FORUM ACUSTICUM EURONOISE 2025

SUMMER SCHOOL

Fundamentals of Acoustics

Course outline

Time table / Lecture modules	TOPIC
DAY 1 - 21/06/2024	
8:30-9:00 h	Registration
9:00-10:30 h	**Lecture**: Introduction (why do we study acoustics) Basic signal properties: Period, wavelength and frequency. Definitions, and fundamental equations for propagation of sound.
10:30-11:00 h	Coffee break
11:00-12:00 h	**Lecture**: More advanced signal properties: Pure and complex sounds, frequency decomposition and sound spectrum. Acoustic quantities: levels and their manipulation, Octave bands and physiology of hearing, binaural hearing.
12:00-13:00 h	Plenary session I. Deep learning, AI and acoustics (Prof. Hamid Krim. North Carolina State University) **(All the topics)**
13:00-14:00 h	Lunch
14:00-15:30 h	**Tutorial**: Tools for acoustic analysis Recording of recorded sound Manipulation of sound
15:30-16:00 h	Coffee break
16:00-17:00 h	**Lecture**: Wave-surface interactions, 1D wave equation solution including reflection cofficient Sound absorption, types of sound absorption materials

Course outline

DAY 2 - 22/06/2024	
9:00-10:30 h	**Lecture**: Sound insulation, governing principles. **Tutorial**: sound absorption and insulation
10:30-11:00	Coffee break
11:00-12:00 h	**Lecture**: Sound propagation in open and enclosed spaces.
12:00-13:00 h	Plenary session II. Carrier paths in Acoustics **(All the topics)**
13:00-14:00 h	Lunch
14:00-15:30 h	**Tutorial**: Sound propagation in open and enclosed spaces HBK demonstration
15:30-16:00	Coffee break
16:00-17:00 h	Test

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FACTS & FIGURES

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Dutch version

Building Acoustics TU/e

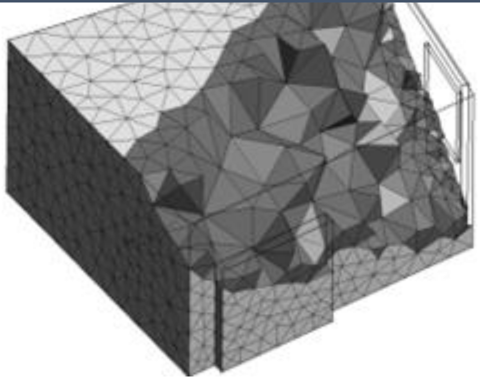
Research dealing with the propagation of sound in the built environment at multiple scales: city level, building level and building element level



