Sound absorbing materials

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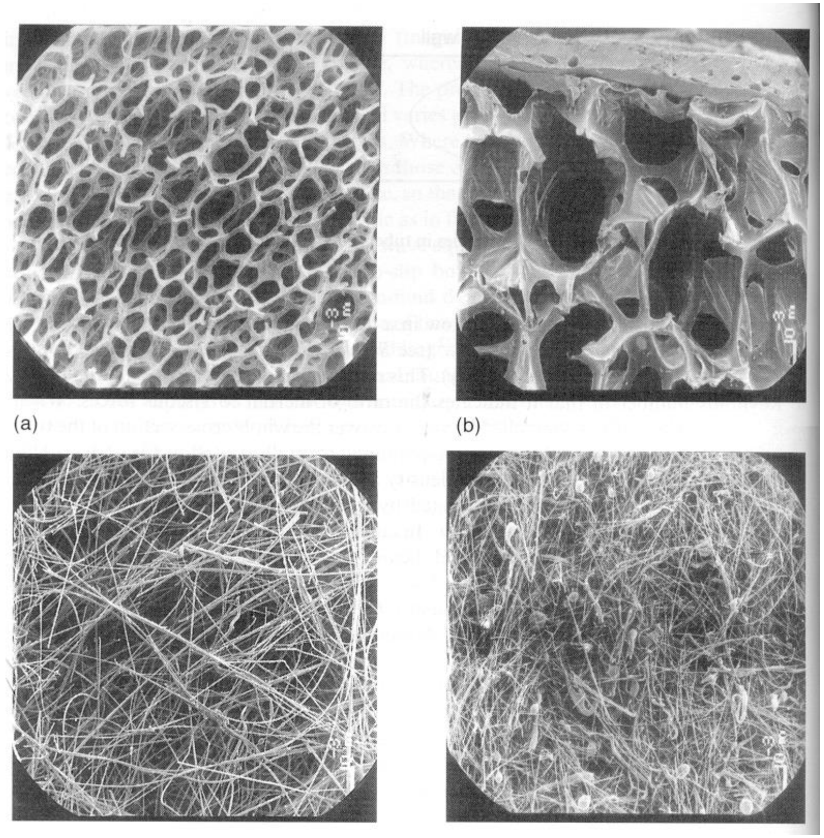
INTRODUCTION

Examples of sound absorbing materials are shown below



(*a*) Fully reticulated plastic foam (x14), (*b*) Partially reticulated plastic foam (x14), (*c*) Glass fibre (bonded mat) (x14), (*d*) Mineral wool (x14)

SOUND ABSORBING MATERIALS AND THEIR USE

Sound absorbing materials are used in almost areas of noise control engineering to reduce sound pressure levels. To use them effectively, it is necessary to:

- Identify the important physical attributes and parameters that cause a material to absorb sound.
- Provide a description of the acoustical performance of sound absorbers used to perform specific noise control functions
- Develop experimental techniques to measure the acoustical parameters necessary to measure the acoustical parameters of sound absorbing materials and the acoustical performance of sound absorbers.
- Introduction of sound absorbing materials in noise control enclosures, covers and wrappings to reduce reverberant build up and hence increase insertion loss
- Introduction of sound absorbing materials onto surfaces of rooms to control reflected sound.

SOUND ABSORPTION

- **Absorptive materials** are used to control airborne sound by reducing reflections (foams, mineral wool).
- These are applied in the passenger compartment and increasingly in the engine bay (under the bonnet, on firewall, on under-trays).
- For an absorptive boundary, the **absorption coefficient** is defined as the ratio of absorbed intensity to incident intensity.

  Note: $0 \leq \alpha \leq 1$.

POROUS ABSORPTIVE MATERIALS

Porous absorbing materials are usually more than 90% air. The small pores lead to dissipation of the sound propagating through them.

- At high frequencies a porous material has an acoustic impedance similar to that of air. Most incident energy enters the porous material and is absorbed there.
- At low frequencies, a layer of porous material behaves acoustically like a stiffness. This leads to large reflection and little absorption.

The most important parameters of a porous material are:

- flow resistivity (r) - the (steady) pressure gradient induced by a unit mean flow velocity.
- layer thickness. Good absorption requires $\lambda < 6l$.

MECHANISM OF SOUND ABSORPTION IN FIBROUS MATERIALS

Thermal Losses

The oscillating pressure acting at the material causes the air molecules to oscillate in the pores at the frequency of the excitation. This results in sound energy being dissipated as heat due to friction losses. This mechanism is important at high frequencies.

Momentum Losses

Changes in flow direction as well as expansions and contractions of the flow through the irregular pores gives rise to a loss of momentum in the direction of wave propagation. This mechanism is important at high frequencies.

MECHANISM OF SOUND ABSORPTION IN FIBROUS MATERIALS

Heat Conduction

The periodic compression and rarefaction of the fluid is also accompanied by changes in temperature. At low frequencies, and therefore time periods of oscillation, there is sufficient time for heat to be exchanged and a flow of heat energy occurs. This mechanism is enhanced by the large surface-to-volume ratio in the pores and the relatively high heat conductivity of the fibres. At low frequencies the adiabatic assumption breaks down.

Mechanical Losses to the 'skeleton'

Forced mechanical oscillations of the elastic skeleton 'structure' is also a source of energy dissipation. This mechanism is believed to be of only a minor importance.

IMPORTANT DESCRIPTORS OF FIBROUS MATERIALS

Porosity: Ratio of pore volume (air) to total volume. Typical porosity between 0.9 and 0.95 for effective materials.

Fiber Diameter: Usually mean and variance specified. Diameter values usually follow a Poisson distribution.

Structure factor: dimensionless parameter which takes into account the effect of pores and cavities that are perpendicular to the direction of sound propagation.

Flow resistively: The most important physical characteristic of a porous material. It is defined as the ratio of pressure gradient across the material to flow velocity in the material.

Definition: $\partial p / \partial x = -ru$, where *u* is the volume flow rate per unit cross-sectional area.

