December 17, 2020

Flow Noise

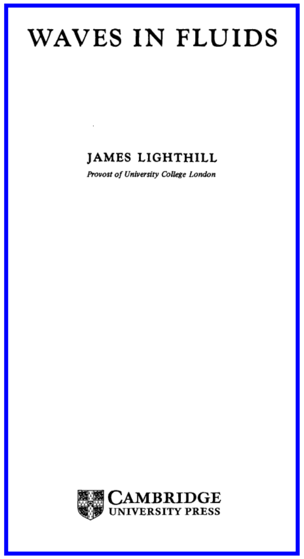
Vibro-Acoustics Consortium Web Meeting

University of Kentucky

Lighthill's Analogy

Assumed only three fundamental types of sources are possible in a fluid.

- Monopole
- Dipole
- Quadrupoles


WAVES IN FLUIDS

JAMES LIGHTHILL

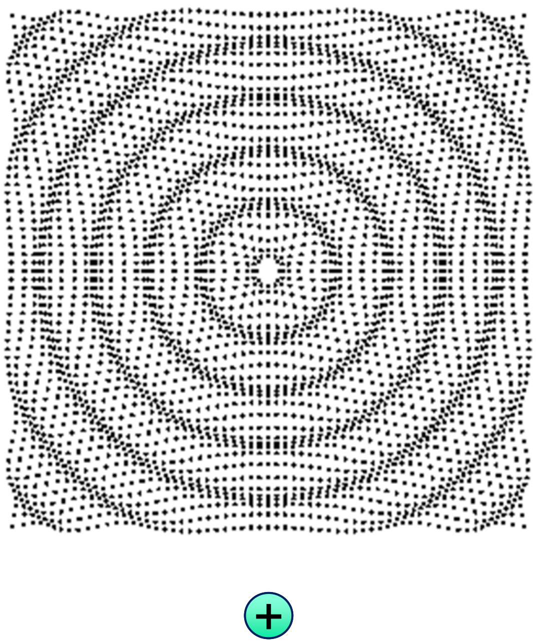
Provost of University College London

CAMBRIDGE UNIVERSITY PRESS

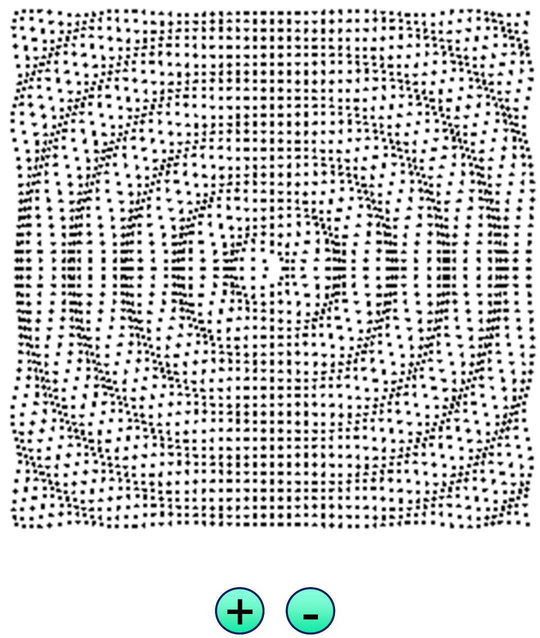
Weakness It ignores the interaction between sound and flow. An important example is the *whistle sound* caused by vortex shedding.

