Title	NOVI - Advanced functional solutions for Noise and Vibration reduction of machinery, Deliverable D1.1 Physical mechanisms of absorption and sound insulation
Author(s)	Uosukainen, Seppo
Citation	VTT (2014), 45 p.
Date	2014
Rights	This report may be downloaded for personal use only.

Business from technology

NOVI - Advanced functional solutions for Noise and Vibration reduction of machinery

D1.1 Physical mechanisms of absorption and sound insulation, VTT

Author:	Seppo Uosukainen
Confidentiality:	Public

Aalto-yliopisto

TAMLINK
TUOTEKEHITYS OY

Summary

Project name NOVI SP1	Project number/Short name 71902 – 1.1.2
Author(s) Seppo Uosukainen	Pages 45
Keywords	

Summary

- Absorption of acoustic wave is due to viscous and thermal losses and relaxation processes in fluid
    - Absorption is emphasized near boundaries, especially in small holes, slits and narrow tubes
    - Viscous losses dominate with small free space dimensions
        - Perforated / microperforated plates
        - Absorbing materials
            - “Holes” and “slits” described by fluid bulk properties (flow resistivity, porosity, tortuosity, viscous and thermal characteristic lengths)
- Sound transmission of a wall is due to two parallel transmission paths
    - Non-resonant and resonant transmission
    - Below coincidence frequency non-resonant transmission dominates except in the resonance region
- With double walls above double-wall resonance, sound insulations in dBs are summed with reasonable amount of absorption in cavity if mechanical coupling is insignificant

Confidentiality	Public

Espoo 16.1.2012

Written by Seppo Uosukainen Senior Scientist	Reviewed by Hannu Nykänen Principal Scientist	Accepted by Johannes Hyrynen Deputy Technology Manager

Table of content

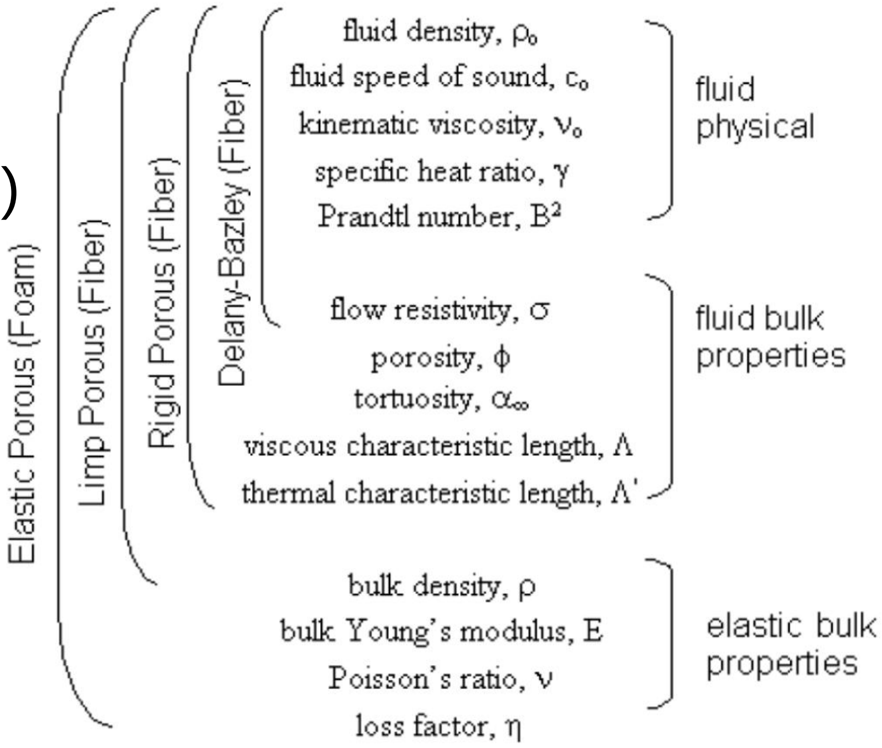
- Physical mechanisms of sound absorption
    - Basic concepts
    - Losses in medium
    - Losses at boundaries
    - Losses in narrow tubes and in small holes and slits
- Physical mechanisms of sound insulation
    - Basic concepts
    - Sound insulation of a single wall in diffuse field
    - Sound insulation of a double wall in diffuse field
    - Sound insulation of sandwich structures

Table of content

- Physical mechanisms of sound absorption
    - Basic concepts
    -
    -
    -
-
    -
    -
    -
    -

Basic concepts

- Physical properties of fluid are responsible for acoustic absorption
    - Viscosity
    - Thermal conductivity (Prandtl number)
- In sound absorbing structures
    - Fluid bulk properties affect the efficiency of absorption
    - Elastic bulk properties increase absorption
        - Energy is transferred to vibration energy which is decreased through internal losses
        - Not handled here



Va One 2010.5 Foam Module – User's Guide, Theory & QA

Fluid bulk properties

- Flow resistivity r (specific flow resistance)
  - Based on ratio of pressure difference Δp between surfaces of material sample, due to volume velocity Q through the sample
- Porosity ϕ
  - Volume of fluid phase V_{fluid} compared to total volume V_{tot} of material sample
- Tortuosity α_∞
  - Unitless quantity relating average fluid path length through material sample normalized by sample thickness
- Viscous and thermal characteristic lengths Λ and Λ'
  - Macroscopic shell dimensions related to viscous and thermal losses (average radius of smaller and larger pores)

$$r = \frac{\Delta p S}{Q h}$$

$$\phi = \frac{V_{\mathrm{fluid}}}{V_{\mathrm{tot}}}$$

S : sample area
h : sample thickness

Absorption coefficient

- Absorptive properties of a structure is defined by absorption coefficient α
  - Includes transmitted sound and vibration power in addition to absorbed sound
  - Function of mounting conditions
  - Function of angle of incidence
  - Absorption coefficient is not handled here, only physical mechanisms involved in sound absorption phenomenon

$$\alpha = \frac{P_{abs}}{P_{inc}} = 1 - \left|R\right|^2$$

$$R = \frac{Z_s - Z_0}{Z_s + Z_0}$$

P_{abs} = absorbed sound power
P_{inc} = incoming sound power
R = reflection coefficient of structure front end
Z_s = impedance of structure front end
(ratio of sound pressure and particle velocity)
Z_0 = impedance of air (= $\rho_0 c_0$, density times speed of sound)

Table of content

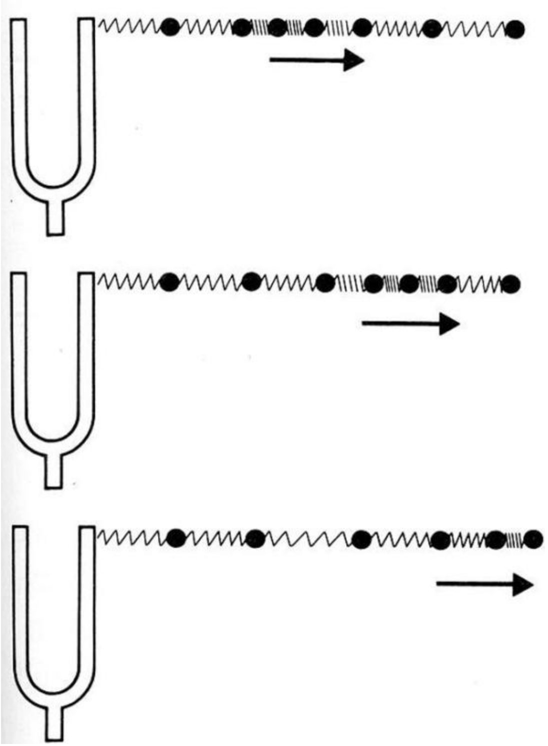
- Physical mechanisms of sound absorption
    -
    - Losses in medium
    -
    -
-
    -
    -
    -
    -

Losses in medium (1)

