gear
- slat horn
- slat/ slat tracks
- fan
- compressor
- combustion
- flap/ flap tracks
- jet
Typical rank ordering of sources at approach

| Source: Airbus |

**Short range aircraft**

<table>
<thead>
<tr>
<th>Slats</th>
<th>Flaps</th>
<th>Landing Gear</th>
<th>Airframe</th>
<th>Engine</th>
<th>Total</th>
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**Long range aircraft**

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- **Airframe noise**

B 747

© Airliners.net

A340

© Airliners.net

© Spiegel.de
Airframe related aircraft noise

1. Airframe (component) noise
   - generation of sound due to (turbulent) flow past airframe components „noise of an aircraft flying at engines off“

2. Source installation effects (exterior + interior noise)

3. Acoustic installation effects (exterior + interior noise)
"Classical" sources of airframe noise at aircraft

- flap side edge
- main landing gears
- nose landing gear
- slat
- flap
- slat horn

"parasitic sources" (construction details)
Parasitic sources at real a/c airframes

- Tone noise from pin-holes in landing gear pins/bolts (hollow for weight reasons)
- Tone noise from pressure release openings
- Broadband excess noise from slat/flap tracks
- Broadband excess noise from recessed geometries

+10-30dB tonal
+2-3dB broadband
+2-4dB broadband
Parasitic tones at wings

Approach noise of Airbus A319

Helmholtz resonator

-M. Pott-Pollenske et al. 2002
Landing gear noise

- considerable experimental research during past 15 years in EU and USA
- most important source of airframe noise (at certification point)
- very broadband in character (slow roll-off of spectrum)
- \(\text{Size}^2\) scaling of intensity for similar geometry (in all details!)
- \(\text{Speed}^6\) scaling of intensity (compact source components)
- No pronounced directivity due to complex cluster of compact sources
- flyable noise reduction measures and new designs successfully developed for NLGs and MLGs
Low noise main landing gear

Optimal combination of modifications yields up to 8 dB(A) source noise reduction for flyable solution
Significance of high lift devices for airframe noise

- Much more difficult to improve, since aerodynamically highly optimized component

→ Noise reduction at landing gear of limited effect for a/c if HLD unaltered

- But: much more difficult to improve, since aerodynamically highly optimized component
Characteristics of slat noise

- significance and main parametric dependencies found by Dobrzynski, 1997/98, hypothesis: trailing edge mechanism
- most physics-based description so far by Guo’s model 2010 (not predictive)
- origin of low frequency spectral characteristics unknown
What mechanism generates low frequency broadband signals in slat flows?

- fluctuating pressure from Poisson equation (incompressible flow near wall)

\[ \Delta p' = -\rho_\infty \nabla \cdot (v \nabla v)' = -\rho_\infty (t \nabla v : \nabla v)' \]

- decomposition in mean + fluctuation \( v = v^0 + v' \)

\[ \Rightarrow \Delta p' \sim -2\rho_\infty (t \nabla v^0 : \nabla v') \]

- order of magnitude estimation like

\[ p'/l_\omega^2 \sim 2\rho_\infty |\nabla v^0| \frac{\sqrt{k}}{l_\omega} \quad \text{with} \quad |\nabla v^0| = \sqrt{\nabla v^0 : \nabla v^0} \]
What mechanism generates low frequency broadband signals in slat flows?

- time scale from LEE pressure equation (compressive part neglected)

\[
\frac{\partial p'}{\partial t} \sim -\dot{v}^0 \cdot \nabla p' - v' \cdot \nabla p^0
\]

\[
p' / l_\omega^2 \sim 2\rho_\infty |\nabla v^0| \frac{\sqrt{k}}{l_\omega}
\]

\[
f_v := \frac{1}{p'} \frac{\partial p'}{\partial t} \sim \frac{|v^0|}{l_\omega} \sim \frac{v_\infty}{l_\omega}
\]

convective frequency

\[
f_p := \frac{1}{p'} \frac{\partial p'}{\partial t} \sim \frac{\sqrt{k} |\nabla p^0|}{2\rho_\infty l_\omega |\nabla v^0| \sqrt{k}} = \frac{|\nabla p^0|}{2\rho_\infty l_\omega |\nabla v^0|}
\]

non-convective frequency

\[
|\nabla p^0| \sim \rho_\infty v_\infty^2 / L_s
\]

\[
|\nabla v^0| \sim v_\infty / l_\omega
\]

\[
\Rightarrow f_c L_s / v_\infty =: \overline{Sr_v} = O(L_s / l_\omega)
\]

\[
\Rightarrow f_p L_s / v_\infty =: \overline{Sr_p} = O(1)
\]
What mechanism generates low frequency broadband signals $Sr \sim 1$ in slat flows?

- repeat dimensional analysis with locally available data from RANS:

$$\sigma := \sqrt{k|\nabla p^0|} \sim \frac{\partial p'}{\partial t}$$

„source“ due to Ribner or Seo, Moon (LPCE)

⇒ Source near trailing edge which is no trailing edge source (need no edge)
What mechanism generates low frequency broadband signals $Sr \sim 1$ in slat flows?

