Seminar – ISAE

Aircraft Noise

A short overview of Aircraft noise

Key features & Issues

Given at ISAE-Supaero

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ÉCOLE CENTRALE LYON

Outline of today's seminar

- Context : Passenger & freight traffic in the EU
- Air traffic noise : General features & stakes
- Some definitions of sound annoyance
- Regulations for community noise and aircraft noise
- **Commercial aircraft noise sources & mitigation**

Context

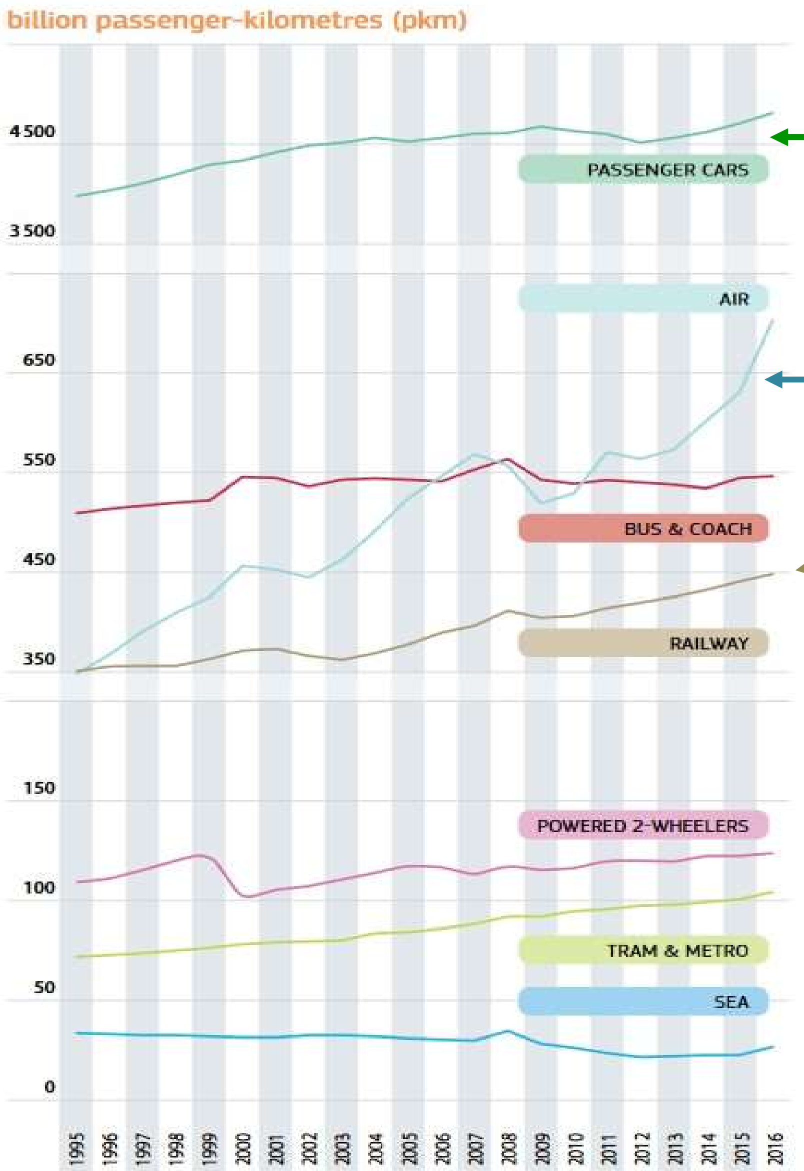
Passenger & freight traffic in the EU

Some figures on transportation in Europe 2010 & 2016

- 900 (1047) billion euros spent by European households on transport, i.e. 13% (=)of their total consumption
- 3 600 (3661) billion tkm of goods inland transport in the European Union:46% (49.3%) by **road**, 37% by boat, 10% (11.2) by **rail**, (0.1% (=) by **plane**)
- 6 500 (6 802) billion pkm of passager inland transport within EU: 73% (71%) by **cars**, 8% (8.1%) by buses, 6% (6.6%) by **train** and 8 % (10.5%) by **plane**

Source EU – Mobility &Transport: pocketbooks 2011 & 2018

Evolution of inland transportation in Europe 1995-2016



- By far the highest contribution (More that 2 times all other modes despite air and railway traffic increase). But moderate increase since 2000
- Substantial increase (~ 95 %) of inland air passenger transportation
- Railway less than 30 % despite public policies
- 180% air traffic increase expected in the EU by 2030

Source EU – Mobility &Transport: pocketbook 2018

Comparison with other Industrialised countries

	PASSENGER TRANSPORT				
	EU-28	USA	JAPAN	CHINA	RUSSIA
billion pkm	2016	2016	2015	2016	2016
Passenger car	*4829.3*	6315.4 (¹)		1022.9 (²)	
Bus + trolley bus + coach	*552.0*	558.1	71.4		129.8
Railway	450.1	40.2	427.5	1257.9	124.6
Tram + metro	*105.6*	23.5	(³)		48.7
Waterborne	*25.0*	0.8	*2.9 (⁴)*	7.2	0.7
Air (domestic/intra-EU-28)	*713.5*	1079.0	88.2	837.8	215.6

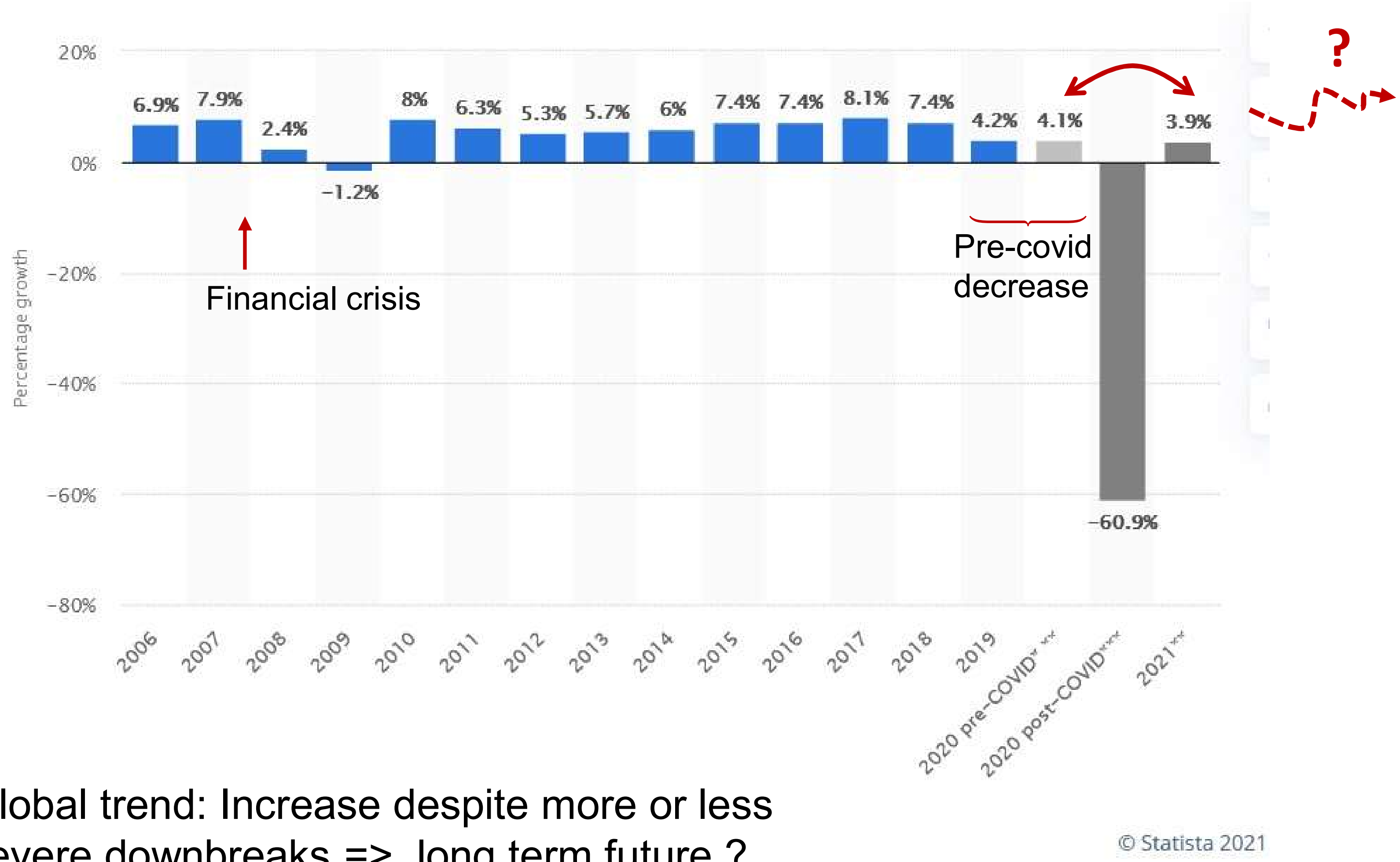
	FREIGHT TRANSPORT				
	EU-28	USA	JAPAN	CHINA	RUSSIA
billion tkm	2016	2015	2015	2016	2016
Road	1803.5	2990.2	204.3	6108.0	234.0
Rail	*411.8*	2547.3 (⁵)	21.5	2375.2	2344.0
Inland waterways	*147.3*	486.5			67.0
Oil pipeline	*115.1*	1411.8		419.6 (⁶)	1308.0
Sea (domestic/intra-EU-28)	1180.8	*251.8 (⁷)*	180.4	9733.9 (⁸)	43.0

Source EU – Mobility &Transport: pocketbook 2018

- Strong variations from country to country
- Does not show the trends
- Influence of:
  - geography
  - cultural habits
  - policies

Notes: (1) USA: including light trucks/vans.
(2) China: including buses and coaches.
(3) Japan: included in railway pkm.
(4) Japan: 2014 value.
(5) USA: Class I rail.
(6) China: oil and gas pipelines.
(7) USA: refers to coastal shipping, 2014 data.
(8) China: both coastwise and inland waterway transport.

Air passenger traffic growth 2006-2021



Global trend: Increase despite more or less severe downbreaks => long term future ?

Source EU – Mobility &Transport: pocketbook 2018

Air passenger traffic a typical day at 2 am

Air traffic noise

General features & stakes

Noise annoyance due to community (environmental) noise

- Noise is perceived as the greatest annoyance by the EU Population. (*e.g.* in France, 54% of the people living in cities with more than 50 000 inhabitants feel annoyed by community noise at home
- According to the WHO (2013), Noise exposure is the 2^{nd} largest source of disease in Europe after air pollution
- Main risks associated with community noise exposure (WHO 2011)
  - **Cardiovascular disease**
  - **Cognitive impairment children**
  - **Sleep disturbance**
  - **Tinnitus**
  - **Annoyance**
- Transportation noise is a major source of community noise

Aircraft annoyance

Airports in densely populated areas:

- Aircraft at low altitude over long distances (Landing)
- Aircraft at full engine power (take-off)

→ Residents highly exposed to aircraft

Some definitions of (acoustic)

annoyance

Two important aspects to distinguish (even if they are related)

Regulations : to be operated, an aircraft must be certified acoustically.

- noise emitted by an aircraft during landing, take-off and flyover must be below given thresholds to be certified by ICAO.

  Index: EPNdB

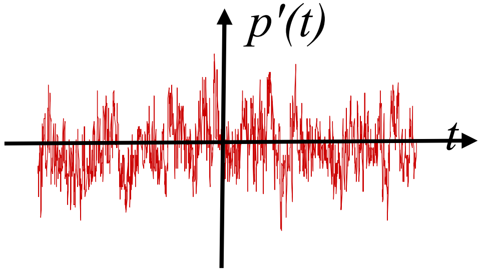
Annoyance

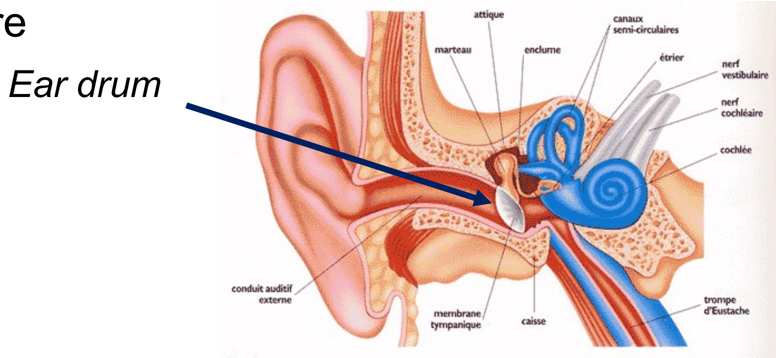
- related to the noise perceived by the population
- cumulative effect: depends on the traffic, the type of vehicle, ...
- Index: L_{den} (equivalent level day-evening-night)

Sound pressure level and annoyance

Sound :

- Unsteady weakly compressible fluctuations (velocity, density, pressure, temperature) that propagate through the air
- Ear drum is a flexible membrane => feels pressure fluctuations $p'(t)$





Noise level : related to the standard deviation (rms value) of $p'(t)$: $p_{rms} = \sqrt{\overline{p'^2}}$

- For signals of finite duration T :

$$\overline{p'^2} = \frac{1}{T}\int_0^T p'^2(t)dt = p_{rms}^2 = P_T = \text{mean power of the signal over } T$$

- For signals of infinite duration $\overline{p'^2} = \lim_{T\to\infty} \frac{1}{T}\int_{-T/2}^{T/2} p'^2(t)dt = p_{rms}^2$