- Phenomena
  - Viscous losses
    - Involved in strain of fluid elements caused by particle velocity of sound wave
  - Thermal losses
    - Involved in thermal conduction from sound pressure maxima to sound pressure minima in sound wave
  - Relaxation
    - Vibration state of molecules is excited due to sound wave
    - Excited state is relaxed after a while

Losses in medium (2)

- Sound wave propagates in successive condensations and dilatations (rarefactions)
    - Fluid is compressed in condensations and rarefied in dilatations
- Proportional motion between condensations and dilatations causes viscous losses
    - Frictional losses
- Heat transfer from higher temperatures in condensations to lower temperatures in dilatations causes thermal losses
- In relaxation process part of molecular kinetic energy is changed to other molecular energy types causing losses



Rossing, T. D. R. The Science of Sound

Losses in medium (3)

- Loss power / unit volume
  - Proportional to frequency squared
- Viscous loss power P_v
  - Maximum at particle velocity maximum
- Thermal loss power P_l
  - Maximum at sound pressure maximum
- P_v and P_l of the same order
- Important only at high frequencies and in large spaces

$$P_v = \left(\frac{\omega}{c_0}\right)^2 \tfrac{4}{3}\mu\left|\vec{u}\right|^2$$

$$P_l = \left(\frac{\omega}{c_0}\right)^2 k_0 \frac{\gamma-1}{\rho_0^2 c_0^2 c_P}\left|p\right|^2$$

ω : angular frequency, c_0 : speed of sound, μ : viscosity factor,
u : particle velocity, k_0 : thermal conductivity,
γ : adiabatic constant, ρ_0 : density,
c_P : specific heat in constant pressure, p : sound pressure

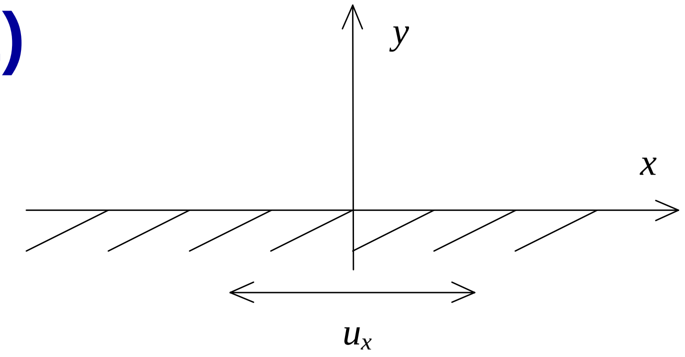
Uosukainen, S. Acoustic Field Theory

Table of content

- Physical mechanisms of sound absorption
  -
  -
  - Losses at boundaries
  -
-
  -
  -
  -
  -

Losses at boundaries (1)

- Based on same mechanisms as above
- Boundaries emphasizes the phenomena
- Viscosity wave u_2 (particle velocity) near boundary
- Thermal wave T' near boundary
- Real part of exponent associated to losses
- Waves couple to acoustic waves u and T
  - Total waves disappear at boundary



$$\vec{u}_2 = u_0 \, \mathrm{e}^{-(1+\mathrm{j})y/\delta_v} \vec{\mathrm{e}}_x$$

$$\vec{u}_{\mathrm{tot}} = \vec{u} + \vec{u}_2$$

$$T' = T_1 \, \mathrm{e}^{-(1+\mathrm{j})y/\delta_l}$$

$$T_{\mathrm{tot}} = T + T'$$

$$\delta_v = \sqrt{\frac{2\mu}{\omega\rho_0}} \qquad \delta_l = \sqrt{\frac{2k_0}{\omega\rho_0 c_P}}$$

u_0 : amplitude of viscous velocity, u : acoustic particle velocity,
T_1 : amplitude for thermal wave, T : acoustic temperature
(temperature fluctuations associated to acoustic fields),
u_{tot}, T_{tot} : total fields
y : distance from boundary, e_x : unit tangential vector on the boundary,
δ_v : boundary layer thickness for viscous wave,
δ_l : boundary layer thickness for thermal wave

Uosukainen, S. Acoustic Field Theory

Losses at boundaries (2)

- Boundary layer thicknesses δ_v and δ_l very small
  - Phenomena important only in close vicinity of boundaries

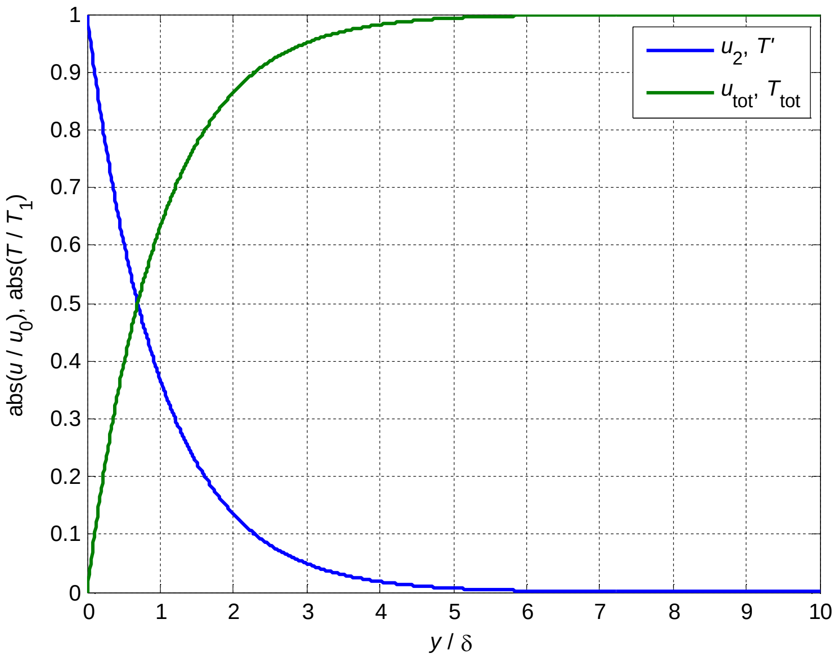
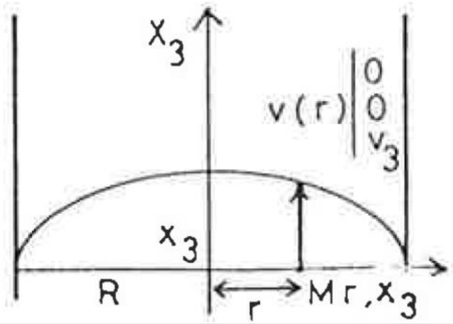


Table of content

- Physical mechanisms of sound absorption
    -
    -
    -
    - Losses in narrow tubes and in small holes and slits
-
    -
    -
    -
    -

Losses in narrow tubes and in small holes and slits (1)

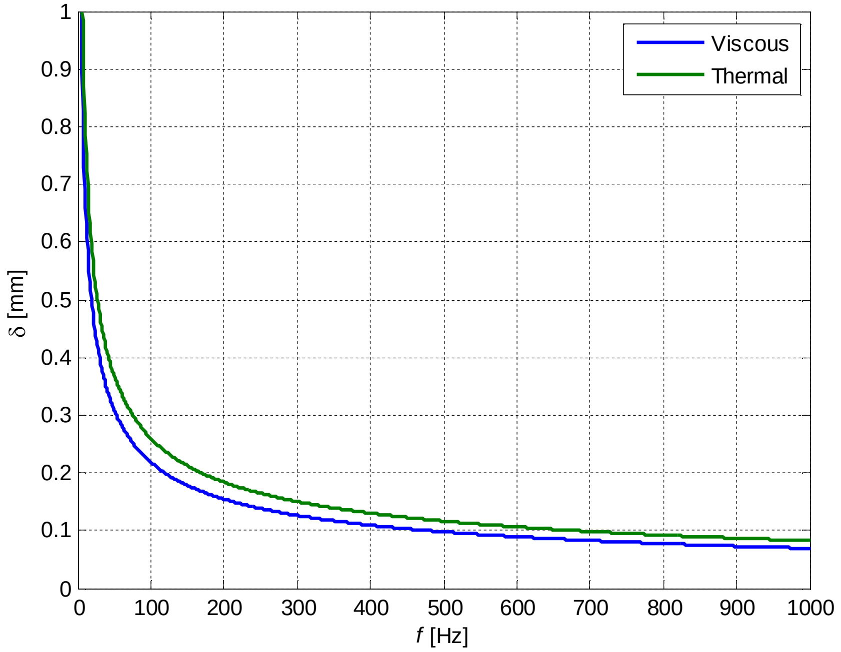
- The viscosity and thermal wave effects are emphasized when
  - Reflecting surfaces form a closed surface
    - Tubes
      - Viscosity and thermal waves are attached to all surfaces decaying exponentially towards the middle of the tube cross section and growing exponentially towards the opposing surface
  - The size of the space between surfaces is of the same order as the boundary layer thicknesses
    - Narrow tubes, small holes and slits
    - Phenomenon affects everywhere between surfaces



