Sound Absorbing Materials

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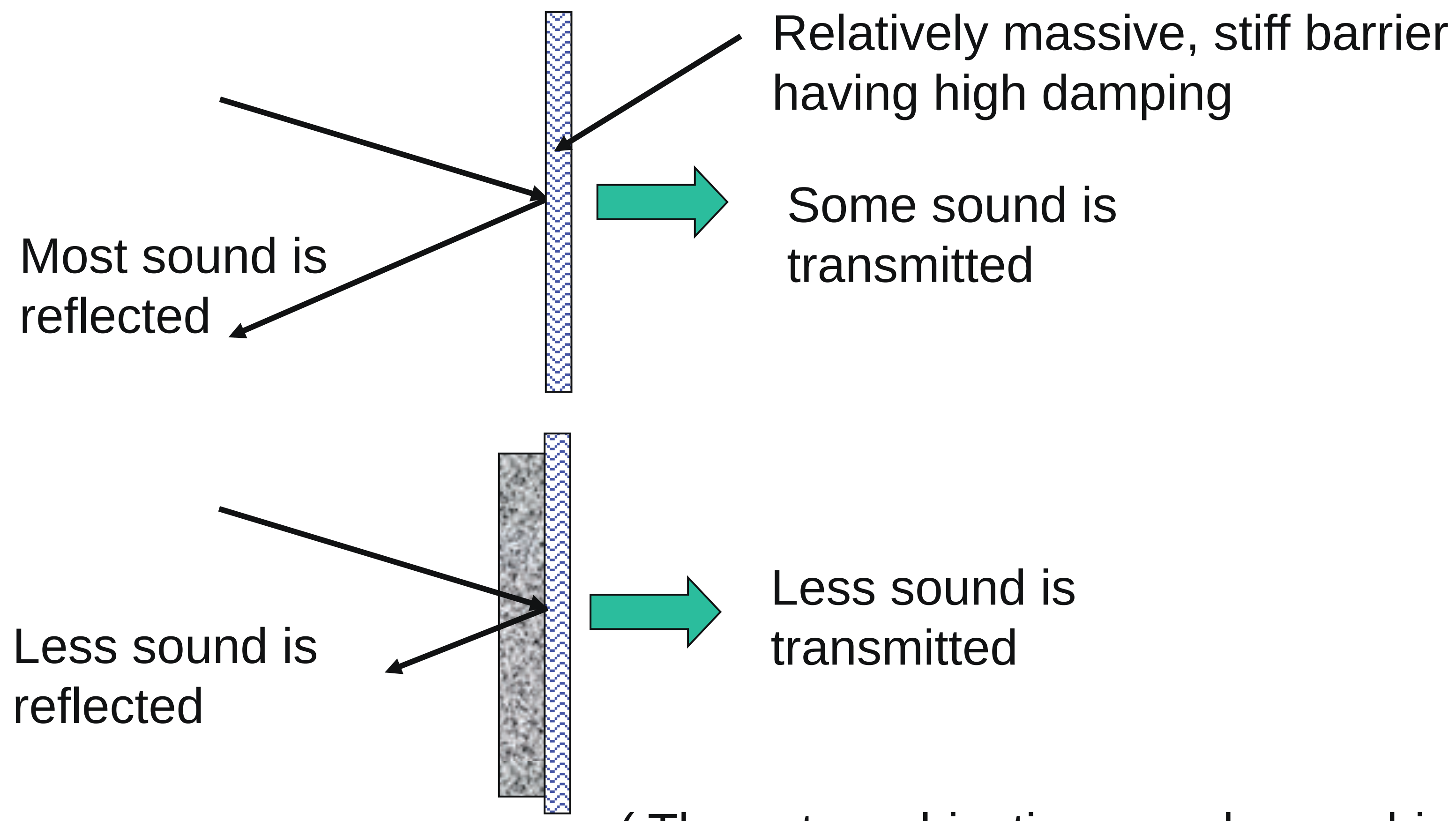
Overview

Sound Absorption by Porous Materials

- The Basics
- Impedance and Absorption
- Transfer Matrix Approach
- Flow Resistivity

Sound Blocking Versus Sound Absorption

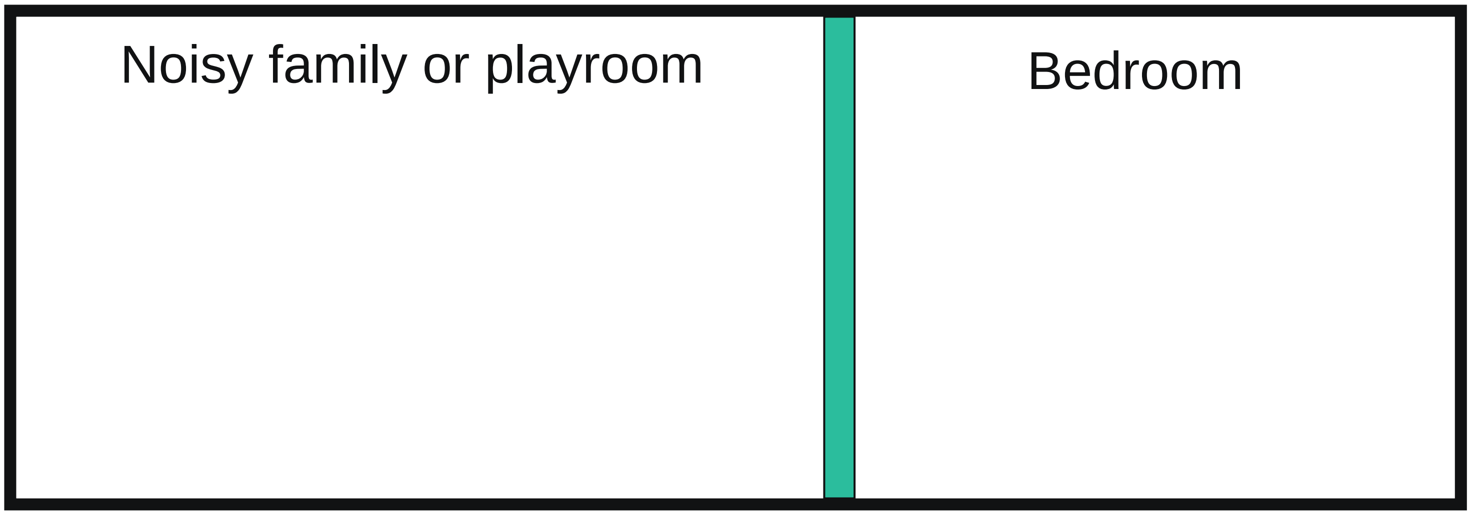
Sound Absorption by Porous Materials



(These two objectives can be combined)

Example

Sound Absorption by Porous Materials

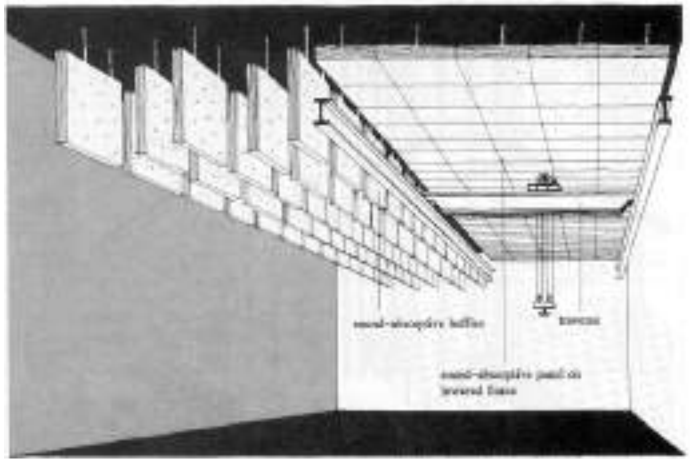


Ways to reduce noise level in the bedroom:

Which use sound blocking and which use sound absorption?