Sound pressure level (SPL in dB): $L = 10\log_{10}\left(\frac{p_{rms}^2}{p_{ref}^2}\right)$ with $p_{ref} = 2.10^{-5} Pa$

(objective measure)

Fluctuations are **extremely small:** $p_{rms} \sim 2\times 10^{-5}\,\text{Pa (0dB) to 20 Pa (120 dB)}$ (NB: $P_{atm} \sim 10^5$)

Perceived level *(subjective measure)*

Measure sound intensity taking into account the level perceived by an “average” person

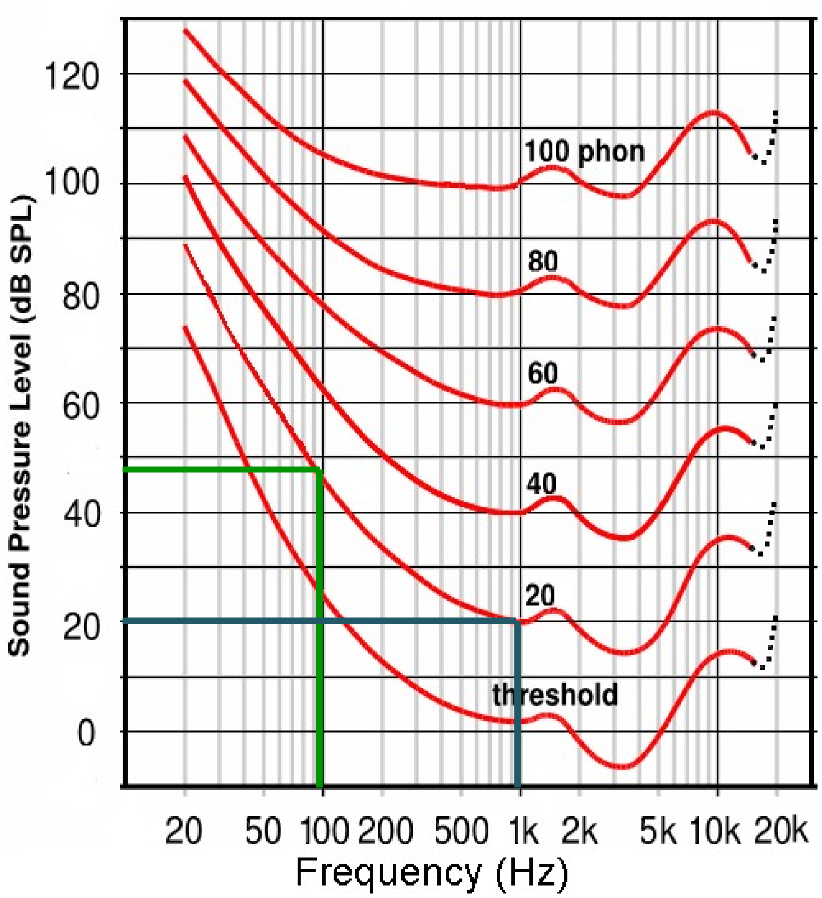
⇒ Representative of the ear response (individual variations are averaged out)
- The response is frequency dependent: the ear acts as a filter
- The frequency response depends on the level

1. Equal-loudness contour

- each curve relates objective sound levels that are equally perceived by the ear.
- the perceived level is arbitrarily set as the corresponding SPL at 1 kHz
- Eg: 20 Phones

  = 20 dB at 1 kHz

  ~38 dB at 100 Hz
- Low and very high frequencies are not perceived as well as medium frequencies
- The frequency filter flattens at high levels=> less sensitivity with respect to frequency



Perceived level *(subjective measure)*

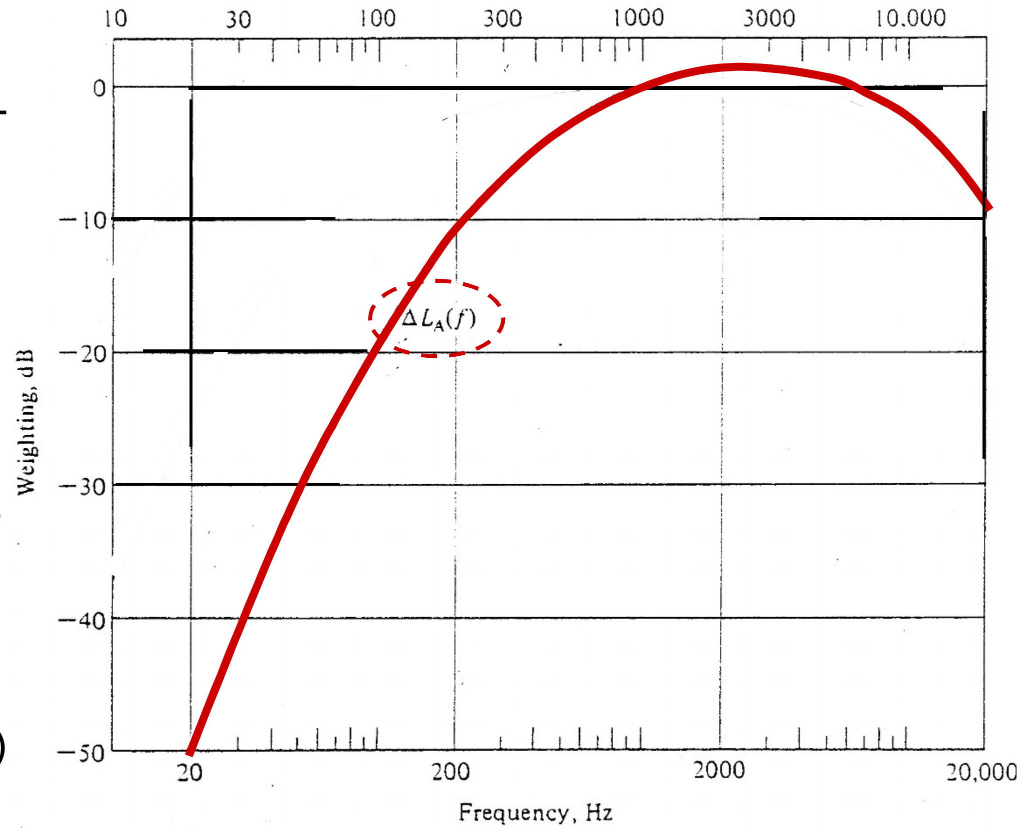
3. A- Weighted sound levels

Iso-loudness contours curves: almost parallel at moderate sound levels => The **A-weighting is a simple way to take into account the perception only as function of frequency** at moderate SPLs

- It is a frequency dependent correction $\Delta L_A(f)$ to add to the objective levels (SPL $L(f)$ in order to obtain an estimate of the perceived level $L_A(f)$

$$L_A(f) = L(f) + \Delta L_A(f)$$

- Unit: dBA
- ΔL_A is set to 0 dB at 1kHz (arbitrary)
- The shape is simplified with respect to the iso-loudness contours=> it is a rough approximation
- A-weighting is used far above its application range as an index (high levels)



octave	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz
$\Delta L_A(f)$	-16.1 dB	-8.6 dB	-3.2 dB	0 dB	1.2 dB	1 dB	-1.1 dB

Levels used for aircraft noise from Leq to EPNL

- **Equivalent sound pressure level L_{eq}**
  - $\mathrm{L}_{eq,T}$ indicates the mean level over a duration T

$$\boxed{\mathrm{L}_{eq,T} = 10\,\log_{10}\left[\frac{1}{T}\int_0^T \frac{p_{A,rms}^2(t)}{p_{ref}^2}\,dt\right] = 10\,\log_{10}\left[\frac{1}{T}\int_0^T \frac{10^{L_A(t)/10}}{p_{ref}^2}\,dt\right]}$$

where

$$\frac{p_{A,rms}^2(t)}{p_{ref}^2} = 10^{L_A(t)/10}\ ;\quad L_A(t) = f\left(L_N(t)\right)\quad \text{with: }\ L_N(t) = 10\log_{10}\left[\frac{p_{rms}^2(t)}{p_{ref}^2}\right]$$

and $p_{rms}^2(t) = \left[\frac{1}{\tau}\int_{t-\tau/2}^{t+\tau/2} p'^2(t')\,dt'\right]$ is the short term rms value over a duration τ

  - NB: these definitions assume that the integration times are long enough to define rms values over shorter durations

On this basis, the L_{den} is defined =>

Levels used for transportation noise

- **Day-evening-night noise level L_{den}**
  - Noise standard used in the (EU) environmental noise directive (2002) for establishing noise maps in Europe’s large cities and near roads, railway tracks and airports
  - Equivalent sound pressure level over the entire day obtained from 3 periods: ***day, evening, night.***
  - An **additional penalty** of 5 dBA for evening noise and 10 dBA for night noise is included
  - In France: day (6am to 6 pm) ; evening (6 pm to 10 pm) ; night (10 pm to 6am)

$$L_{den} = 10 \log_{10}\left[\frac{12}{24}10^{L_{day}/10} + \frac{4}{24}10^{(L_{evening}+5)/10} + \frac{8}{24}10^{(L_{night}+10)/10}\right]$$

  - This definition is an attempt to concentrate the noise annoyance perceived over a whole day into a single number : the perception change depending on the time is crudely taken into account by the penalties

All the annoyance measures discussed here are only partly explaining the annoyance: many personal or society factors modify the noise perception. Overall levels such as L_{den} do only partly account for the frequency content of the noise (broadband or tonal, impulsive or not, etc..

Levels used for aircraft noise

Other metrics used mostly for aircraft certification (by ICAO(*))

- for global air traffic: $\mathrm{L}_{\mathrm{den}}$
- For a single aircraft operation: EPNL (at 3 certification points approach, sideline , cutback) → see next slide

- **Noisiness**
  - Very close to loudness (slide 15)
  - Equal-noisiness curves similar to the equal – loudness curves but slightly different at medium frequencies
  - Unit: Noy or N
- **Perceived Noise Level (PNL)**
  - Logarithmic scale defined from Noy: $\mathrm{L}_{PN} = 40 + 33.22 \log_{10} N_t$
    N_t determined from levels in octave bands
- **Effective Perceived Noise Level (EPNL)**
  - PNL corrected to account for the annoyance due to the presence of pure tones in a broadband noise and for an appropriate duration of the signal

