MAE 298 - Aeroacoustics

(Aerodynamically Induced Noise)

What is Aeroacoustics

- Aeroacoustics = Aerodynamics + Acoustics
- Aeroacoustics is defined as aerodynamically induced noise
- **Aeroacoustics** is a branch of acoustics that studies noise generation via either *turbulent fluid motion* or *aerodynamic forces* interacting with surfaces.

About Instructor

- Ph.D. Aerospace Engineering, Penn State, 2009 (Minor : Acoustics)
  - Research: Rotorcraft Noise, Computational Aeroacoustics
- Post-doc at Penn State, 2009-2010
  - Research : Rotorcraft Noise, Jet Noise
- Lead Mechanical Engineer at GE Global Research, 2010-2015
  - Research : Wind Turbine Noise, Aircraft Engine Noise
- Assistant Professor, UC Davis, 2015

Introduce Yourself

- Your name
- Your pursuing graduate degree (MS or PhD) and year
- Your advisor
- Your research area

Motivation

- Why do you take this course?

Goals

- You will learn fundamental theories and practical applications of aerodynamically induced noise including jet noise, rotorcraft noise, turbomachinery noise, wind turbine noise, etc.
- You expand your knowledge in fluid mechanics, aerodynamics, and acoustics

Topics

- Introduction to Acoustics
- Moving sources
- Lighthill acoustic analogy
- Jet noise
- Helicopter noise
- FW-H equation and Farassat's formulation 1 and 1A
- Turbomachinery noise (aircraft engine fan noise)
- Wind turbine noise
- Turbulent inflow noise
- Turbulent trailing edge noise
- Atmospheric sound propagation

Resource

- UC Davis Canvas (https://canvas.ucdavis.edu/)
  - Homework problems
  - Papers
  - Grades

MAE 298 - Aeroacoustics

<u>Change the course unit from 1 to 4</u>

Grading Policy

- Homework: 40 % (4 assignments, 10% for each assignment) – no late submission is allowed
- Mid-term exam: 30 %
- Project: literature study report and presentation: 30 %
- *Letter grades will be assigned*

Office Hour

- Thursday, 10 am at 2013 Bainer Hall or by appointment

Final Project

- Choose one area in aeroacoustics, write down a literature survey, and present the summery in class
- Avoid too broad or too narrow topics
- Good examples:
  - Helicopter blade-vortex interaction noise
  - Amplitude modulation of wind turbine noise
  - Jet broadband noise
  - Slat noise
  - Landing gear noise
  - Trailing edge noise
  - Leading edge noise
- Send me an email about your topic by Oct. 13th
- Format
  - Margin: 1 in
  - Font: Times New Roman
  - Font size: 12 in
  - Line spacing: single line
  - Page limit: maximum 10 pages excluding references

MAE 298 - Aeroacoustics

Text book/note

- **Instructor's notes will be used as primary course materials.**

Useful references but not required

- **Dowling, Ann P and Ffowcs Williams, JE** (1983) *Sound and sources of sound,* Ellis Horwood Publishers
- **Hubbard, Harvey H.** (1995) *Aeroacoustics of Flight Vehicles,* Acoustical Society of America
- **Smith, Michael J.** (1989) *Aircraft Noise,* Cambridge University Press
- **Howe, Michael S** (2003) *Theory of Vortex Sound,* Cambridge University Press
- **Goldstein, Marvin E.** (1976) *Aeroacoustics,* McGraw-Hill
- **Salomons, Erik M.** (2001) *Computational Atmospheric Acoustics,* Kluwer Academic Publishers
- **Rienstra, S. W. and Hirschberg, A.** (2003) *An Introduction to Acoustics.* Eindhoven University of Technology

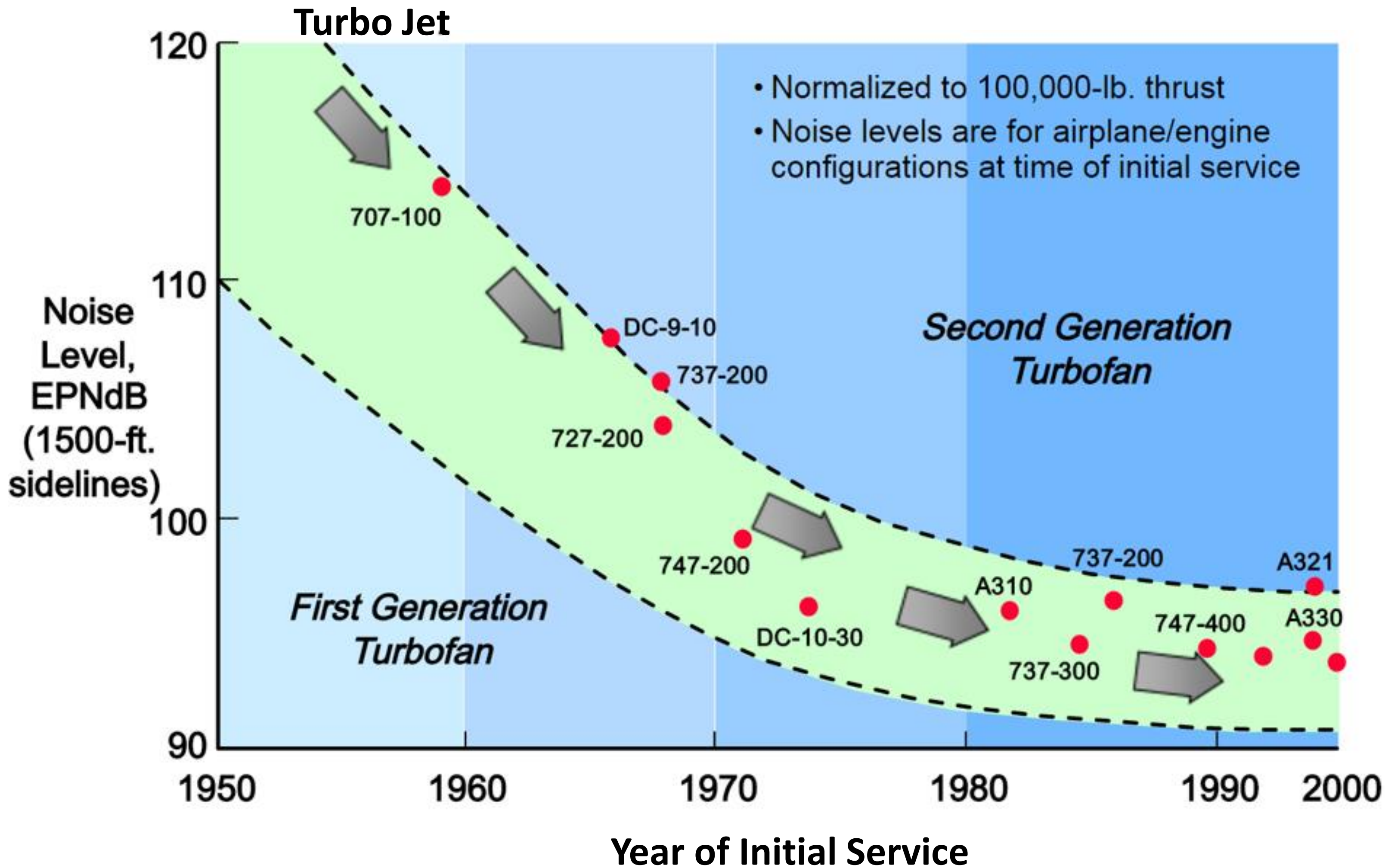
My teaching style

- I like to combine basic concepts, mathematical derivations, and real-world problems. These three elements are equally important
- I also like to tell history of research
- I encourage students to ask questions in class, break time, after class, or in office hour