Elementary Sources

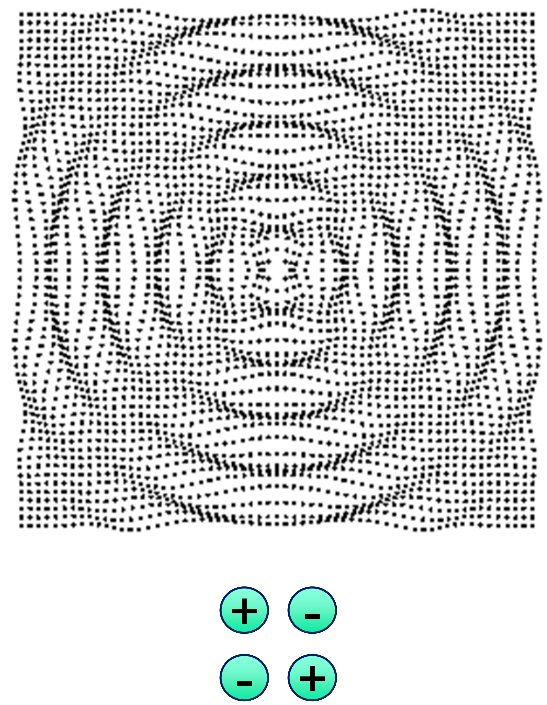
Monopole



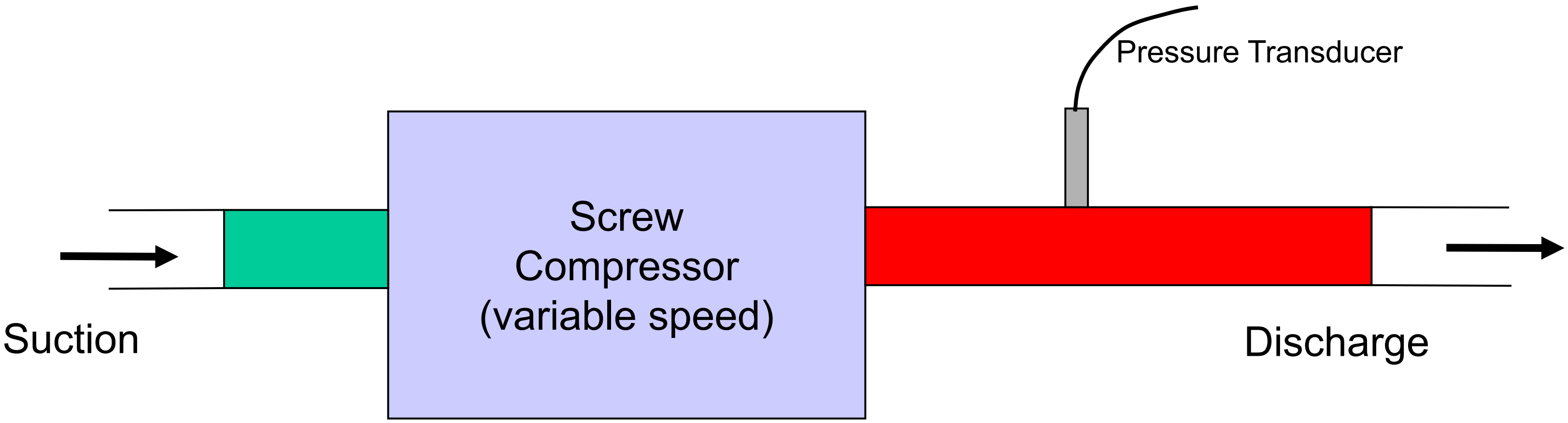
Dipole

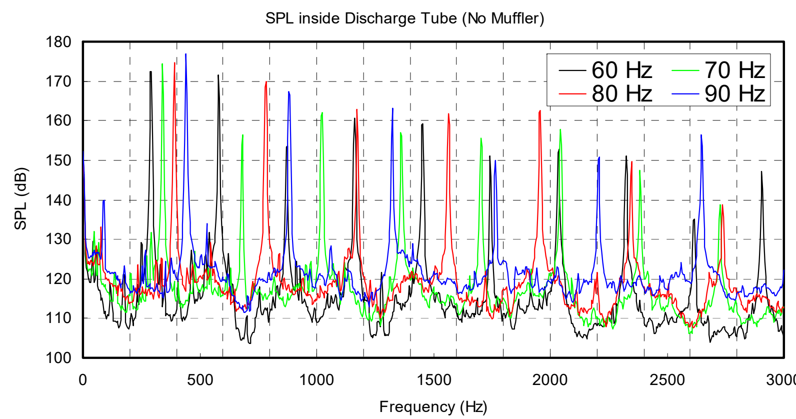


Quadrupole

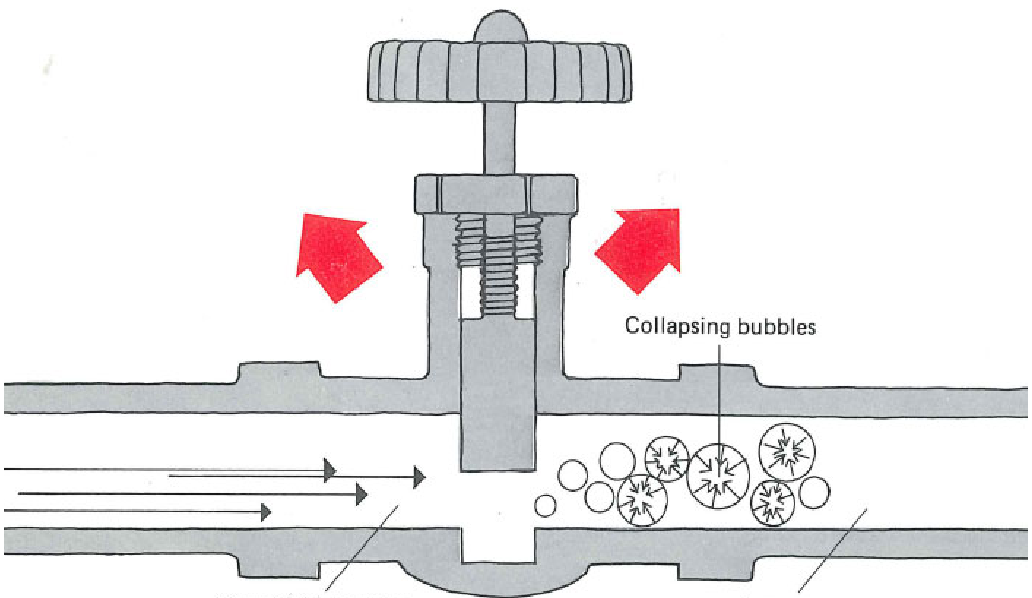


Flow Noise Sources Monopoles





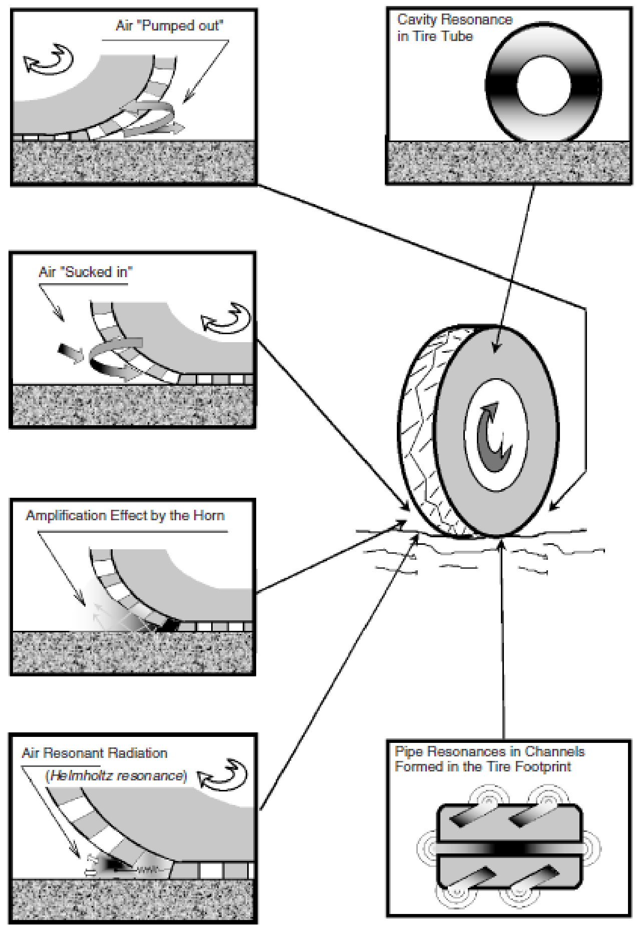
Flow Noise Sources Monopoles



$$Q \propto \frac{d(\Delta V)}{dt}$$

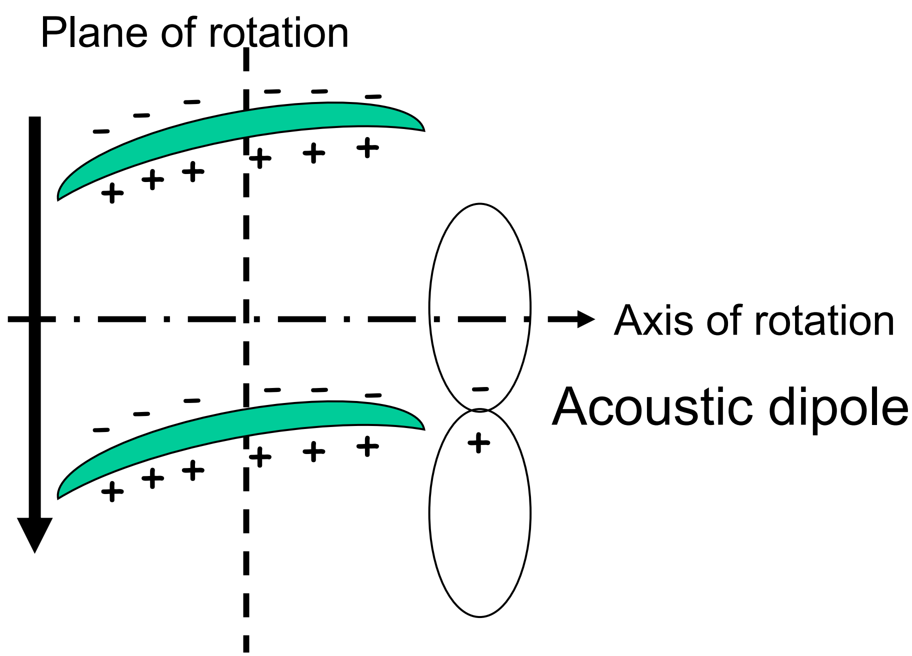
The implosion of a cavitation bubble is a strong source of sound, because it occurs in a very short time span (Åbom, 2011).