(*) ICAO: International Civil Aircraft Organisation

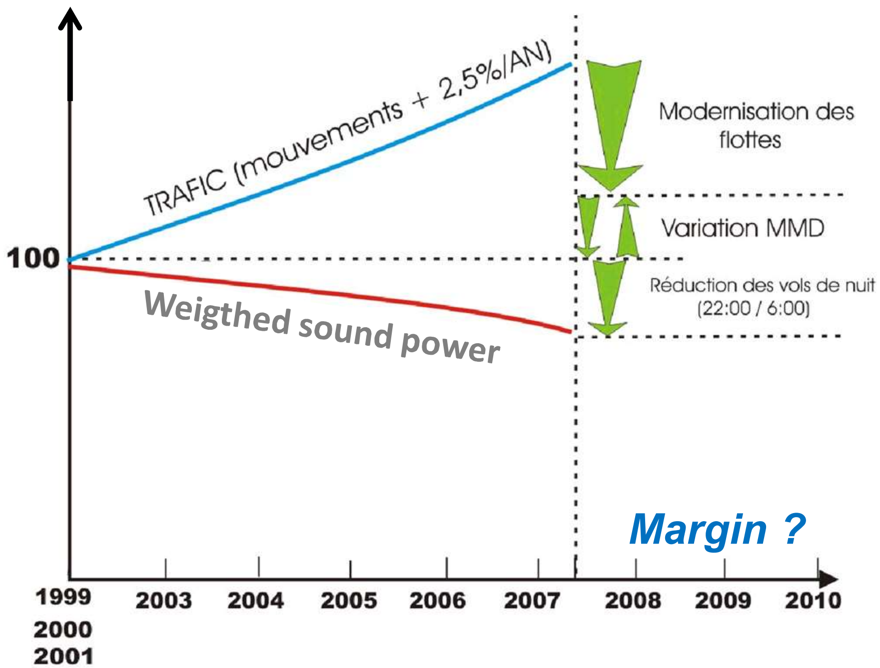
Regulations for community noise

and

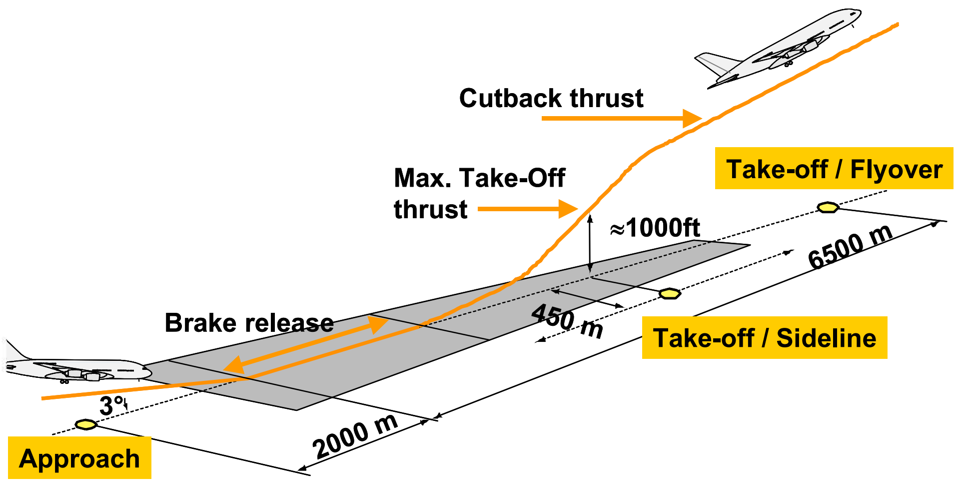
aircraft noise

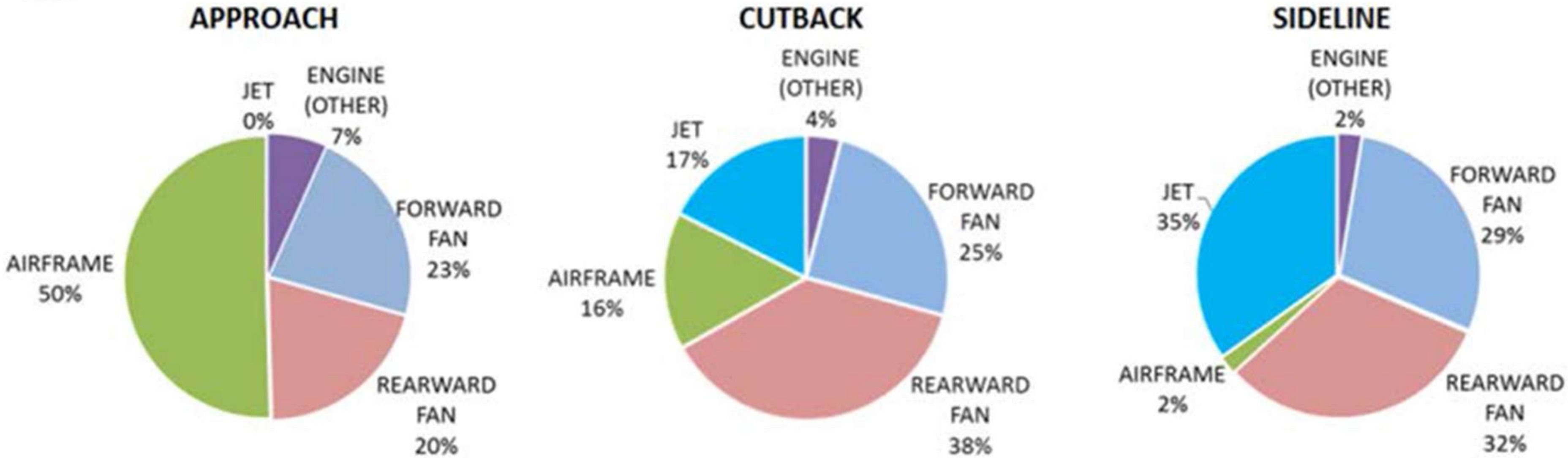
Aircraft noise regulations (1)

Is it worth reducing aircraft noise ?



Flight regimes of aircraft near ground





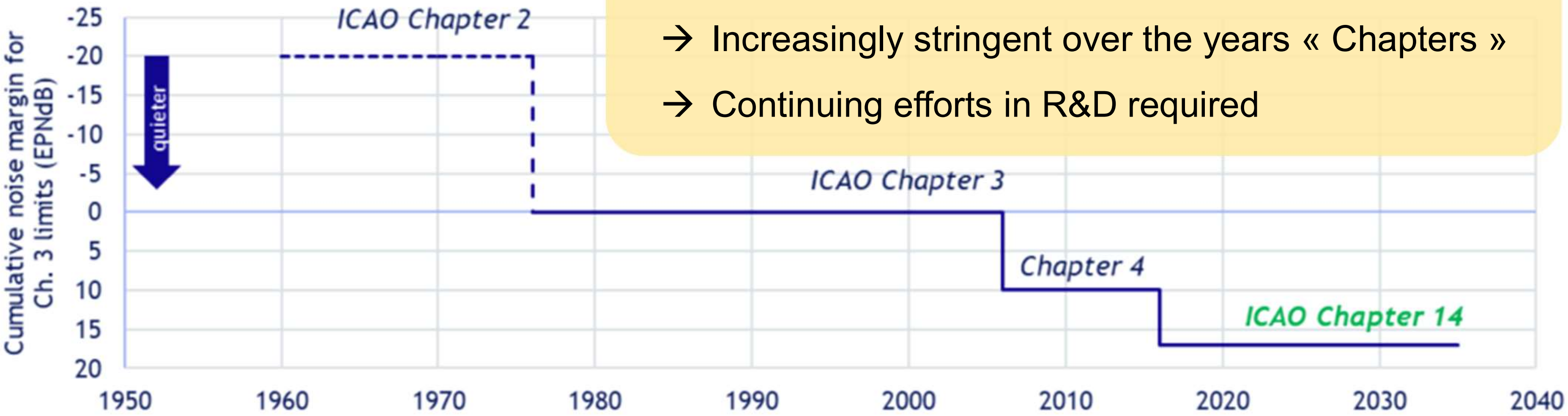
Aircraft noise regulations (2)

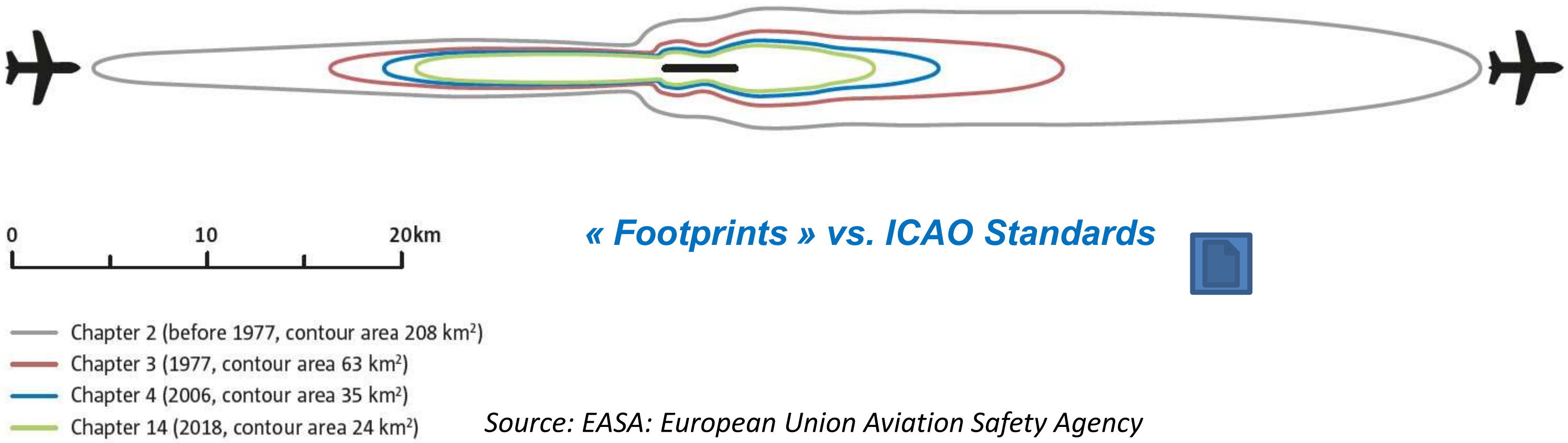
Aircraft Noise in the vicinity of airports

ICAO(*) Standards

→ Increasingly stringent over the years « Chapters »

→ Continuing efforts in R&D required





« Footprints » vs. ICAO Standards

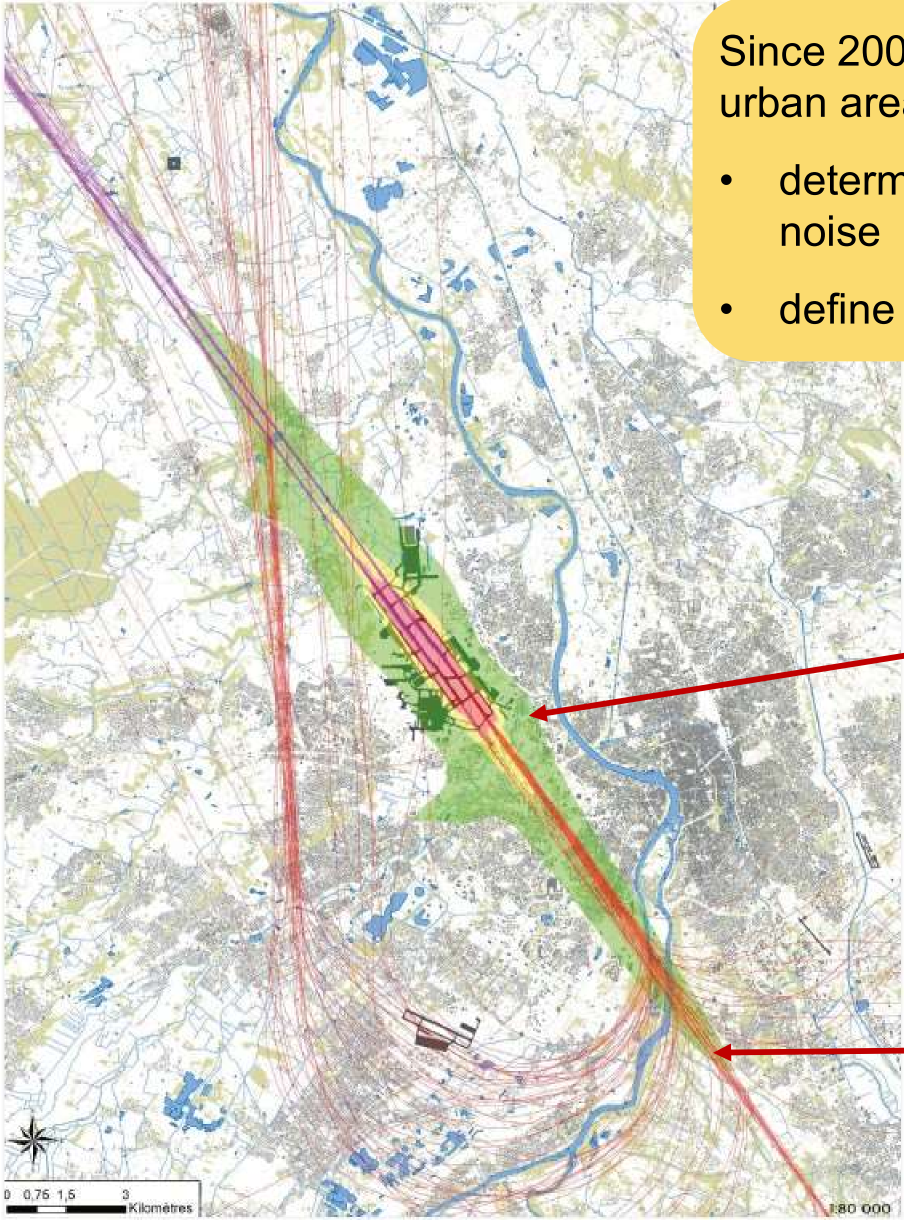
Source: EASA: European Union Aviation Safety Agency

(*) ICAO: International Civil Aircraft Organisation

Aircraft noise regulations (3)

Since 2002, the EU regulation 2002/49/CE requires that urban areas with more 100 000 inhabitants :

- determine noise maps, for railway, aircraft and road traffic noise
- define noise management plans



Blagnac Airport Noise Plan: Night time

Source : Autorité de Contrôle des Nuisances aéroportuaires, Rapport d'activités 2019

Hospital (Purpan) Z-III ☹

Zone I : Lden 70 dBA
Zone II : Lden 65 dBA
Zone III : Lden 55 dBA

Ramonville Z-III ☹

Commercial aircraft

noise sources & mitigation

Main aircraft noise sources

Three major contributions to community noise:

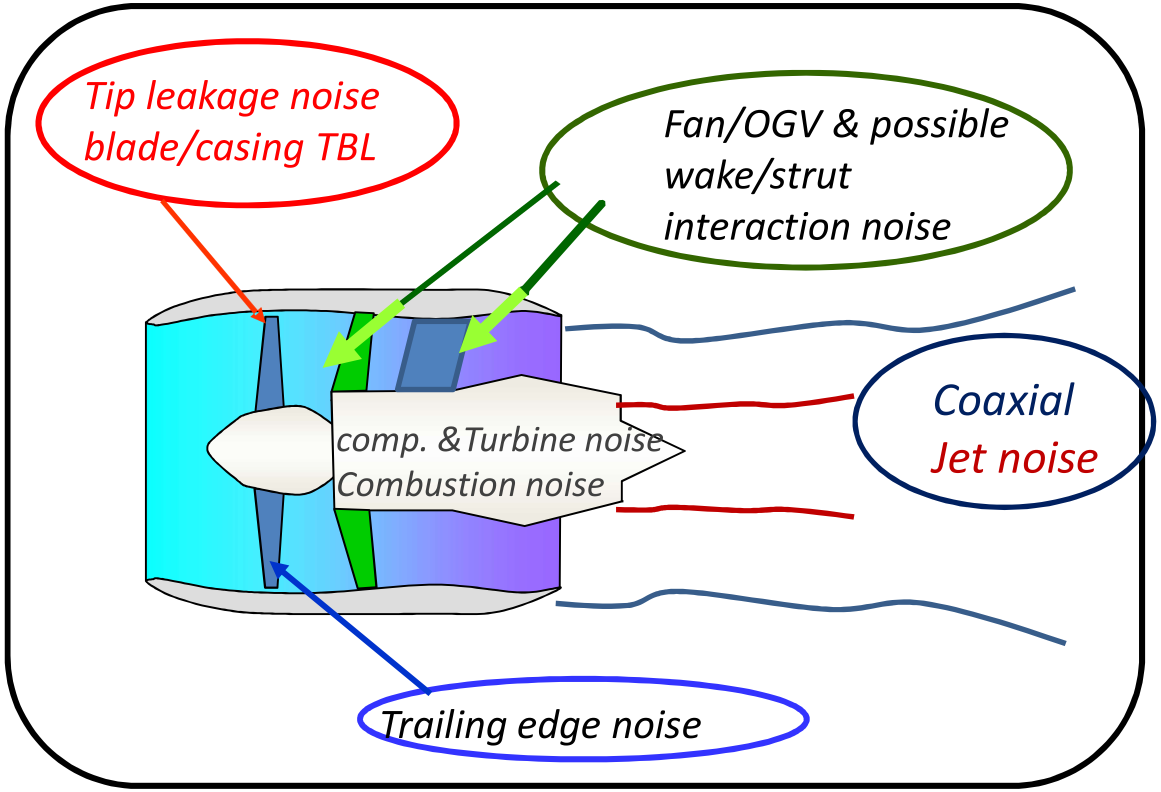
- **Engine noise**
  - engine Fan-OGV noise, propeller noise, jet noise
  - predominant at take–off (for civil aircraft)
  - Always predominant for Helicopter noise, open rotors powered aircraft, supersonic aircraft
- **Airframe noise**
  - Landing gear, high lift devices, cavities
  - Dominant at approach for modern civil aircraft
- **Engine installation noise (Engine/Airframe)**
  - important source for modern and novel architectures