Introduction to Aircraft Noise and Aeroacoustics

Aircraft Noise Trend

- Aircraft noise trend



NASA's Vision

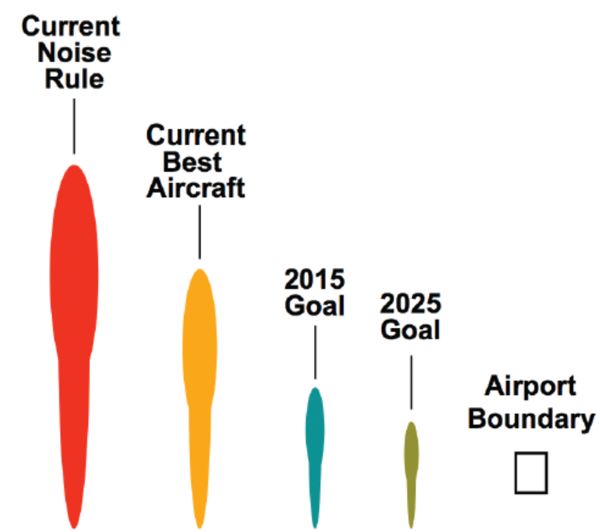
NASA's Goals for Green Aviation

- **Fuel Efficiency :** Burn 60% less fuel by 2025
- **Emissions :** Cut NOx emissions greater than 80% by 2025
- **Noise :** Shrink the nuisance noise footprint within airport property boundary (52dB EPNL reduction)
  - *Advanced and fundamental research in aeroacoustics needed*

v2013.1

TECHNOLOGY BENEFITS*	TECHNOLOGY GENERATIONS (Technology Readiness Level = 4-6)		
	N+1 (2015)	N+2 (2020**)	N+3 (2025)
Noise (cum margin rel. to Stage 4)	-32 dB	-42 dB	-52 dB
LTO NOx Emissions (rel. to CAEP 6)	-60%	-75%	-80%
Cruise NOx Emissions (rel. to 2005 best in class)	-55%	-70%	-80%
Aircraft Fuel/Energy Consumption‡ (rel. to 2005 best in class)	-33%	-50%	-60%

Courtesy: NASA, 2013



Challenges of Aeroacoustic Predictions

- Small magnitude and a wide range of pressure amplitudes

  - Aerodynamic: $p / p_{amb} \sim O(1)$

  - Acoustic: $p / p_{amb} \sim O(10^{-6})$

- CAA requires robust and efficient algorithms, good turbulence models, and parallel code capability, etc.

  - Numerical dissipation and dispersion errors require high order numerical schemes in space and time

  - Require non-reflective boundary conditions

Milestones of Aeroacoustics

- James Lighthill…a father of aeroacoustics
  - 1952, Rearranged Navier-Stokes equation into acoustic equation with equivalent sources (acoustic analogy)
  - Found the role of turbulence in the noise generation

- Ffowcs Williams
  - 1969, Generalized Lighthill's acoustic analogy for moving surfaces (FW-H)

- Feri Farassat
  - 1982, Found integral solutions of FW-H equation Widely used in rotorcraft noise, jet noise

- Christopher Tam
  - 1990s, Computational aeroacoustics, jet noise

Lighthill's Acoustic Analogy

- **Aeroacoustics began with Lighthill's acoustic analogy, which is rearrangement of N-S equations**

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

$$- \quad \frac{\partial}{\partial x_i} \quad \cancel{\frac{\partial}{\partial t}\left(\rho u_i\right)} + \frac{\partial}{\partial x_j}\left(\rho u_i u_j + p_{ij}\right) = 0$$

$$p_{ij} = -\sigma_{ij} + \delta_{ij} p$$

$$\sigma_{ij} = \mu \left\{ \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial xi} - \frac{2}{3}\left(\frac{\partial u_i}{\partial x_i}\right)\delta_{ij} \right\}$$

subtract $c_0^2 \nabla^2 \rho$

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

$$T_{ij} = \rho u_i u_j + p_{ij} - c_0^2 \rho \delta_{ij}$$

$$\rho = \rho' + \rho_0$$

- **Aerodynamic noise is generated by Lighthill stress tensor (T_{ij}) and propagted with the speed of sound (c_0)**

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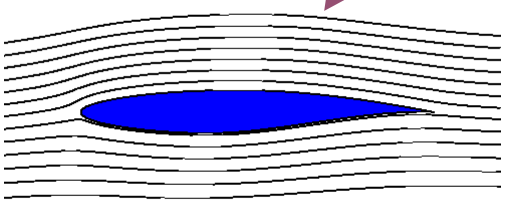
FW-H Equation

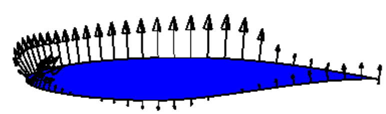
- Ffowcs Williams–Hawkings Equation : Generalized acoustic analogy for rotating blades as noise source

$$\Box^2 p'(\vec{x},t) = \frac{\partial}{\partial t}\left[Q\delta(f)\right] - \frac{\partial}{\partial x_i}\left[F_i\delta(f)\right] + \frac{\bar{\partial}^2}{\partial x_i \partial x_j}\left[T_{ij}H(f)\right]$$

