UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II

Experimental Vibroacoustic

Absorption

Teachers:

Prof. Massimo Viscardi – Prof. Ernesto Monaco

DIPARTIMENTO DI INGEGNERIA INDUSTRIALE

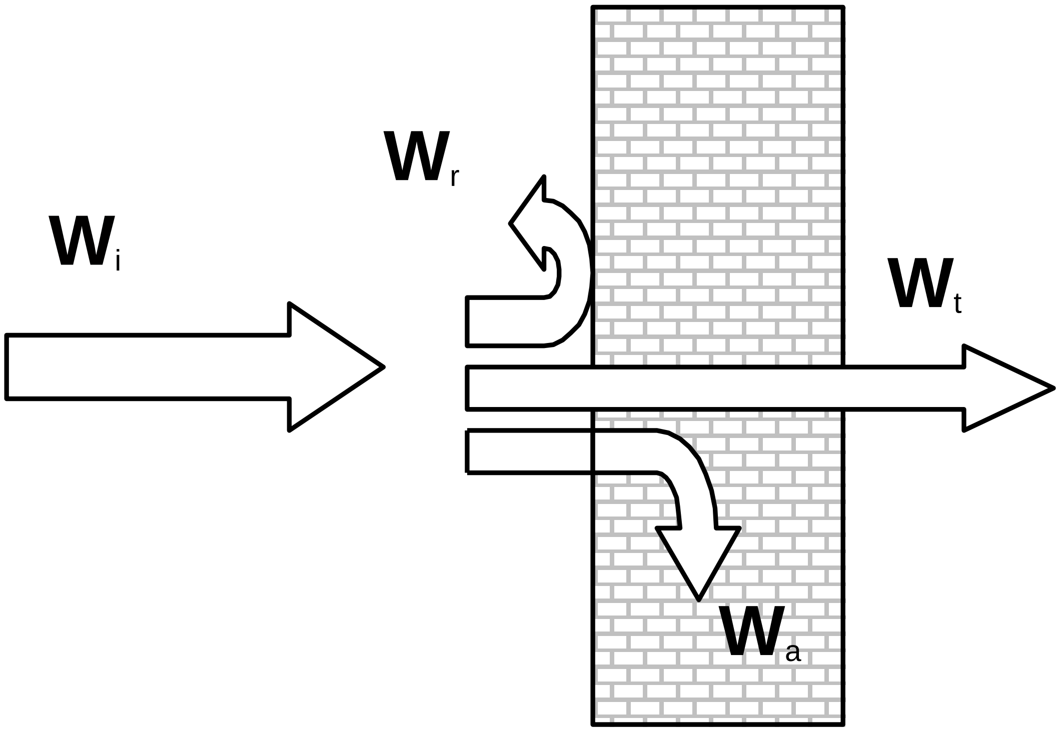
OVERVIEW

- Absorption Introduction
- Absorption Measurement
- Intensity Probe
- Impedance
- Bulk Properties
- Microstructural Properties
- Numerical Models

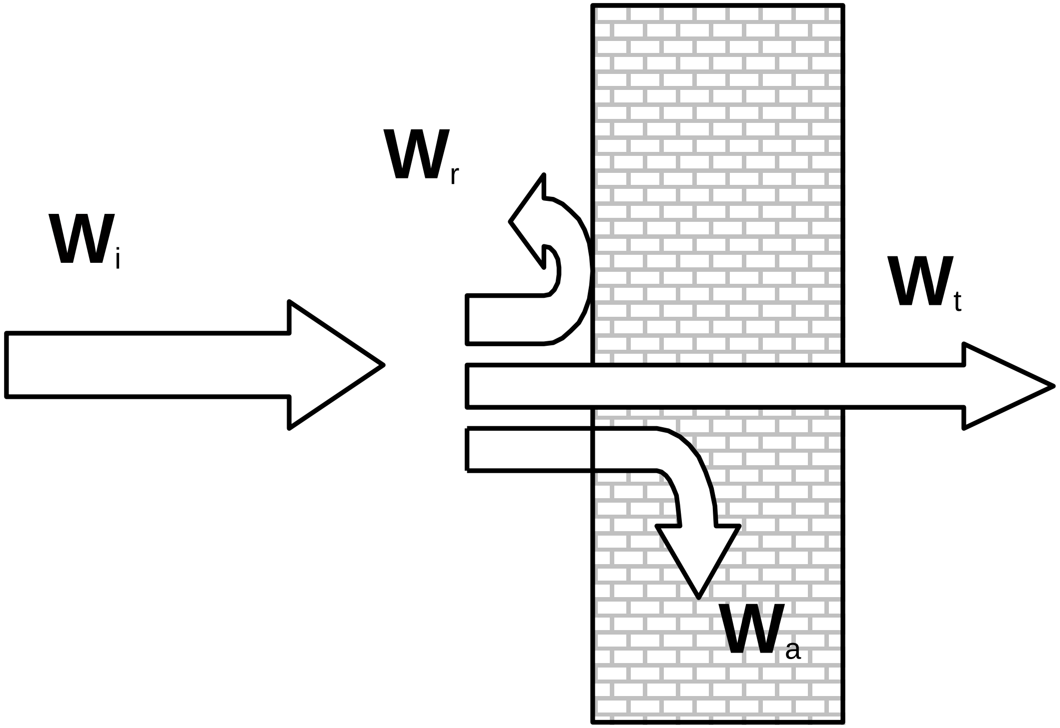
ABSORPTION – INTRODUCTION

INTRODUCTION

When an acoustic wave interacts with a wall it is splitted into three contributes. The incidence energy (W_i) is reflected (W_r) or absorbed (W_a) or transmitted through the wall (W_t).



ENERGY EQUATION



The energy balcance can be written as:

$$W_i = W_a + W_r + W_t$$

The same equation, in a more general way, can be normalized respect to the incident energy. The new equation is:

$$1 = \alpha + r + \tau$$

ACOUSTIC COEFFICIENTS

$$1 = \alpha + r + \tau$$

$$\alpha = \frac{W_a}{W_i} \qquad r = \frac{W_r}{W_i} \qquad \tau = \frac{W_t}{W_i}$$

They are called absorption coefficient, reflection coefficient, transmission coefficient. The coefficients can vary in the range [0 – 1] with 1 theorically included.

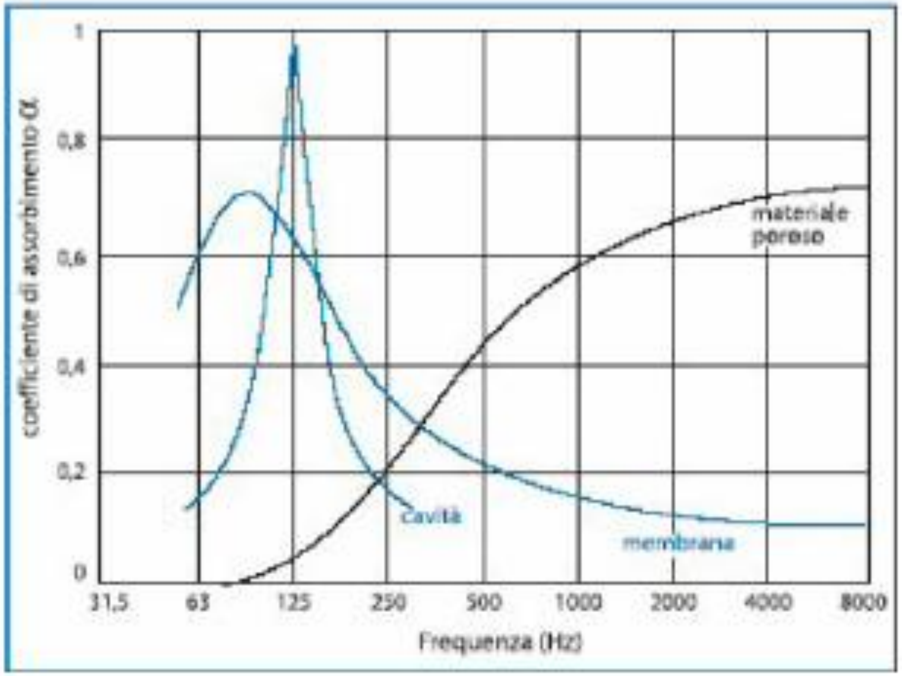
The coefficients depend from:

- Material;
- Surface fixture;
- Incidence angle of sound;

ABSORPTION

There are three ways a material (or a structure) can absorbe acoustic waves

- Porous medias;
- Cavity or Helmholtz resonators;
- Membrane resonators;



ABSORPTION – POROUS MEDIA

This is the concept at the base of open-cell porous and fibrous materials absorbing property.

