Noise control and prediction technologies for sustainable aviation

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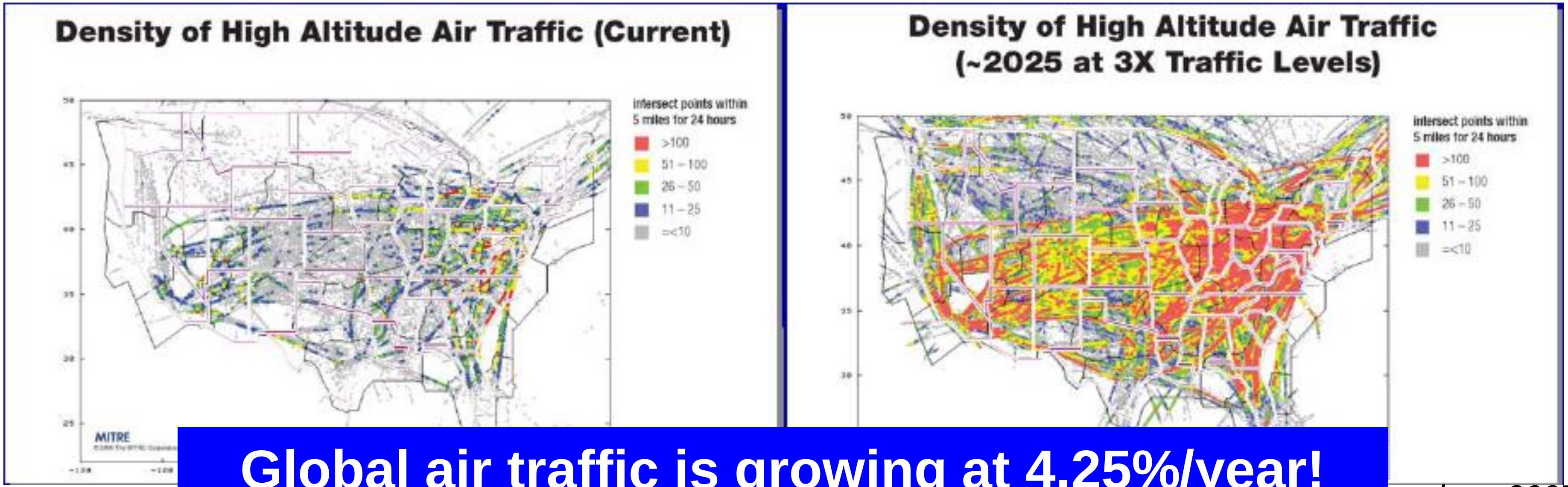
Future challenges (1)

For years population mobility has increased because of more and quicker transportation systems. In the States, the Joint Planning and Development Office (JPDO) is currently developing a new system NextGen to increase the air traffic by a factor 3 in 2025.

Reducing noise sources is critical to achieve such a goal as the JPDO indicates that without a substantial effort the number of people exposed to high noise levels will grow significantly.

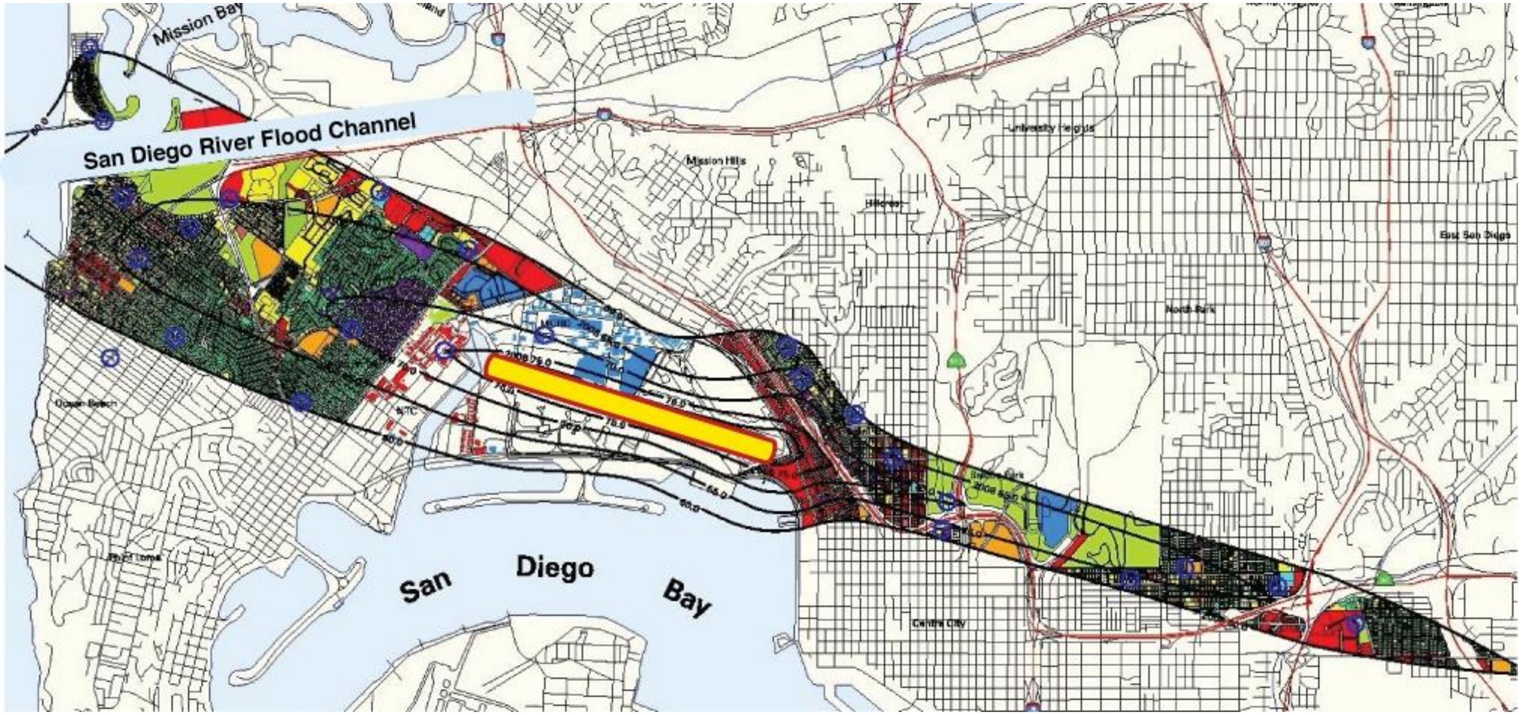


Global air traffic is growing at 4.25%/year!

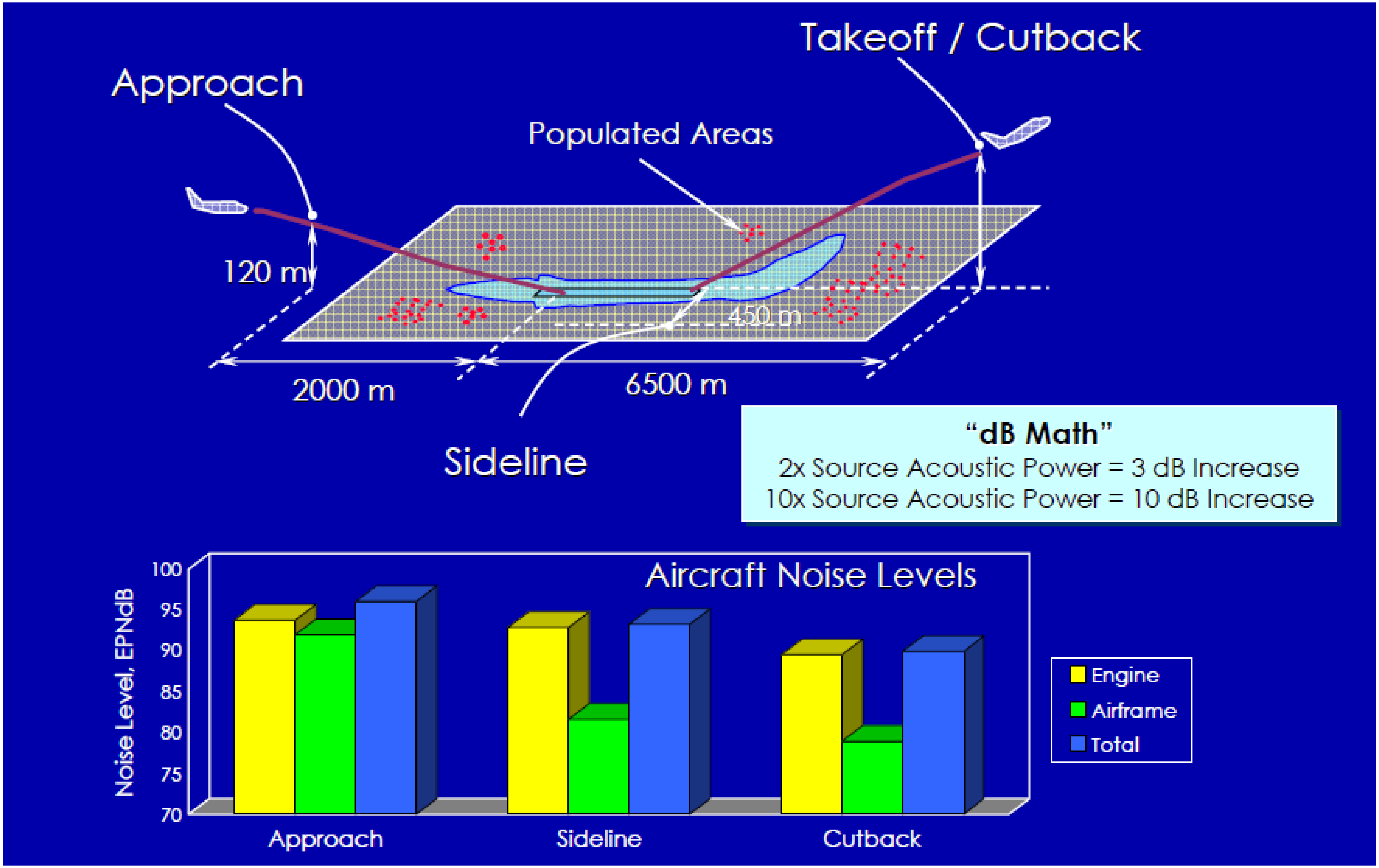
seminar, 2007

Future challenges (2)

In large cities population has increased so much and so fast that the airport area becomes surrounded by the city and more and more people are exposed to high noise levels daily (*health issue*).



Aircraft acoustic certification



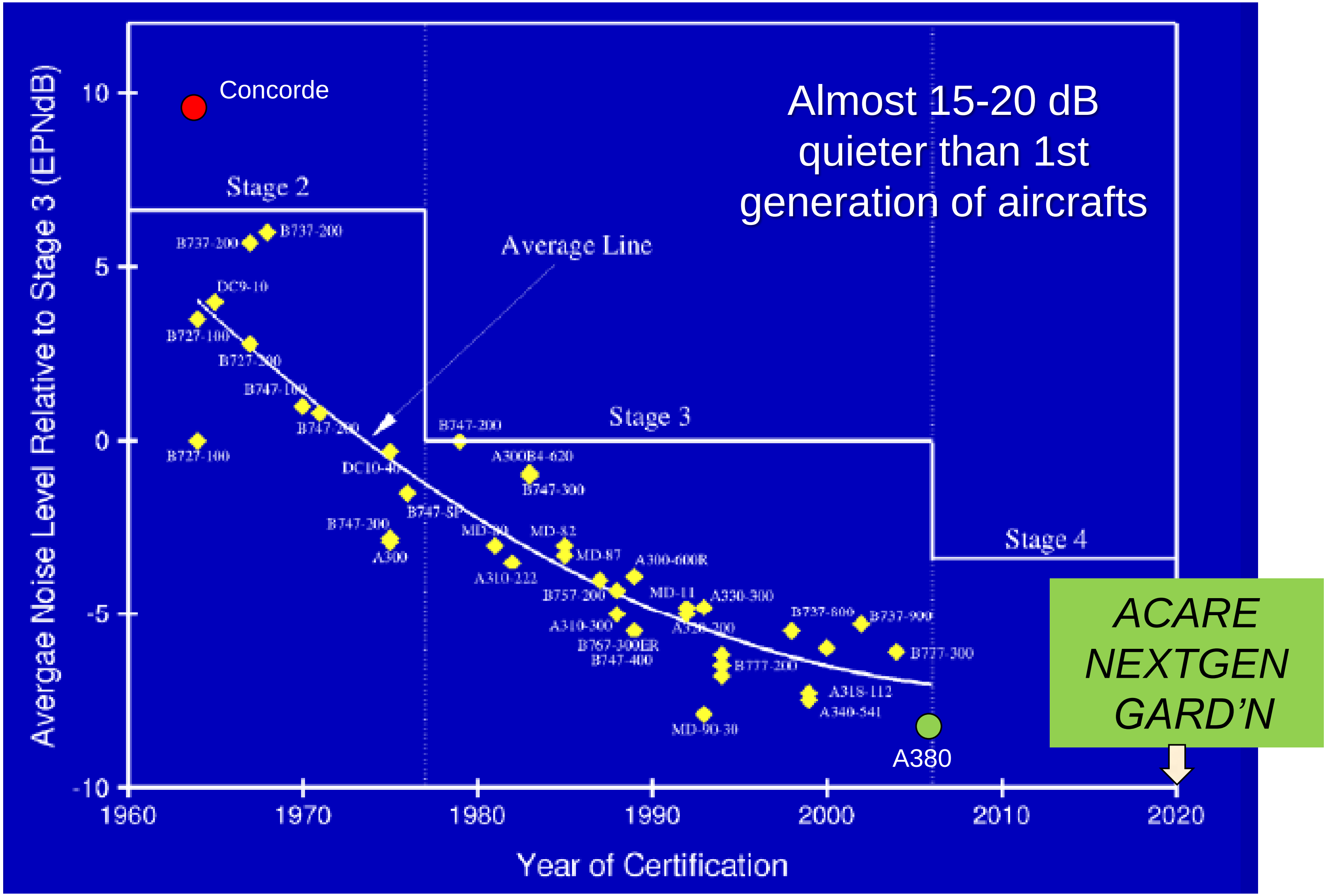
"dB Math"

2x Source Acoustic Power = 3 dB Increase

10x Source Acoustic Power = 10 dB Increase

Source: Envia, ARMD Technical seminar, 2007

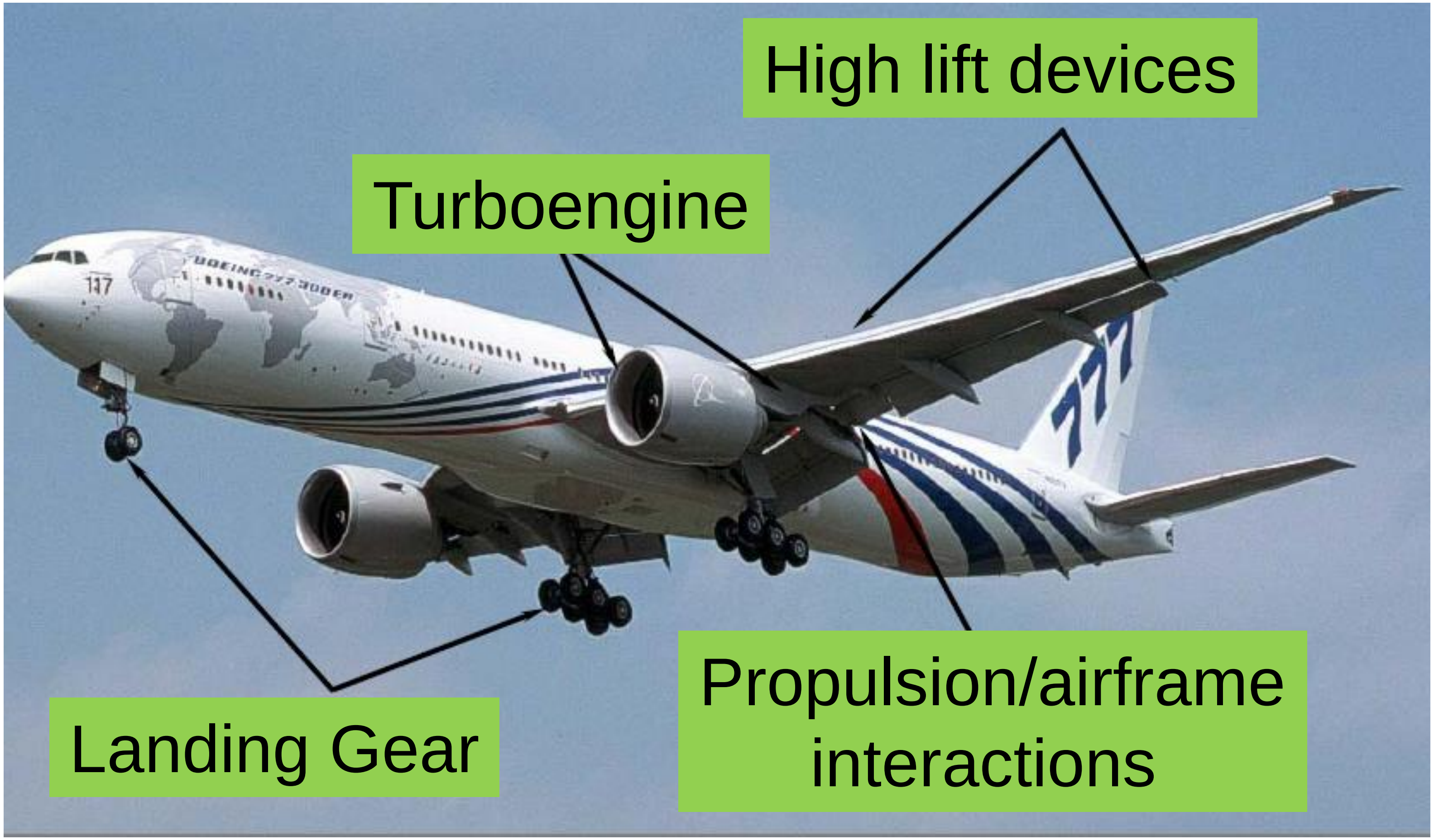
Evolution of aircraft noise



Almost 15-20 dB quieter than 1st generation of aircrafts

ACARE NEXTGEN GARD'N

Aircraft noise sources



High lift devices

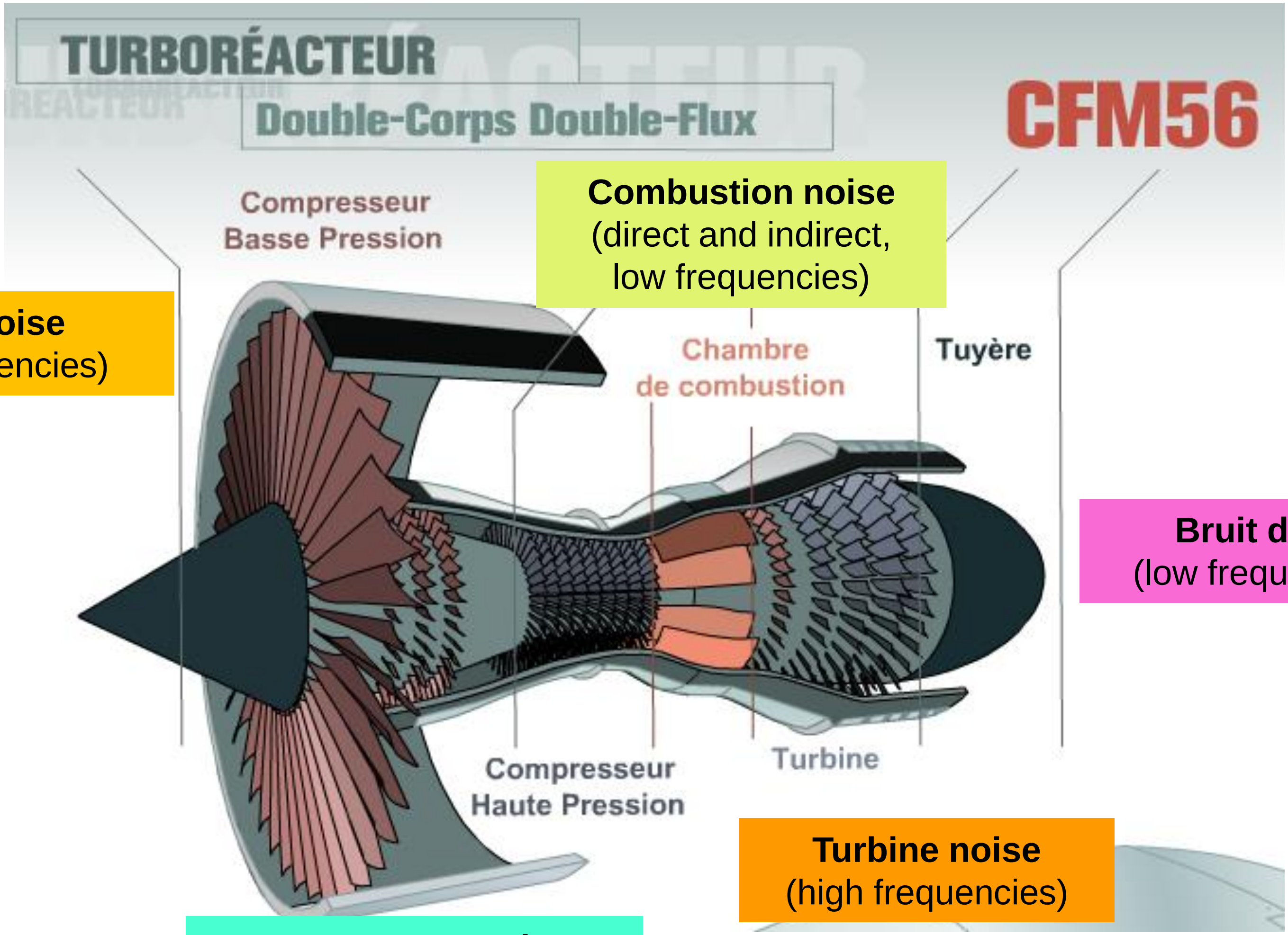
Turboengine

Landing Gear

Propulsion/airframe interactions

An aircraft is a complex set of acoustic sources, a problem of interactions, of transmission and propagation