BULK AND LOCALLY REACTING LINERS

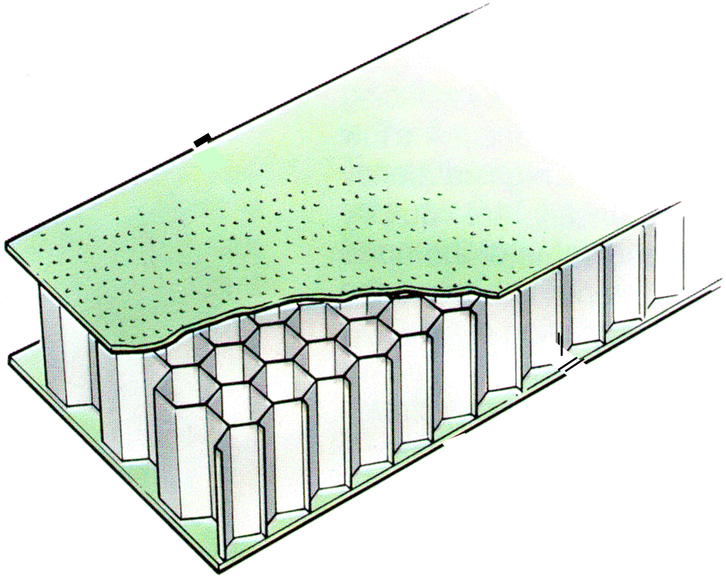
The sound absorbing effectiveness of sound absorbing material for plane wave angle of incidence at angles other than normal incidence is different for locally reacting and bulk-reacting (or extended reacting liners).

Locally reacting liners: Particle velocity confined to the direction *normal* to the surface. Examples are partitioned porous layers, small plate absorbers, honeycomb absorbers.

Bulk-reacting liners: No restriction on the direction of wave propagation in the sample. Examples include homogeneous fibrous absorbers and thick plates. The normal component of particle velocity at any point on the interface is influence, not only by the local sound pressure, but also by waves arriving from all other on the medium.

LOCALLY REACTING LINERS

Wall impedance z_i is independent of the angle of incidence θ. Reflection coefficient is determined by how much the wall impedance matches the impedance of the incident wave, i.e., $p/(u\cos\theta) = Z_0 / \cos\theta$



PROPAGATION CONSTANTS IN POROUS MATERIALS

A solution to the harmonic (single-frequency) one-dimensional wave equation is

$$p(x,t) = p_0 e^{-i\gamma x} e^{i\omega t}$$

where γ is the complex propagation constant (wavenumber)

$$\gamma = \alpha + j\beta$$

rate of change of phase with distance

rate of attenuation. It is principally controlled by viscous losses, i.e., due to the flow resistivity *r*

FUNDAMENTAL PARAMETERS

It may be shown that in a porous material of porosity *h*, flow resistance *r* and restructure factor *s*

$$\gamma = j\omega\sqrt{\rho' / \kappa}$$

where

$$\rho' = s\rho / h + r / j\omega$$ Effective mass

$$\kappa = \rho c^2 / h$$ Effective stiffness (Bulk modulus)

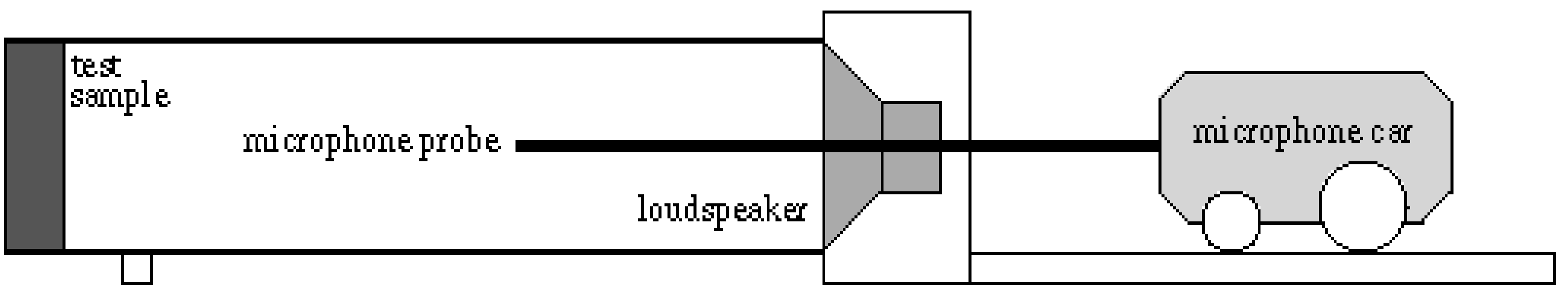
The characteristic specific acoustic impedance of the medium is given by the complex quantity

$$z_c = p/u = \sqrt{\kappa\rho'}$$

MEASURING SOUND ABSORPTION

(a) Normal incidence: ‘Impedance tube’

- Finite tube terminated with a sample of absorbent (particular thickness).
- Measure pressure at different locations along the tube.
- From amplitude and phase of incident and reflected waves deduce normal specific impedance for this thickness.
- Repeat for other thicknesses to get material acoustic impedance.



MEASURING SOUND ABSORPTION

(b) Diffuse incidence: reverberation room

- Measure reverberation time T_1 without the absorptive material.
- Introduce 10 m^2 sample of absorbent material and measure modified reverberation time 1. Absorption A of sample can be deduced.
- NB it is possible to obtain $\alpha_d > 1$.

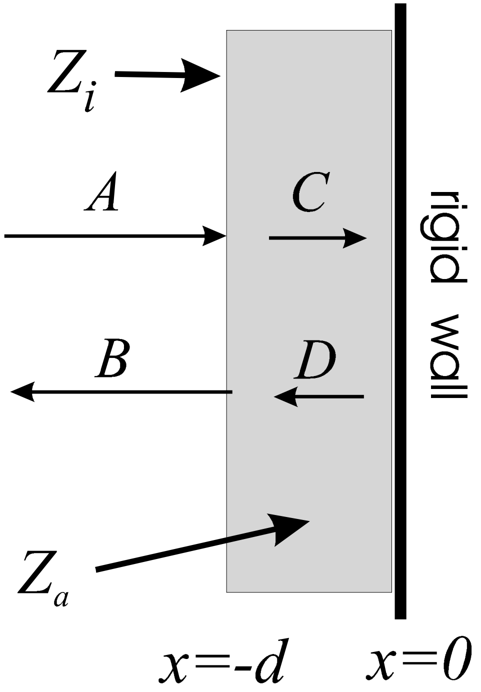
$$A = 0.161V\left(\frac{1}{T_2} - \frac{1}{T_1}\right)$$