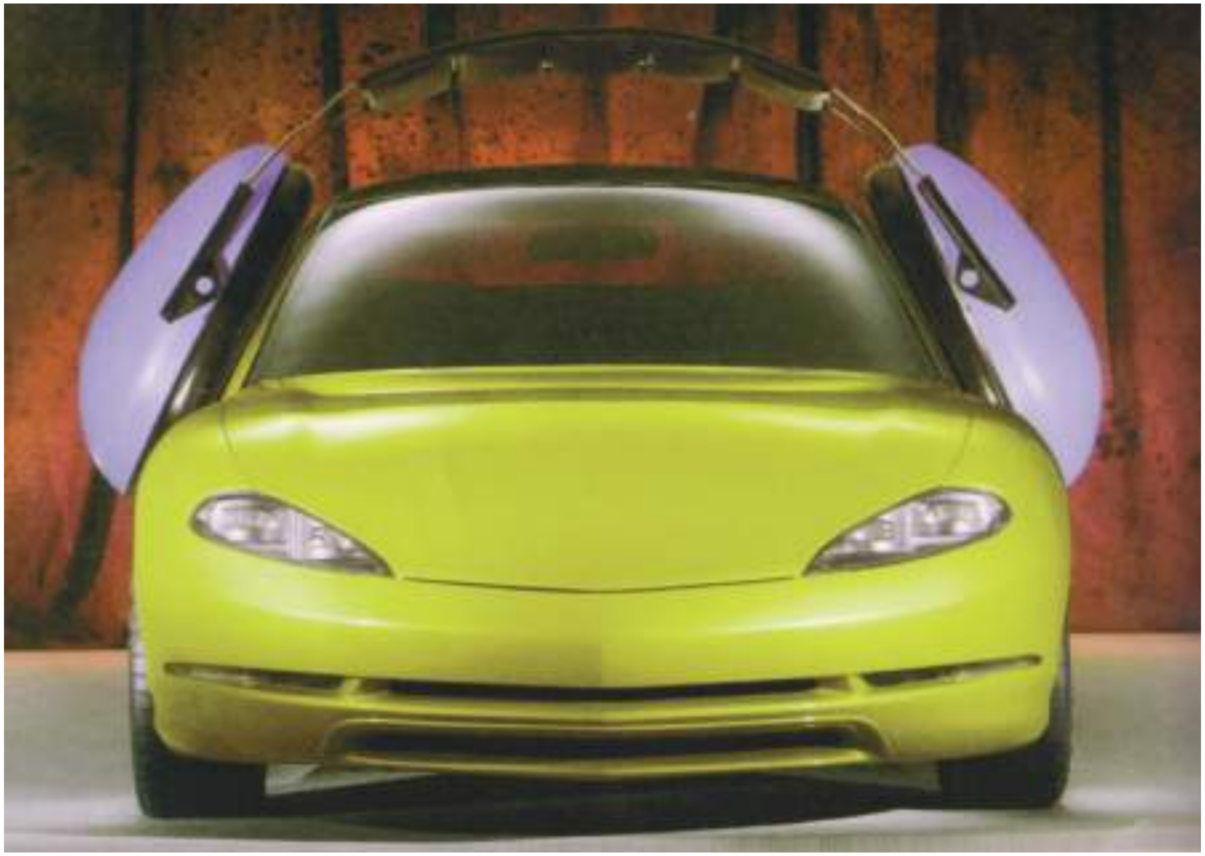
Sound Absorbing Materials

Sound Absorption by Porous Materials



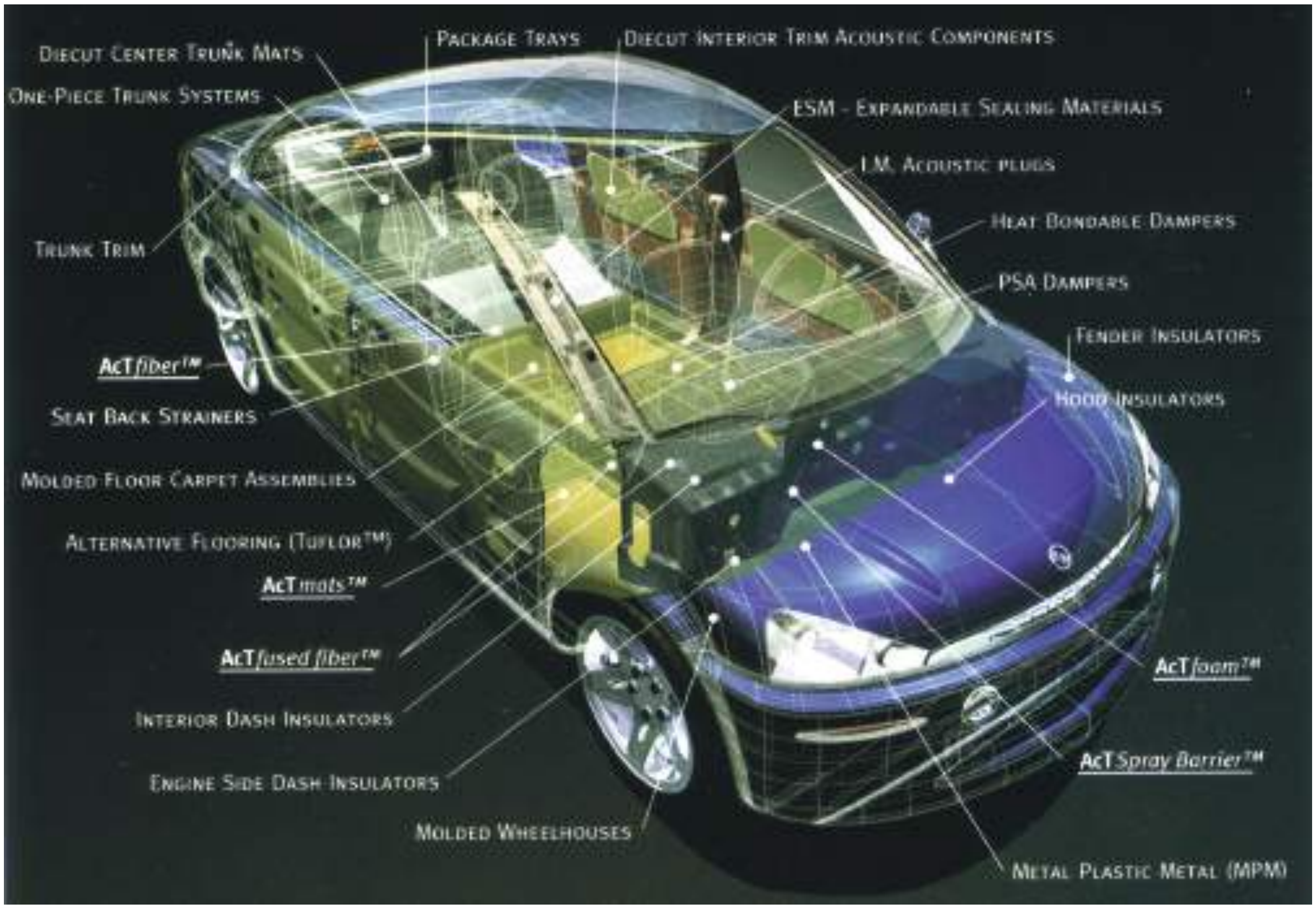
NVH Applications Driven by Auto Industry

Sound Absorption by Porous Materials



Sound Absorbing Materials in Car

Sound Absorption by Porous Materials



Examples of Sound Absorbing Materials

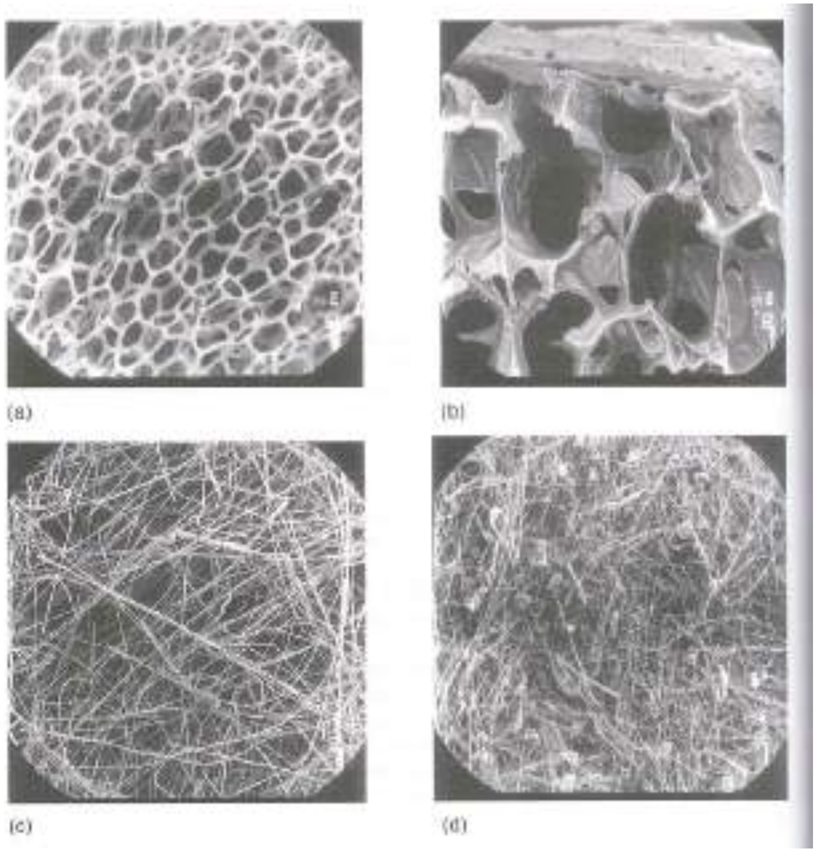
Sound Absorption by Porous Materials

a: fully reticulated plastic foam (x14)

b: partially reticulated plastic foam (x14)

c: glass fiber (x14)

d: mineral (rock) wool (x14)



Foam Manufacture and Foam Types

Sound Absorption by Porous Materials

- Foams are made of various materials including polyurethane, polyethylene, and polypropylene.
- Foams are created by pouring premixed liquid products onto a conveyor and allowing the chemical process to create cells (voids) of various size as the foam cures and hardens. Similar to bread rising.
- If the cell walls are fractured, the foam is called "open cell"
- If the cell walls remain intact, the foam is called "closed cell"
- Coverings such vinyl, aluminum, urethane, or aluminized mylar protect the surface, improve appearance, and reduce absorption of liquids, dirt, etc.
- Coverings may also act as a barrier, e.g., loaded vinyl

Applications of Sound Absorbing Materials

Sound Absorption by Porous Materials

- Suspended baffles in gymnasiums or factories
- Under hood applications for engine noise
- Vehicle interiors
- Inside building walls – improves transmission loss
- Inside office and computer equipment – reduces reverberant buildup of sound
- Ceiling tiles and carpeting
- HVAC applications – duct liner

Mechanisms of Sound Absorption

Sound Absorption by Porous Materials

Sound is “absorbed” by converting sound energy to heat within the material, resulting in a reduction of the sound pressure.

Two primary mechanisms:

- vibration of the material skeleton - damping
- friction of the fluid on the skeleton - viscosity

Vibration of Material Skeleton

Vibration of the material matrix is caused by sound pressure and velocity fluctuations within the material.

Damping of the material converts sound to heat.

Important for light materials at low frequencies.

Difficult to model and measure (ignored here)

Friction of the Fluid on the Skeleton

The oscillating fluid particles within the material rub against the matrix and create heat by friction (viscosity).

Primary material parameters affecting absorption:

- porosity (fraction of air volume in the material)
- structure factor (orientation of fibers, tortuosity)
- flow resistance

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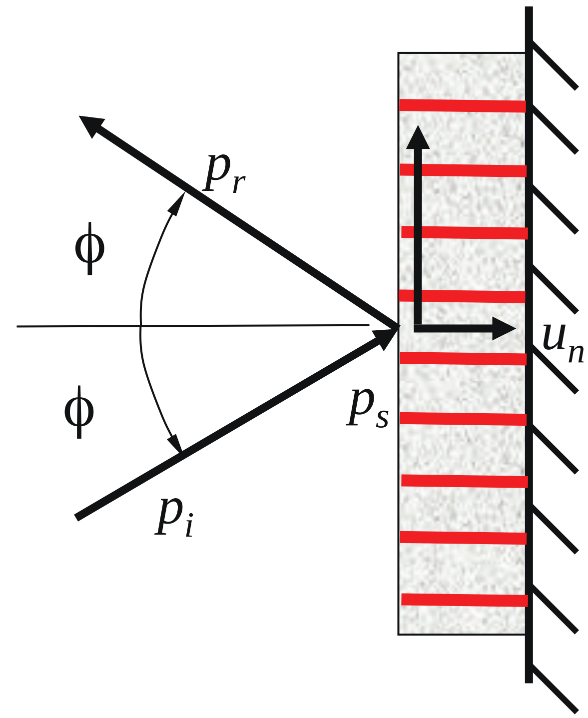
The Local Reaction Model

Sound Absorption by Porous Materials

- The wave component within the material parallel to the surface is attenuated rapidly
- The material is similar to a set of rigid-wall, parallel capillaries
- The particle velocity u_n in the material is normal to the surface and only a function of the *local* sound pressure p_s at the surface (u_n is independent of the form of the incident wave)



$$z = \frac{p_s}{u_n} \quad \text{(independent of } p_i\text{)}$$

Specific Boundary Impedance

Sound Absorption by Porous Materials

$$z = \left.\frac{p}{u_n}\right|_{\text{surface}} = r + jx$$

resistance (r) — reactance (x)

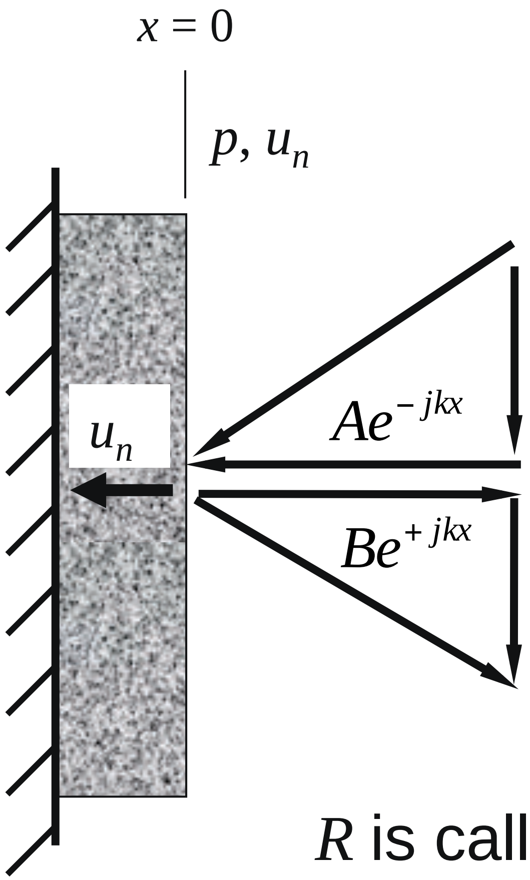
Units: $$\frac{\text{Pa}}{\text{ms}^{-1}} = \text{kg}\,\text{m}^{-2}\text{s}^{-1} \equiv \text{rayl}$$ (named in honor of Lord Rayleigh)

