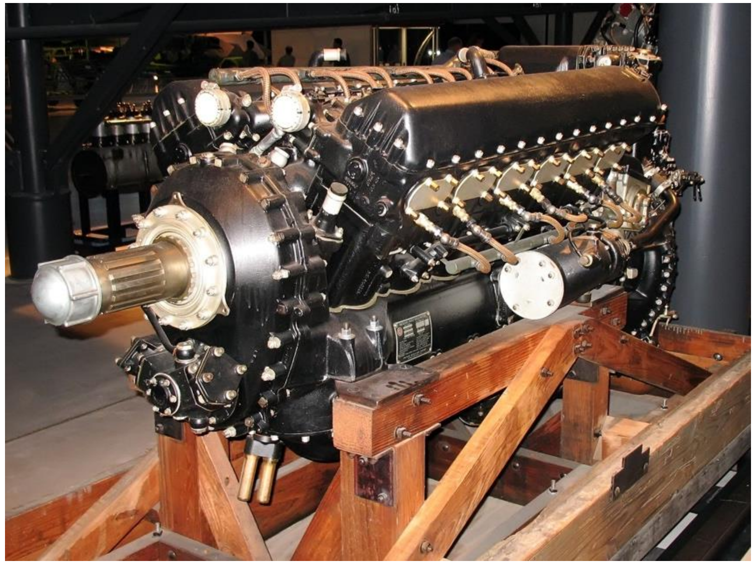
History time-line

- **Before 1950**
  - Most airplanes had **large piston engines** without exhaust mufflers, and they employed propellers that rotated at high tip speeds, generating ***considerable noise***
  - At that time, the main goal was maximizing engine power and aircraft performance, and the resulting ***high noise levels were viewed as an unimportant byproduct***

P-51 Mustang

DC-6, piston engines

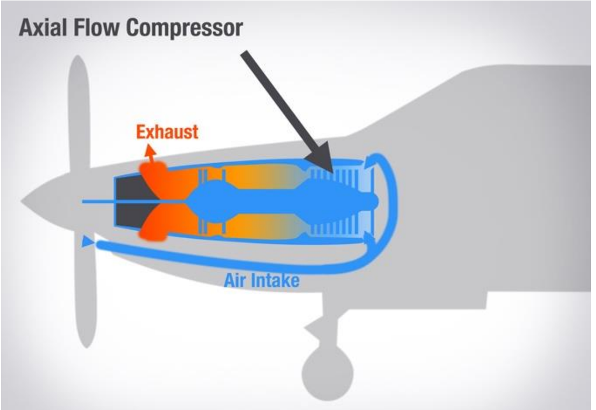


[Watch and hear]

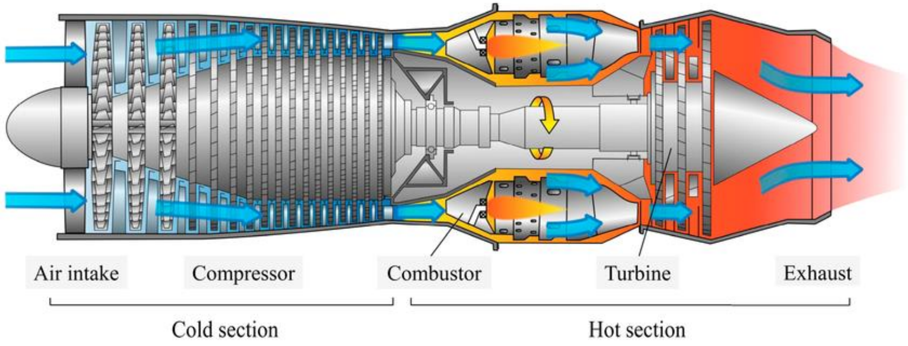
History time-line

- ❑ **1950's**
  - ➢ **Turboprops** and **turbojets** were adopted in airliners and military aircraft
    - More efficient and powerful engines
    - Produced even **higher noise levels**, especially during takeoffs and landings, which resulted in a significant public backlash and legislative actions

Vickers Viscount: The First Turboprop Powered Airliner

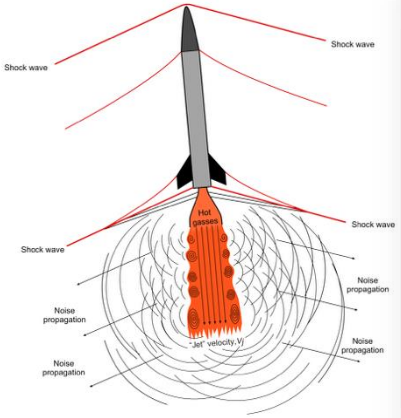


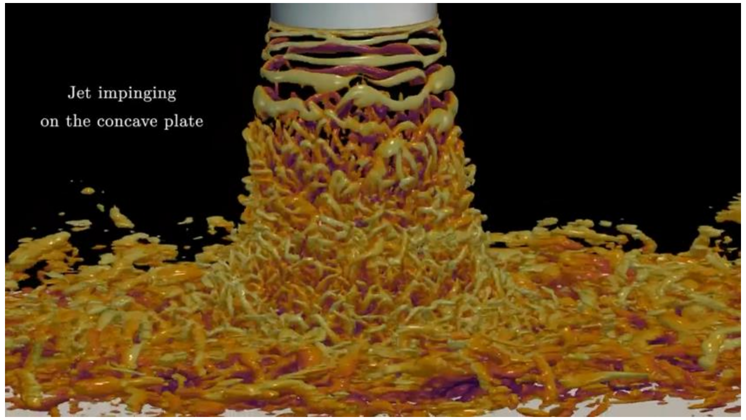
First American jet passenger airliner flight (July 15, 1954)
The Boeing 367-80 or Dash-80 was a prototype, which was later developed into the 707…

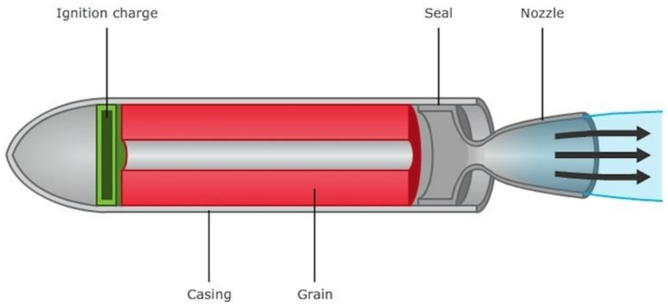


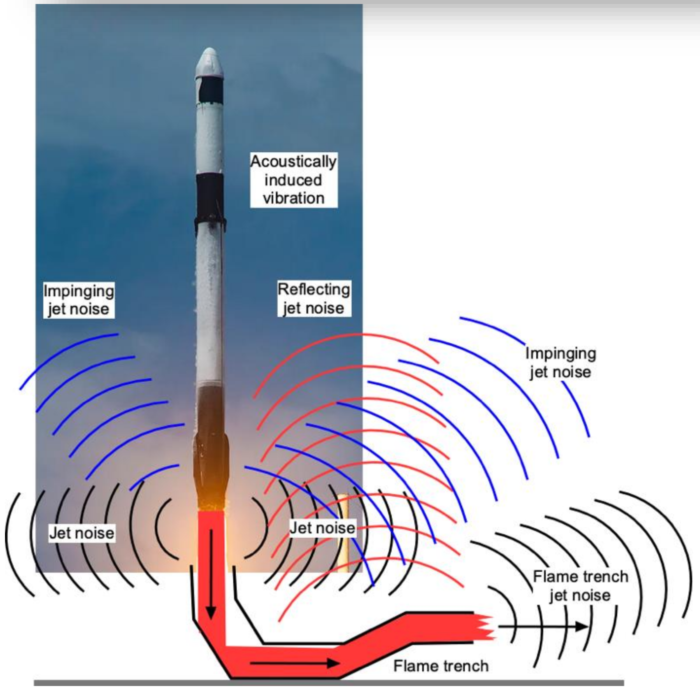
History time-line

- **1960's**
  - Space exploration…
  - Rockets generate an intense ***"crackling" noise*** from combustion and ***turbulent mixing in the supersonic exhaust (jet) flow***
    - Likely above the threshold of pain for any observer within several kilometers of the rocket
    - **Jet noise is directional** - mainly propagates in one dominant direction



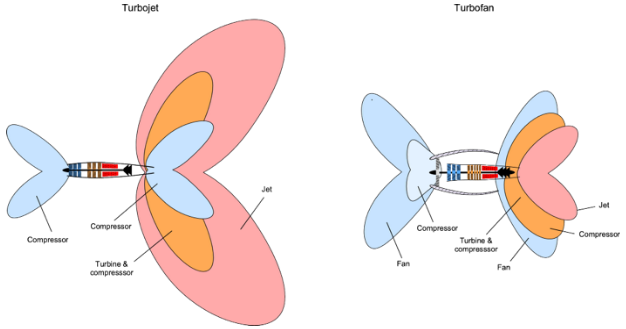


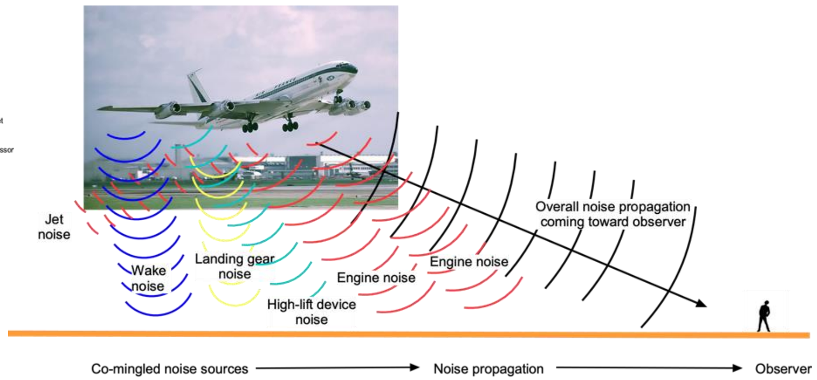




A rocket launch will produce intense noise levels from the high-speed gases exhausted from the rocket engines.

History time-line

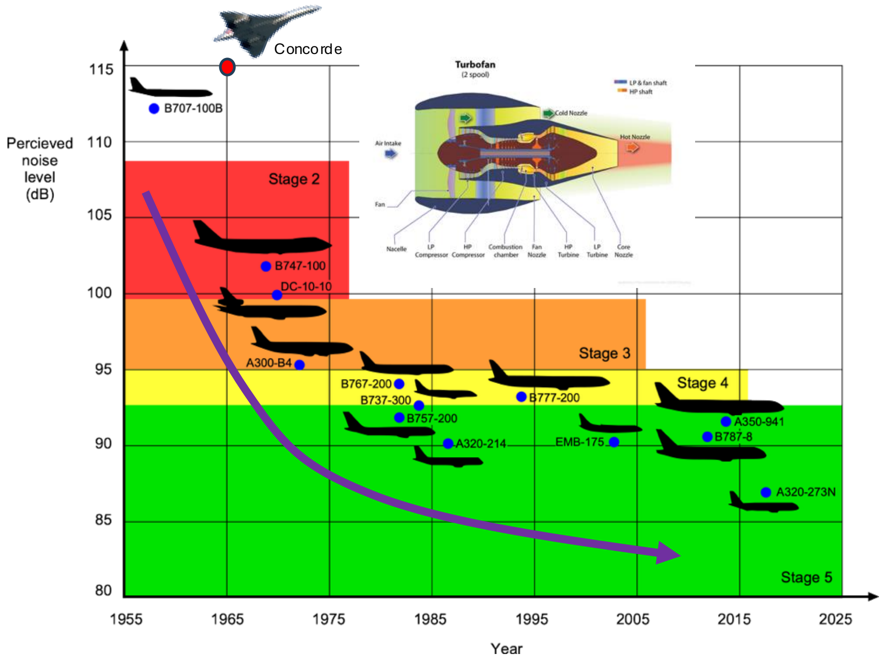




An airplane creates several co-mingled noise sources from the engines and airframe.