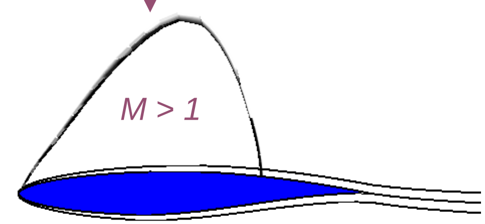
f = 0 describes the integration surface



Thickness
displacement of fluid generates sound



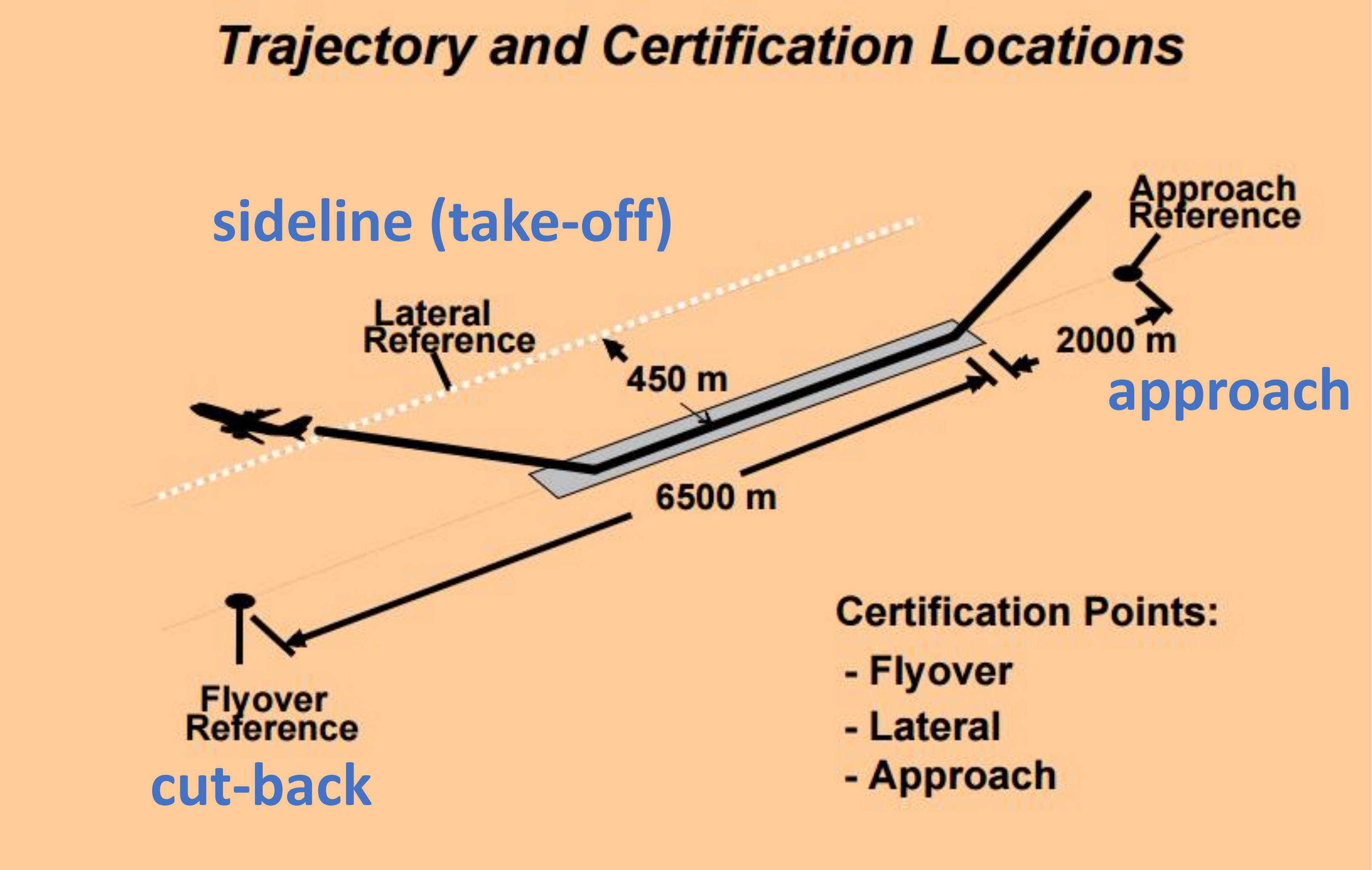
Loading
accelerating force distribution generates sound (unsteady flows)



Quadrupole
All volume sources, non-linear effects nonuniform sound speed

Aircraft Noise Certifications

Aircraft Noise Certification Locations



EPNL (Effective Perceived Noise Level)

- EPNL is measured in units of EPNLdB and it is a single number indicator of the subjective effects of airplane noise on human beings
- EPNLdB is used in aircraft noise certification
- EPNLdB is a measure of human annoyance to aircraft noise which has special spectral characteristics and persistence of sounds.
- It accounts for human response to spectral shape, intensity, tonal content and duration of noise from an intensity, tonal content and duration of noise from an aircraft.
- Certification quality EPNLdB cannot be directly measured, it has to be calculated in a standard manner as described in Annex 16.

5 Steps of EPNL Calculation

For each ½ second sample,

1. SPL converted to PNL (using a formula for noy values)
2. Tone correction factor C is calculated (this involves length computations by averaging SPLs)
3. PNLT=PNL+C
4. Duration coefficient D is calculated

$$D = 10\log\left[\left(\frac{1}{T}\right)\sum_{k=0}^{d/\Delta t} \Delta t \cdot antilog\frac{PNLT(k)}{10}\right] - PNLTM$$

   where PNLTM is the maximum value of PNLT, T is a normalizing time constant (10 sec) and Δt=is the length of the equal increments of time (0.5 sec), and d is the time interval to the nearest second during which PNLT(k) is within a specified value h of PNLTM (h=10 dB)

5. EPNL=PNLTM+D
   where PNLTM=Max(PNLT). EPNL is the total subjective effects of an airplane flyover.

EPNL Calculation

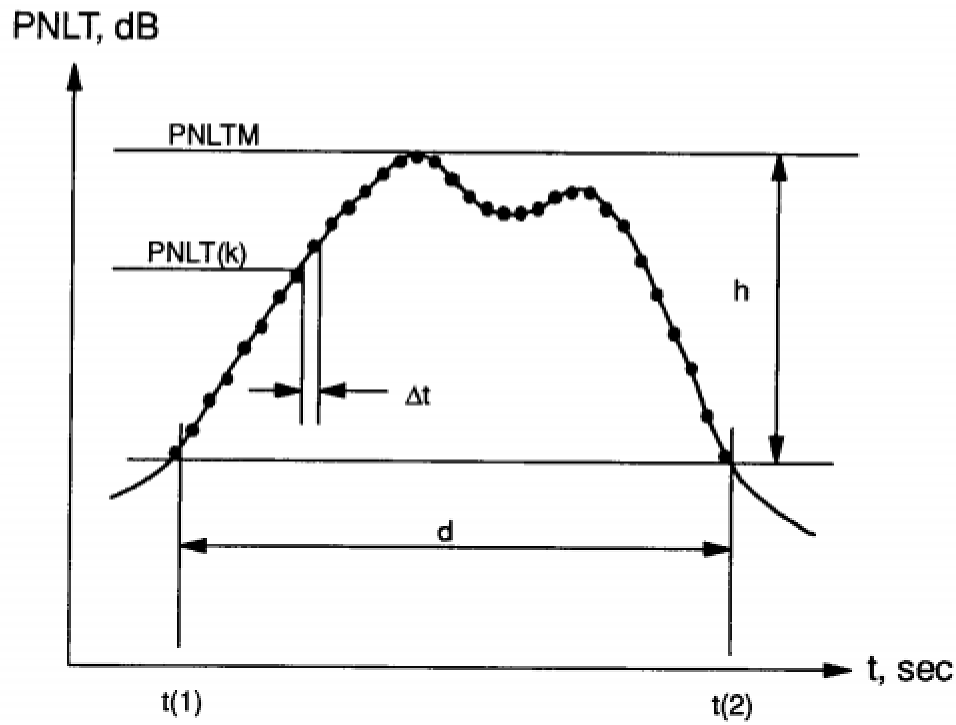


Figure 2.2. The noise time history and the related terms.