Absorption coefficient:

$$\alpha(\phi) = \frac{\text{Sound Energy Absorbed}}{\text{Sound Energy Incident}}$$

Specific Boundary Impedance

Sound Absorption by Porous Materials



$$z_n = \left.\frac{p}{u_n}\right|_{x=0} = \frac{A+B}{\left(\frac{A-B}{\rho_o c}\right)} = \rho_o c\,\frac{1+(B/A)}{1-(B/A)}$$

$$\frac{z_n}{\rho_o c} = \frac{1+R}{1-R}$$

$$R = \frac{B}{A}$$

R is called the *pressure reflection coefficient*

Absorption Coefficient and Impedance

Sound Absorption by Porous Materials

While the specific boundary impedance is independent of angle of incidence, the absorption coefficient is not:

$$\alpha(\phi) = \frac{4r_n' \cos\phi}{\left(1 + r_n' \cos\phi\right)^2 + \left(x_n' \cos\phi\right)^2} \quad \text{where} \quad r_n' = \frac{r_n}{\rho_o c} \quad x_n' = \frac{x_n}{\rho_o c}$$

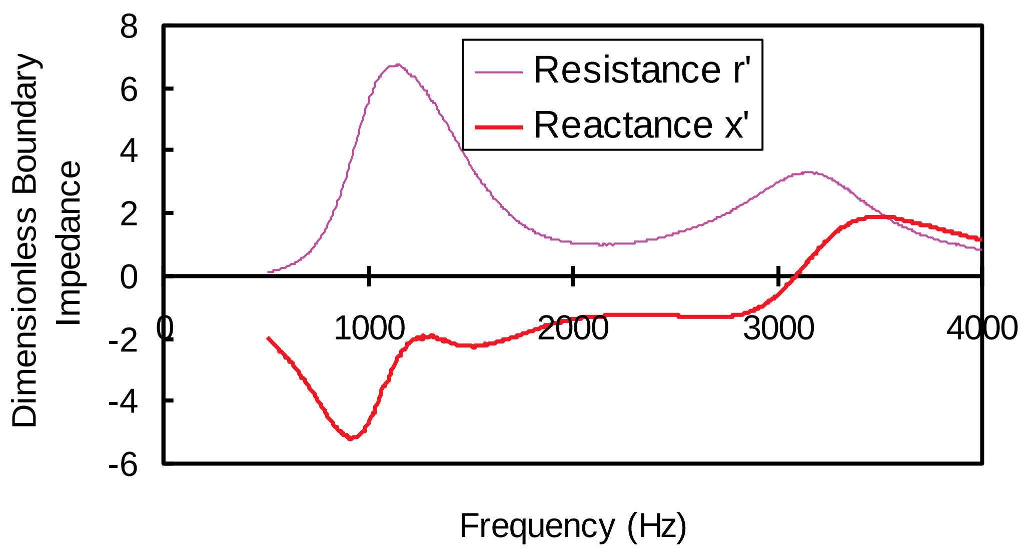
An angle of maximum absorption exists: $\phi_{\max} = \cos^{-1}\left(\sqrt{\left(r_n'\right)^2 + \left(x_n'\right)^2}\right)$

The maximum absorption here is: $\alpha_{\max} = \dfrac{2r_n'}{\left(\left|z_n'\right| + r_n'\right)}$

$$\alpha(0^\circ) \rightarrow 1 \text{ if } r_n' \rightarrow 1 \text{ and } x_n' \rightarrow 0$$

