Overview of Turbofan Engine Noise

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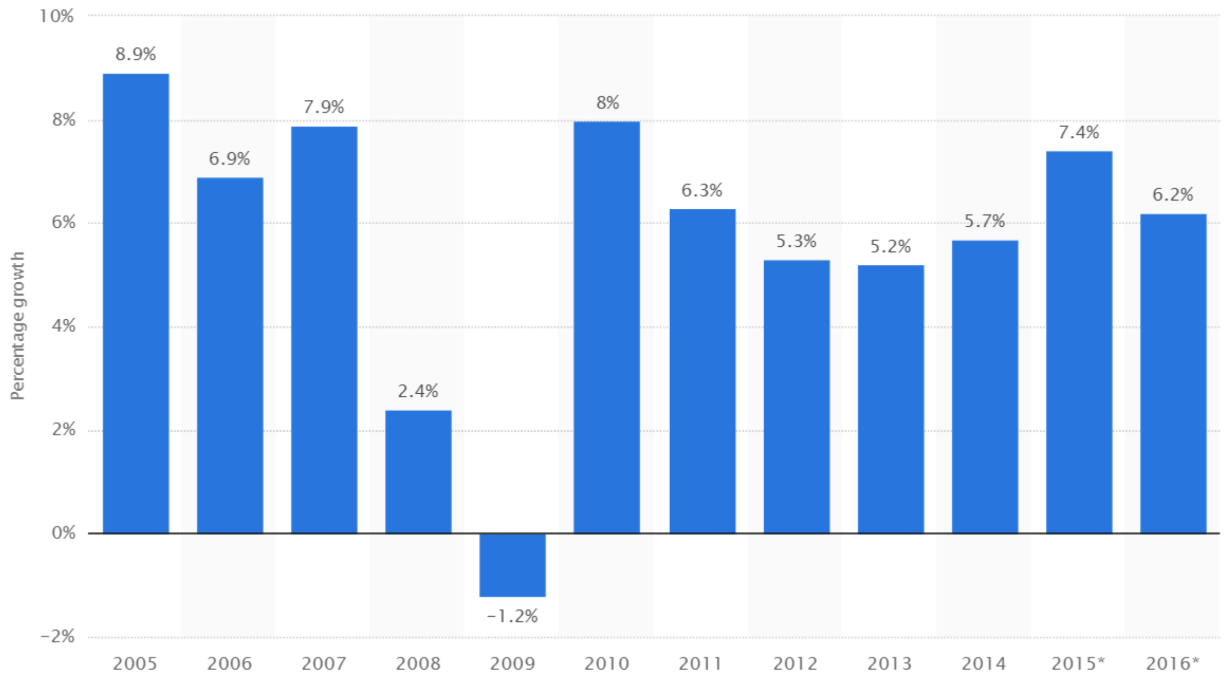
Some statistics…

- Current aircraft are 20-30 dB quieter than first generation turbofans
- Natural improvement in energy efficiency is 1.5% per annum
- Noise levels of new aircraft entering service are reducing at 0.5 dB per annum

Annual Growth in Air Traffic Demand

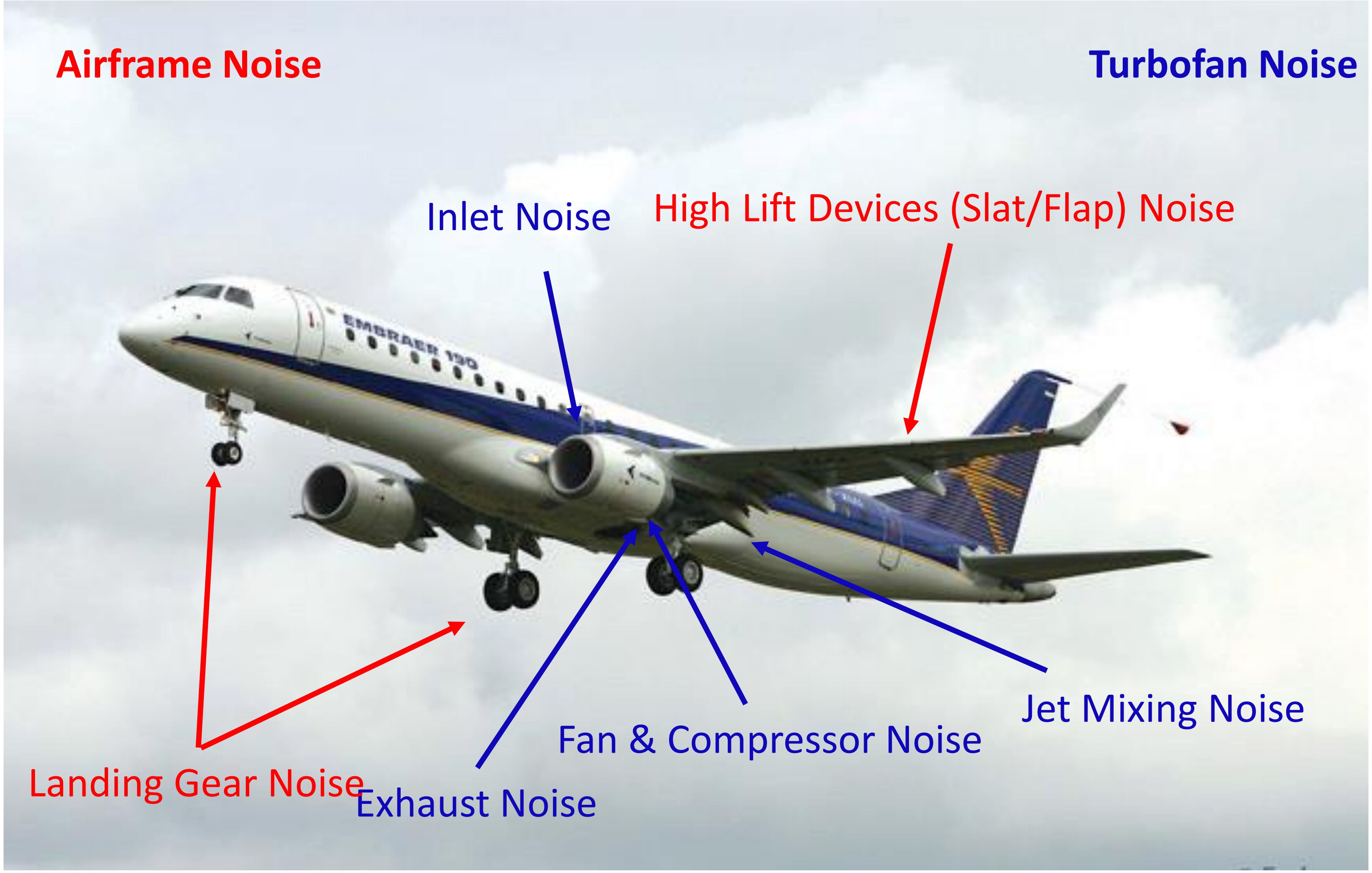


- **Global air traffic is growing at 5% per annum since 2005**

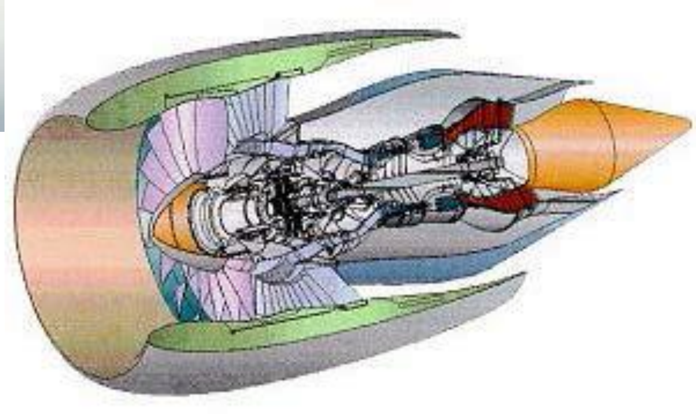
Aircraft Noise

British Airways Airbus A321 flies over Myrtle Avenue on its landing path to Heathrow runway 27L. Myrtle Avenue is on the south east edge of London (Heathrow) Airport.