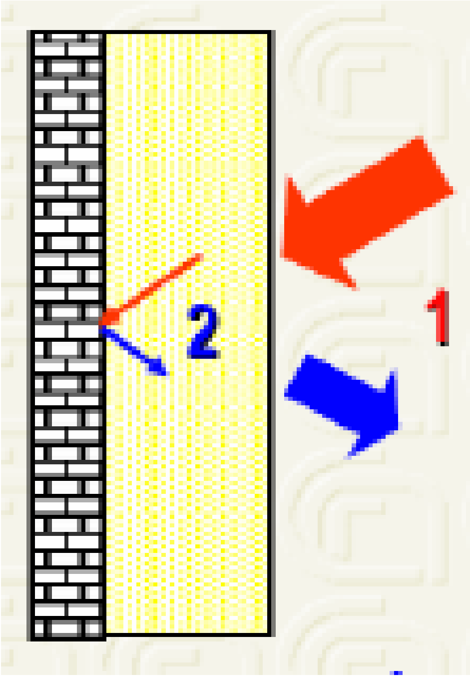
The sound is dissipated slowing the air speed letting them passes through the thight and windy paths.

The absorption coefficient of these materials depend, basically, from material’s air flow resistivity and material’s tortuosity.

TORTUOSITY INFLUENCE

The material's tortuosity has a great influence on material acoustic properties...

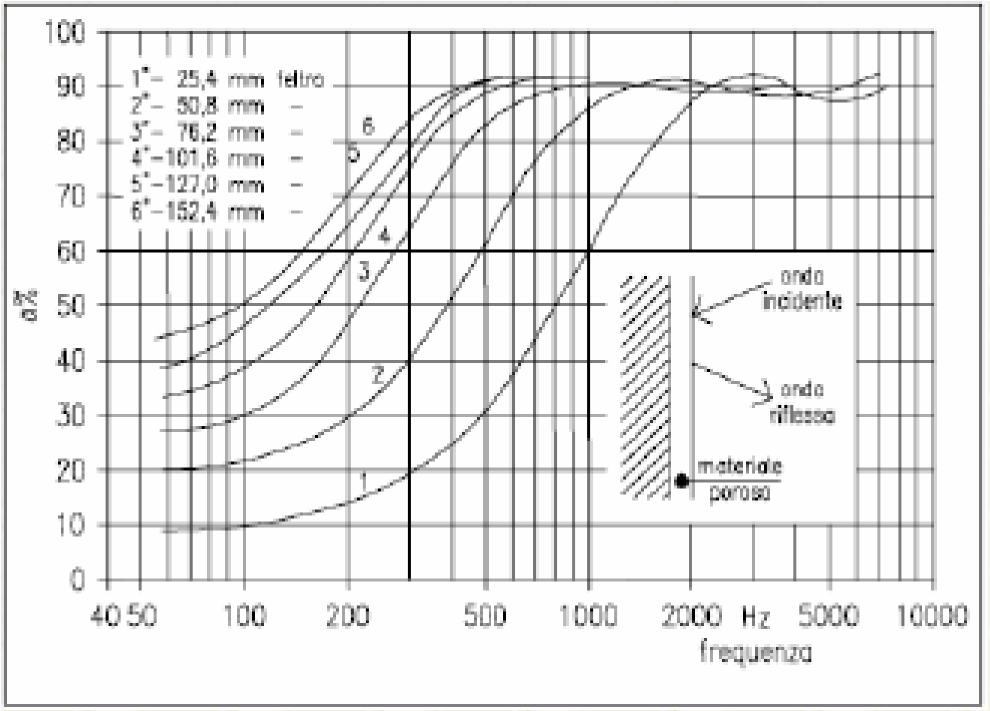
...But how?



Tortuosity must be low to minimize the reflected energy.

Tortuosity must be high to minimize air coming out to the material.

POROUS MEDIA – REMARKS



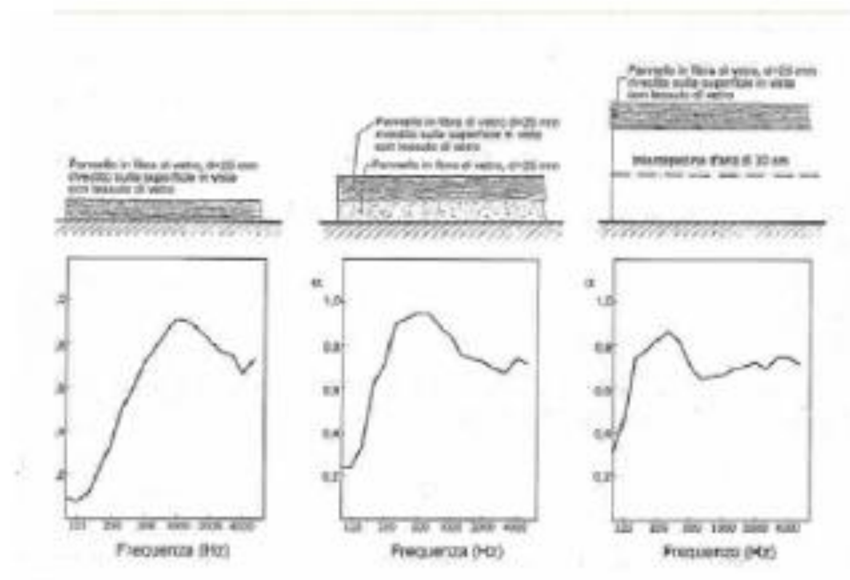
Porous materials are, generally, cheapers and easy to design and mount. This is the most common solution used to absorbe sound.

REMARK 1: Lower is the frequency to absorbe greater is the material thickness needed.

REMARK 2: The maximum absorption occurs at a frquency with a wavelength four times the thickness of the material.

AIR GAP INFLUENCE

Introducing an air gap between the wall and the porous media drastically changes the absorption coefficient behavior.



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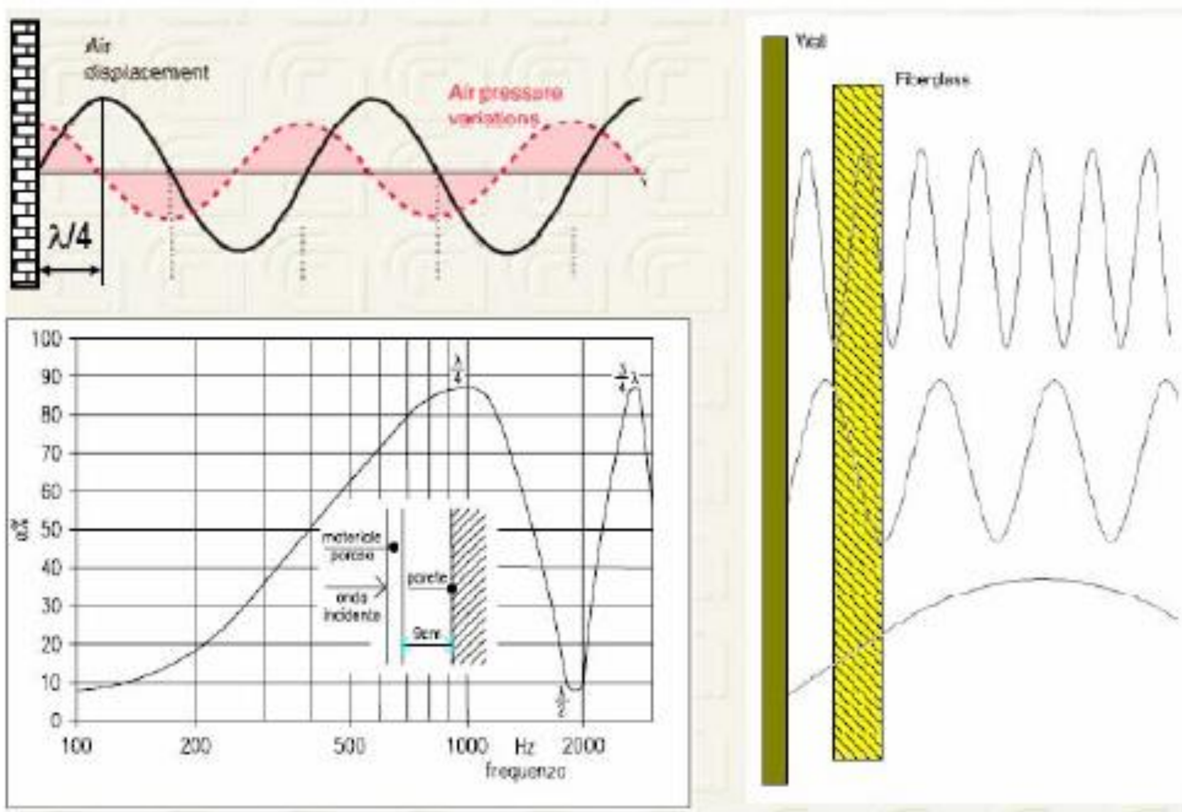
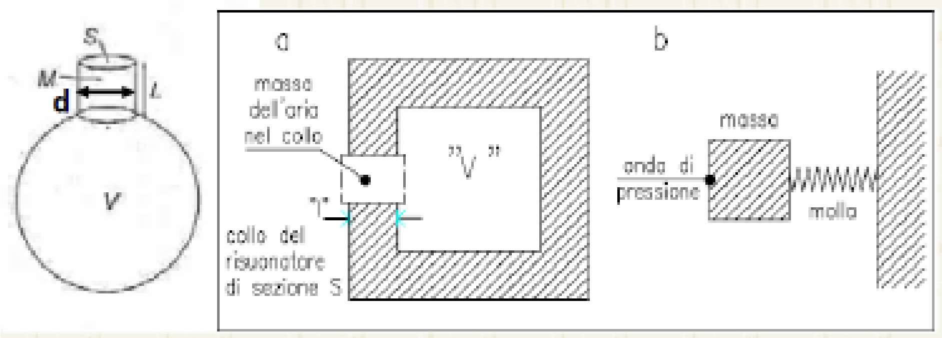