Allard, J. F. Propagation of Sound in Porous Media

Losses in narrow tubes and in small holes and slits (2)

- Viscous and thermal boundary layer thicknesses as functions of frequency



Uosukainen, S. Acoustic Field Theory

Losses in narrow tubes and in small holes and slits (3)

- Equivalent complex density in circular tube or hole for viscous wave

$$\bar{\rho}_0 = \rho_0 \left(1 - \frac{2}{K_v R} \frac{J_1(K_v R)}{J_0(K_v R)} \right)^{-1}$$

- Equivalent complex compressibility in circular tube or hole for thermal wave

$$\bar{Q}_0 = Q_0 \left(1 + \frac{2(\gamma - 1)}{K_l R} \frac{J_1(K_l R)}{J_0(K_l R)} \right)$$

- Imaginary parts associated to losses

$$K_v^2 = -\mathrm{j}\frac{\omega\rho_0}{\mu} = -\mathrm{j}\frac{2}{\delta_v^2}$$

- Also end corrections to real and imaginary parts to be taken into account

$$K_l^2 = -\mathrm{j}\omega\frac{c_P\rho_0}{k_0} = -\mathrm{j}\frac{2}{\delta_l^2}$$

J_0, J_1 : Bessel functions of order 0 and 1
R : radius of cross section
Q_0 : compressibility of air

References:
Maa, D.-Y. Noise Control Eng. J. 29(1987)3
Maa, D.-Y. J. Acoust. Soc. Am. 104(1998)5
Allard, J. F. Propagation of Sound in Porous Media
Uosukainen, S. Acoustic Field Theory

Losses in narrow tubes and in small holes and slits (4)

- At low frequencies (cross section small compared to wavelength):

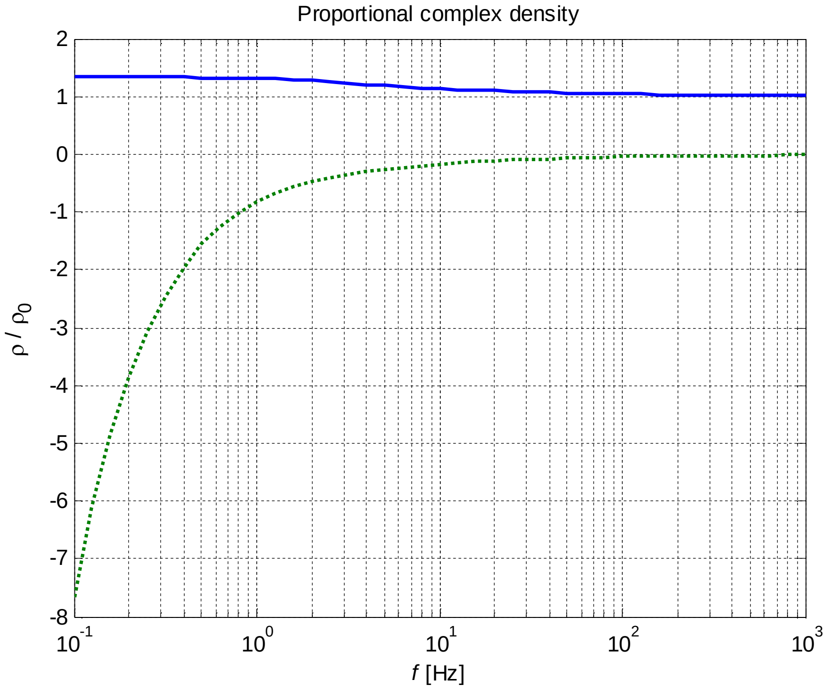
$$\bar{\rho}_0 \approx \rho_0 \left[\tfrac{4}{3} - \mathrm{j} \left(\frac{2\delta_v}{R} \right)^2 \right] \qquad \bar{Q}_0 = Q_0 \left[\gamma - \mathrm{j}(\gamma - 1) \left(\frac{R}{2\delta_l} \right)^2 \right]$$

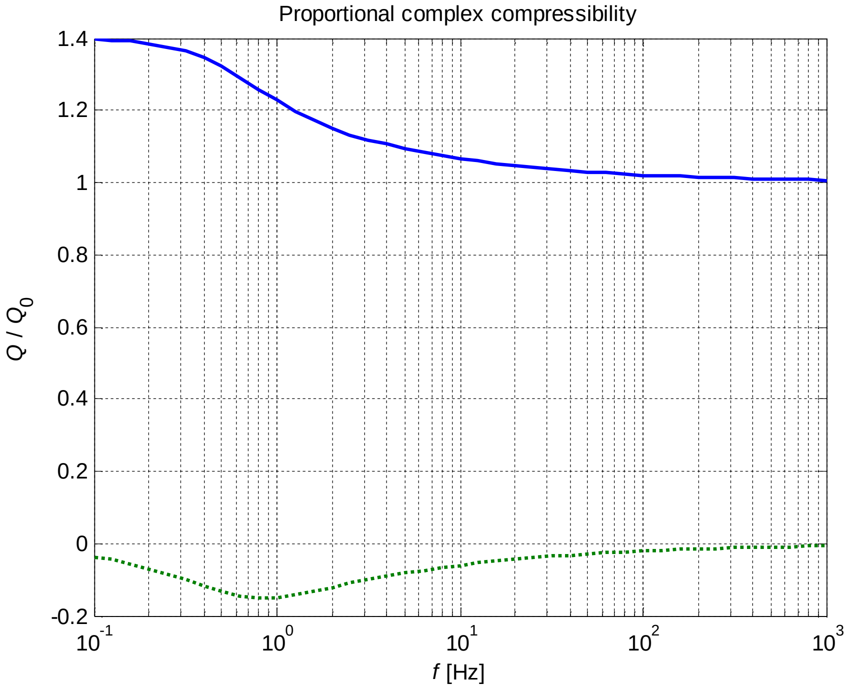
  - Viscous losses grow without limit when $R \to 0$
  - Thermal losses approach zero when $R \to 0$
  - Equivalent density approaches γQ_0 when $R \to 0$

$\Rightarrow$ Viscous losses dominate and isothermal conditions approached instead of adiabatic

Uosukainen, S. Acoustic Field Theory

Losses in narrow tubes and in small holes and slits (5)





R = 0.5 cm
— real part
··· imaginary part

Uosukainen, S. Acoustic Field Theory

Losses in narrow tubes and in small holes and slits (6)

- Applications of above:
    - Perforated / microperforated plates
    - Absorbing materials
        - Most important loss mechanism
            - ”Holes” and ”slits” described by fluid bulk properties
                - Flow resistivity most important
                - Porosity, tortuosity, viscous and thermal characteristic lengths
        - Irreversible effects in the skeleton affect also

- Viscosity of air is the most important phenomenon causing acoustic losses in (micro)perforated plates and absorbing materials

Losses in narrow tubes and in small holes and slits (7)