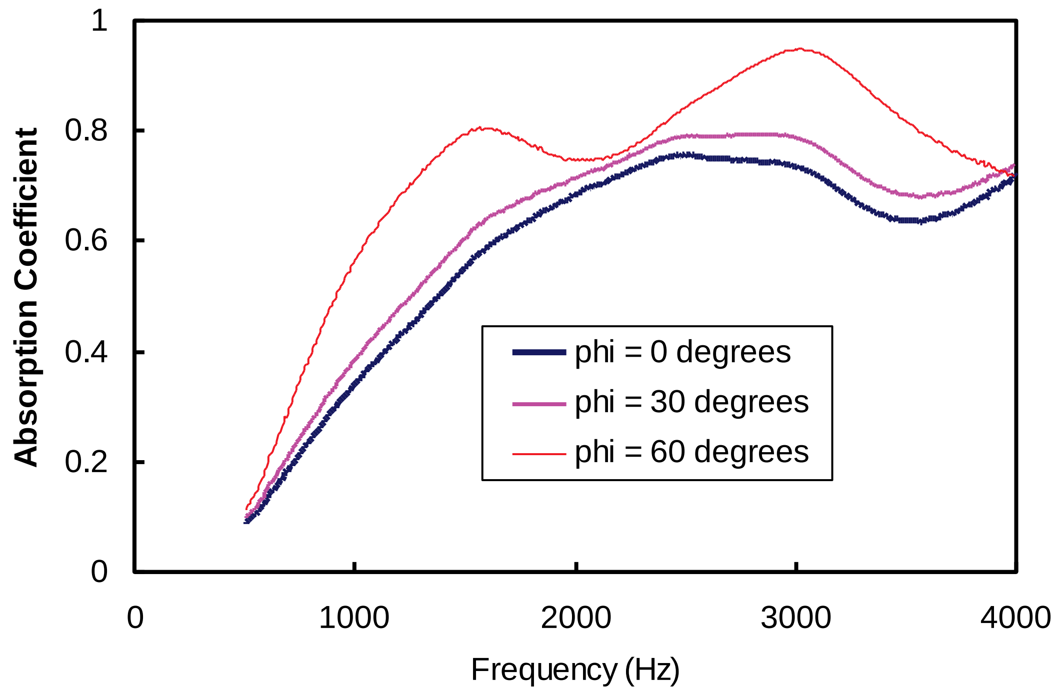
Example Impedance of Foam

Sound Absorption by Porous Materials



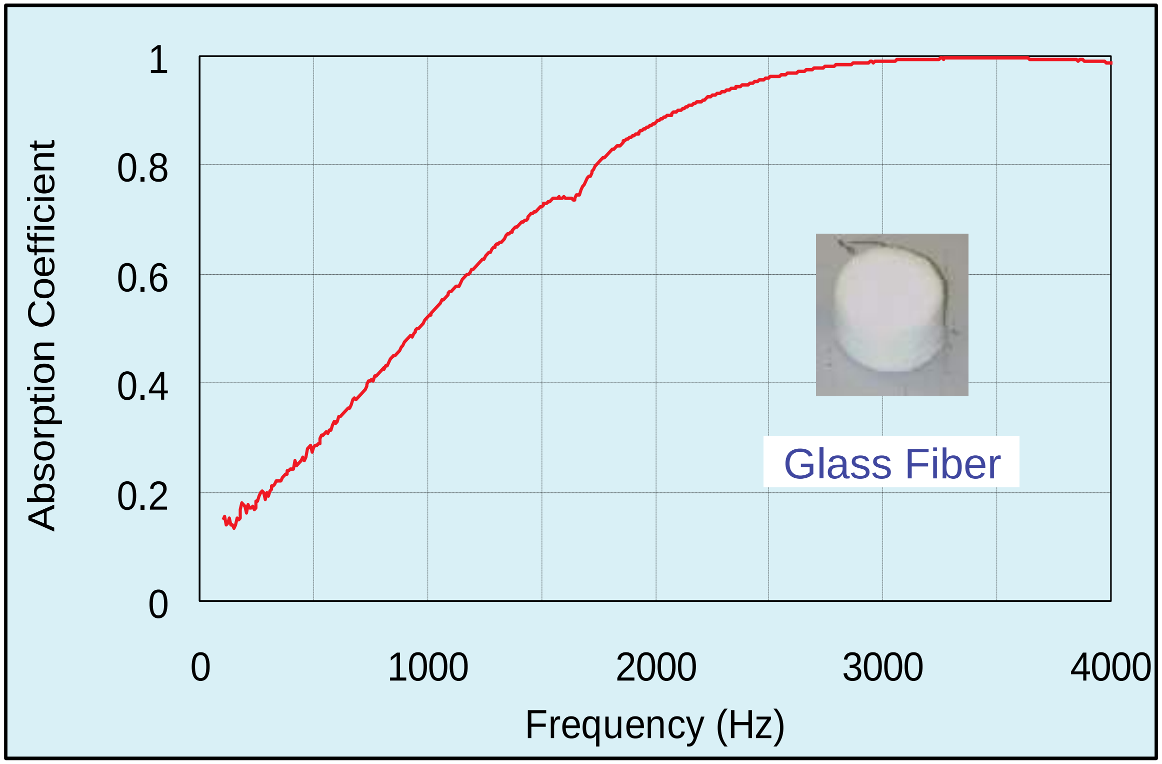
Example Sound Absorption Coefficient

Sound Absorption by Porous Materials



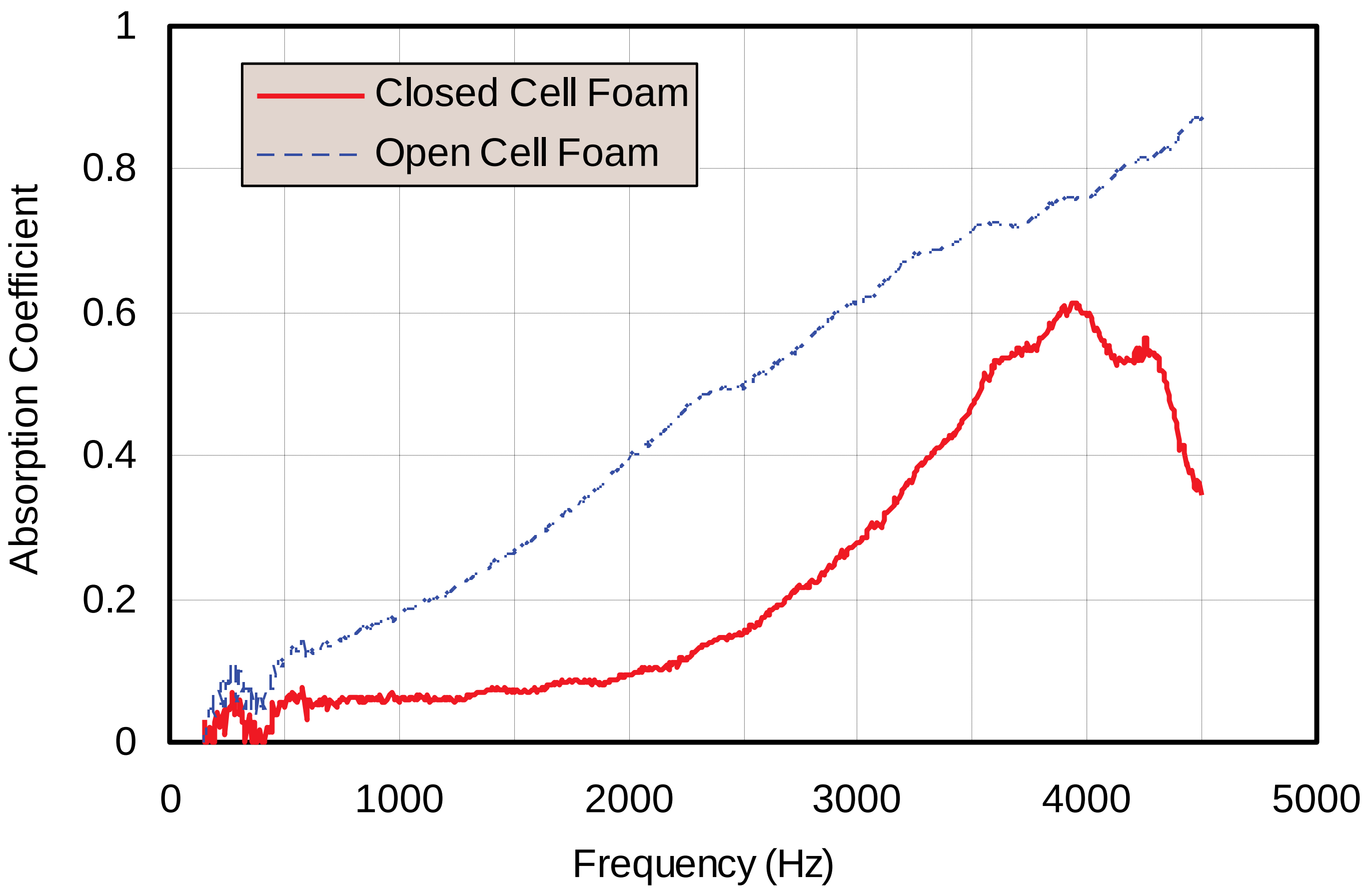
Common Glass Fiber

Sound Absorption by Porous Materials



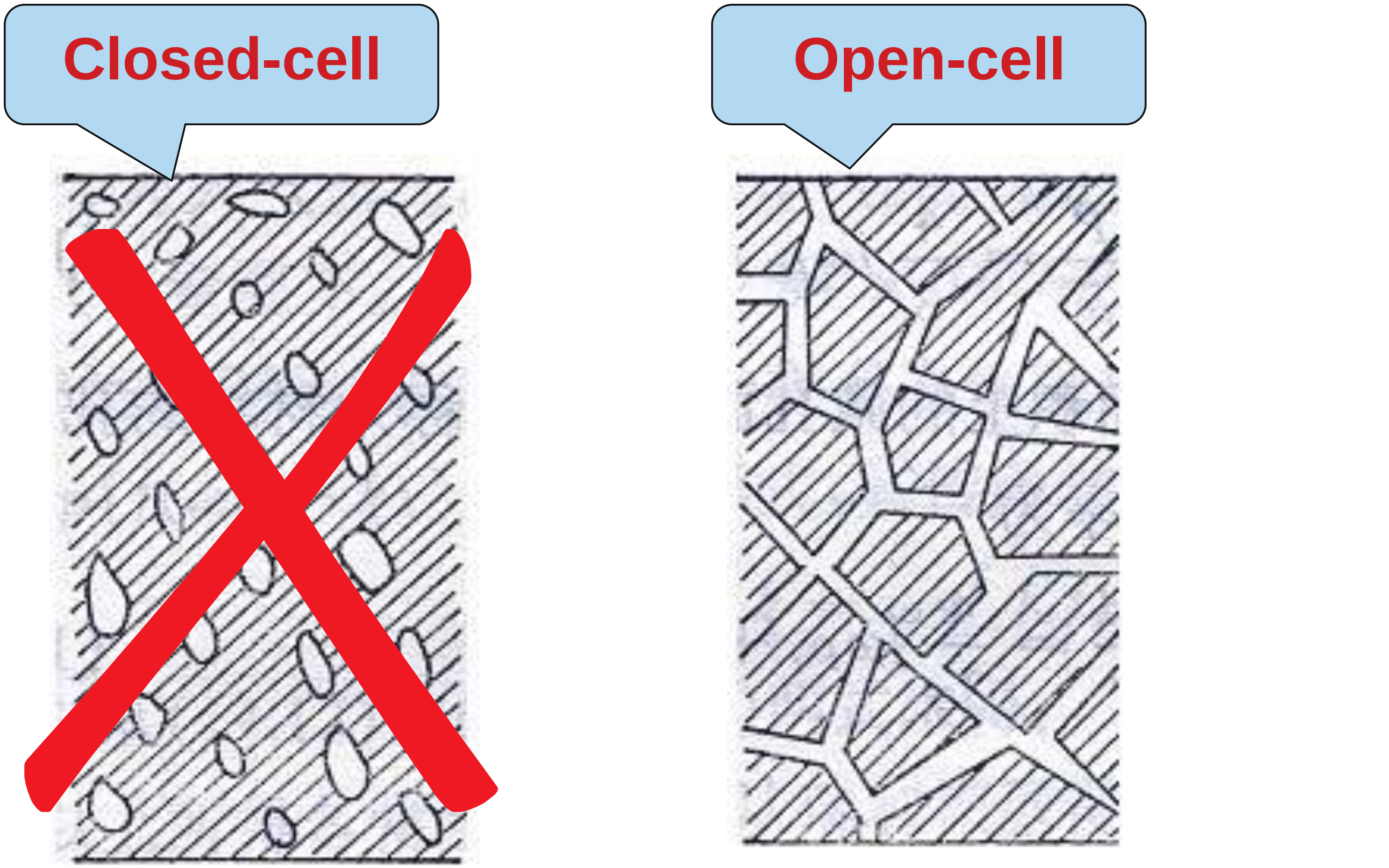
Closed Cell vs. Open Cell Foam

Sound Absorption by Porous Materials



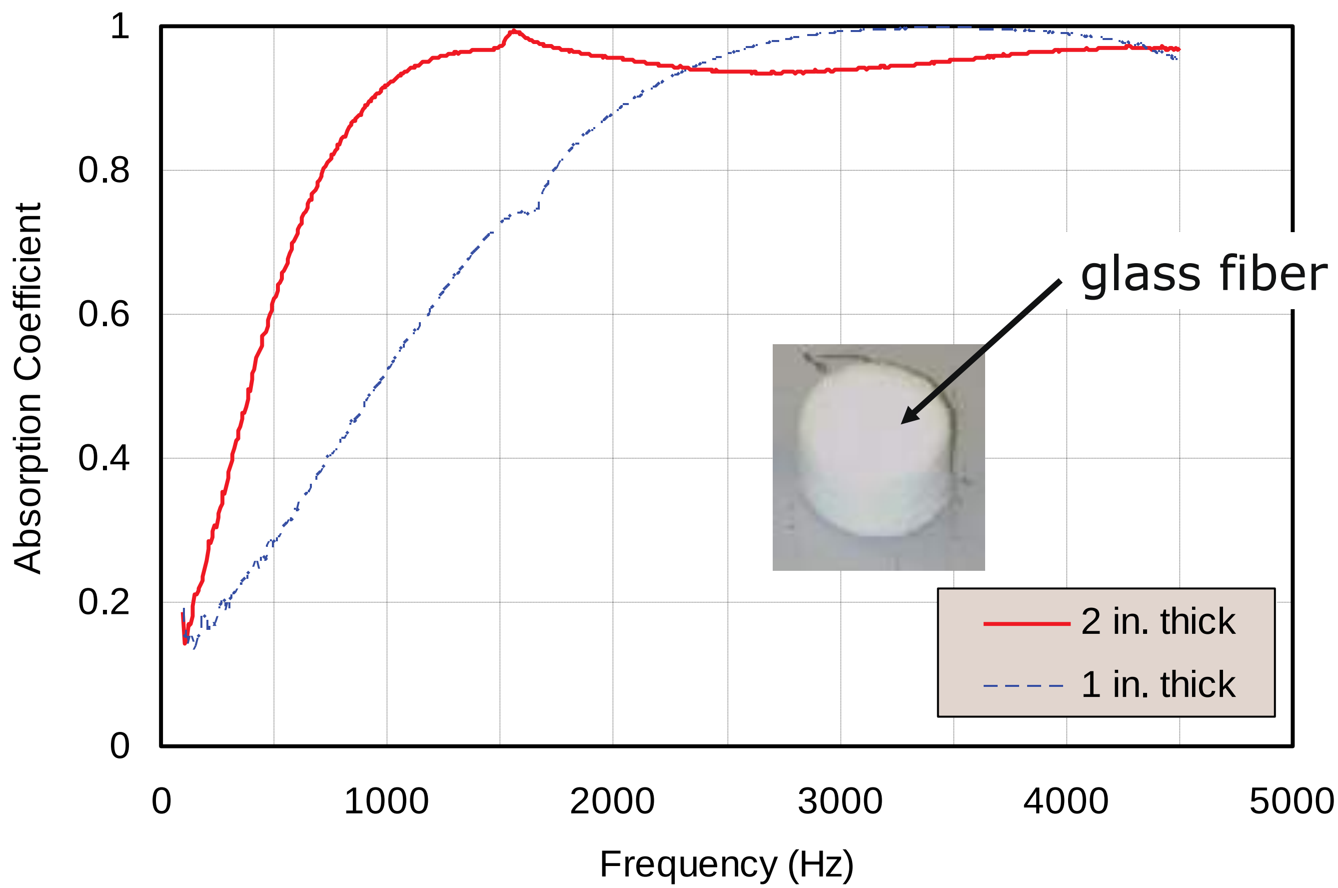
Foam Absorbers must be Open Cell

Sound Absorption by Porous Materials



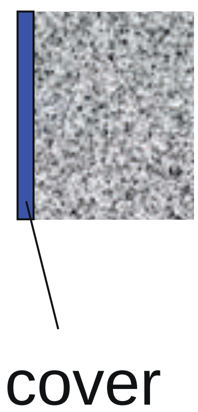
Effect of Thickness

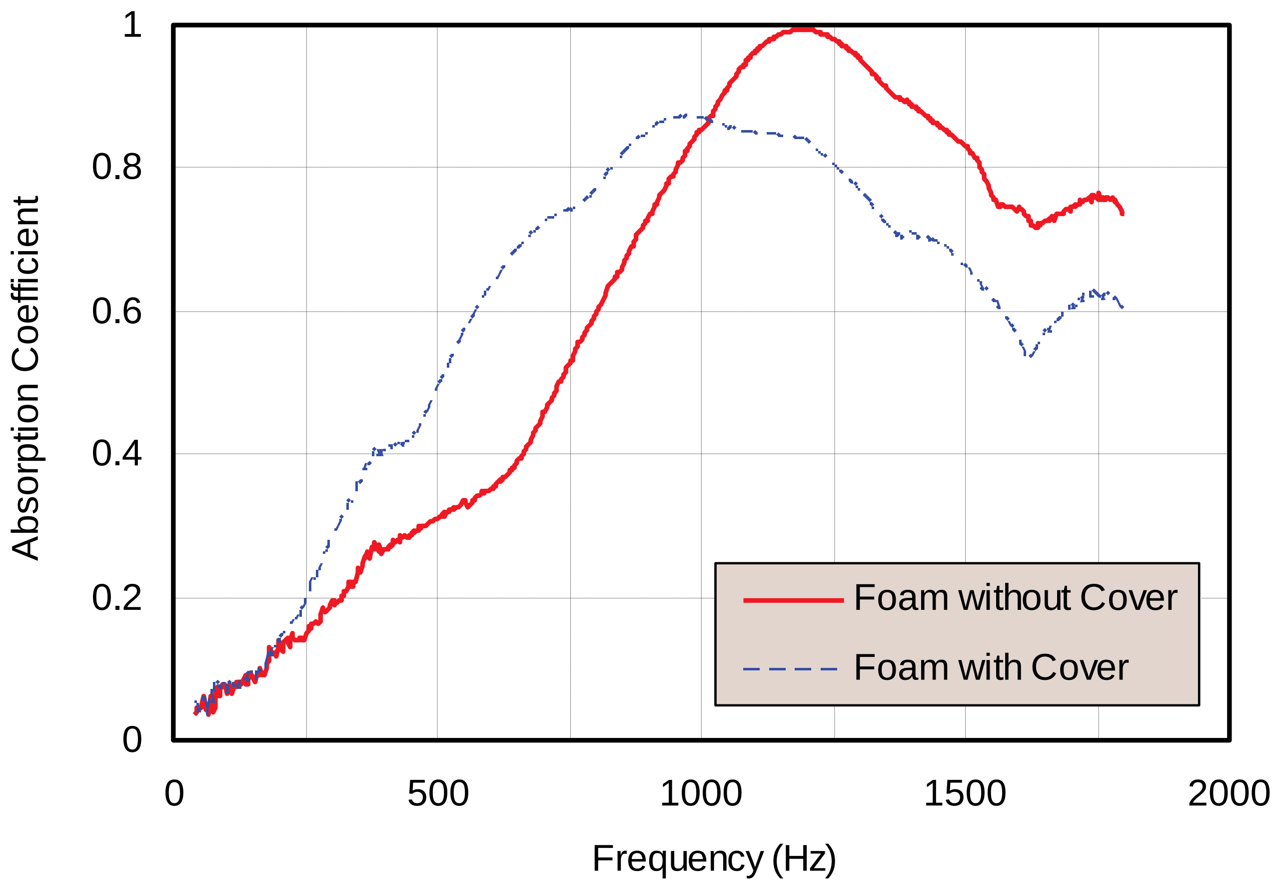
Sound Absorption by Porous Materials



Effect of Covering an Absorber

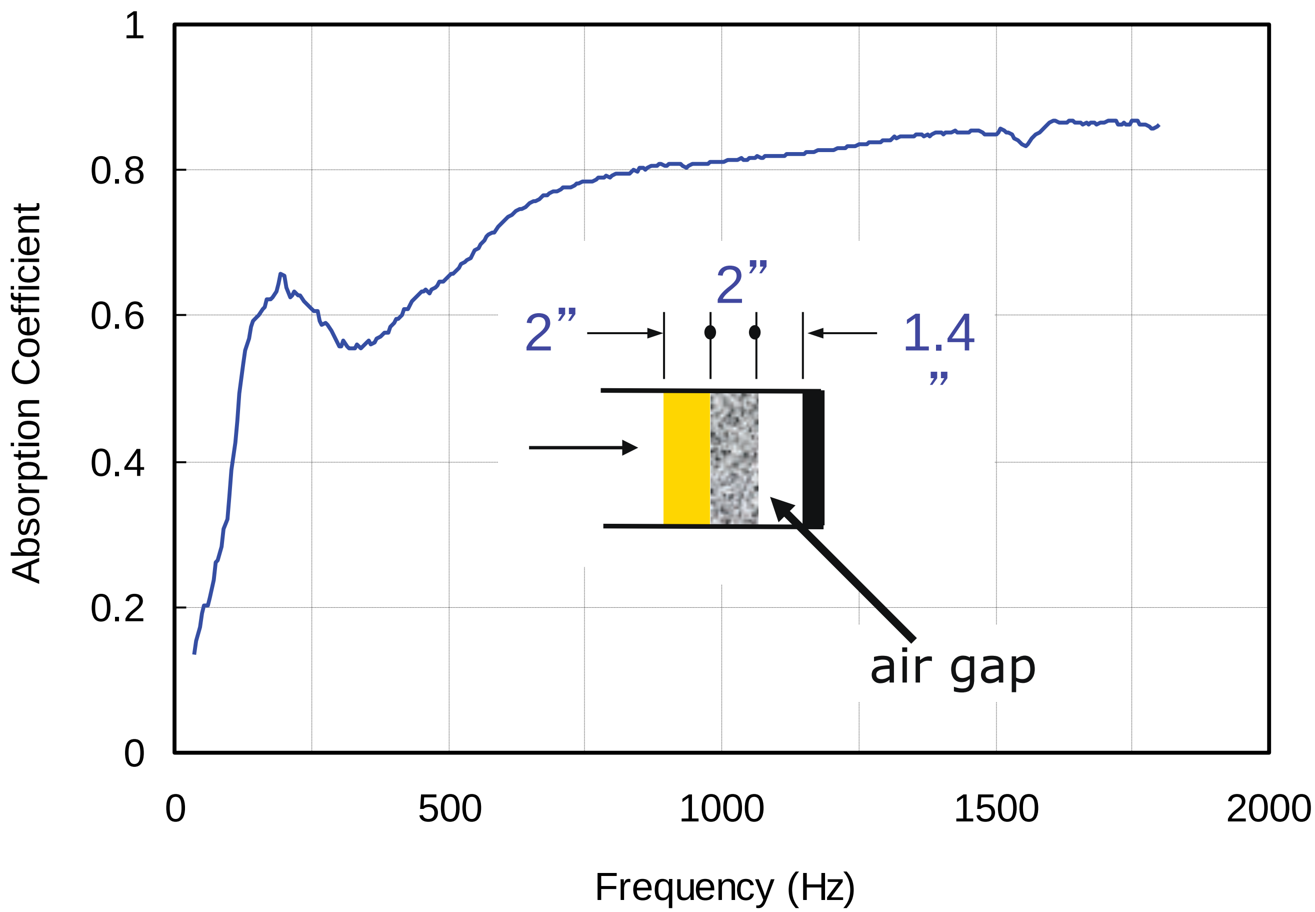
Sound Absorption by Porous Materials





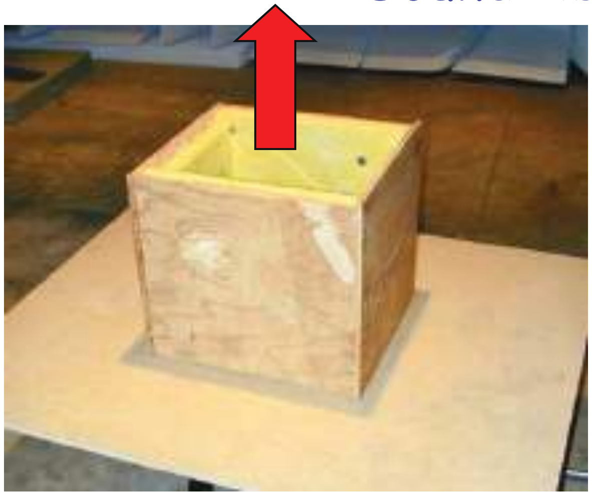
Layering of Materials

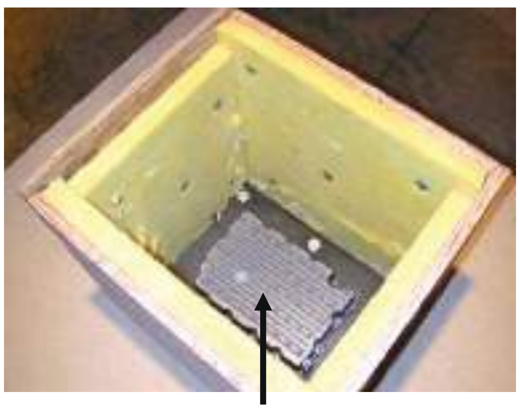
Sound Absorption by Porous Materials



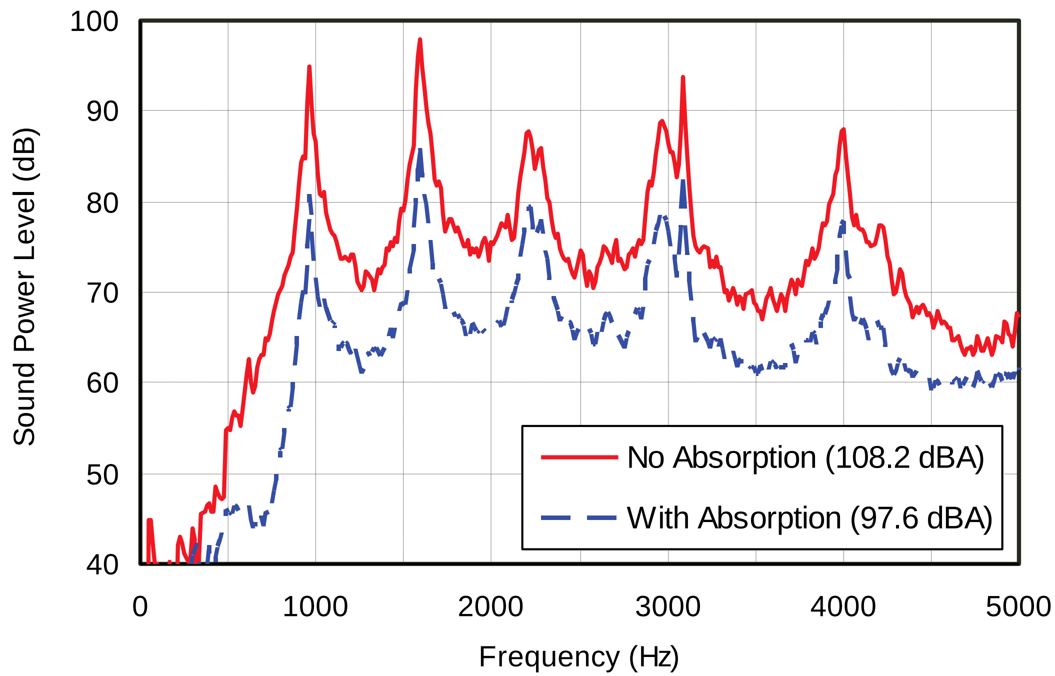
Lining of Partial Enclosures

Sound Absorption by Porous Materials



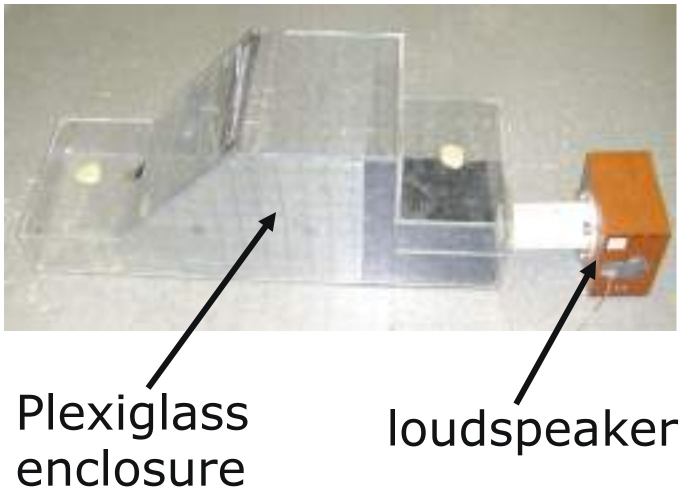


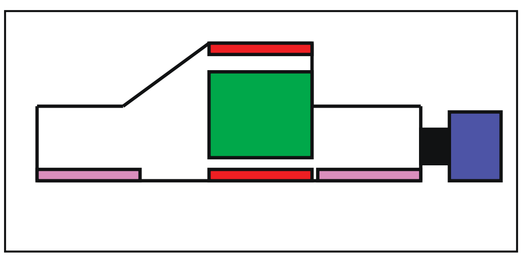
vibrating surface

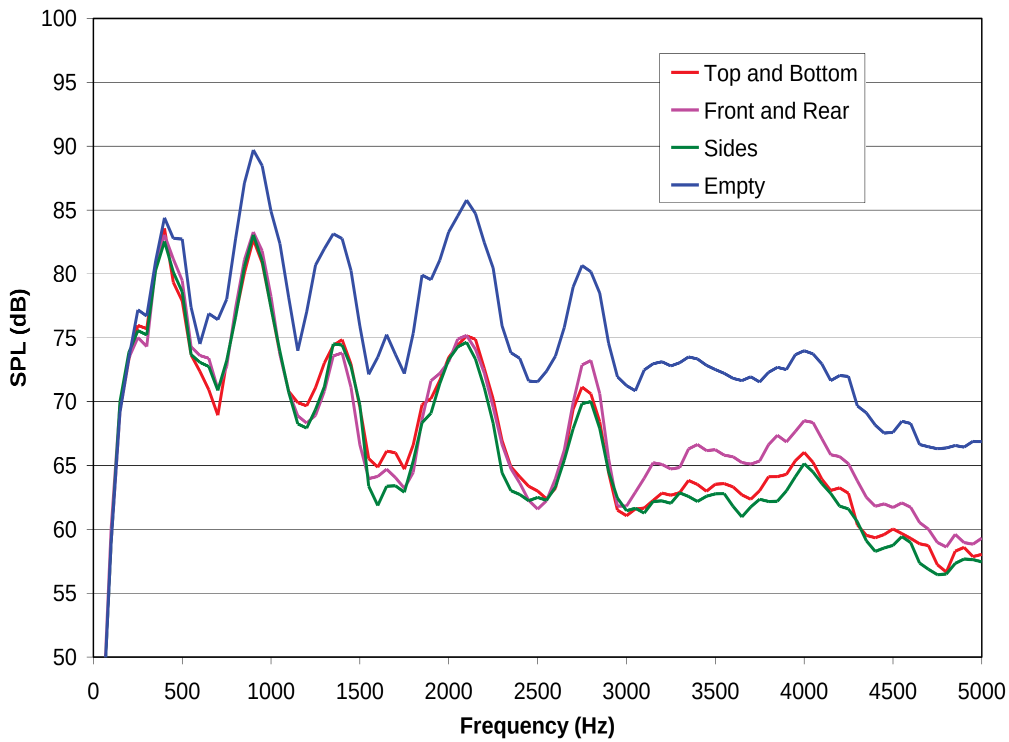


Full Enclosure