ABSORPTION – CAVITY RESONATOR



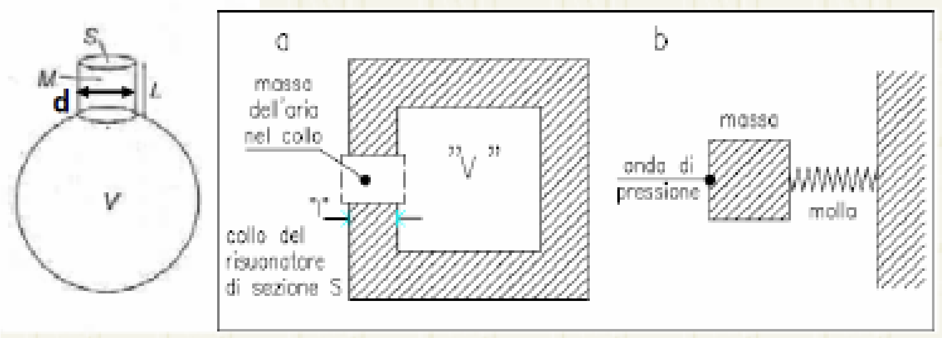
It is based on the mass – spring oscillator to absorbe sound.

The resonator is maiden up by two parts. A cavity connected to the outside with a small hole.

The air in the cavity works as the spring of the system and the air in the neck of the resonator works as the mass of the system.

As all 1 DOF models the resonator works properly at just one frequency. The behavior far away the resonance frequency is really poor.

CAVITY RESONATOR – FREQUENCY

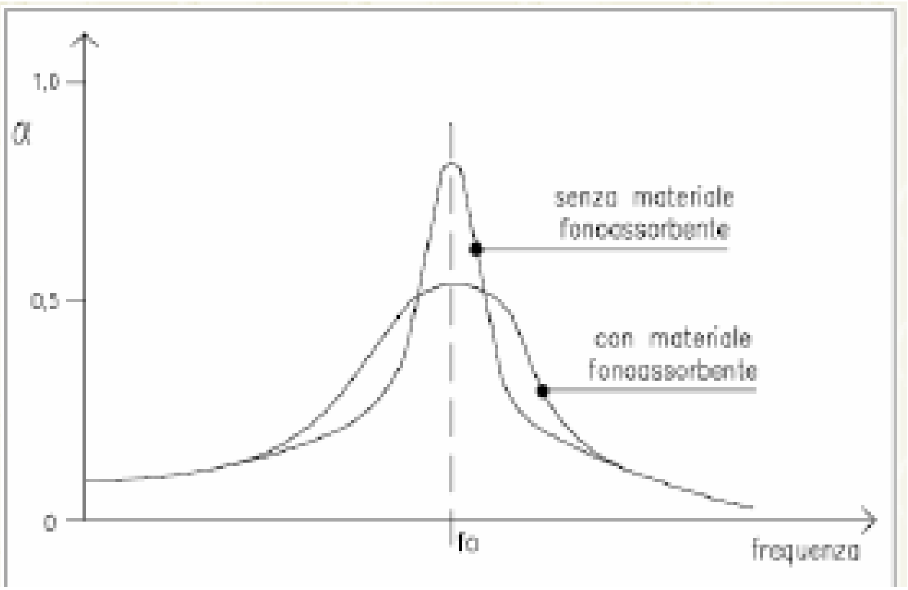


The resonance frequency is calculated with the following equation

$$f_c = \frac{c}{2\pi}\sqrt{\frac{S}{VL_e}}$$

$$L_e = L + 0.8dm$$

CAVITY RESONATOR – POROUS MATERIAL

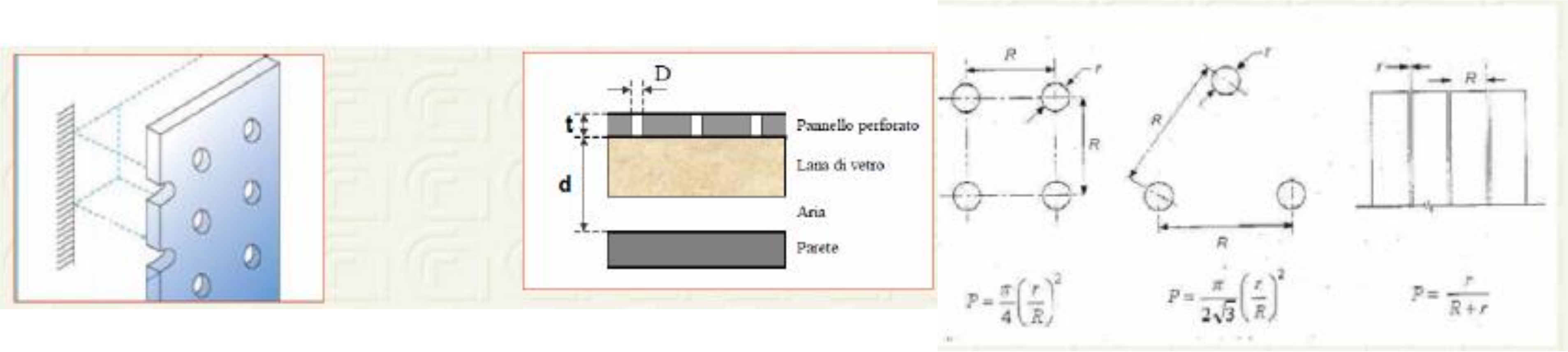


The frequency performances of a cavity resonator can be improved adding porous material inside the cavity.