$$EPNL = PNLTM + D$$

Stage 3 Noise Regulation

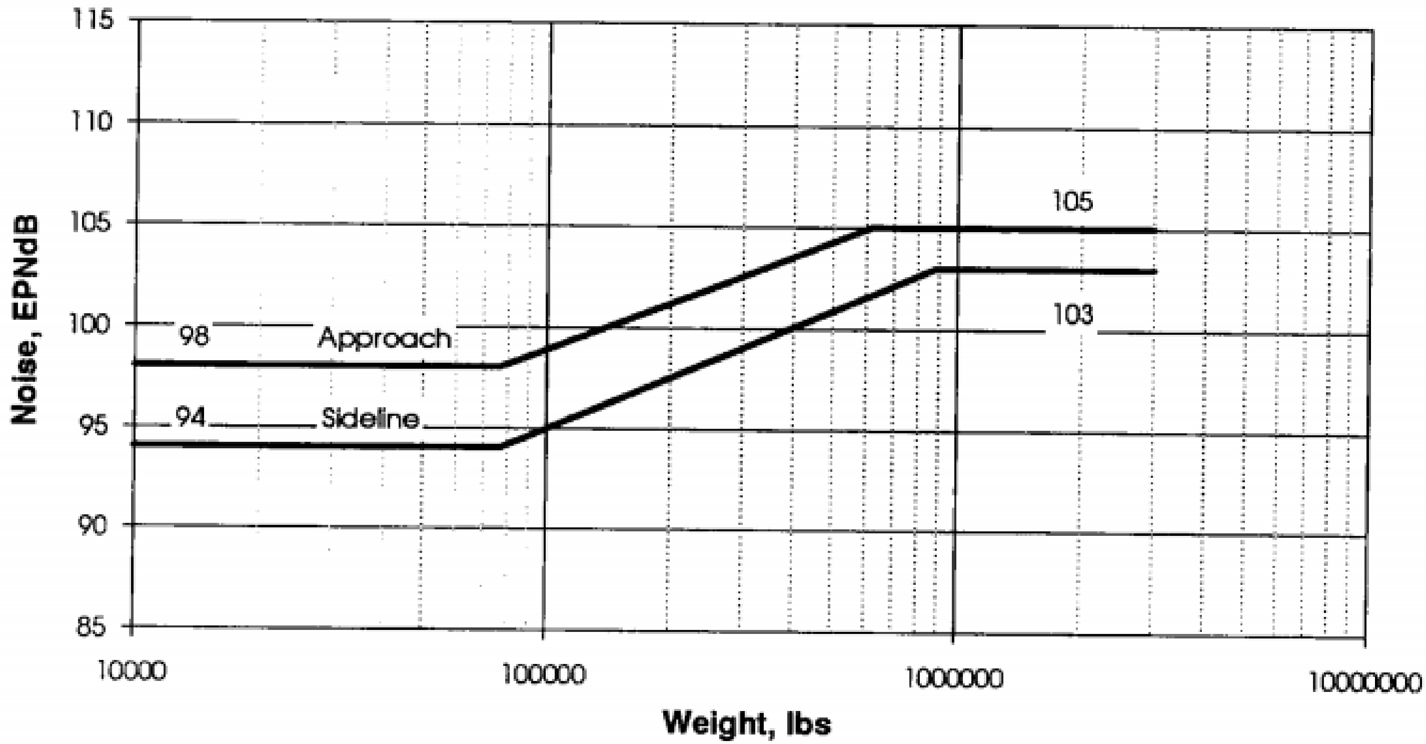
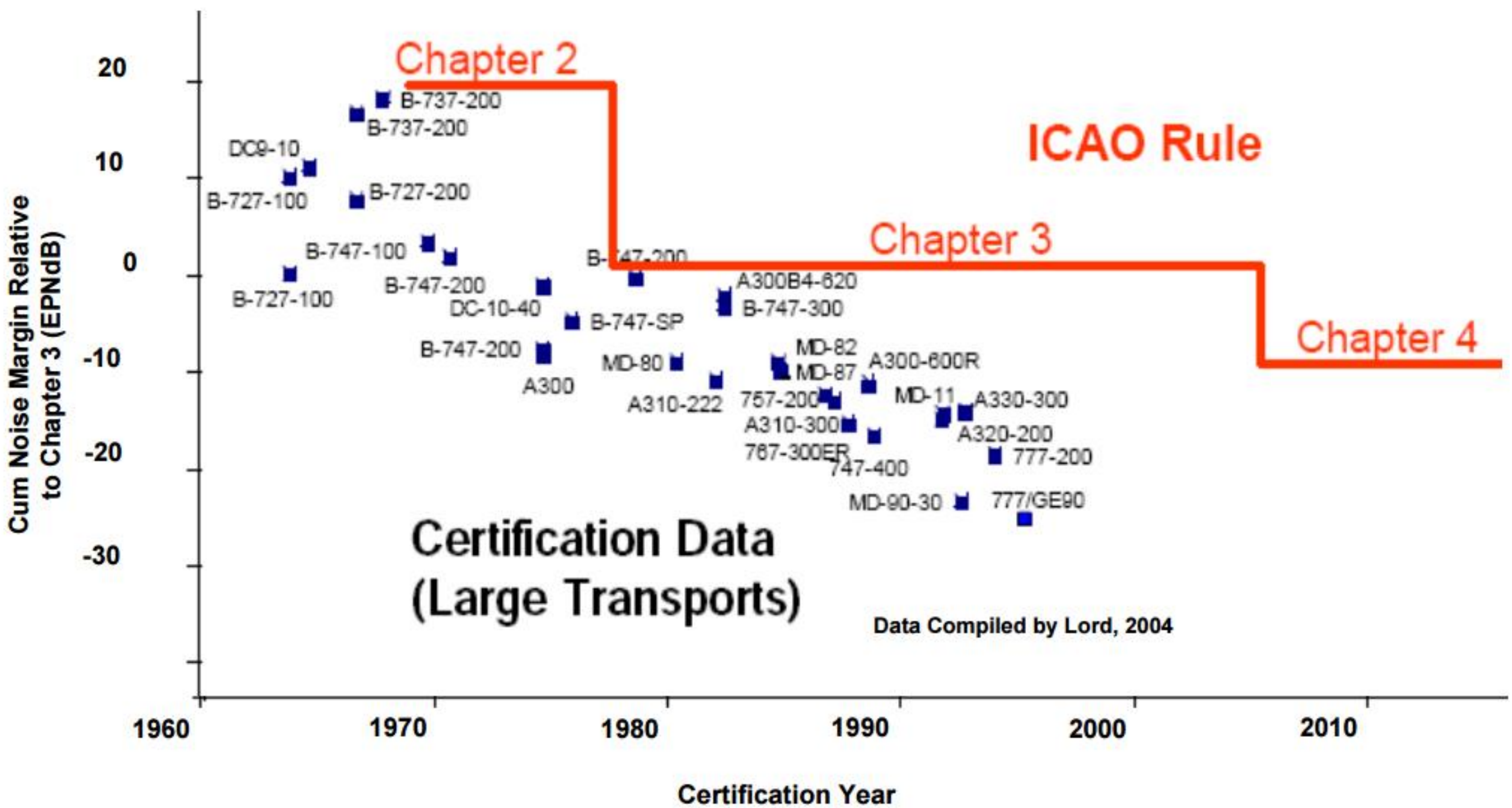


Figure 3.2 Stage 3 certification requirements for sideline and approach.