POROUS SOUND ABSORBERS OF INITE

THICKNESS IN FRONT OF A RIGID WALL

In many cases the fibrous sound absorbing sample is of finite thickness *d* and mounted directly onto a rigid wall. The impedance seen by an incoming plane wave is now clearly different from its value if it were of infinite thickness.

$$p(x) = C\mathrm{e}^{-j\gamma x} + D\mathrm{e}^{j\gamma x}$$



The particle velocity *u* is

$$u(x) = \frac{1}{Z_a}\left[C\mathrm{e}^{-j\gamma x} - D\mathrm{e}^{j\gamma x}\right]$$

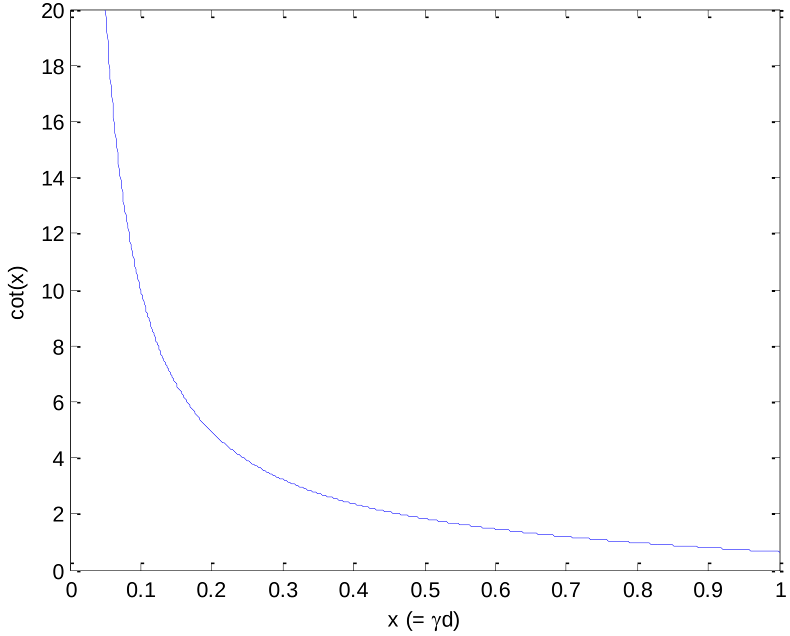
The particle velocity at $x = 0$ is zero so that $C = D$. The impedance at the face of the sample now becomes

$$z_i = z_a \frac{\mathrm{e}^{j\gamma d} + \mathrm{e}^{-j\gamma d}}{\mathrm{e}^{j\gamma d} - \mathrm{e}^{-j\gamma d}} = z_a \cot \gamma d$$

IMPLICATIONS FOR SOUND ABSORBERS

A plot of cot(x) is presented below

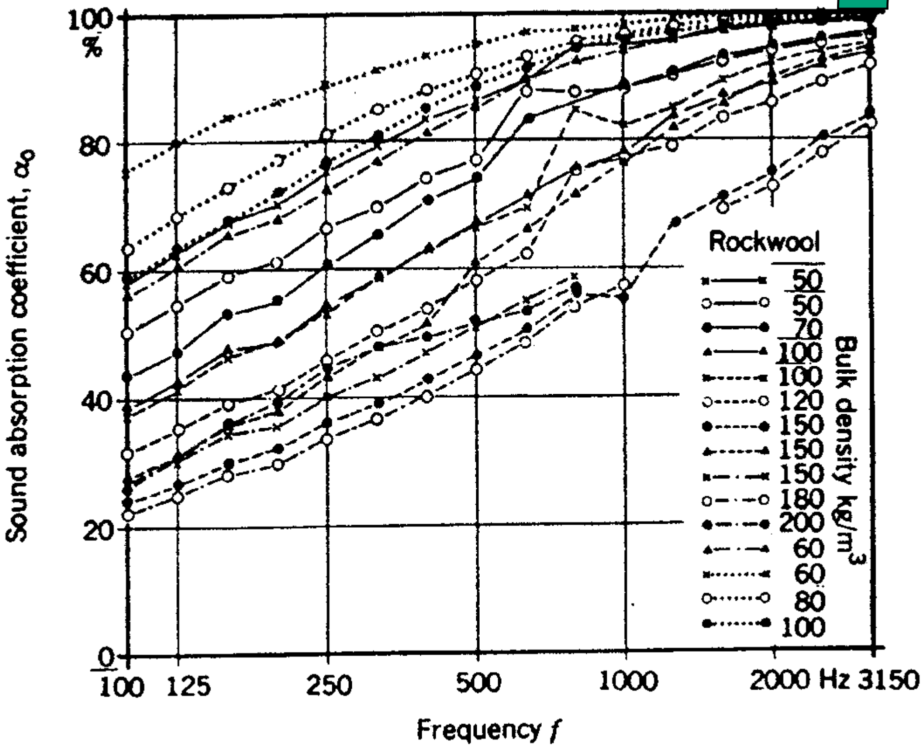
For thin absorbers at low frequencies such that $d > \lambda/4$ ($x < \pi/2$), the magnitude of z_i is large. Consequently the impedance mismatch between z_i and that of the fluid medium is also large which leads to a small sound absorption coefficient. This is reason why has one has absorbed sound absorbing paint!

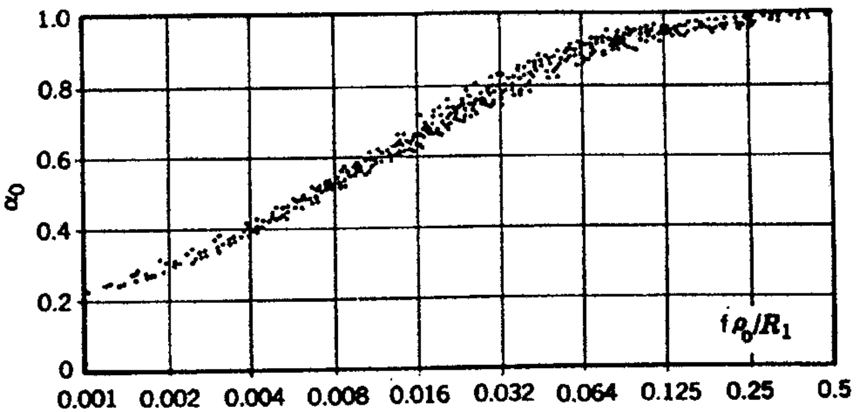


For large sample thickness at high frequencies such that $d < \lambda/4$ ($x < \pi/2$), and cos $\gamma d \mapsto 1$ and $z_i \mapsto z_a$ and the samples is the as that as if it of infinite thickness.