This has two mainly effects on the acoustic behavior of resonator:

- The maximum value is reduced;
- The frequency behavior is improved;

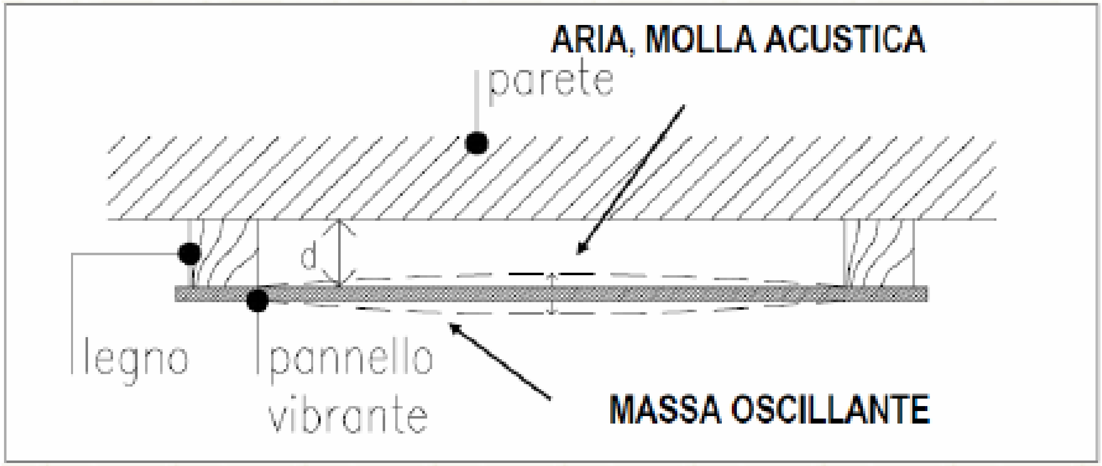
CAVITY RESONATOR – PANELS



Multiple resonatos can be putted in series to create an coustic absorber panel. In this case the resonance frequency is expressed as:

$$f_c = \frac{c}{2\pi}\sqrt{\frac{P}{dt}}$$

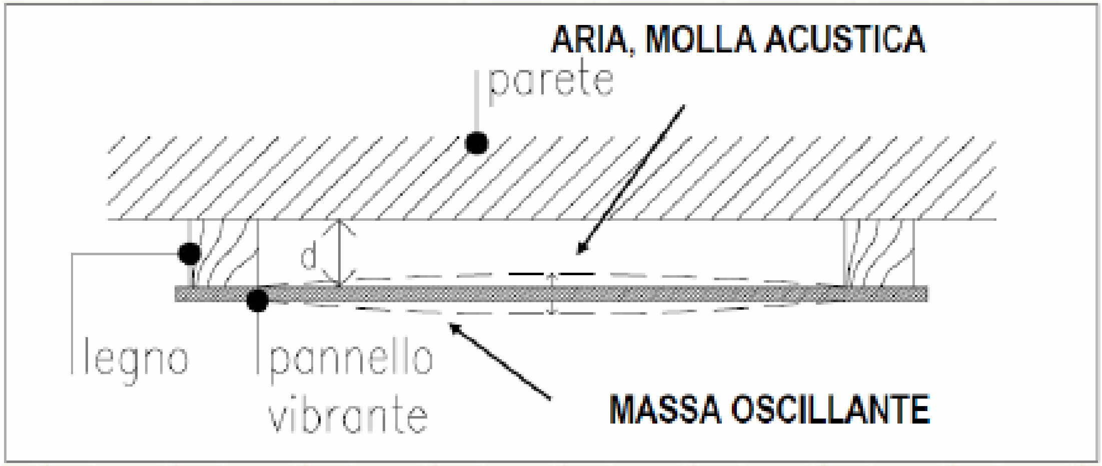
ABSORPTION – PANEL RESONATOR



The absorption is based on resonance phenomena of a 1 DOF model.

The mass is a vibrating panel. The spring the air enclosed in a small gap between the wall and the panel.

ABSORPTION – PANEL RESONATOR



The resonance frequency is:

$$f_c = \frac{c}{2\pi}\sqrt{\frac{\rho}{md}}$$

- ρ air density
- m panel mass
- d distance from the wall

ABSORPTION – MEASUREMENT

NORMAL SURFACE IMPEDANCE

The reason energy reflects at a change in medium is because of the change in wave impedance seen by the wave.

In general, the impedance seen at the surface of an absorber depends on the porous media bulk properties, the geometry of the absorber and the mounting conditions of the absorber.

The surface impedance is angular dependent, but if the material is locally reacting, the effective surface impedance is locally reacting, the effective surface impedance at any angle is related to the normal surface impedance, Z_n by the formula

$$Z(\theta) = \frac{Z_n}{\cos(\theta)}$$

MEASURING ALFA AND IMPEDANCE (1/2)

Usually there are two ways to measure the absorption of materials.

The two methods are sligthly different and the value calculated with one method is not comparable with the value calculated with the other one.

The two methods are:

- Kundt or impedance tube;
- Sabine room;

A third method is available and is based on Intensity Probe (PV or PP)

MEASURING ALFA AND IMPEDANCE (2/2)

Probably the simplest methods for estimating normal incidence absorption and surface impedance α_n and Z_n, are using plane waves impedance tubes

Two industry standards

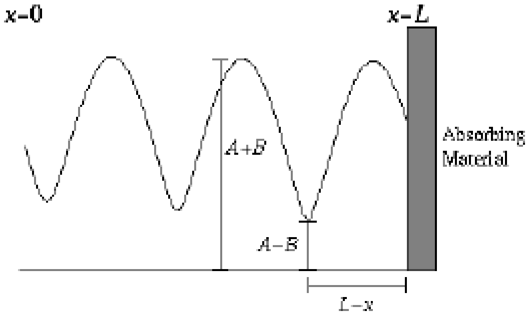
- ASTM C384/ISO 10534 Standing Wave Impedance Tube
- ASTM E1050/ISO 10534 -2 Two Microphone Impedance Tube

Both methods measure the magnitude and phase of the pressure reflection coefficient, $\hat{r} = r \angle \theta$, and then

$$\alpha = 1 - |\hat{r}|^2 = 1 - r^2 \qquad \hat{Z}_n = \frac{1-\hat{r}}{1+\hat{r}}$$

For both methods, the upper frequency is limited to frequencies where only plane waves can propagate in the impedance tube (f<0.586c/d where c = speed fo sound and d = tube diameter)

ASTM C384-04 (1/2)

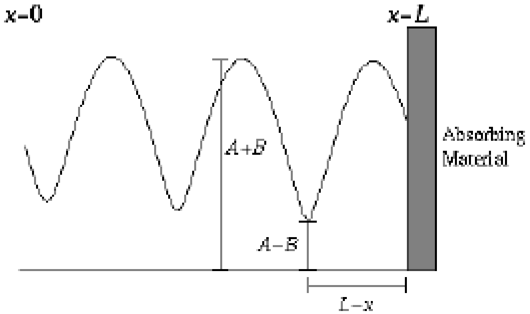


Measure the ratio of peak amplitude to min amplitudes of standing wave, the standing wave ratio called SWR

Measure distance from sample to the closest pressure min, L-x

This method is fairly foolproof, but it is also only applicable for single frequencies and is fairly time consuming. No microphone calibration is required.

ASTM C384-04 (2/2)



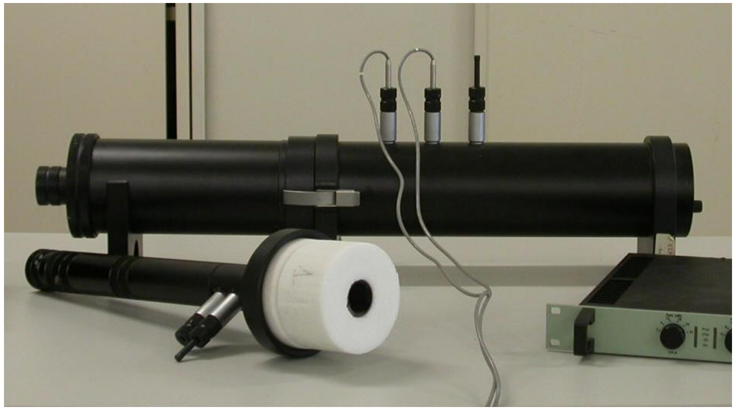
Lower frequency limited by tube length, you must be able to support a half a standing wave with at least one peak and one null

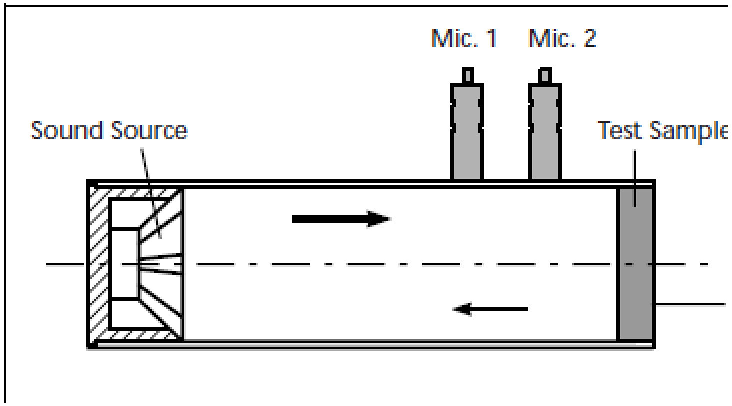
$$SWR = \frac{A+B}{A-B}$$

$$r = \frac{SWR-1}{SWR+1}$$

$$\theta = 2k(L-x) + \frac{\pi}{2}$$

ASTM E1050-98 (1/2)