- Slits:
  - Same conclusions than with tubes and holes can be deduced

$$\bar{\rho}_0 = \rho_0\left(1 - \frac{\tanh(K_v' d/2)}{K_v' d/2}\right)^{-1}$$

$$\bar{Q}_0 = Q_0\left(1 + (\gamma - 1)\frac{\tanh(K_l' d/2)}{K_l' d/2}\right)$$

$$K_v'^2 = \frac{\omega\rho_0}{\mu} = \mathrm{j}\frac{2}{\delta_v^2}$$

$$K_l'^2 = \mathrm{j}\omega\frac{c_P\rho_0}{k_0} = \mathrm{j}\frac{2}{\delta_l^2}$$

d : slit width

Allard, J. F. Propagation of Sound in Porous Media

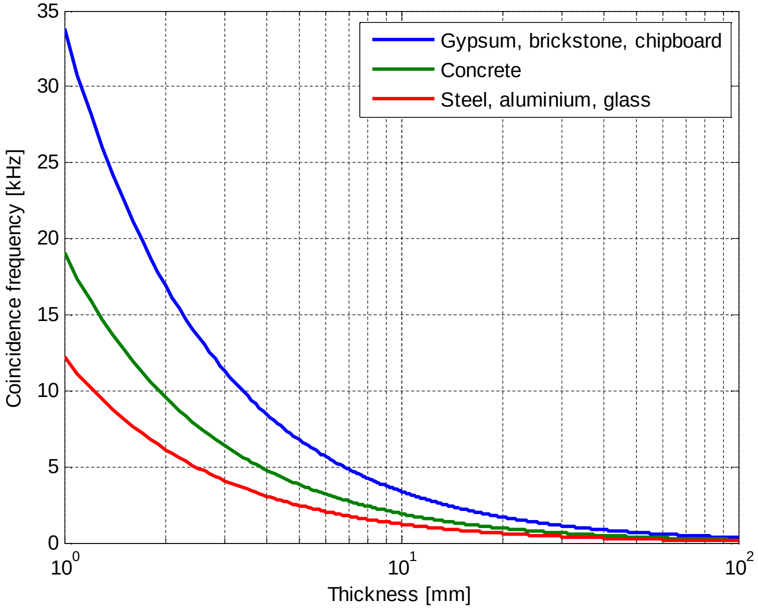
Table of content

Basic concepts (1)

- Coincidence frequency f_c (critical frequency) of a plate
  - The frequency at which the speed of bending wave (~ $\sqrt{f}$) in plate is equal to sound speed in air
  - Plate vibration and sound field are well coupled at frequencies above coincidence frequency and especially at f_c
- Also modal coincidence frequencies for each mode

$$f_c = \frac{c_0^2}{2\pi}\sqrt{\frac{m}{D}} = \frac{c_0^2}{2\pi h}\sqrt{\frac{12(1-\nu^2)\rho_s}{E}}$$

Plate parameters:
m = mass per unit area
ρ_s = density
D = bending stiffness
E = Young’s modulus
h = thickness
ν = Poisson’s ratio



Basic concepts (2)

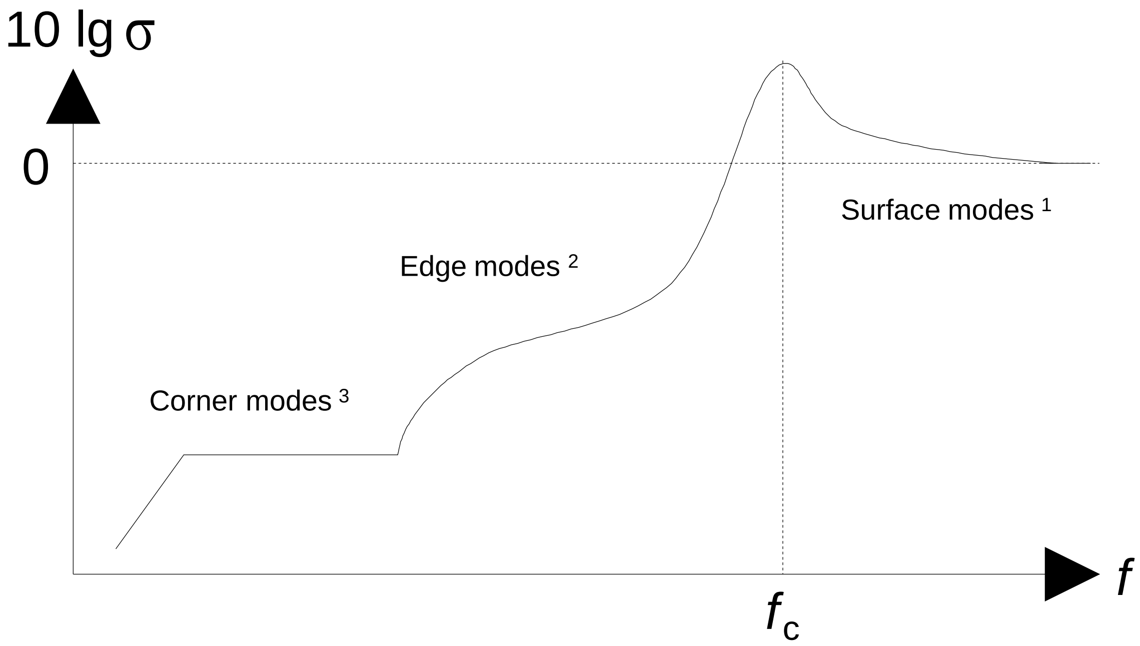
- Radiation ratio σ of vibration
  - Measure of proportional radiation efficiency
  - Depends on vibration types
    - Proportions of resonant and non-resonant vibration
      - Depends on excitation (mechanical / acoustical)

$$P = \sigma \rho_0 c_0 S \left\langle |v|^2 \right\rangle$$

Plate parameters:
P = radiated sound power
S = area
v = vibration velocity
< > = mean value

Basic concepts (3)

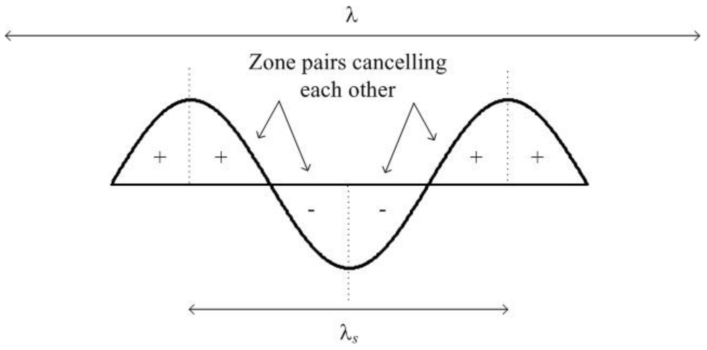
- Radiation ratio of non-resonant vibration of a single mode
    - Typically constant and > 1 at frequencies above modal coincidence frequency
- Modal averaged radiation ratio of resonant vibration:
    - With edge and corner modes, radiation from inefficient surface parts cancel each other