MEASURED NORMAL INCIDENCE ABSORPTION COEFFICIENT OF DIFFERENT ROCKWOOL SAMPLE THICKNESSES

(After F. P. Mechel, JASA 83(3), 1988)





Measured normal sound absorption coefficient a_0 for different rockwools of practically infinite thickness (between 0.5m and 1m thick) as a function of frequency for different bulk densities.

The empirical method for determining sound absorption characteristics from material properties, although provides limited physical insight into the physical absorption mechanisms, is presently the most accurate. Absorption data for a wide variety of rockwool densities collapses on the non-dimensional parameter $E= rf/R$,

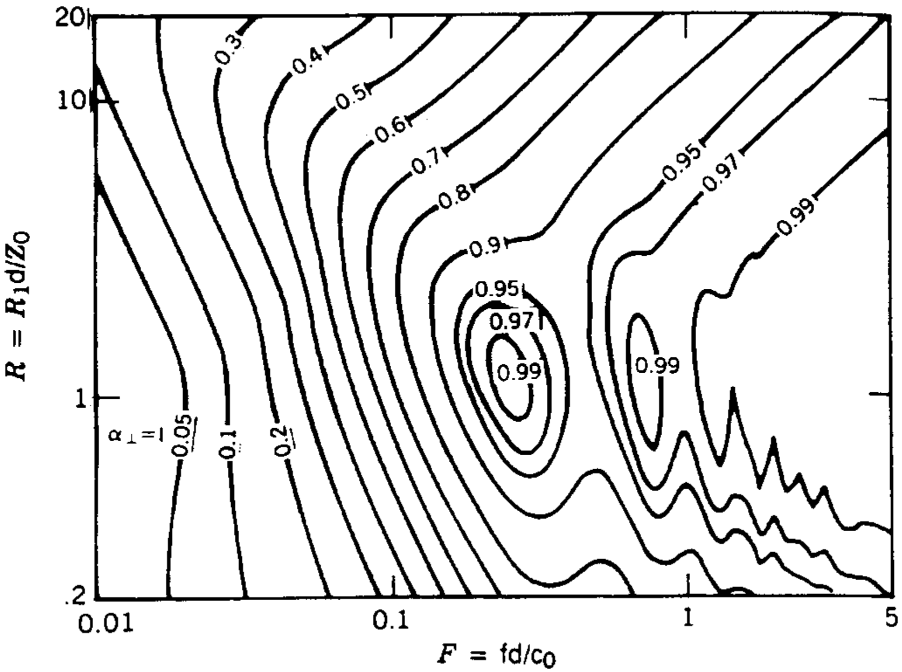
DESIGN CHARTS FOR THE PREDICTION OF SOUND ABSORPTION FROM SINGLE-LAYER FIBROUS ABSORBERS

(After F. P. Mechel, JASA 83(3), 1988)

For practical design is it is useful to be able to predict sound absorption from easily measurable properties of the absorber such as thickness *d*, flow resisitivity R_1, and frequency *f*.

It has been found by experiment that the absorption coefficient can be predicted accurately from the two dimensionless variables