Sources of Aircraft Noise



Important Source of Aircraft Noise

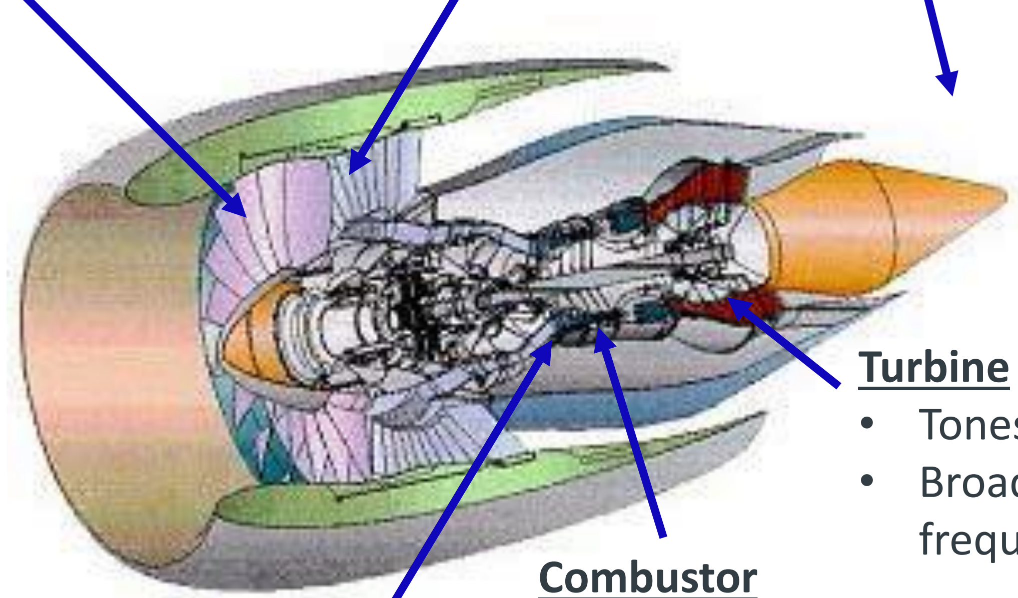


Sources of Turbofan Engine Noise

Fan/Rotor
- Tones (harmonic)
- Broadband Noise
- “Bazz-Saw” Noise

Stator
- Tones (harmonic)
- Broadband Noise
- Duct modes

Jet
- Broadband Noise (Low frequency)
- Distributed



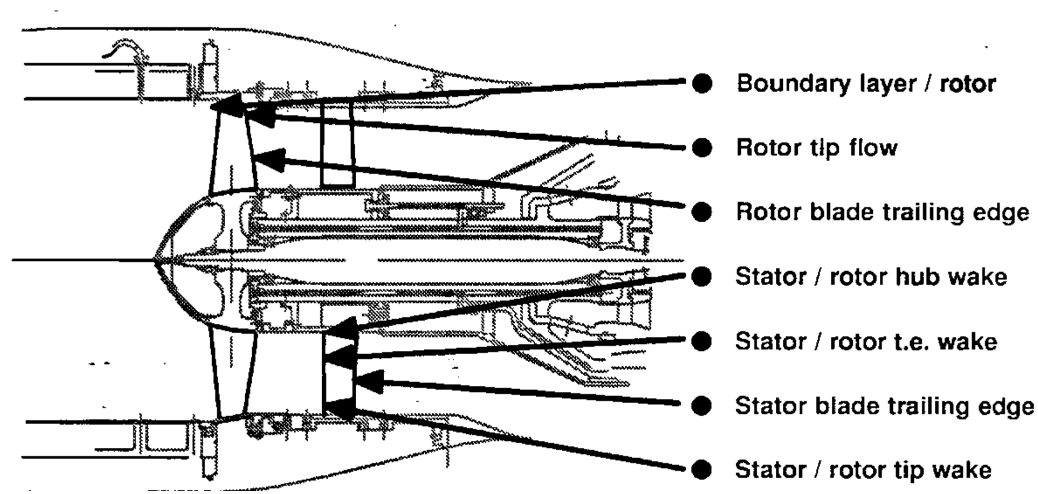
Turbine
- Tones (High frequency)
- Broadband Noise (High frequency)

Combustor
- Broadband Noise (Low frequency)

Compressor
- Tones (High frequency)
- Broadband Noise

Sources of Broadband Noise

Broadband noise is produced when a turbulent flow interacts with a solid surface.



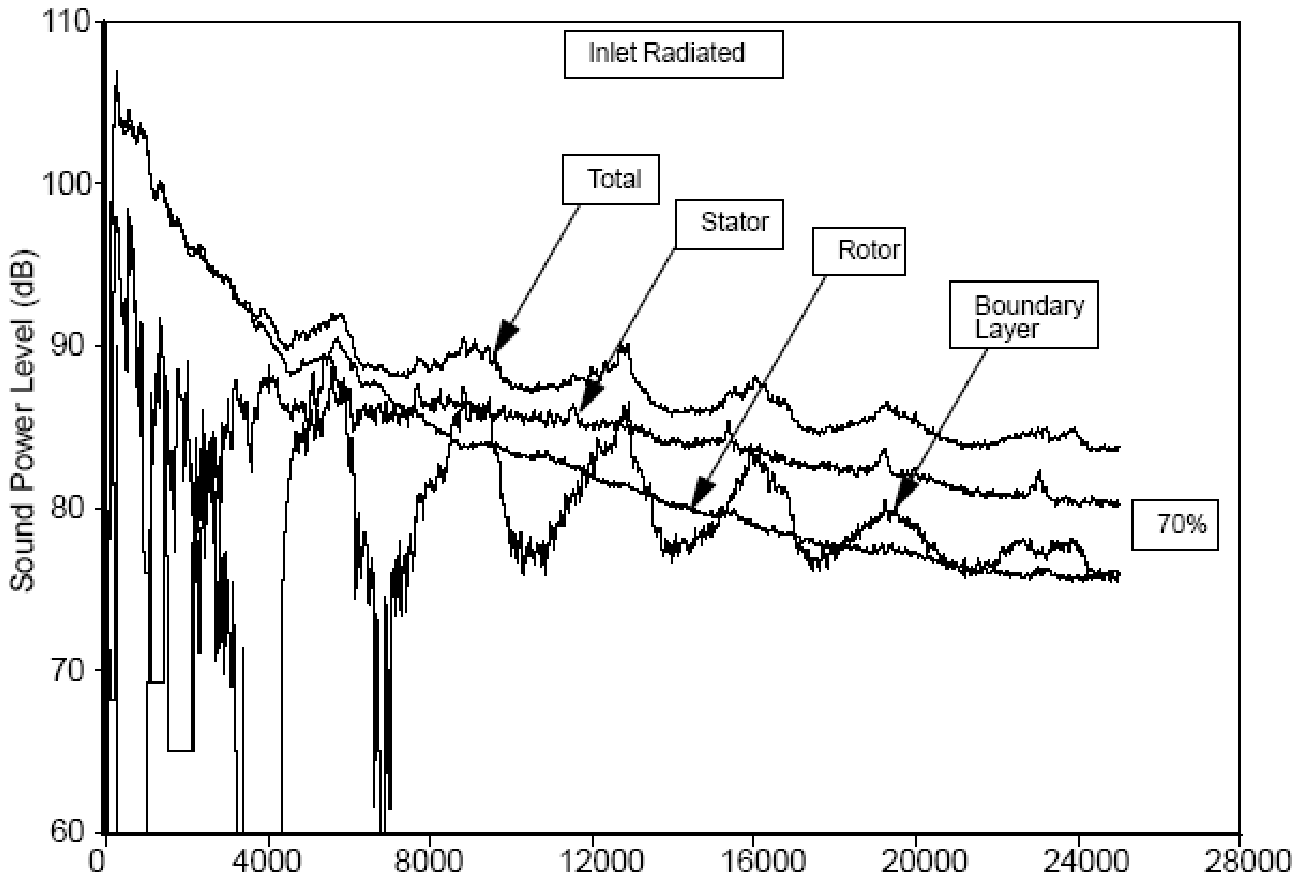
Ingested turbulent flow onto the rotor

Blade tip interaction with the turbulent boundary at the casing wall

Turbulence generated in the blade boundary layer and scattered from the rotor trailing edge

Turbulent wakes shed from the rotor impinging onto the stator.