❑ Over the last few decades

- ➢ Increased awareness of the **environmental impact** of **aircraft noise** has led to widespread **public concerns and regulatory actions**
- ➢ The **International Civil Aviation Organization (ICAO)** has implemented increasingly stringent noise standards, focusing on noise abatement procedures and moving airports farther away from urban areas
- ➢ ICAO established "**Stages**" to categorize and regulate the noise emissions of different aircraft
  - ▪ **Stage 5** is the current standard
- ➢ Forced aircraft manufacturers to heavily invest in R&D to **design quieter engines and airframes**
- ➢ **Most focus has been invested in reducing engine noise,** leading to advancements such as **high-bypass turbofan engines**, which **significantly reduced aircraft noise**

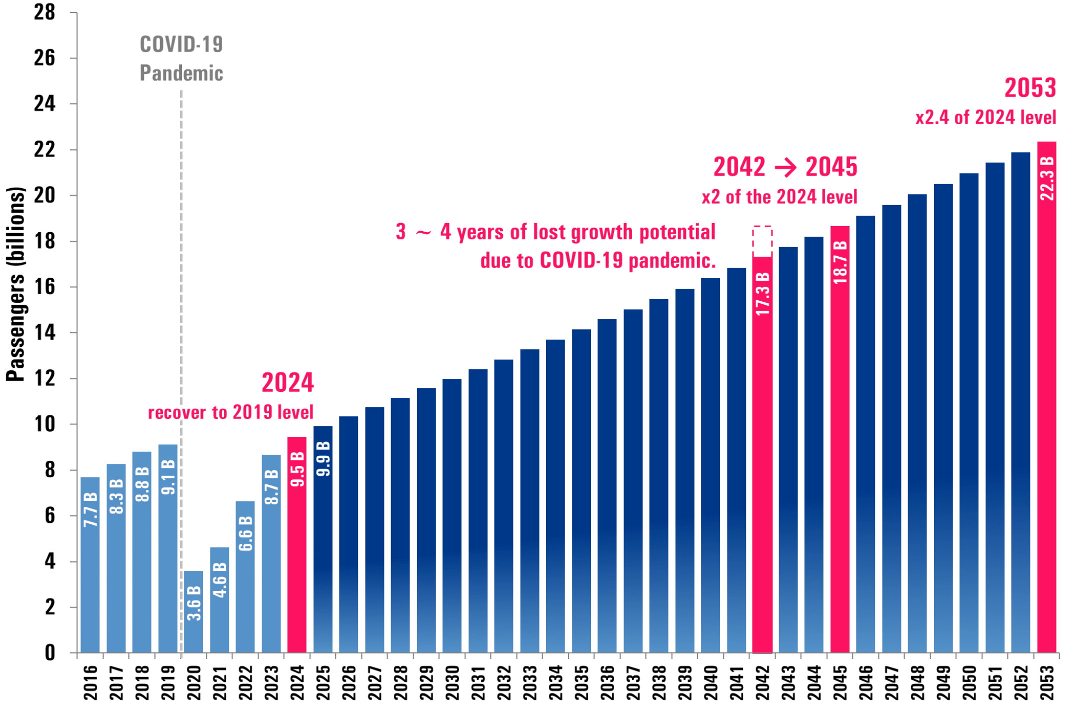


The noise levels of modern airliners must meet much more stringent noise requirements, with many already meeting ICAO Stage 5 standards.

What next?

- By 2053, air traffic is expected to grow by x2.4!

Long-term global passenger traffic forecast
(2016–2053)

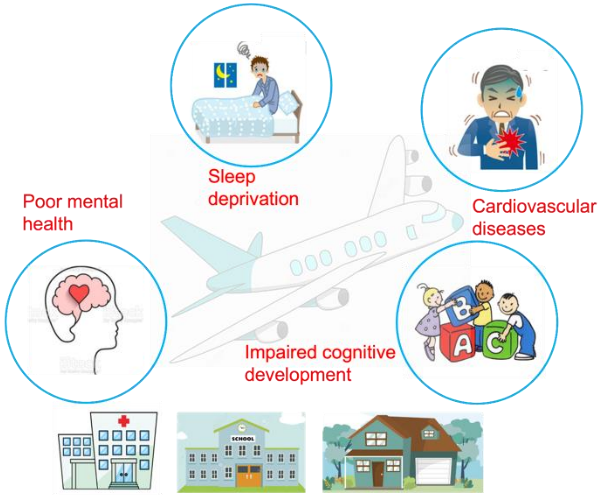


[ACI World Airport Traffic Forecasts 2024–2053]

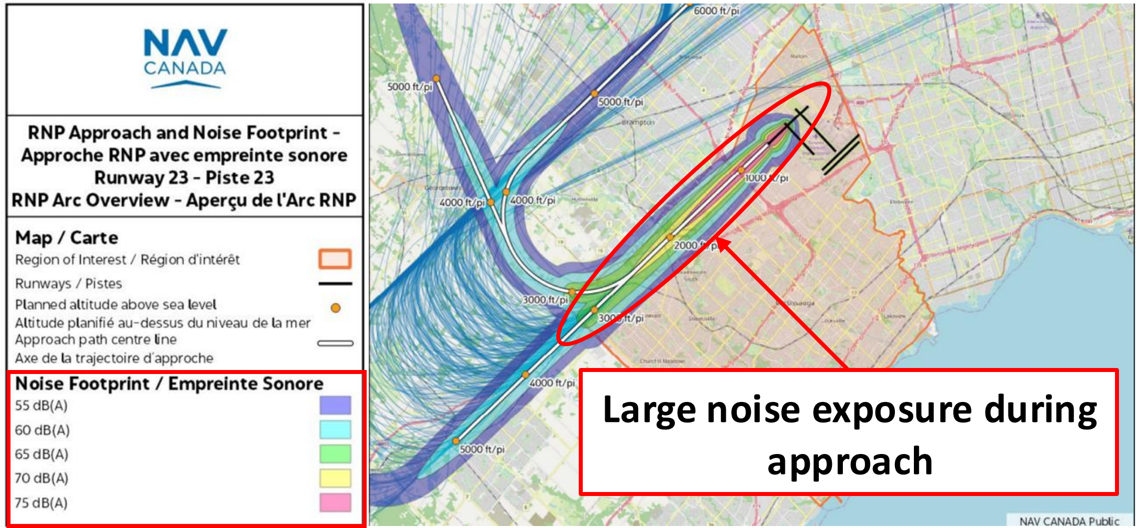
What next?

- **Future aircraft noise exposure** in urban areas around airports will be **much higher**
  - Negative effect on the communities' health
  - Stricter aircraft noise certification standards
- A **challenge** for the growth of the aviation sector

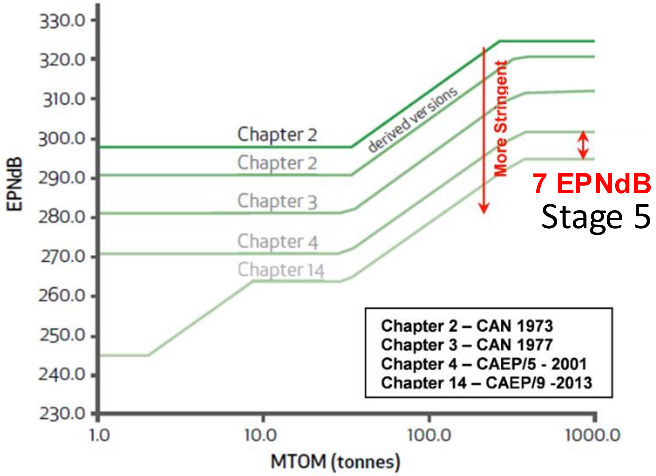
Significant reduction in aircraft noise emissions, and specifically *airframe noise*, is to be achieved



Toronto Pearson International Airport, Canada



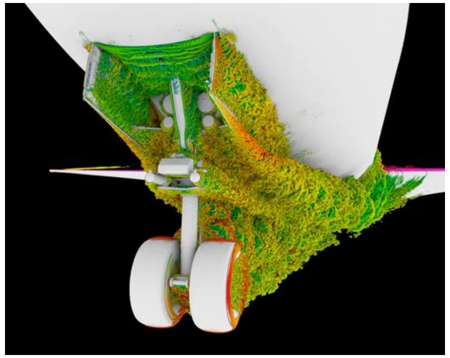
International Civil Aviation Organization (ICAO) Annex 16

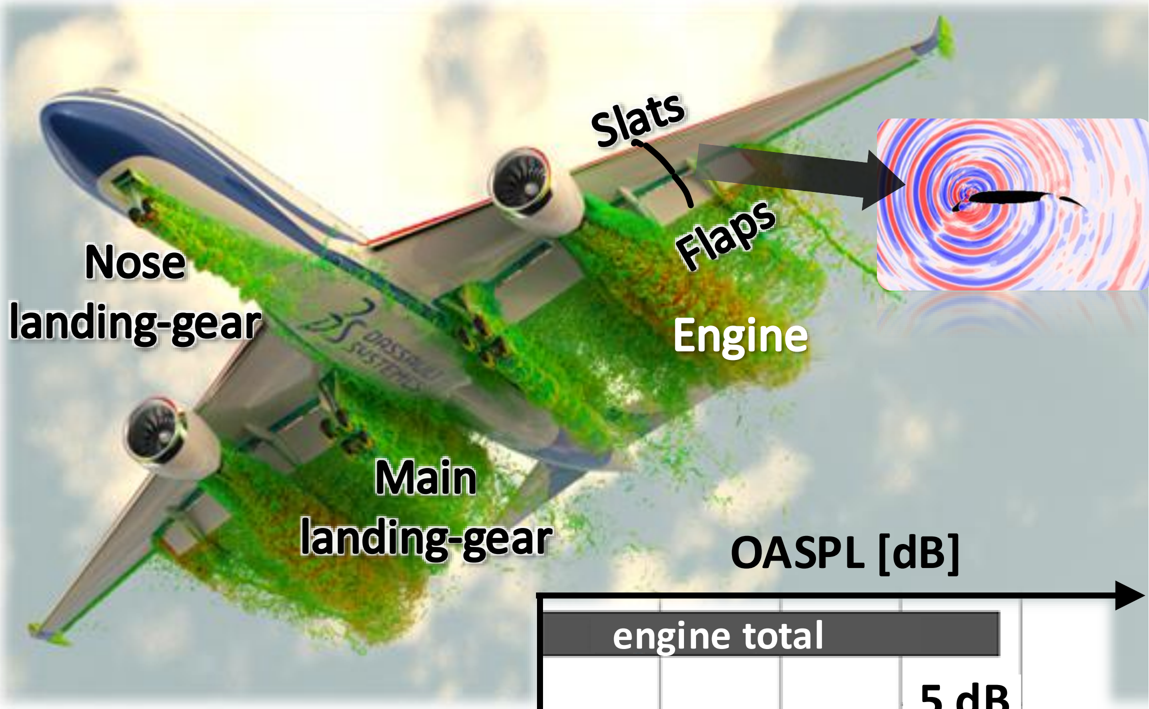


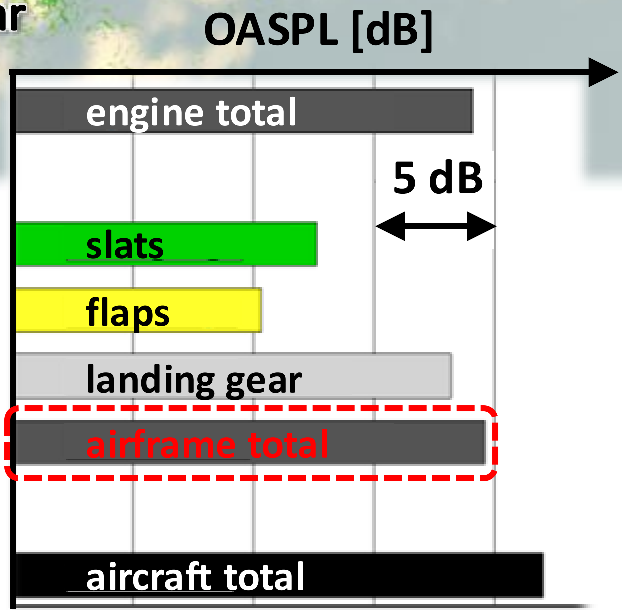
ICAO: Reduction of noise at source

Example: Airframe noise

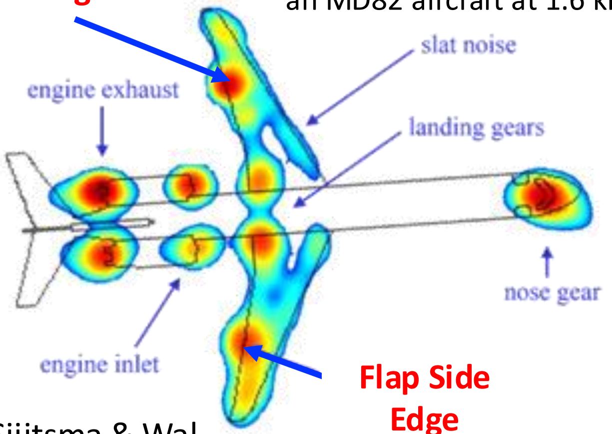
- **Airframe noise** is recognized as a ***significant contributor*** to the overall aircraft noise during approach scenarios
  - Landing gears
  - HLD - High-lift devices
    - slat/flaps



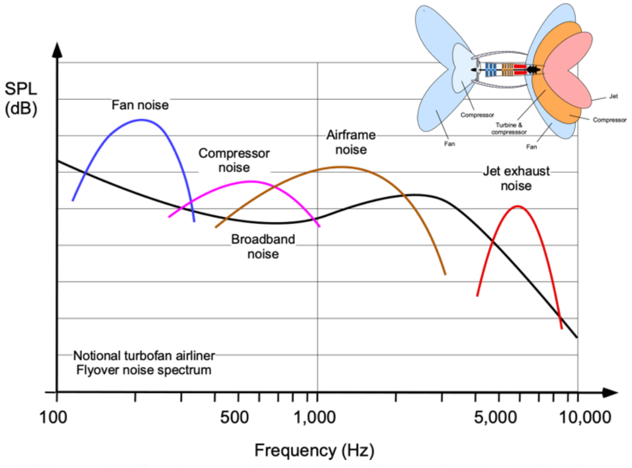




1/3 octave band fly-over result of an MD82 aircraft at 1.6 kHz

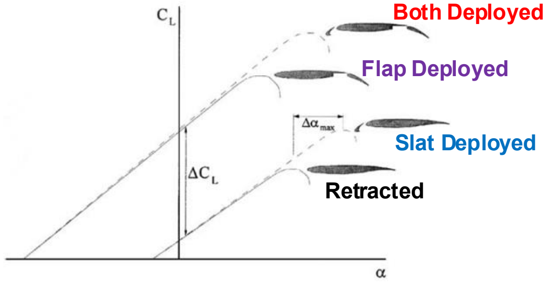


Sijitsma & Wal (2004)



The overall noise signature of an airplane is characterized by specific noise sources that occur across a range of frequencies.