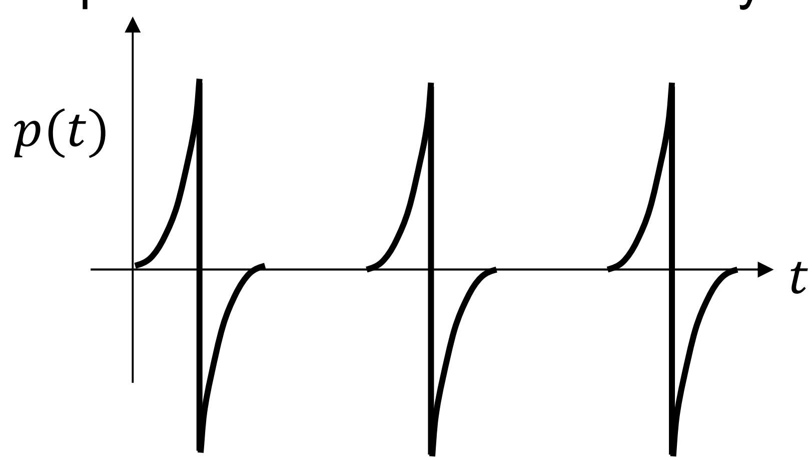
Flow Noise Sources Monopoles



Flow Noise Sources Dipoles

- A fan blade is a moving airfoil
- Positive and negative pressures produce noise to a stationary observer



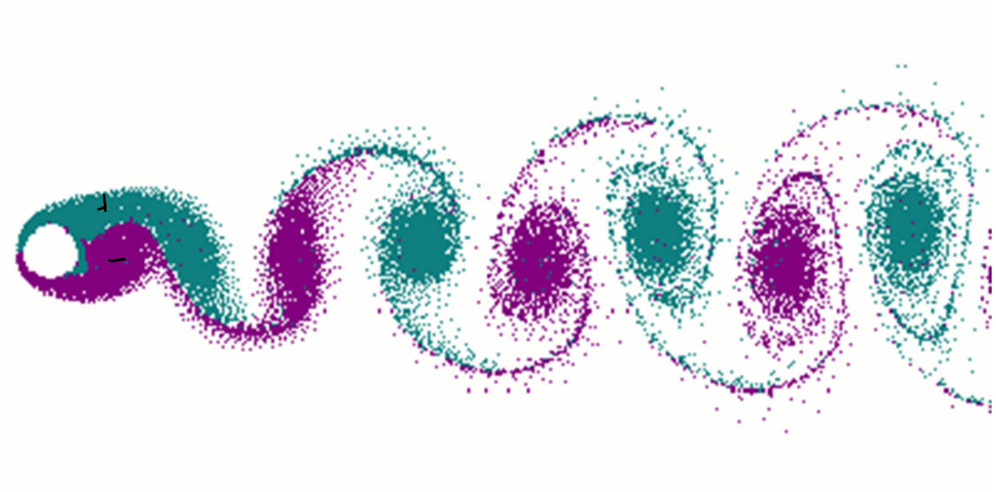


$$\rightarrow \quad f_B = \left(\frac{N}{60}\right) B$$

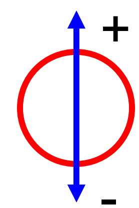
B = number of blades

Flow Noise Sources Dipoles

Flow over a rod

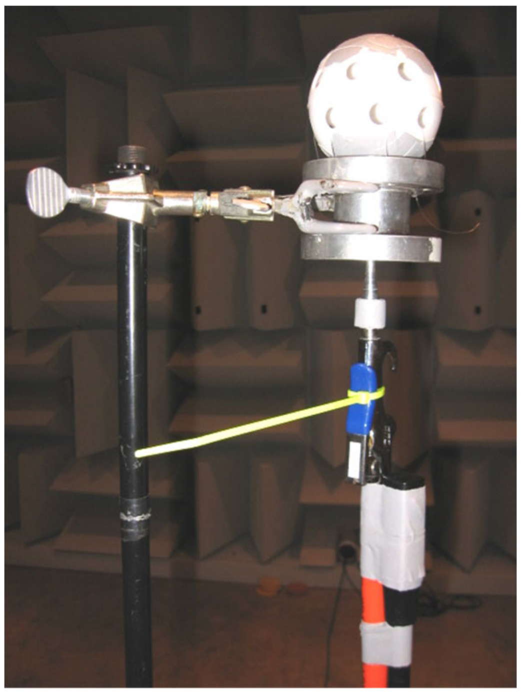


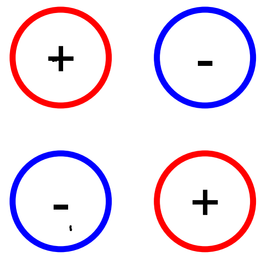
Oscillating



Flow Noise Sources Quadrupoles

Turbulence





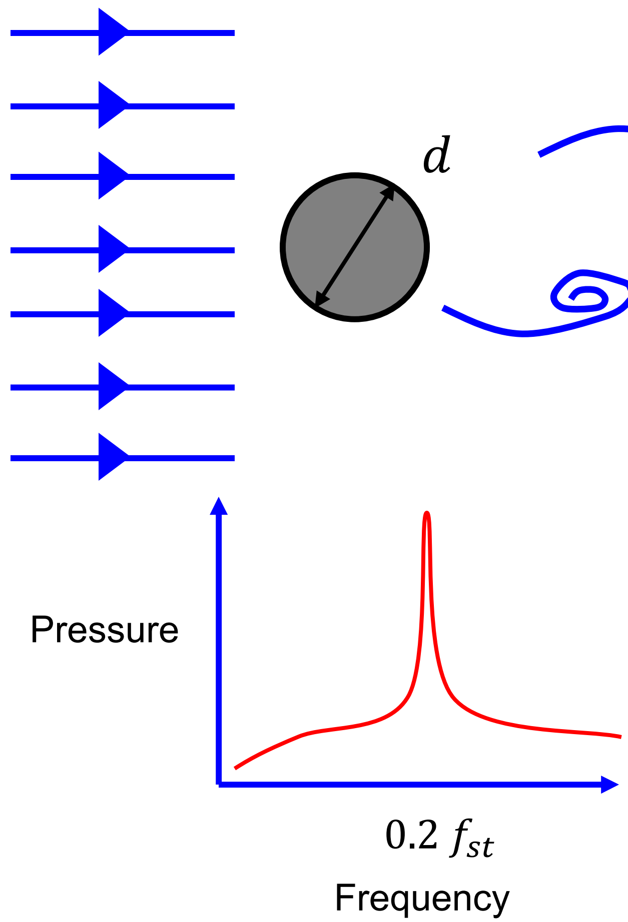
The Strouhal Frequency

The frequency content scales to or is proportional to the Strouhal frequency.

$$f_{st} = \frac{U}{d}$$

Where d is the dimension of the source and U is the flow velocity.