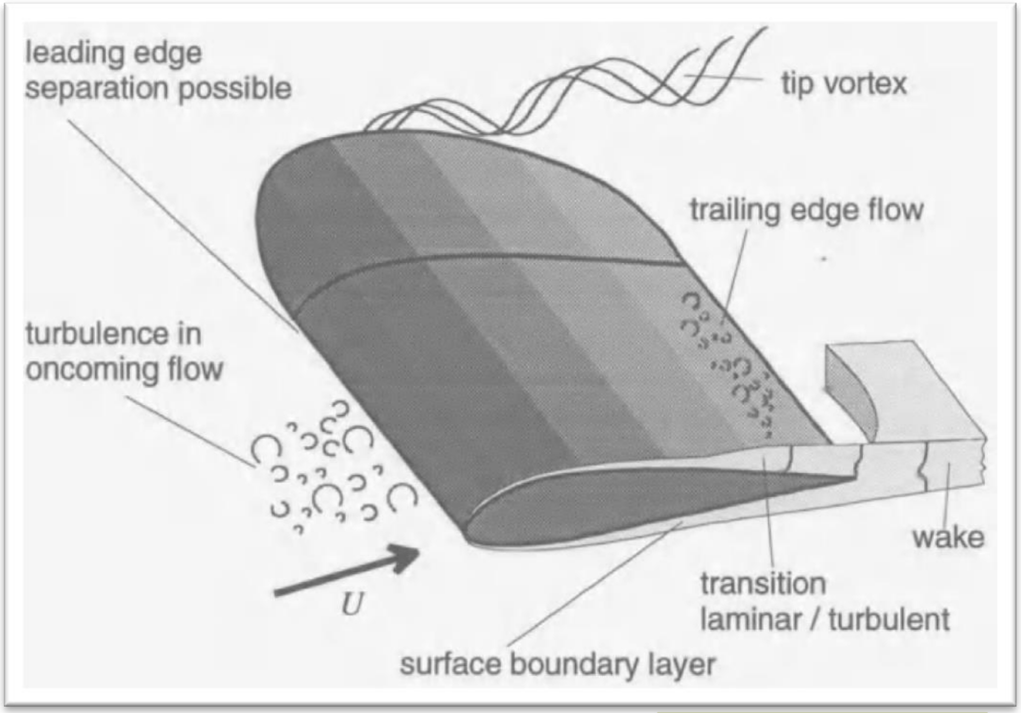
Characteristics of Broadband Noise



Gantz et al., 1998

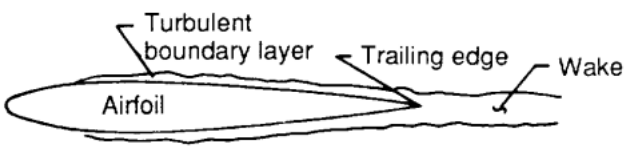
Blade Noise Mechanisms

Airfoil noise is produced whenever turbulence interacts with a solid surfaces

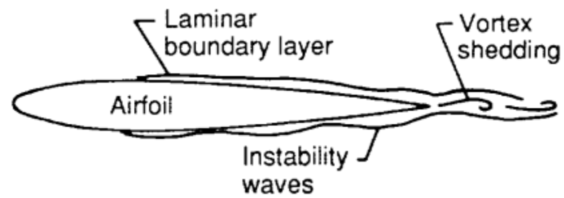


Wagner et al, 1996

Classification of Self-Noise Mechanisms

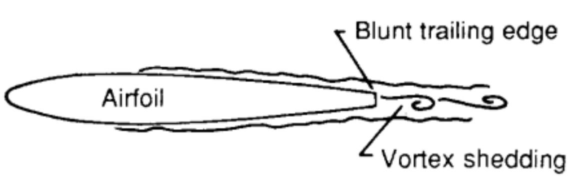


Turbulent boundary layer noise

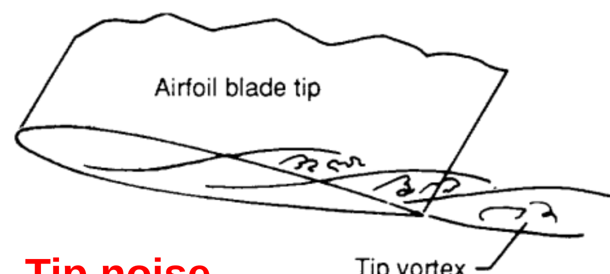


Laminar boundary layer, vortex shedding noise