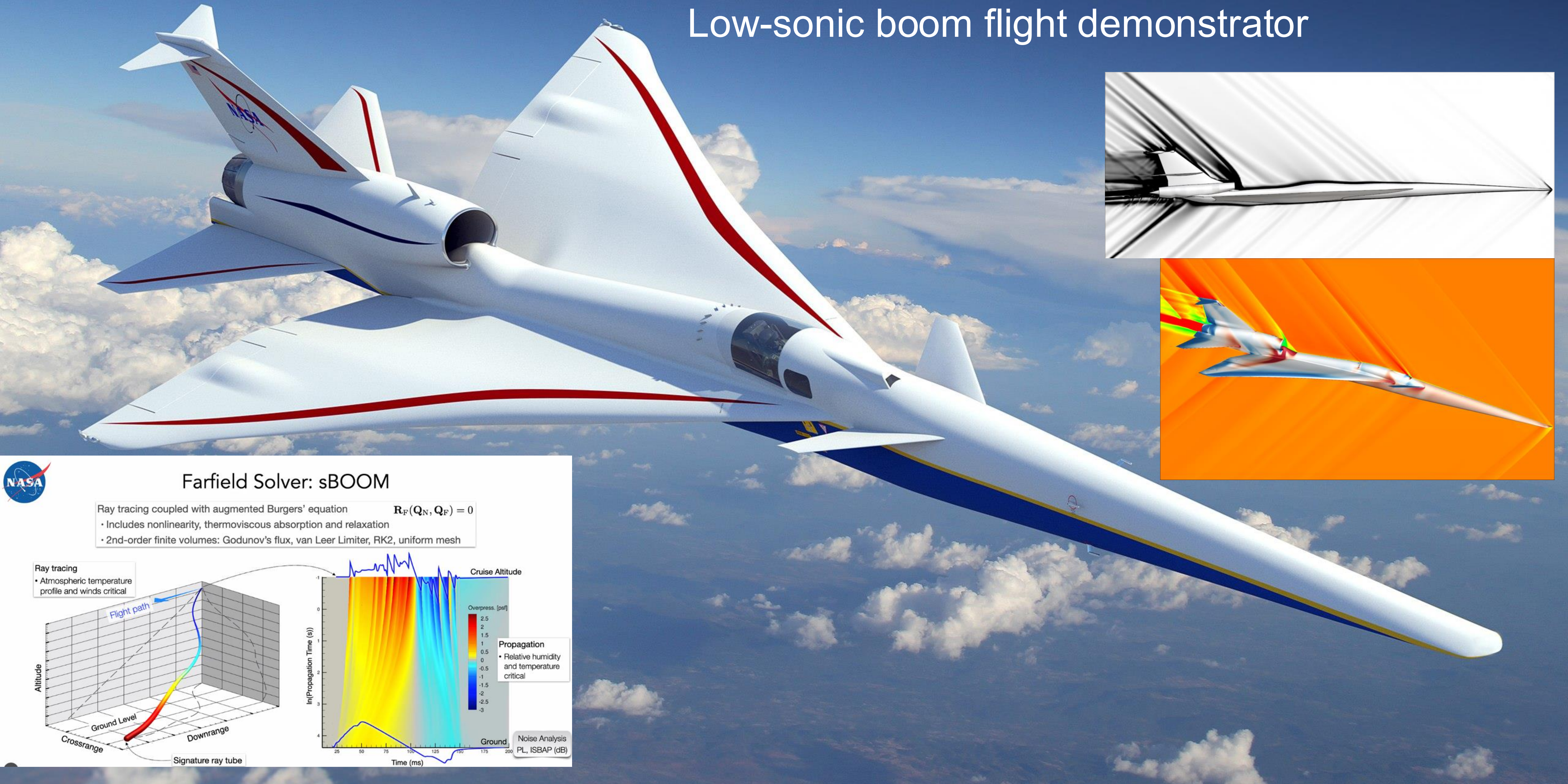
Van Dam (2002)



Van Dam, C. P. (2002) "The aerodynamic design of multi-element high-lift systems for transport airplanes," *Progress in Aerospace Sciences*, 38(2), pp. 101-144.
Sijtsma, P. and van der Wal, H. M. M. (2004) "Identification of noise sources on civil aircraft in approach using a phased array of microphones," *NATO RTO-MP-SET-079*.

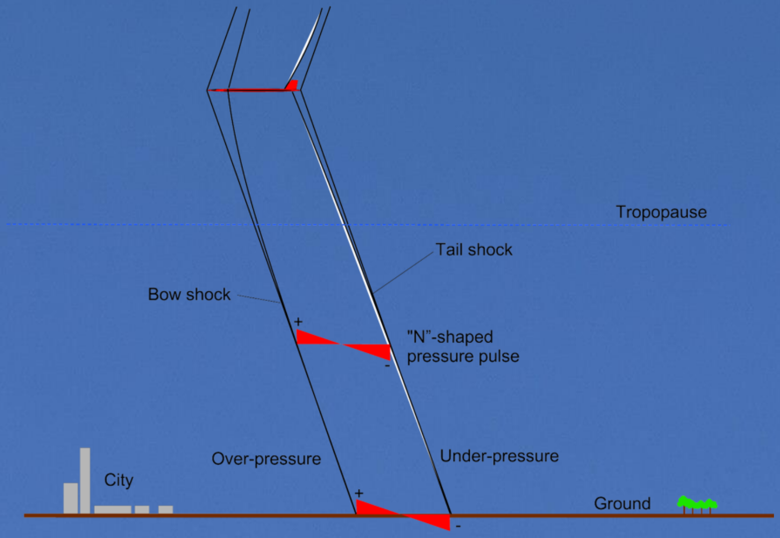
Lockheed Martin X-59 QueSST

Low-sonic boom flight demonstrator



Lockheed Martin X-59 QueSST

Low-sonic boom flight demonstrator



The signature of a sonic boom is an "N" shaped pressure pulse, which can be loud and startling to an observer on the ground.

First Flight - 28 October 2025

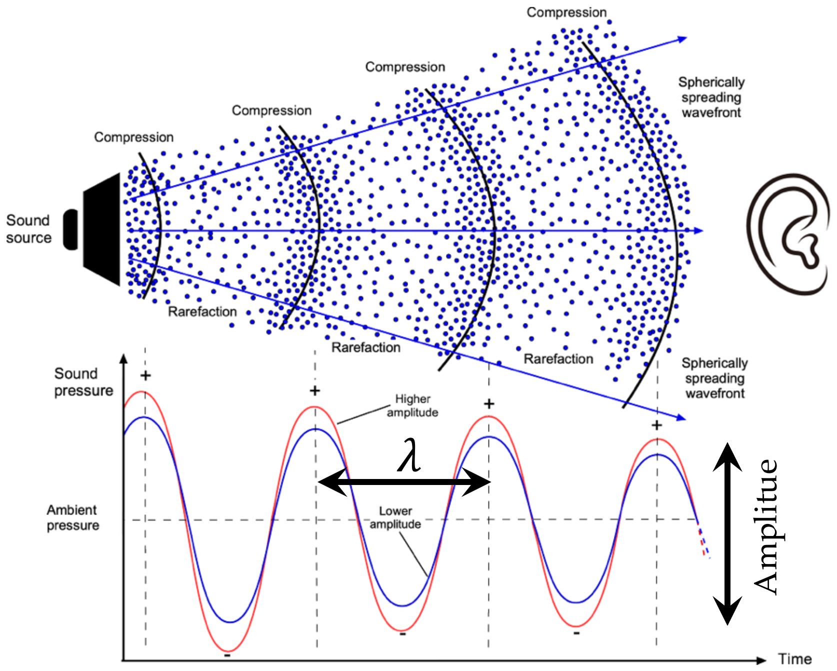
Sound wave

❑ Sound

- An **energy wave** that travels through the air by compressing and rarefying the molecules
- Characterized by **small time-dependent fluctuations in fluid pressure or density**
  - Hence, it is **associated with the compressibility of the fluid**
- **Human ear responds to pressure or compression**, so the pressure/density *fluctuations* are what is known as "sound"
- The propagation of sound in a **homogeneous** and **isotropic fluid** is quantified by physical quantities decomposable into ***average value* (index o)** and ***fluctuating quantities* (')**:

$$\boxed{p(\mathbf{x},t) = p_o + p'(\mathbf{x},t)} \quad \text{where:} \quad |p'(\mathbf{x},t)| \ll p_o$$

  - p' – **acoustic pressure [Pa]**
  - A sound wave is propagated in **air** at $c_o = 340$ m/s (at SL) as a longitudinal wave
  - **Amplitude** – intensity or "loudness" of the sound



Sound is an energy wave that travels by compressing and rarefying the air molecules.

Frequency $\boxed{f = \dfrac{c_o}{\lambda}}$ For a stationary observer

Speed of sound $\boxed{c_o = \sqrt{\gamma R T} = \sqrt{\dfrac{\gamma p_o}{\rho_o}}}$

Calorically perfect gas

For air, $R = 287 \left[\frac{\mathrm{J}}{\mathrm{kg \cdot K}}\right]$

Speed of sound

Brief review of thermodynamics

- 1^{st} **Law:** **Energy conservation (e)** — *Energy cannot be created or destroyed*

$$\boxed{de = \delta q + \delta w}$$

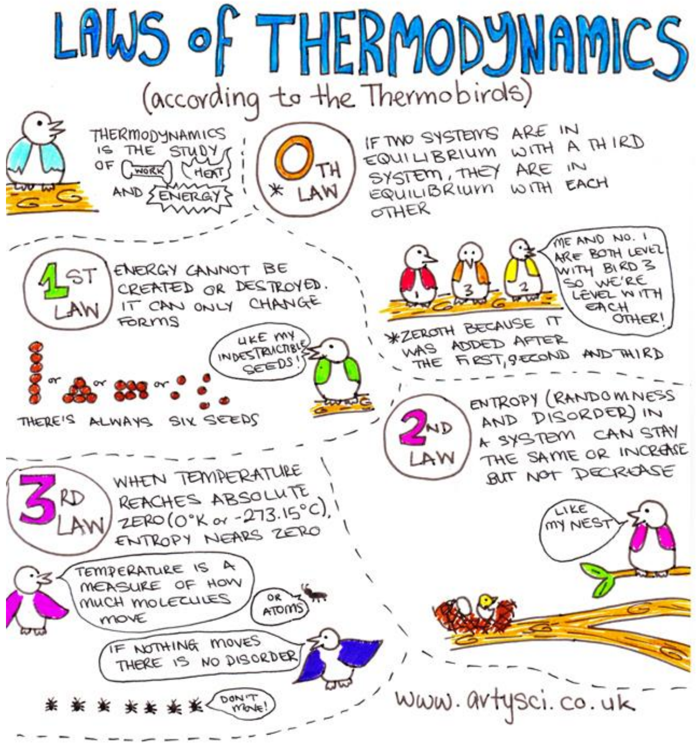
  - $+\delta q$ – **heat added** to system
  - $+\delta w$ – **work done** on system
  - de – **change in energy** (dependent on initial and final states)