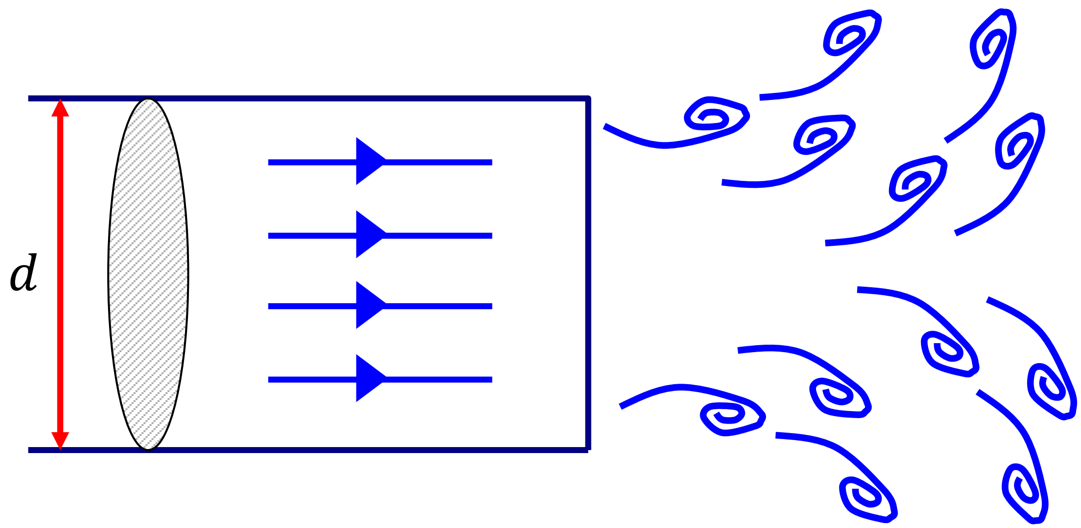
Case 1 Periodic Vortex Shedding

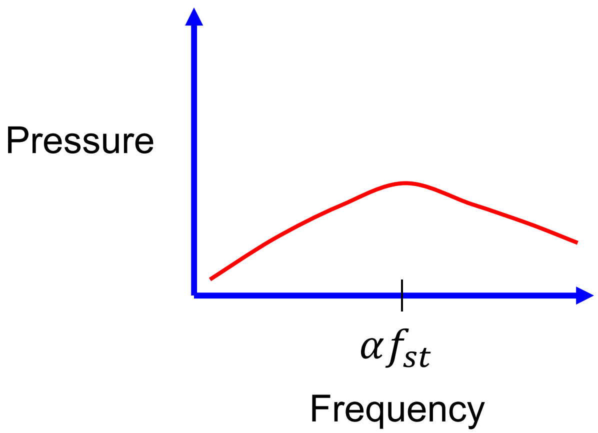


Vortex Shedding Frequency

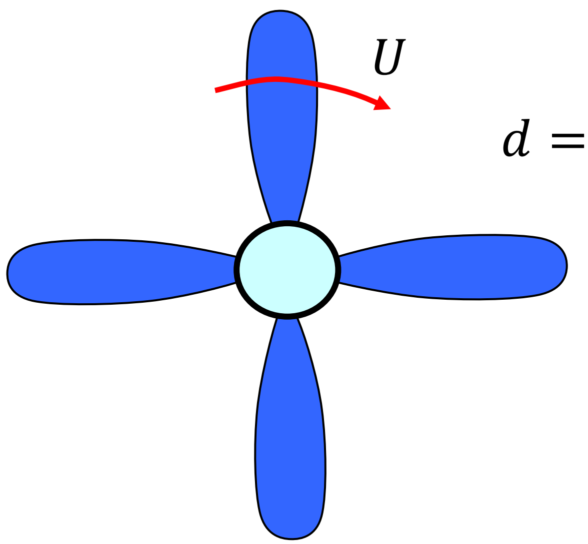
$$f_{vs} = \frac{0.2U}{d}$$

Case 2 Turbulent Jet

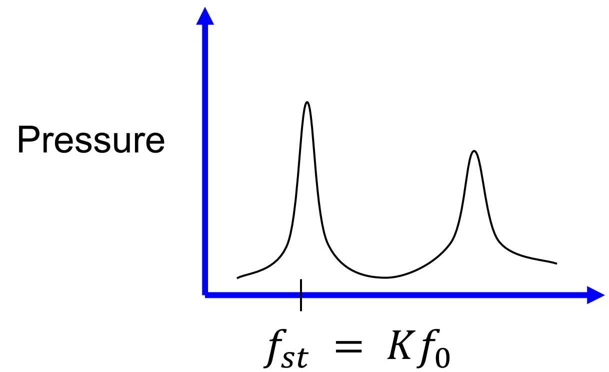




Case 3 Fan or Propeller



$$d = \frac{\pi D}{K}$$



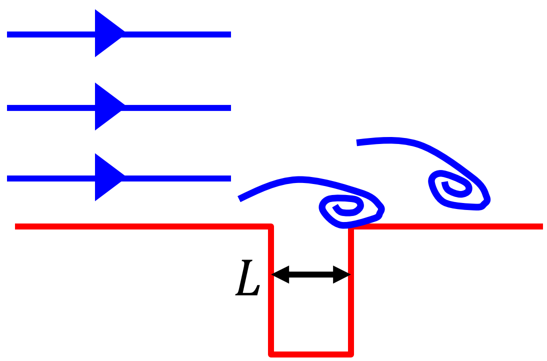
$$f_{st} = \frac{U}{d} = \frac{\pi f_0 D}{\pi D / K}$$

Where D is the diameter of the source, K is the number of blades, and f_0 is the rotational frequency.

Case 4 Air Flow over Cavities

Rossiter's Equation (for Air)

$$f_{vs} = \left(\frac{j-\gamma_R}{1/K_R + M}\right)\frac{U}{L} = \left(\frac{j-\gamma_R}{1/K_R + M}\right) f_{st}$$



L	streamwise cavity length
$j = 1, 2, 3, \ldots$	mode number
$\gamma_R = 0.25$	phase shift of acoustic scattering at downstream edge
$K_R = 0.61 \text{ to } 0.66$	ratio of convective speed of the shear layer vortices to free stream velocity

Case 5 Whistle Tones

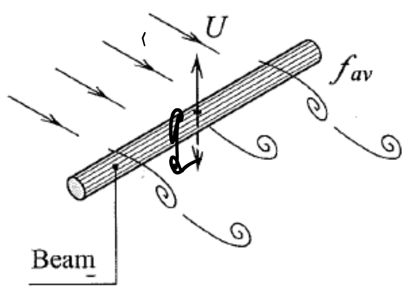
Vortex Shedding Frequency

$$f_{vs} = \alpha f_{st}$$

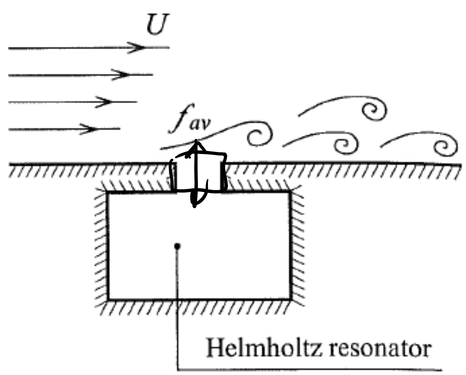
Self Excited Acoustic Oscillation

$$f_{vs} = f_{res}$$

Case I



Case II



Objectives

- Applied overview of aeroacoustic sources
- Scaling laws for sound power
- Practical measures to avoid problems

Sound Power Relationships

Relationship between a monopole and dipole

$$\frac{\bar{W}_{dipole}}{\bar{W}_{monopole}} = \frac{(kd)^2}{3}$$

Relationship between a dipole and quadrupole

$$\frac{\bar{W}_{quadrupole}}{\bar{W}_{dipole}} = \frac{(kd)^2}{5}$$

where d is the dimension of the source assuming the source region is assumed to be small compared to an acoustic wavelength.