Separation stall noise



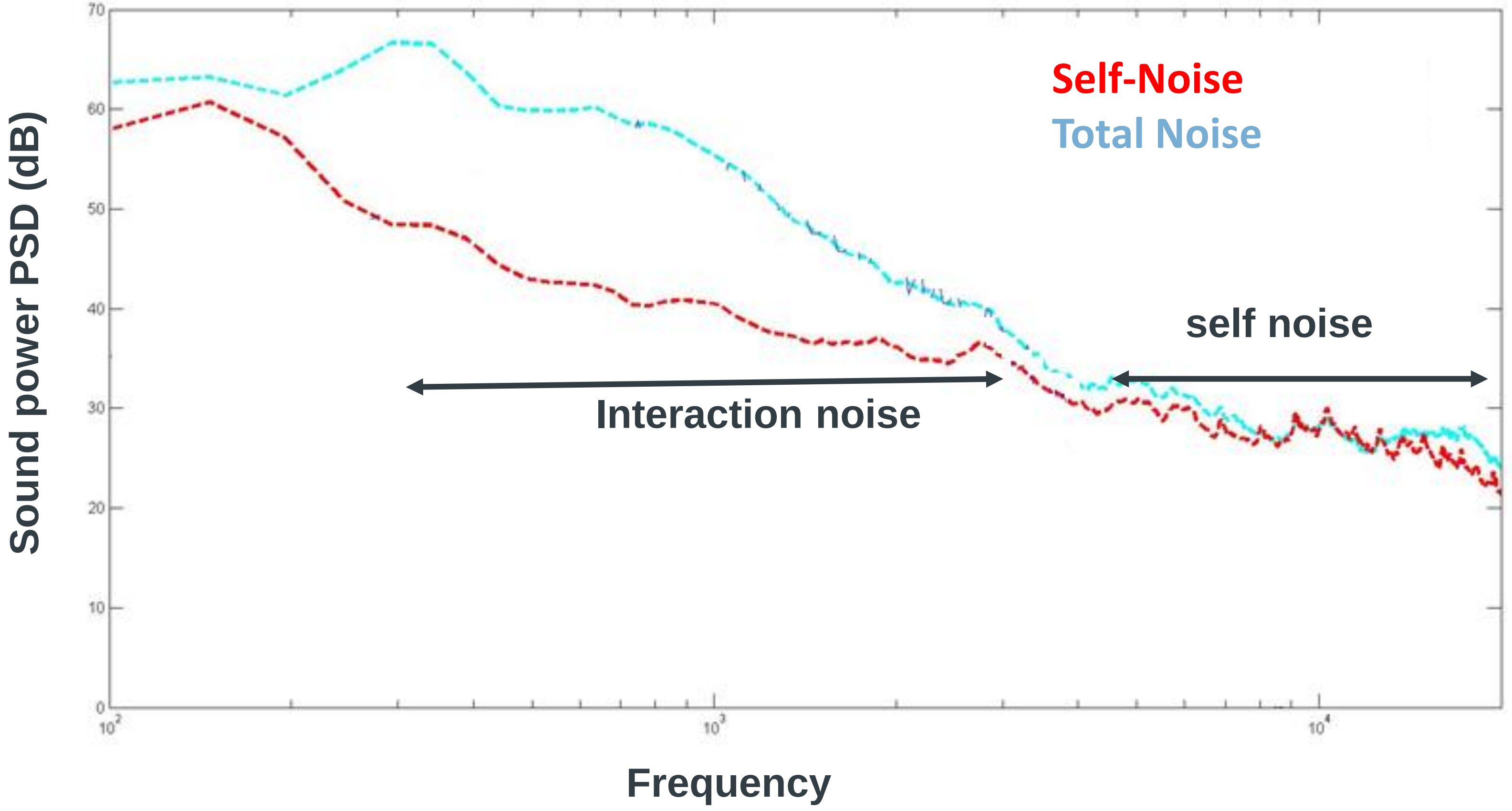
Bluntness noise

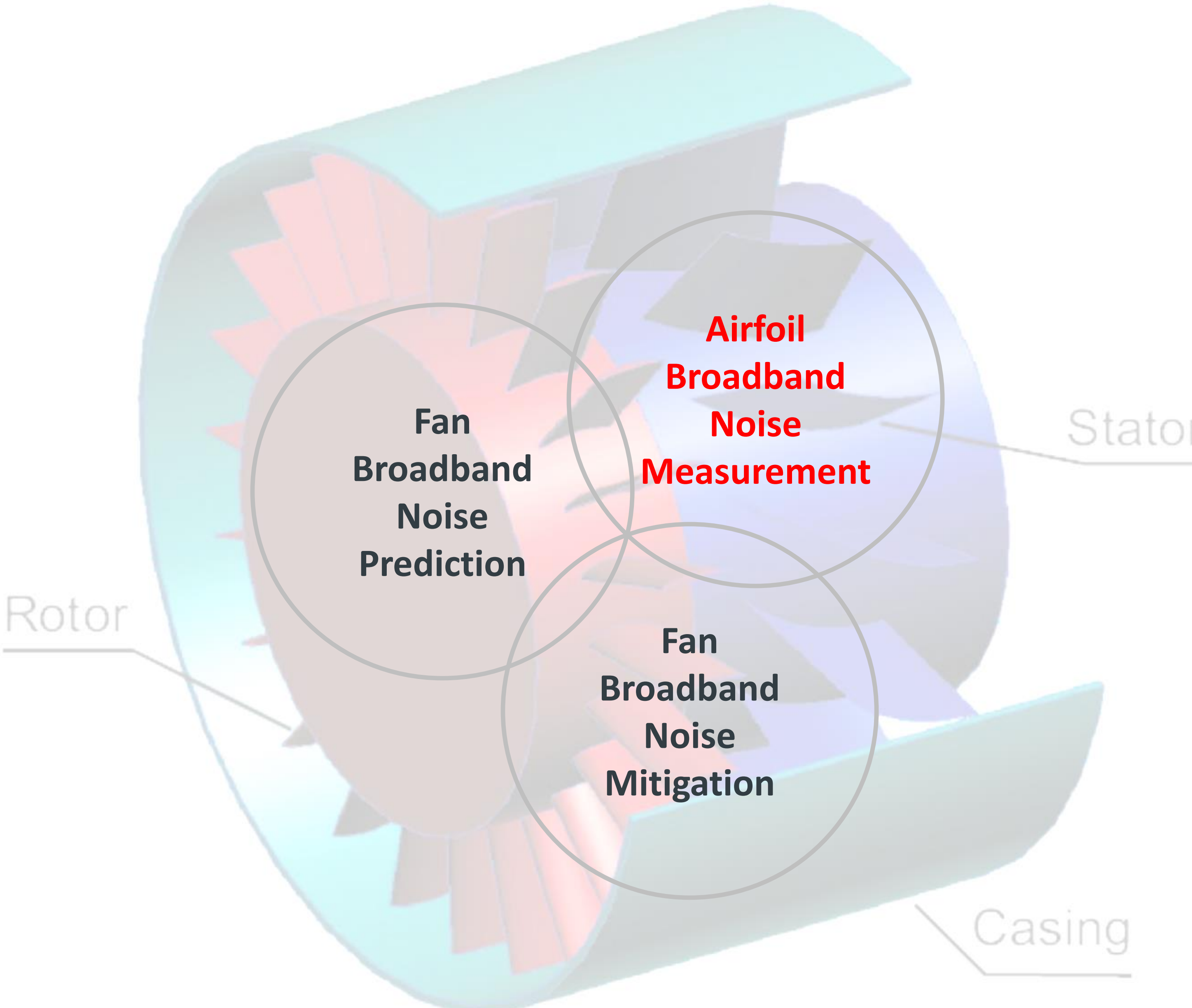


Tip noise

Airfoil Noise

NACA006 at $\alpha = 0°$



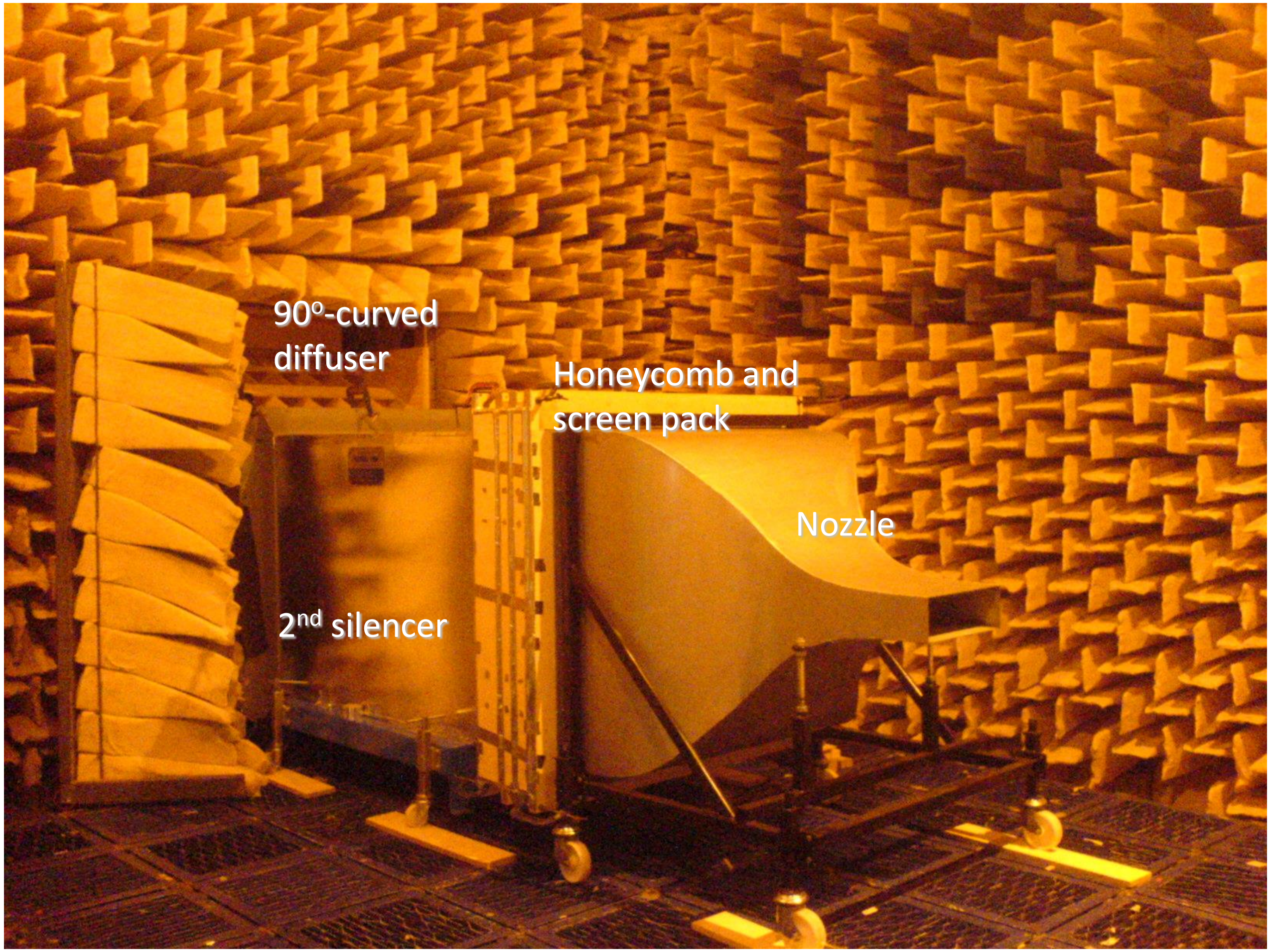


Fan Broadband Noise Prediction

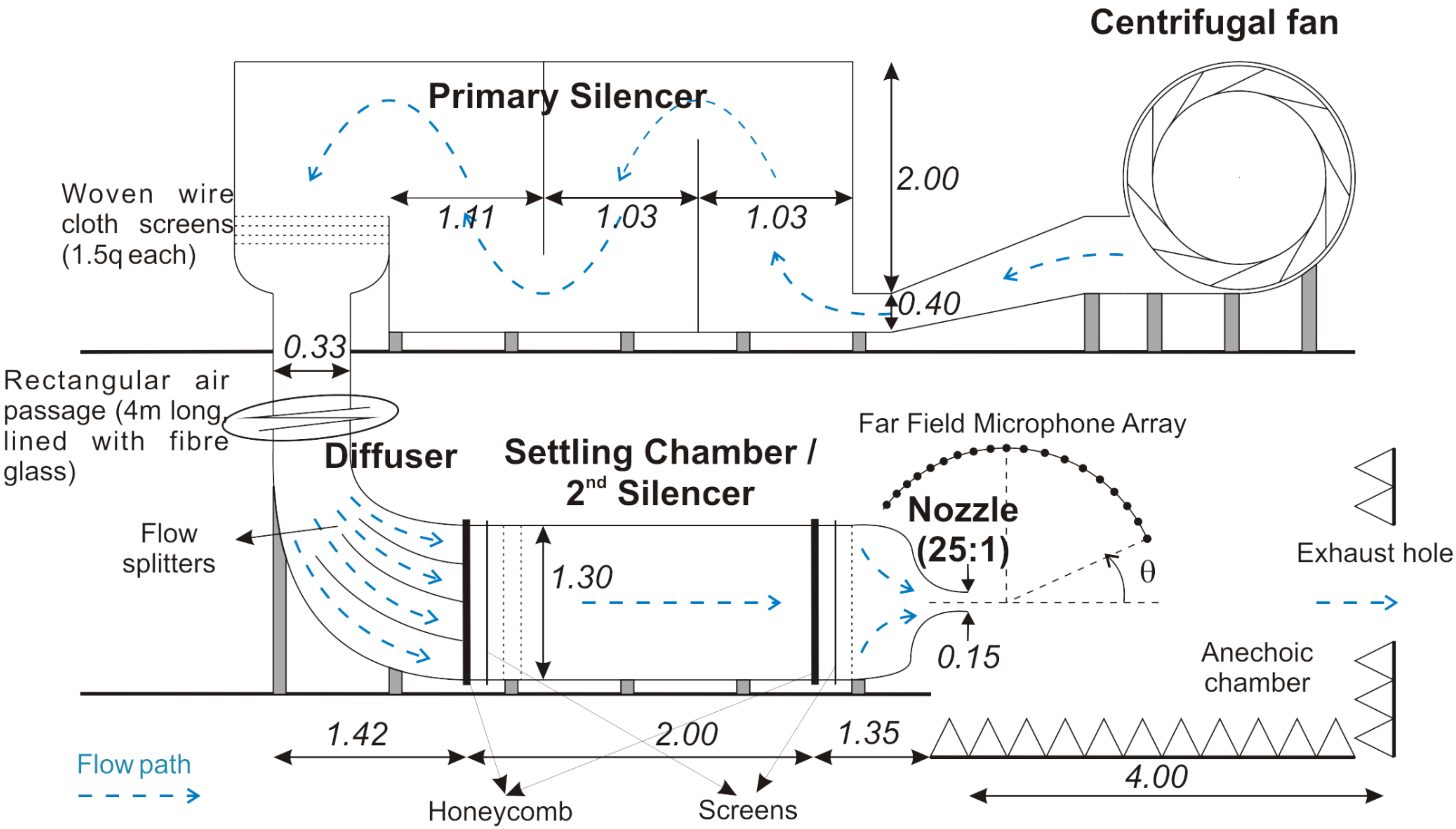
Airfoil Broadband Noise Measurement

Fan Broadband Noise Mitigation

ISVR Open Jet Wind Tunnel

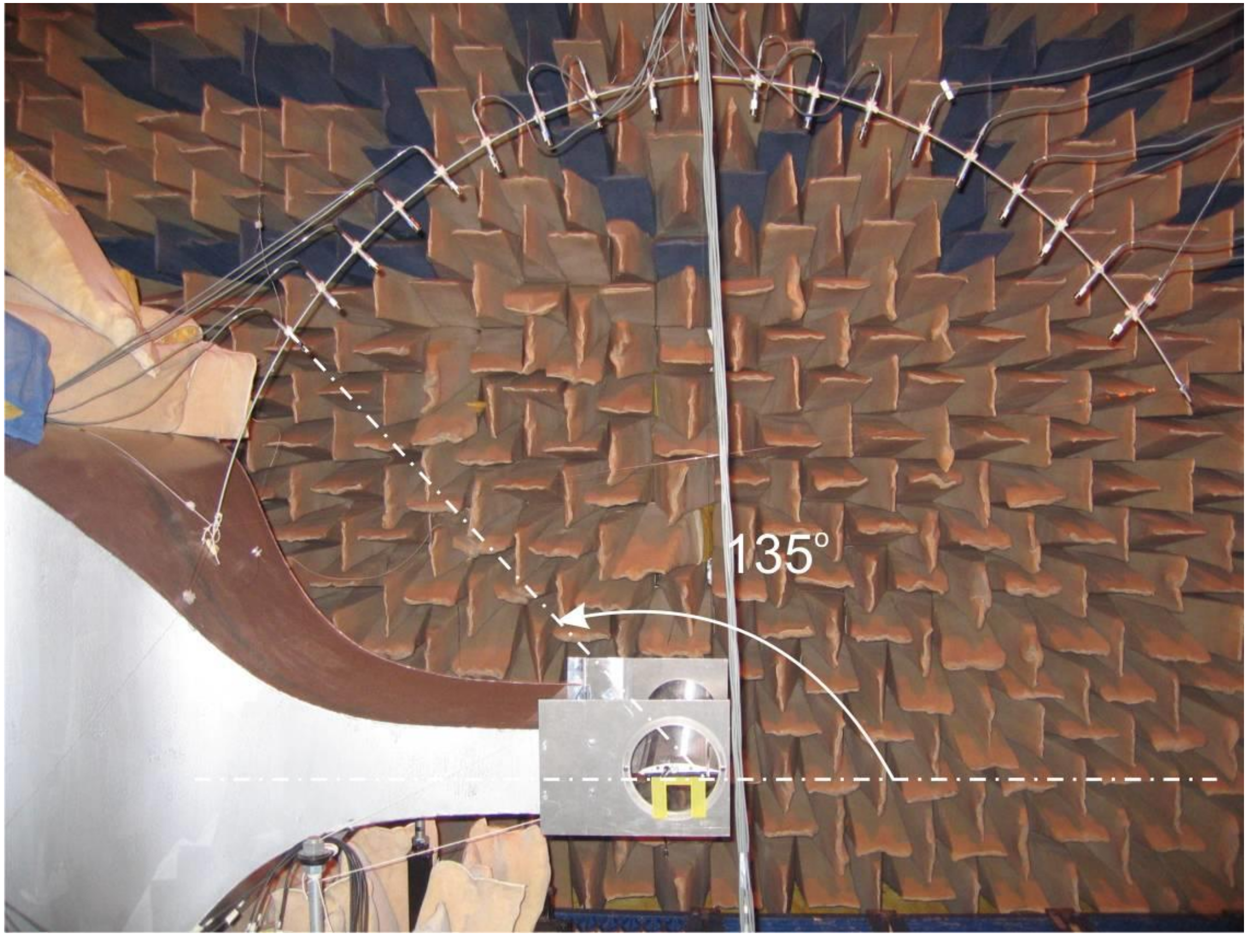


ISVR Open Jet Wind Tunnel Design