Trend of Aircraft Noise Regulations



Current and Future FAA Noise Standards

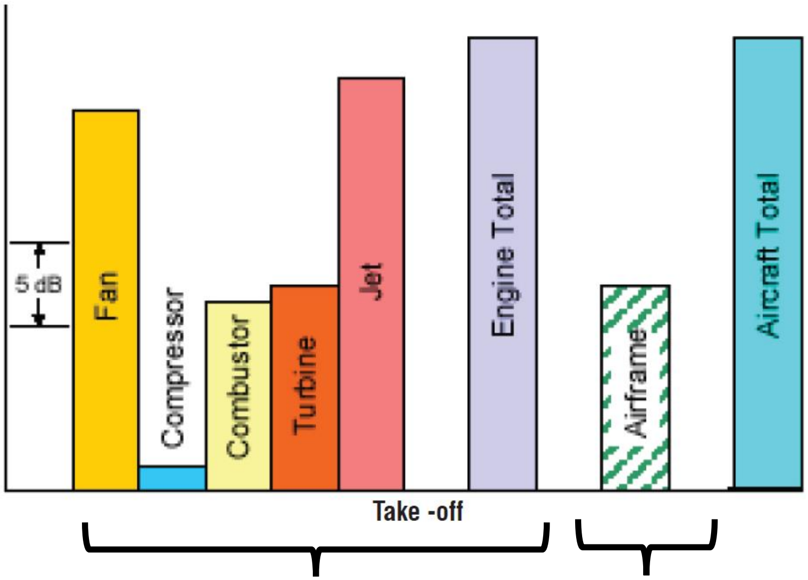
- The current FAA noise standards applicable to new type certifications of ***jet and large turboprop aircraft is Stage 4***. It is equivalent to the ICAO Annex 16, Volume 1 Chapter 4 standards. Recently, the international community has established and approved a more stringent standard within the ICAO Annex 16, Volume 1 Chapter 14, which became effective July 14, 2014. The FAA is adopting this standard and promulgating the rule for ***Stage 5 that is anticipated to be effective for new type certificates after December 31, 2017 and December 31, 2020***, depending on the weight of the aircraft. The Notice of Proposed Rule Making (NPRM) for Stage 5 was published on January 14, 2016.
- ***For helicopters***, the FAA has noise standards for a ***Stage 3*** helicopter that became effective on May 5, 2014. These more stringent standards apply to new type helicopters and are consistent with ICAO Annex 16, Volume 1 Chapter 8 and Chapter 11.

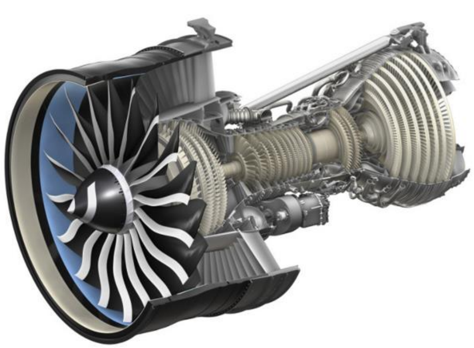
Aircraft Noise Sources & Applications of Aeroacoustics