Size of the Source Region

$$kd = \left(\frac{2\pi f_{st}}{c}\right) d = \left(\frac{2\pi}{c}\right)\left(\frac{U}{d}\right) d = 2\pi M$$

Flow acoustic sources are acoustically small for small Mach (M) numbers.

$$\frac{\overline{W}_{dipole}}{\overline{W}_{monopole}} \propto M^2 \qquad \frac{\overline{W}_{quadrupole}}{\overline{W}_{dipole}} \propto M^2$$

Sound Power of a Monopole

Sound power for a monopole

$$\overline{W}_m = \frac{\rho_0 c k^2}{4\pi} Q^2 \qquad k = \frac{2\pi f_{st}}{c} = \frac{2\pi}{c}\left(\frac{U}{d}\right)$$

Where the volume velocity (Q) is $Q \propto U d^2$ Speed × Area

$$\overline{W}_m \propto \frac{\rho_0 c}{4\pi}\left(\frac{2\pi}{c}\frac{U}{d}\right)^2 (U d^2)^2$$

$$\overline{W}_m \propto \rho_0 d^2 \frac{U^4}{c} = \rho_0 d^2 U^3 M$$

Scaling Laws for Sound Power

Dimension	Monopole	Dipole	Quadrupole
1-D	$\rho_0 c d^2 U^2$	$\rho_0 d^2 U^3 M$	$\rho_0 d^2 U^3 M^3$
2-D	$\rho_0 d^2 U^3$	$\rho_0 d^2 U^3 M^2$	$\rho_0 d^2 U^3 M^4$
3-D	$\rho_0 d^2 U^3 M$	$\rho_0 d^2 U^3 M^3$	$\rho_0 d^2 U^3 M^5$

Relative Importance of the Sources

Ordering Based on Mach Number

$$W_M : W_D : W_Q :: M : M^3 : M^5$$

Ordering Based on Flow Velocity (sources of same type)

$$W_M : W_D : W_Q :: U^4 : U^6 : U^8$$

Ordering Based on Frequency

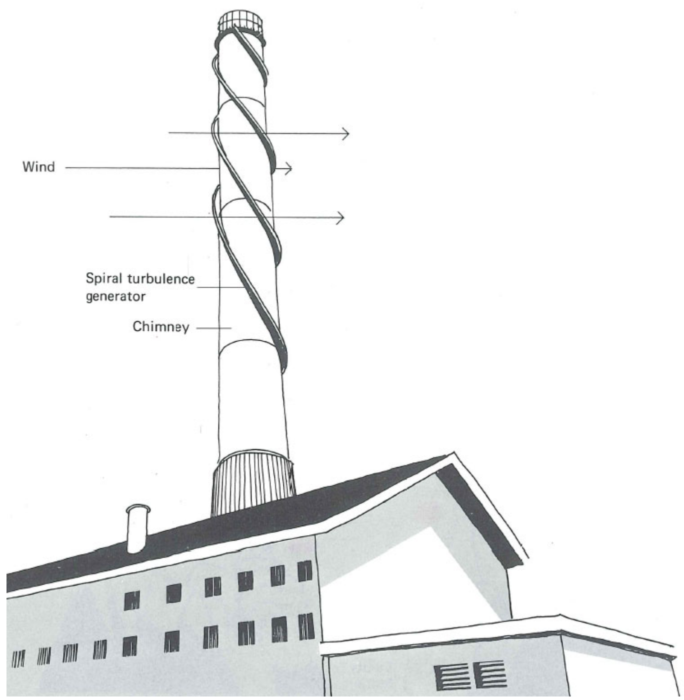
$$W_M : W_D : W_Q :: f : f^2 : f^4$$

Objectives

- Applied overview of aeroacoustic sources
- Scaling laws for sound power
- Practical measures to avoid problems

Prevention Vortex Shedding

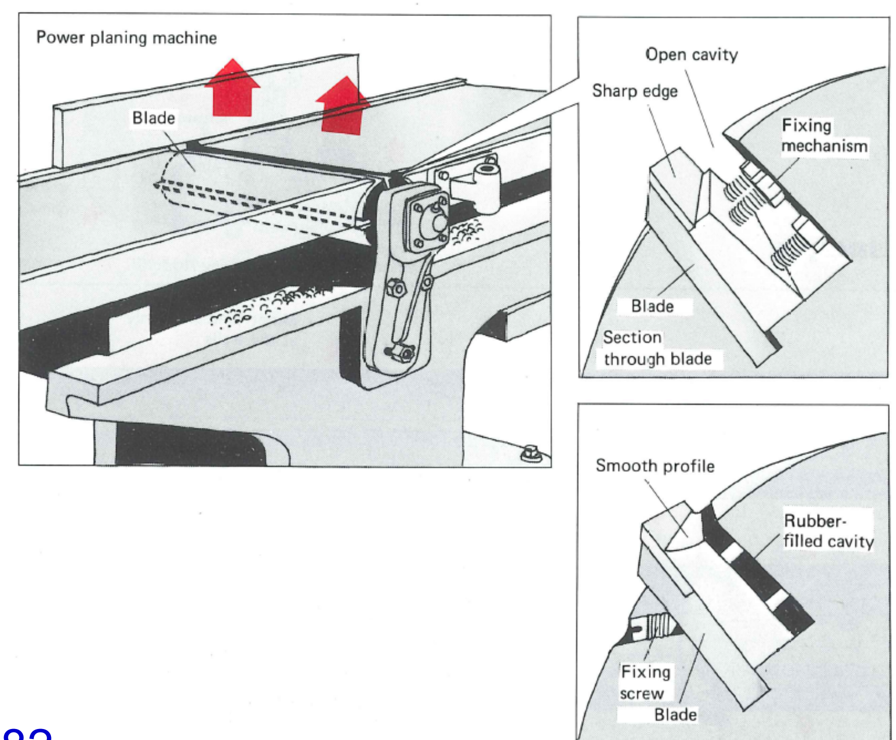
Add spoilers to a smoke stack since the flow direction is variable.



Brüel and Kjaer, 1982

Prevention Air Flow over Cavities

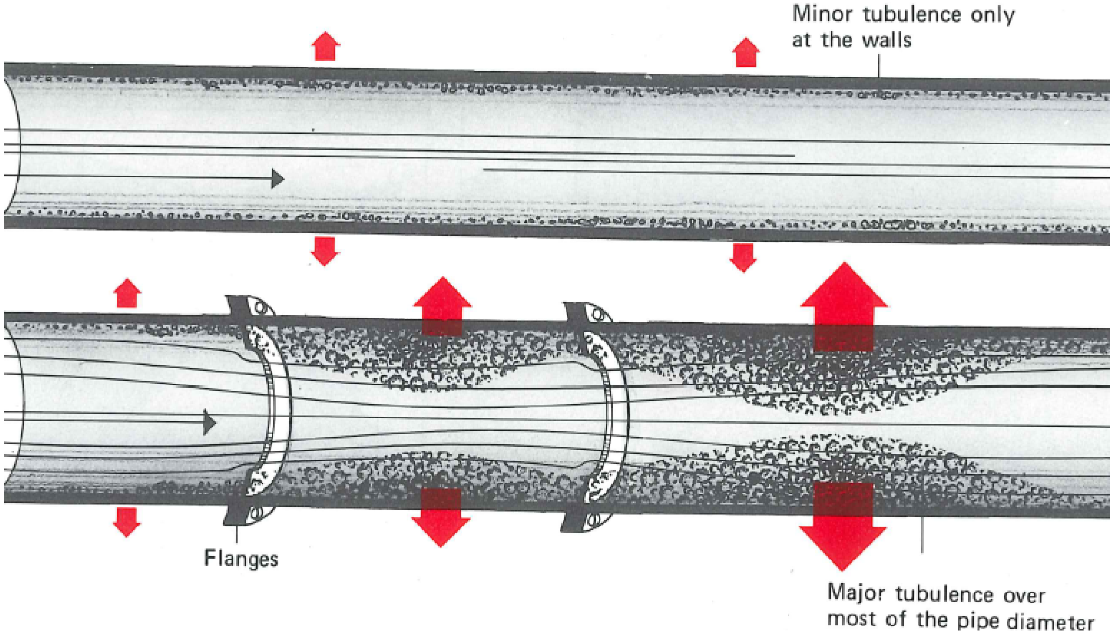
1. Round the edges to reduce a whistle.
2. Fill cavities to avoid resonant amplification of sound.