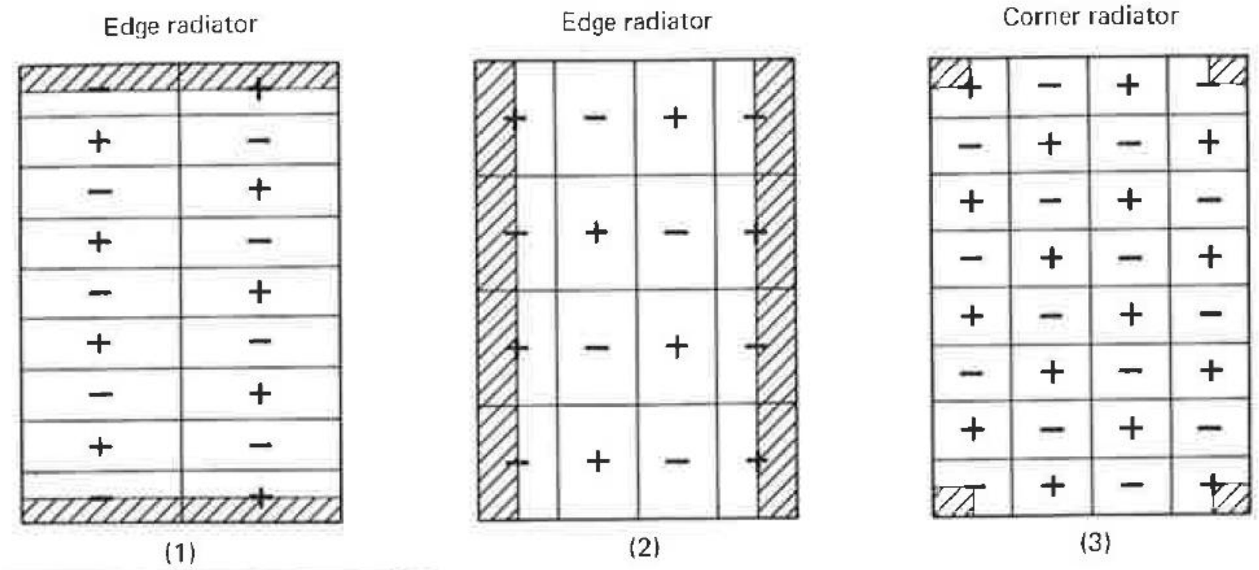


Efficient radiation from:
^{1} whole surface
^{2} plate egdes
^{3} plate corners

Basic concepts (4)

- With resonant vibration below f_c, acoustic wavelength λ > structural wavelength λ_s
  - Near-by vibration zones with opposite signs cancel sound radiation of each other $\rightarrow$ acoustical short circuit
  - Only edges or corners remain unaffected





Regions of uncancelled sound radiation below f_c
Fahy, F. Sound and Structural Vibration

Basic concepts (5)

- Below coincidence frequency, airborne noise is transmitted via a plate mainly by non-resonant vibration except in the resonance region (presented later)
    - Low vibration modes, especially first (volume velocity mode), most important especially well below coincidence frequency
- Above coincidence frequency, both vibration types affect

- Definition of sound insulation (sound transmission loss) R [dB]

$$R = 10\log_{10}\left(\frac{P_i}{P_t}\right)$$

P_i = sound power incident to insulating structure
P_t = sound power transmitted through structure

Table of content

- Physical mechanisms of sound insulation
    - Sound insulation of a single wall in diffuse field

Sound insulation of a single wall in diffuse field (1)

- Two basic phenomena in sound transmission working as parallel transmission paths:
    - Non-resonant transmission
        - Transmission coefficient τ_n
    - Resonant transmission
        - Transmission coefficient τ_r
    - Total transmission coefficient τ
    - Sound insulations R_n, R_r, R
        - In practice, lowest of R_n and R_r determines total sound insulation R
- Wave impedance law for continuums rejects sound insulation at high frequencies

$$\tau = \tau_n + \tau_r$$

$$R_n = 10\log_{10}(1/\tau_n)$$

$$R_r = 10\log_{10}(1/\tau_r)$$

$$R = 10\log_{10}(1/\tau)$$

Sound insulation of a single wall in diffuse field (2)

- Non-resonant transmission
  - Lowest modes above their eigenfrequencies
  - Extra stiffness effects below lowest eigenfrequency and above coincidence frequency

$$\tau_n = \pi\tau_0$$

- Resonant transmission

$$\tau_r = \tau_0 \frac{\pi f_c}{2f} \frac{\sigma^2}{\sigma\sqrt{\tau_0} + \eta}$$

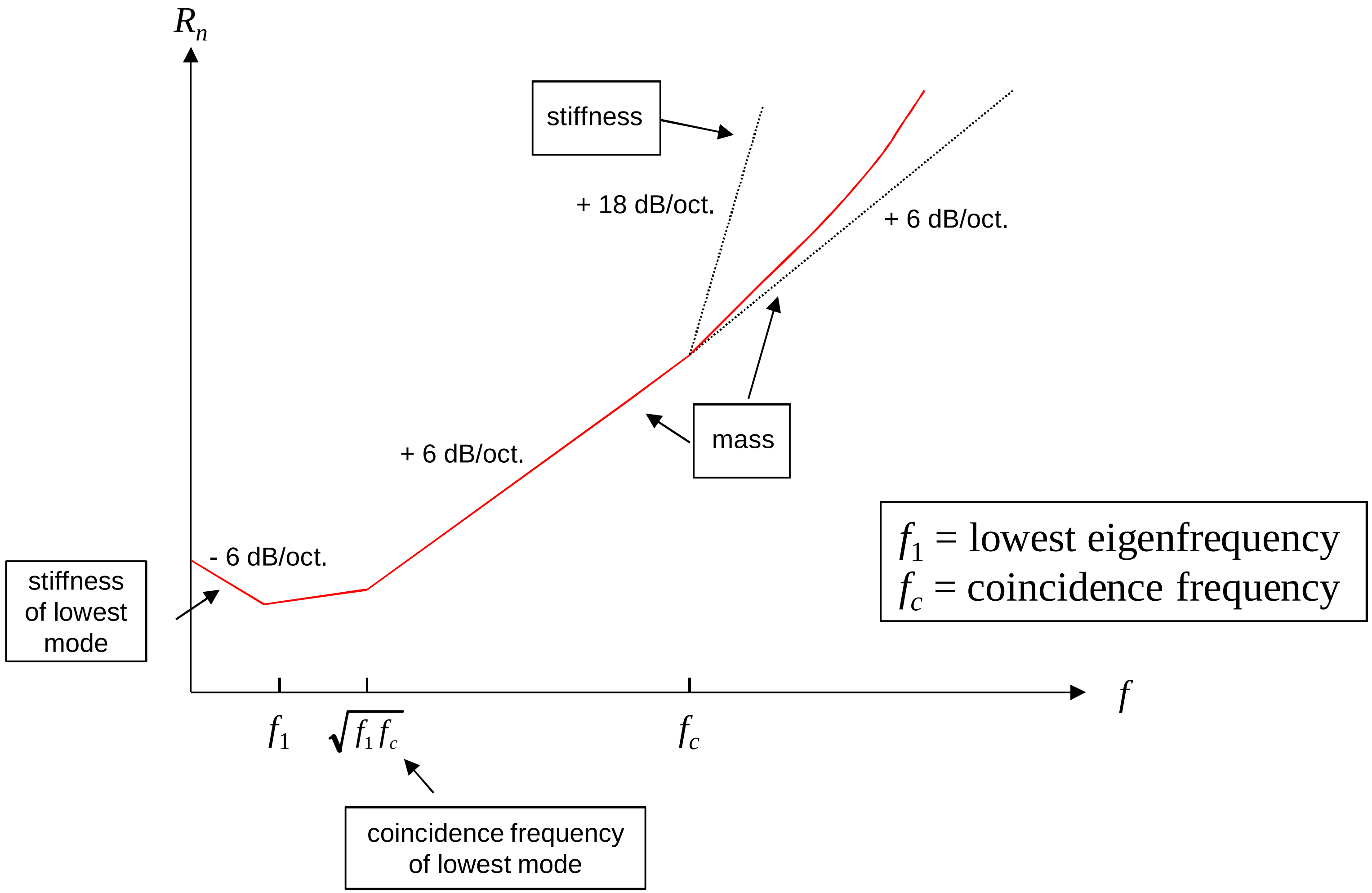
- Auxiliary variable τ_0
  = non-resonant transmission coefficient
  with normal incidence (”mass law”)

$$\tau_0 = \frac{1}{1 + \left(\frac{\omega m}{2\rho_0 c_0}\right)^2}$$

Wall parameters:
m = mass per unit area
f_c = coincidence frequency
σ = radiation ratio of resonant vibration
η = loss factor