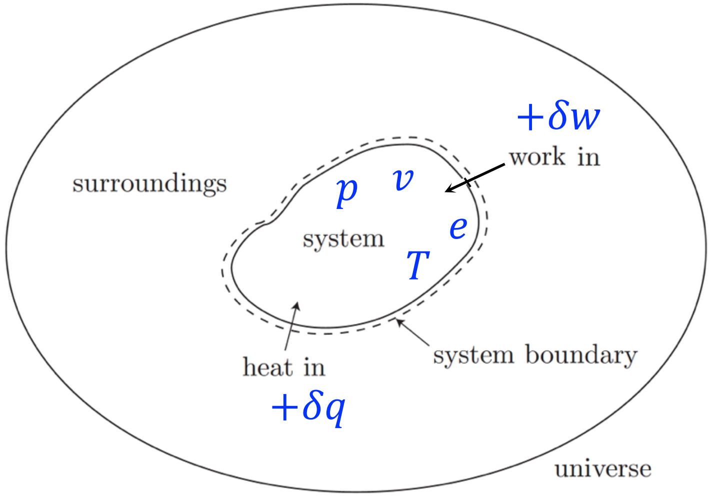
- <u>Some cases of interest</u>:
  1. **Adiabatic** (no heat transfer) $\Rightarrow$ $\delta q = 0$
  2. **Reversible** (hypothetical): no dissipative/diffusive mechanism
  3. **Isentropic**: cases 1 and 2

- *Example*: molecules in a particle expand by a distance Δx to fill a larger volume $(V \rightarrow V + dV)$
  - Particle is very small, thus pressure is *constant* over the surface S
  - Total work done *by* the particle:

$$w_{1\rightarrow 2} = \int_1^2 p\Delta x dS \quad \Rightarrow \quad \boxed{w = -pdv}$$

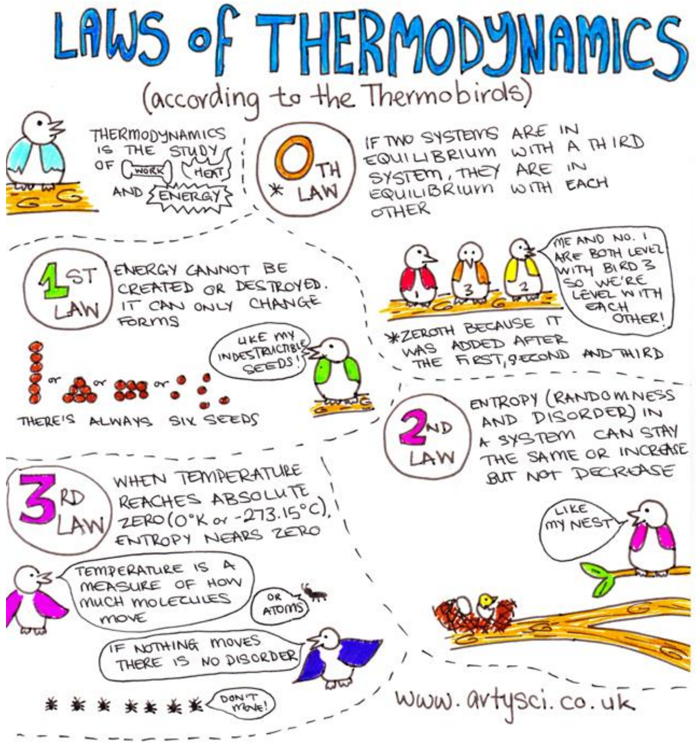
v - specific volume, $v = 1/\rho$
dv - incremental change in volume





Speed of sound

Brief review of thermodynamics



- ❑ 1^{st} **Law:** **Energy conservation (e)** *Energy cannot be created or destroyed*

$$\boxed{de = \delta q - pdv}$$

- ❑ We define a state variable called the ***enthalpy***: $\boxed{h = e + pv}$
  - ➢ Since $dh = de + pdv + vdp$, we can write the 1^{st} law as:

$$dh = \delta q - pdv + pdv + vdp \quad \Rightarrow \quad \boxed{dh = \delta q + \frac{dp}{\rho}} \qquad v = \frac{1}{\rho}$$

- ❑ If heating takes place at either ***constant volume*** or ***constant pressure***, then the **temperature *T* of the system is increased**
- ❑ Specific heats for const. volume and const. pressure:

$$c_v = \left(\frac{\partial q}{\partial T}\right)_V = \left(\frac{\partial e}{\partial T}\right)_V$$

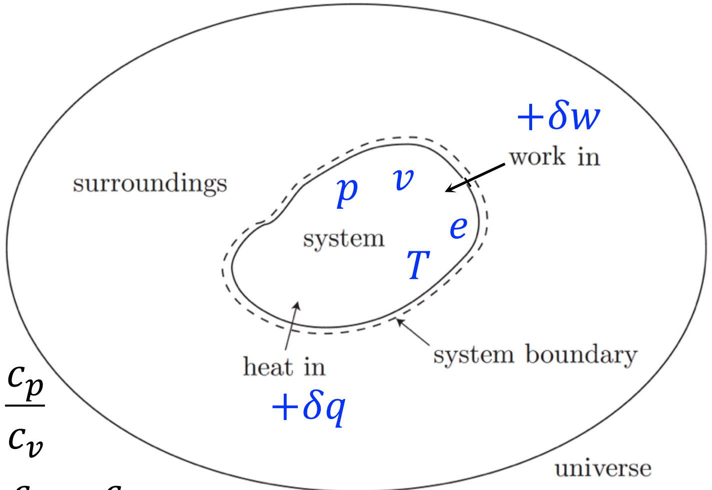
$$c_p = \left(\frac{\partial q}{\partial T}\right)_p = \left(\frac{\partial h}{\partial T}\right)_p$$

***Thermally* Perfect gas** $e, h = f(T)$ ⟹ $\boxed{de = c_v dT \quad dh = c_p dT}$

***Calorically* Perfect gas** $c_v, c_p = \text{const.}$ ⟹ $\boxed{e = c_v T \quad h = c_p T}$

$$\gamma = \frac{c_p}{c_v}$$

$$R = c_p - c_v$$



Speed of sound

Brief review of thermodynamics

- **2nd Law:** entropy (s) - energy unavailability to do work

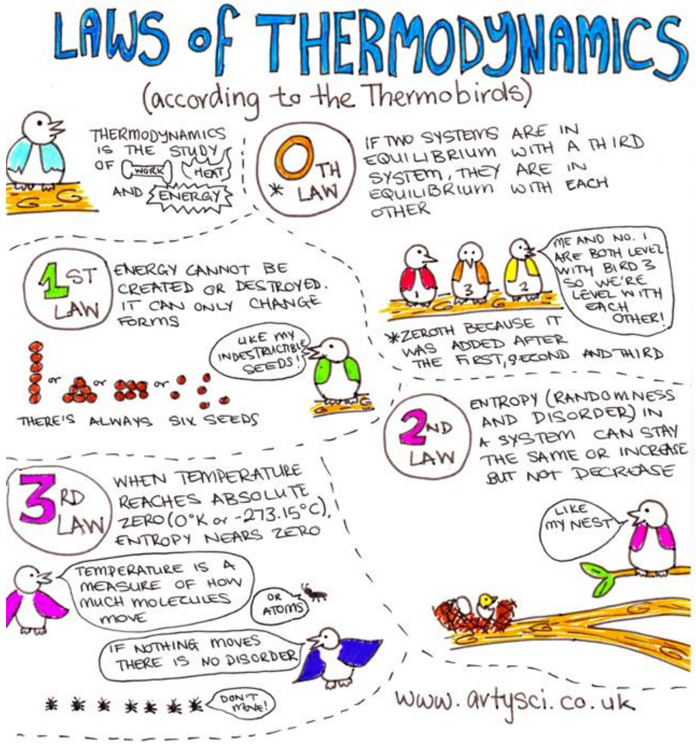
$$ds \geq \frac{\delta q}{T} \qquad ds = \frac{\delta q_{\text{rev}}}{T}$$

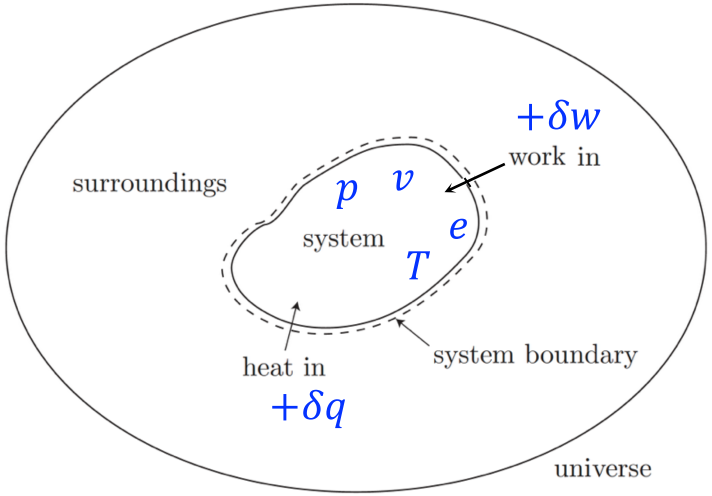
  - δq_{rev} - Reversible heat addition
  - **Adiabatic** $\Rightarrow$ $\delta q = 0$, $ds \geq 0$
  - **Isentropic = adiabatic + reversible** $\Rightarrow$ $\delta q = 0$, $ds = 0$

- For a **reversible process** we can write: $Tds = \delta q_{\text{rev}} = \delta q$
- Therefore, the 1st law can be expressed as:

$$\boxed{de = Tds - pd(1/\rho)}$$

$$\boxed{dh = Tds + dp/\rho}$$





Speed of sound

Brief review of thermodynamics

- **2^{nd} Law:** entrop (s) - energy unavailability to do work

- **Reversible process:** $\boxed{de = Tds - pd(1/\rho)}$ $\boxed{dh = Tds + dp/\rho}$

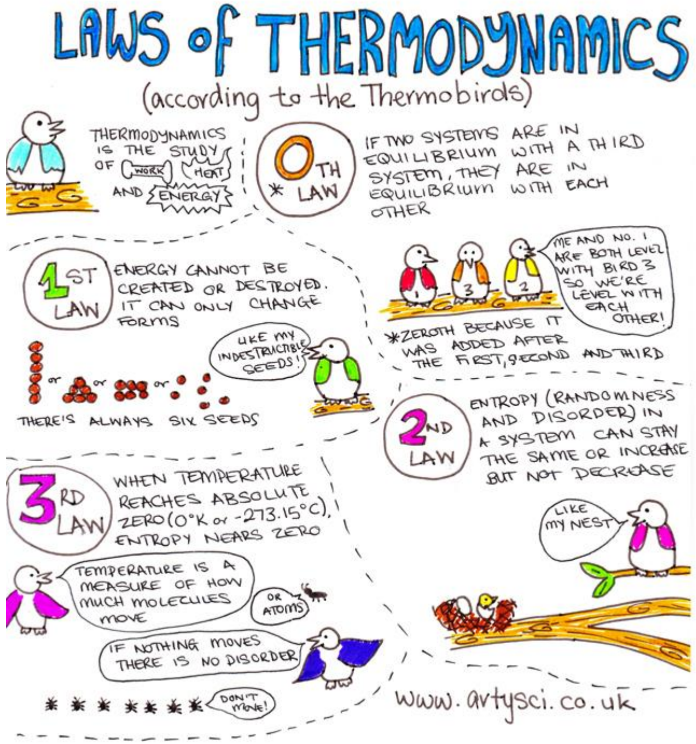
- Substituting the above equations and rearranging yields:

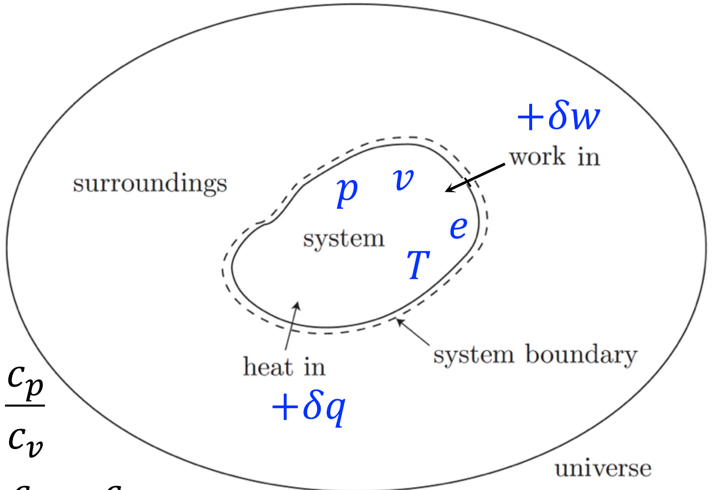
$$\frac{de}{dh} = \frac{Tds - pd(1/\rho)}{Tds + dp/\rho} \xrightarrow[\text{Calorically Perfect gas}]{e = c_v T,\; h = c_p T} \frac{Tds + dp/\rho}{c_p} = \frac{Tds - pd(1/\rho)}{c_v}$$

$$\xrightarrow[\text{Perfect gas law}]{p/\rho = RT} \frac{Tds + RTdp/p}{c_p} = \frac{Tds - \rho RTd(1/\rho)}{c_v} \Rightarrow \frac{ds + Rdp/p}{c_p} = \frac{ds + Rd\rho/\rho}{c_v}$$

$$\Rightarrow ds + R\frac{dp}{p} = \gamma ds + \gamma R\frac{d\rho}{\rho} \Rightarrow (\gamma - 1)ds = R\frac{dp}{p} - \gamma R\frac{d\rho}{\rho}$$

$$\Rightarrow \boxed{ds = c_v\frac{dp}{p} - c_p\frac{d\rho}{\rho}}$$





$$\gamma = \frac{c_p}{c_v}$$

$$R = c_p - c_v$$

Speed of sound

Brief review of thermodynamics

- 2nd Law: entropy (s) - energy unavailability to do work

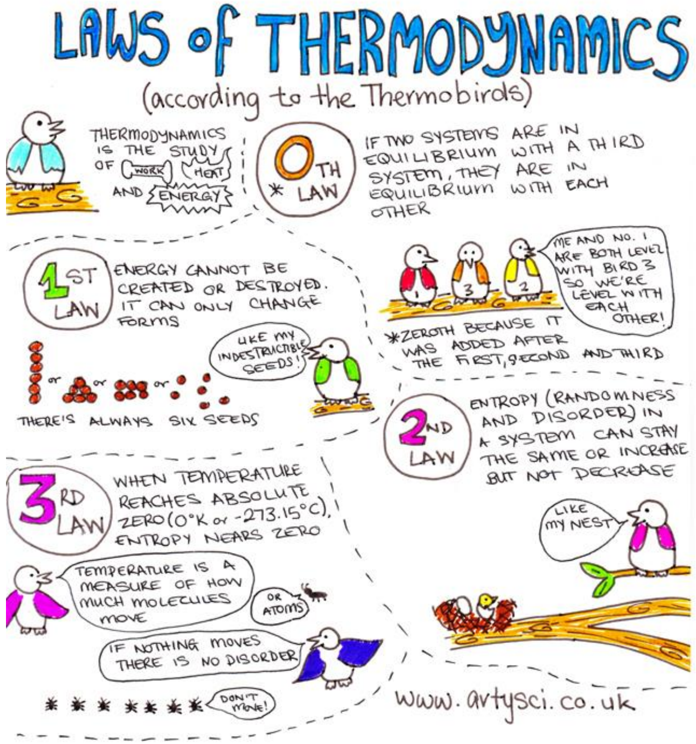
$$\boxed{ds = c_v \frac{dp}{p} - c_p \frac{d\rho}{\rho}}$$

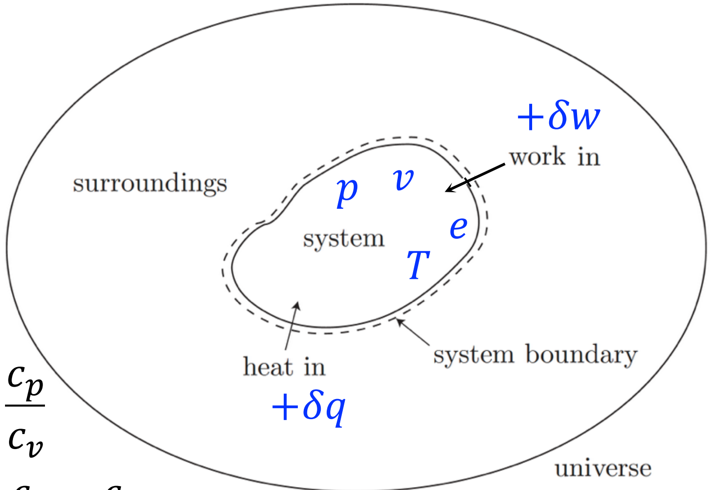
- **Isentropic conditions ($ds = 0$):**

$$\Rightarrow \quad c_v \frac{dp}{p} = c_p \frac{d\rho}{\rho} \quad \Rightarrow \quad \frac{dp}{p} = \gamma \frac{d\rho}{\rho} \quad \Rightarrow \quad \boxed{\left(\frac{dp}{d\rho}\right)_s = \frac{\gamma p}{\rho}} \qquad \left(\frac{p}{\rho^\gamma}\right) = \text{const.}$$

  - Isentropic relations: $\dfrac{p_2}{p_1} = \left(\dfrac{\rho_2}{\rho_1}\right)^\gamma$, $\dfrac{p_2}{p_1} = \left(\dfrac{T_2}{T_1}\right)^{\gamma/(\gamma-1)}$, $\dfrac{\rho_2}{\rho_1} = \left(\dfrac{T_2}{T_1}\right)^{1/(\gamma-1)}$

- **The expression above equal to the sound speed squared**





$$\gamma = \frac{c_p}{c_v}$$

$$R = c_p - c_v$$

Speed of sound

- **For sound waves:** $|p'| \ll p_o$, $|\rho'| \ll \rho_o$
- Therefore, we can replace the pressure and density with their mean values to give:

$$\boxed{c_o^2 = \left(\frac{dp}{d\rho}\right)_s = \frac{\gamma p_o}{\rho_o} = \gamma RT}$$

Isentropic bulk modulus
The speed at which sound waves propagate

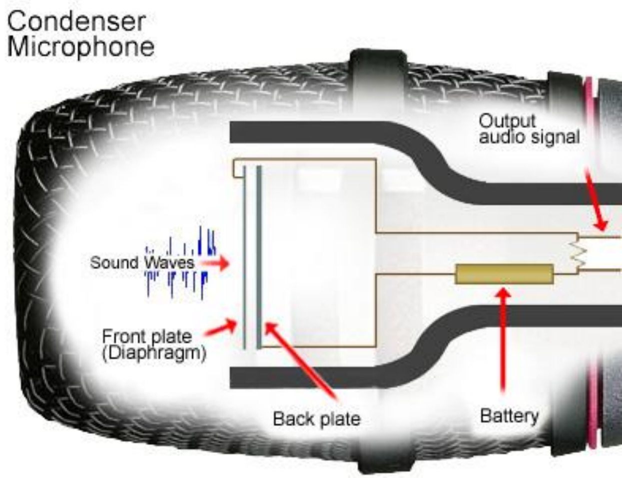
- We can also re-interpret the equation for ds as an expression that relates the acoustic perturbations in a sound wave (p' and ρ'), for which **we assume the changes are isentropic ($ds = 0$)**, then:

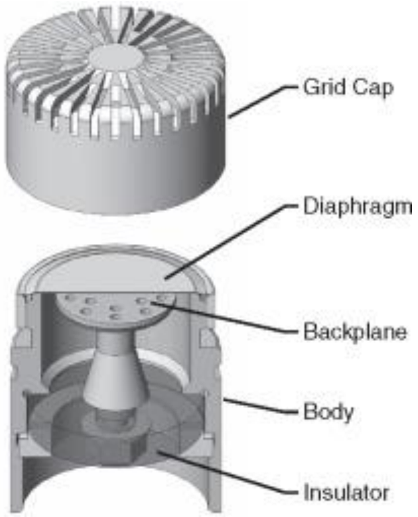
$$ds = c_v \frac{dp}{p} - c_p \frac{d\rho}{\rho} \quad \Longrightarrow \quad ds = 0 = c_v \frac{p'}{p_o} - c_p \frac{\rho'}{\rho_o} \quad \Longrightarrow \quad \boxed{p' = c_o^2 \rho'}$$

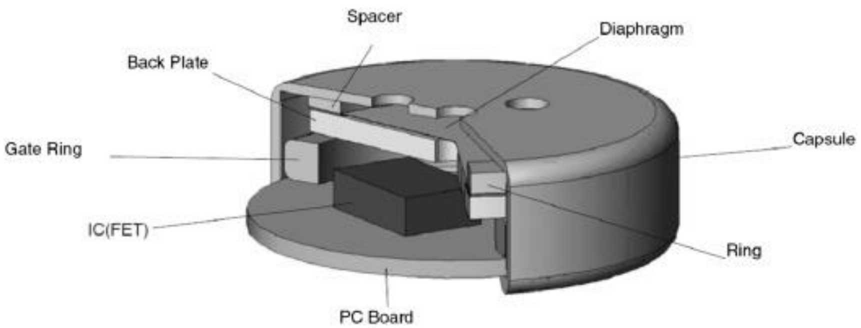
- This expression applies to fluid flows where the ***entropy is the same everywhere*** **($s = const.$) –** ***homentropic*** **conditions**

Sound wave measurement

- ❑ ***Pressure* can be measured much more easily than density**
  - Microphones measure pressure fluctuations mechanically using a membrane
  - A very thin conductive membrane is displaced under the pressure fluctuations, moving toward/away from a rigid backplate
  - As the distance between the membrane and the backplate changes, the capacitance of the membrane-backplate capacitor changes as well, producing a corresponding voltage variation
  - *Sort of a fluid-structure interaction (FSI)…*







Sound waves and turbulence

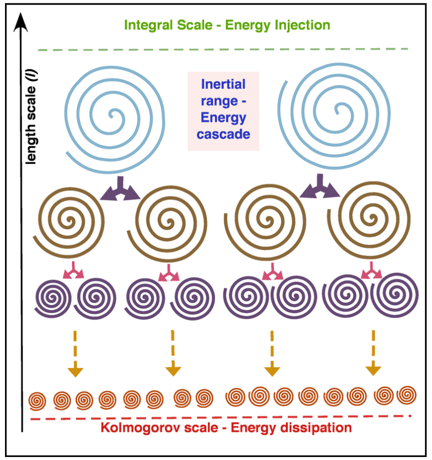
- ❑ Turbulent flows consist of velocity fluctuations (**u**') caused by instabilities in viscous shear flows breaking down into random vortical motion over a wide range of sizes (called *Eddies*)
- ❑ *Rotation of fluid* generates *forces* that are balanced by *local pressure gradients* (∇p)
- ❑ If the inertia of the vortices is disrupted over time (e.g., vortex deformation), the associated pressure variation induces a **density variation** due to *compressibility effects*
- ❑ **Density changes propagate as sound**

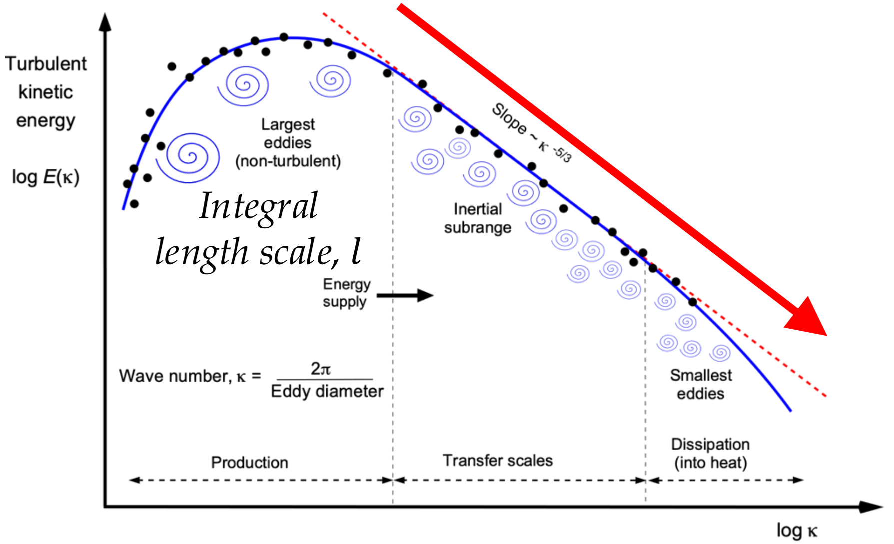
Int. length scale

$$l = \frac{k^{3/2}}{\varepsilon}$$

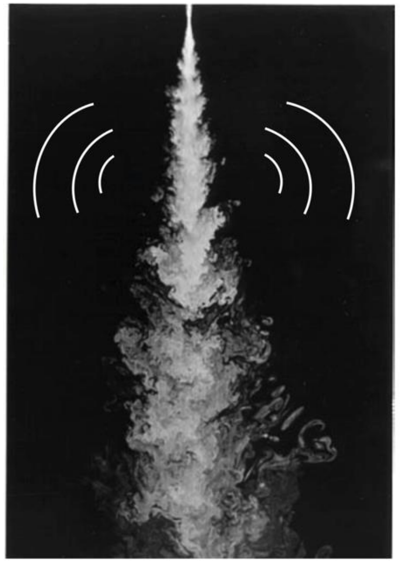
$$\eta = \left(\frac{\nu^3}{\varepsilon}\right)^{1/4}$$