Engine noise sources



Fan noise
(all frequencies)

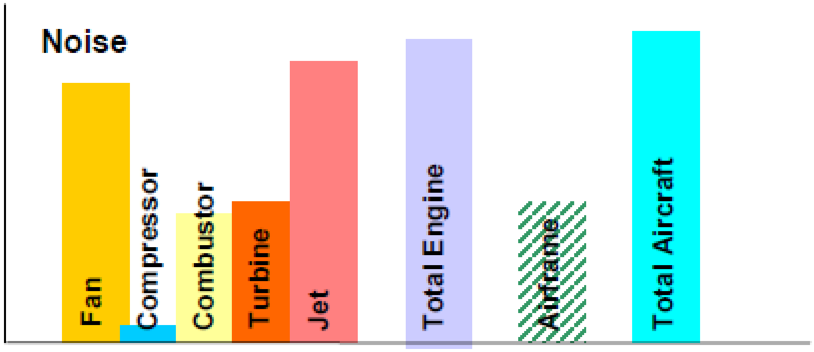
Combustion noise
(direct and indirect, low frequencies)

Bruit de jet
(low frequencies)

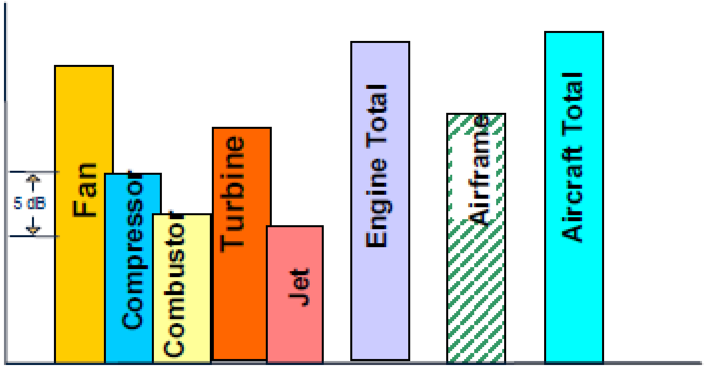
Turbine noise
(high frequencies)

Compressor noise
(high frequencies)

Hierarchy of engine noise sources



Séparation de sources T/O

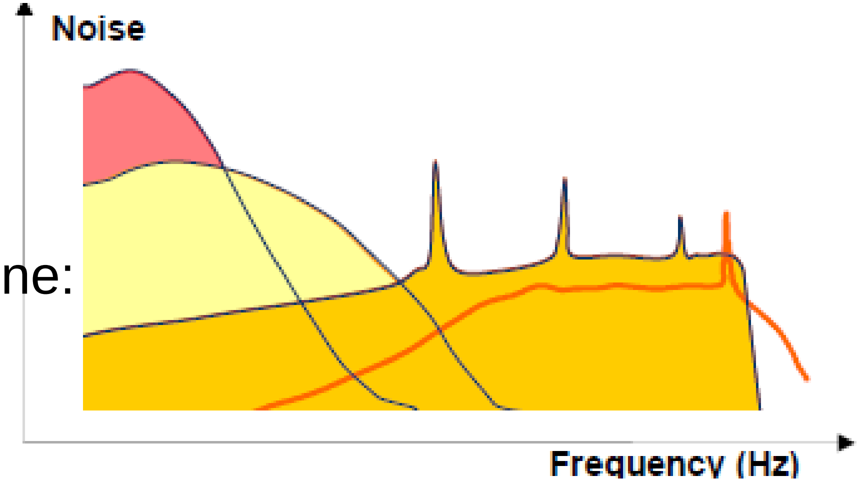


Sources breakdown at approach

<u>At take-off</u>, the dominant sources are **the jet and the fan**

<u>At approach</u>, the dominant source is **the fan** and more and more *the turbine*

Acoustic signature of a typical turboengine:

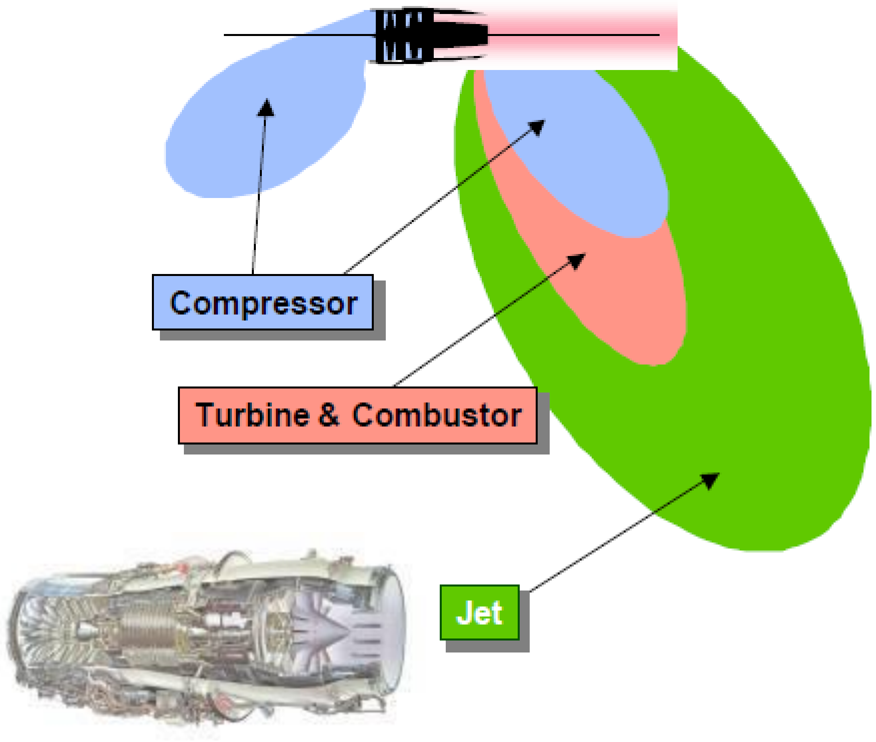


Source: Julliard, IROQUA Technical seminar, 2006

Strong variations with engine types

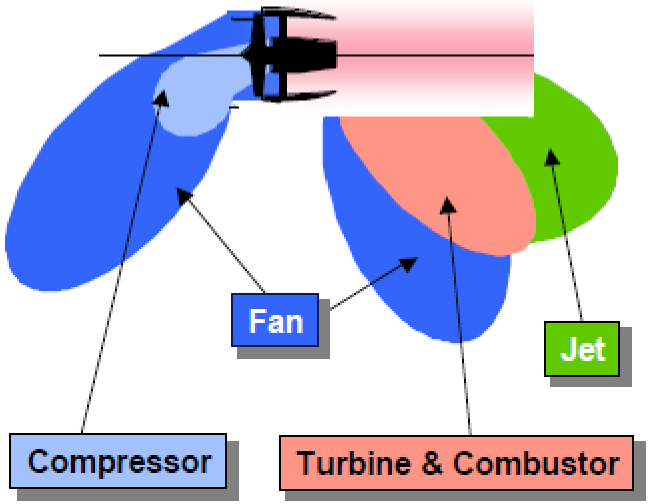
Strong variations of pressure levels around an engine (strong directivity)

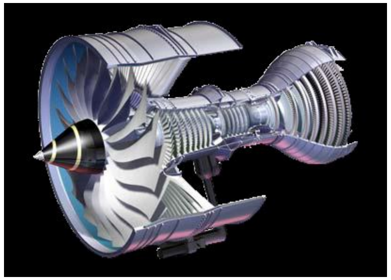
Noise of a typical 1960s engine



Turbojet noise dominated by single-flux high-speed jet (aft)

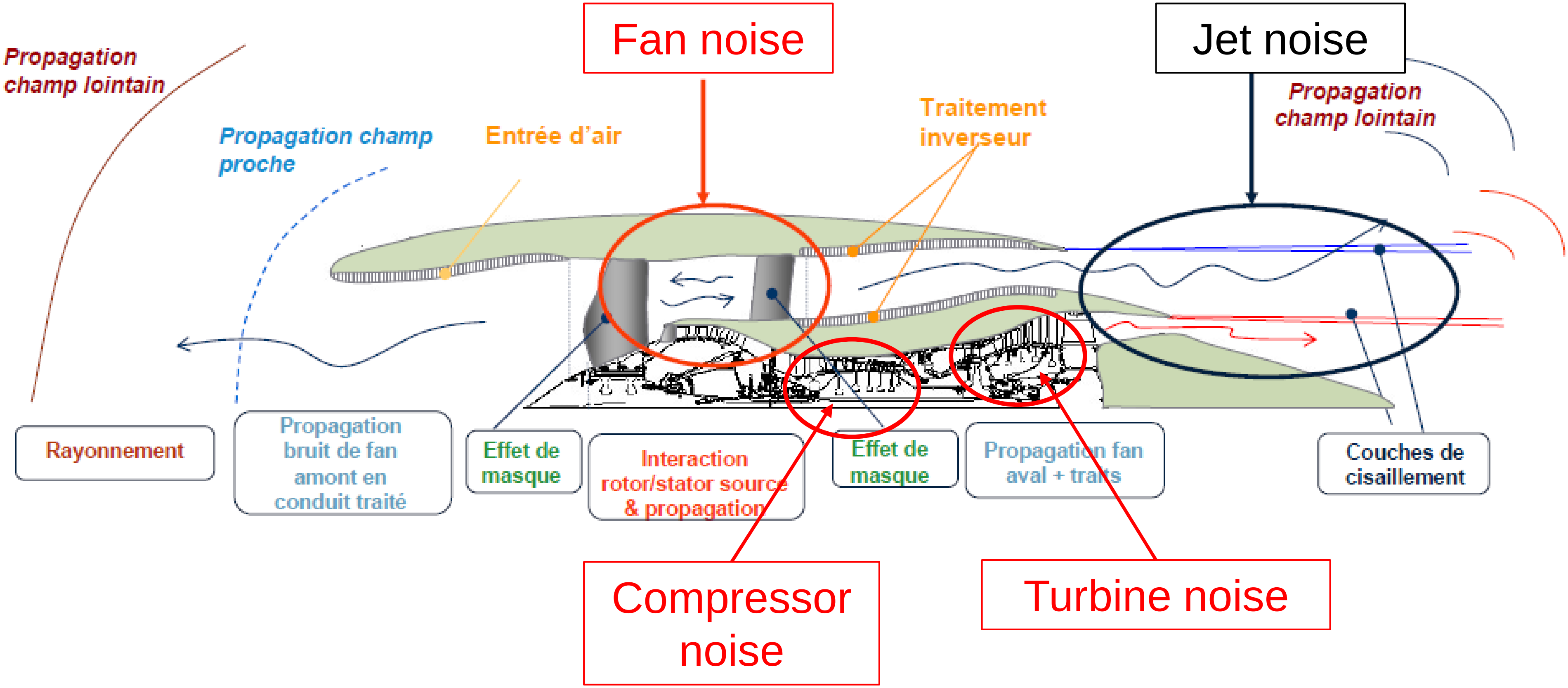
Noise of a typical 1990s engine





Turbofan noise with high by-pass ratio dominated by fan (forward) and jet (aft)

Noise generation and propagation in a turboengine



Fan noise

Jet noise

Compressor noise

Turbine noise

Source: Julliard, IROQUA Technical seminar, 2006

Conservation equations in a fluid

Mass conservation: (continuity equation):

$$\frac{\partial\rho}{\partial t}+\frac{\partial}{\partial x_i}\left(\rho\, u_i\right)=0 \quad ou \quad \frac{\partial\rho}{\partial t}+\nabla\bullet\left(\rho\,\vec{u}\right)=0$$

Momentum conservation:

$$\rho\left(\frac{\partial u_j}{\partial t}+u_i\frac{\partial u_j}{\partial x_i}\right)=-\frac{\partial p}{\partial x_j}+\cancel{\frac{\partial\tau_{ij}}{\partial x_j}} \quad ou \quad \rho\frac{D\vec{u}}{Dt}=-\nabla p+\cancel{\nabla\bullet\vec{\vec{\tau}}}$$

Energy or entropy conservation:

$$\rho T\left(\frac{\partial s}{\partial t}+u_i\frac{\partial s}{\partial x_i}\right)=-\frac{\partial q}{\partial x_i}+\cancel{\tau_{ij}\frac{\partial u_j}{\partial x_i}} \quad ou \quad \rho T\left(\frac{\partial s}{\partial t}+\vec{u}\bullet\nabla s\right)=-\nabla\bullet\vec{q}+\cancel{\vec{\vec{\tau}}:\nabla\vec{u}}$$

Need to solve them directly (DNS) to extract the sound.

For high Reynolds number flows, URANS can provide tones and LES the broadband component.

Linearized Euler Equations

Linearized Euler equations in a **non-uniform** fluid (p_0, ρ_0, s_0, u_0…) within a mean **steady** field:

Mass:

$$\boxed{\frac{\partial \rho'}{\partial t} + \vec{u}_0 \bullet \nabla \rho' + \vec{u}' \bullet \nabla \rho_0 + \rho_0 \nabla \bullet \vec{u}' + \rho' \nabla \bullet \vec{u}_0 = 0 \qquad (1)}$$

Momentum:

$$\boxed{\rho_0 \left(\frac{\partial \vec{u}'}{\partial t} + \vec{u}_0 \bullet \nabla \vec{u}' + \vec{u}' \bullet \nabla \vec{u}_0 \right) + \rho' \vec{u}_0 \bullet \nabla \vec{u}_0 = -\nabla p' \qquad (2)}$$

$$\boxed{\frac{\partial p'}{\partial t} + \vec{u}_0 \bullet \nabla p' + \vec{u}' \bullet \nabla p_0 = c_0^2 \left(\frac{\partial \rho'}{\partial t} + \vec{u}_0 \bullet \nabla \rho' + \vec{u}' \bullet \nabla \rho_0 + \left(\frac{p'}{p_0} - \frac{\rho'}{\rho_0} \right) \vec{u}_0 \bullet \nabla \rho_0 \right) \qquad (3)}$$

Its simplifies to a general wave equation in a uniform fluid at rest.

Otherwise numerical integration is still needed!

Still cumbersome and computationally intensive

Lighthill’s equation

$$\frac{\partial}{\partial t}\left[\frac{\partial\rho}{\partial t}+\frac{\partial(\rho u_i)}{\partial x_i}=0\right]$$

continuity

$$-\frac{\partial}{\partial x_i}\left[\frac{\partial(\rho u_i)}{\partial t}+\frac{\partial(\rho u_i u_j)}{\partial x_j}=\frac{\partial\sigma_{ij}}{\partial x_j}\right]$$

momentum

$$\boxed{\frac{\partial^2\rho}{\partial t^2}-\frac{\partial^2(\rho u_i u_j)}{\partial x_i\,\partial x_j}=-\frac{\partial^2\sigma_{ij}}{\partial x_i\,\partial x_j}}$$

$$\left(\frac{\partial\sigma_{ij}}{\partial x_j}=-\frac{\partial p}{\partial x_j}+\frac{\partial\tau_{ij}}{\partial x_j}\right)$$

$$-c_0^2\frac{\partial^2\rho}{\partial x_j^2} \qquad\qquad -c_0^2\frac{\partial^2\rho}{\partial x_j^2}$$

A reference state is introduced:

$$\rho'=\rho-\rho_0;\; p'=p-p_0$$

$$\boxed{\frac{\partial^2\rho'}{\partial t^2}-c_0^2\frac{\partial^2\rho'}{\partial x_j^2}=\frac{\partial^2}{\partial x_i\,\partial x_j}\underbrace{\left[\rho u_i u_j+(p'-c_0^2\rho')\delta_{ij}-\tau_{ij}\right]}_{\text{Lighthill's tensor } T_{ij}}}$$

Lighthill's acoustic analogy

(sound produced by a local turbulent spot of turbulence, 1952)

Flow region

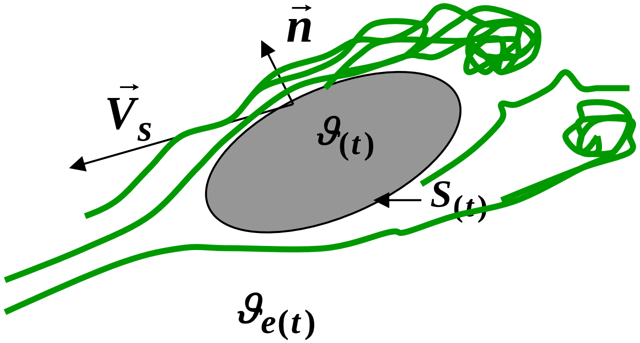
Complex problem ruled by Navier-Stokes equations

● **Far-field observer**

The problem reduces to simpler linear acoustic propagation,

- For the observer, the flow field is replaced by equivalent sources radiating in a medium at rest.
- The problem then boils down to the definition of equivalent sources (*aerodynamic*).