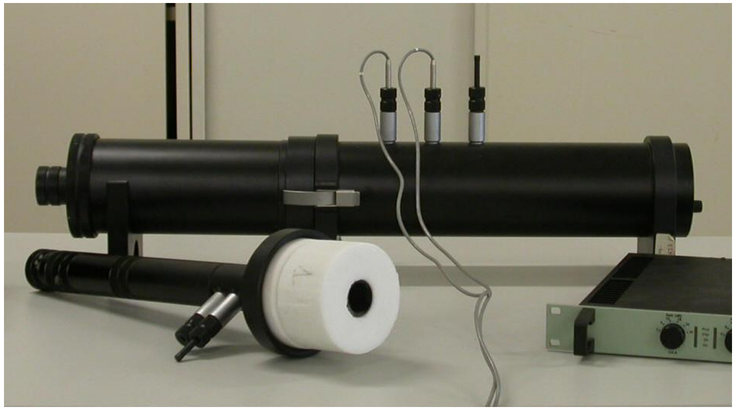
Measure the transfer function, H(f) between two mics, spaced s apart, and a distance l from sample to get r using the quation

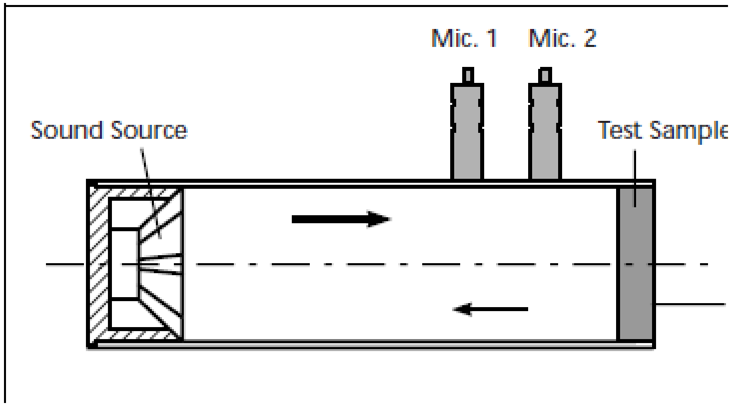
$$\hat{H} = \frac{\widehat{p_1}}{\widehat{p_2}} \qquad \hat{r} = \frac{\hat{H} - e^{-jks}}{e^{jks} + \hat{H}}$$

The frequency limited by mic spacing as well as tube diameter – raccomandations are for

$$0.05\frac{c}{s} < f < 0.45\frac{c}{s}$$

ASTM E1050-98 (2/2)





If the microphone switching method not is used, the microphones must be calibrated for magnitude and phase and H must be corrected before computation of r

Absorptive media put between source and sample to damp out the standing waves

RANDOM ABSORPTION COEFFICIENT

Since α is a function of angle, selecting a representative value arbitrary incidence is hard

If we average $\alpha(\theta)$ over θ we would get what we call the random incidence coefficient α_{rand}

For a locally reacting surface we can do that analytically and would find that $\alpha_{rand}=\alpha(55°)$

We could also try to measure by placing a material sample in a room and exposing it to a diffuse sound field. That is done in ASTM C423/ISO 354. This standard measures a Sabine absorption coefficient.

ASTM C423/ISO 354 (1/2)

This method measures the change in the reverberant decay rate in a reverberant room from the addition of a sample

Sabine equation is used to extract the Sabine absorption coefficient, α_{sab}

ASTM C423/ISO 354 (2/2)

$$\alpha = 0.9210 \frac{V}{CS}(d_2 - d_1) + \alpha_1$$

V is room volume

c is speed of sound

S is surface area of sample

α_1 is absorption coefficient of covered surface

d_1 and d_2 are sound decay rates (dB/s) with and without the sample

ASTM C423 AND SABINE ABSORPTION

Many of us are familiar withthe absorption coefficient listed on material data sheets measured by ASTM C423, the reverberation Room Method. These are αsab

$\alpha_{sab} \neq \alpha_{rand}$ i.e. It is not a random incident absorption coefficient, its only closely related. Numbers greater than unity given on data sheets are not a mistake.

α_{sab} is a measure of decay rate. It is only through the Sabine equation that we equate it to absorption

ASTM C423 AND SABINE ABSORPTION

α_{sab} is very useful measure if you want to predict the effect the reverberation time of a room with that material

α_{sab} is a poor measure of absorption if you want to do other types of noise control (such as line an engine shroud)

There is no simple conversion from α_{sab} to α_{rand} or α_n

INTENSITY PROBE

DEFINITION

Sound intensity is defined as the eergy carried by the sound wave per unit area.

Sound intensity, I is defined as

$$\hat{I} = p\hat{v}$$

Where p is the sound pressure and v is the particle velocity.

Particle velocity is a vectorial quantity and same happens for intensity.

Sound intensity cannot be measured with a standard microphones. To measure sound intensity we need the sound intensity probe.

There are two kinds of intensity probes called pp and pv respectively.

PP PROBE

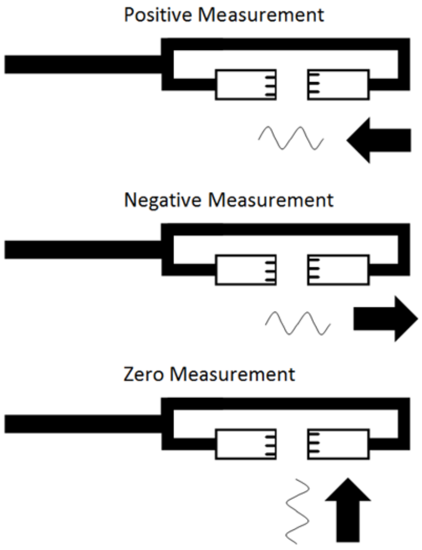
PP stands for pressure – pressure, the probe is maiden with two different microphones facing each other.

The intensity value is derived measuring the sound pressure in two different points really close each other.

The total pressure is estimated as the mean value between the two pressure measured.

The particle velocity is measured calculating the time for a phased wave to move from one microphone to the other one.

The pp probe can measure only the intensity along the microphones direction

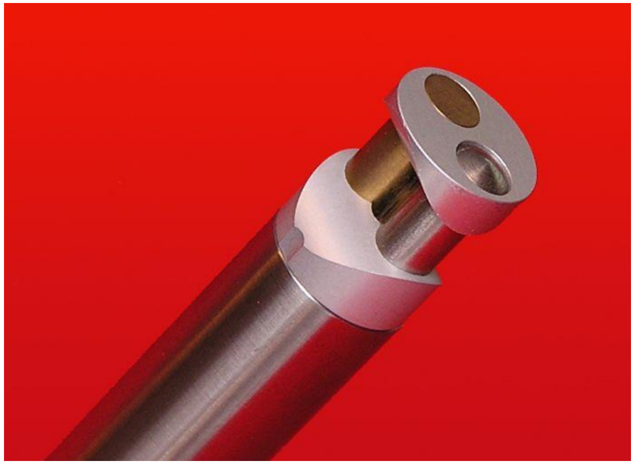


PV PROBE

PV stands for pressure – velocity, the probe is maiden with a microphone and a hotwire anemometer

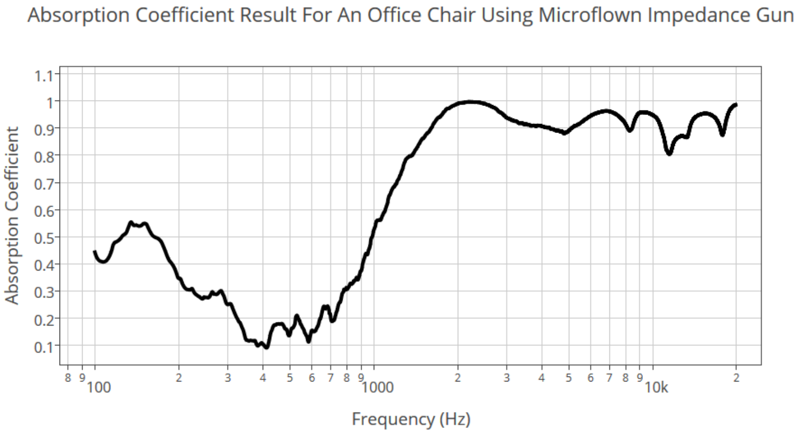
The intensity value is measured directly knowing the pressure in a point and the particle velocity in a really close point, almost the same

The pv probe can measure the intensity along three perpendicular directions.