Sound Absorption by Porous Materials







Placement of material is often flexible

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Sound Propagation – Porous Material

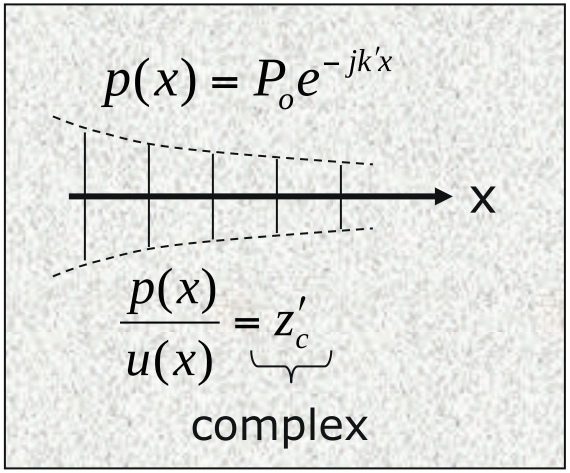
Sound Absorption by Porous Materials

Plane waves in a porous material:

- amplitude decreases with distance
- p and u are not in phase
- characteristic impedance z'_c is a complex number
- wave number k' is a complex number

$$k' = \beta - j\gamma$$

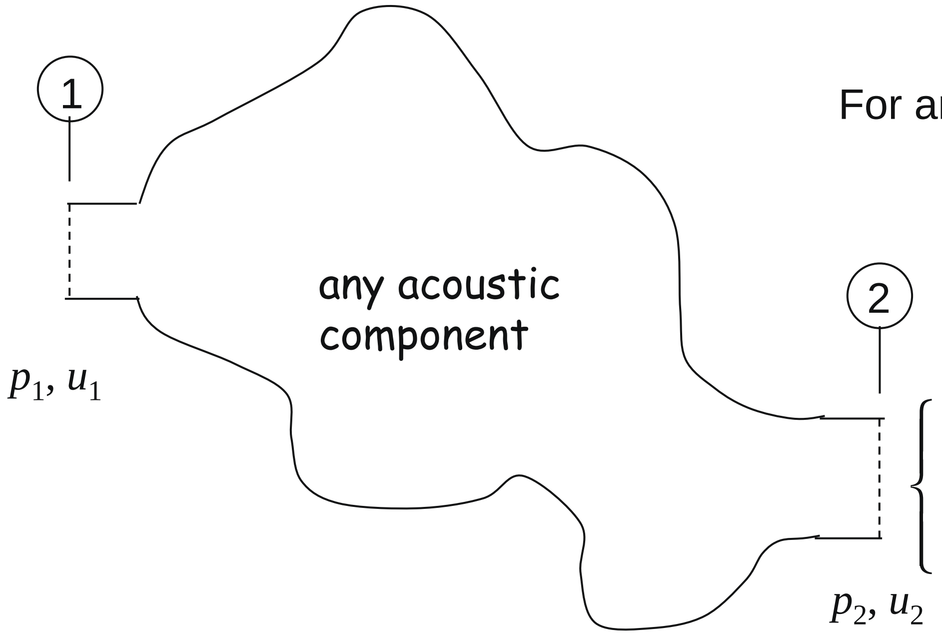
Attenuation constant
(responsible for wave attenuation)



The Basic Idea

Sound Absorption by Porous Materials

The sound pressure p and the particle velocity v are the acoustic state variables



For any passive, linear component:

$$p_1 = Ap_2 + BS_2u_2$$

$$S_1u_1 = Cp_2 + DS_2u_2$$

or

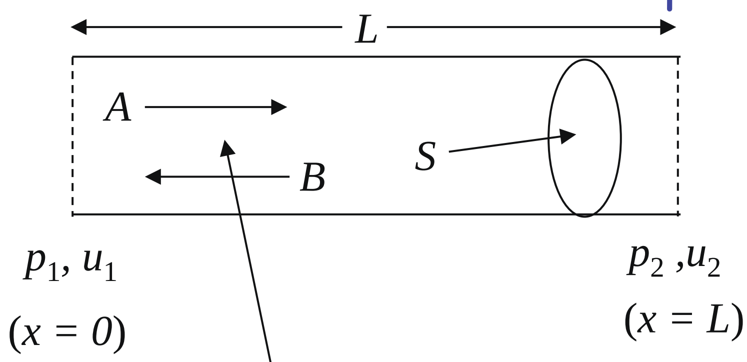
$$\begin{Bmatrix} p_1 \\ S_1u_1 \end{Bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{Bmatrix} p_2 \\ S_2u_2 \end{Bmatrix}$$

Transfer, transmission, or four-pole matrix

(A, B, C, and D depend on the component)

The Straight Tube

Sound Absorption by Porous Materials



must have plane waves

Solve for A, B in terms of p_1, u_1 then put into equations for p_2, u_2.

$$p(x) = Ae^{-jkx} + Be^{+jkx} \qquad u(x) = \frac{-1}{jk\rho_o c}\frac{dp}{dx}$$