Building Acoustics TU/e

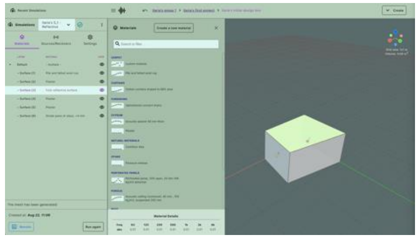
Building Acoustics TU/e

Research

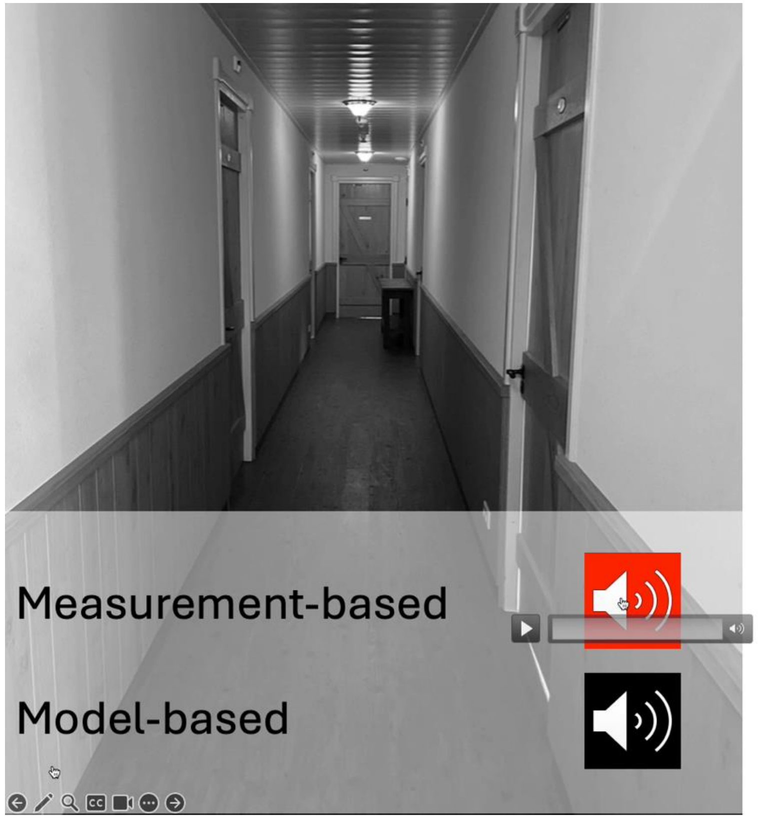


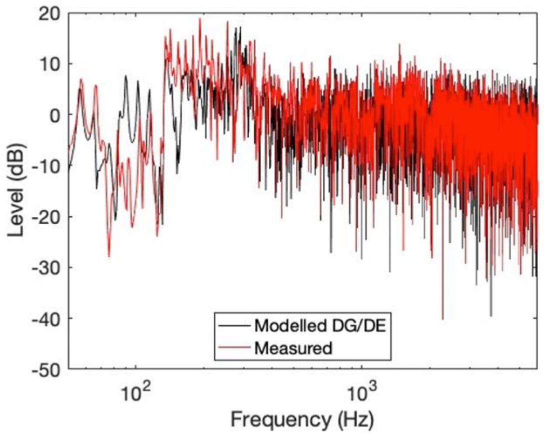
Education

Software



Impact


Measurement-based
Model-based


Level (dB)
Frequency (Hz)
Modelled DG/DE
Measured


Slaapkamer 3
Badkamer
Slaapkamer 4
Badkamer mindervalide
R8
R7
R6
R5
R4
R3
R2
R1
S1

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My view on open science

MAARTEN HORNIKX ON WHY OPEN SCIENCE IS ESSENTIAL FOR SOCIETAL IMPACT

‘Open science is not a bonus, but the essence of good research'

JUNE 2, 2025

Hornikx: “We need to make our non-traditional outputs, like software, much more visible — and show what kind of impact they have. That’s when you can say: this is modern science, and here’s the difference we’re making.”