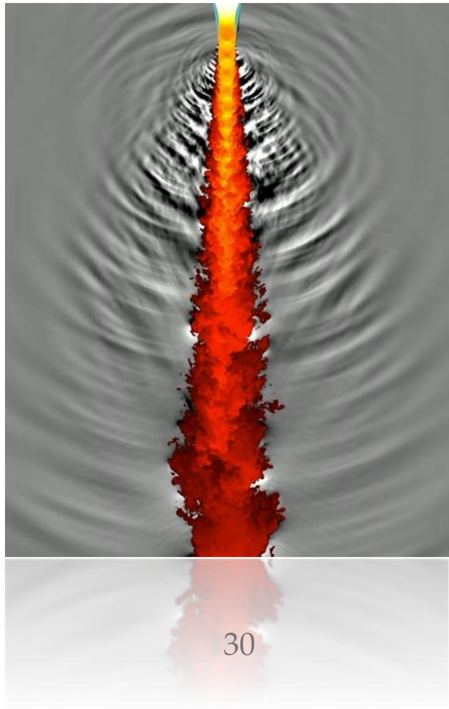
Kolmogorov scale





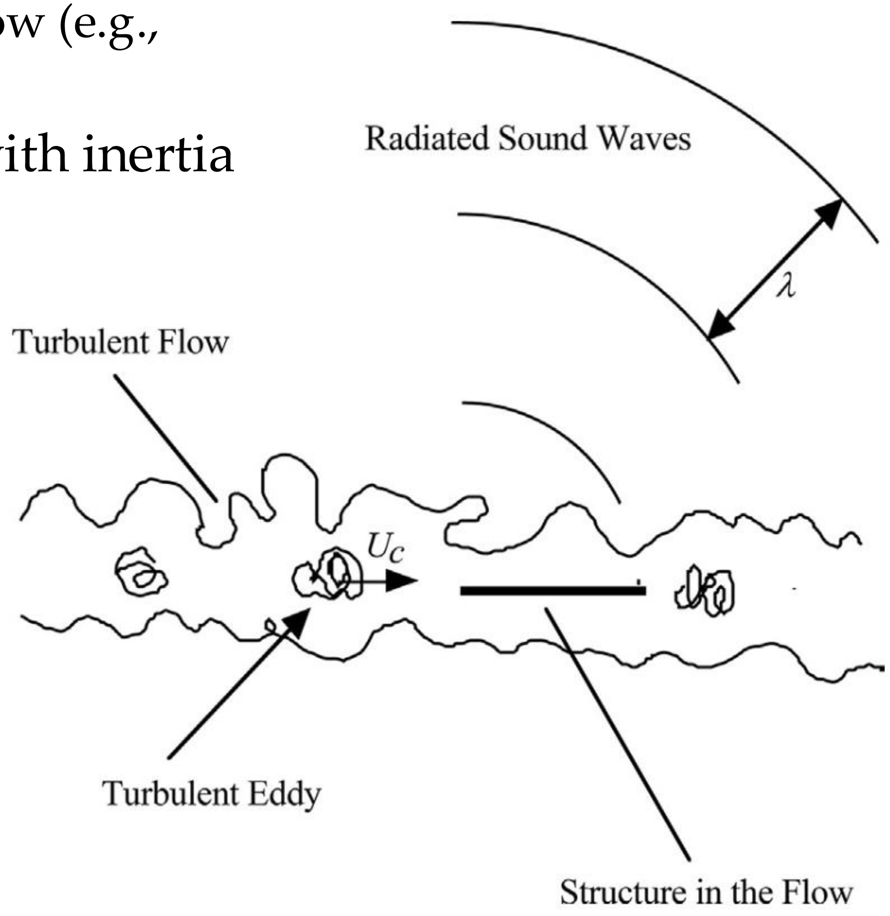
Kolmogorov scale, η





Sound waves and turbulence

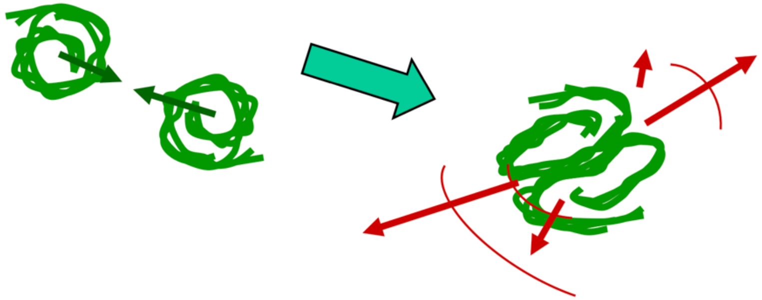
- **Not all pressure fluctuations are acoustics**
  - Some would exist in a purely incompressible rotational flow (e.g., hydrodynamic pressure perturbations propagating at U_c)
- A large portion of **pressure fluctuations** is associated with inertia
  - Only a small part is due to compressibility
- **True acoustic waves form due to density fluctuations**
  - *Not easily extracted experimentally (as shown before)*



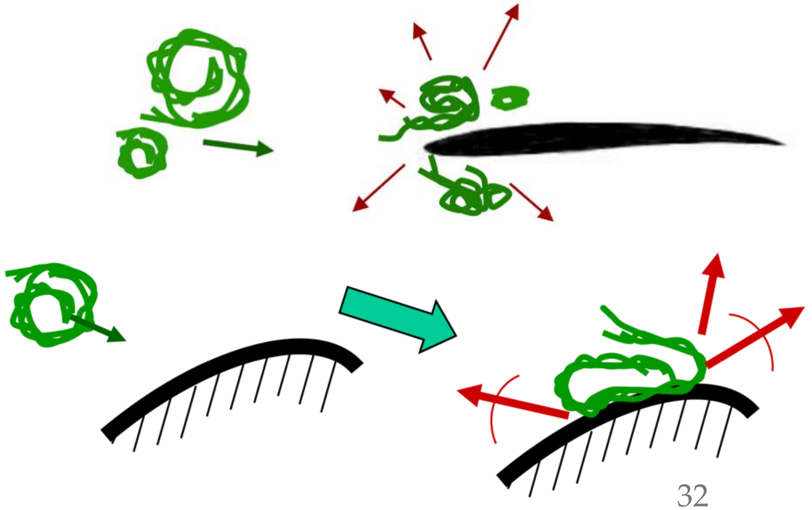
Sound waves and turbulence

- It is an experimentally evident fact that **turbulent flow makes noise**

- **Two vortices interacting (*deformation*)**
  - Mutual **deformation** of vortices generates sound that propagates (e.g., jet noise)

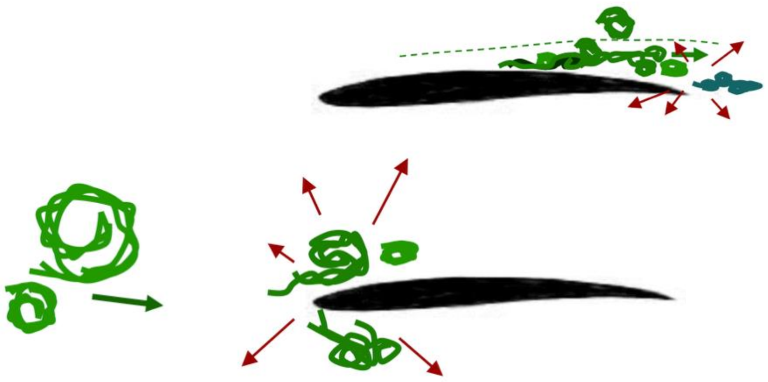


- **Vortex impacting a solid surface (*compression*)**
  - Generates **rapid changes of pressure on the solid surface** that radiate as sound waves through the fluid
  - Strong noise generator (e.g., leading-edge noise)



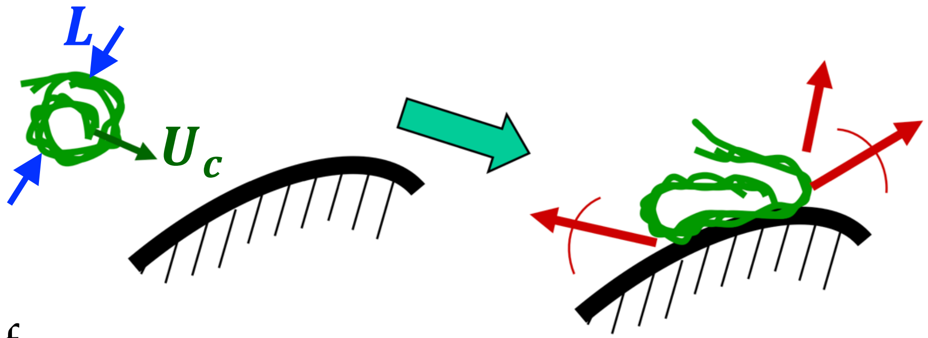
Sound waves and turbulence

- The **effectiveness of acoustic radiation depends on the surrounding surfaces**
- **Geometric singularities** are strong sources of vortex deformation and therefore increase aerodynamic noise by **diffraction** from the nearest induced sources (edges, corners, roughness)
- **For noise reduction**
  - *Reduce flow unsteadiness*, or
  - At least ***move it away from singularities in solid surfaces***...



$$\boxed{\frac{\mathrm{d}}{\mathrm{d}t}(\nabla \times \mathbf{u}) \;\Rightarrow\; \textbf{noise}}$$

Sound waves and turbulence



- **Taylor's hypothesis**
  - Turbulence is sometimes conceptualized as if it consisted of eddies convected at constant velocity $\boldsymbol{U_c}$ through the medium *without* evolving in the convected frame of reference
  - $\boldsymbol{U_c}$ – average convection velocity; typically for boundary layers, $U_c = 0.6 - 0.8U_\infty$
- **When convected turbulence encountered a solid surface**
  - Rapid pressure changes form on the surface, radiating as sound waves through the fluid
  - The frequency $\boldsymbol{f}$ of the pressure fluctuations can be determined by the eddy size $\boldsymbol{L}$ and its convection velocity $\boldsymbol{U_c}$
- At low Mach, $\boldsymbol{U_c \ll c_o} \Rightarrow$ **Acoustic wavelength $\boldsymbol{\lambda}$ is much larger than flow length scales $\boldsymbol{L}$**
- Large disparity between **hydrodynamic scales** and **acoustic scales** makes aeroacoustics very challenging

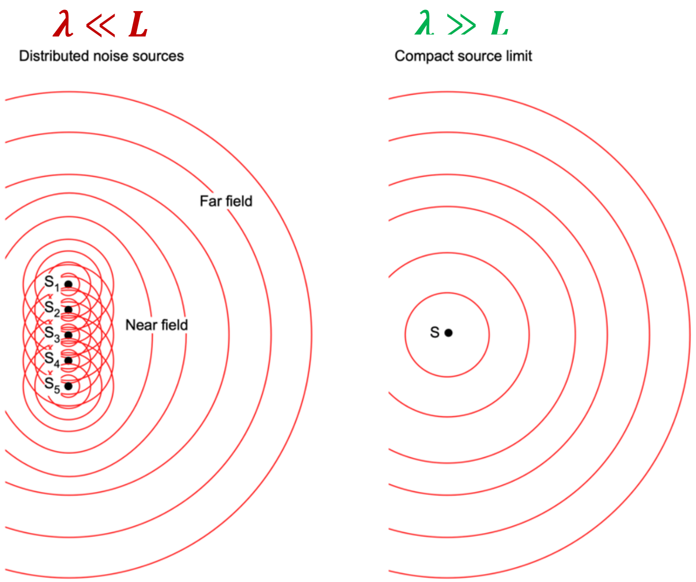
$$f \approx \frac{U_c}{L} \Rightarrow \lambda \approx \frac{L c_o}{U_c} \Rightarrow \lambda \gg L$$

$$f = \frac{c_o}{\lambda} \qquad \frac{c_o}{U_c} \gg 1$$

Compactness

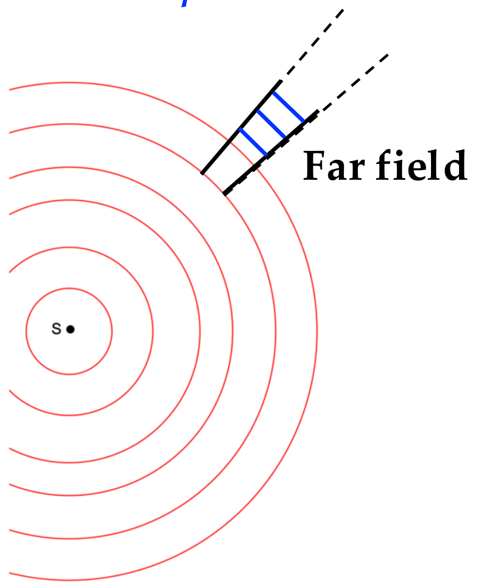
$$\boldsymbol{\lambda \gg L}$$

- ***Acoustic compactness* occurs when the body size (L) is smaller compared to the wavelength of the sound waves it generates (λ)**
- When a body is **large** compared to the wavelength of the sound waves it generates ($L >> \lambda$), *interference of wavefronts* from different parts of the body produces **complicated sound patterns**
  - Especially important in the region near the body's so-called **near field**
- When the body is **small** relative to the wavelength scale of the sound it generates ($L << \lambda$), or the sound is at high frequency, the phase differences between different source points are minor
  - The body can then be treated as a ***point source*** that radiates sound waves uniformly in all directions from the source (spherical wavefronts)
- In acoustics, the relative size of the body at a given frequency is referred to as its **compactness**
  - **A compact source** radiates sound similarly to a point source
  - **Non-compact bodies** in the near field require more detailed treatment
- The **compact source limit** allows for a more *straightforward* analysis than considering the detailed geometry of the acoustic sources