Cabin noise:

- **Induced Fuselage panel vibrations**
  - engine (Tones + jet noise) , fuselage Boundary Layer

Engine noise

Turbo Engine noise sources (commercial aircraft)



Jet Noise (subsonic flight)

Due to jet turbulence:

- Broadband around preferred Frequency $fD/U \sim 0.3$
- Sound power scales with U^8

Fan noise

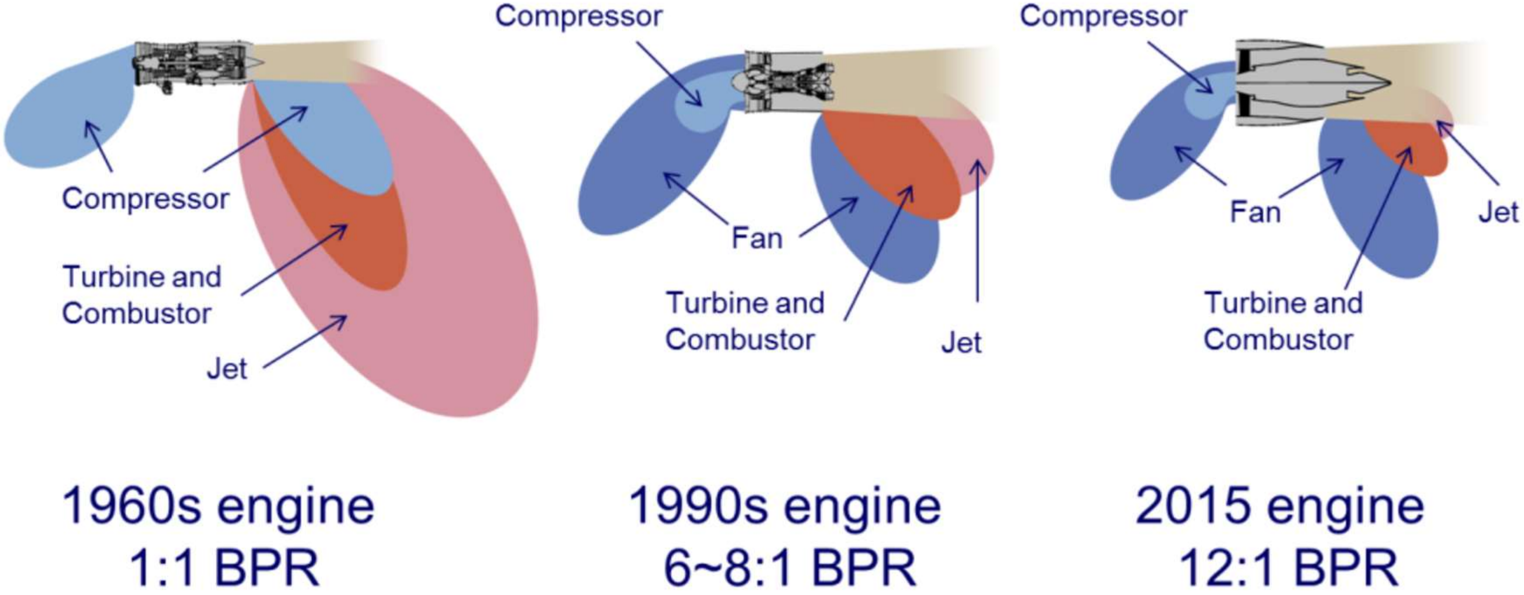
Due to flow fan & OGV interactions:

- Tonal (periodic motion) at blade passing frequency
- Buzsaw, tonal (fan tip shocks at take-off)
- Broadband (Turbulence)
- Sound power scales with U^6

Other noise sources: relative importance increasing as other sources reduced

- LP and HP compressors (high frequency tones dominant+broadband)
- Turbines (high frequency tones & broadband)
- Combustion (broadband low freq.)

Engine noise: individual source contributions

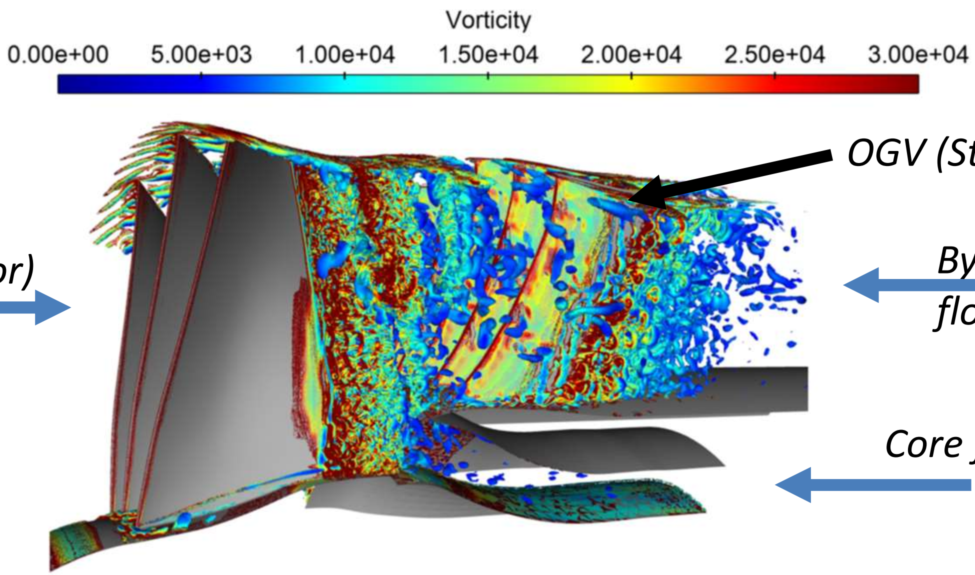


Source: A. Epstein, ISABE 2015,

End of 60's first bypass flow engines

Increasing bypass ratio

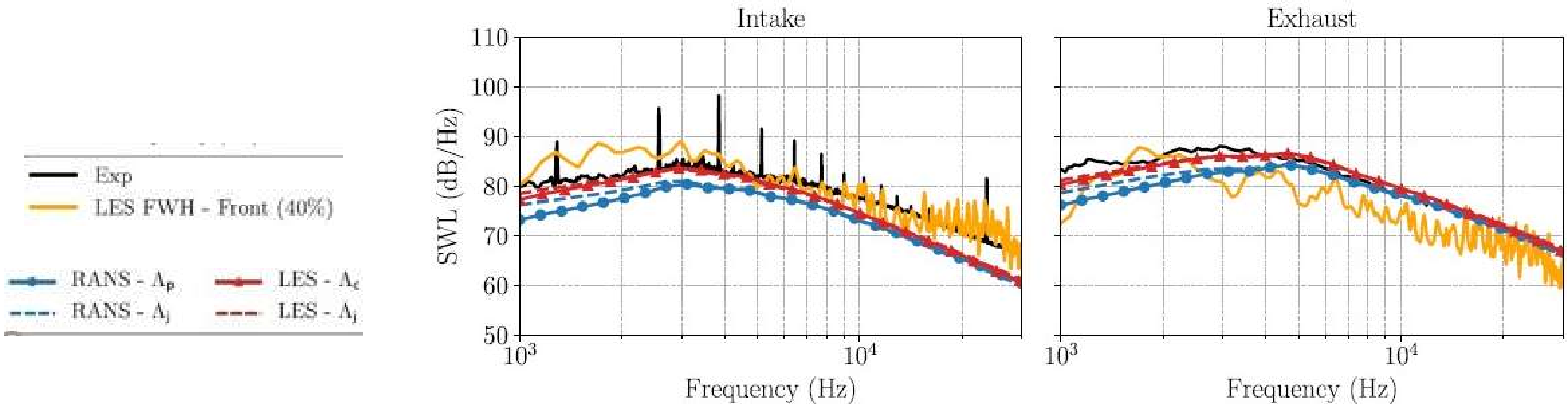
Interaction noise: Fan-OGV interaction noise



Source : Lewis et al . 2021 AIAA Journal: Q-criterion isosurface (7 × 106 s-2) colored by the vorticity magnitude.

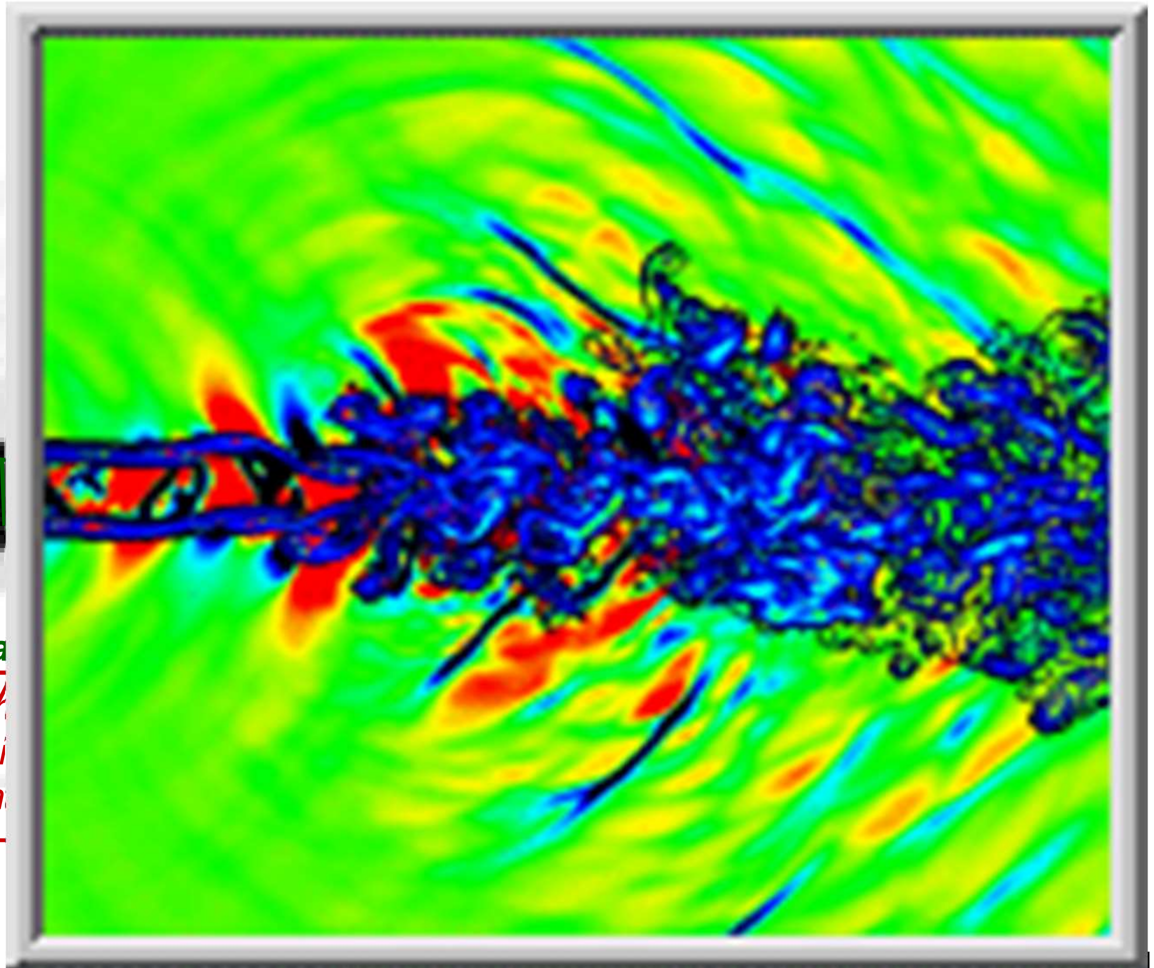
Large eddy simulation of Turbulent Fan-OGV flow