Ffowcs Williams & Hawkings' analogy (1969)



Solid body in motion in air:

$$f(\vec{x},t)=0$$

J.E. Ffowcs Williams

Formulation according to distributions

$$\frac{\partial^2 \rho}{\partial t^2} - c_0^2 \frac{\partial^2 \rho}{\partial x_j^2} = \frac{\partial^2 T_{ij}}{\partial x_i \partial x_j}$$

$$+\frac{\partial}{\partial x_i}\left(\sigma_{ij}\,\delta(f)\frac{\partial f}{\partial x_j}\right)+\frac{\partial}{\partial t}\left(\rho_0 V_{si}\,\delta(f)\frac{\partial f}{\partial x_i}\right)$$

Self-noise of flow fields (quadrupoles)

Distributed in exterior volume

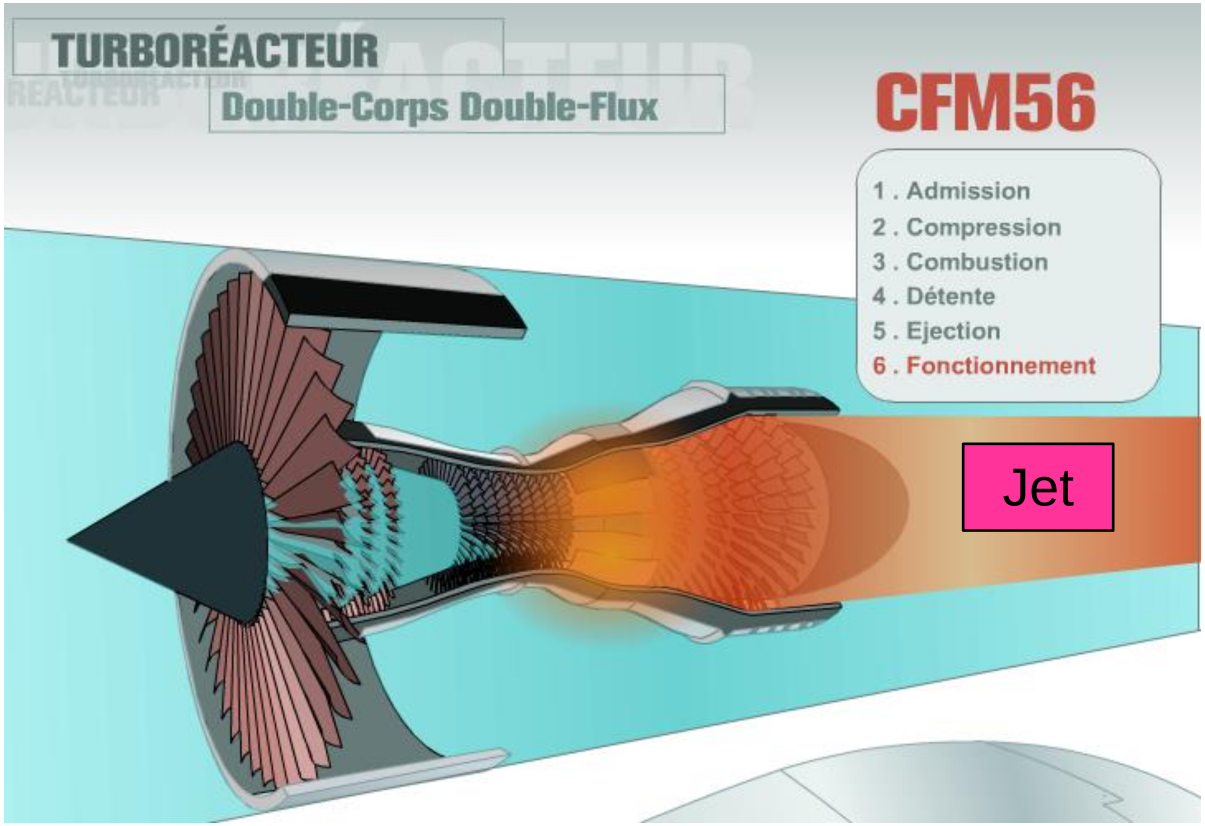
Distributed on surfaces

Loading noise (dipoles)

Thickness noise (monopoles)

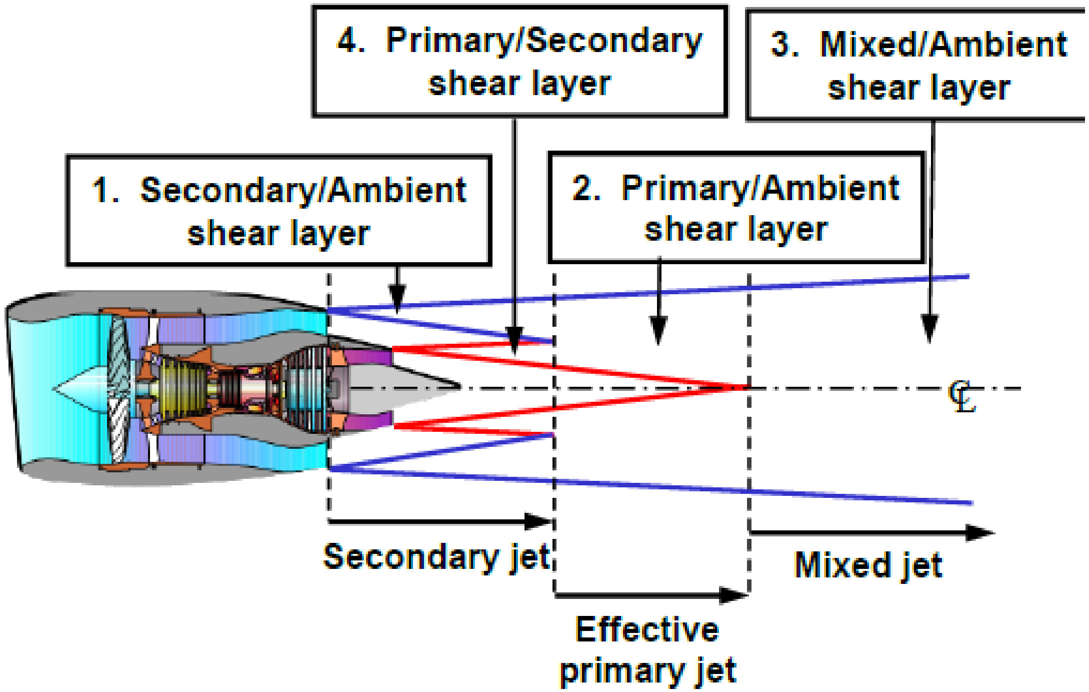
Jet noise

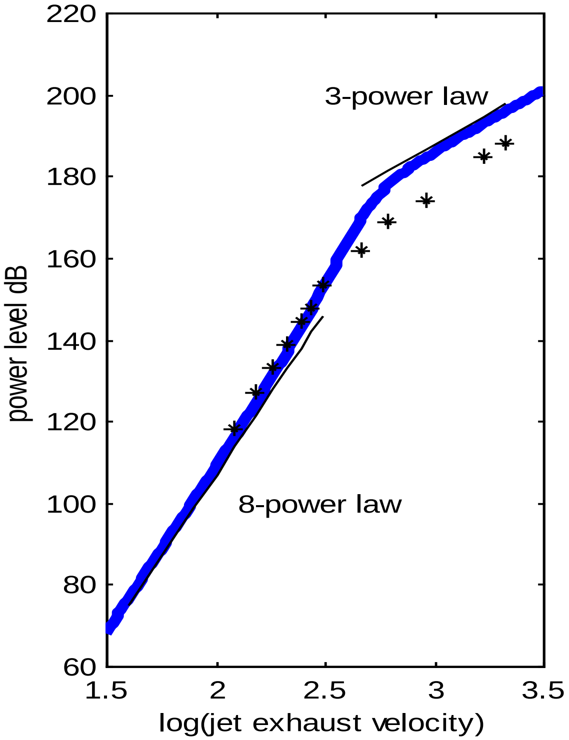
(Lighthill, Ribner, etc…)



The jet is the first example of mixing noise (success of Lighthill's analogy)

Jet noise mechanisms





- Sources distributed downstream of the nozzle
- Sound scaling as U^8 or U^3 (U exhaust, jet velocity).
- Source strength depends on unsteady turbulent mixing
- Large noise data bases available for single and coaxial cold and hot jets (spectral models proposed by Tam, Viswanathan)

Comparaison between subsonic and supersonic turbulent jets

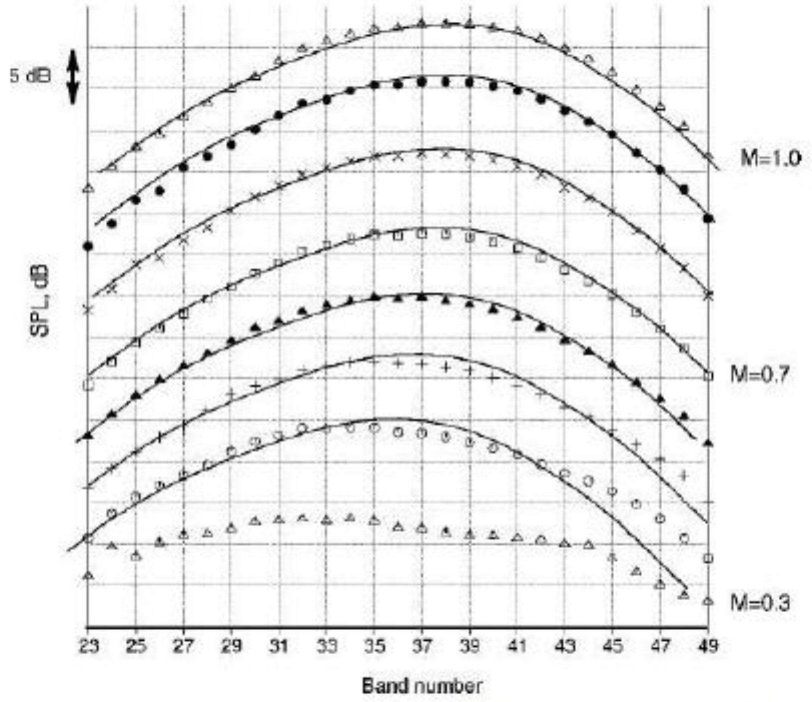


Fig. 12 Comparison of spectra from cold jets, D = 1.5 in., angle = 90 deg: △, M = 0.3; ○, M = 0.4; +, M = 0.5; ▲, M = 0.6; □, M = 0.7; ×, M = 0.8; ●, M = 0.9; △, M = 1.0; and ——, FSS spectrum.

D'après Viswanathan, 1994

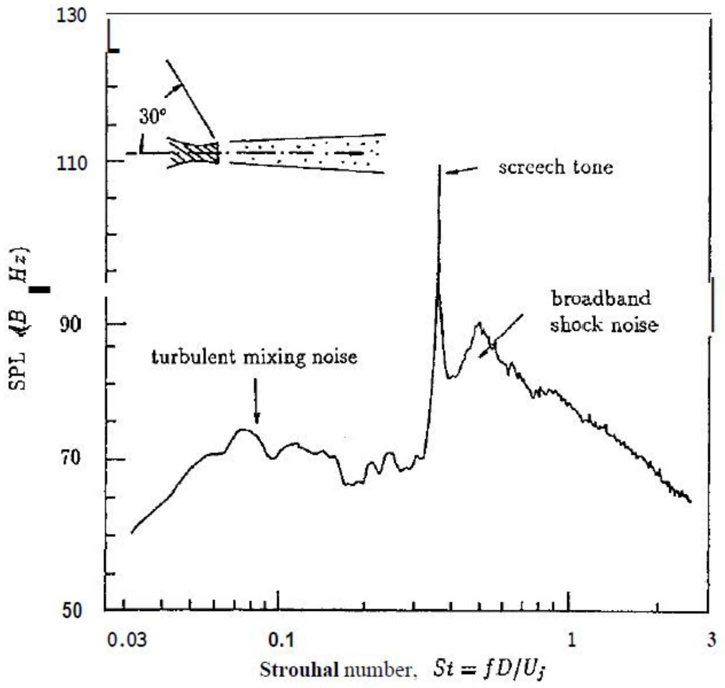
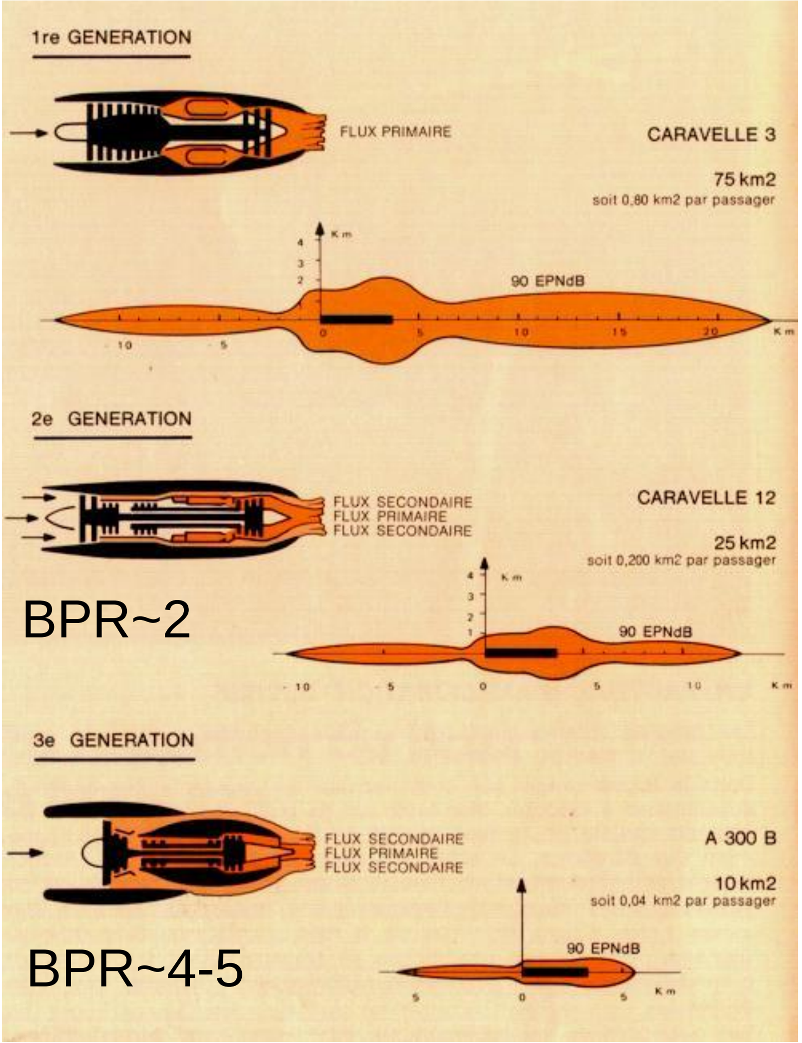


Fig. 2 Typical far-field noise spectrum of an imperfectly expanded supersonic jet, measured at 30-deg inlet angle, showing the three principal noise components. Data from Seiner[1] Nozzle design Mach number 2.0. Jet Mach number 1.5.

D'après Tam, 1995

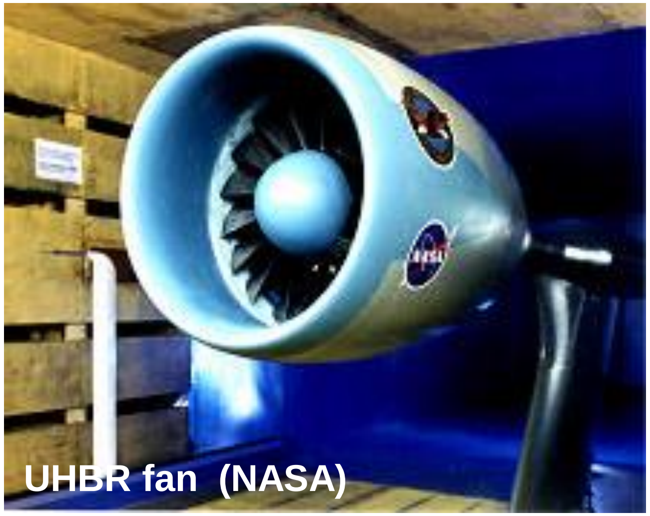
Impact of BPR technology on jet noise

- The sound nuisance of an engine can be estimated by the noise footprint on the ground (EPNdB), compared to the number of passengers.
- The switch to dual-stream engine with a small then a large by-pass ratio has allowed reducing noise significantly. The reduction of ejection speeds by increasing diameters allow reducing mixing noise according to 8th power law.
- Moreover, the dual-stream technology also allow reducing shear (softer mixing).