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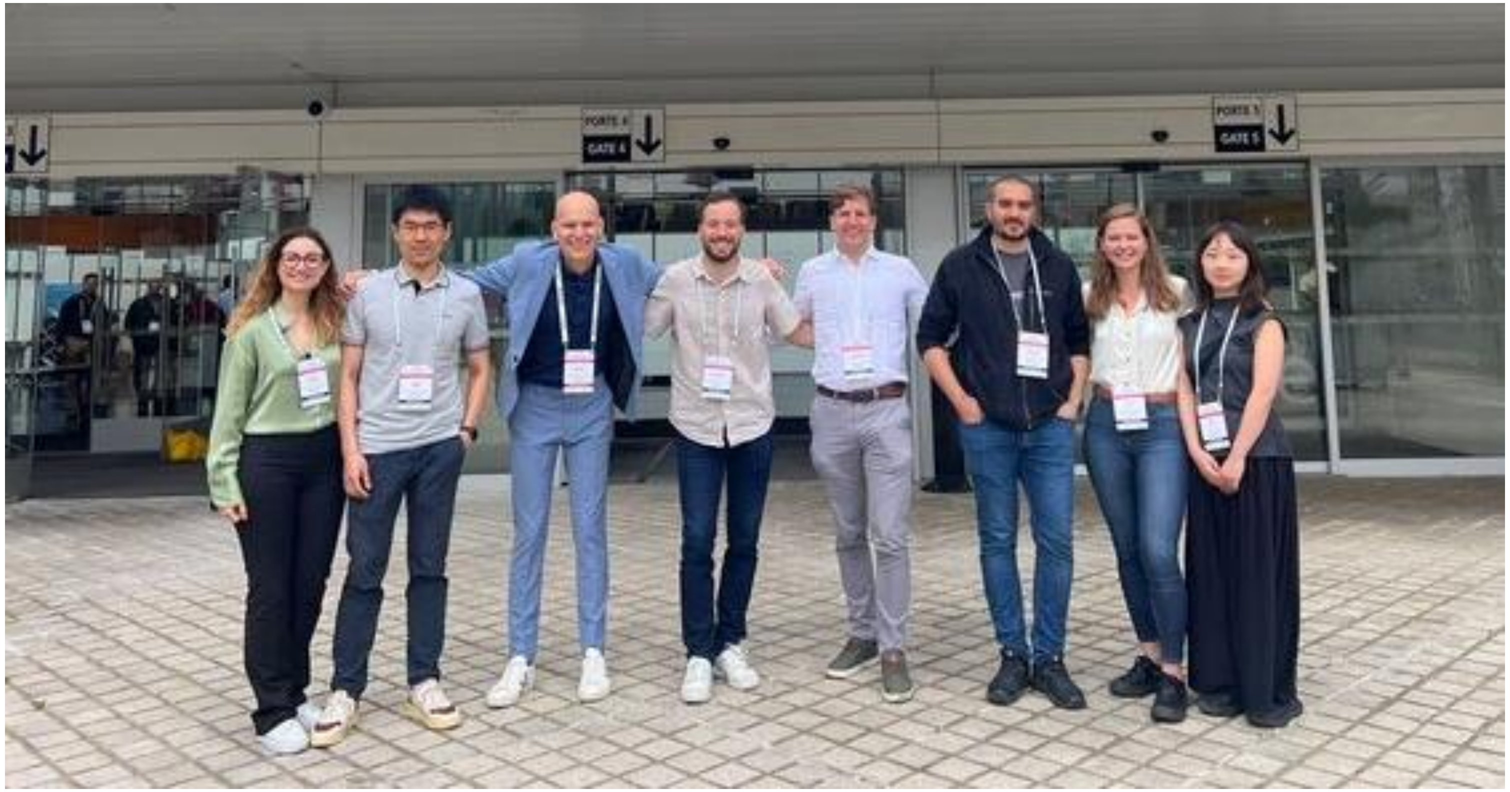
Building Acoustics Research group