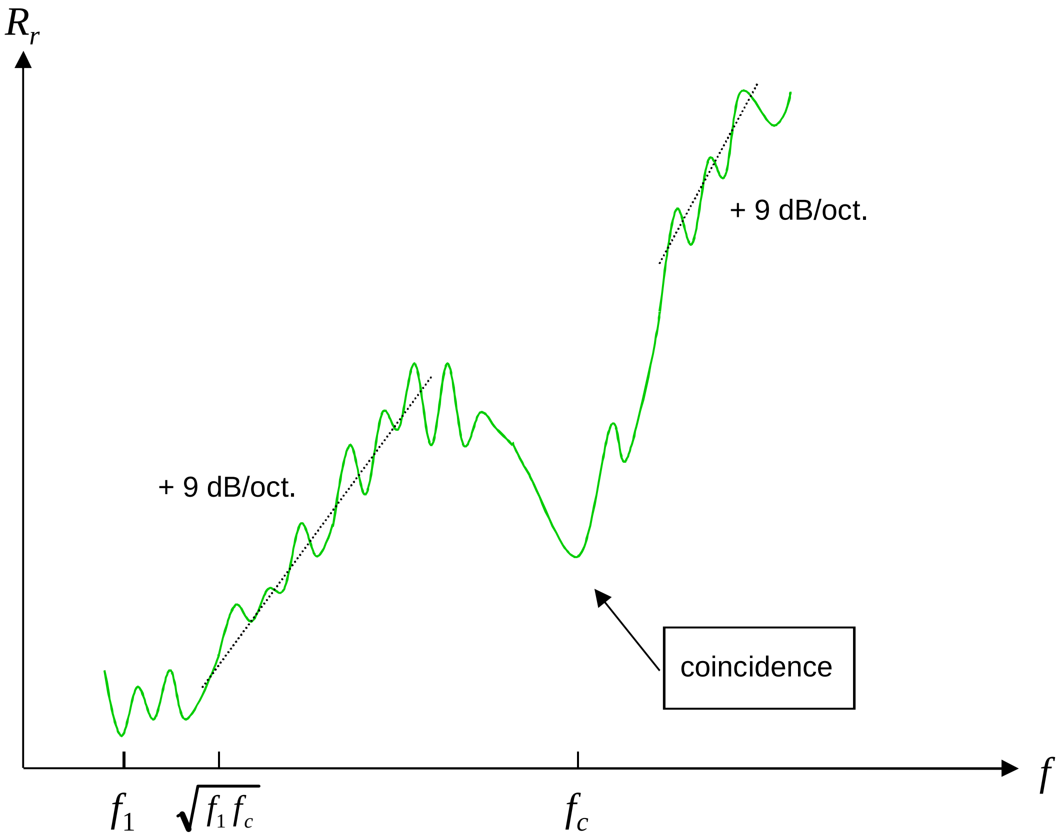
References:
Beranek, L. L. Noise and Vibration Control
Uosukainen, S. & Pesonen, K. Ääntäeristävien koteloiden äänitekninen mitoitus ja valinta