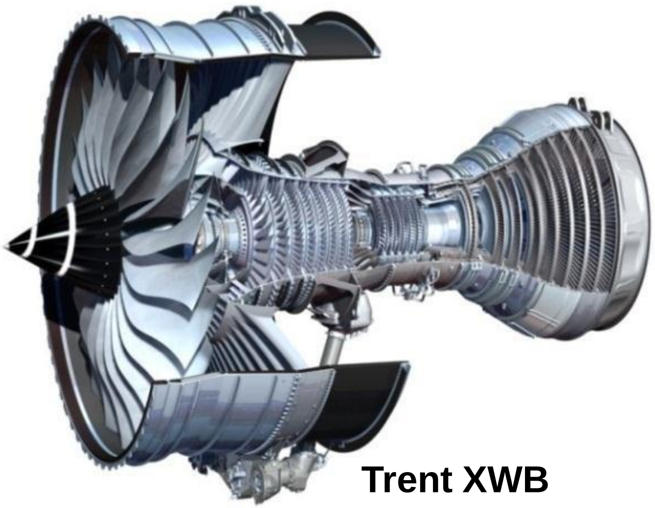


According to the French civil aviaiion

Ultra High By-Pass Ratio (UHBR)



UHBR fan (NASA)



Trent XWB

Approach:
- BPR>10
- Reduce jet exhaust velocities
- Increase mass flow to achieve thrust

Potential noise reduction:
- Jet mixing noise - 5 to 10 dB

Key Issues:
- Increased installation drag and weight - engine is bigger in diameter
- Fan mechanical design - larger fan blades

Sources: Rushwald, Airport Noise Symposium 2002
Whurr from R&R, ETC 2013 keynote

Jet noise control

Concept: Modify the turbulent structure of the jet; promote faster mixing of jet exhaust; Minimize turbulence creation in mixing process

- Forced mixers for buried nozzles
- Chevrons for short cowl
- Deployable tabs (SMA)
- Offset and scarfed nozzles
- Other flow control devices…

Potential noise reduction:

Jet mixing noise - 2 to 4 dB

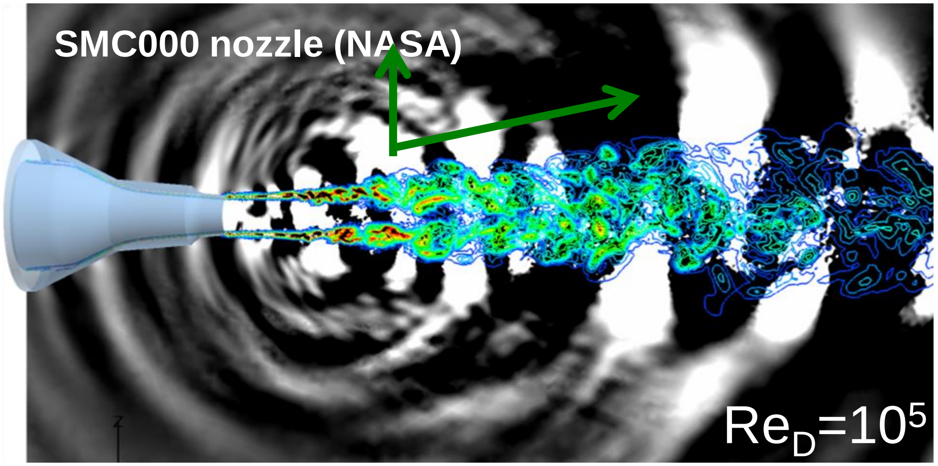
Key Issues:

- More effective at lower BPR
- Aerodynamic losses - reduces thrust, increases fuel consumption
- Mechanical design - structural integrity, vibration

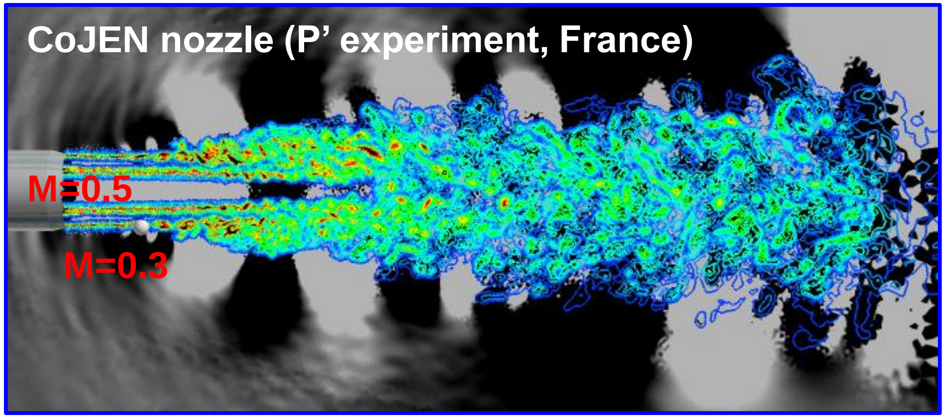
Boeing Rolls-Royce QTD 1

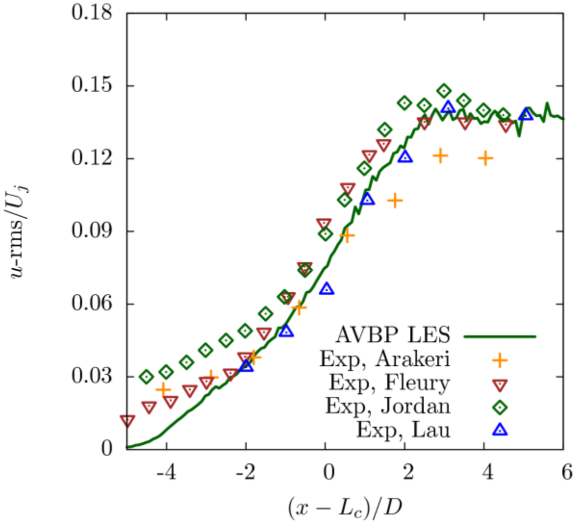
Sources: Rushwald, Airport Noise Symposium 2002
Astley, Omega AOR Workshop 2008

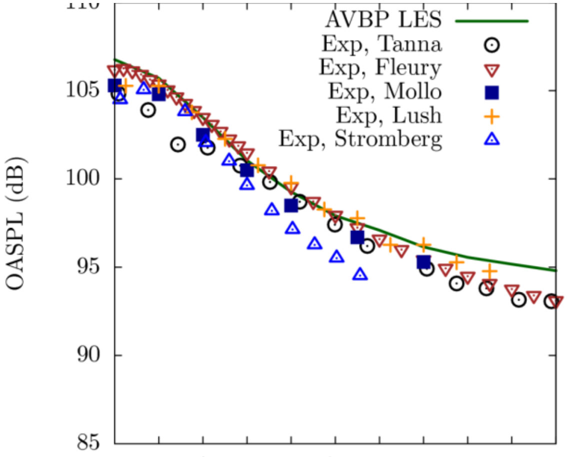
Jet Noise Prediction -1



Sanjose *et al, AIAA 2011;*Fosso *et al, AIAA 2012*



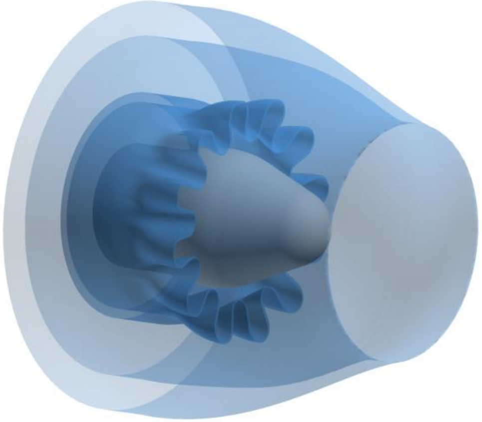


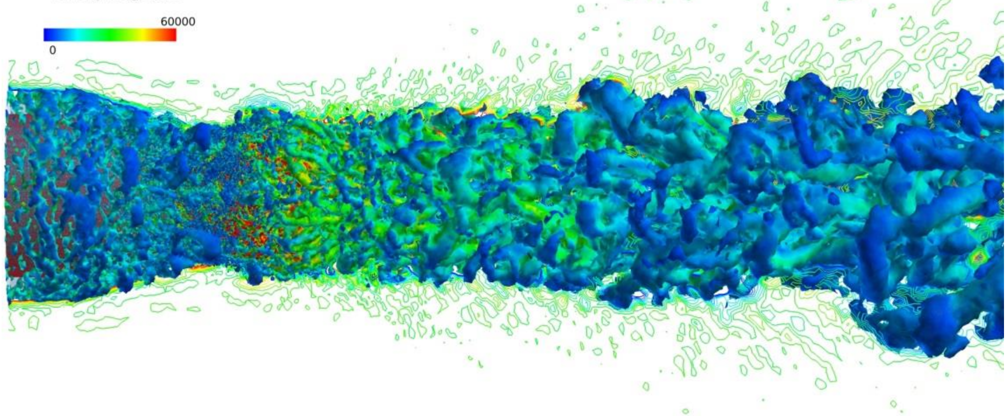


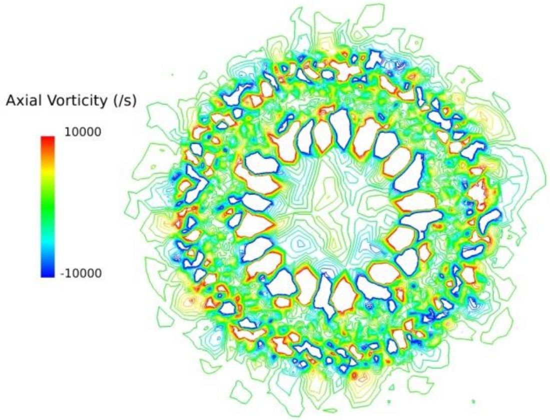
Two main directions of noise emission (30° & 90°)
Proper turbulence development in the shear layers & jet

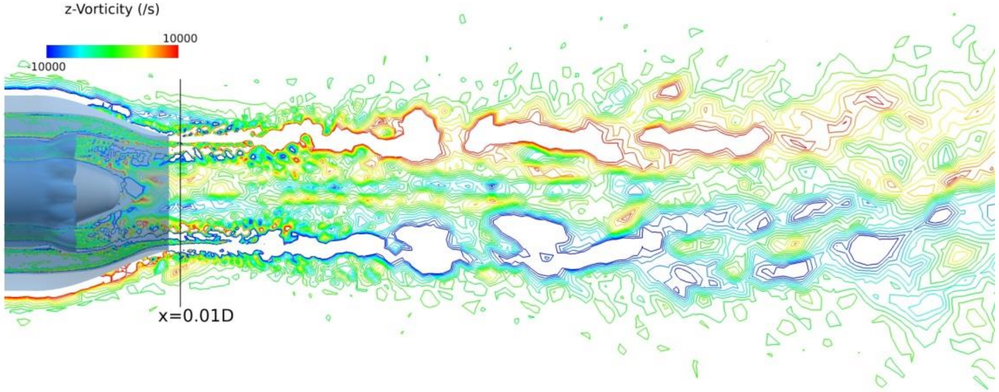
Jet Noise Prediction -2

Fosso *et al, CFD-Canada 2013*



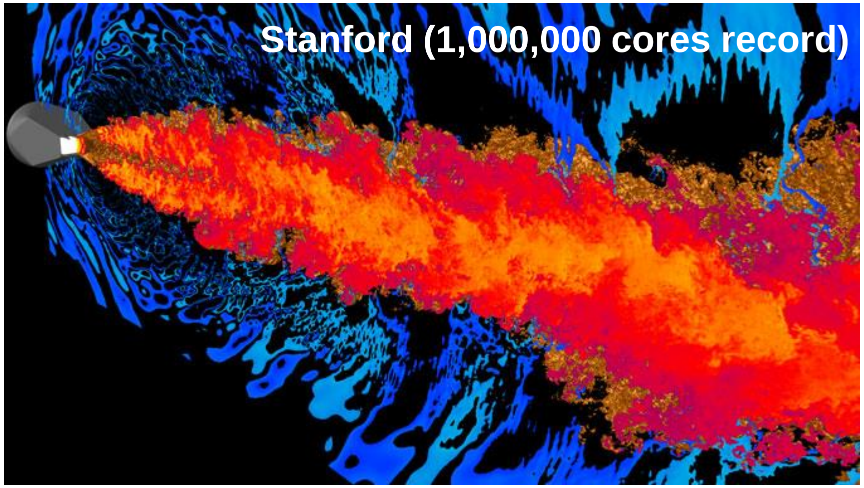






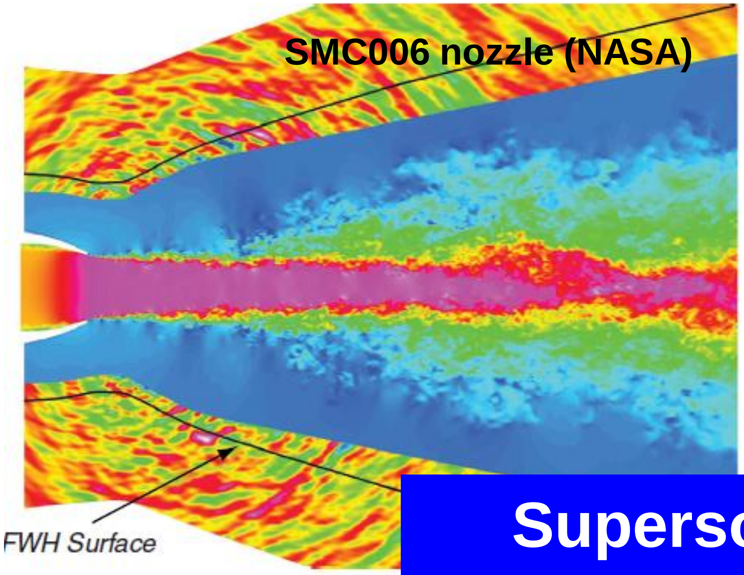
Enhanced mixing (much finer scales at nozzle exits)
Strong streamwise vorticity induced by lobes

Jet Noise Prediction -3

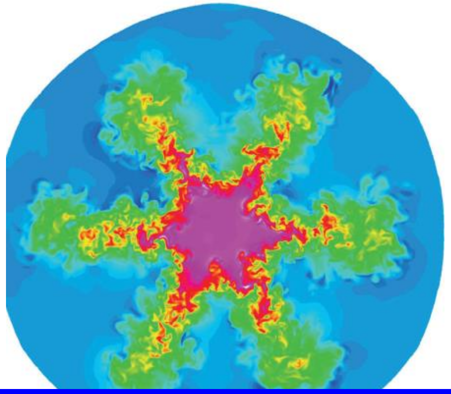


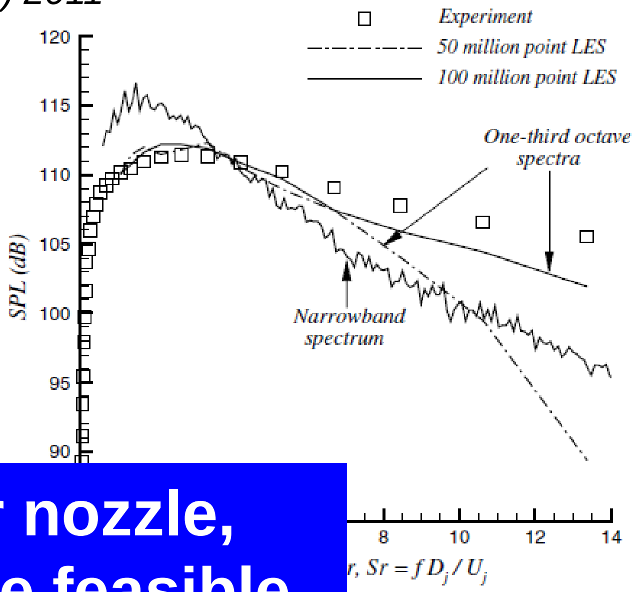
Stanford (1,000,000 cores record)

Source: *Uzun et al, IJA 10(5) 2011*



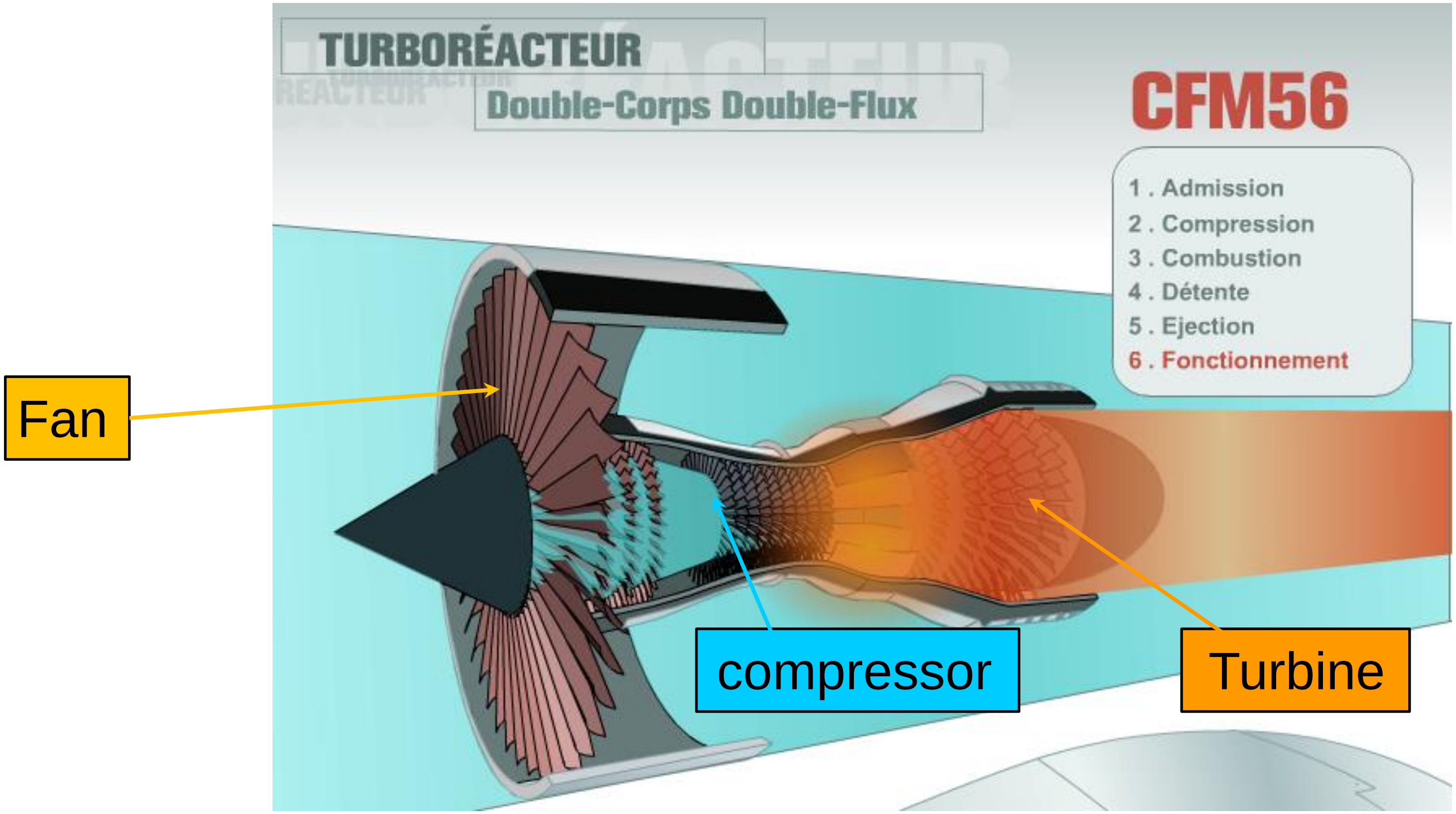
SMC006 nozzle (NASA)





Supersonic rectangular nozzle, Chevrons simulations are feasible

Turbomachinery/Surface noise

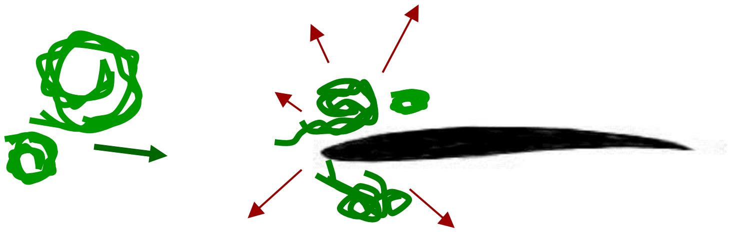


<u>Note</u>: the contribution of broadband noise from solid walls can represent half of the fan noise. Given its random nature an isolated profile is initially enough.