Website

LinkedIn

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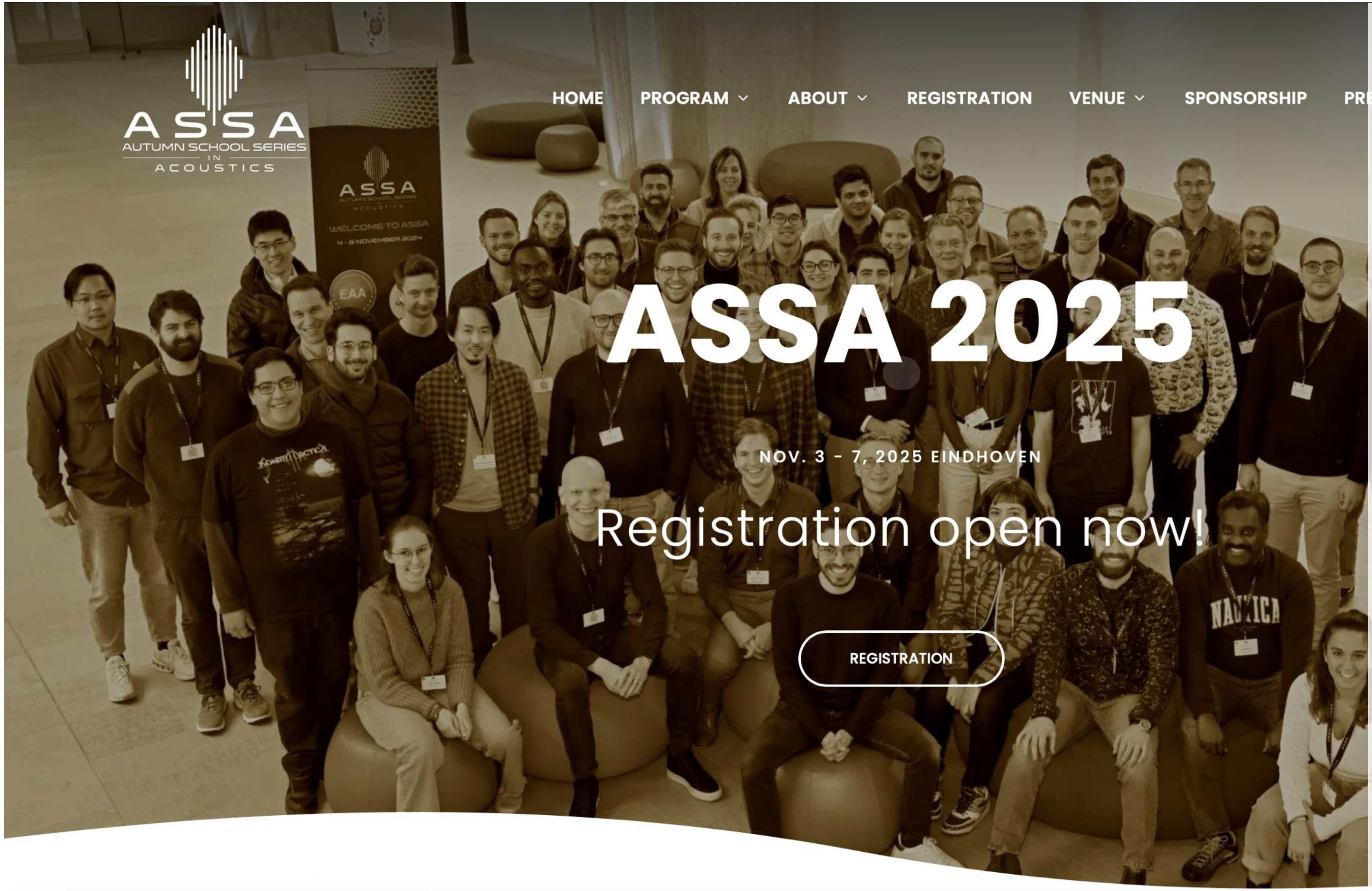