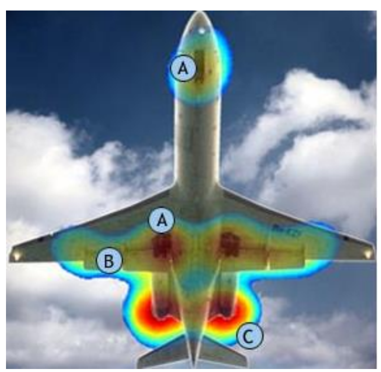
Aircraft Noise Sources

Relative Weight of Aircraft Noise Sources

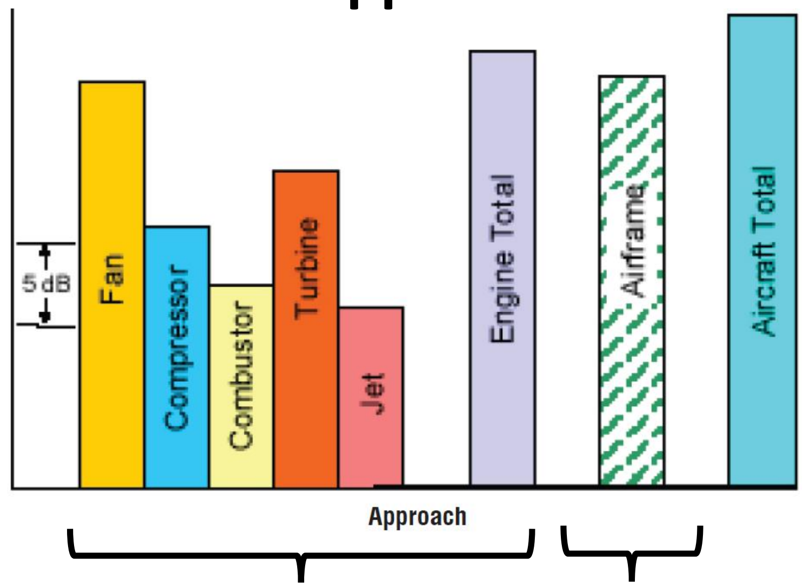
Take-off



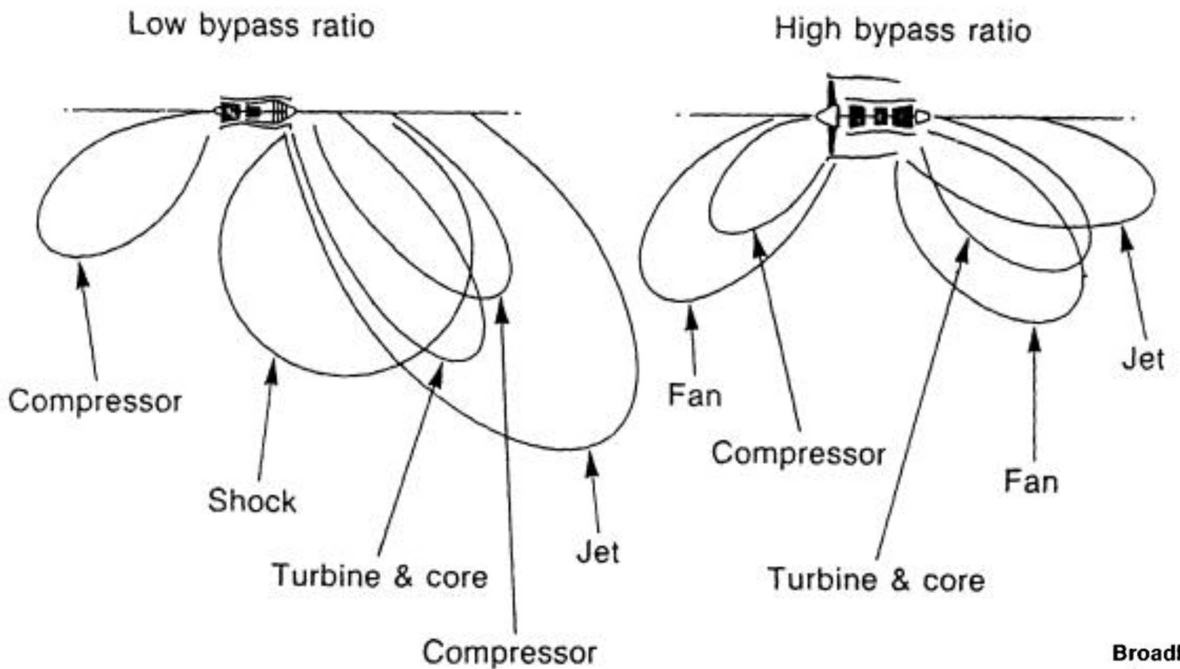


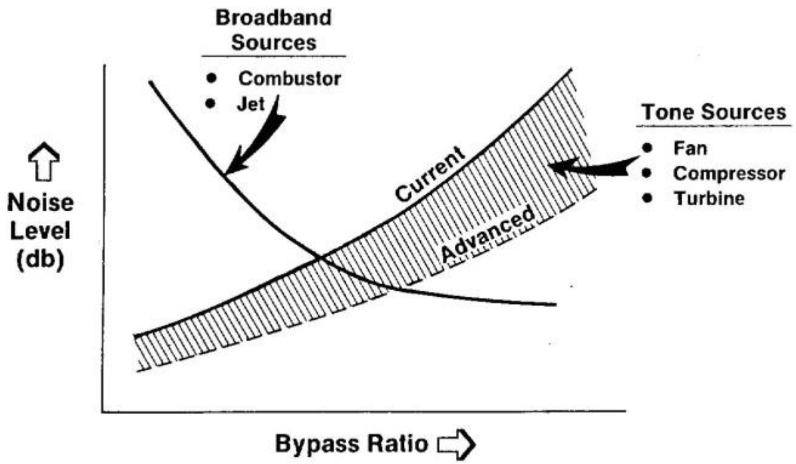


Approach



Engine Noise Level and Directivity

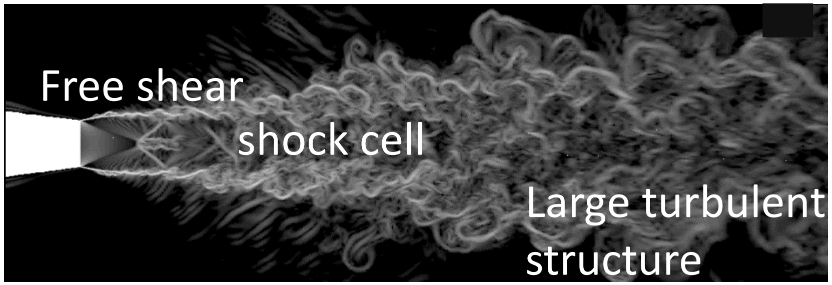


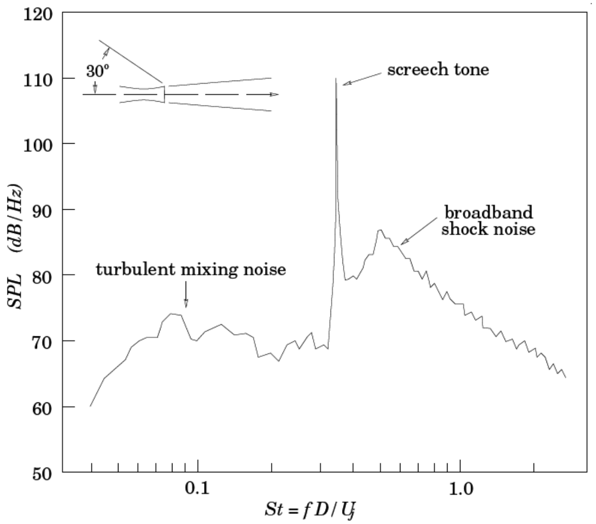


Jet Noise

- Jet noise sources
  - Turbulent mixing noise
  - Broadband shock noise
  - Screech tone noise
- Research Topic
  - Analytical turbulent theory
  - Prediction : CFD
  - Experiment
- Reduction of jet noise
  - Chevron, fluidic injection : increase turbulent mixing and reduce jet flow speed

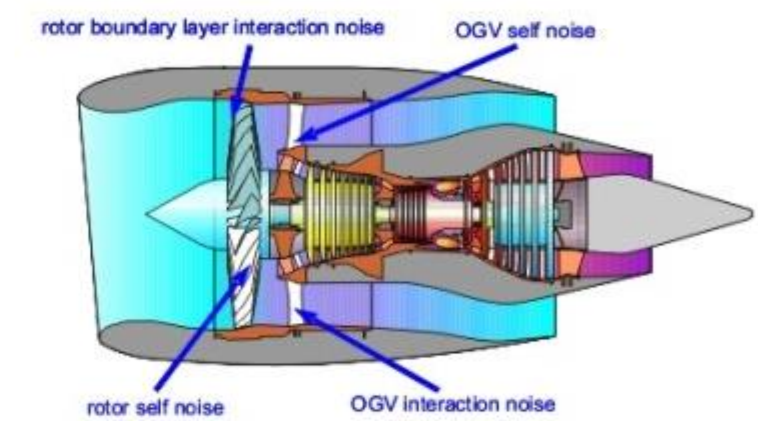
M.L. Shur et. al. AIAA 2006-485





Turbomachinery Noise

- Engine noise (Fan Noise)
  - Fan wake and OGV interaction noise
  - Fan shock noise (high speed)



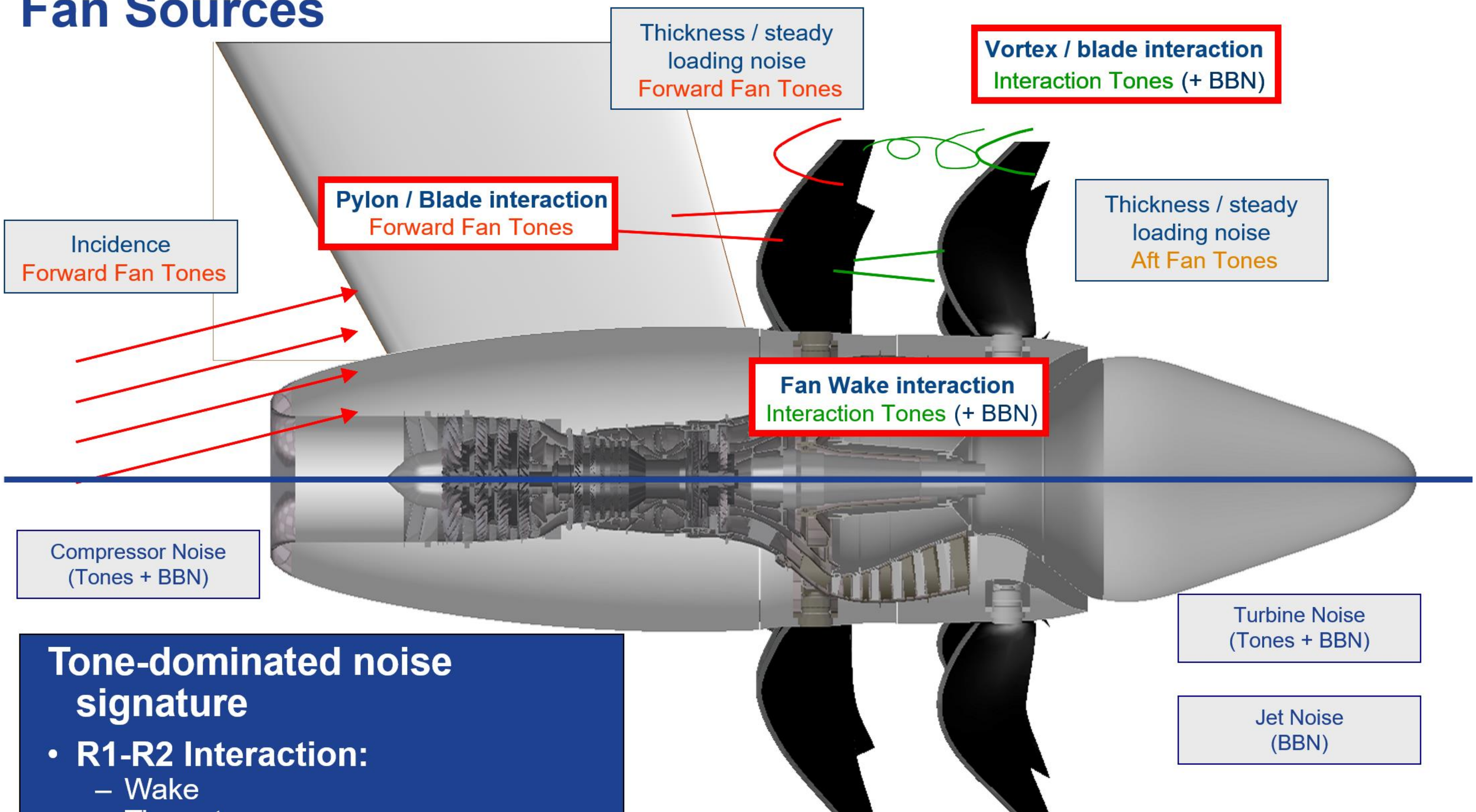
- Research topics
  - Duct acoustics (acoustic liner)
  - Turbomachinery CFD
  - Open rotor noise