$$p(0) = p_1 = A + B$$

$$u(0) = u_1 = \frac{A - B}{\rho_o c}$$

$$p(L) = p_2 = Ae^{-jkL} + Be^{+jkL}$$

$$u(L) = u_2 = \frac{Ae^{-jkL} - Be^{+jkL}}{\rho_o c}$$

$$p_1 = p_2 \cos(kL) + u_2 (j\rho_o c)\sin(kL)$$

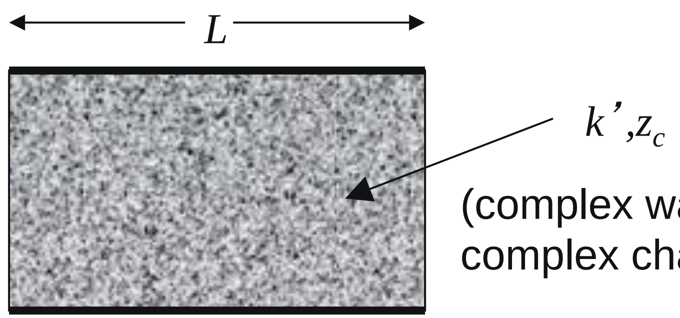
$$u_1 = p_2 (j/\rho_o c)\sin(kL) + u_2 \cos(kL)$$

$$\begin{Bmatrix} p_1 \\ S_1 u_1 \end{Bmatrix} = \begin{bmatrix} \cos(kL) & \frac{j\rho_o c}{S_2}\sin(kL) \\ \frac{jS_1}{\rho_o c}\sin(kL) & \frac{S_1}{S_2}\cos(kL) \end{bmatrix} \begin{Bmatrix} p_2 \\ S_2 u_2 \end{Bmatrix}$$

(note that the determinant $A_1 D_1$-$B_1 C_1 = 1$)

Straight Tube with Absorptive Material

Sound Absorption by Porous Materials

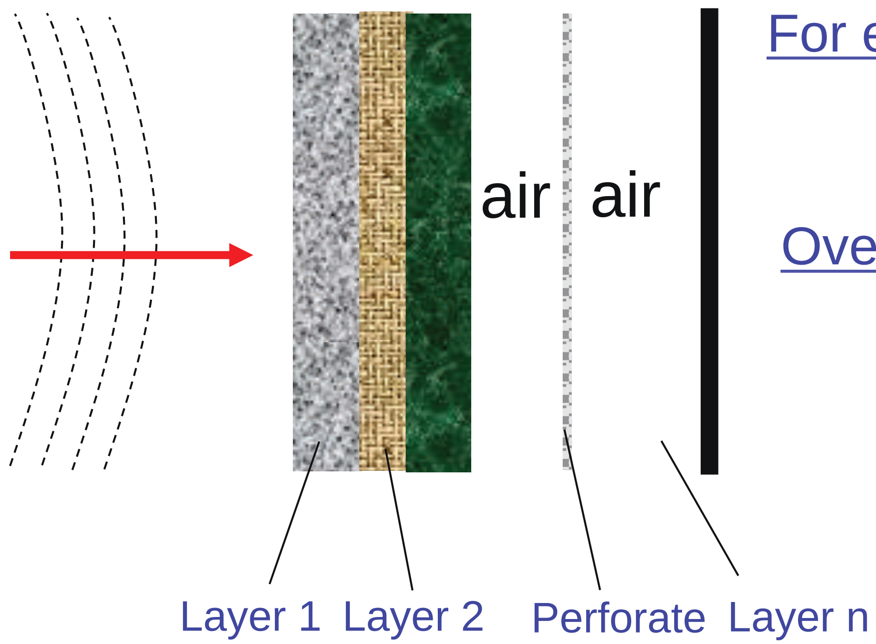


(complex wave number and complex characteristic impedance)

$$\begin{Bmatrix} p_1 \\ S_1 u_1 \end{Bmatrix} = \begin{bmatrix} \cos(k'L) & \dfrac{jz_c}{S_2}\sin(k'L) \\ \dfrac{jS_1}{z_c}\sin(k'L) & \dfrac{S_1}{S_2}\cos(k'L) \end{bmatrix} \begin{Bmatrix} p_2 \\ S_2 u_2 \end{Bmatrix}$$

Transfer Matrix Approach

Sound Absorption by Porous Materials



For each layer:

$$\begin{bmatrix} p_i \\ Su_i \end{bmatrix} = \begin{bmatrix} A_i & B_i \\ C_i & D_i \end{bmatrix} \begin{bmatrix} p_{i+1} \\ Su_{i+1} \end{bmatrix}$$