$$F = \frac{fd}{c} \qquad R = \frac{R_1 d}{Z_0}$$

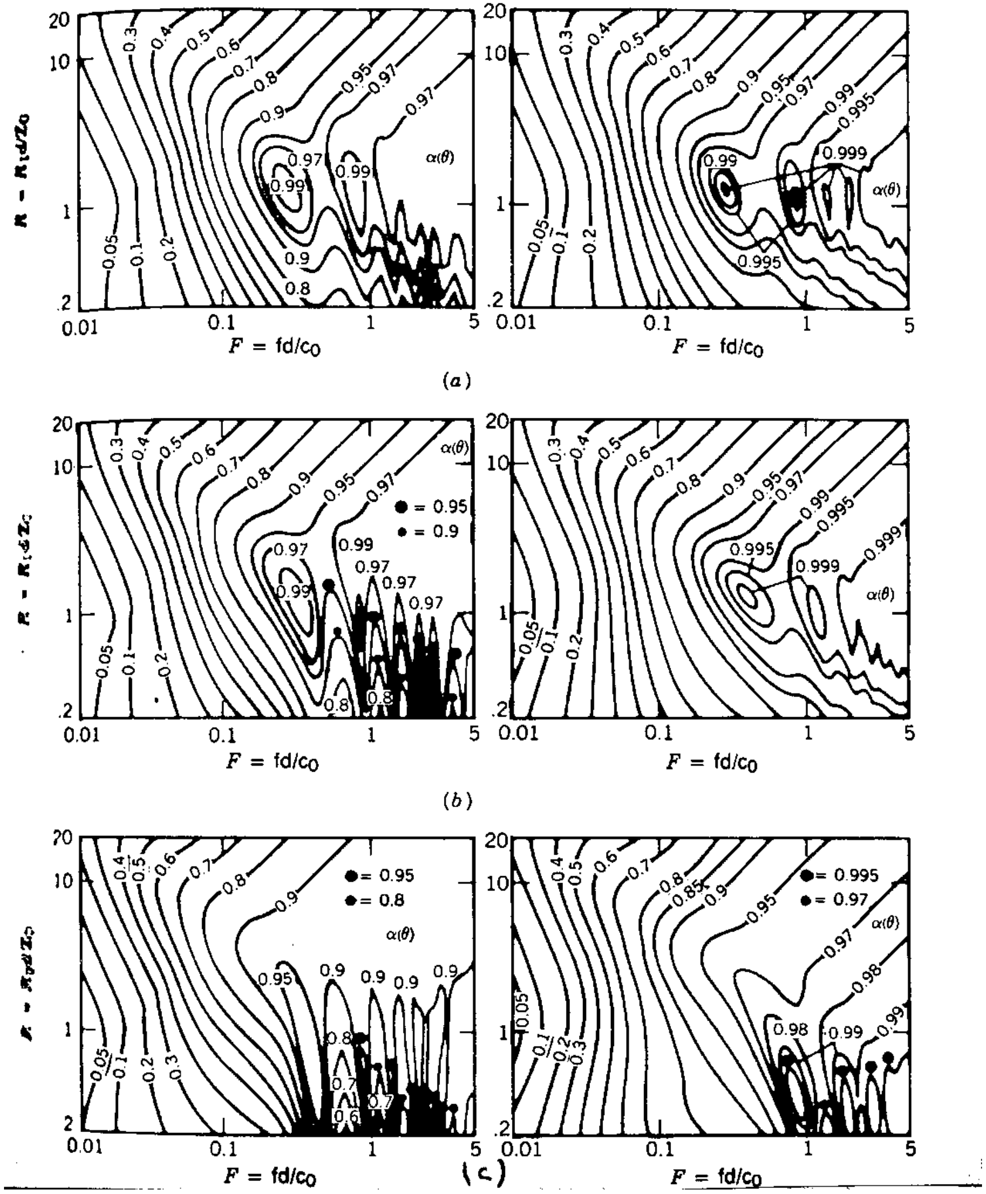


Contours of normal incidence sound absorption for fibrous absorbers. No air gap

DETERMINATION OF ABSORBER THICKNESS

(After F. P. Mechel, JASA 83(3), 1988)

Contours of sound absorption for fibrous absorbers with ***no air space****. Left locally reacting, Right bulk reacting. (a) θ=30°, (b) θ=45°, (c) θ=60°*

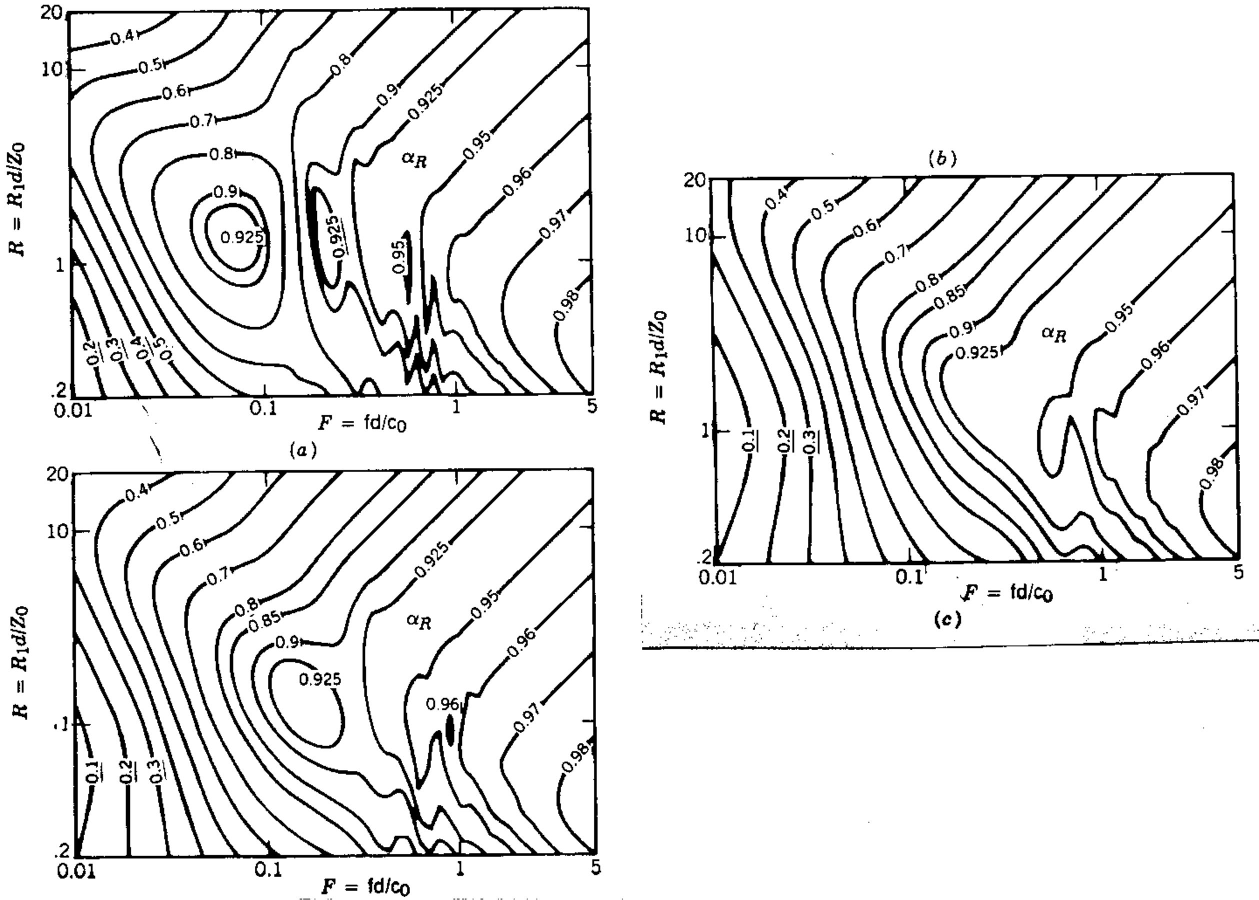


TWO-LAYER ABSORBERS; NO AIR GAP

(After F. P. Mechel, JASA 83(3), 1988)

The presence of an air gap below the absorber may act to enhance the sound effectiveness of the absorber