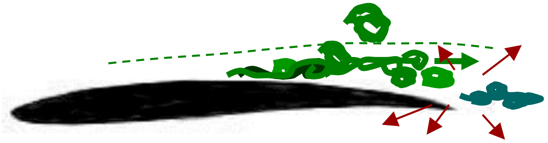
Broadband airfoil noise mechanisms

On a profile, the pressure fluctuations or unsteady loading induced on the surface by a vortical field (turbulent, random) can yield many mecanisms:

Turbulence-interaction noise (TIN)

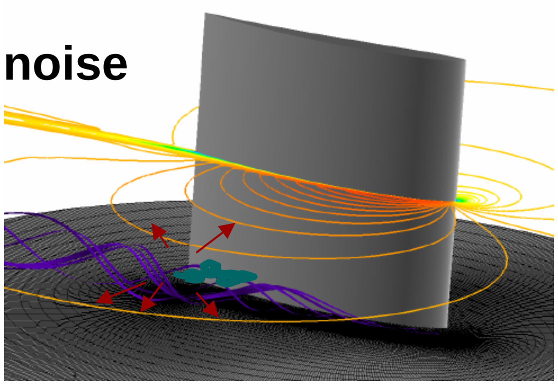


Trailing-edge noise (TEN)

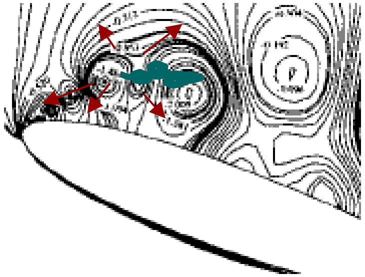


Vortex shedding noise

Tip noise

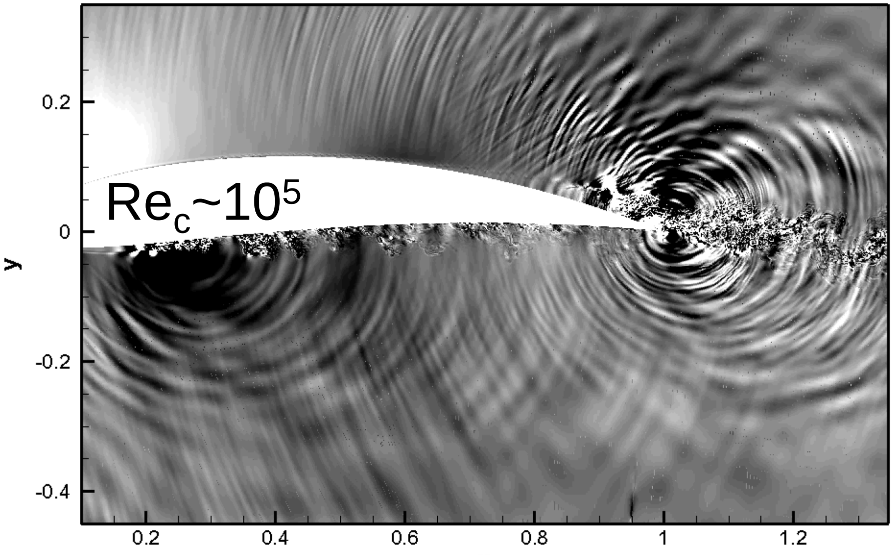


Stall noise

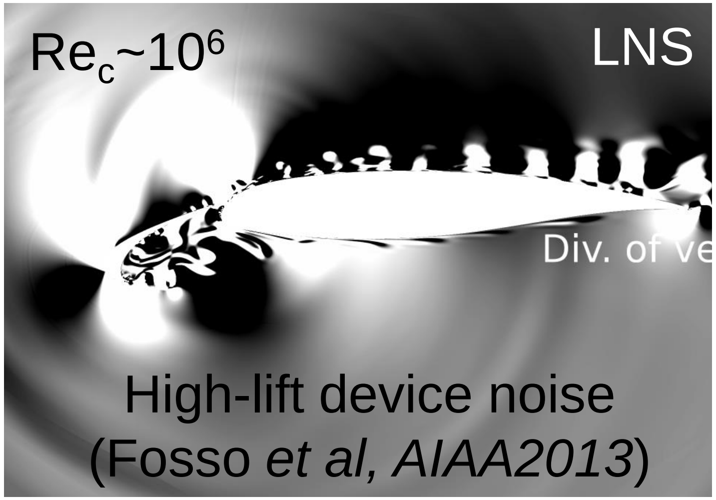


NB: the variation of vorticity spreads over about one characteristic vortex length

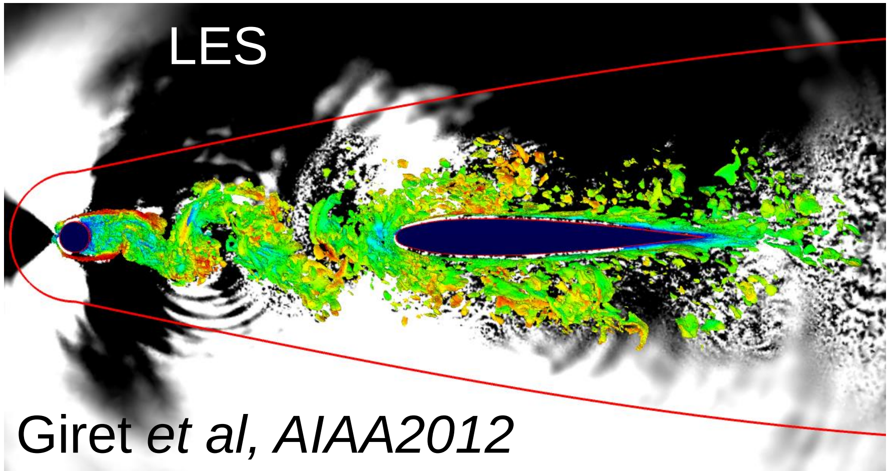
Airfoil/bluff body noise predictions



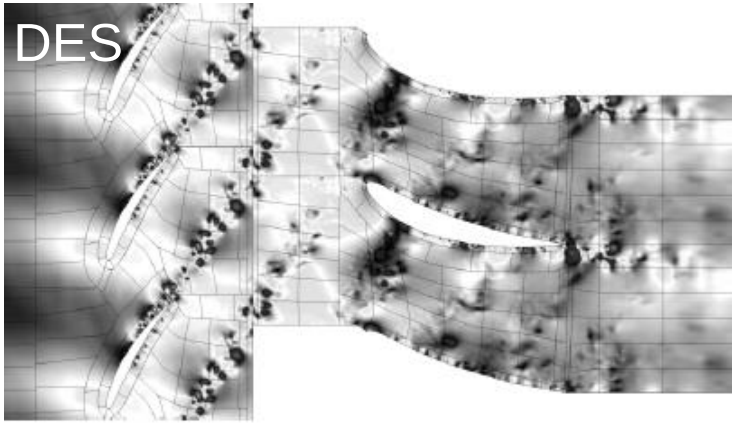
Detailed DNS simulations
(Winkler *et al*, *AIAA2012*)



High-lift device noise
(Fosso *et al, AIAA2013*)



Giret *et al, AIAA2012*



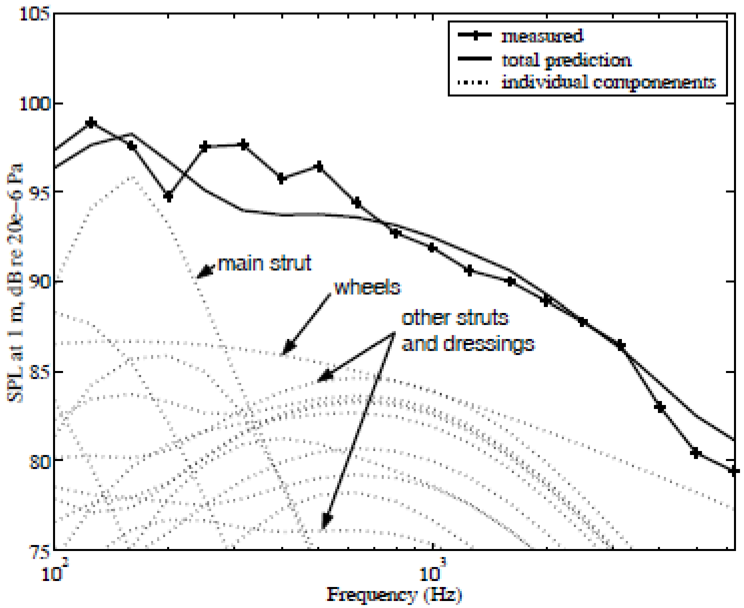
Turbomachinery stator noise
(Greshner *et al, AIAA2012*)

Airframe noise mechanisms

Main contributors:

- *Landing gears*
  - turbulent wakes of landing gears and struts
  - surface pressure fluctuations on these structures
  - fuselage turbulent BL passing over wheel-well cavities (cavity noise)
- *High lift slats and flaps*
  - scattering of BL turbulent eddies over their trailing edges
  - Turbulence impact on leading edges
  - turbulent flow over and in the vicinity of flap side-edge

Scaling of these sources~ U^6

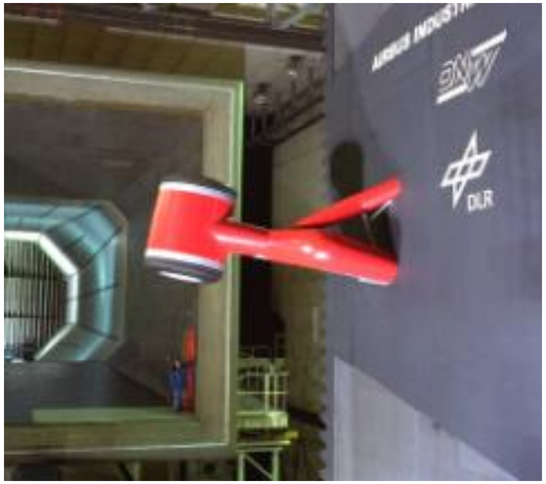


Source: Astley, Omega AOR Workshop 2008

Airframe noise control

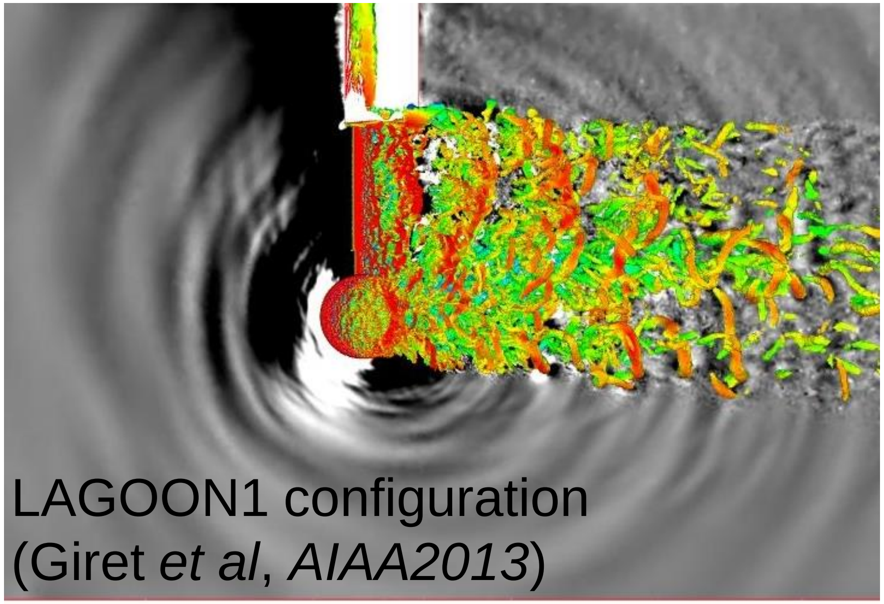
Approach: Improved aerodynamics & low speed performance

- Fairings and simplified design of landing gears
- Liners for leading edge slots
- Brushes and porous edge treatments for flaps
- slat cove fillers
- Possible Flow control

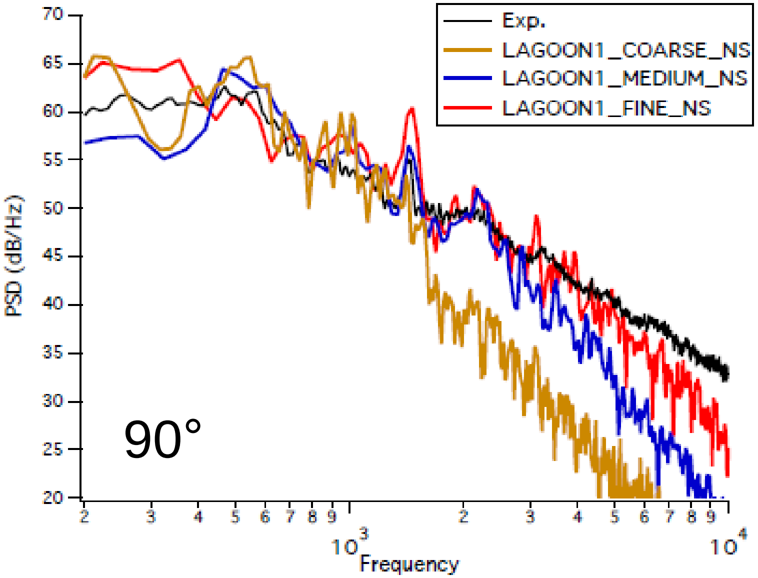


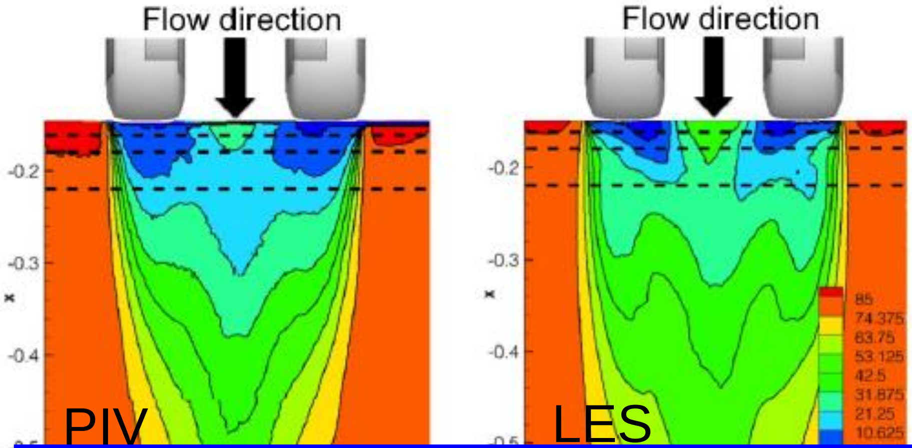
Sources: Rushwald, Airport Noise Symposium 2002; Envia, ARMD Technical seminar, 2007

Prediction of landing gear noise



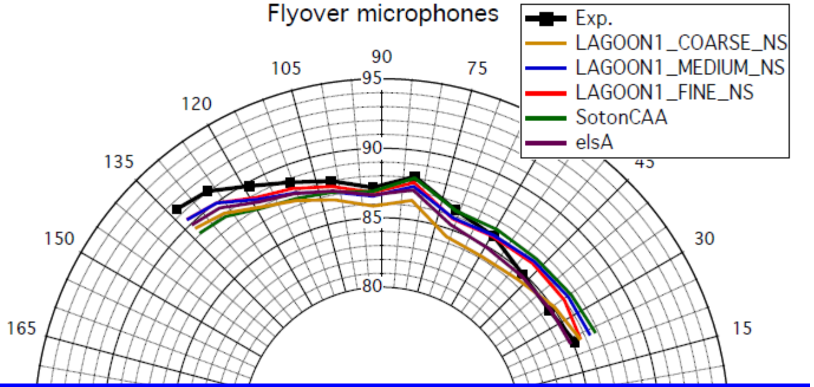
LAGOON1 configuration
(Giret *et al*, *AIAA2013*)





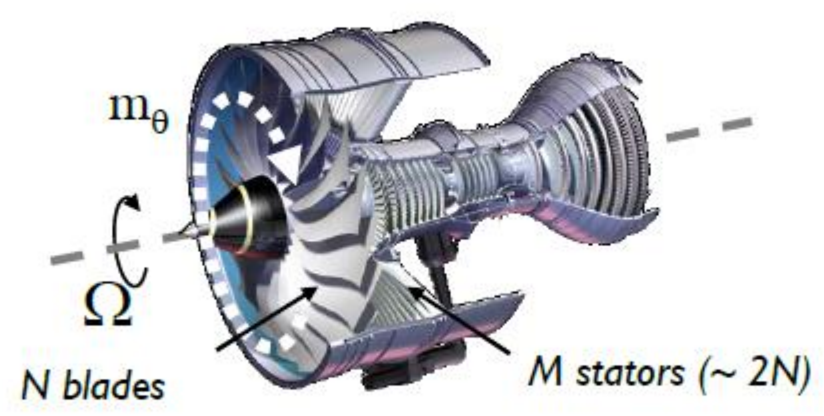
PIV

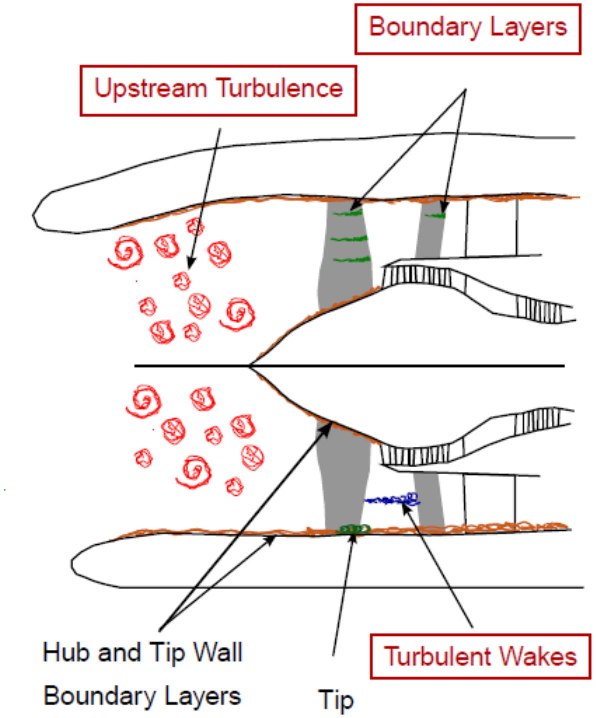
LES



Excellent overall agreement & noise source localization

Fan noise mechanisms





$$BPF = N\,\Omega$$

Periodic events –Tones

- Rotor alone *BPF, 2BPF,..*
- Shock related buzz saw tones
- Rotor-stator interaction tones
- Inflow distortion tones

Random events – broadband noise

- Rotor and stator self noise
- Rotor-stator interaction noise
- Blade tip interaction noise
- Inflow distortion (turbulent gusts)

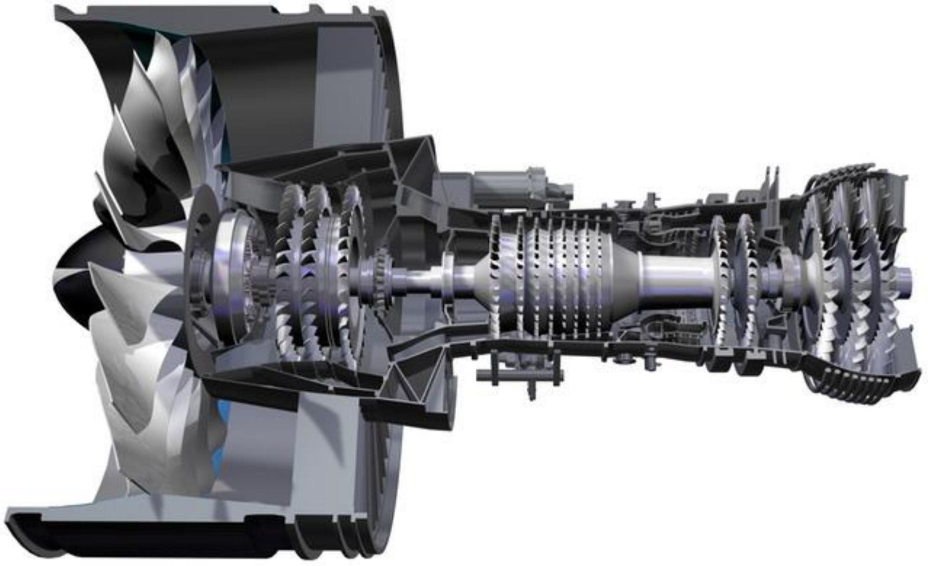
Fan speed optimization (geared fans)