Overall:

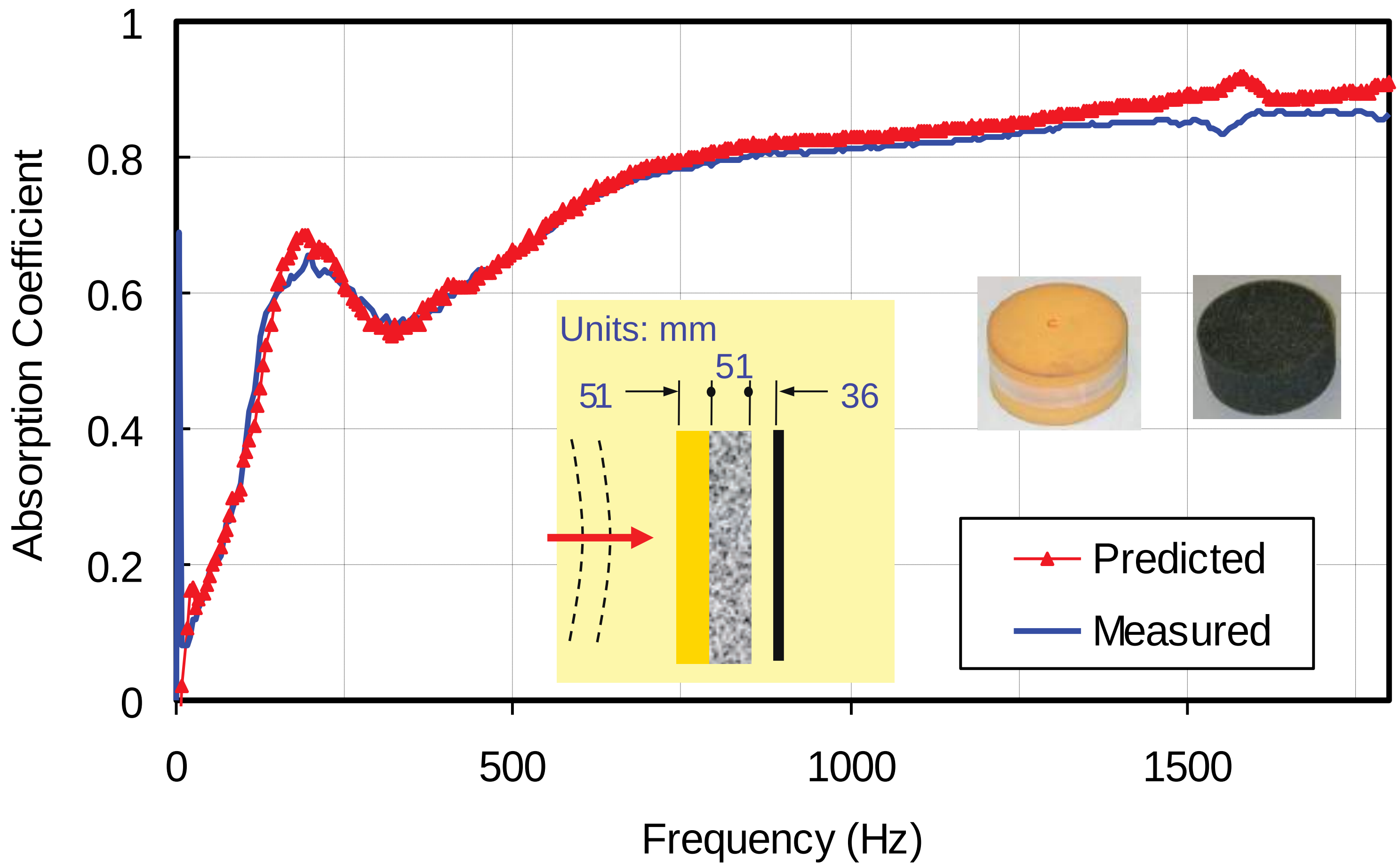
$$[T_{total}] = [T_1][T_2][T_3]..[T_n] = \begin{bmatrix} A_T & B_T \\ C_T & D_T \end{bmatrix}$$

$$\tilde{Z} = \frac{p_1}{u_1} = \frac{SA_T}{C_T}$$

Plane Wave Assumption

Example - Layered Materials

Sound Absorption by Porous Materials



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Designing the Absorber from Scratch

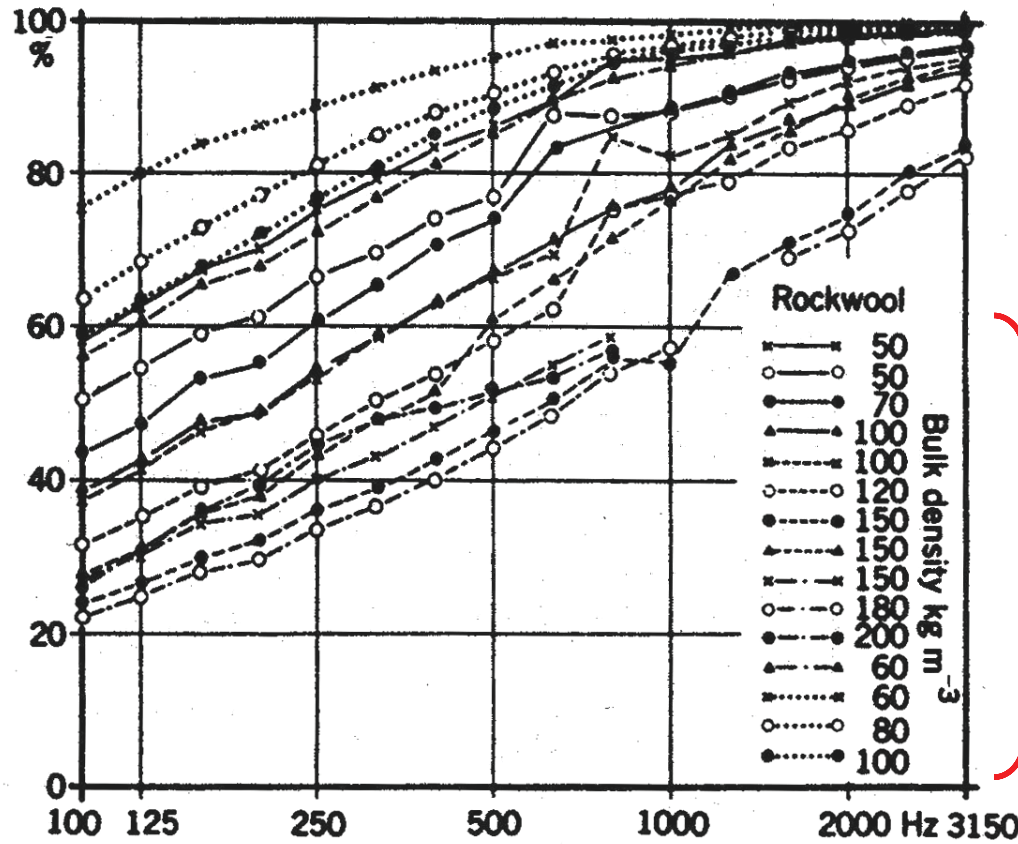
Sound Absorption by Porous Materials

Bulk k' and z'_c → **Surface** z and α → **Layered** z and α

↑ ????

Absorption Coefficient vs. Frequency

Sound Absorption by Porous Materials



α_o

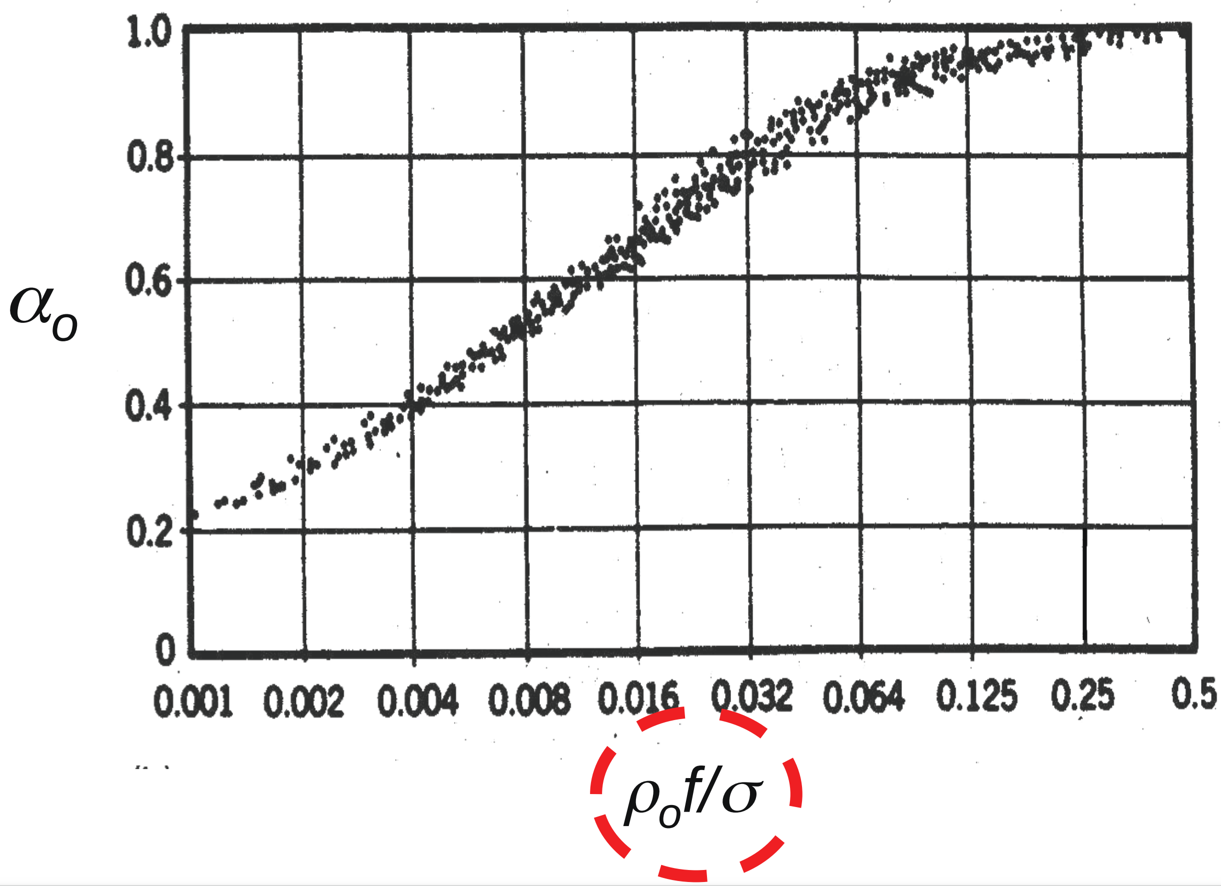
Frequency (Hz)

Different densities and thicknesses

(Mechel, 1988)