Acoustic pressure and harmonic plane wave

Acoustic wavefronts can be treated as *plane waves*



- The acoustic pressure for a **plane harmonic sound wave** moving in the positive x-direction may be represented in a *simple* form by:

$$\boxed{p'(x,t) = \hat{p}(x)\cos(2\pi f - kx)}$$

  - Where $\hat{p}(x)$ is the amplitude of the acoustic wave

- In *complex form*, the **harmonic solution** of the acoustic pressure of a **plane wave** is:

1𝔻: $\boxed{p'(x,t) = \hat{p}(x)e^{i(\omega t - kx + \phi)}}$ ϕ - phase [rad]

Angular Frequency [rad/sec] $\boxed{\omega = 2\pi f}$

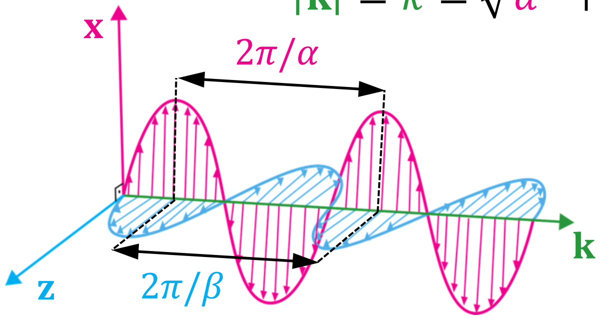
Time period [sec] $\boxed{T = \frac{2\pi}{\omega} = \frac{1}{f}}$

Wavenumber [rad/m] $\boxed{k = \frac{2\pi}{\lambda} = \frac{\omega}{c_o}}$ $f = \frac{c_o}{\lambda}$

3𝔻: $\boxed{p'(\mathbf{x},t) = \hat{p}(\mathbf{x})e^{i(\omega t - \mathbf{k}\cdot\mathbf{r} + \phi)} = \hat{p}(\mathbf{x})e^{i(\omega t - \alpha x - \beta z + \phi)}}$

$\mathbf{k} = \alpha\hat{x} + \beta\hat{z}$

$|\mathbf{k}| = k = \sqrt{\alpha^2 + \beta^2}$



Decibel (dB) scale

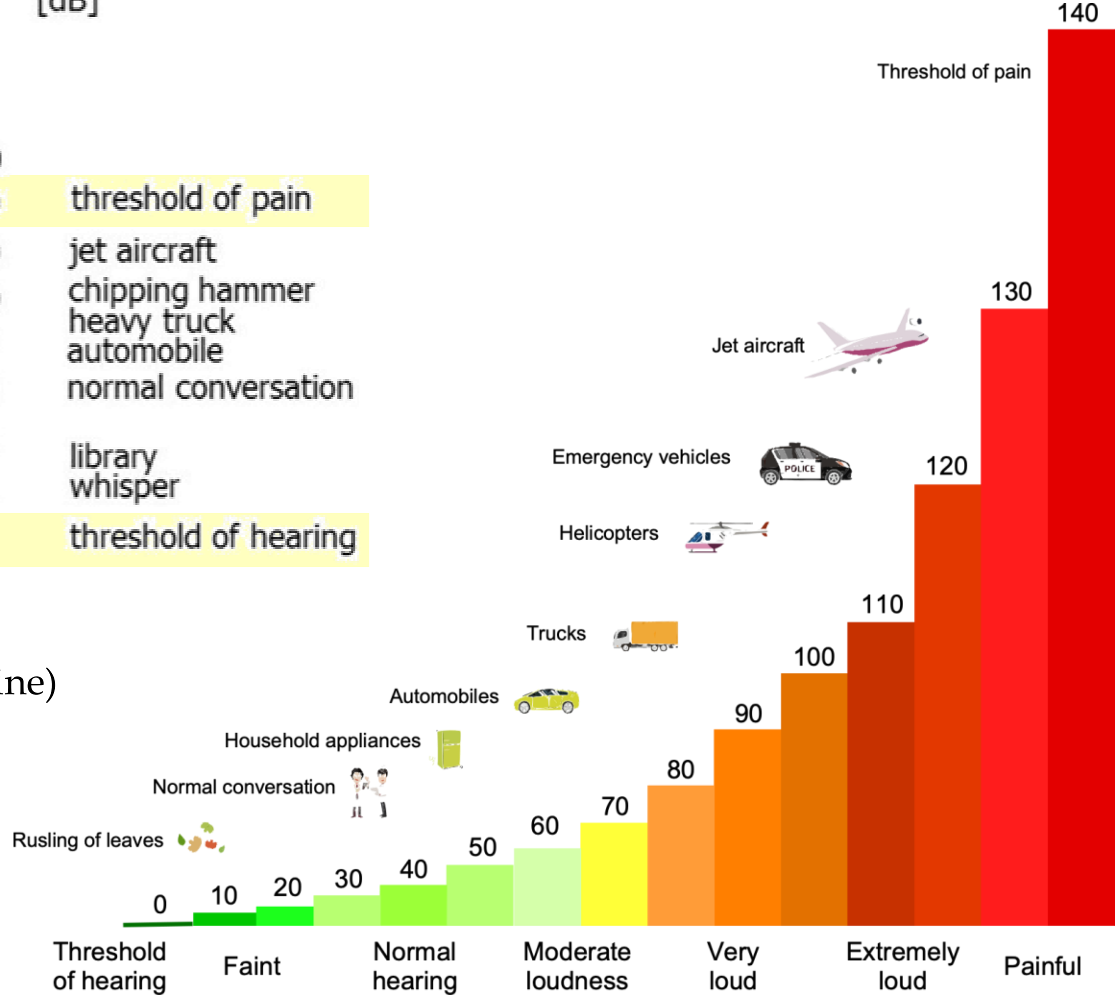
- ❑ **Logarithmic scale**
- ❑ **Sound Pressure Level (SPL)**

$p_{rms} \sim p'$

$$\boxed{\mathrm{SPL} = 10\log_{10}\left(\frac{p_{rms}^2}{p_{ref}^2}\right) \quad [\mathrm{dB}(\mathrm{re}\ p_{ref})]}$$

- p_{ref} – human audibility threshold
  - Air: $p_{ref} = 20\ \mu\mathrm{Pa}$
  - Other media: $p_{ref} = 1\ \mu\mathrm{Pa}$
- Sound pressure 1 Pa = 94 dB
- **Threshold of pain** is 200 Pa = 140 dB (3 m from a jet engine)

Effective sound pressure [N/m²]	Sound pressure level [dB]	
2000	160	
200	140	threshold of pain
20	120	jet aircraft
2	100	chipping hammer heavy truck
0.2	80	automobile
0.02	60	normal conversation
2×10^{-3}	40	library
2×10^{-4}	20	whisper
2×10^{-5}	0	threshold of hearing



The intensity of sound and noise is quantified using the decibel (dB) scale.

Question: **70 dB + 70 dB = $\cancel{140}$ dB ?**

70 dB + 70 dB = 73 dB

Decibel (dB) scale

- Logarithmic scale
- Sound Pressure Level (SPL)

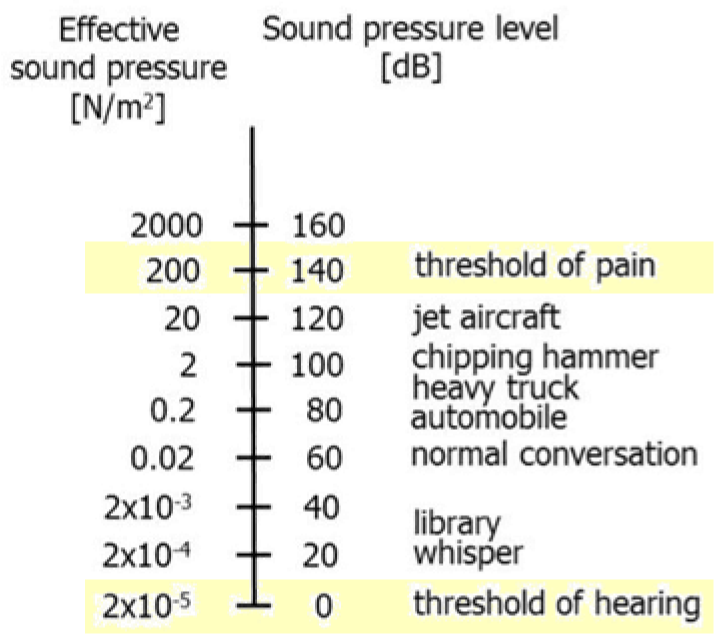
$$\boxed{\frac{p_{\mathrm{rms}}}{p_{\mathrm{ref}}} = 10^{\mathrm{SPL}/20}}$$

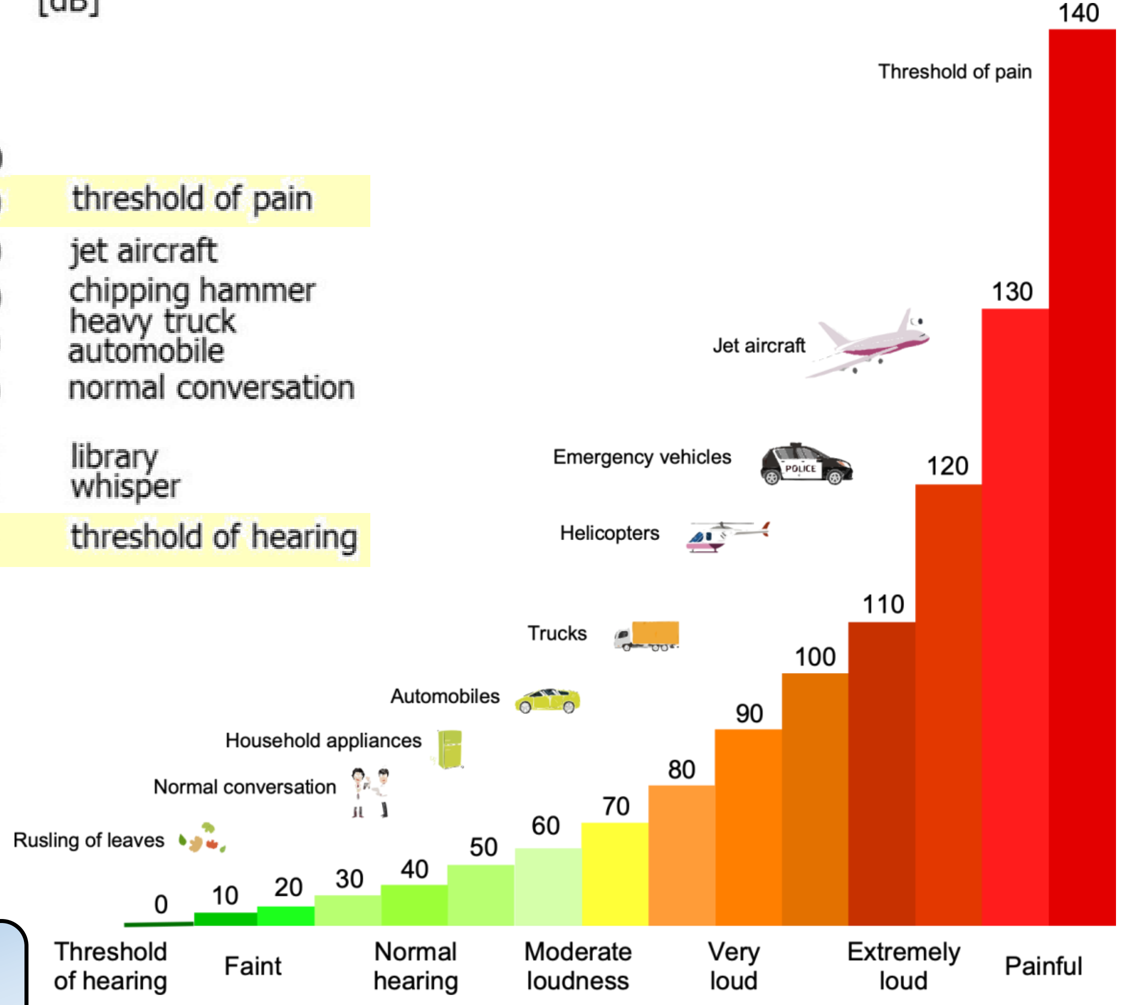
- **For SPL = 140 dB(re 20 μPa):**

$$\Longrightarrow \frac{p_{\mathrm{rms}}}{p_{\mathrm{ref}}} = 10^7 \Longrightarrow \frac{p_{\mathrm{rms}}}{p_o} = 10^7 \frac{p_{\mathrm{ref}}}{p_o}$$

$p_{\mathrm{rms}} \sim p'$
$p_{\mathrm{ref}} = 2 \cdot 10^{-5}$ Pa $\Longrightarrow$ $\dfrac{\boldsymbol{p'}}{\boldsymbol{p_o}} = 10^7 \dfrac{2 \cdot 10^{-5}}{10^5} = 2 \cdot 10^{-3} \ll \mathbf{1}$
$p_o \approx 10^5$ Pa

$p' = c_o^2 \rho'$
$c_o^2 = \dfrac{\gamma p_o}{\rho_o}$ $\Longrightarrow$ $\dfrac{\boldsymbol{\rho'}}{\boldsymbol{\rho_o}} = 10^7 \dfrac{2 \cdot 10^{-5}}{10^5} = 1.4 \cdot 10^{-3} \ll \mathbf{1}$





The intensity of sound and noise is quantified using the decibel (dB) scale.