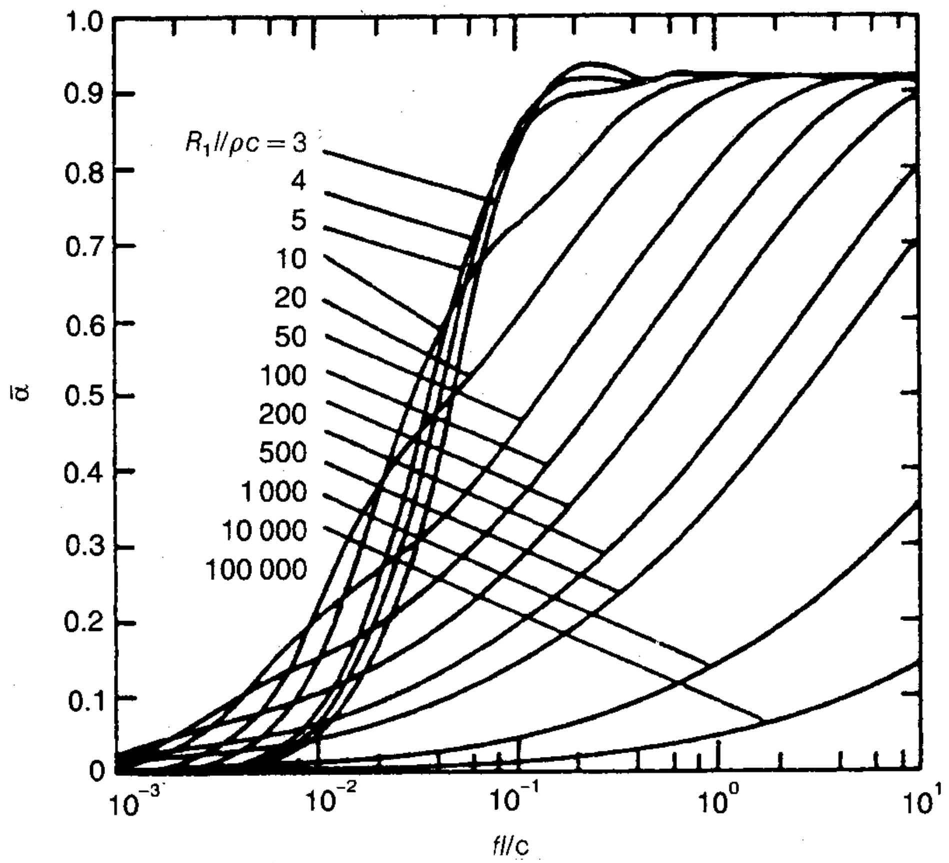
Contours of random incidence absorption for bulk reacting absorber layer of thickness din front of a locally reacting air gap of thickness t ratio of d/D = d/(d+t) of (a) 0.25, (b) 0.5, (c) 0.75



ABSORPTION COEFFICIENT OF A FINITE LAYER OF POROUS MATERIAL

Influence of the **flow resistivity**:

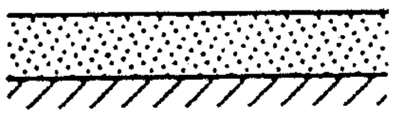
- if flow resistivity is too large, get too much reflection at free surface
- if flow resistivity is too small, get too little damping, so waves are not effectively absorbed in the material, leading to high amplitude of standing waves.
- Practical compromise (rule of thumb): $rl \approx 3\rho_0 c_0$.
- For fl/c<0.1 absorption is low whatever the material ($\lambda < 6l$).



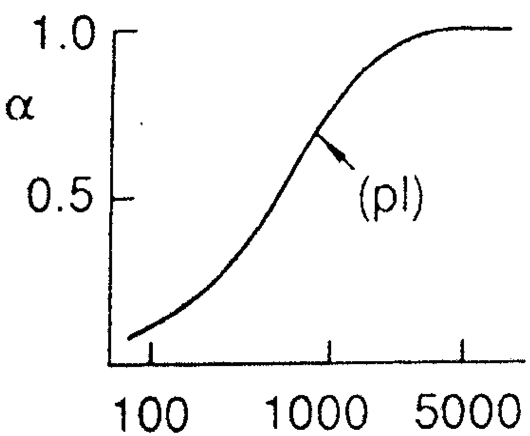
PRACTICAL FORMS OF SOUND ABSORBERS

- The performance of a porous layer is severely limited at low frequencies by its thickness.

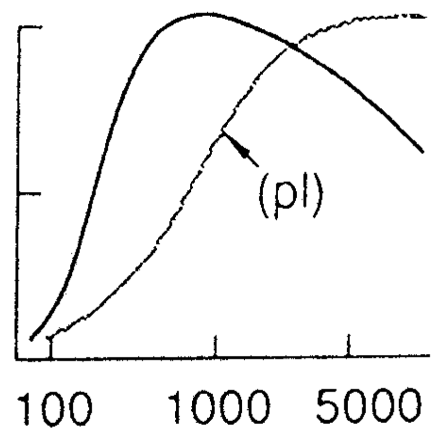
- Porous sheets covered by perforated or slotted impermeable sheets - resonance mechanism.



Porous layer (pl)



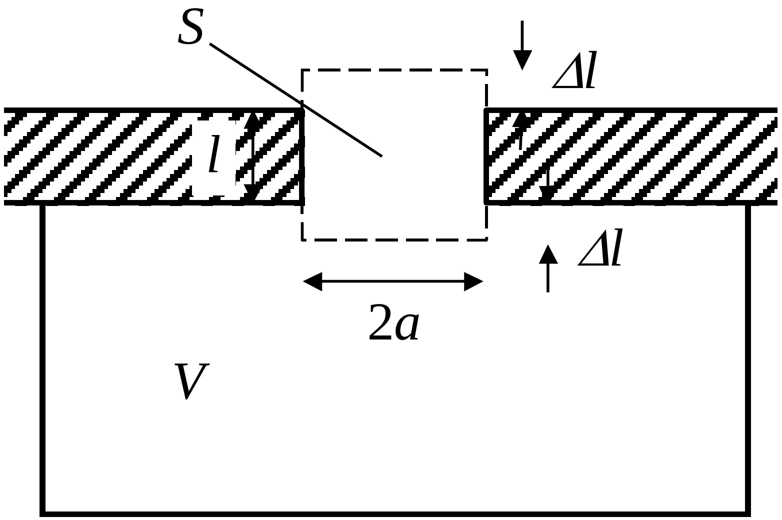
Porous layer plus perforated cover



HELMHOLTZ RESONATORS

- air volume acts as a spring
- opening acts as a mass
- 'damping' introduced by radiation from the orifice
- frequency given by

$$f_0 = \frac{c_0}{2\pi}\sqrt{\frac{S}{V(l + 16a/3\pi)}}$$



where

S is area of opening (radius a)