Non-resonant transmission

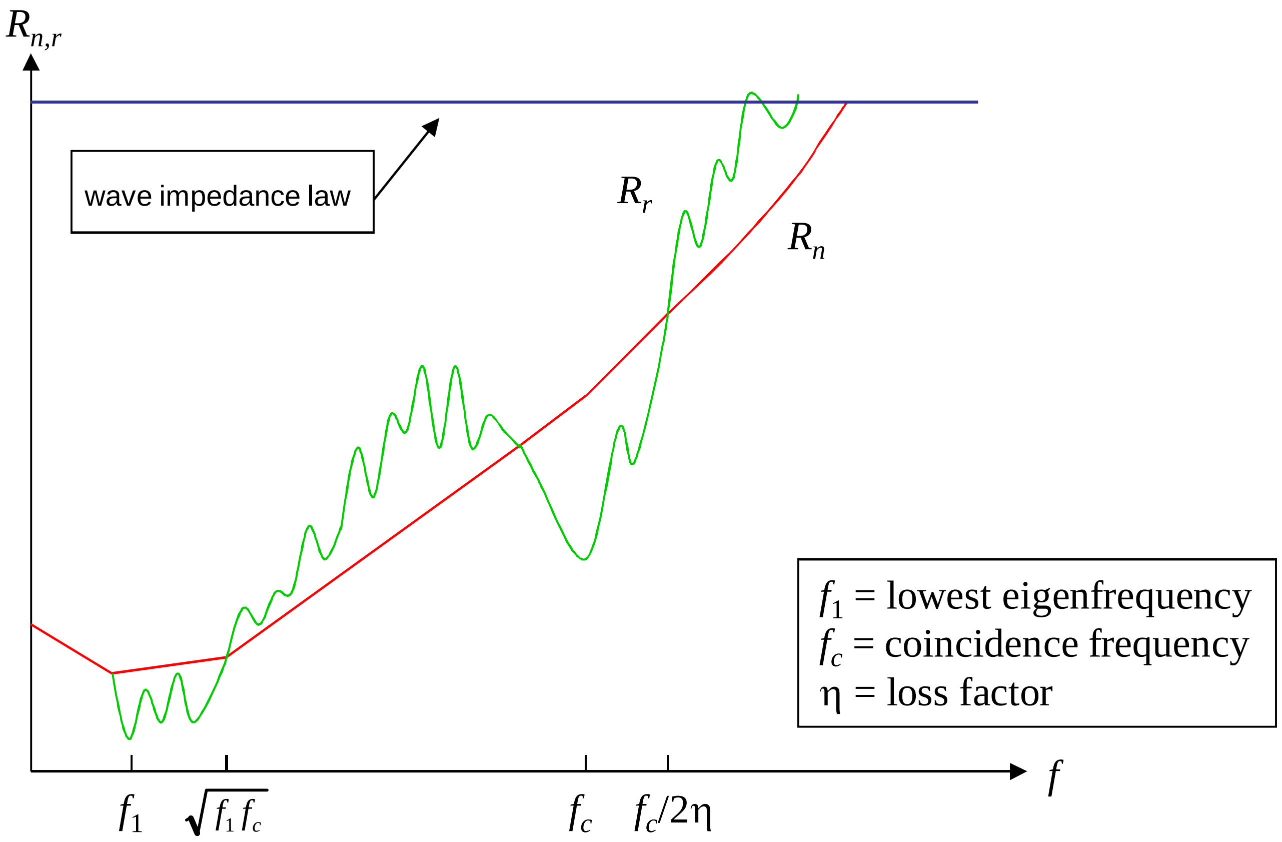


f_1 = lowest eigenfrequency
f_c = coincidence frequency

Resonant transmission

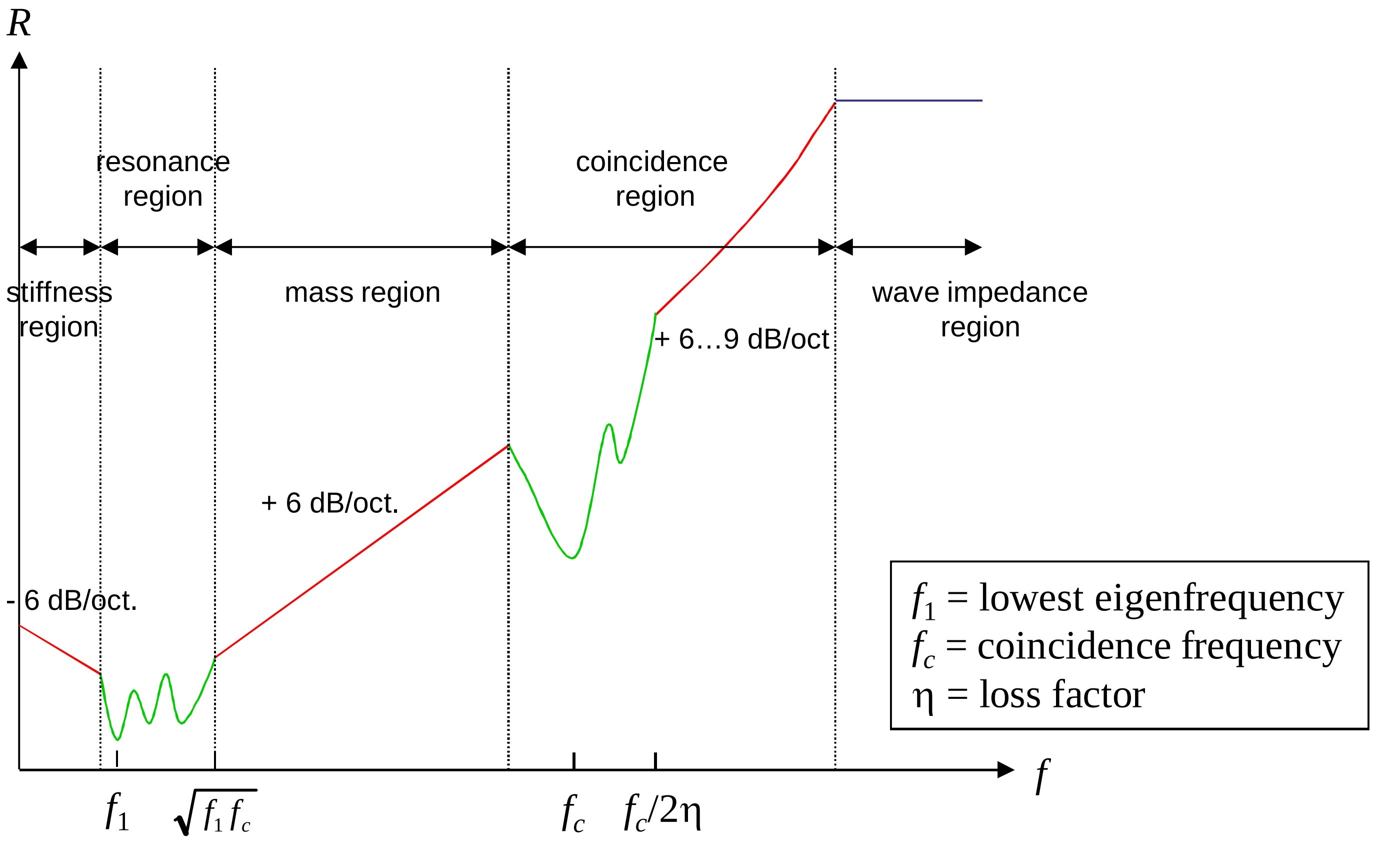


Non-resonant and resonant transmission



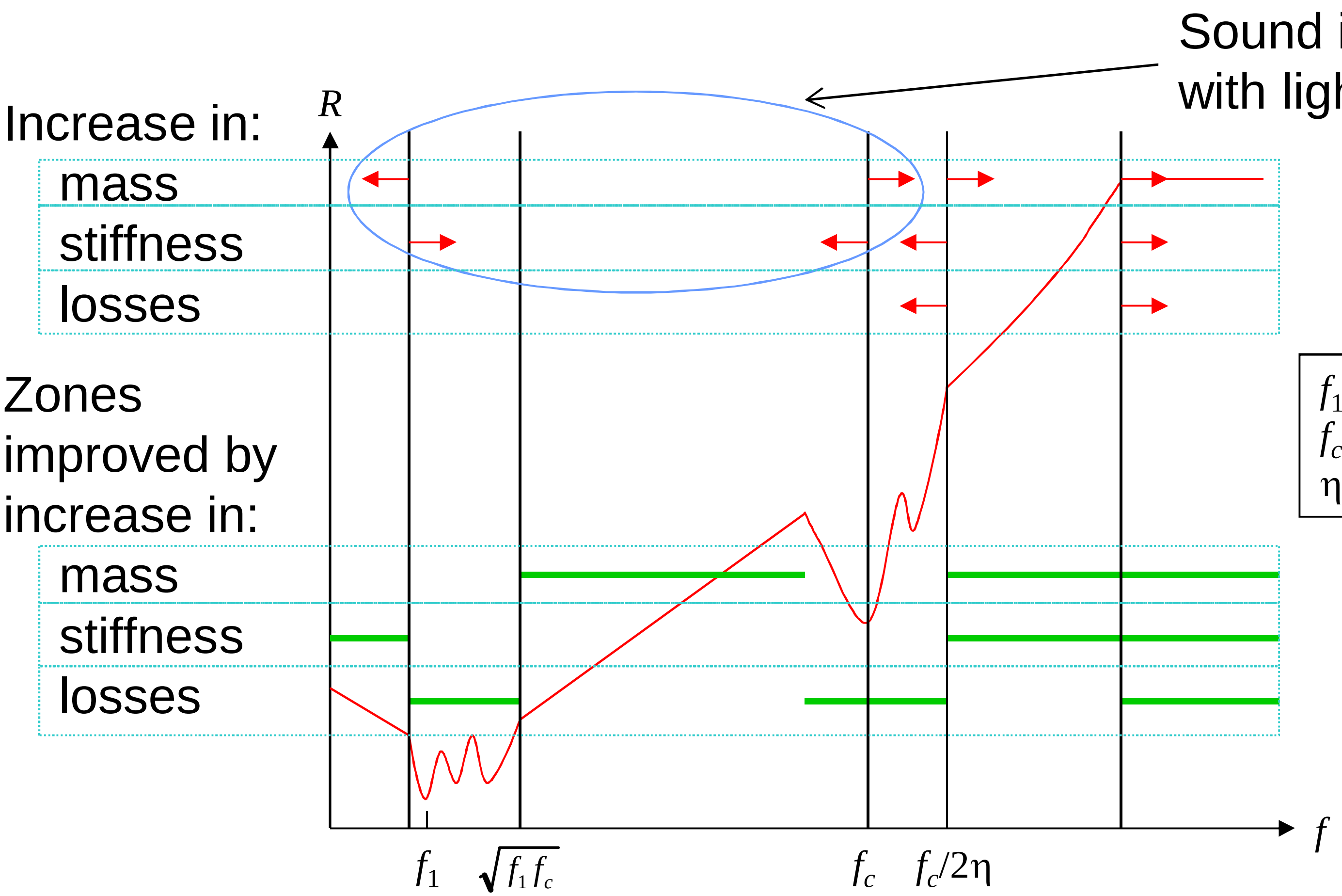
f_1 = lowest eigenfrequency
f_c = coincidence frequency
η = loss factor

Total transmission



f_1 = lowest eigenfrequency
f_c = coincidence frequency
η = loss factor

Effects of material parameters on sound insulation



Sound insulation poor with light and stiff plates

Increase in:
- mass
- stiffness
- losses

Zones improved by increase in:
- mass
- stiffness
- losses

f_1 = lowest eigenfrequency
f_c = coincidence frequency
η = loss factor

Mass increase:	Stiffness increase:	Loss increase:
Barrier mats	Pretensioned or curved plates Stiffeners	Lossy edge mounting Viscoelastic layers

Tanttari, J. & Saarinen, K. Työkoneiden melun vähentäminen - perusteet

Table of content

-
  -
  -
  -
  -
- Physical mechanisms of sound insulation
  -
  -
  - Sound insulation of a double wall in diffuse field
  -

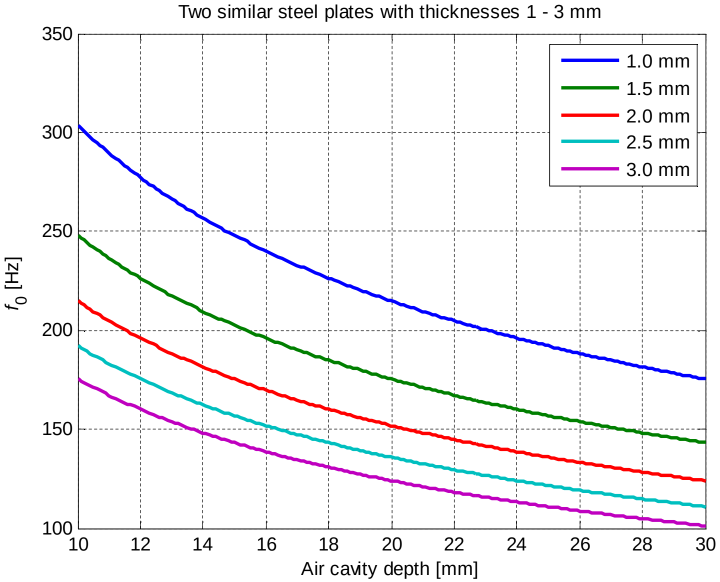
Sound insulation of a double wall in diffuse field (1)