This method is a true alternative for the well known Kundt's method or reverberant room method.

The usable frequency range of the system is 300Hz to 10kHz, on sample sizes of at least 300x300mm



IMPEDANCE

INTRODUCTION

Acoustic impedance and specific acoustic impedance are measures of the opposition that a system presents to the acoustic flow resulting of an acoustic pressure applied to the system.

The SI unit of acoustic impedance is the pascal second per cubic metre (Pa s / m^3) or the Rayl per square metre (rayl / m^2)

For a linear time – invariant system, the relationship between the acoustic pressure applied to the system and the resulting acoustic volume flow rate through a surface perpendicular to that pressure at its point of application is given by

$$p(t) = [R * Q](t) \rightarrow Q(t) = [G * p](t)$$

Where p is the pressure, Q is the acoustic volume flow rate, R is the acoustic resistance in the time domain, G = R^{-1} is the acoustic conductance in time domain (R^{-1} is the convolution inverse of R) and * is the convolution operator

DEFINITION

Acoustic impedance, Z, is the Laplace transform or the Fourier transform or the analytical representation of time domain acoustci resistance

$$Z(s) \stackrel{\text{def}}{=} \mathcal{L}[R](s) = \frac{\mathcal{L}[p](s)}{\mathcal{L}[Q](s)}$$

$$Z(\omega) \stackrel{\text{def}}{=} \mathcal{F}[R](\omega) = \frac{\mathcal{F}[p](\omega)}{\mathcal{F}[Q](\omega)}$$

$$Z(t) \stackrel{\text{def}}{=} R_a(t) = \frac{1}{2}[p_a * (Q^{-1})_a](t)$$

Where a indicates the analytic representation operator and Q^{-1} is the convolution inverse of Q

ACOUSTIC RESISTANCE AND REACTANCE (1/3)

Acoustic resistance, R, and acoustic reactance, X, are the real part and imaginary part of the acoustic impedance respectively

$$Z(s) = R(s) + iX(s)$$

$$Z(\omega) = R(\omega) + iX(\omega)$$

$$Z(t) = R(t) + iX(t)$$

ACOUSTIC RESISTANCE AND REACTANCE (2/3)

Inductive acoustic reactance and capacitive acoustic reactance denoted as X_L and X_C respectively, are the positive part and negative part of acoustic reactance respectively

$$X(s) = X_L(s) + X_C(s)$$

$$X(\omega) = X_L(\omega) + X_C(\omega)$$

$$X(t) = X_L(t) + X_C(t)$$

ACOUSTIC RESISTANCE AND REACTANCE (3/3)

Acoustic resistance represents the energy transfer of an acoustic wave. The pressure and motion are in phase, so work is done on the medium ahead of the wave.

Acoustic reactance represents, as well, the pressure that is out of phase with the motion and causes no average energy transfer. For example, a closed bulb connected to an organ pipe will have air moving into it and pressure, but they are out of phase so no net energy is transmitted into it. While the pressure rises, air moves in, and while it falls, it moves out, but the average pressure when the air moves in is the same as that when it moves out, so the power flows back and forth but with no time averaged energy transfer. The electrical analogy for this is a capacitor connected across a power line. Current flows through the capacitor but it is out of phase with the voltage, so no net power is transmitted into it.

ACOUSTIC ADMITTANCE

Acoustic admittance, Y, is the Laplace trnasform or the Fourier transform, or the analytic representation of time domain acoustic conductance

$$Y(s) \stackrel{\text{def}}{=} \mathcal{L}[G](s) = \frac{1}{Z(s)} = \frac{\mathcal{L}[Q](s)}{\mathcal{L}[p](s)}$$

$$Y(\omega) \stackrel{\text{def}}{=} \mathcal{F}[G](\omega) = \frac{1}{Z(\omega)} = \frac{\mathcal{L}[Q](\omega)}{\mathcal{L}[p](\omega)}$$

$$Y(t) \stackrel{\text{def}}{=} G_a(t) = Z^{-1}(t) = \frac{1}{2}[Q_a * (p^{-1})_a](t)$$

ACOUSTIC CONDUCTANCE AND SUSCEPTANCE

Acoustic conductance, G, and acoustic susceptance, B, are the real part and imaginary part of acoustic admittance respectively

$$Y(s) = G(s) + iB(s)$$

$$Y(\omega) = G(\omega) + iB(\omega)$$

$$Y(t) = G(t) + iB(t)$$

SPECIFIC ACOUSTIC IMPEDANCE (1/2)

For a linear time – invariant system, the relationship between the acoustic pressure applied to the system and the resulting particle velocity in the direction of that pressure at its point of application is given by

$$p(t) = [r * v](t) \rightarrow v(t) = [g * p](t)$$

Where p is the acoustic pressure and ve the particle velocity, r is the specific acoustic resistance in the time doamin and g $=r^{-1}$ is the specific acoustic conductance in the time domain (r^{-1} is the convolution inverse of r)

SPECIFIC ACOUSTIC IMPEDANCE (2/2)

Specific acoustic impedance, z, is the Laplace transform or the Fourier transform or the analytic representation of time domain specific acoustic resistance

$$z(s) \stackrel{\text{def}}{=} \mathcal{L}[r](s) = \frac{\mathcal{L}[p](s)}{\mathcal{L}[v](s)}$$

$$z(\omega) \stackrel{\text{def}}{=} \mathcal{F}[r](\omega) = \frac{\mathcal{F}[p](\omega)}{\mathcal{F}[v](\omega)}$$

$$z(t) \stackrel{\text{def}}{=} r_a(t) = \frac{1}{2}[p_a * (v^{-1})_a](t)$$

As for acoustic impedance we can define the specific acoustic resistance, specific acoustic reactance and so on

RELATIONSHIPS

A one dimensional wave passing through an aperture with area A is now considered. The acoustic volume flow rate Q is the volume of medium passing per second through the aperture. If the acoustic flow moves a distance dx = v dt, then the volume of medium passing through is dV = A dx, so

$$Q = \frac{dV}{dt} = A\frac{dx}{dt} = Av$$

Provided that the wave is only one-dimensional, it yields

$$Z(s) = \frac{\mathcal{L}[p](s)}{\mathcal{L}[Q](s)} = \frac{\mathcal{L}[p](s)}{A\mathcal{L}[v](s)} = \frac{z(s)}{A}$$

$$Z(\omega) = \frac{\mathcal{L}[p](\omega)}{\mathcal{L}[Q](\omega)} = \frac{\mathcal{L}[p](\omega)}{A\mathcal{L}[v](\omega)} = \frac{z(\omega)}{A}$$

$$Z(t) = \frac{1}{2}[p_a * (Q^{-1})_a](t) = \frac{1}{2}\left[p_a * \left(\frac{v^{-1}}{A}\right)_a\right] = \frac{z(t)}{2}$$

BULK PROPERTIES

INTRODUCTION (1/2)

Bulk properties are those properties that describe the material/sound wave interaction but are independent of the material thickness and area (i.e. Absorber size)

In anisotropic materials such as layered fiberglass, the bulk properties can be a function of direction so keep that in mind

INTRODUCTION (2/2)

Among the important bulk properties are:

Characteristic Impedance, Z_c and characteristic wavenumber, k_c or alternatively dynamic density, ρ_e and dynamic bulk modulus, k_e