Approach:

- Match fan tip speed to engine bypass ratio
- Reduce fan tip speed to minimize aerodynamic shocks ahead of fan rotor blades

Potential noise reduction:

- Fan tone noise 2 to 4 dB
- Fan broadband noise 1 to 3 dB



Pratt & Whitney PW1000G

Key Issues:

- Aerodynamic performance of fan, compressor and LP turbine
- Geared Fan Penalties: weight, efficiency, maintenance, reliability & cost
- Broadband noise (white noise) limits possible reductions

Fan noise control

At Source

- Low noise fan and OGV optimized for tones and buzz, optimization driven by 3D CFD
- Rotor sweep to minimize shocks ahead of fan blades
- Stator sweep and lean to reduce unsteady load & radiation efficiency
- Porous stator vanes

Potential noise reduction:

- Fan tone intake noise 2 to 4 dB
- Fan tone exhaust noise 1 to 3 dB

By acoustic/flow control

- Optimized and improved liner configurations for intake and bypass ducts and tip casing
- Active stators (plasma/MEMS)
- Blade tip blowing & VG on vanes

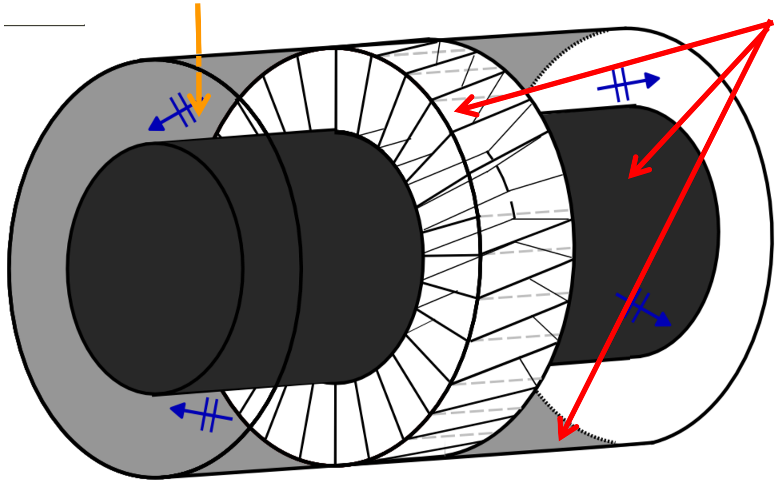
Sources: Rushwald, Airport Noise Symposium 2002; Julliard, IROQUA Technical seminar, 2006 Astley, Omega AOR Workshop 2008; Mileshin, ETC 2013 keynote

Goldstein's acoustic analogy (1976)

V(t)= duct interior

S(t)= blade + duct

= $S_p(t)$ + $S_d(t)$



Self-noise of flow fields (quadrupoles)

$$\rho'(\vec{x},t)=\frac{1}{c_0^2}\int_{-T}^{T}\int_{V(t)}\frac{\partial^2 G}{\partial y_i \partial y_j}T_{ij}'\,d\vec{y}\,dt$$

$$+\frac{1}{c_0^2}\int_{-T}^{T}\int_{S(t)}\frac{\partial G}{\partial y_i}f_i\,dS(\vec{y})\,dt+\frac{1}{c_0^2}\int_{-T}^{T}\int_{S(t)}\rho_0 V_n'\frac{D_0 G}{Dt}\,dS(\vec{y})\,dt$$

Distributed in exterior volume

Distributed on surfaces

Blade loading

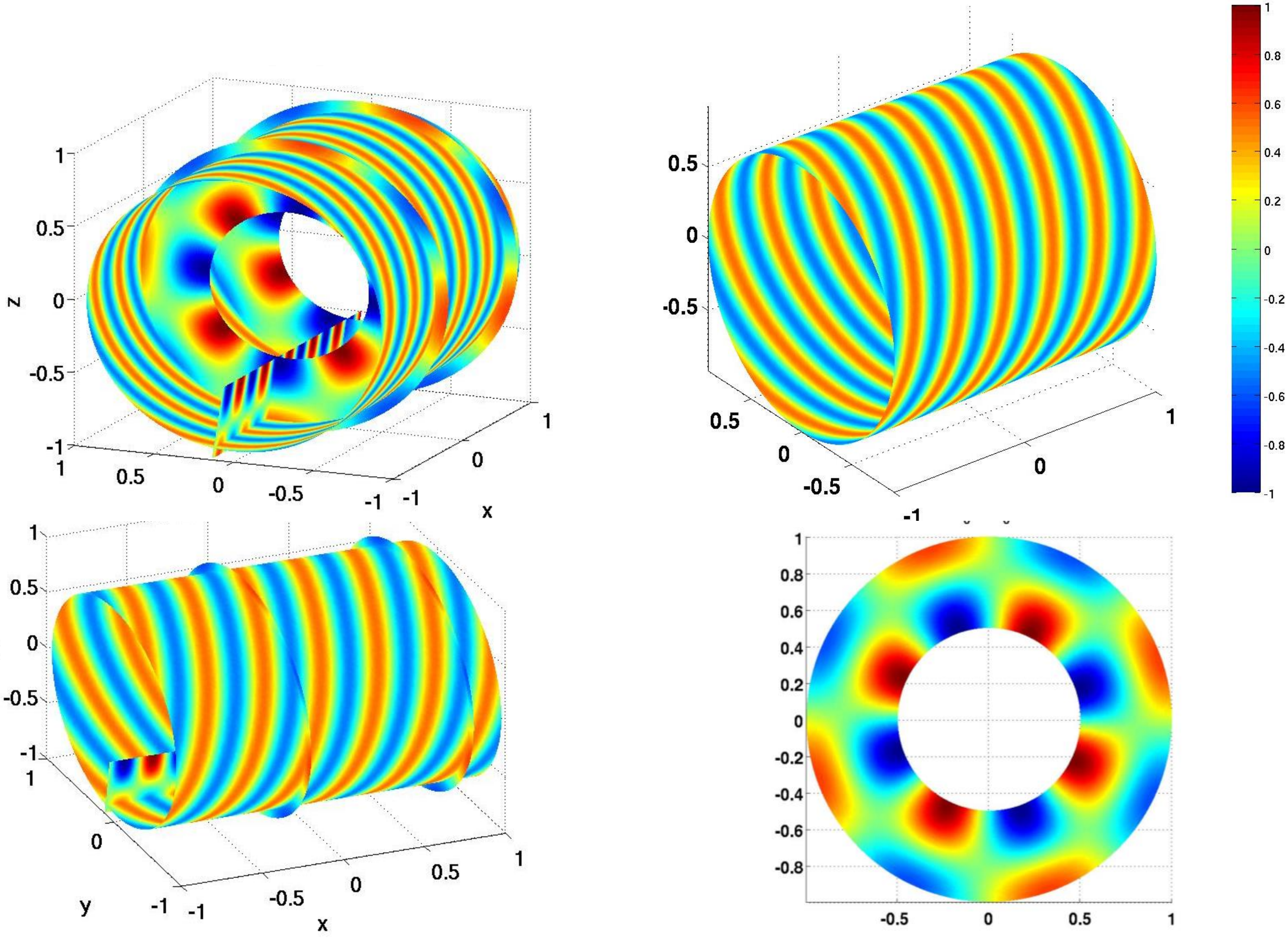
Relative normal velocity

Annular duct Green’s function

H=0.5

(n,j)=(4,1)

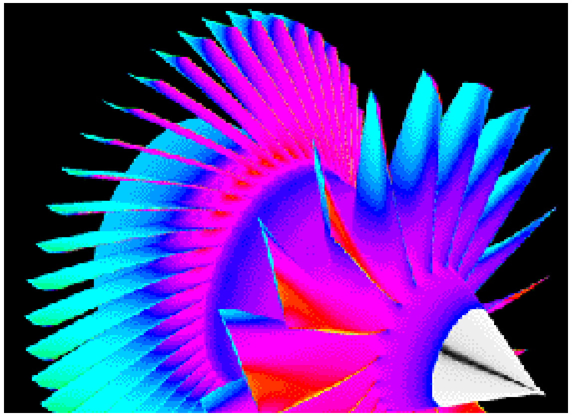
$k_0RT=20$

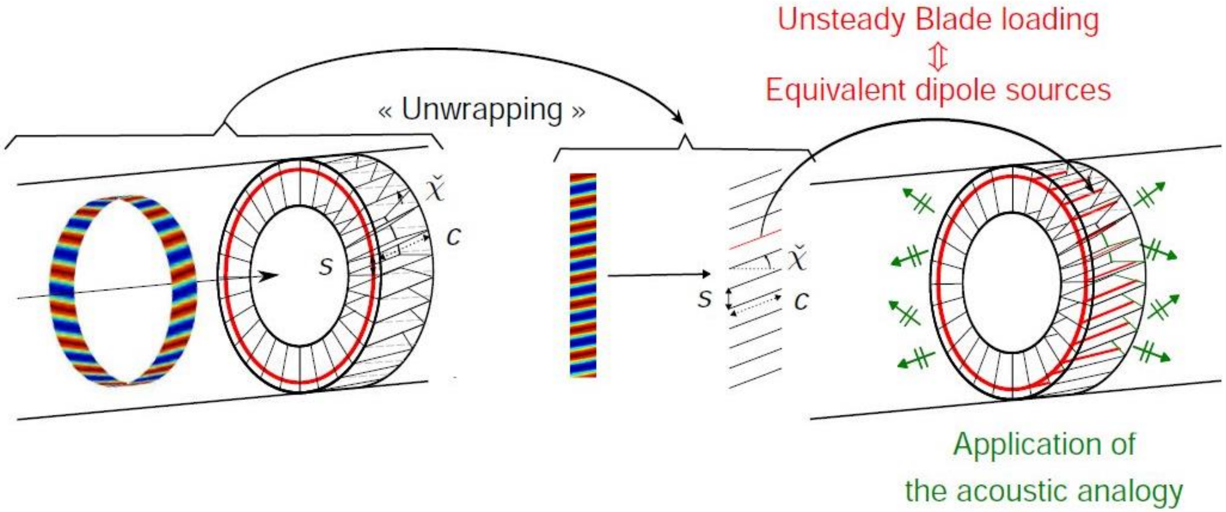


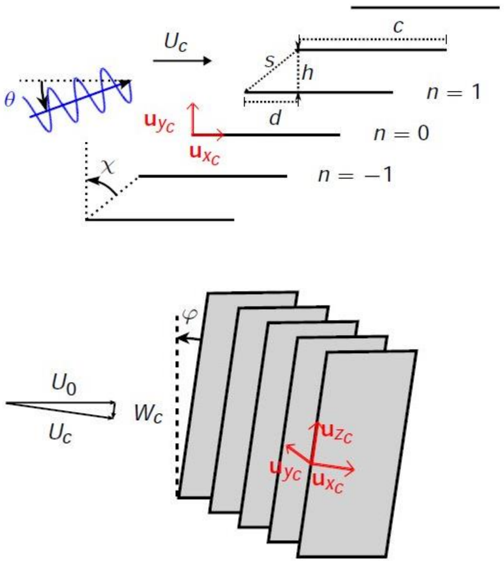
Fan Noise Predictions

Approach:

- Develop advanced computational models for predicting aerodynamics and noise of fan system
- Improved semi-analytic parametric design for BB

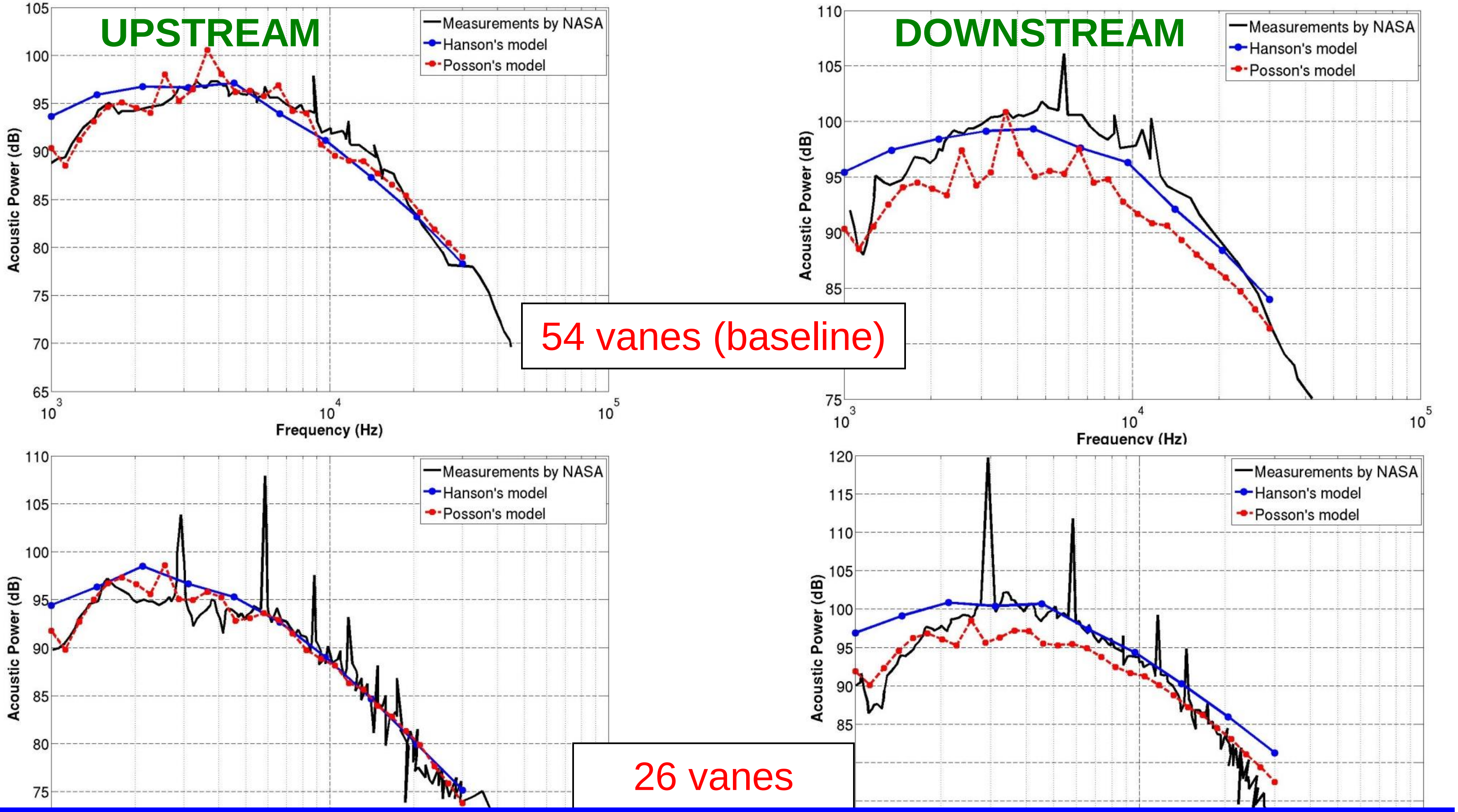






Glegg, JSV 1999, vol. 227
Posson et al., JFM 2010, vol.663; JSV 2010, vol.329

Analytical Fan BBN Predictions



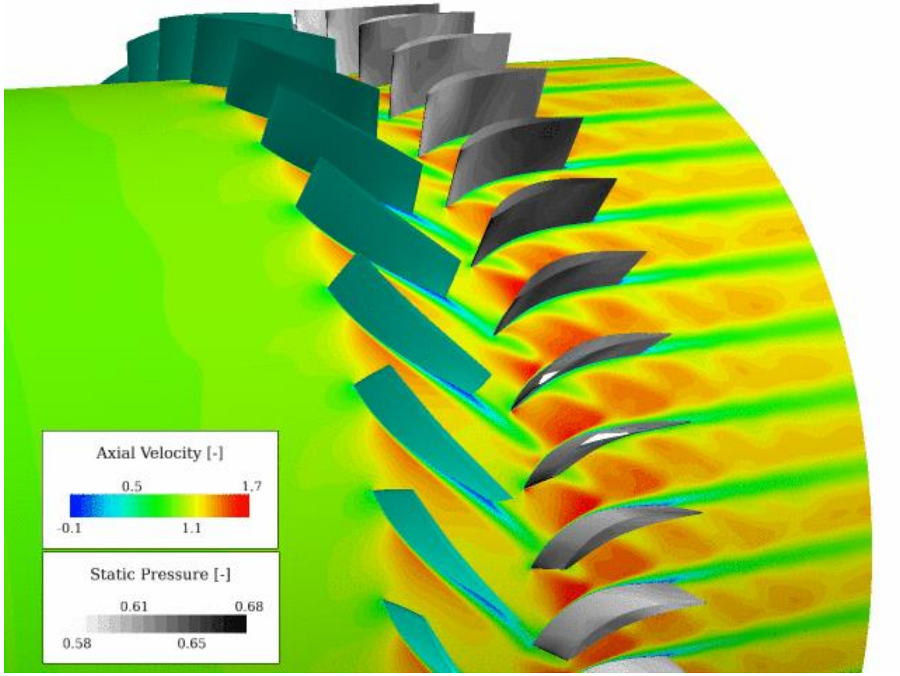
54 vanes (baseline)

26 vanes

Posson: good prediction upstream but low downstream
Hanson: good prediction except at low frequencies