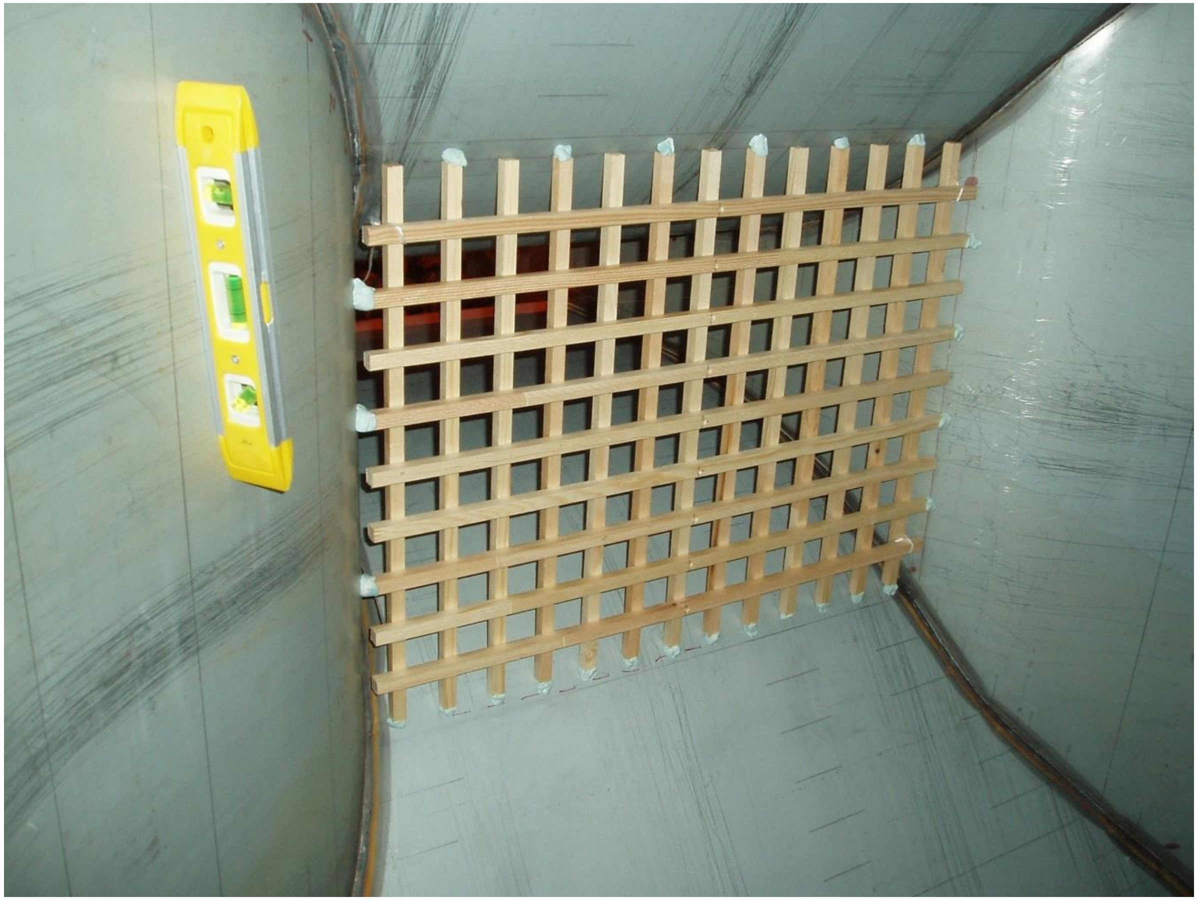
Maximum speed well above 100m/s

Far-Field Directivity Measurements



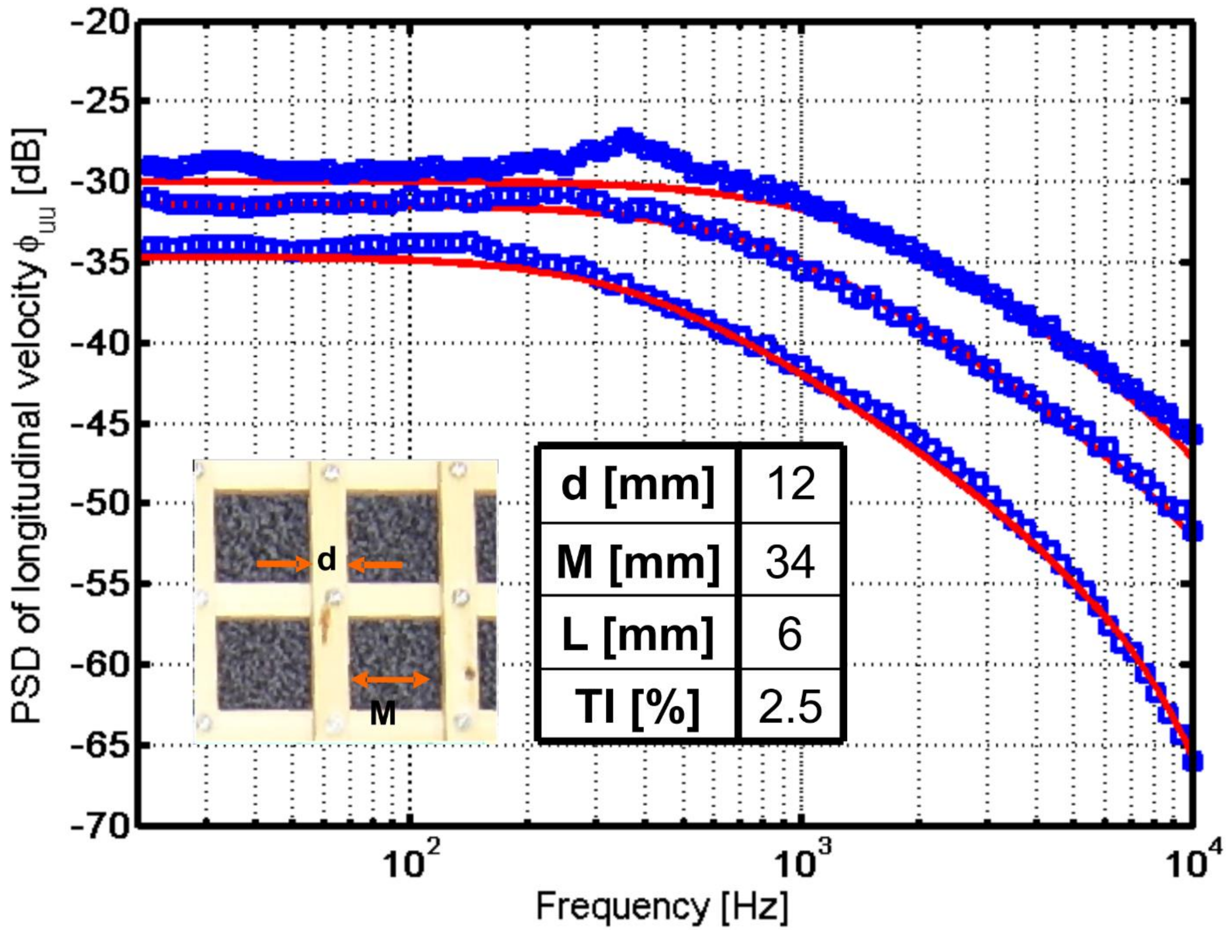
→19 B&K microphones
→45^{o} to 135^{o}

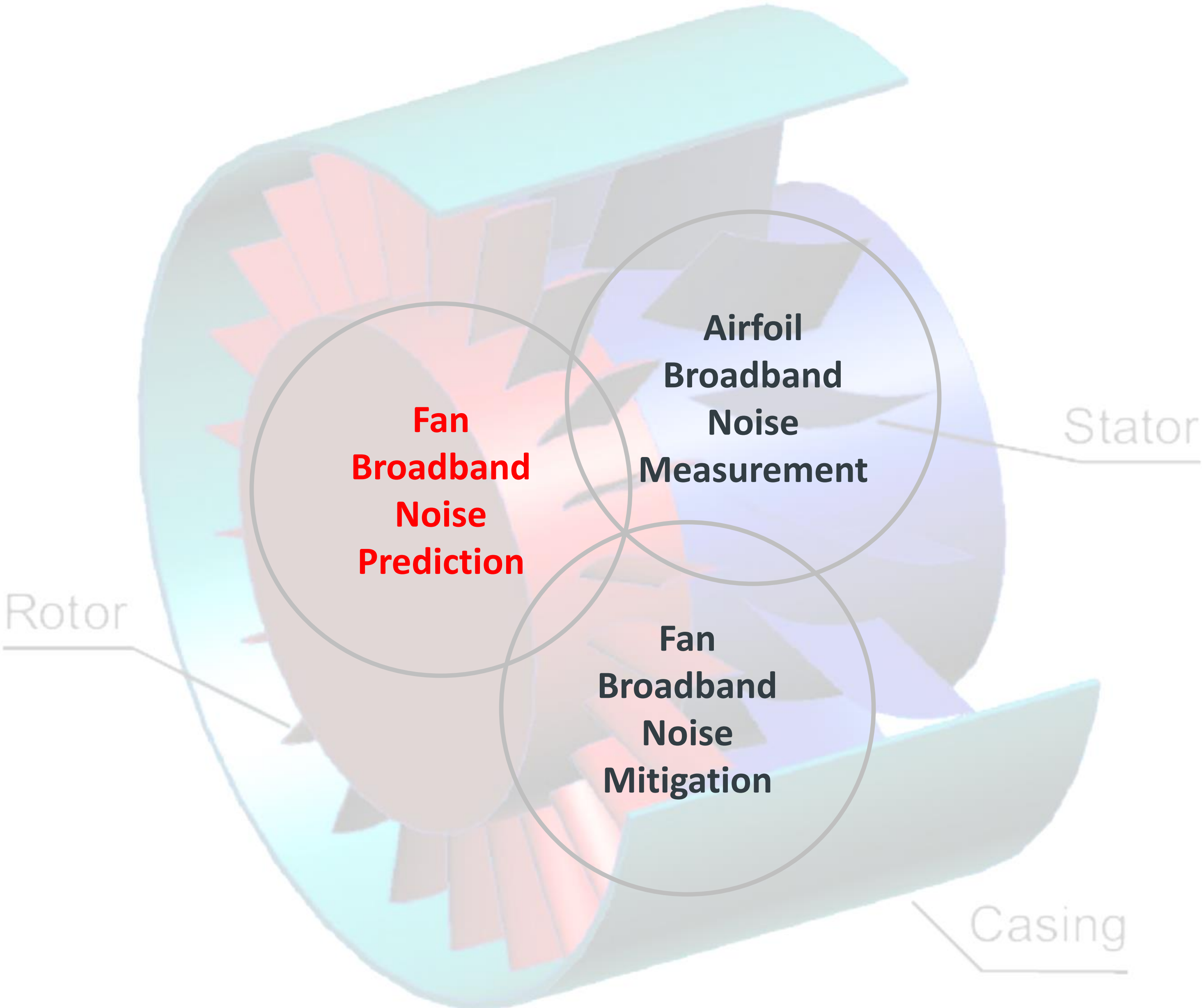
Passive Grid – Turbulence Generator



Turbulence level is limited to 10%

Isotropic Turbulence Spectrum

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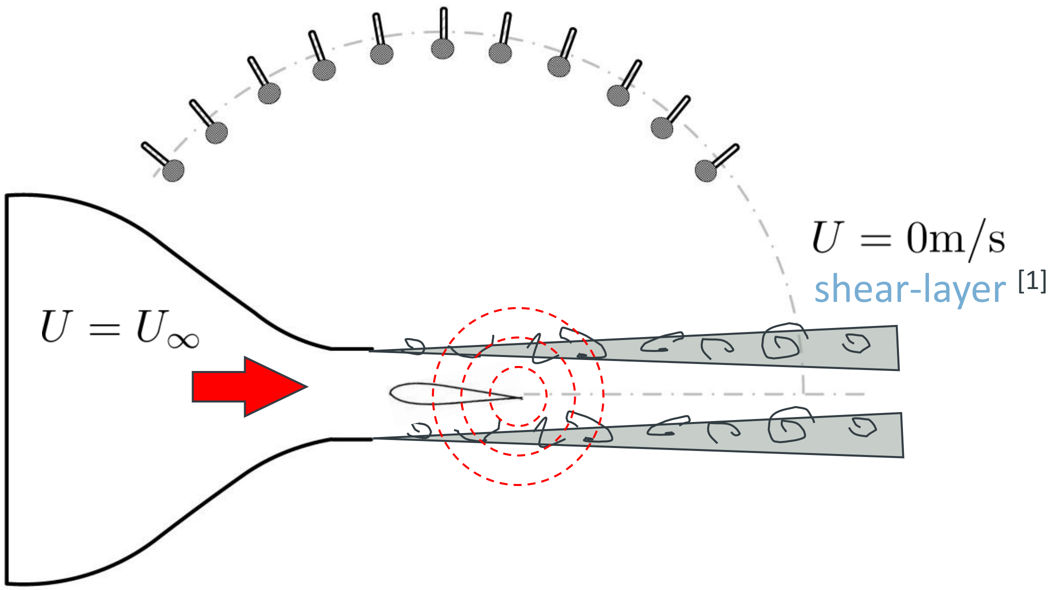
Fan Broadband Noise Mitigation
Stator
Rotor
Casing