Brüel and Kjaer, 1982

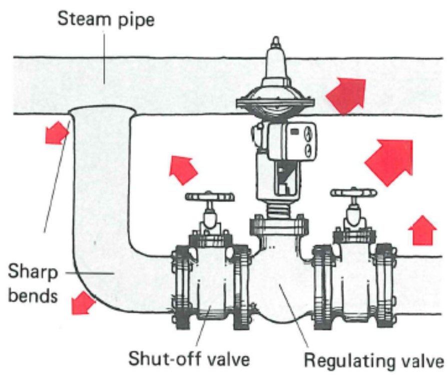
Prevention Turbulence in Pipes

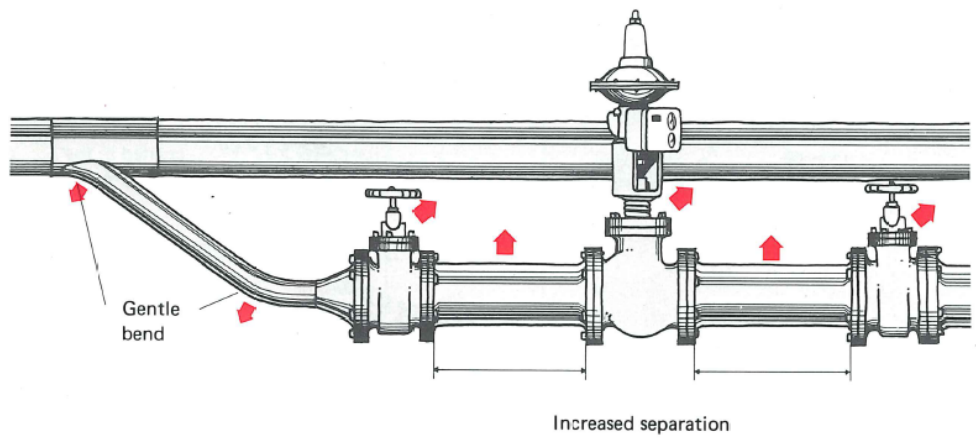
1. Avoid obstacles and sharp bends.
2. Add length to allow turbulence to settle.



Brüel and Kjaer, 1982

Prevention Turbulence in Pipes

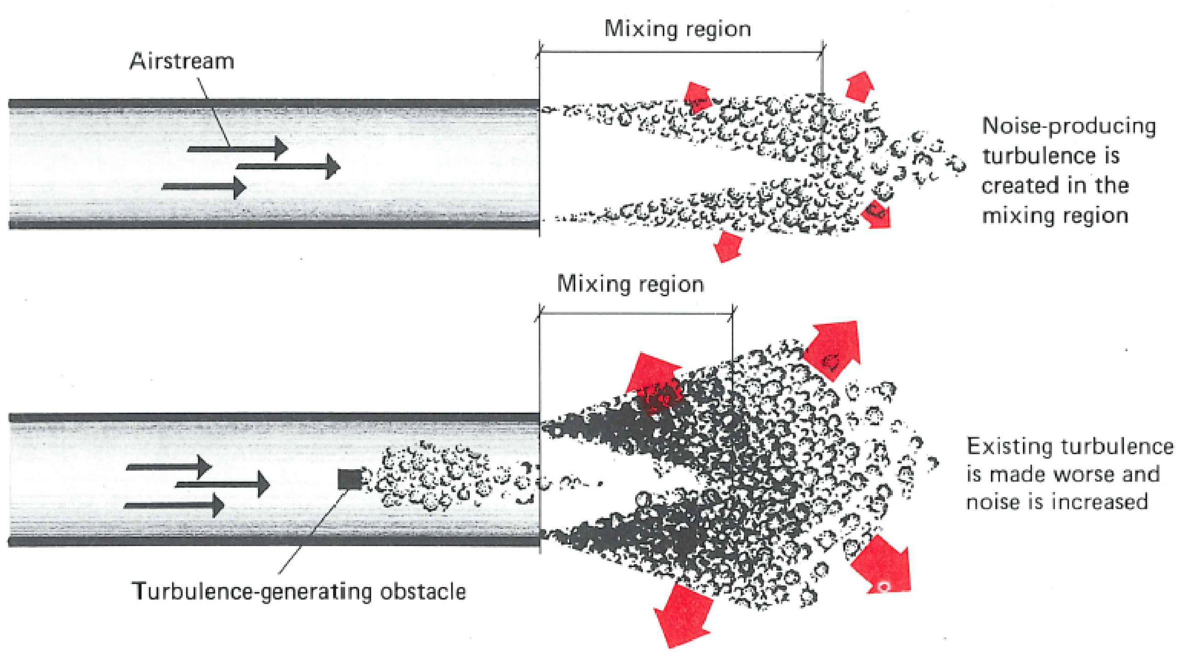




Brüel and Kjaer, 1982

Prevention Exhaust Noise

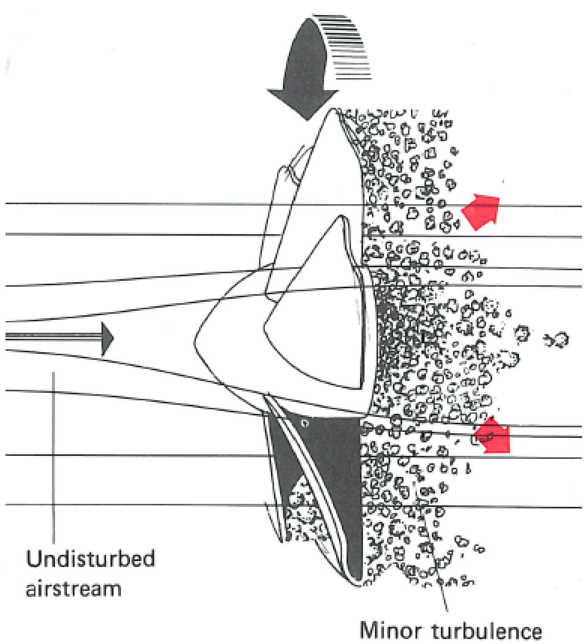
1. Avoid obstacles in the flow (can amplify sound up to 20 dB).
2. Halving the speed leads to a noise reduction of about 15 dB.