- Noise reduction
  - Acoustic linear
  - Blade counts / spacing
  - Low speed fan

Courtesy : NASA

Open Rotor Noise

Fan Sources

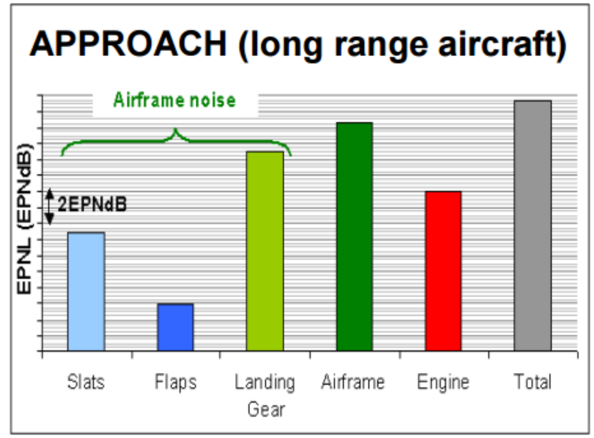


Tone-dominated noise signature

- **R1-R2 Interaction:**
  - Wake
  - Tip vortex
  - LE vortex

Airframe Noise I

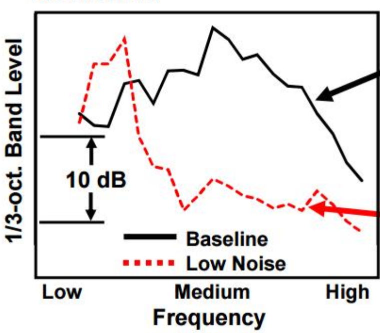
- Airframe noise sources
  - Landing gears
  - Slotted slat
  - Flap side-edges
  - Spoilers
  - Gear wake and flap interaction



Courtesy : Airbus

Landing gear noise reduction

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

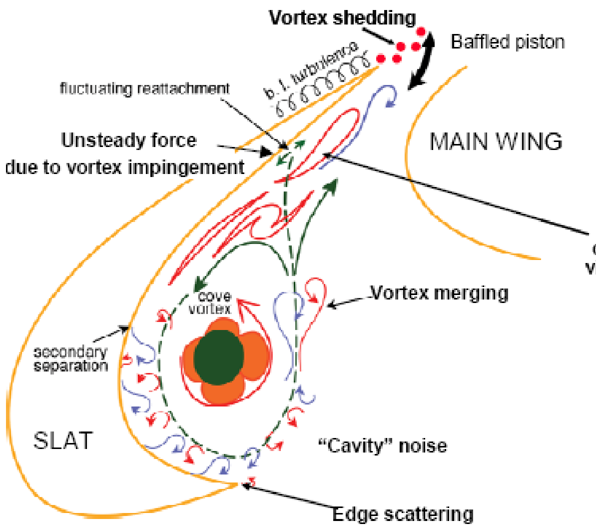


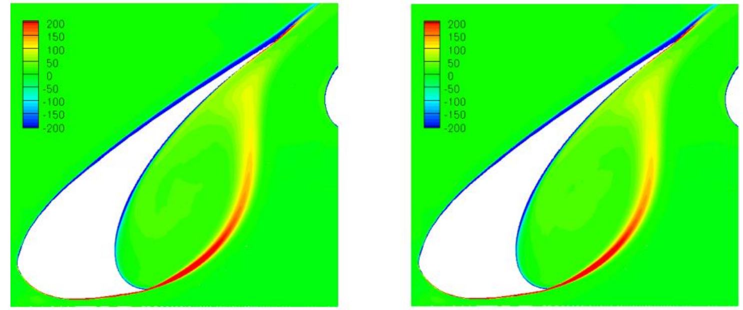
First full scale LG test in 1995:

Courtesy : DLR

Airframe Noise II

- Slat Noise





(a) $dt = 0.0016464$ (b) $dt = 0.0008232$

Figure 7. Spanwise vorticity, $\omega_z c/U_\infty$, around the slat averaged both temporally and in the spanwise direction.