Anechoic Wind Tunnel



$$\text{NACA-0012}\ \alpha = 0^\circ$$

$$c = 0.2\,\text{m}\ L_3 = 0.45\,\text{m}$$

$$U_\infty = 20 - 80\,\text{m/s}$$

Boundary layer - tripped

- Far-field sound
  - 11 B&K microphones
- Surface pressure
  - 8 remote microphones
- Boundary layer properties
  - hot-wire anemometry

[1] Amiet, R.K., *J. Sound Vib*. (1978)

Broadband noise source modelling

$$\mathscr{P}_w(k_1, k_3 = 0, \omega) = 4\rho^2 \frac{k_1^2}{k^2} \int\limits_0^{\delta} \Lambda_{2|22}(x_2) \left(\frac{\partial U_1(x_2)}{\partial x_2}\right)^2 \overline{u_2^2}(x_2) \phi_{22}(k_1, k_3 = 0) \phi_m(\omega - U_c(x_2) k_1) e^{-2|k| x_2} \mathrm{d}x_2$$

$\Lambda_{2|22}(x_2)$ - vertical integral length scale

$\frac{\partial U_1(x_2)}{\partial x_2}$ - mean shear

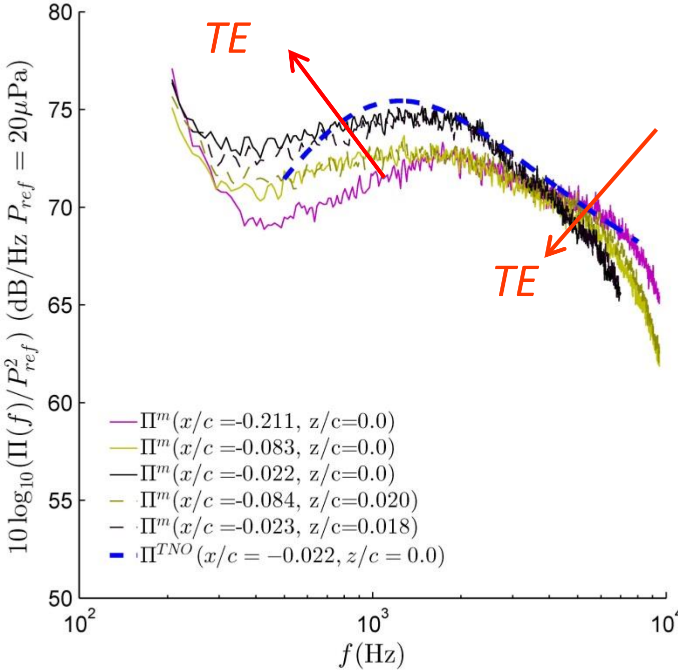
$\overline{u_2^2}(x_2)$ - vertical velocity intensity

$\phi_{22}(k_1, k_3)$ - wavenumber spectra of u_2

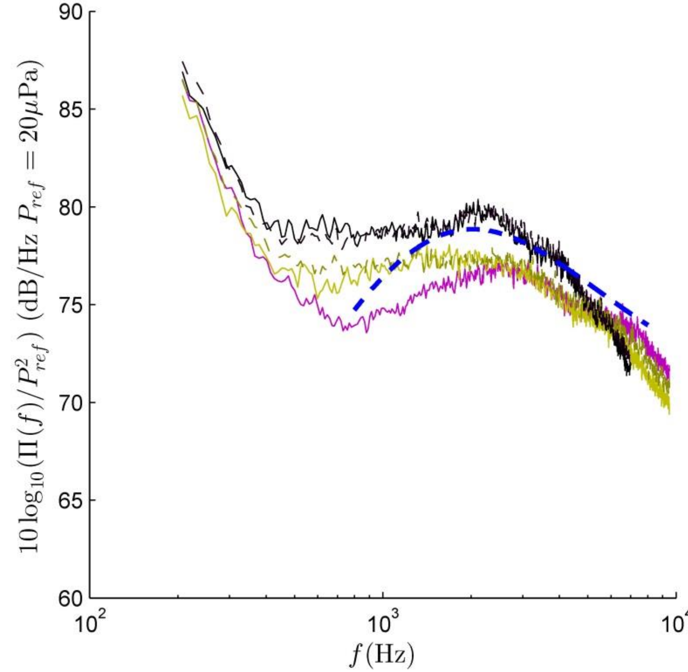
$\phi_m(\omega)$ - moving axis spectra

Surface Pressure Measurements

$Re_c = 520 \times 10^3,\ M = 0.12$



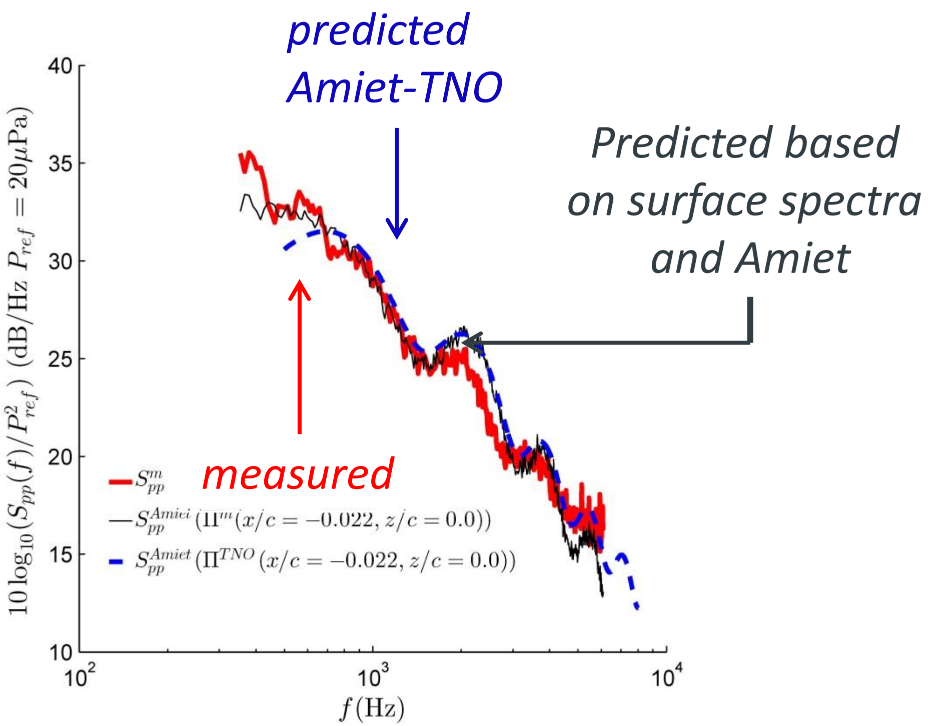
$Re_c = 780 \times 10^3,\ M = 0.18$



- As the jet speed increases the low frequency range dominated by jet noise

Far-field Sound Pressure Level

$Re_c = 520 \times 10^3,\ M = 0.12$



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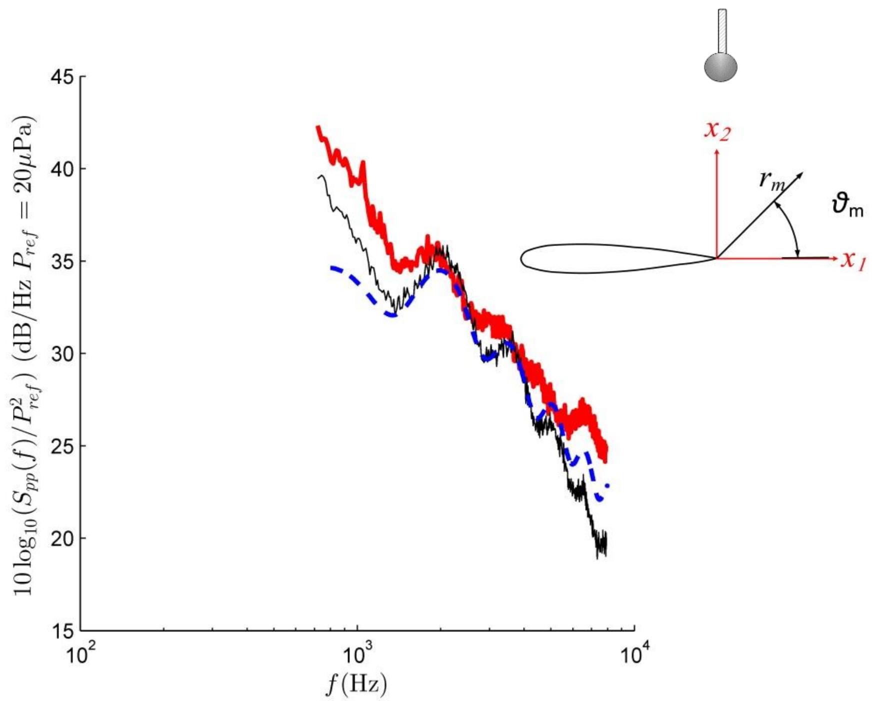
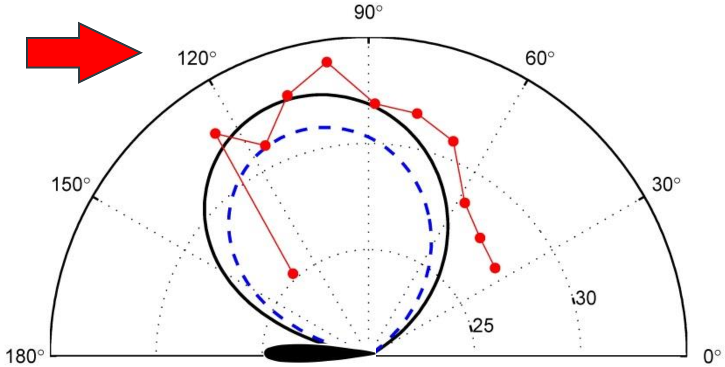