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Saturday 21 June

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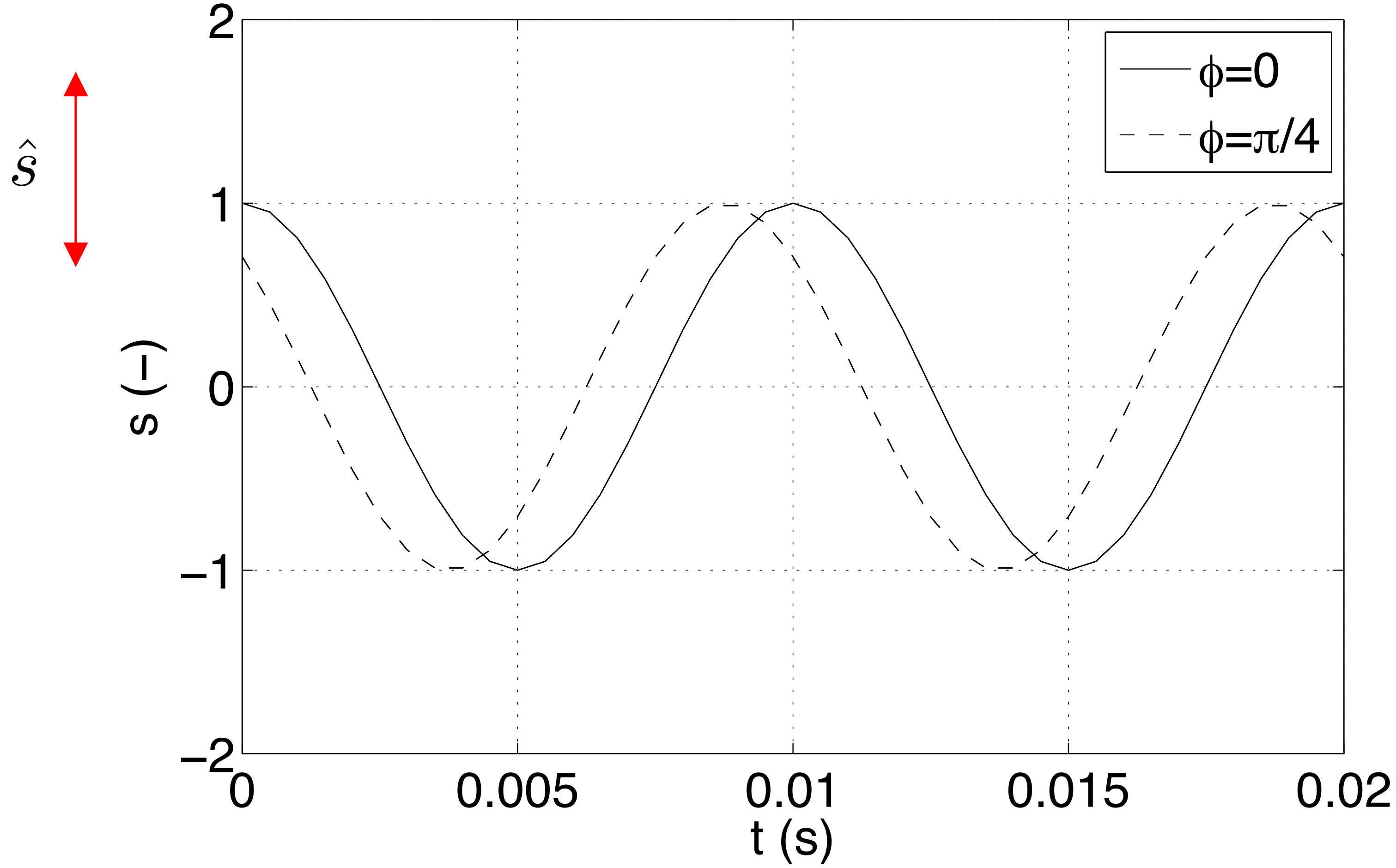
Sound and vibration signals: harmonic motions

$$s(t) \quad = \quad \hat{s}\cos(\omega t + \phi)$$

$s(t)$	Displacement (m)
$\hat{s}$	Displacement amplitude
ω	Angular frequency
ϕ	Phase shift

Sound and vibration signals: harmonic motions

$$s(t) \quad = \quad \hat{s}\cos(\omega t + \phi)$$



Harmonic motion: time averaged signal

$$\langle s^2 \rangle \quad = \quad \frac{1}{t_0} \int_0^{t_0} [s(t)]^2 dt = \tilde{s}^2$$