Linear acoustics **in** **air** **is valid for** ***small*** **perturbations up to** **140 dB(20 μPa)**

Water – limit is 220 dB(1 μPa)

Pressure rms

- Given $p(t)$ as the *instantaneous pressure signal* at a point in the fluid, where p_o being the *background pressure*, and $p'(t)$ is the *time-varying pressure perturbation*, we can compute the pressure rms (root-mean-square), as follows:

$$\boxed{p_{rms}^2 = \frac{1}{2T}\int_{-T}^{T}[p(t) - p_o]^2\, dt = \frac{1}{2T}\int_{-T}^{T}[p'(t)]^2\, dt = \overline{[p'(t)]^2}}$$

$$p'(t) = p(t) - p_o$$

  - Where T is the sample time period (**must include many cycles**)

For a simple harmonic wave:

$$\boxed{p_{rms} = \frac{p_{max}}{\sqrt{2}}}$$

p_{max} is the amplitude of the sound wave

Sound and pseudo-sound

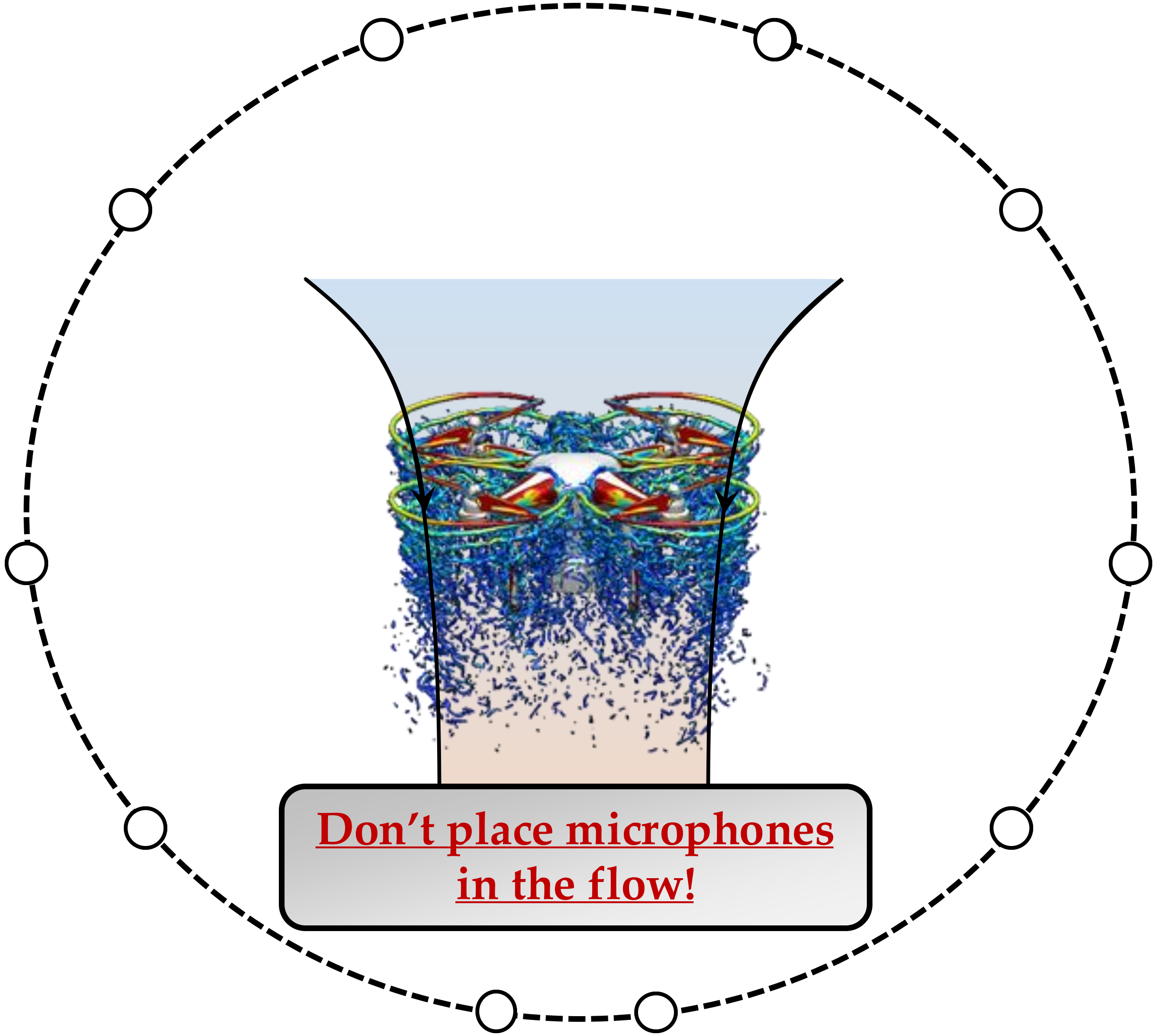
- **Where should you place microphones?**
  - *Turbulent flow* has velocity fluctuations that are associated with **hydrodynamic pressure fluctuations**

***Hydrodynamic* pressure fluctuations** $\gg$ ***Acoustic* pressure fluctuations**

- *Typical* velocity fluctuations in *turbulent flow* - $O(10^{-1}U_{\infty})$
- *Typical* hydrodynamic pressure fluctuations - $O(10^{-2}p_{\infty})$

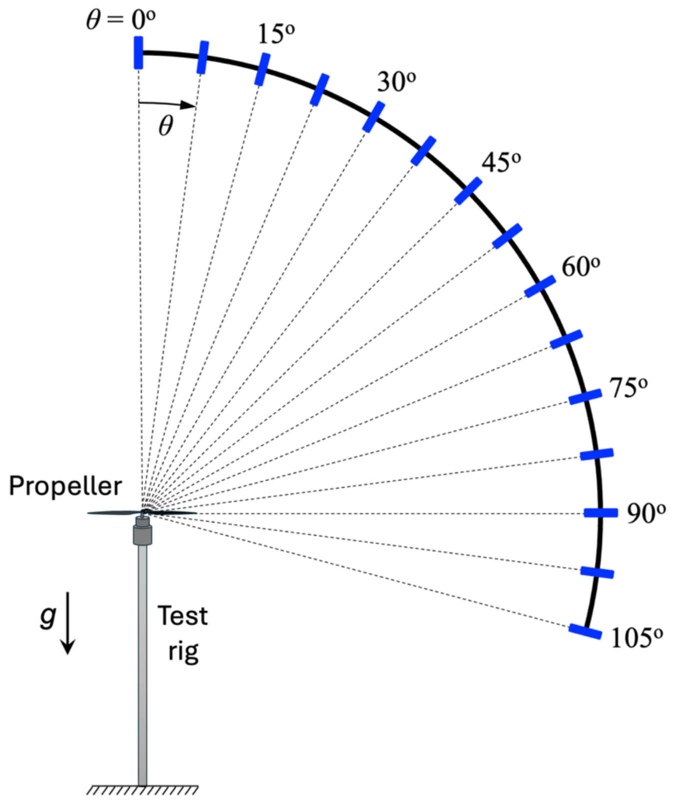
Microphones measure *sound pressure*:
sound (~80 dB)

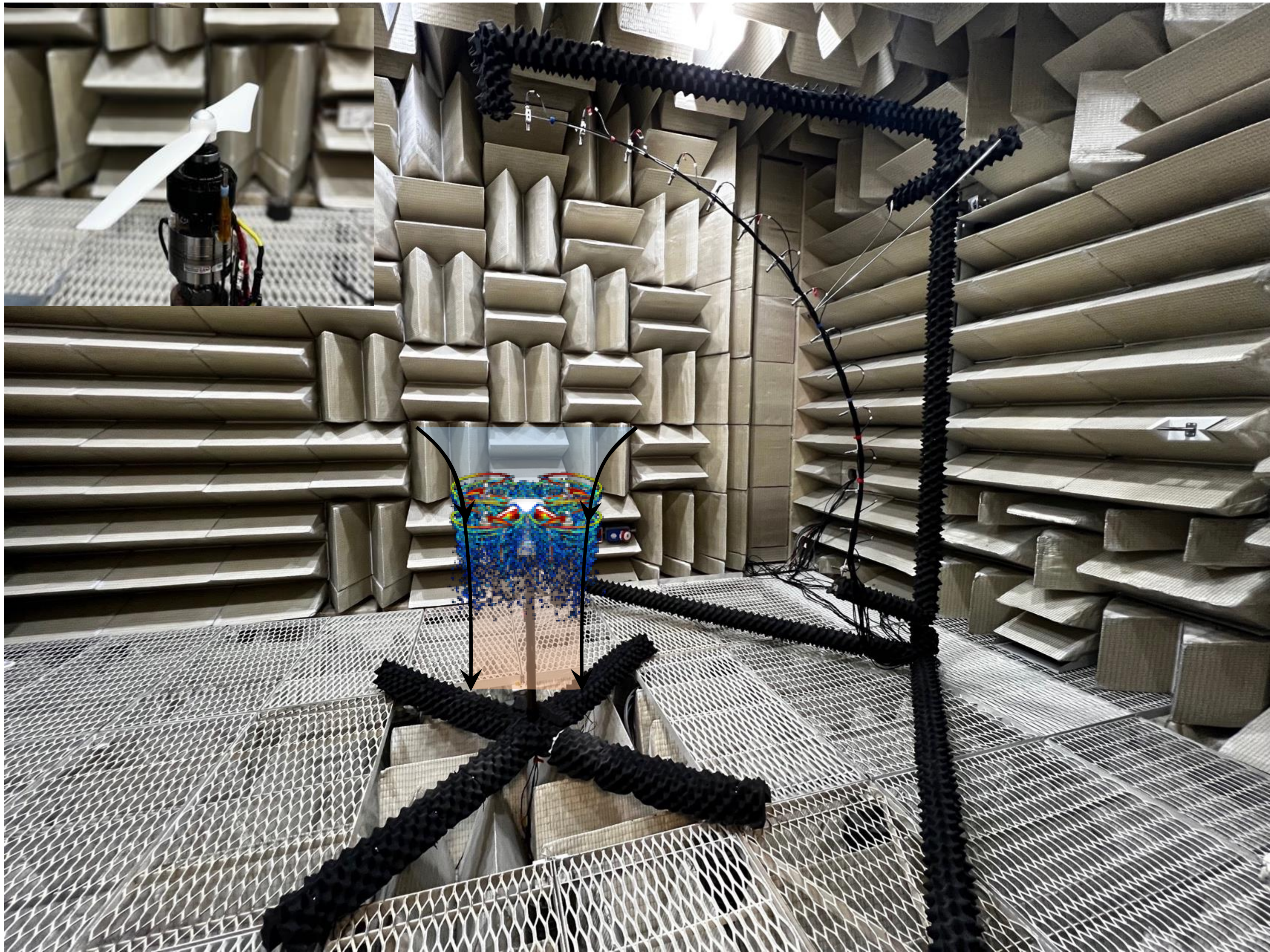
Microphones measure *sound* & *hydrodynamic* (*total*) *pressure*:
pseudo-sound (~150 dB)



Sound and pseudo-sound

- For example…





Sound and pseudo-sound

$$p_{\mathrm{rms}}^2 = \overline{[p'(t)]^2}$$