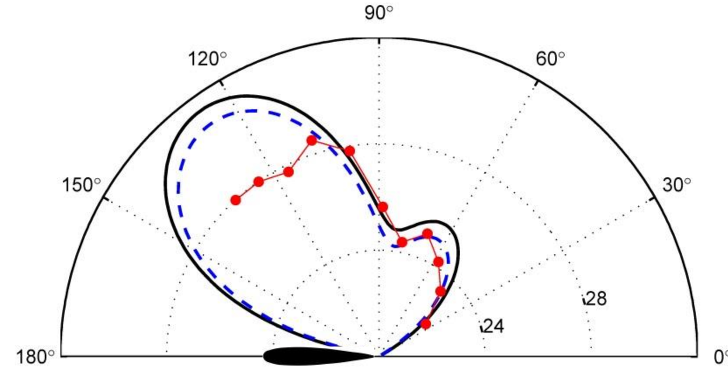
- Far-field pressure was corrected for shear-layer refraction

Directivity Patterns

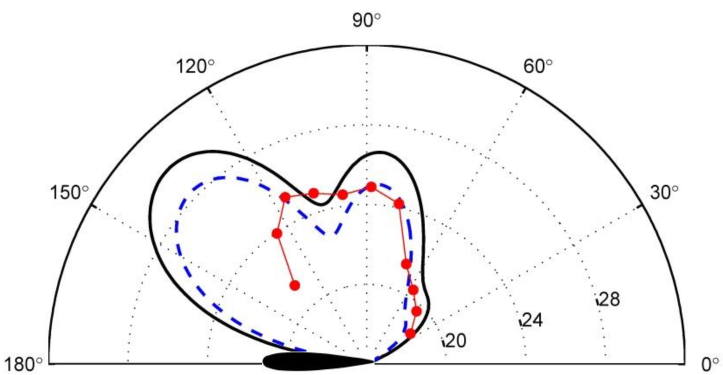
$$Re_c = 520 \times 10^3,\ M = 0.12$$



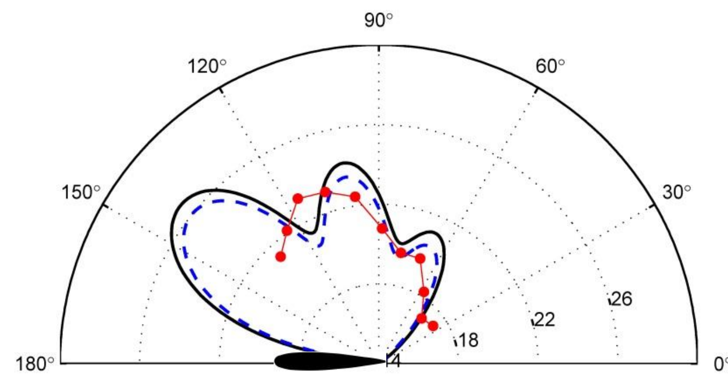
$k_0 c = 2.5$



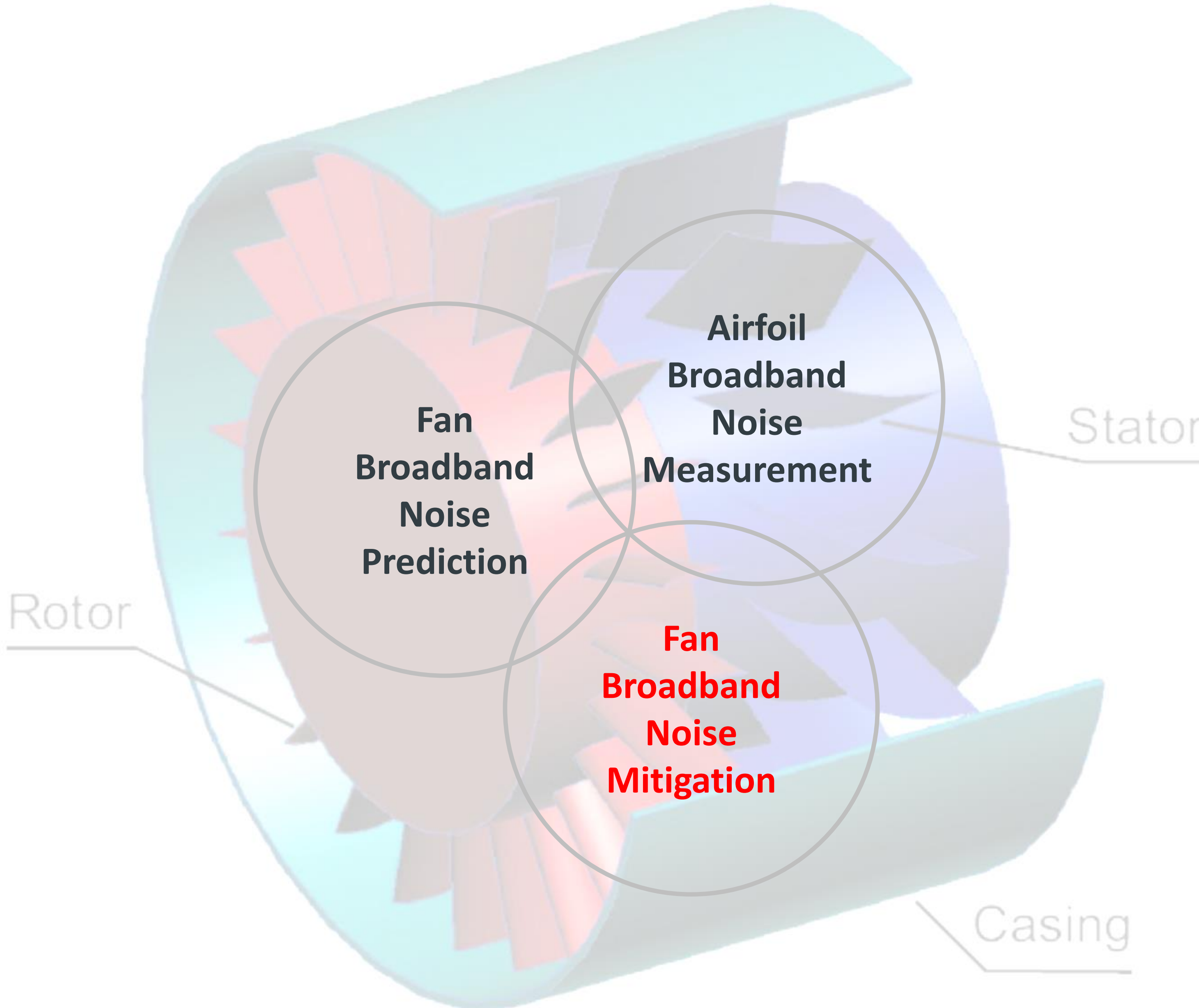
$k_0 c = 5$



$k_0 c = 7.5$



$k_0 c = 10$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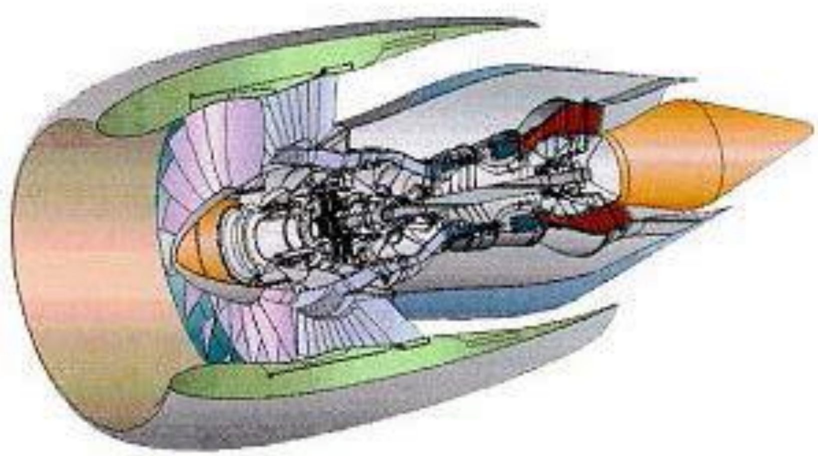
Fan Broadband Noise Mitigation

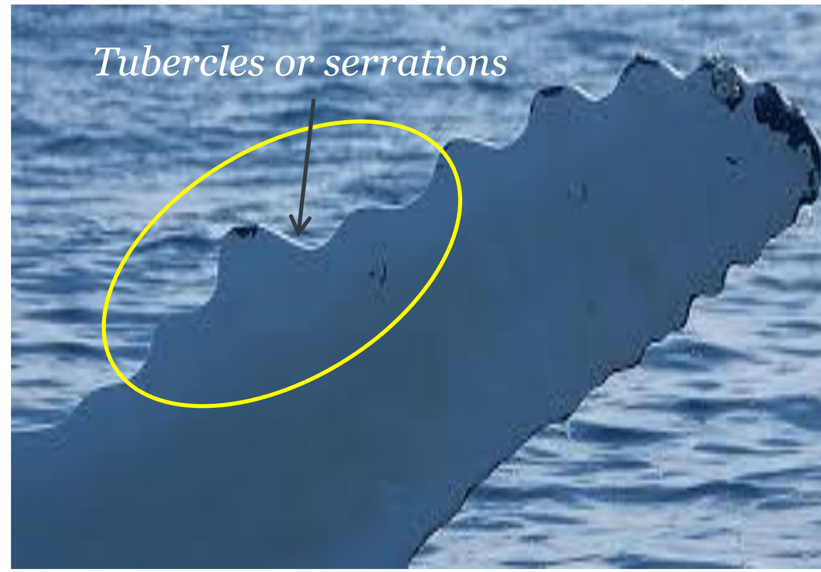
- Mitigation of fan noise can be achieved either by
  - reducing the noise at source through low noise design of the fan and stator
  - attenuating the sound by acoustic treatment in the intake and bypass ducts before it reaches the observer