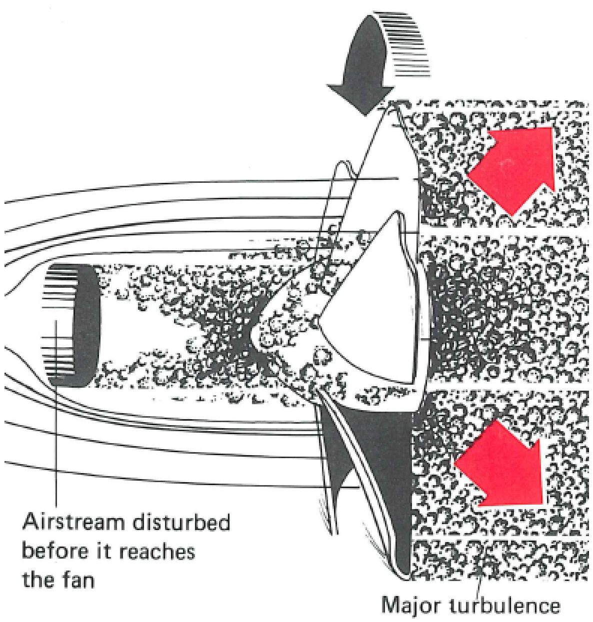


Brüel and Kjaer, 1982

Prevention Fan Noise

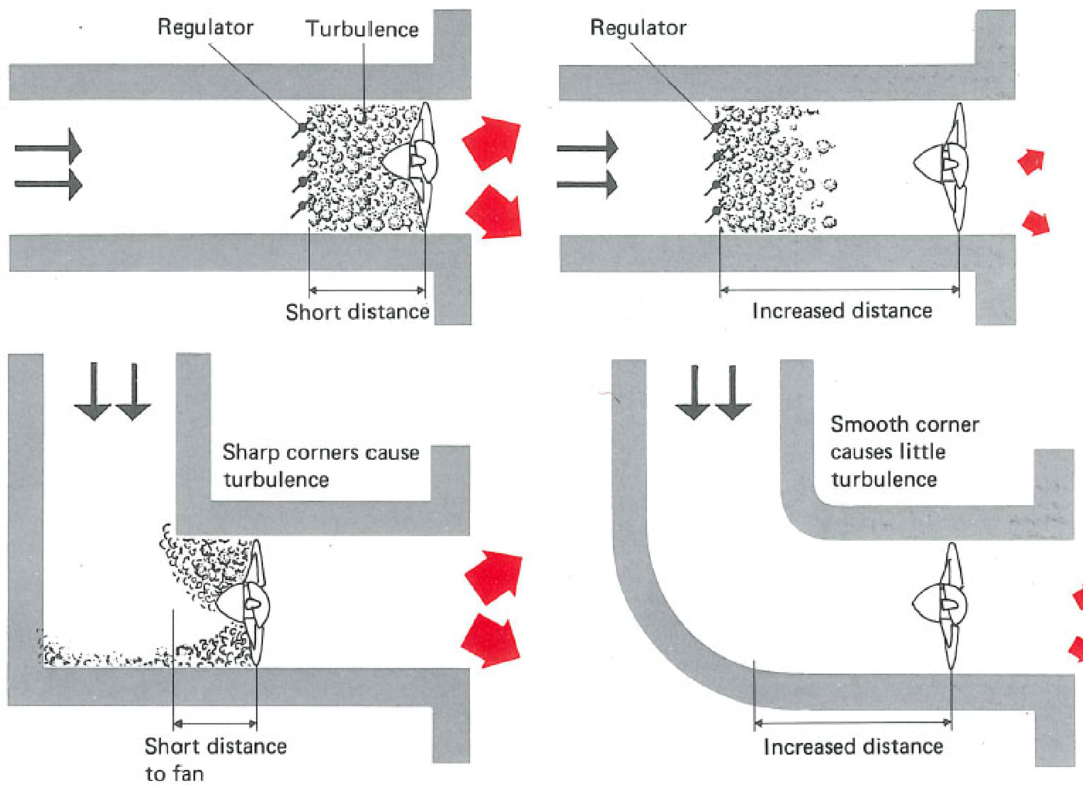
Place fans well downstream of obstacles or bends.





Brüel and Kjaer, 1982

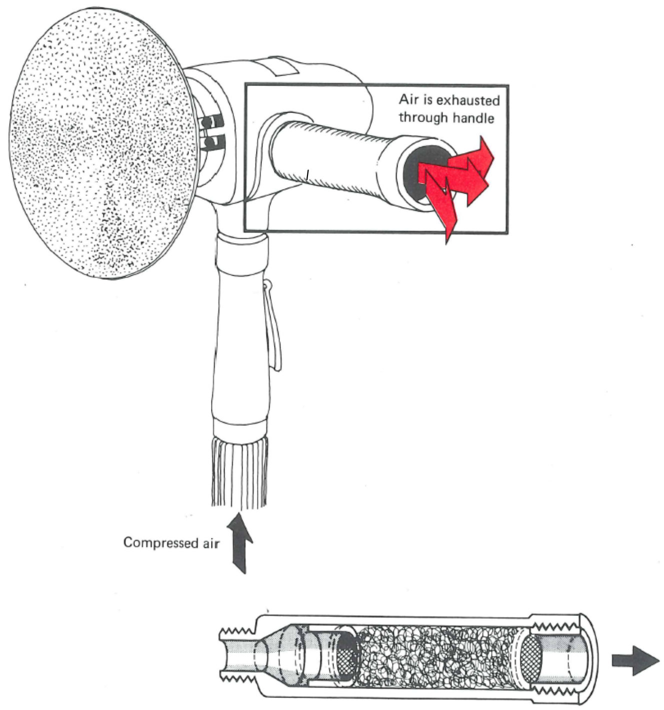
Prevention Fan Noise



Brüel and Kjaer, 1982

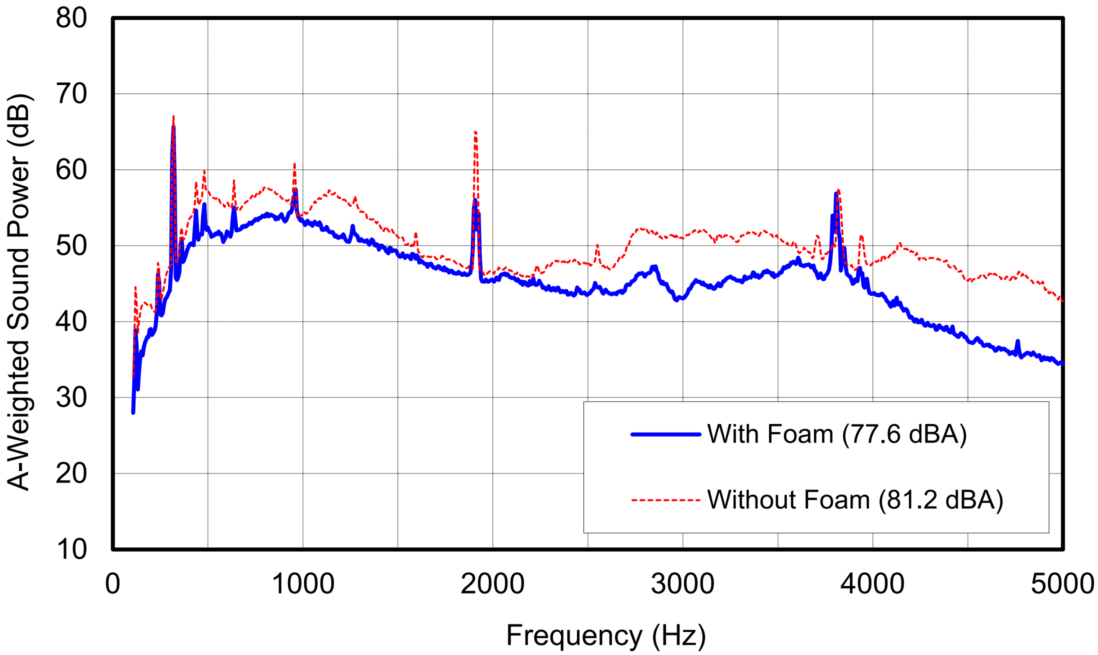
Prevention Exhaust Noise

Add absorption in pipe to smooth turbulence and absorb sound.