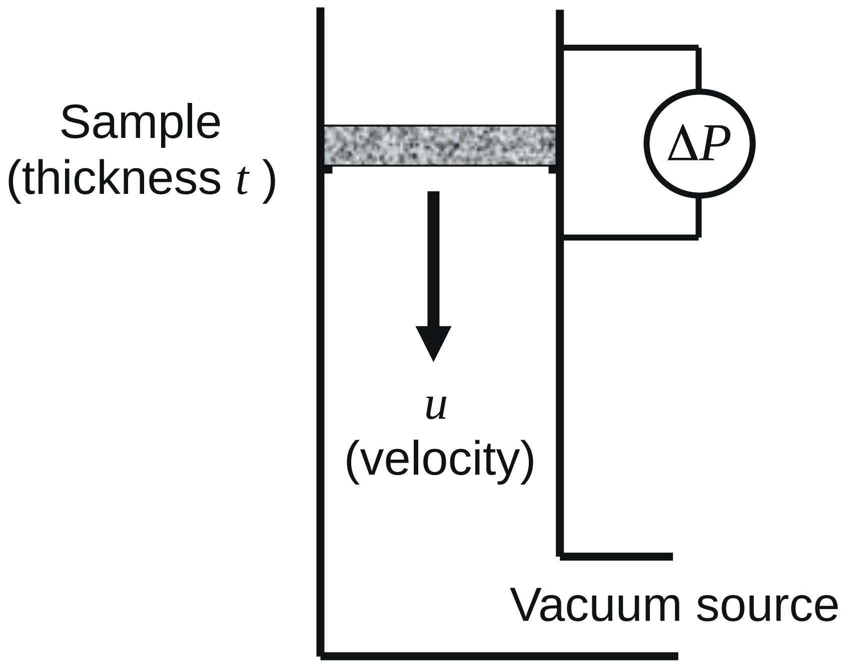
Flow Resistivity and Absorption

Sound Absorption by Porous Materials



Flow Resistance and Flow Resistivity σ

Sound Absorption by Porous Materials



Flow resistance:

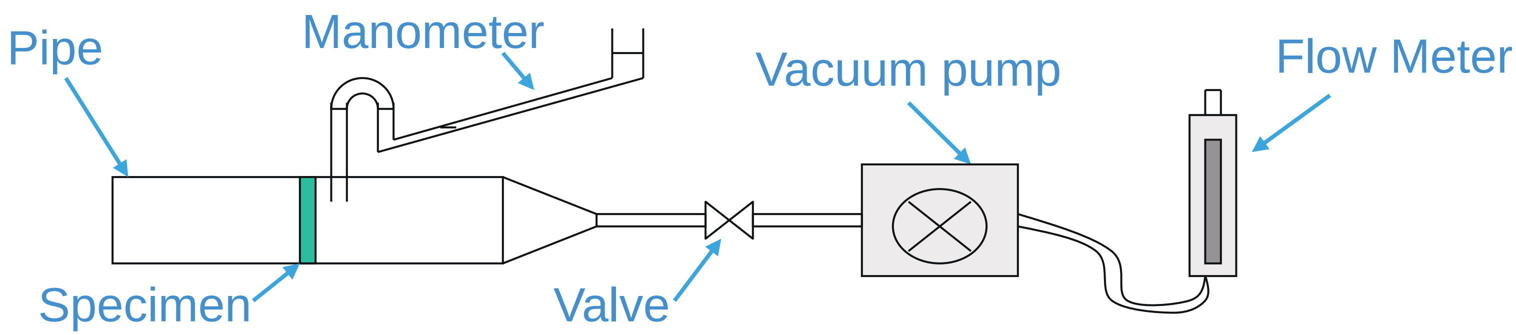
$$r_s = \frac{\Delta P}{u}$$

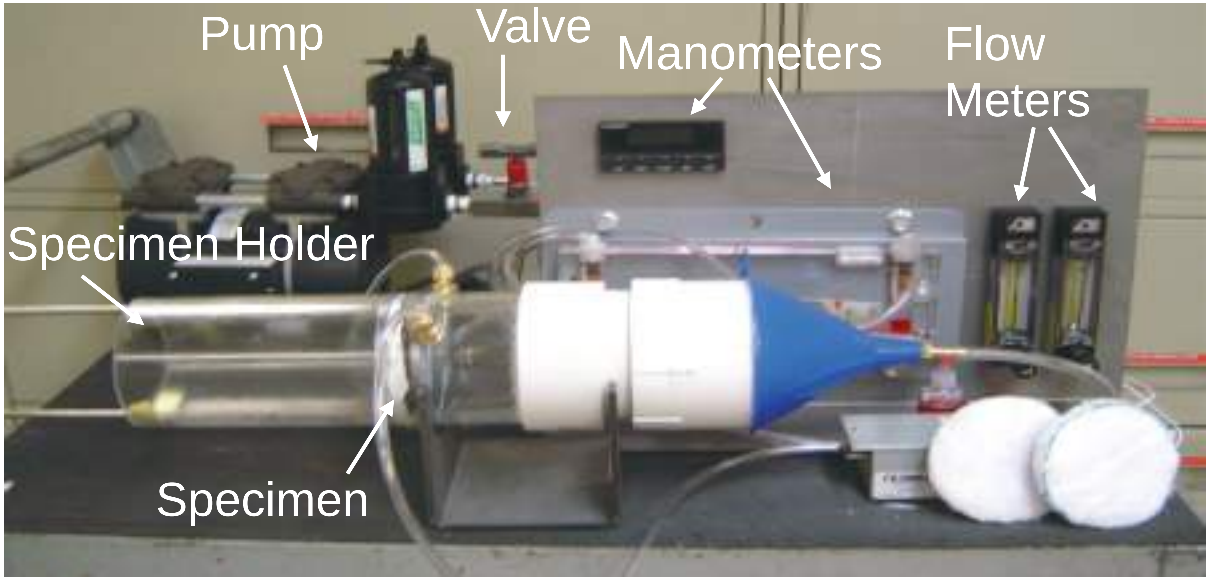
Flow resistivity:

$$\sigma = \frac{r_s}{t}$$

Flow Resistance Measurement

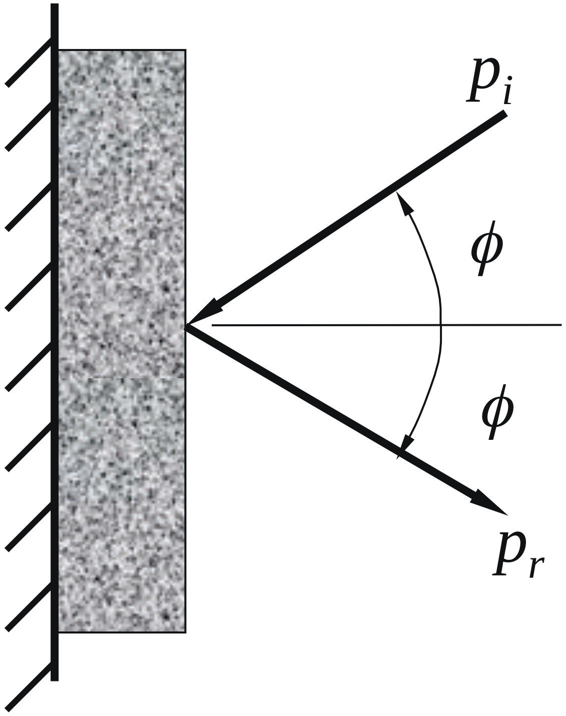
Sound Absorption by Porous Materials





Absorption Coefficient

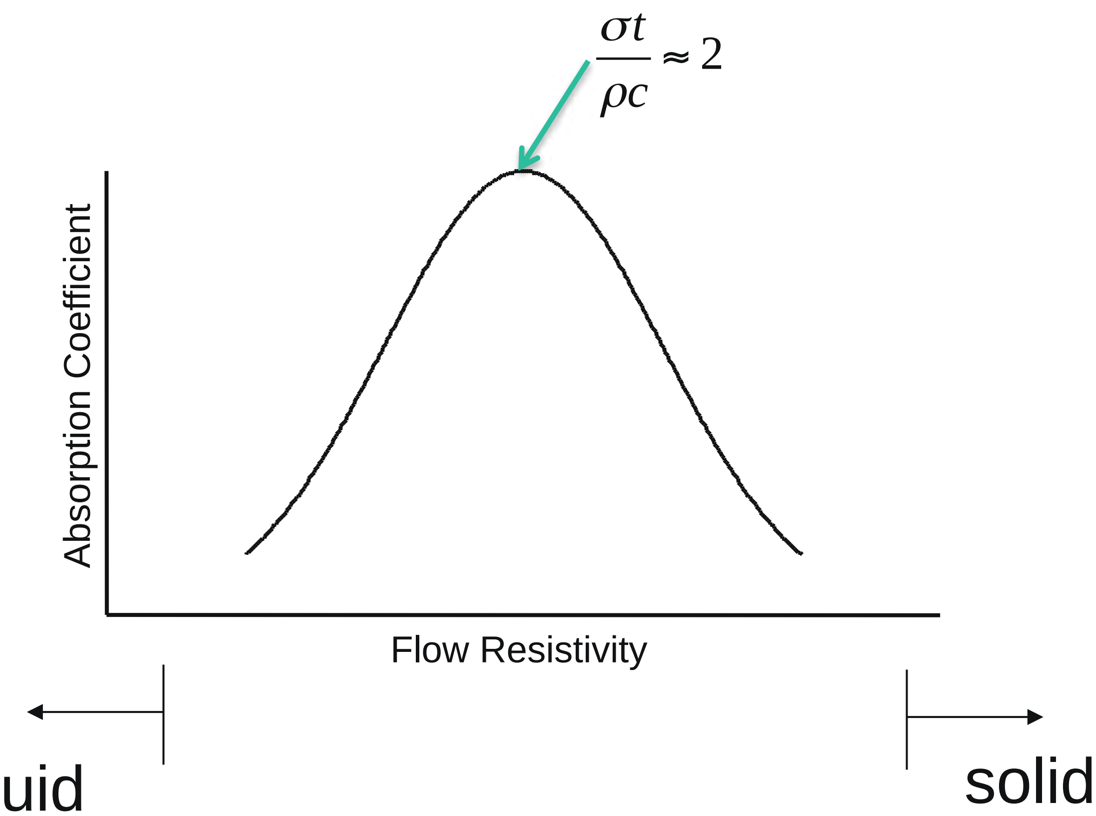
Sound Absorption by Porous Materials



$$\alpha(\phi) = \frac{\text{sound energy absorbed}}{\text{sound energy incident}}$$

Absorption Coefficient and Flow Resistivity

Sound Absorption by Porous Materials



Three Empirical Models

Sound Absorption by Porous Materials

$$X = \rho_o f / \sigma$$

$$k'/k = (1 + 0.188X^{-0.554}) - j0.163X^{-0.592}$$

$$z_c'/z_o = (1 + 0.209X^{-0.548}) - j0.105X^{-0.607}$$

Wu, 1988 – 17 plastic foam materials;

f = 200-2000 Hz; 2900 ≤ σ ≤ 24300 rayls; 0.01 < X < 0.83

$$k'/k = (1 + 0.0978X^{-0.700}) - j0.189X^{-0.595}$$

$$z_c'/z_o = (1 + 0.0571X^{-0.754}) - j0.087X^{-0.732}$$

Delaney and Bazly, 1970 – fibrous materials; f = 250-4000 Hz; σ = ?; 0.012 < X < 1.21

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for $X < 0.025$:

$$k'/k = (1 + 0.136X^{-0.641}) - j0.322X^{-0.502}$$

$$z_c'/z_o = (1 + 0.081X^{-0.699}) - j0.191X^{-0.556}$$

for $X > 0.025$:

$$k'/k = (1 + 0.103X^{-0.716}) - j0.179X^{-0.663}$$

$$z_c'/z_o = (1 + 0.0563X^{-0.725}) - j0.127X^{-0.655}$$

Mechel (after Fahy) – fibrous materials; f = ?; σ = ?; 0.002 < X < 0.5