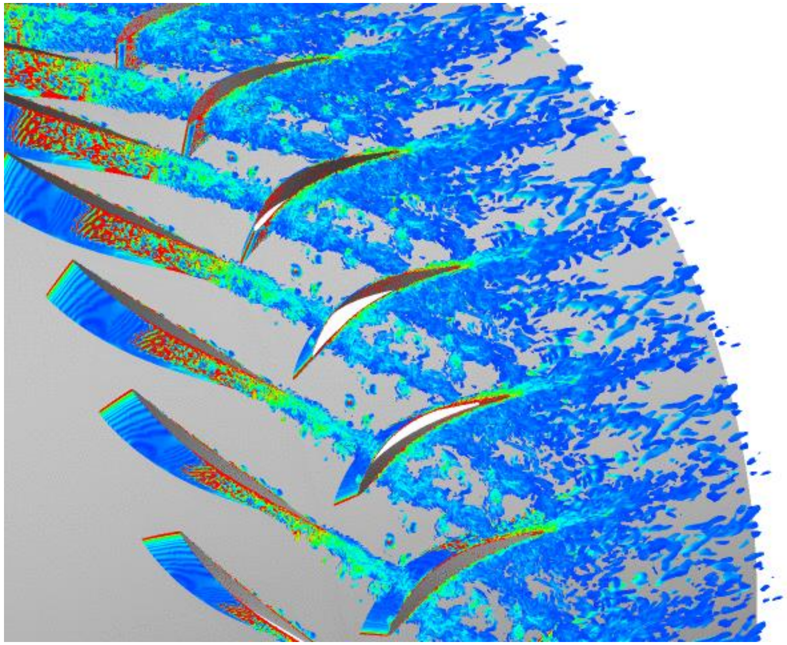
Numerical Fan Noise Predictions

URANS for tonal noise



De Laborderie *et al, AIAA 2012*

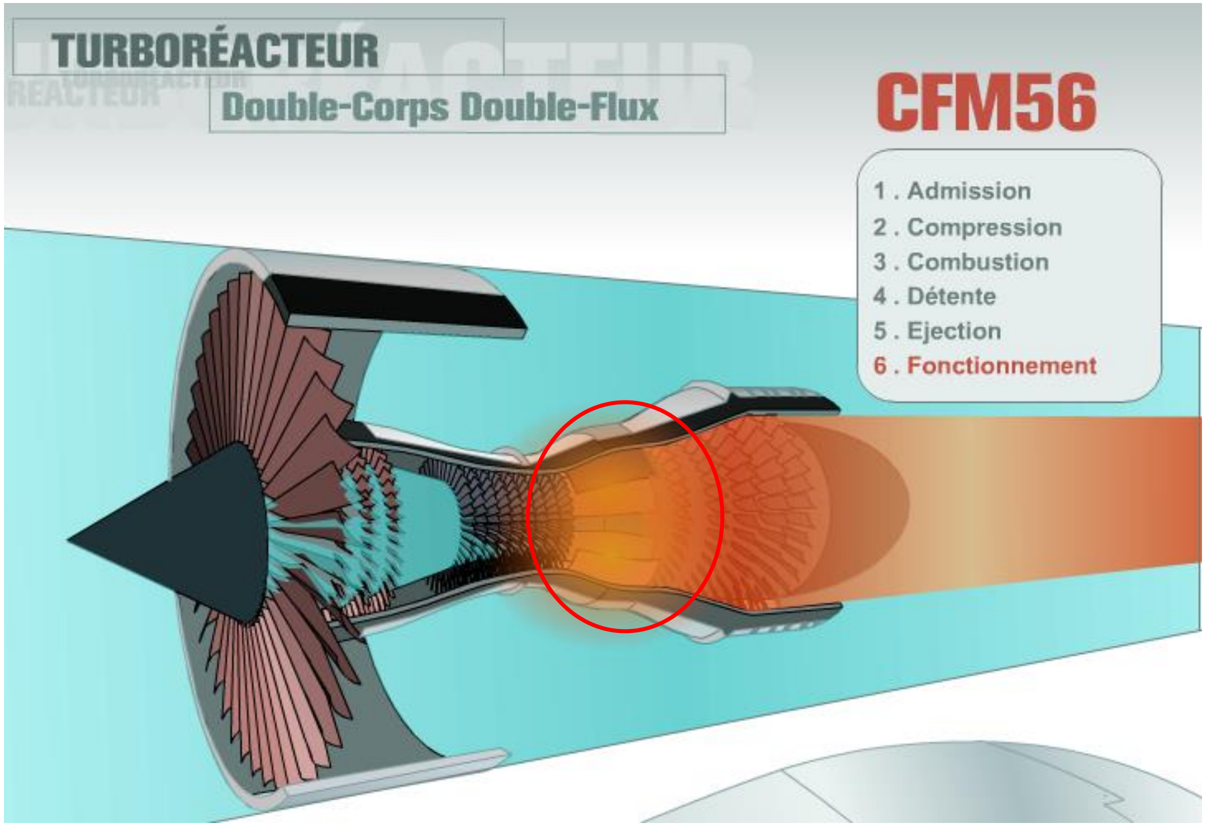
LES for broadband noise



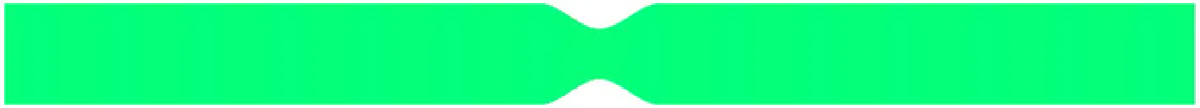
De Laborderie *et al, CFD-Canada 2013*

Potentially strong differences between URANS & LES
Tonal and BB noise sources for Golstein’s analogy
Direct near-field acoustics

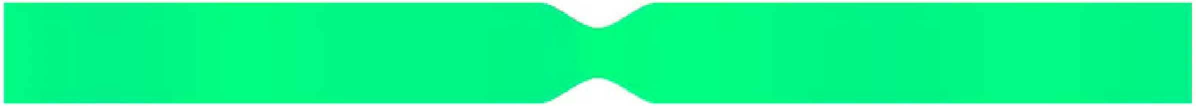
Combustion noise



Combustion indirect noise

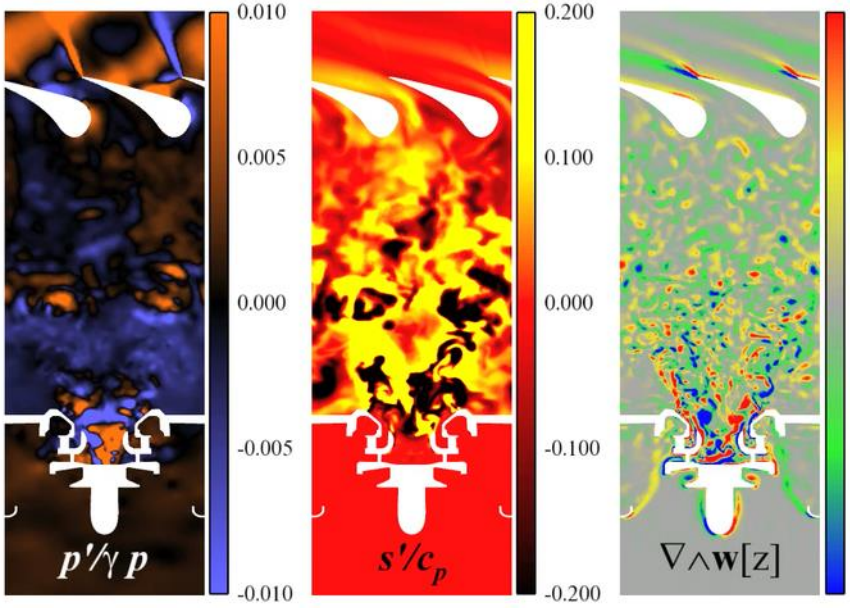


Temperature fluctuations

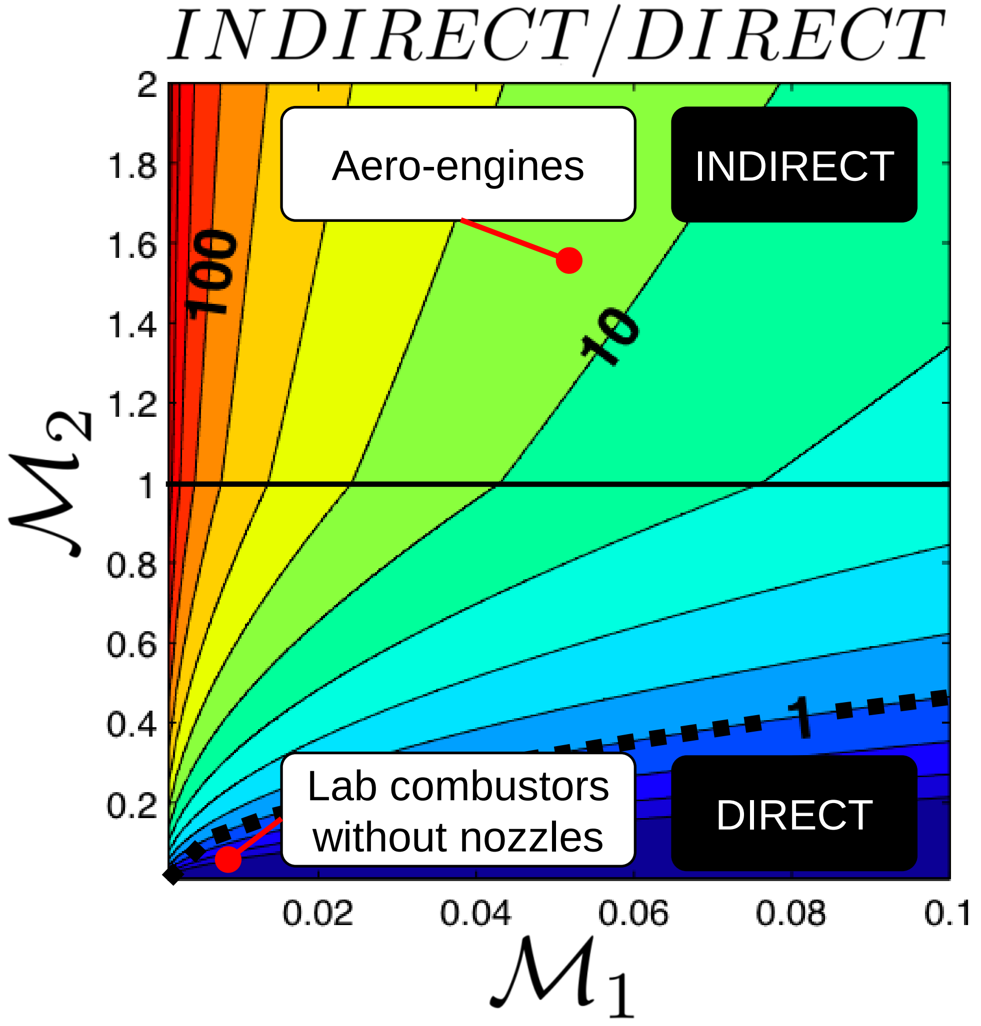


Pressure fluctuations

LES in a combustion chamber (1 sector)

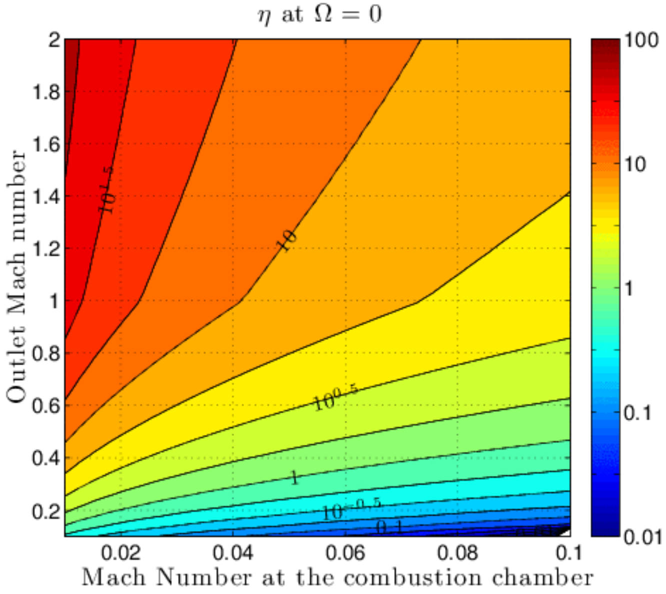


Ratio between direct and indirect noise



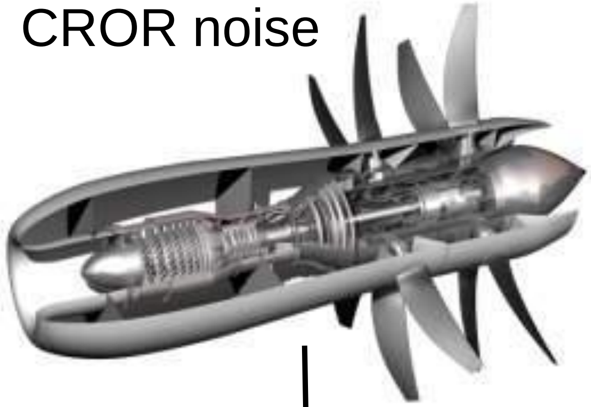
(Leyko, AIAAj 2009)

Modern turboengines (pressure ratio between 30 and 40)

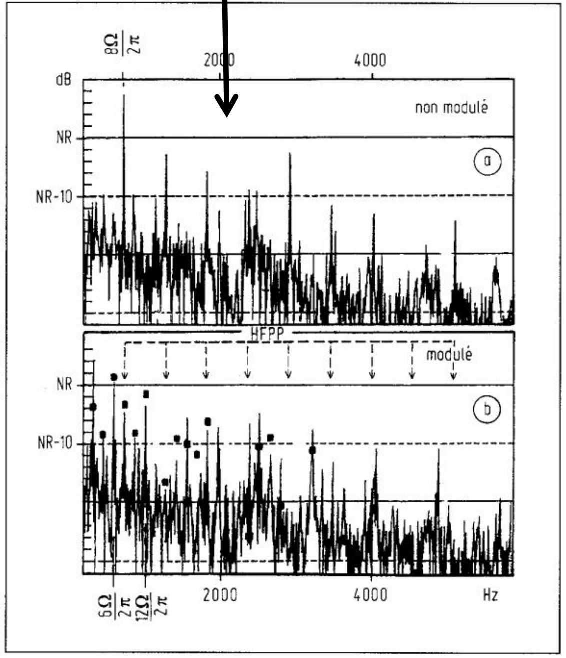


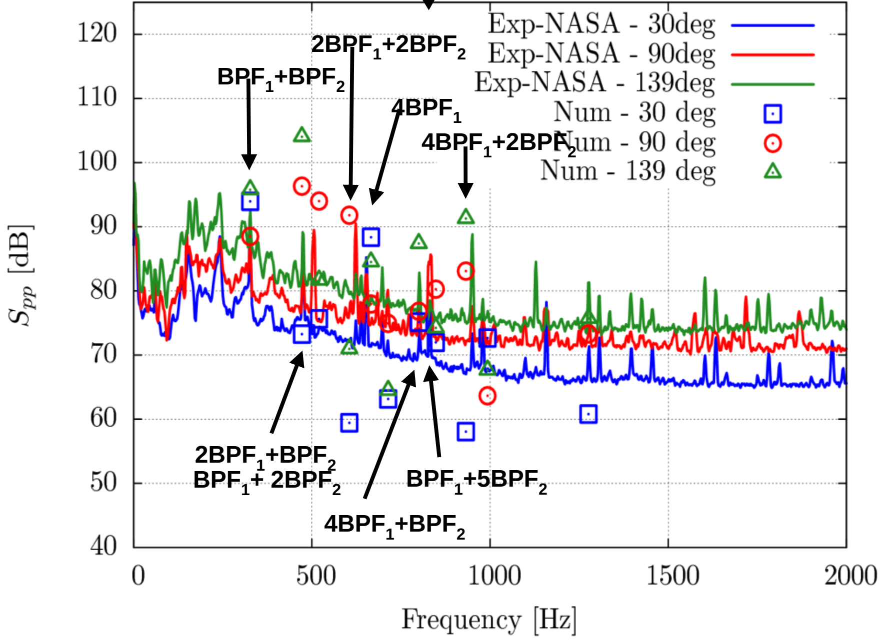
Open rotor noise

CROR noise



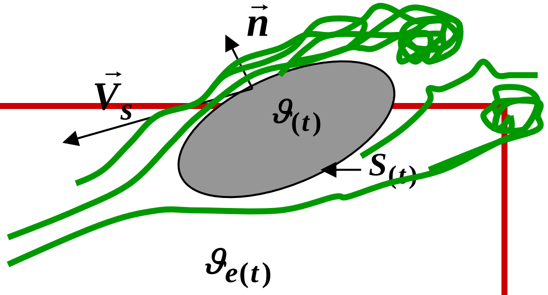
Helicopter tail and main rotor





Solution to FWH equation in free space

With the free field Green's function...



$$c_0^2\,\rho'(\vec{x},t)=\frac{1}{4\pi}\frac{\partial^2}{\partial x_i\,\partial x_j}\int_{\vartheta_e}\left[\frac{T_{ij}}{R|1-M_r|}\right]d\vec{\eta}-\frac{1}{4\pi}\frac{\partial}{\partial x_i}\int_S\left[\frac{P_i}{R|1-M_r|}\right]dS_{\vec{\eta}}-\frac{1}{4\pi}\frac{\partial}{\partial t}\int_S\left[\frac{\rho_0 V_n}{R|1-M_r|}\right]dS_{\vec{\eta}}$$

$R=|\vec{R}|$ *Distance to the observer*

$M_r=|\vec{V}_s|\cos\theta/c_0$ *Relatif Mach number*

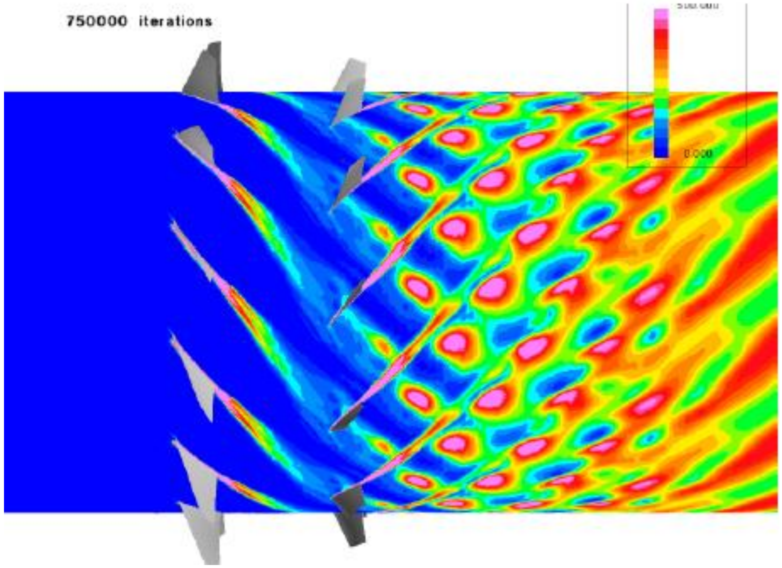
$\vec{P}$ *Pressure of blade on fluid*

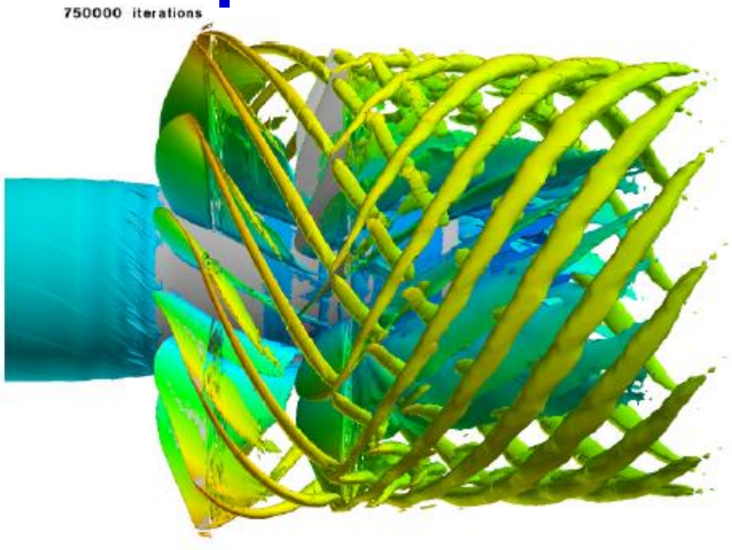
S *Surface*

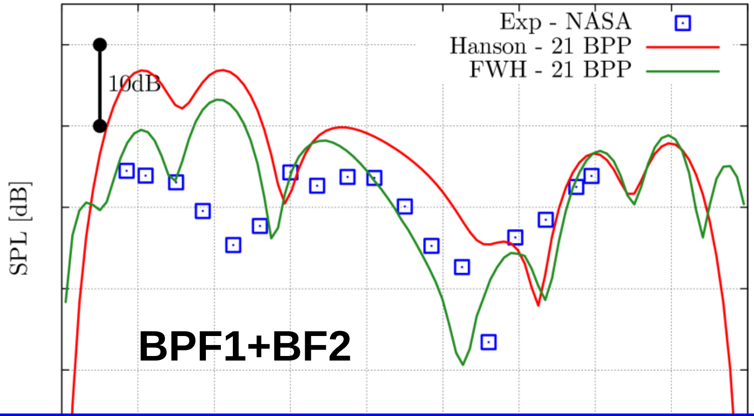
$V_n=\vec{V}_s\cdot\vec{n}$ *Normal velocity*

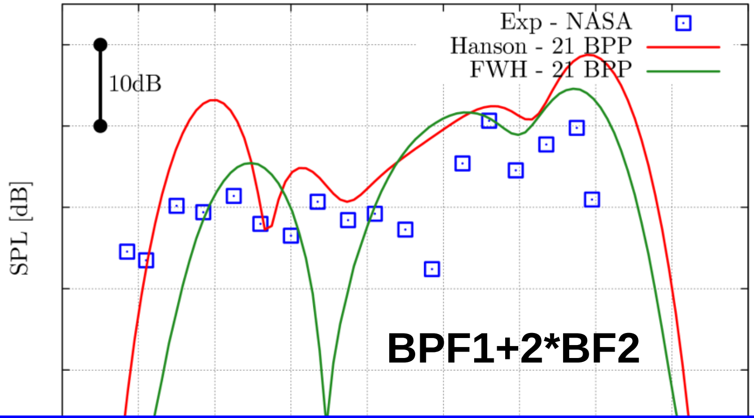
The solution is expressed in a reference frame relative to the surfaces in motion. The sources are described in this reference frame. The surface kinematics (Doppler factor and normal speed) are defined w.r.t. a fixed reference frame of the observer. **The behavior of sources is clearly separated from their entrainment movement**. The bracket means an evaluation at the retarded time.