Reference: AIAA 2009-3101

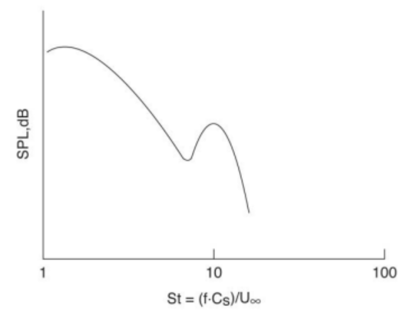


Figure 1: *Typical slat frequency spectrum. Cs represents slat chord.*

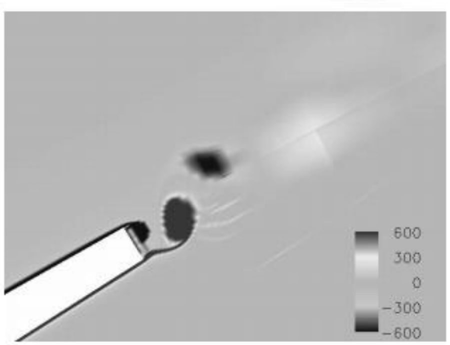


Figure 2: *Instantaneous spanwise vorticity field at slat trailing edge.*

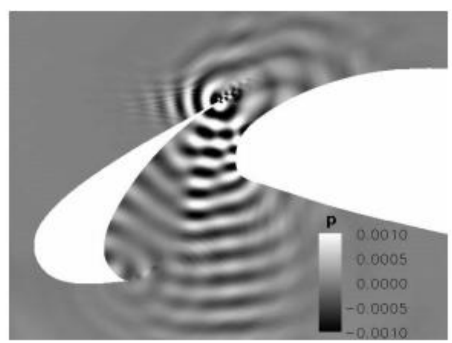


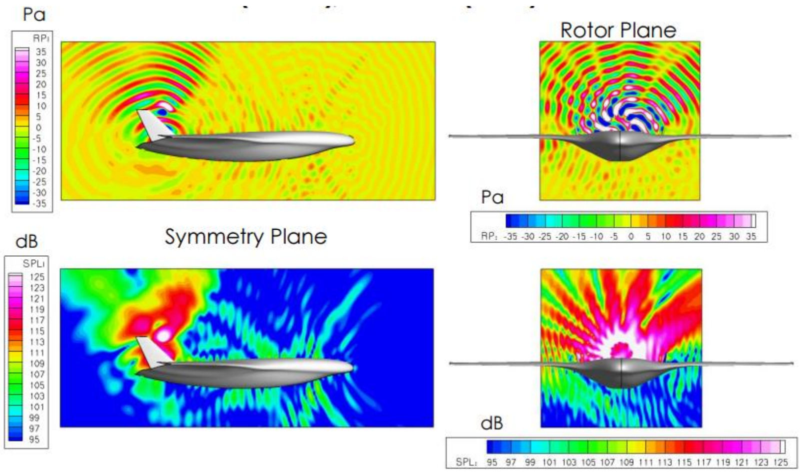
Figure 3: *Instantaneous fluctuating pressure field.*

Figure 4: *Instantaneous spanwise vorticity field for partially laminar simulation of cove.*

Reference: EUROMECH 2003

Propulsion Airframe Integration

- Hybrid wing body concept (over-the-wing engines)
- Huge potential to reduce engine noise by shielding (main concept to meet NASA's 2025 noise vision: 52dB noise reduction)
- Acoustic scattering : accurate and efficient numerical tools are essential
- Challenges due to installation, maintenance, public acceptance, etc.

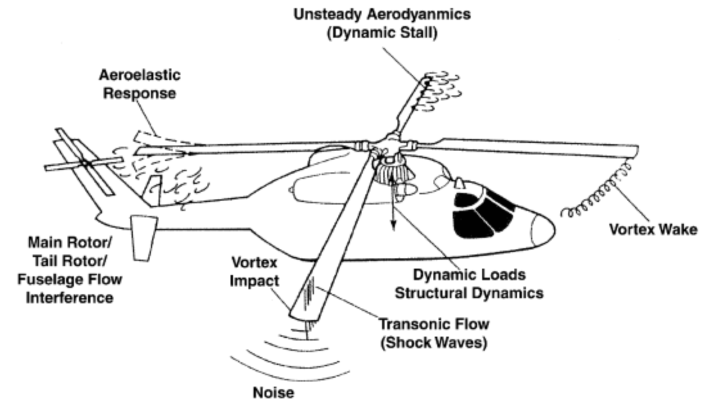


Courtesy : NASA

Rotorcraft Noise

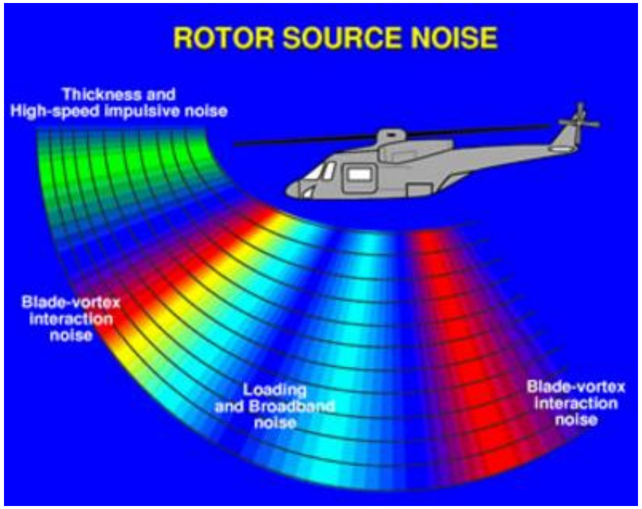
- Main noise sources
  - Blade self noise (thickness & loading)
  - Blade vortex interaction noise
  - High speed impulsive noise
  - Broadband noise
- Research topics
  - Prediction (CFD/FW-H)
  - Maneuvering noise
  - Co-axial rotor
  - Acoustic scattering
- Noise reductions
  - Active blade control
  - Low noise blade design

Helicopter aeromechanical challenges



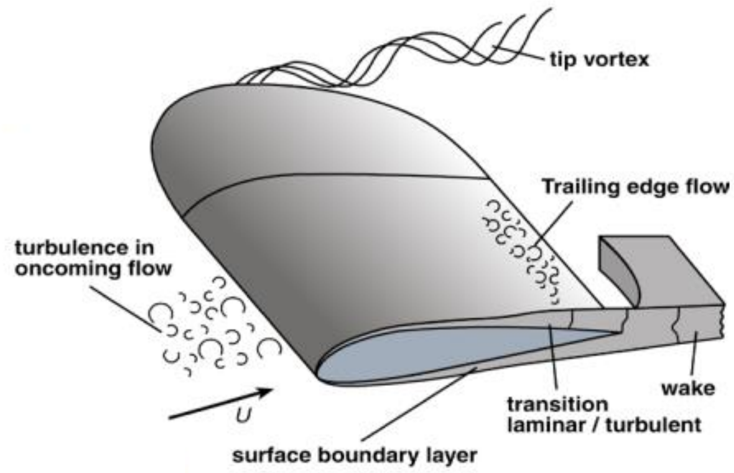
Courtesy : Progress in Aerospace Sciences, 2003

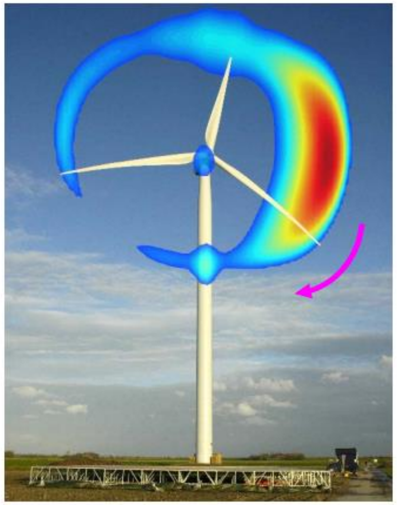
Rotorcraft noise source and directivity



Wind Turbine Noise

- Aerodynamic noise
  - Trailing edge noise
  - Inflow turbulence noise
  - Flow Separation noise
  - Tip noise
  - Typically, broadband noise
  - Associated with blade motion
    - Doppler amplification
    - Directivity
- Research topics
  - Serrated trailing edge
  - Low noise airfoil
  - Amplitude modulation
  - Far-field noise propagation





Wind Turbine Noise (MultiScience, 2011)