V is volume of resonator

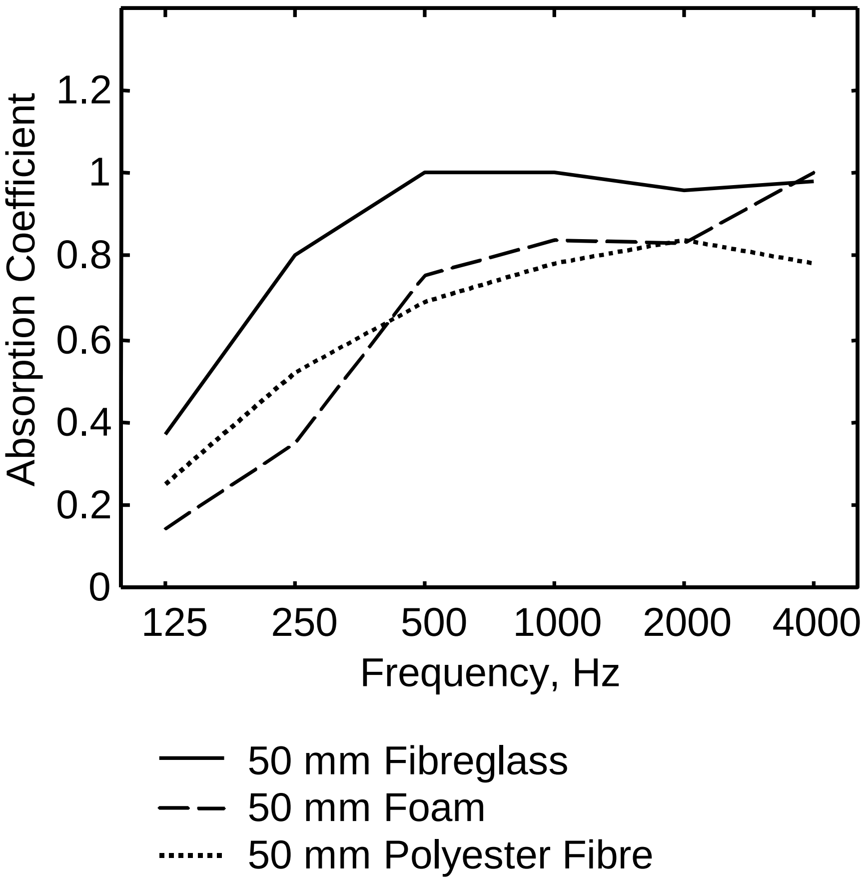
l is length of opening

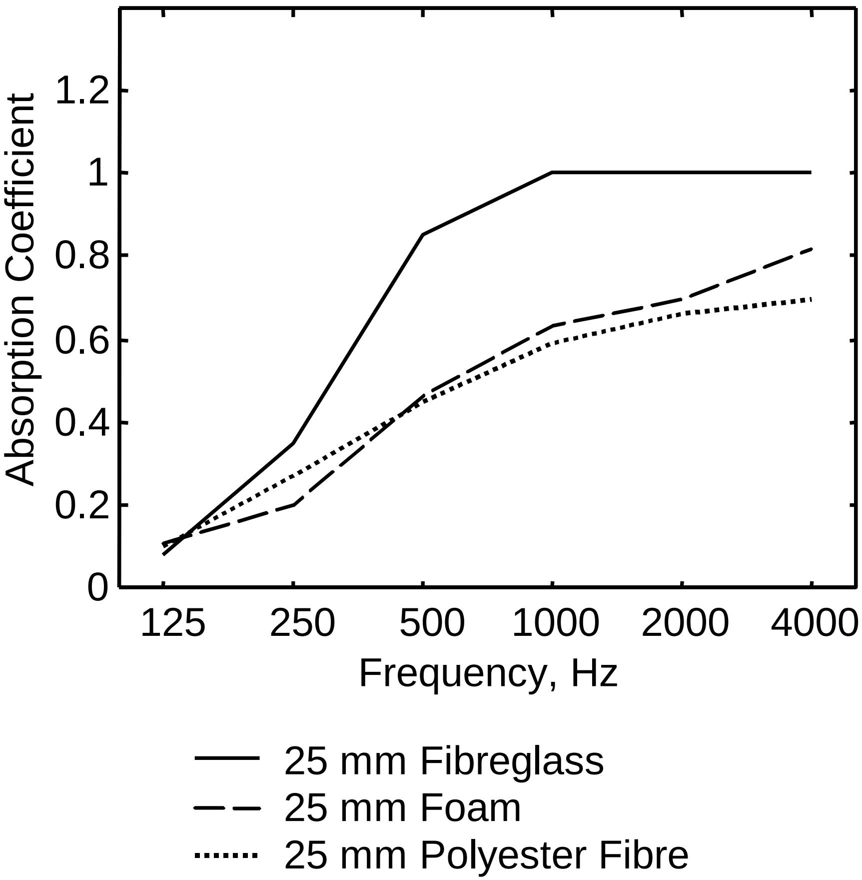
$16a/3\pi$ is end correction (inner and outer)

To be effective the internal loss factor has to be closely matched to the radiation loss factors, i.e. generally it should be small. Far more effective when used in arrays.

EXAMPLES OF MEASURED ABSORPTION COEFFICIENTS

- Effect of material and thickness

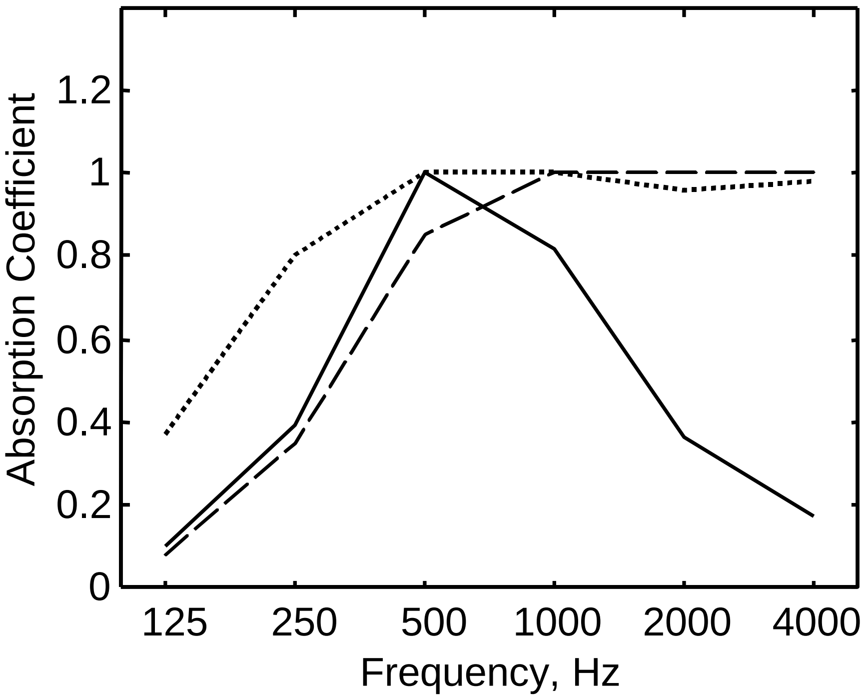




[courtesy of Salex Acoustic Materials]