Modern CROR noise prediction



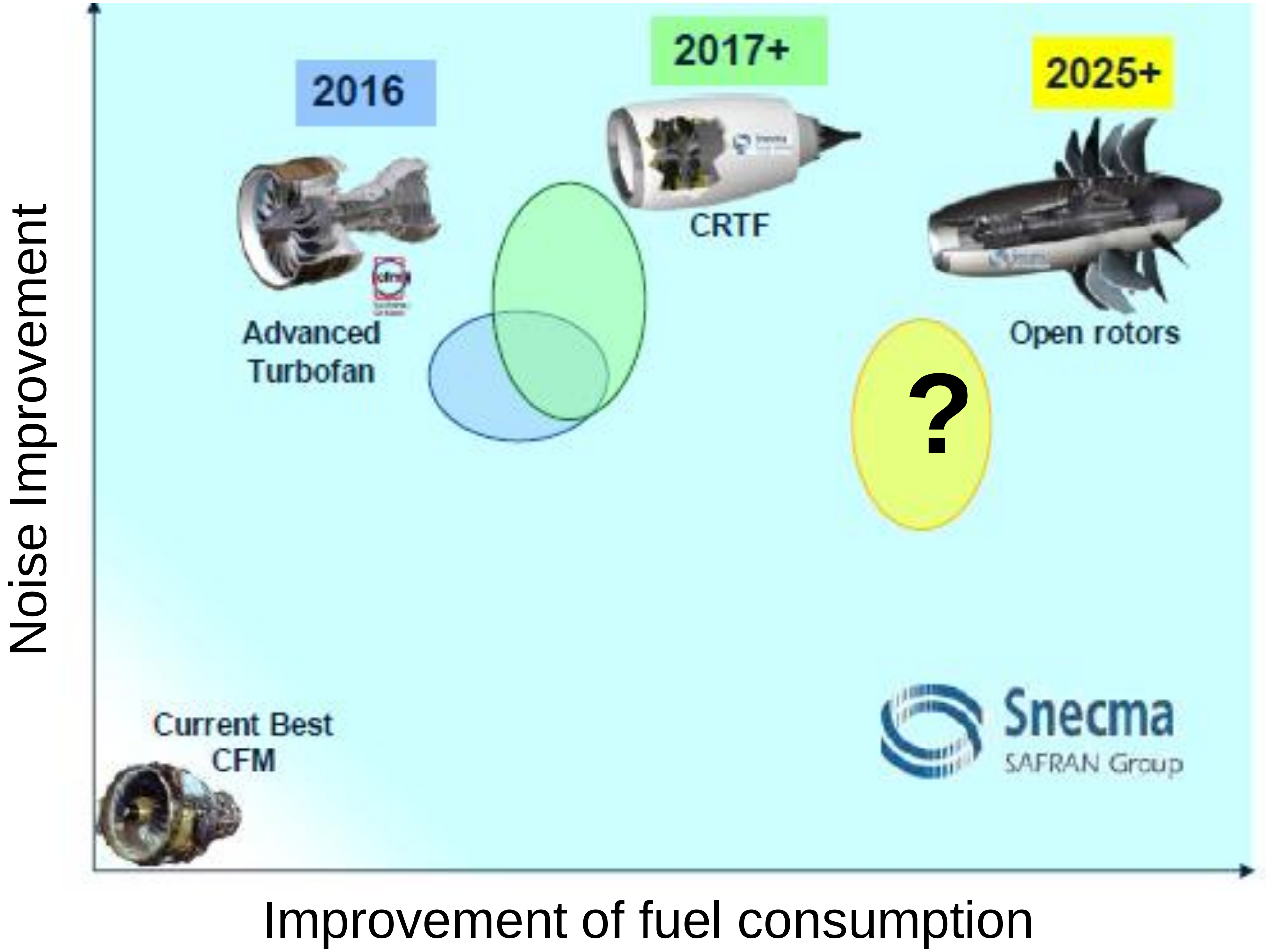






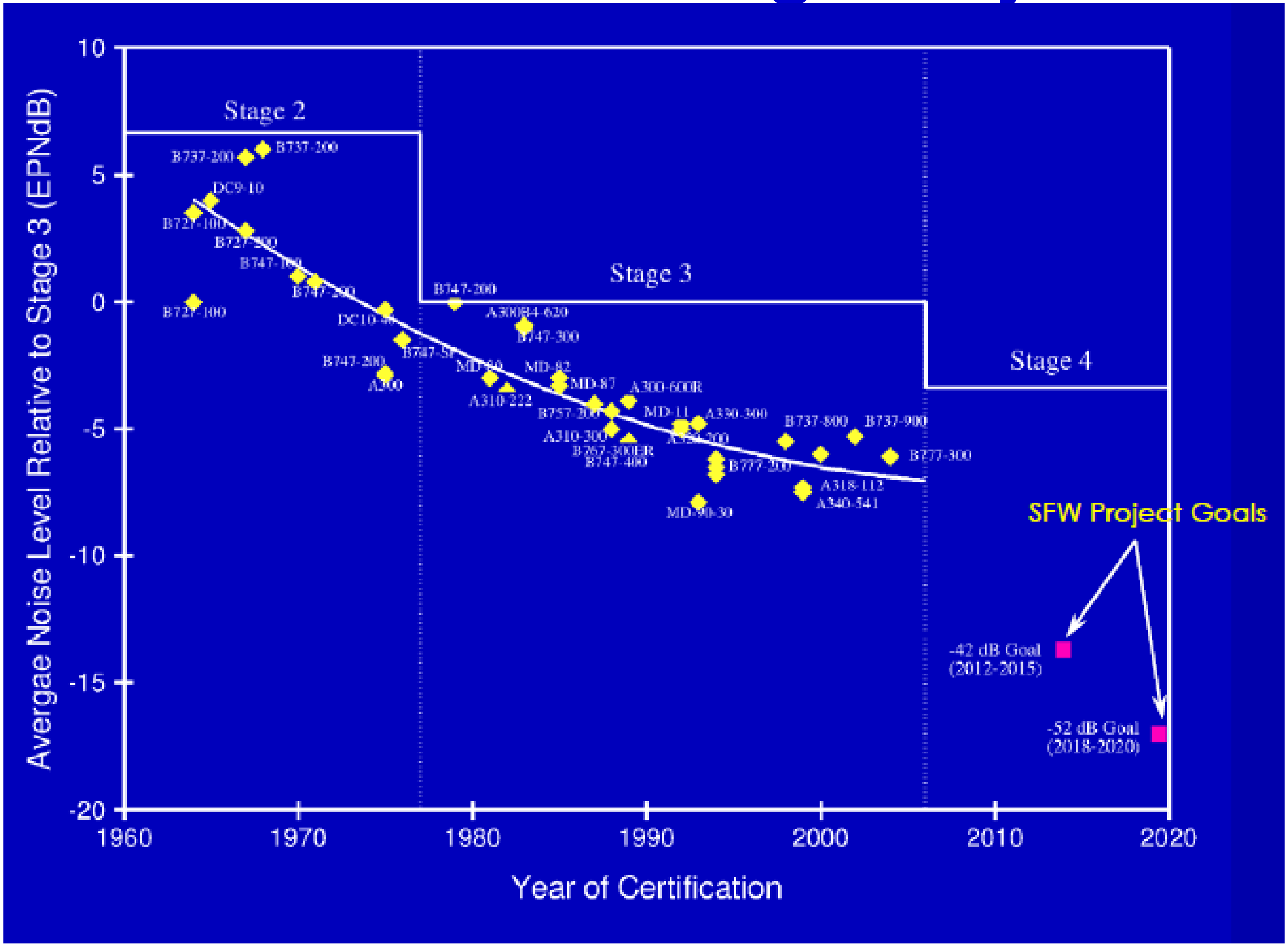
Strong wake-interaction on R2 and potential interaction on R1
Strong tip and horse-shoe vortices: secondary sources

New engine architectures



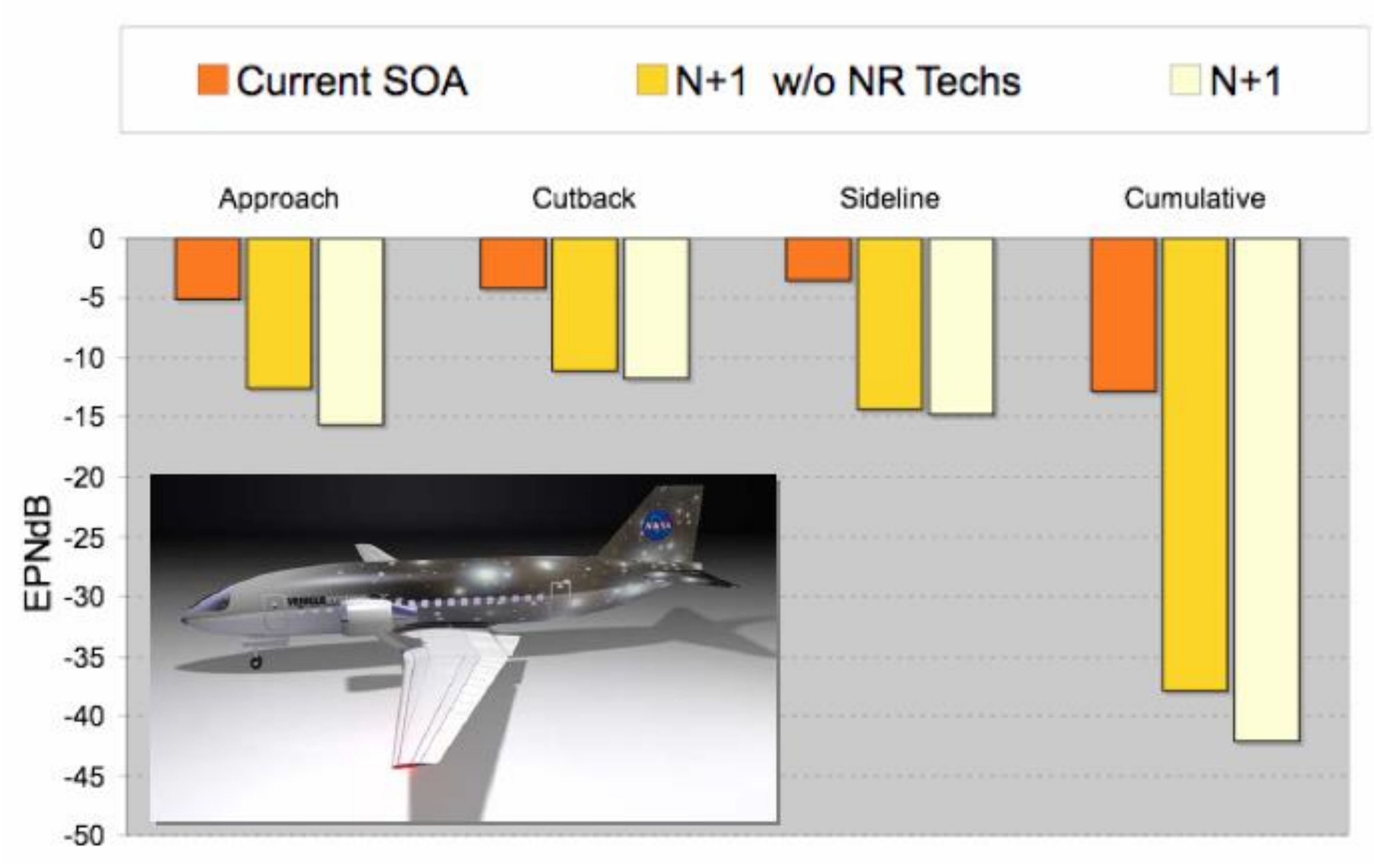
Will open rotors meet the future noise specifications (ACARE 2020 goals) ?

Subsonic Fixed Wing Project Goals



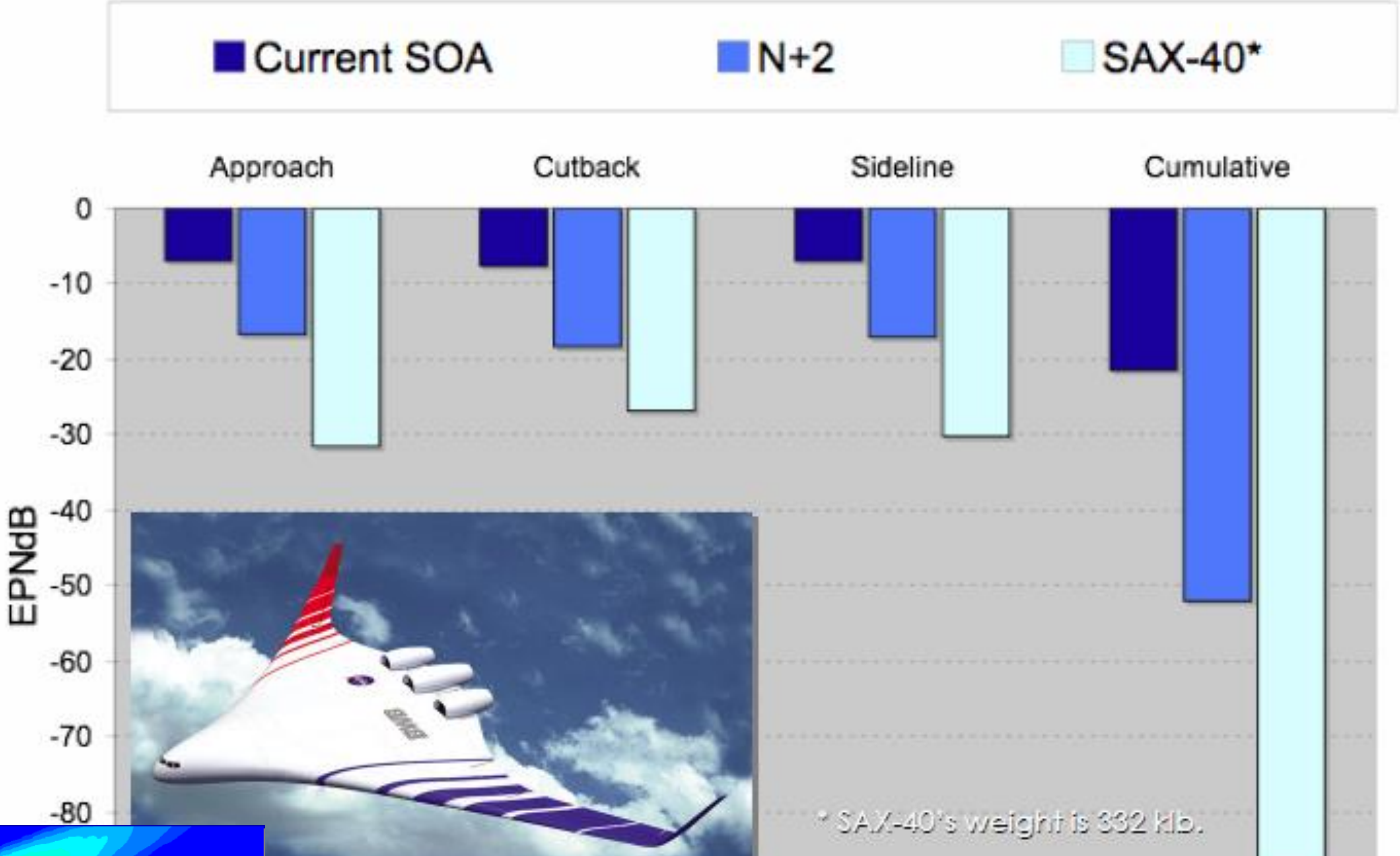
Source: Envia, ARMD Technical seminar, 2007

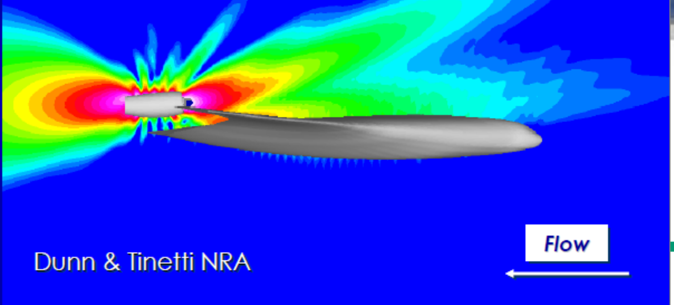
N+1 Aircraft Noise Gains



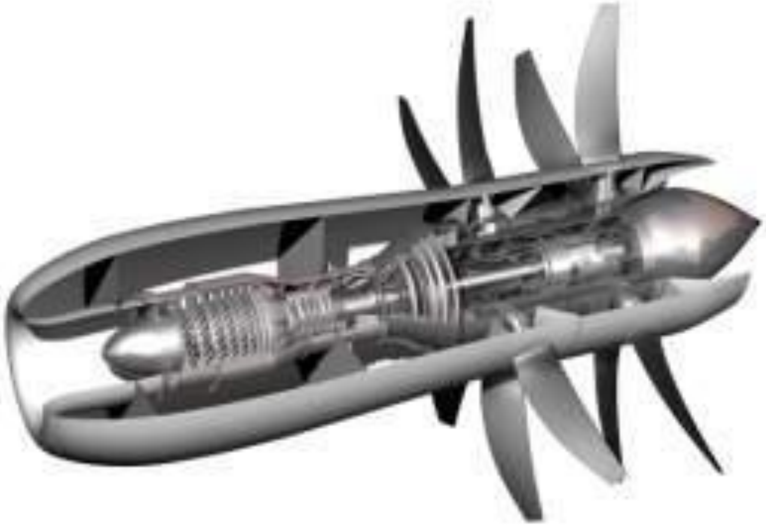
Source: Envia, ARMD Technical seminar, 2007

N+2 Aircraft Noise Gains





Source: Envia, ARMD Technical seminar, 2007



THANK YOU VERY MUCH FOR YOUR ATTENTION