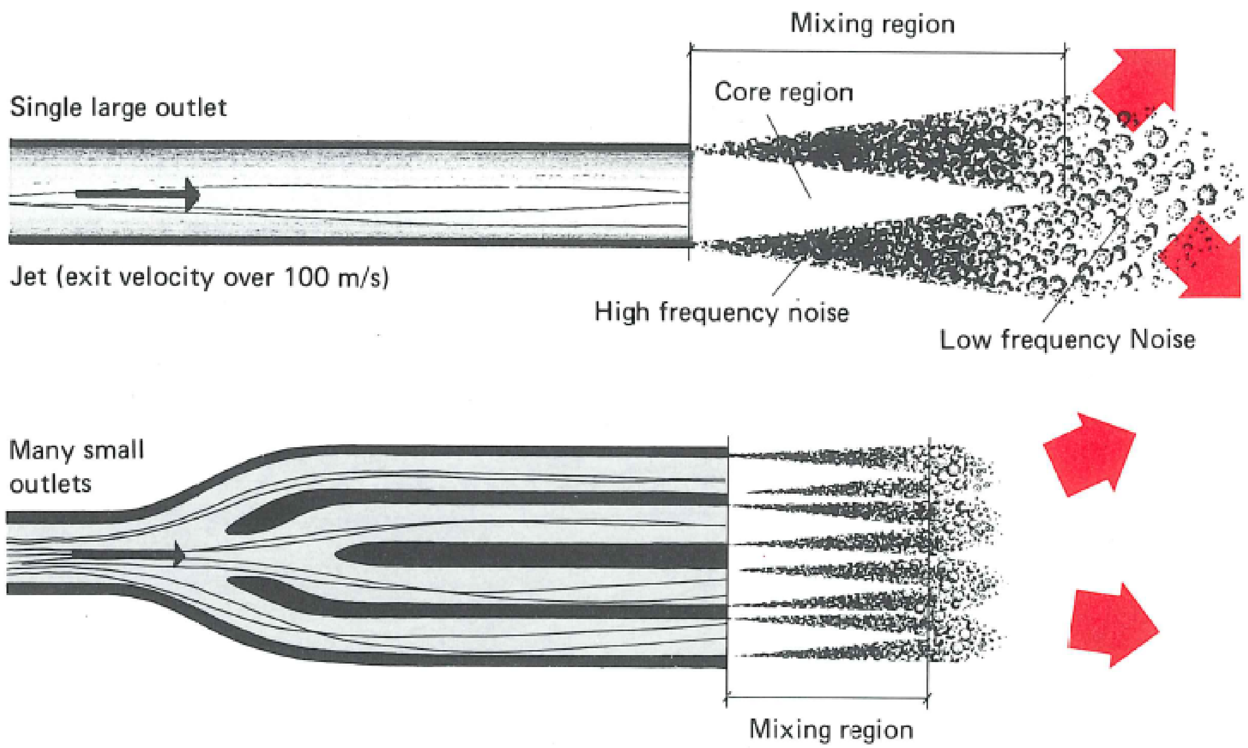
Brüel and Kjaer, 1982

Prevention Exhaust Noise



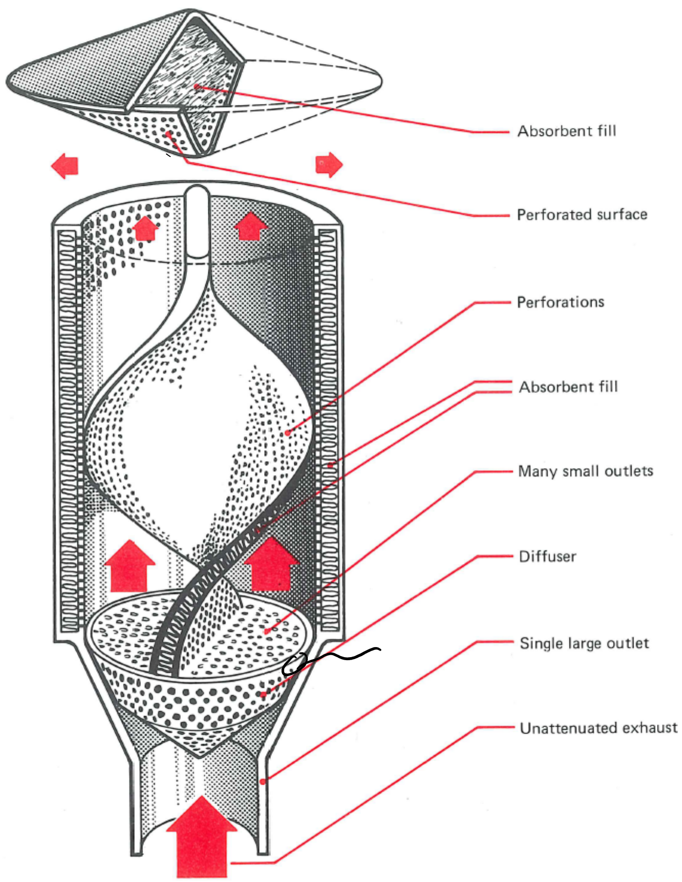
Prevention Exhaust Noise

Replace a large exhaust by a number of small pipes.



Brüel and Kjaer, 1982

Prevention Exhaust Noise

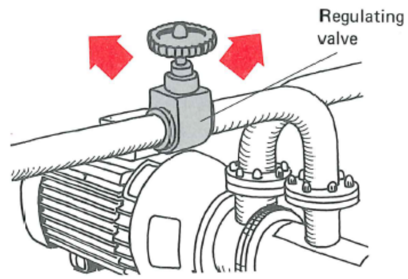


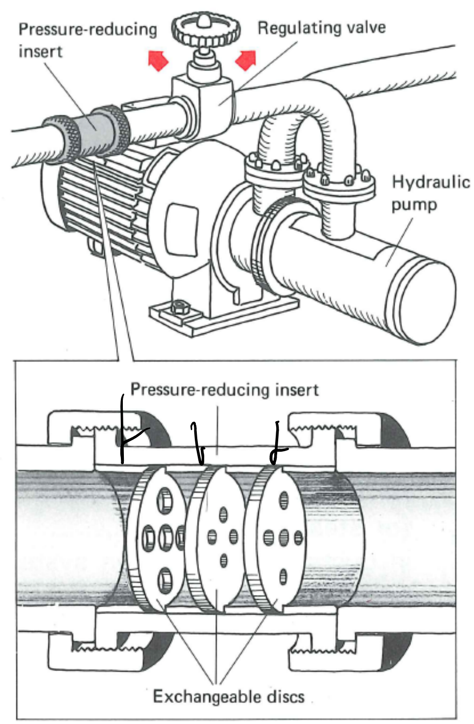
Brüel and Kjaer, 1982

Change the noise problem from low to high frequency so that absorption can be used to attenuate the sound.

Prevention Cavitation

Lower pressures in a number of small steps.





Brüel and Kjaer, 1982

References

- ✓ H. P. Wallin, U. Carlsson, M. Åbom, H. Bodén, and R. Glav, "Chapter 8: Sound Generation and Radiation," Sound and Vibration, Marcus Wallenberg Laboratory, Stockholm (2011).
- ✓ Noise Control: Principles and Practice, Brüel and Kjaer, Denmark (1982). https://www.bksv.com/media/doc/bn1299.pdf