Aeroacoustic analogy



Estimation of radiated sound power vs. experimental data

Development of subsonic turbulent jet - Illustration



Potentia

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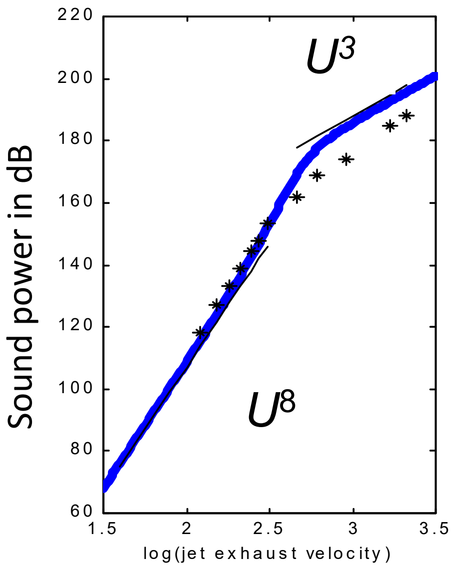
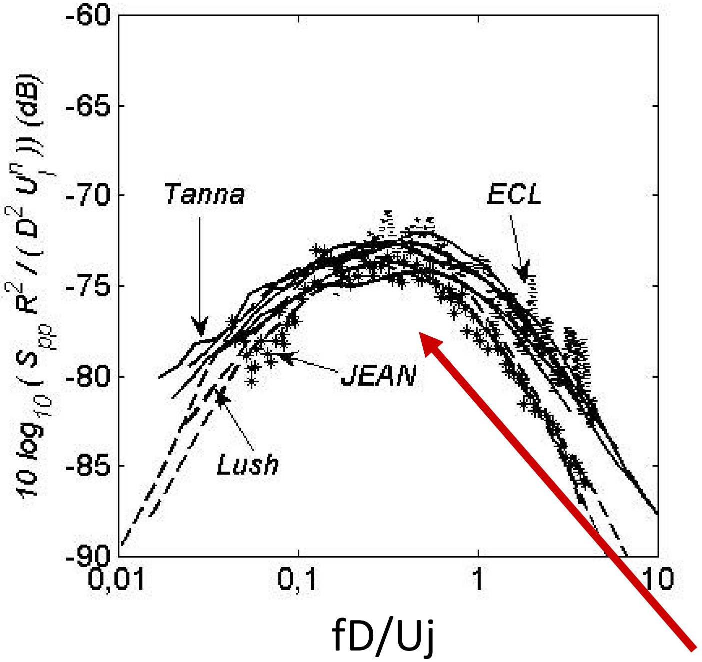


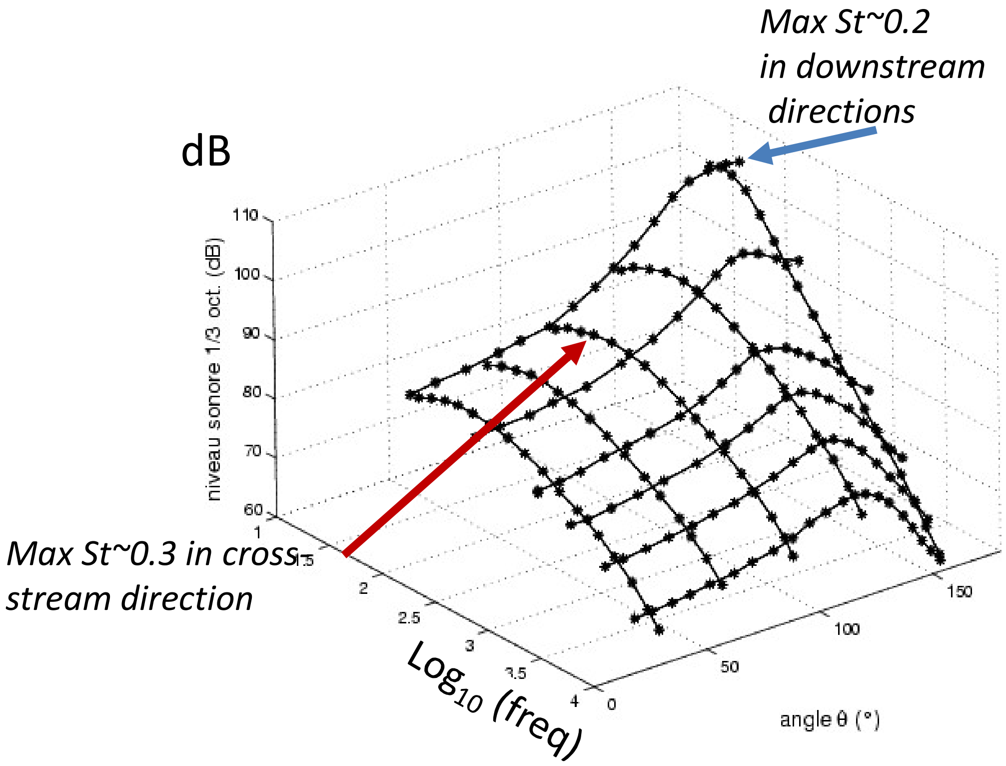
8-th power law valid far beyond M=1 (up to M ~ 1.5)

ully
developed region, at about 15 diameters.

Spectra (subsonic jets)

Third-octave jet-noise spectra for a high-bypass ratio engine of the type CFM 56, and corresponding directivity.





here $\theta = 0$ corresponds to the upstream direction

➔ "Universal" behavior over lar Re number an Mach range

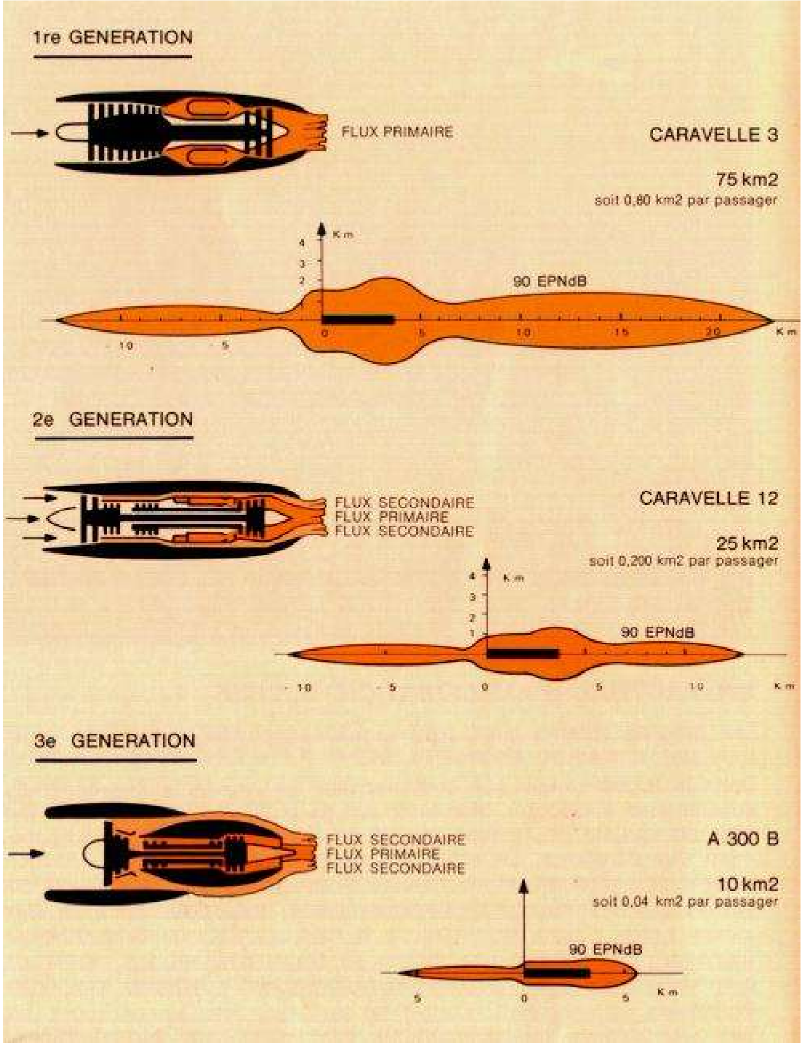
Impact of technology on jet aircraft noise

- The noise exposure around airports is quantified by means of footprints of equal EPNL, with respect to the number of passengers.
- turbojets → low bypass ratio → high bypass ratio

  ➔ Significant reduction.

- Physical reason:

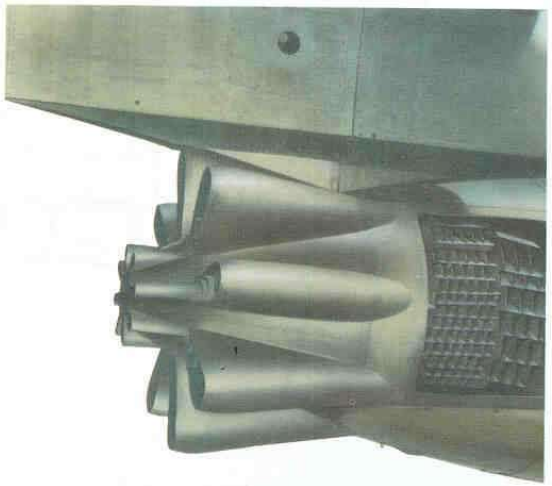
  Shear flow from core flow to ambient in two steps => 8th power law (not linear !) applies to much lower velocities



From a brochure of the 'secrétariat général à l'aviation civile'

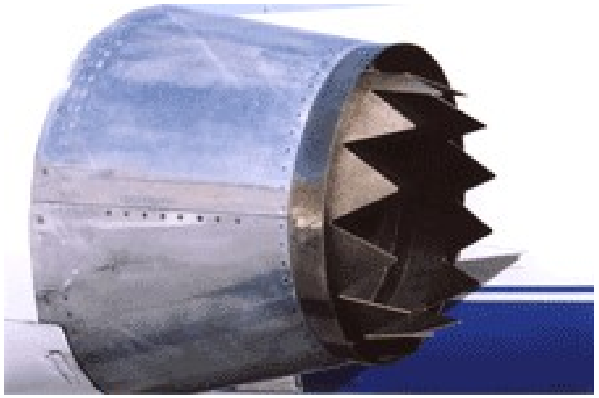
Other Reduction techniques

CORRUGATED INTERNAL MIXER



LOBE-TYPE NOZZLE

1 – corrugated nozzles

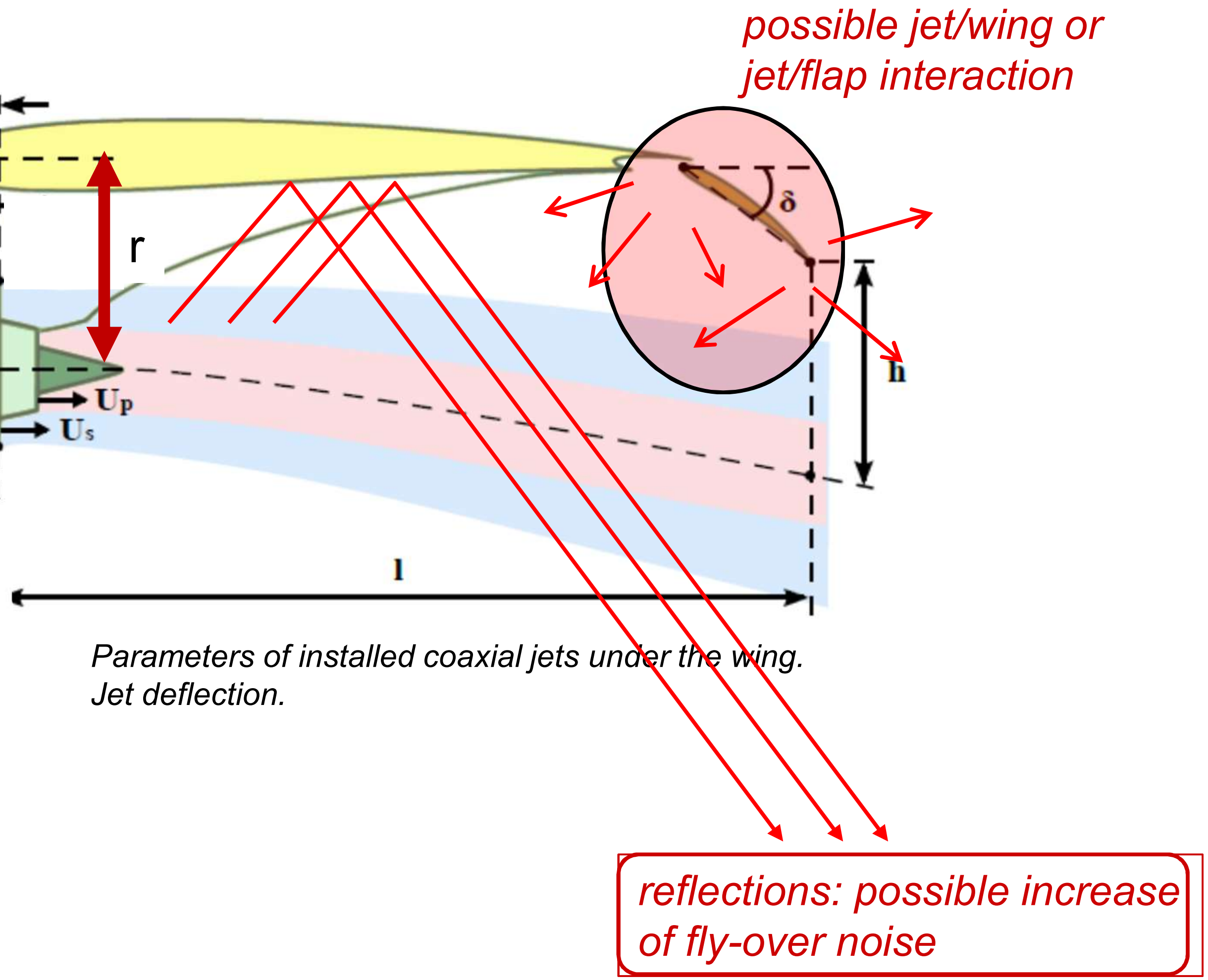


2 - chevrons

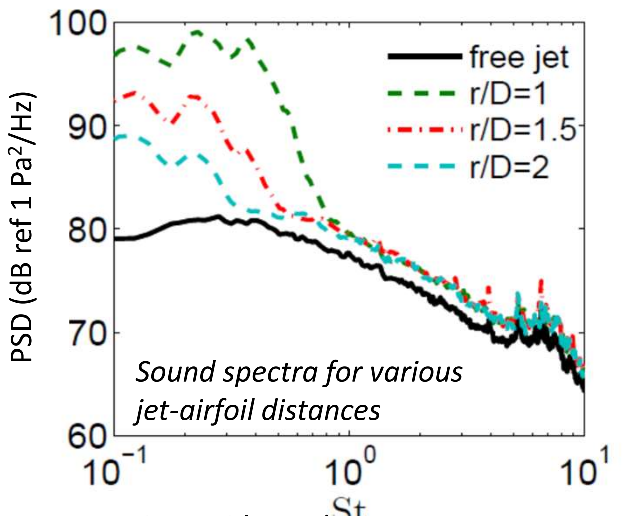
- moderate noise reduction
- small reduction of thrust

objective: reduce azimuthal correlation & global jet modes → large scales

During take-off and landing operations the jet can interact with wing elements (flaps…), which induces either additional interaction-noise sources or jet-noise scattering.