Imaginary part of k_c is related to acoustic damping in the material, the imaginary part of Z_c is related to energy storage mechanisms

$$Z_c = \sqrt{K_e \rho_e}$$

$$k_c = \omega \sqrt{\frac{\rho_e}{K_e}}$$

USE OF Z_c AND K_c

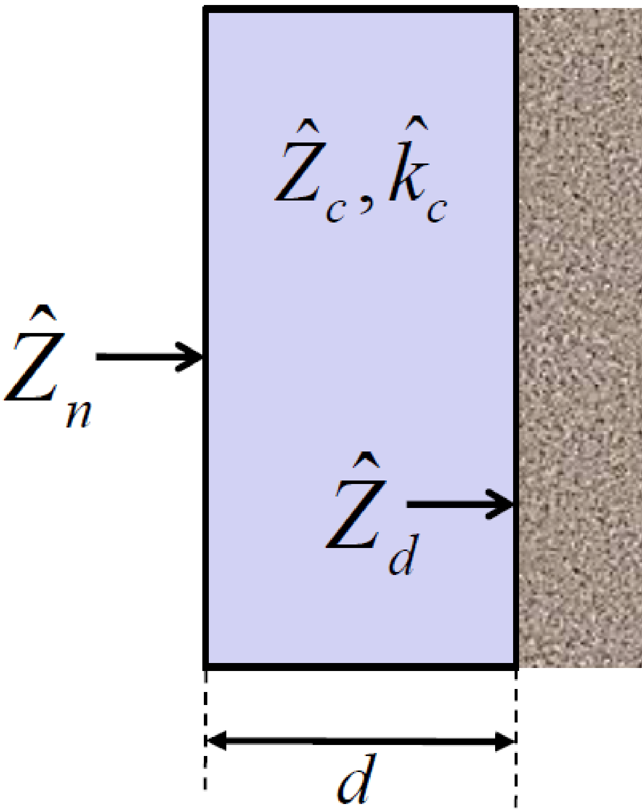
We usually use Z_c and k_c directly for designing absorber. For example, the normal surface impedance of a layer of a porous material of against a wall with Z_d is

$$\widehat{Z_n} = \widehat{Z_c}\frac{\widehat{Z_d}+j\widehat{Z_c}\tan(\widehat{k_c}d)}{\widehat{Z_c}+j\widehat{Z_d}\tan(\widehat{k_c}d)}$$

For

$$\widehat{Z_d} \rightarrow \infty$$

$$\widehat{Z_n} = -j\widehat{Z_c}\cot(\widehat{k_c}d)$$



MEASURING BULK PROPERTIES

We can use the impedance tube to estimate Z_n for two samples of different d and/or Z_d conditions to estimate Z_c and k_c this is the two load method

We need two conditions to solve for both Z_c and k_c

We can use the four-mic transfer matrix method of Song and Bolton to measure Z_c and k_c in one measurement

FOUR-MIC METHOD

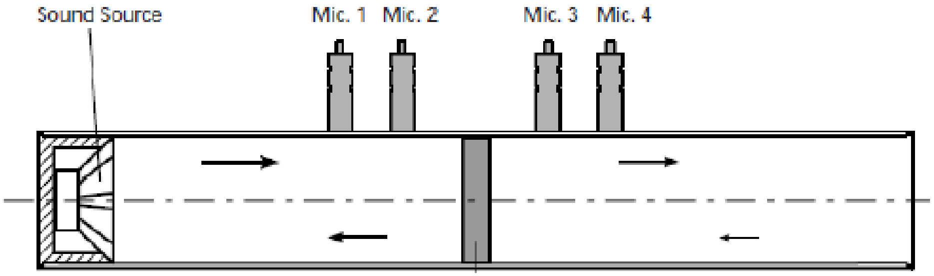
This is a variation on the standard impedance tube using two pairs of mics

The mics measure both reflected and transmitted waves to get Z_c and k_c with only one measureemnt

You can also estimate normal incident transmission loss with the same measurement

ASTM and ISO are currently under development

Works better for high porosity, low flow resistivity materials than the two microphones impedance tube



MICROSTRUCTURAL PROPERTIES

INTRODUCTION

The microstructural properties are the geometry details that describe the interaction of the sound wave and the material. These properties define the bulk properties

Knowledge of the microstructural properties is very useful for designing absorber with specific bulk properties

Among the important microstructural properties are

- Flow Resistivity
- Porosity
- Tortuosity
- Characteristic Length

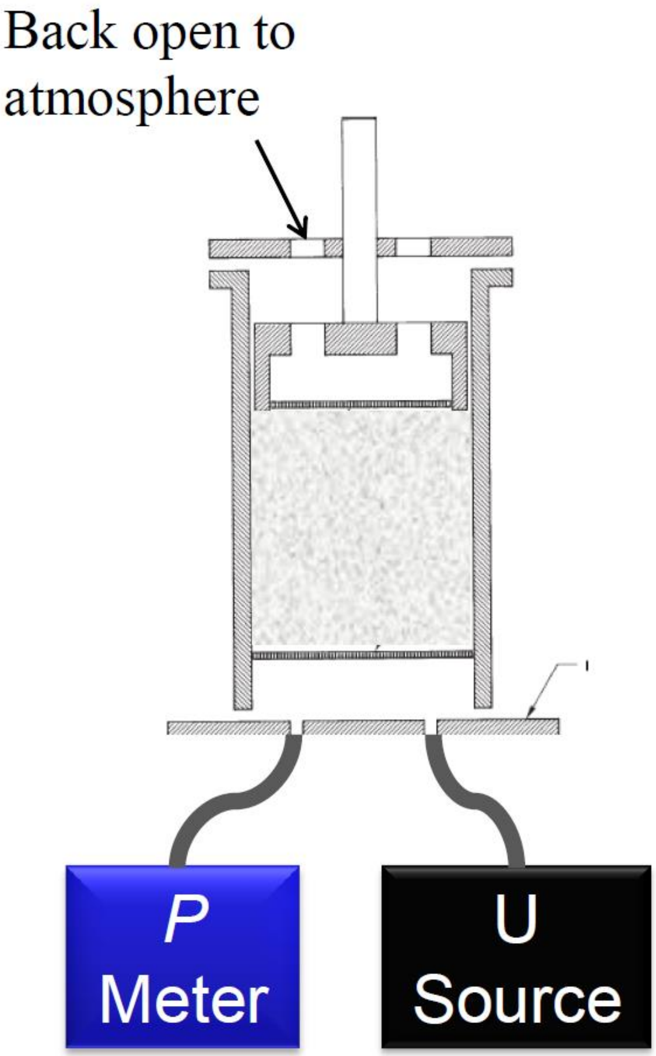
FLOW RESISTIVITY (σ)

Flow resistivity σ is the ratio of static pressure drop ΔP to a volume flow U for a small sample length, d

$$\sigma = \frac{\Delta P}{Ud}\left[\frac{Ns}{m^4}\right] = MKS \rightarrow \frac{rayl}{m}$$

This can be measured using ASTM C522

To maintain laminar flow, the flow velocity should be kept under 50 mm/s



POROSITY (φ) (1/2)

Porosity is the ratio of interconnected void volume to total volume fo a material and is surprisingly hard to measure

You should think you can just measure the volume and mass of an absorber sample but it is not that simple

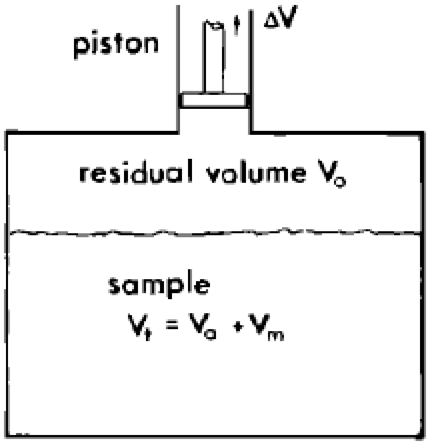
It is hard to measure in open cell foams because it is hard to determine which cells are really open and interconnected

It is hard to measure accurately for fibrous absorber because measuring the exact volume of a compressible sample can be hard

Porosities fo 95 – 98% if fibrous absorber are not uncommon

POROSITY (φ) (2/2)

One method is to fill the sample pores with a liquid and measure that volume. But that can contaminate the sample and preclude making other parameters measurements



Another popular method uses thermodynamics

Sample is placed in chamber which is compressed by ΔV. The internal pressure will increase by ΔP according to Boyles law

$$V_0 + V_t = -\frac{P_0 + \Delta P}{\Delta P}\Delta V$$

TORTUOSITY (q)

Tortuosity is a measure of the non-straightness of the pore structure of the porous material

The more complex the path, the more time a wave is in contact with the absorber

One method is to saturate the sample with an electrically conducting fluid and measure the electrical resistivity of the saturated sample, rs, and comprare to the resistivity of the fluid alone, rf, then

$$q = \phi \frac{r_s}{r_f}$$

CHARACTERISTIC LENGTHS, Λ and Λ'

Two more important microstructural properties are the characteristic viscou length Λ and thermal length Λ' which relate to viscous and thermal losses

The thermal length, Λ', is the twice ration of volume to surface area in connected pores. This is geometric and can be measured directly

The viscous length, Λ, is nearly the same, but each integral is weighted by the square of the fluid velocity in the pore. This cannot be measured directly

$$\Lambda' = 2\,\frac{\int dV}{\int dS} = \frac{V_{sample}}{S_{porewall}}$$

$$\Lambda = 2\,\frac{\int v_{fluid}^2 dV}{\int v_{fluid}^2 dS}$$

NUMERICAL MODELS

INTRODUCTION

Some numerical models have been developed to calculate numerically absorption coefficient of porous or fibrous materials.