- Do CAA simulation with/without slat trailing edge ("without" = slat extended by infinitely thin surface along t.e. streamline)

$\Rightarrow$ two sources at work, one due to acceleration, one classical edge noise source
Simulation based aeroacoustic Design

Optimum slat settings

flow: TAU
sound: PIANO

F16

OVERLAP (OL)

GAP [%]

\[ \Delta L \] [dB]

\[ c_{L_{\text{max}}} \]

\[ c_{L_{\text{max}}} \]

\[ \Delta L \] [dB]

\[ \text{GAP} \] [%]
Optimum slat settings

Aeroacoustic cost function

$K = \Delta SPL + 10 \lg \left( \frac{CL_{\text{max}}_{\text{ref}}}{CL_{\text{max}}} \right)^{5/2}$
Simulation based aeroacoustic Design

Optimum slat settings

Background noise issue at frequencies below 1.5kHz (spurious noise from model attachment)
Slat noise of high lift airfoil 30P30N

Comparison of stochastic approach (PIANO) with other groups

NASA, 70Mpts, AIAA 2009-3101

DLR, 150kpts

flow: TAU
sound: PIANO

PSD

290° w.r.t. flow

20 dB
Airframe related aircraft noise

1. Airframe (component) noise
   - generation of sound due to (turbulent) flow past airframe components „noise of an aircraft flying at engines off“

2. Source installation effects (exterior + interior noise)
   - change/occurrence of aerodynamic sound generation at an aircraft component due to its attachment to the aircraft
   - typically accompanied by change in/occurrence of acoustic power

3. Acoustic installation effects (exterior + interior noise)
Installation sources of exterior noise at aircraft

- Flap track / side edge interference
- Gear cavity / flap interference
- Spoiler / slat interference
- Wing / fan or prop interaction
- Wing / landing gear interference
- Pylon / jet interference
- Gear wake / flap interference
- Jet / flap interference
Jet flap interference (JFI)

Flight speed $U_\infty = 60$ m/s
Jet speed $U_{\text{jet}} = 185$ m/s (cold single stream jet)

$Pott-Pollenske, \ Dierke, \ Lufo \ HIT \ 2011$
Source installation effects of pylon on OR sound generation

Flight Mach No. M=0.2, take-off
Difference in OASPL 10D from rotor axis

- 6.5dB increase upstream on front rotor downstroke side of pylon
- 4.5 dB increase downstream on rear rotor downstroke side of pylon

⇒ Importance of sense of rotation for installation at aircraft
Airframe related aircraft noise

1. Airframe (component) noise
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2. Source installation effects (exterior + interior noise)
   - change/occurrence of aerodynamic sound generation at an aircraft component due to its attachment to the aircraft
   - typically accompanied by change in/occurrence of acoustic power

3. Acoustic installation effects (exterior + interior noise)
   - change in the sound radiation of an aircraft component due to influence of the a/c geometry
   - typically not accompanied by change in acoustic power
Acoustic installation phenomena of exterior/interior noise at aircraft

- Refraction + turbulent scattering
- Diffraction
- Source positioning
- Reflection
- A/C configuration
Unexpected installation effect on fan tones at High Lift Wing

- Simplified flow assumption overpredicts shielding by 10dB!
- Strong viscous flow effects on noise shielding even at low M
A/c configuration / shielding of CROR sound

- Ray tracing approach fails for representation of largely extended sources, e.g. Contra Rotating Open Rotors
- Need complete solution to wave equation: Fast Multipole BEM code
- Shielding of rotor alone tone $BPF_{\text{front rotor}} = 171.5 \text{ Hz}$
A/c configuration / shielding of CROR sound

- Shielding of rotor alone tone $BPF_{\text{rear rotor}} = 137.0 \text{ Hz}$
Concept and Integration

Acoustic installation effect of CROR
-sense of rotation-

Acoustic installation effect of CROR
- LNA vs. rear mounted -
Cabin noise excitation at transport aircraft

- **External noise sources:**
  - engine noise
  - fuselage boundary layer

- **Interior noise sources:**
  - Air system
  - (hydraulic systems)
Fuselage sound pressure level from engine tone signals

$M = 0.75$

**CAA (boundary layer)**

$\delta \approx 0.3m$

$d = 2.5m$

$L = 9.3m$

$Re_L = 200M$

$L \approx 35m$
Fuselage sound pressure level from engine tone signals

- $Re = 200 \text{ M}$
- RANS/FRPM/LEE
- active Thompson b.c.
  to specify incoming wave

Surface pressure levels point source

$M = 0.75$
$d = 2.5 \text{ m}$
$\delta \approx 0.3 \text{ m}$

$\Delta L_p [\text{dB}]$
- 20 dB
- 50 dB
- 20 dB

- 400 Hz
- 1000 Hz

$4 \text{ m}$
- $4 \text{ m}$
- $-8 \text{ m}$
- $-8 \text{ m}$

$4 \text{ m}$
- $4 \text{ m}$
- $-8 \text{ m}$
- $-8 \text{ m}$

- 5.0 m
- 2.5 m

Without boundary layer
Time averaged boundary layer

Siefert, Delfs, Caruelle, AIAA2011
Fuselage sound pressure level from engine tone signals

Refraction & Scattering at turb. eddies ⇒ Doppler shift (position dependent)!
Conclusions

- significance of airframe for a/c noise is high and related to
  i) component source noise
  ii) installation sources
  iii) acoustic installation effects
- high lift system is THE challenge for approach noise
- noise of new generations of transport a/c will be dominated by installation sources
- a/c exterior/interior noise depends on the installation of the engine. Effects may be exploited at current and new a/c configurations
Outlook

- challenges in airframe component noise:
  - flow permeable trailing edges extremely efficient reduction devices
    why do they work? how can one predict/model their effect?
  - efficient non-empiric aero-acoustic design capability
  - Adaptive structures/ active flow control?

- challenges in source installation effects:
  - Definition of relevant, but generic test cases
  - Hard to do validation, necessarily in large acoustic facilities

- challenges in acoustic installation effects:
  - Full a/c simulation for frequencies up to 10kHz?
  - Taking into account viscous flow effects on shielding
  - Realistic prediction of engine related fuselage pressure fluctuations:
    boundary layer effects extremely important, i) hard to simulate. ii)
    extremely hard to measure!