Bio-inspired Solutions

Leading Edge Serrations

Whale Flipper

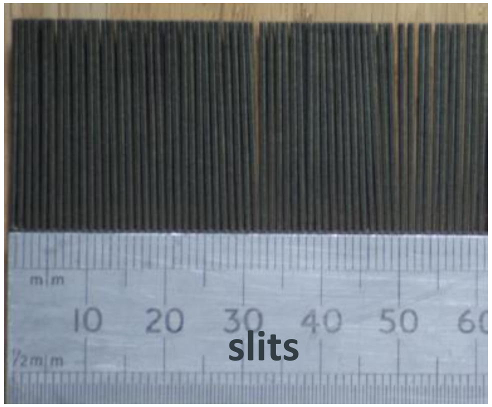


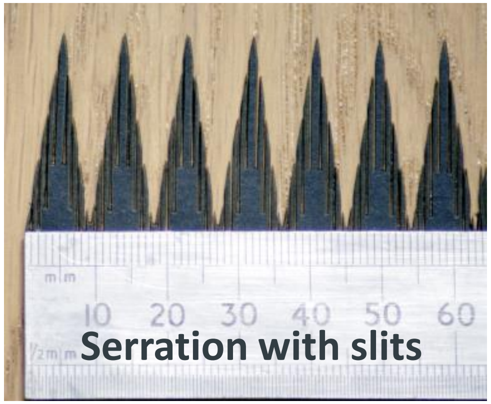
Novel Trailing Edge Geometries

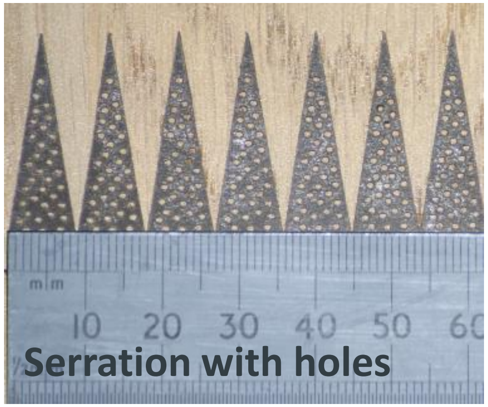
Axial cooling fan

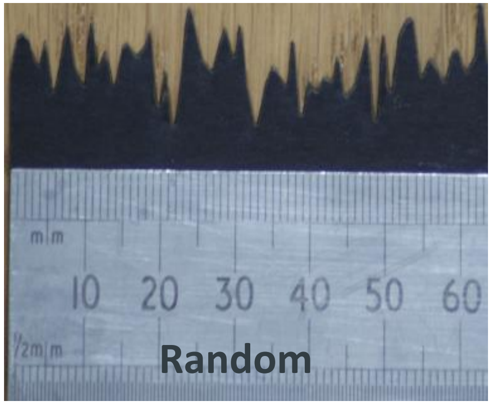
Wind turbine

Novel Trailing Edge Geometries

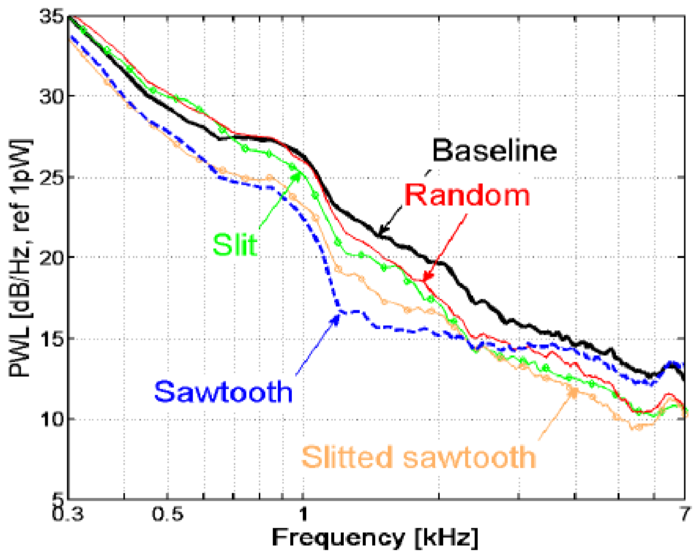




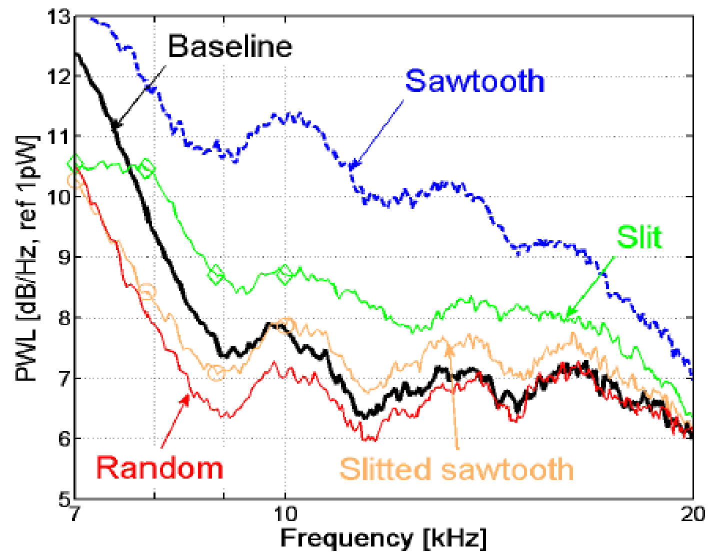




Novel Trailing Edge Geometries



(a) At 5^o AoA from 300 Hz to 7 kHz.

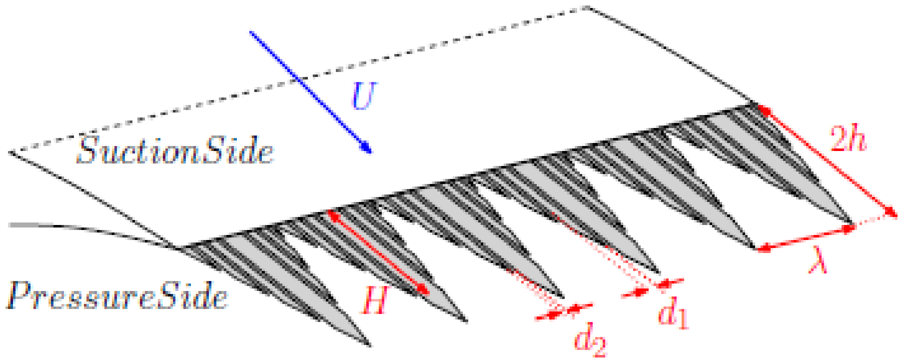


(b) At 5^o AoA from 7 kHz to 20 kHz.

Best Trailing Edge Geometry

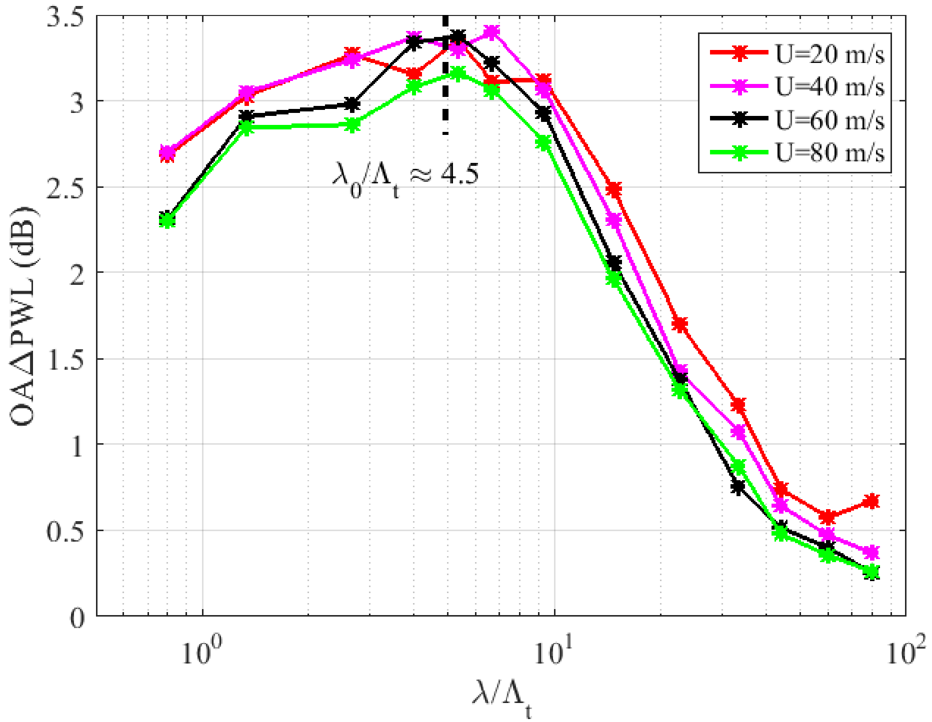
The slitted sawtooth serrated geometry was found to give the best overall noise reduction performance

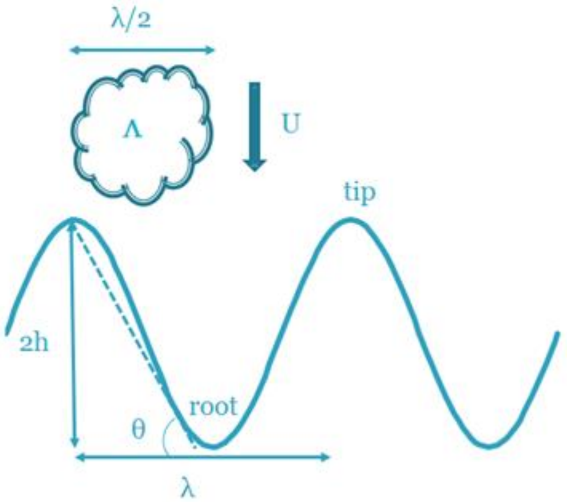
It combines the benefits of oblique edges but the slits allow equalisation of the mean pressure across the TE to prevent micro-jets, and hence high frequency noise generation

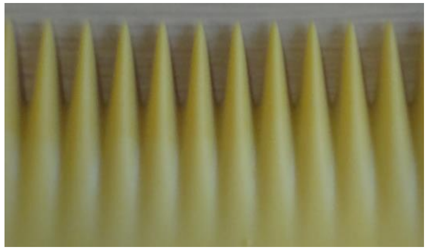


Leading Edgy Geometry

NACA 65- (12)10







The optimum serration angle obtained when integral length = $\lambda/2$

Thank you!