These models has a practical application in absorber design and optimization

They can save time avoiding expansive and time consuming experimental methods

The numerical models are used to calculate the Z_n and k_n parameters for a single material or for a layered assembly

Z_n and k_n are used to calculate absorption coefficient (at specific incidence angle or diffuse)

MONO-PARAMETRIC MODEL (1/2)

The simplest model we can use is a mono-parametric model

The only required parameter is the air flow resistivity

It was originally developed by Delany – Bazley for simple porous materials and later extended to a wide range of different materials optimizating the model coefficients

It is semi-empirical model

General equation for Z_c and k_c are

$$Z_c = \rho_0 c_0 \left[1 + \alpha_1 \left(10^3 \frac{f}{\sigma} \right)^{-\alpha_2} - j\alpha_3 \left(10^3 \frac{f}{\sigma} \right)^{-\alpha_4} \right] \qquad k_c = \frac{\omega}{c_0} \left[\beta_1 \left(10^3 \frac{f}{\sigma} \right)^{-\beta_2} - j \left(1 + \beta_3 \left(10^3 \frac{f}{\sigma} \right)^{-\beta_4} \right) \right]$$

MONO-PARAMETRIC MODEL (2/2)

$$Z_c = \rho_0 c_0 \left[1 + \alpha_1 \left(10^3 \frac{f}{\sigma} \right)^{-\alpha_2} - j\alpha_3 \left(10^3 \frac{f}{\sigma} \right)^{-\alpha_4} \right] \qquad k_c = \frac{\omega}{c_0} \left[\beta_1 \left(10^3 \frac{f}{\sigma} \right)^{-\beta_2} - j \left(1 + \beta_3 \left(10^3 \frac{f}{\sigma} \right)^{-\beta_4} \right) \right]$$

α and β are numerical coefficients depending from the specific model

The more used models are Delany – Bazley and Miki

	α_1	α_2	α_3	α_4	β_1	β_2	β_3	β_4
DELANY – BAZLEY	9.08	0.75	11.9	0.73	10.3	0.59	10.8	0.70
MIKI	5.5	0.632	8.43	0.632	11.41	0.618	7.81	0.618

The model is valid if

$$0.01 < \frac{f}{\sigma} < 1.0$$

MONO-PARAMETRIC MODEL (2/2)

$$Z_c = \rho_0 c_0 \left[1 + \alpha_1 \left(10^3 \frac{f}{\sigma} \right)^{-\alpha_2} - j\alpha_3 \left(10^3 \frac{f}{\sigma} \right)^{-\alpha_4} \right]$$

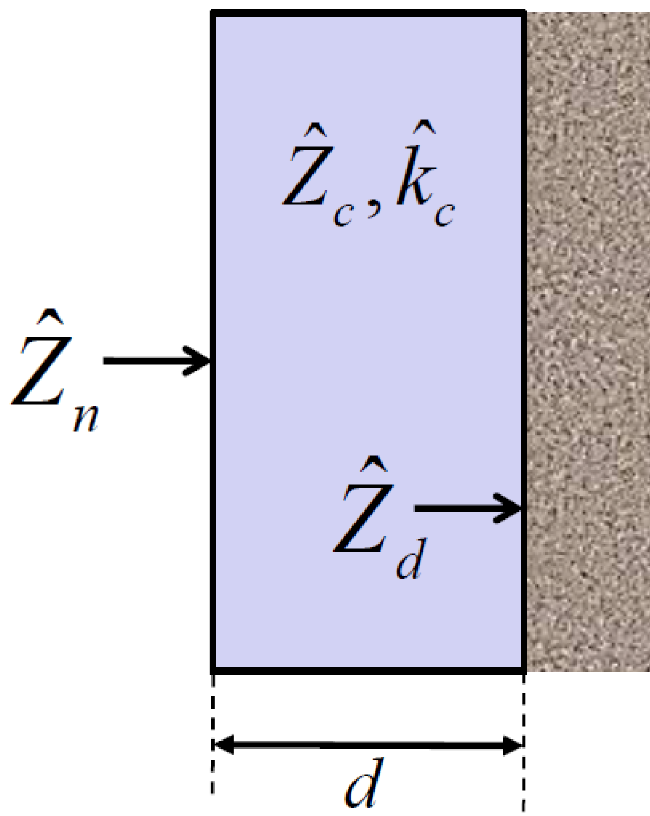
$$k_c = \frac{\omega}{c_0} \left[\beta_1 \left(10^3 \frac{f}{\sigma} \right)^{-\beta_2} - j \left(1 + \beta_3 \left(10^3 \frac{f}{\sigma} \right)^{-\beta_4} \right) \right]$$

The model shown here give us Z_c and k_c

For absorption calculation we need to know Z_n

Z_n for DB and MIKI is expressed as

$$Z_n = -j \frac{Z_c}{\tan(k_c d)}$$



MULTI-PARAMETERS MODELS (1/2)

Delany – Bazley model was starting point for more complex numerical models developed during last 30 years

These models are really hard to apply due to the lack in material properties value

The more complex models require some or all microsctructural properties

MULTI-PARAMETERS MODELS (2/2)

Here are listed the most common multi-parameters model

- Johnson-Champoux-Allard (JCA) : Porosity, Air Flow Resistivity, Tortuosity, Viscous Characteristic Length
- Johnson-Champoux-Allard-Lafarge (JCAL)) : Porosity, Air Flow Resistivity, Tortuosity, Viscous Characteristic Length
- Johnson-Champoux-Allard-Pride-Lafarge (JCAPL) : Porosity, Air Flow Resistivity, Tortuosity, Viscous Characteristic Length, Thermal Characteristic Length
- Wilson (WL) : Porosity, Air Flow Resistivity, Tortuosity, Viscous Characteristic Length, Thermal Characteristic Length

ABSORPTION CALCULATION

As described before there are two way to calculate absorption coefficient.

The diffuse coefficient (Sabine like) is calculated with the London equation as shown below

$$\alpha_d = \frac{8r}{x^2+r^2}\left[1+\frac{r^2-x^2}{x(x^2+r^2)}\operatorname{atan}\left(\frac{x}{1+r}\right)-\frac{r}{x^2+r^2}\log(1+2r+x^2+r^2)\right]$$

Where r is the real part of acoustic impedance and x the complex one

Absorption coefficient and a single incident angle (θ) is given as

$$\alpha_i = 1-\left|\frac{Z-\frac{Z_0}{\cos\theta}}{Z+\frac{Z_0}{\cos\theta}}\right|^2$$

Where Z_0 is the air acoustic impedance, $Z_0 = \rho_0 c_0$

EXERCISE

For these conditions of thickness and air flow resistivity

	Air Flow Resistivity (σ) [Rayl/m²]	Thickness (d) [mm]
SAMPLE 1	20000	10
SAMPLE 2	10000	15
SAMPLE 3	8310	30
SAMPLE 4	12500	50

Task to do:

- Calculate indicence alfa for θ=90° with DB and MIKI models in frequency range 100 – 10000 Hz

Optional tasks:

- Compare incidence alfa for θ in 0:180 rangeù
- Calculate diffuse alfa (London equation) for DB and MIKI models
- Compare incidence alfa with diffuse alfa (London equation)