Parameters of installed coaxial jets under the wing. Jet deflection.

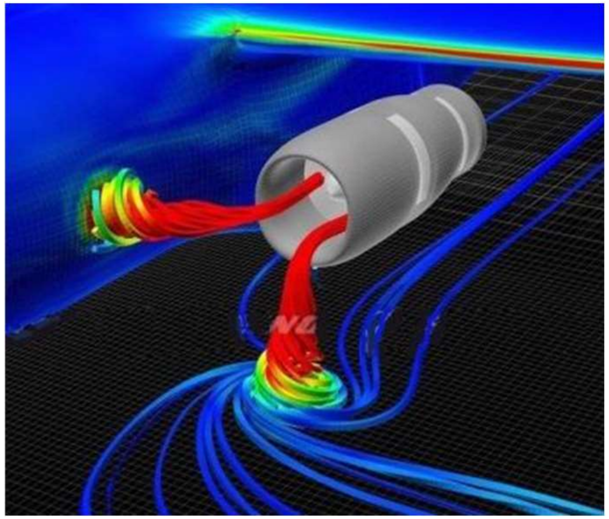


Sound spectra for various jet-airfoil distances

Source: Piantanida et al AIAA paper 2015-2998

Example: ingestion noise due to ground vortices

A steady flow distortion crossed by a rotating blade is perceive as an unsteady flow perturbation by the blade

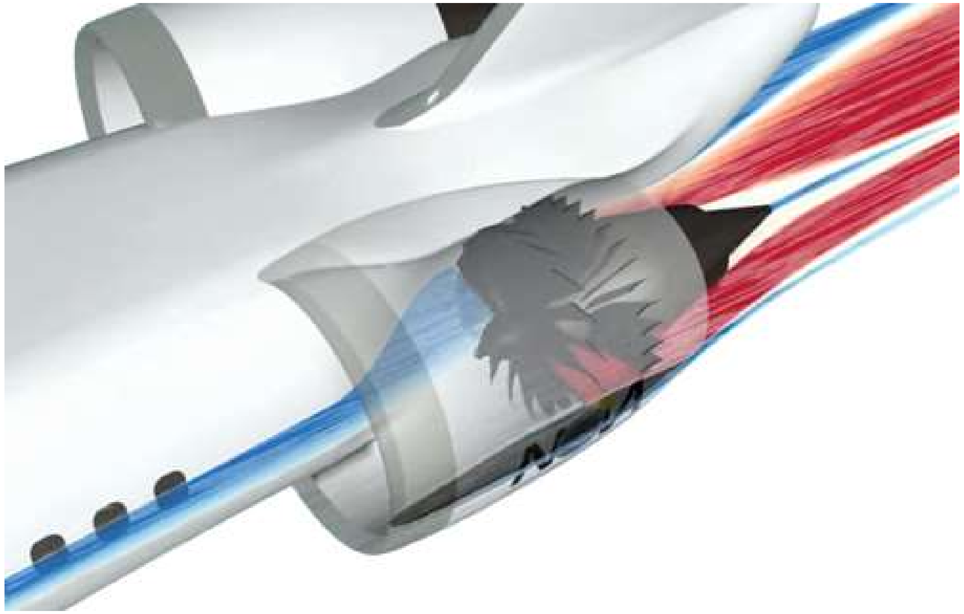


slow large vortices and coherent turbulent structures, are stretched when they are accelerated and then chopped by several blades.

Other inlet distortions ➔

Other inlet distortions sources

- Side wind
- Boundary layer ingestion

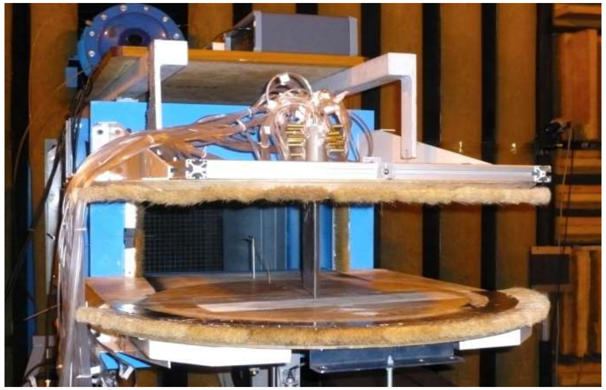


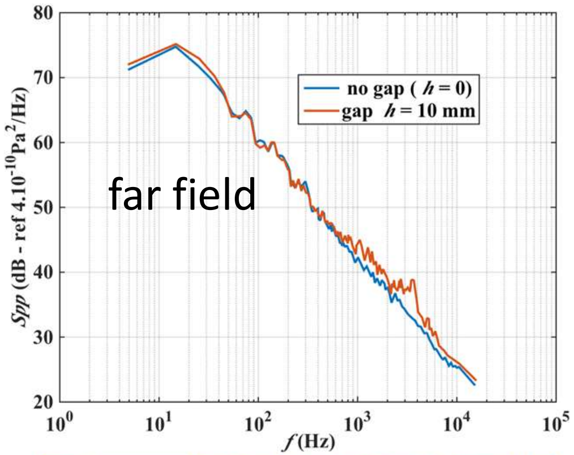
Source Onera NOVA aircraft concept

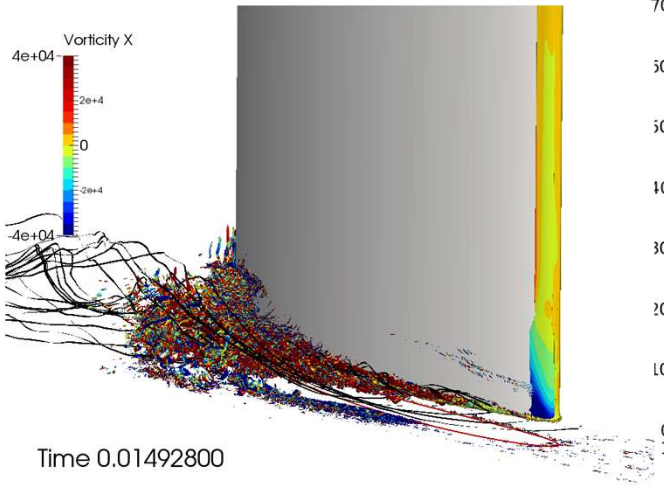
- Scarfed inlet

Tip clearance flow

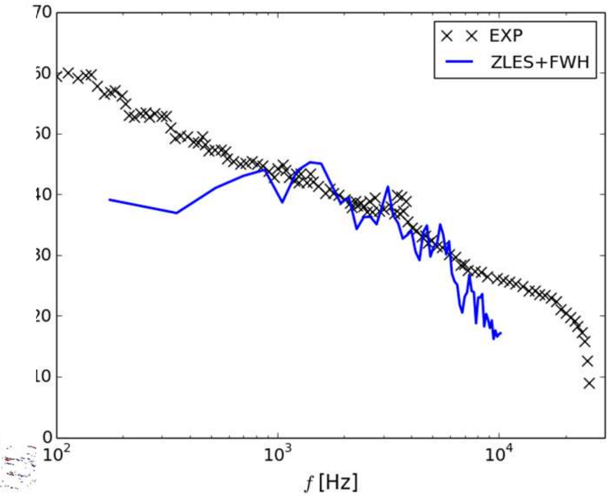
Application : Slat/body junction, fan tip/casing ...
Configuration: here, fixed loaded airfoil in ***M*=0.2** flow with ***h*/*c* = 5%** tip clearance at $\mathbf{Re_c \sim 10^6}$
→ large streamwise tip leakage vortex + turb^{ce}
→ broadband noise