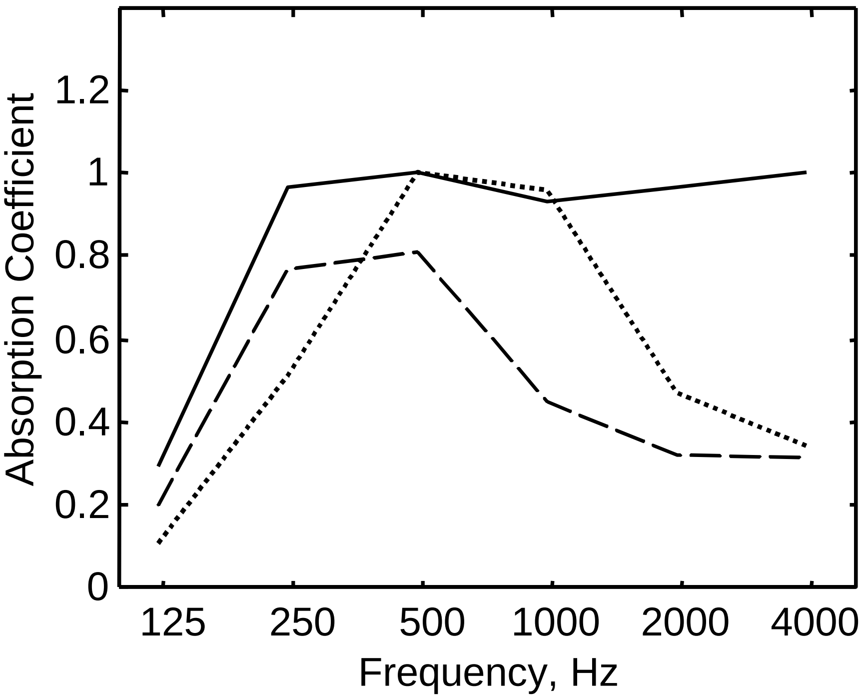
EXAMPLES OF MEASURED ABSORPTION COEFFICIENTS

Effect of facing material



25 mm Fibreglass with vinyl facing
25 mm Fibreglass
50 mm Fibreglass

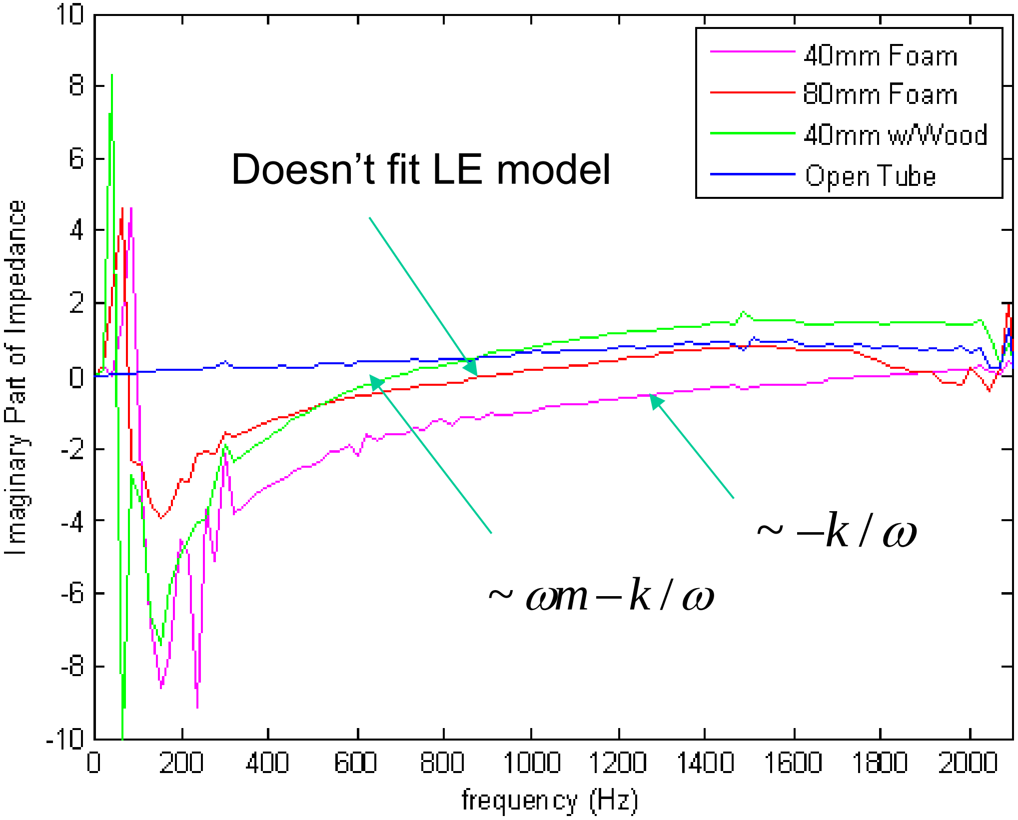
Use of Helmholtz resonators



Multiple Helmholtz Composite 40 mm
Multiple Helmholtz 315Hz tuned 25 mm
Multiple Helmholtz 630Hz tuned 25 mm

[courtesy of Salex Acoustic Materials]

EXAMPLES OF MEASURED IMPEDANCES



Lumped element model

$$m\ddot{x} + c\dot{x} + kx = Fe^{j\omega t}$$

can be used to solve for the impedance $z = F/\dot{x}$

$$\boxed{\begin{aligned} \mathrm{Im}\{z\} &= \omega m - \frac{k}{\omega} \\ \mathrm{Re}\{z\} &= c \end{aligned}}$$