- Double-wall resonance frequency f_0
    - Obtained from Eq. (10) in D2.2, m displaced by equivalent mass m_e
    - Mass-air-mass resonance
- Three frequency regions with different behavior:
    - $f > f_0$
    - $f \approx f_0$
    - $f < f_0$

$$f_0 = \frac{c_0}{2\pi}\sqrt{\frac{\rho_0}{m_e h}}$$

$$m_e = \frac{1}{1/m_1 + 1/m_2}$$

h = depth of air cavity
subscripts 1 and 2 = indices of walls 1 and 2



Sound insulation of a double wall in diffuse field (2)

- At frequencies above double-wall resonance
  - With reasonable amount of absorption in cavity, R_1 and R_2 in dBs are summed in total sound insulation R_{12} (max. $R_1 + R_2 + 6$)

effect of direct field in cavity

effect of reverberant field in cavity

$$R_{12} = R_1 + R_2 - 10\log_{10}\left(\frac{1}{4} + \frac{1}{R_v / S + \tau_1 + \tau_2}\right)$$

$$R_v = \frac{\alpha A}{(1-\alpha)}$$

R_v = room constant of air cavity
S = wall area (one side)
αA = absorption area of air cavity
α = mean absorption coefficient inside air cavity
subscripts 1 and 2 = indices of walls 1 and 2

References (adapted):
Beranek, L. L. Acoustics
Beranek, L. L. Noise and Vibration Control
Uosukainen, S. & Pesonen, K. Ääntäeristävien koteloiden äänitekninen mitoitus ja valinta

Sound insulation of a double wall in diffuse field (3)

- At double-wall resonance frequency
    - Sound insulation is close to 0 dB without absorbents in cavity and with a small amount of mechanical damping
        - Increasing internal losses to double increases sound insulation 6 dB
        - Using walls of different mass per unit area increases sound insulation
            - This degrades sound insulation at higher frequencies
- At frequencies below double-wall resonance
    - Sound insulation is as with a single wall, m replaced by total mass $m_1 + m_2$

Fahy, F. & Gardonio, P. Sound and Structural Vibration

Sound insulation of a double wall in diffuse field (4)

- Double wall with identical walls

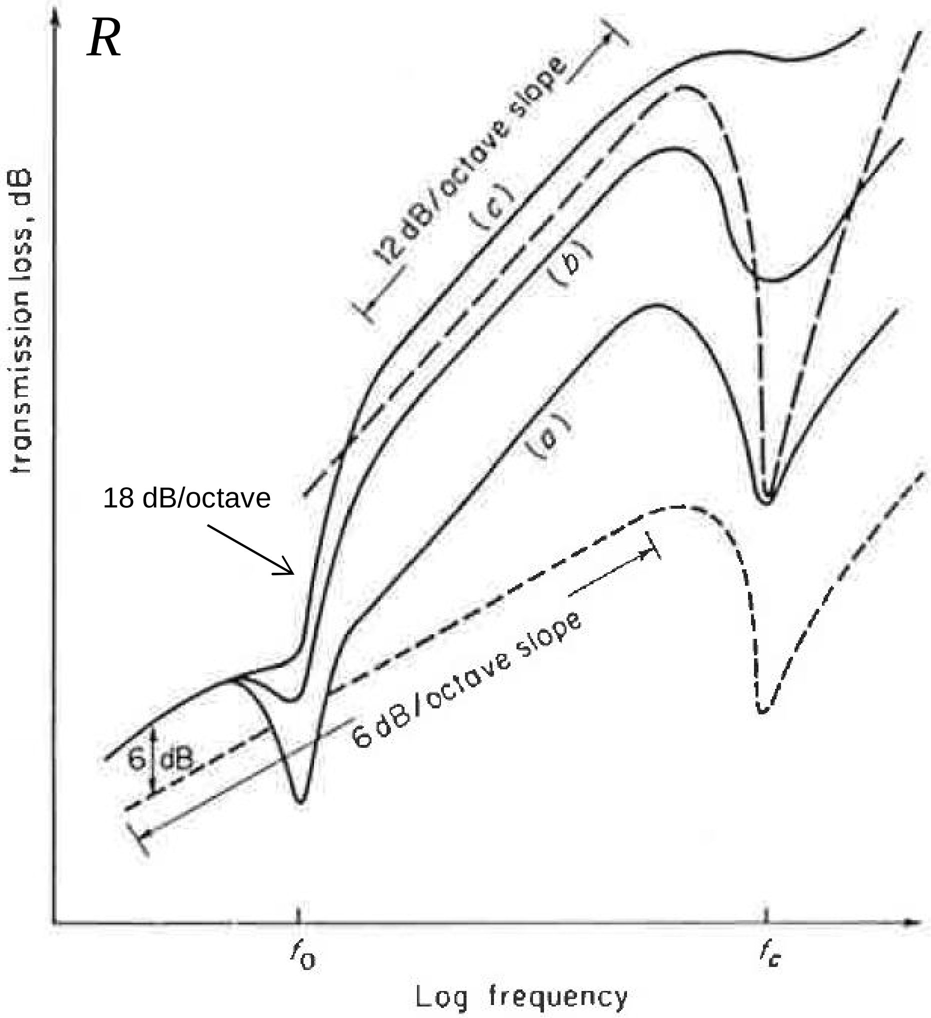
- Lower dashed curve:
  single wall $R = R_1$
- Upper dashed curve: $R = 2R_1$

(a) No absorbent in cavity

(b) Some absorbent in cavity

(c) Cavity uniformly filled with absorbent

Beranek, L. L. Noise and Vibration Control



Sound insulation of a double wall in diffuse field (5)

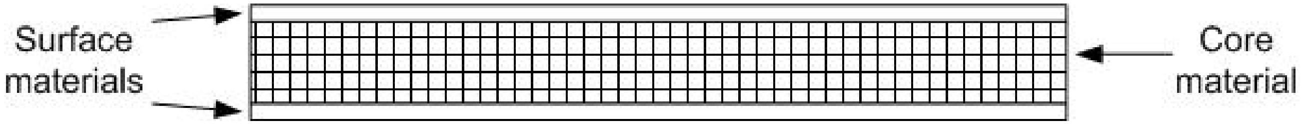
- Mechanical coupling via supporting structures or absorbent in cavity degrades sound insulation at whole frequency range, especially with resonant vibration
    - Double-wall resonance occurs at higher frequencies
    - Coupling decreases with resilient mounting
- Effects of coincidence and lowest modes can be splitted in two frequencies with lower dips using different walls
    - Sound insulation at high frequencies decreases
- Air cavity resonances degrade sound insulation at high frequencies
    - Effects decrease with using absorbent in air cavity
- Effects of absorbent (increase of losses) are higher with deeper cavities

Tanttari, J. & Saarinen, K. Työkoneiden melun vähentäminen - perusteet

Table of content

- Physical mechanisms of sound insulation
  - Sound insulation of sandwich structures

Sound insulation of sandwich structures



- Light and stiff (in normal direction) structures
  - Sound insulation properties between single and double wall
  - Coincidence frequency low
    - Coincidence can be avoided by tuning shear wave speed c_s in core material below speed of sound c_0
      - Rejects bending wave speed below c_0
  - Double-wall resonance frequency typically higher than with a double wall with air cavity
    - Stiff core material and light masses at surfaces
    - Can be tuned above relevant frequencies by more stiff core structure in normal direction (e.g., honeycomb)

$$c_s = \sqrt{\frac{Gh}{m}}$$

Tanttari, J. & Saarinen, K. Työkoneiden melun vähentäminen - perusteet

G = shear modulus of core material
h = thickness of core
m = total surface mass of surface plates

VTT creates business from technology