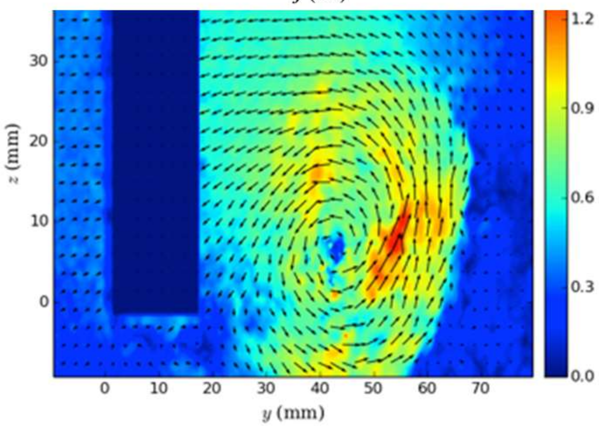




LES by Boudet et al



Far field comparison



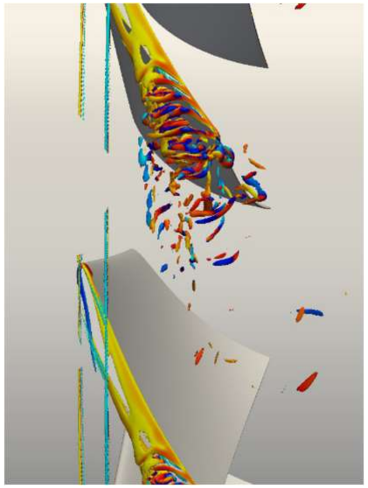
Measurements by Jacob et al

Tip clearance noise mitigation

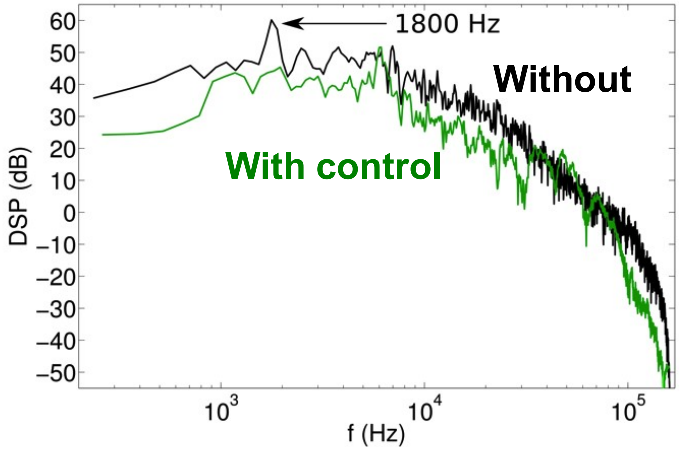
Flow control

Suction at fan casing of low M fan-rig

No suction



With suction

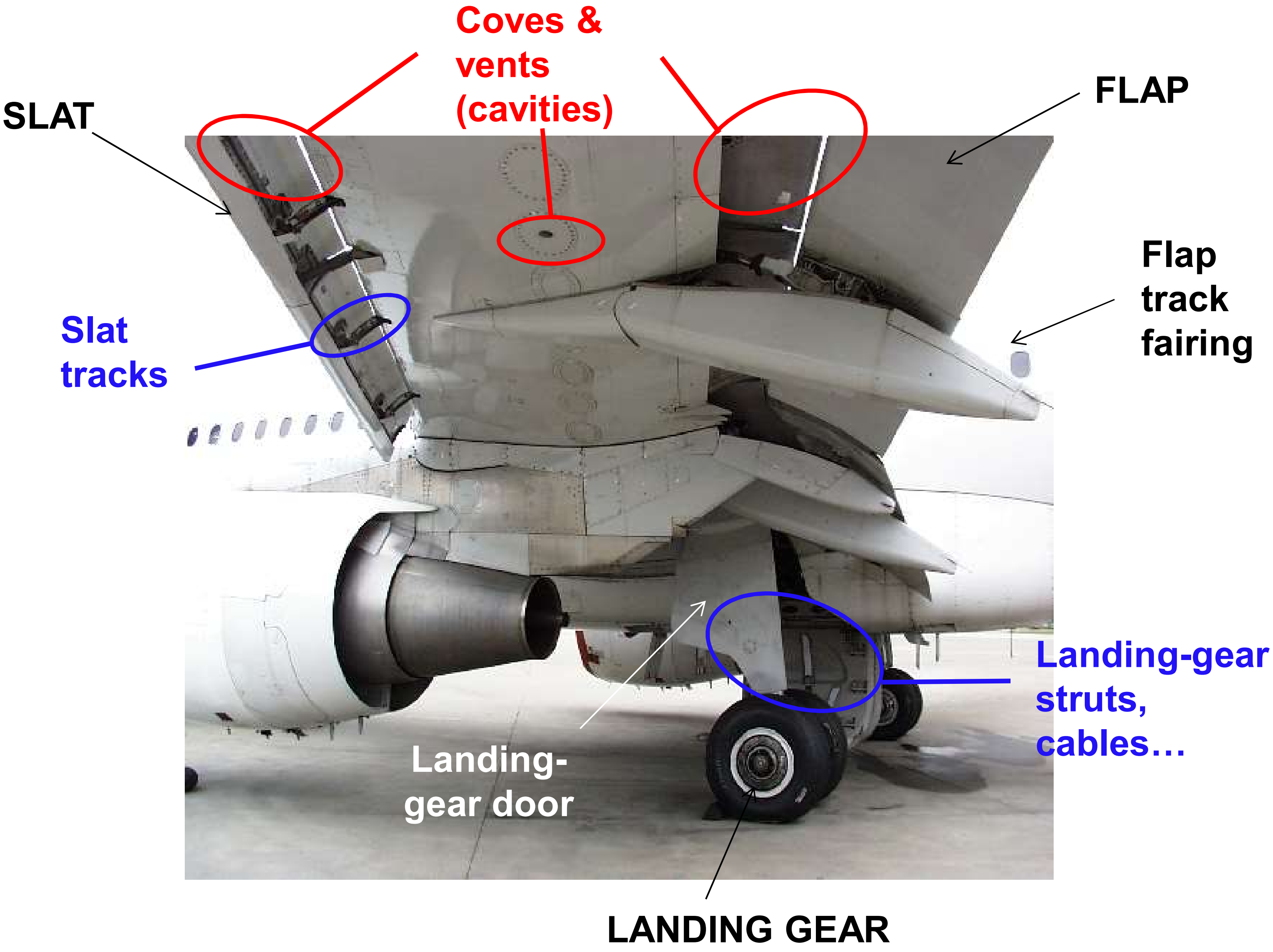


Far field

LES of fan rotor by Cahuzac et al

Airframe noise

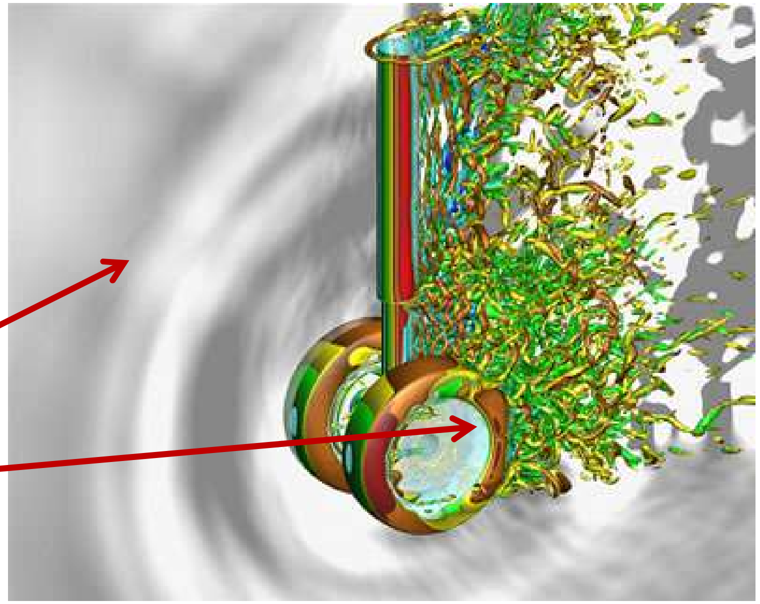
Airframe Noise Sources



Landing-gear noise numerical studies

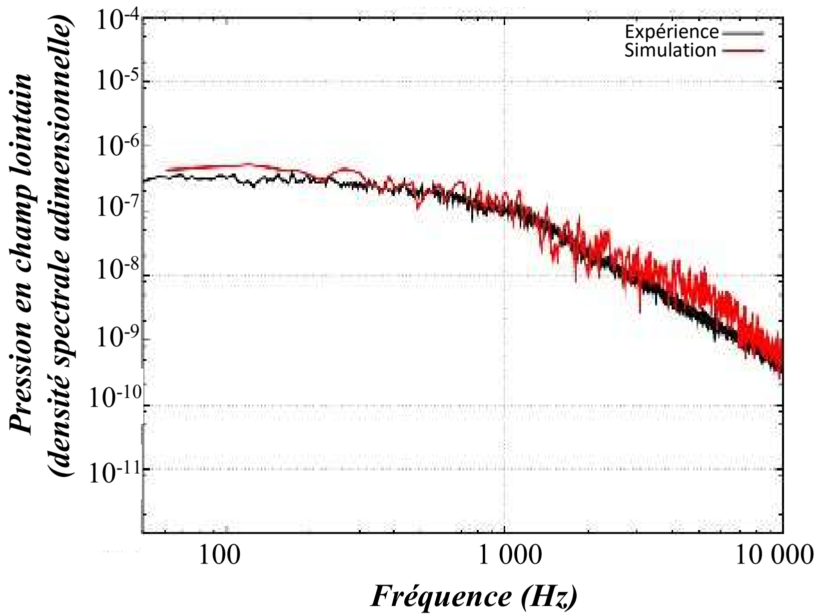
Two examples from recent studies

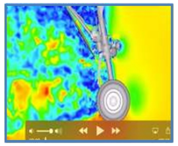
Onera LES computation+ CAA
Landing gear benchmark
(**Lagoon**) simplified model.



sound waves

Turbulent eddies





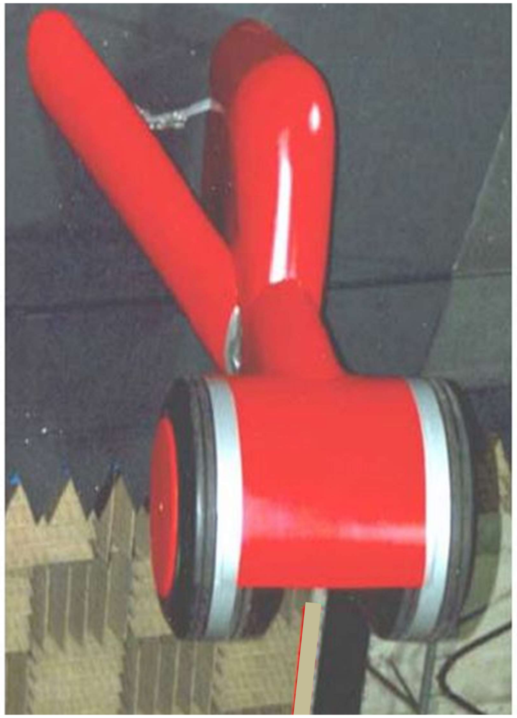
Exa: LBM (Powerflow) computation + FWH analogy
Landing gear benchmark (Lagoon) simplified model: left: far field spectra; above : video of vortical structures => Tonal Noise ??

Noise mitigation of landing gears

Large reductions can be achieved by fairings (more than 10 dB) but not always applicable on aircrafts. Partial fairings ensure reductions of about 5-6 dB on some elements.

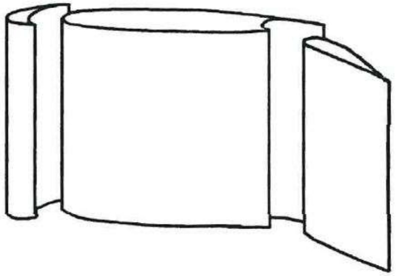
Main idea : streamlining

EC projects RAIN, SILENCER… MAMBO (2021 – 2025)



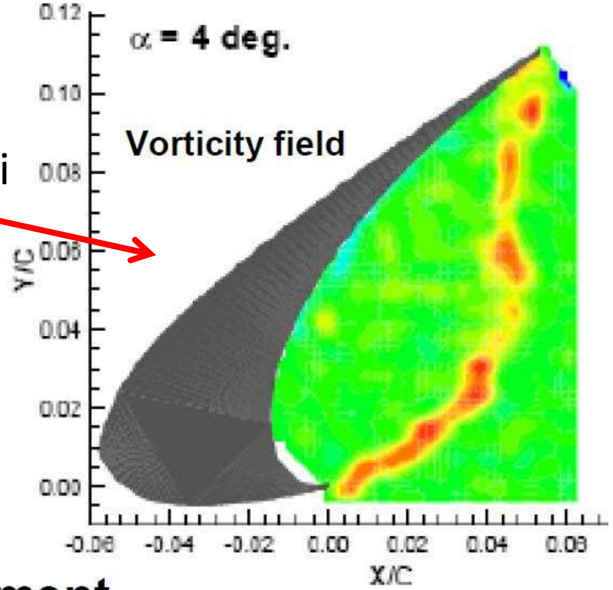
W. Dobrzynski (2008) **-** Almost 40 Years of Airframe Noise Research - What did we achieve?, *14th Aeroacoustics Conference*, keynote lecture, Vancouver.

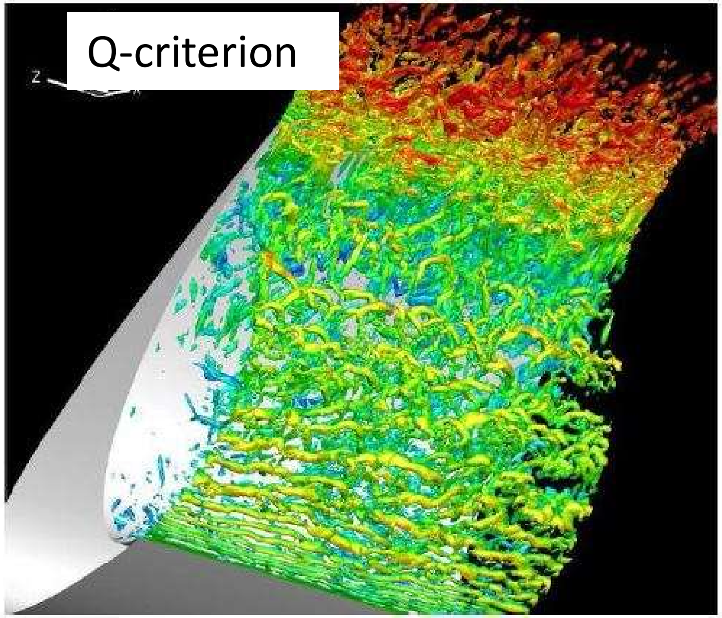
High lift devices Slat and flap coves as 2D cavities

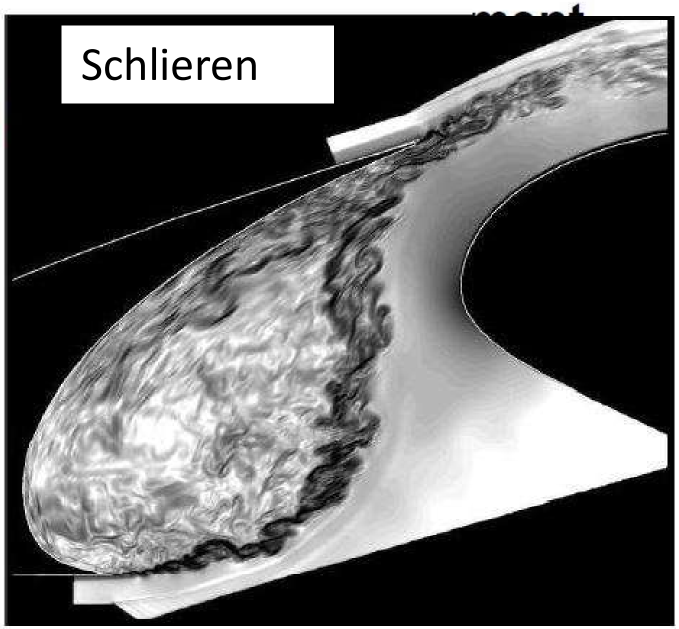


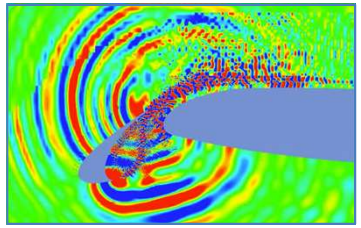
Typical simplified mock-up for wind-tunnel testing or numerical simulations

PIV (Dobrzynski 2008)







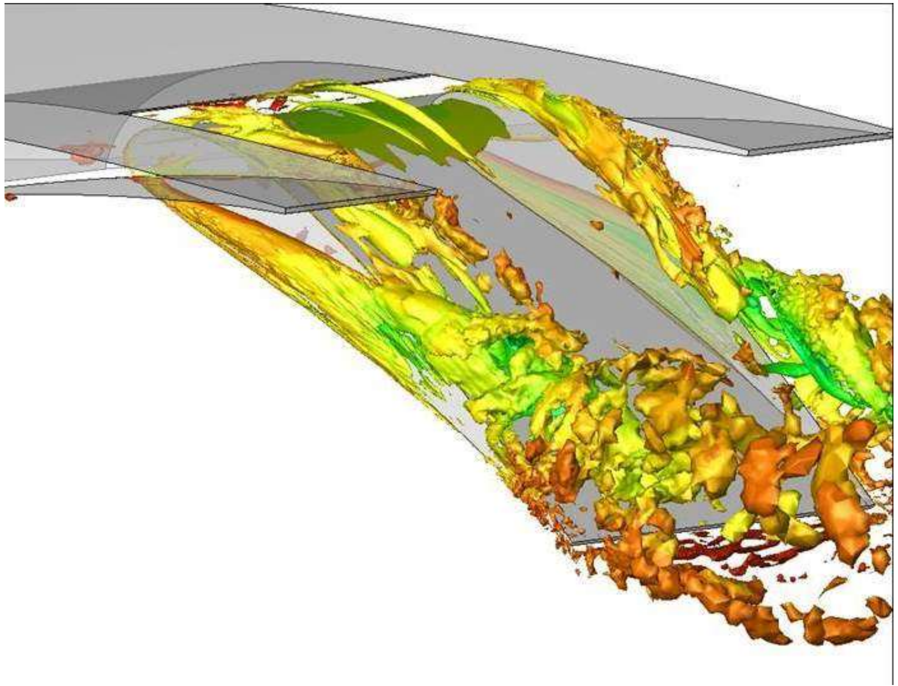


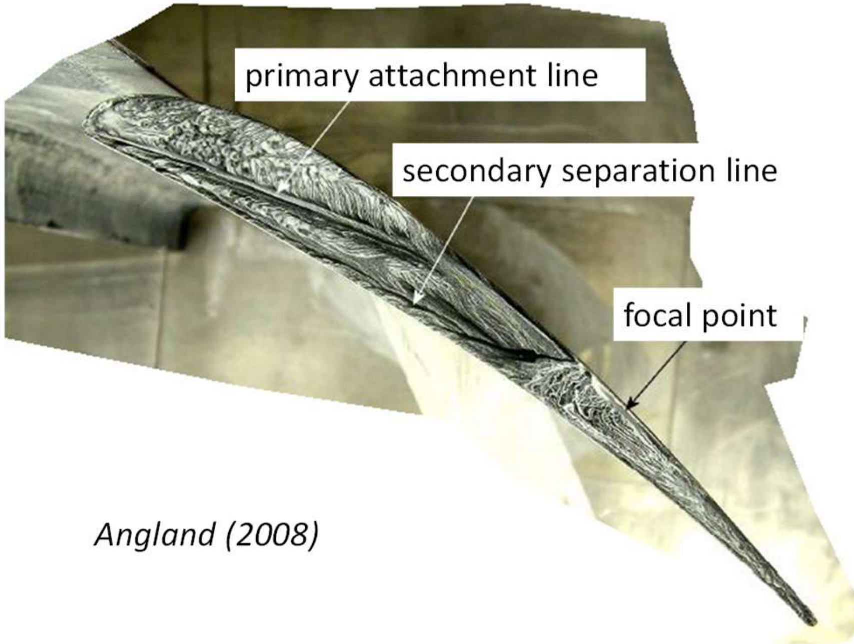
E. Manoha

E. Manoha, M. Terracol, B. Lemoine, I. Le Griffon & T. Le Garrec (2012) AIAA paper **2012-2100.**

Side-Edge Sources

Shown here for Flaps





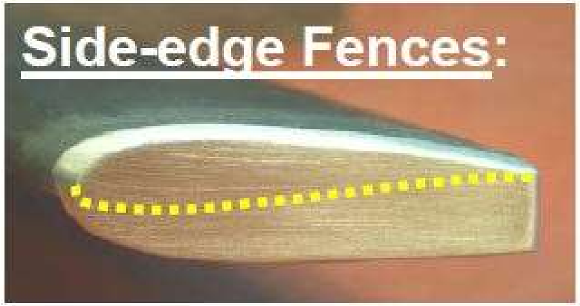
From Galdeano *et al* (Dassault 2013) - Flow simulations compared to streak-line visualizations (Angland 2008).

Flap side edge Noise mitigation

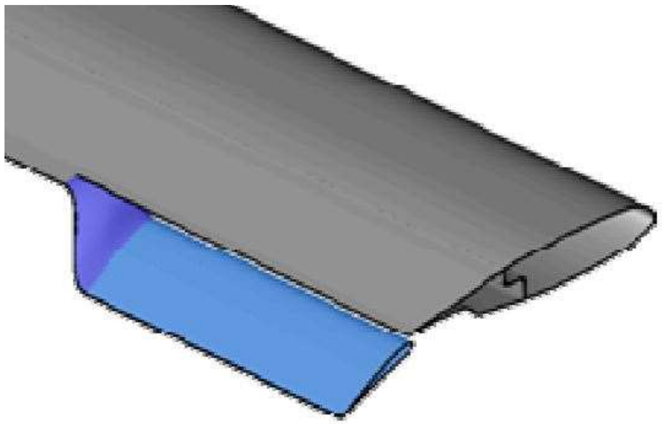
Side-edge fences

Porous materials

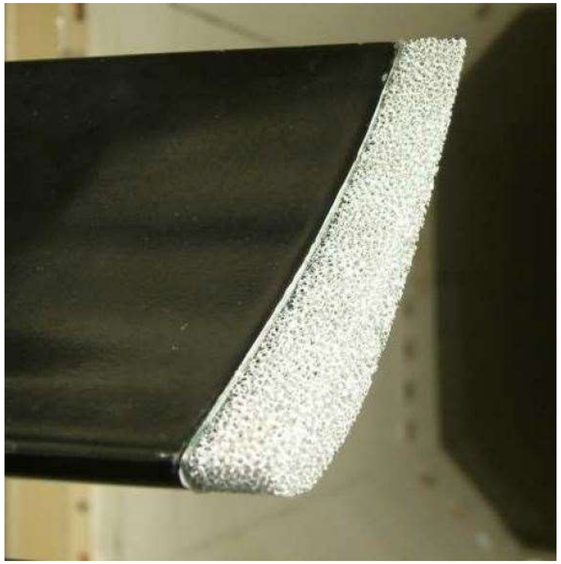
Moldline junctions



From Dobrzynski (2008)



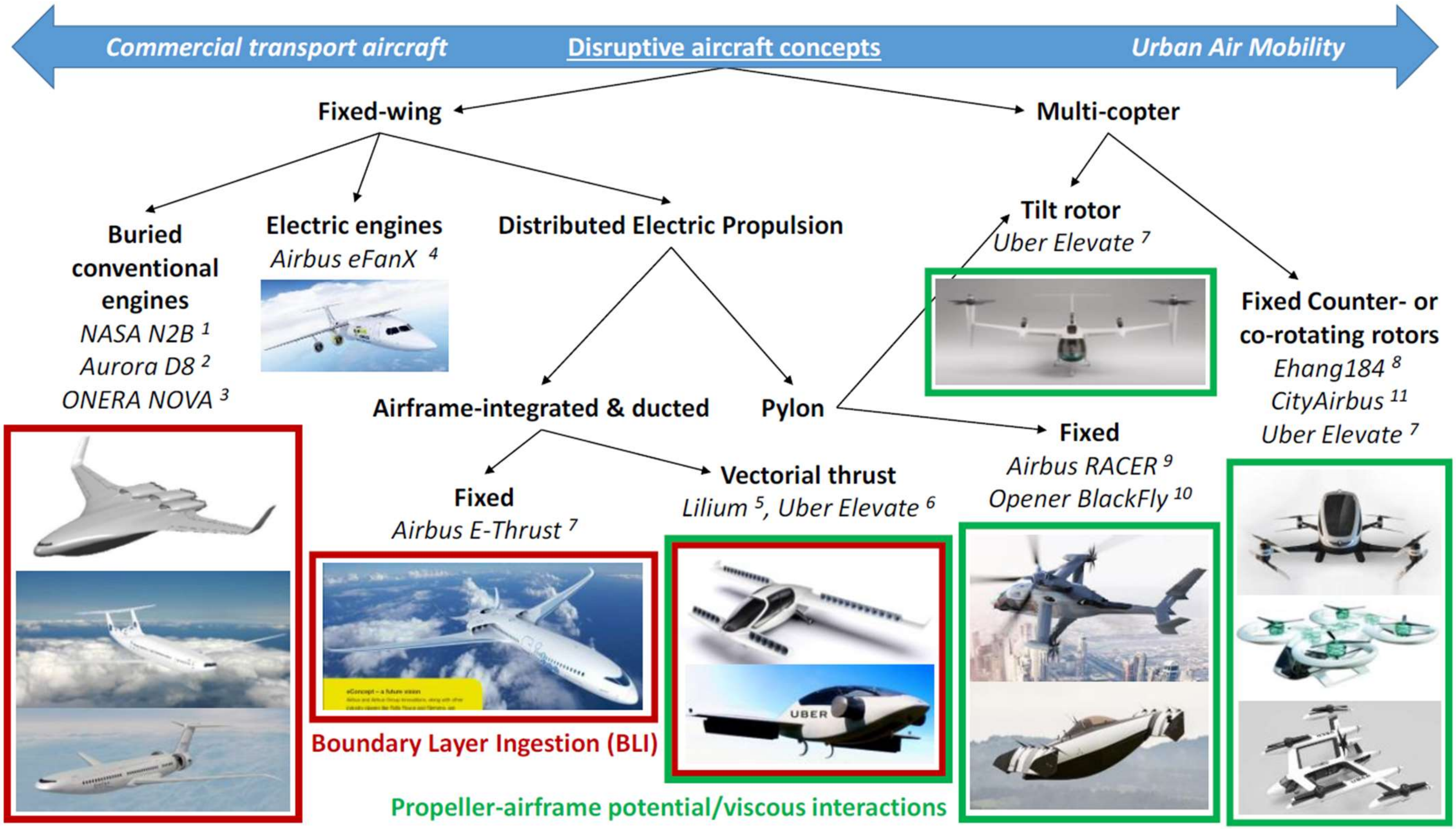
From Dobrzynski (2008), NASA source



From Angland (2008)

Perspectives

What's next ?

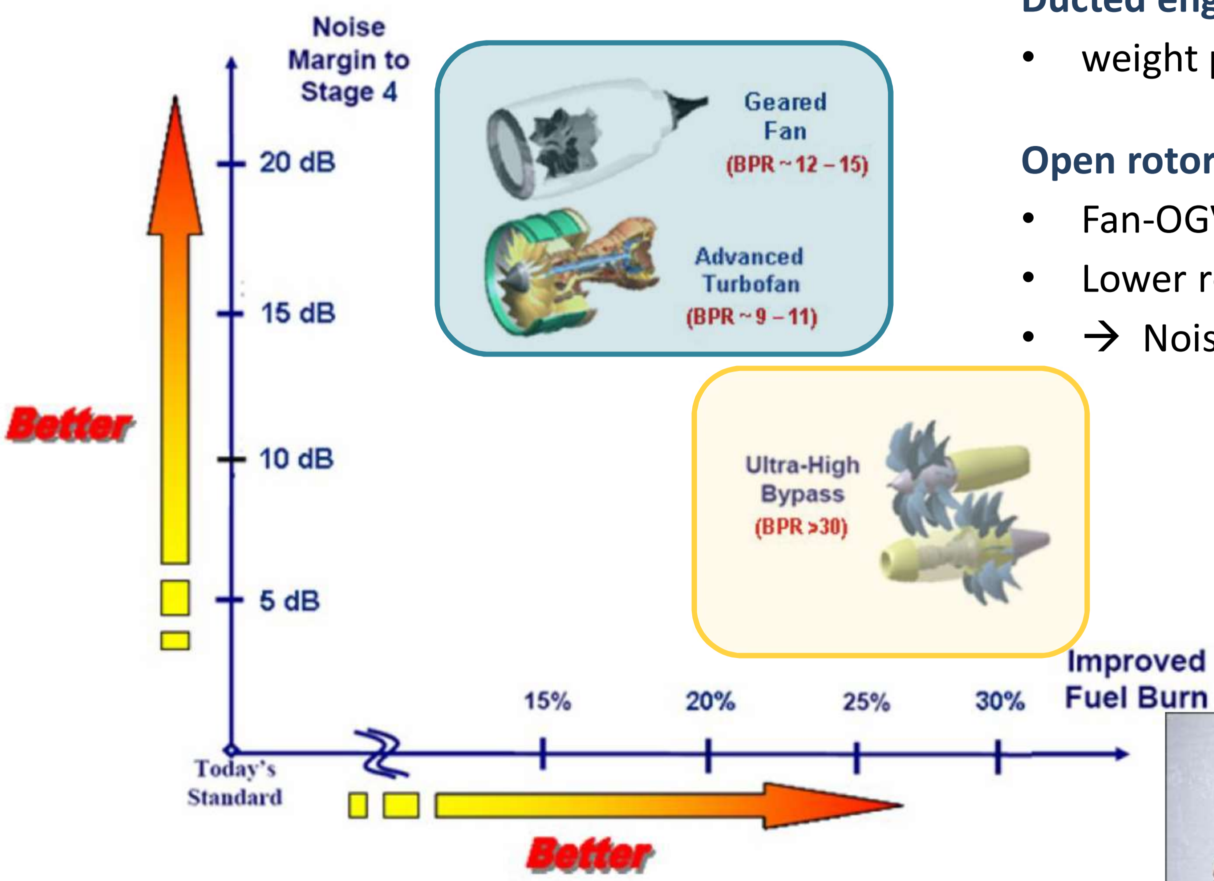


&drones

Source : European project ENODISE 2020-2024: extend current prediction tools to a variety of new architectures

What's next ?

New engine architectures for commercial airplanes



Ducted engines

- weight penalty ↗ when bypass ratio ↗

Open rotors

- Fan-OGV unducted, higher BPR
- Lower rotational speed
- → Noise ↗ expected

New challenges for Sound engineering:

International student competition

Opening soon finishing Sept 2024

Organized by Von Karman Institute (Brussels) and associated partners of the ENODISE project (*) + external particpants

Design silent Aircraft

- **Specifications given**

  (size, weight, payload, range)
- **No fuel penalty**

How: research project during your Master

Jury: september 2024

Detailed anouncement to come

(*): *TU-Delft, TU-Twente, Ecole Centrale de Lyon, RWTH – Aachen, Univ. Bristol, Univ. Roma 3 ONERA, DLR, NLR, Pipistrel Vertical Solutions, GPU Prime, Siemens Industry Software NV*

The End …