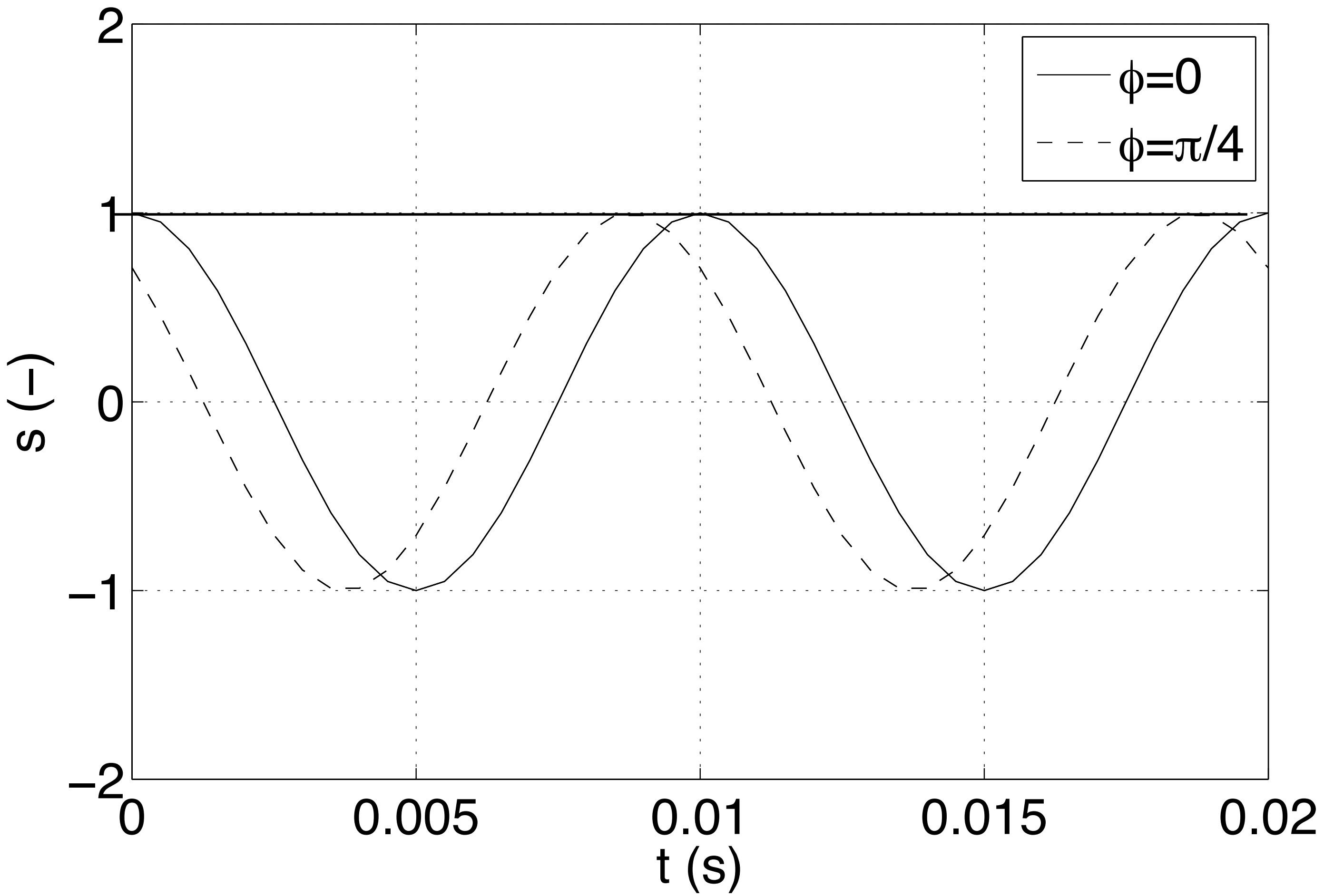
$$\langle s^2 \rangle = \tilde{s}^2$$ Effective value

$$\tilde{s} \quad = \quad \hat{s}/\sqrt{2}$$ For harmonic signals

Harmonic motion: time averaged signal

$$\tilde{s} \quad = \quad \hat{s}/\sqrt{2}$$

For harmonic signals



Demo

Complex numbers

Easy way to compute the amplitude (effective value) and phase of a harmonic signal

$$
\begin{aligned}
s(t) &= \hat{s}e^{j(\omega t+\phi)} \\
e^{jz} &= \cos(z) + j\sin(z)
\end{aligned}
$$

Physical signal is the real value of the complex signal, thus

$$\hat{s}\cos(\omega t + \phi)$$

Complex numbers

$$s(t) = \hat{s}e^{j(\omega t+\phi)}$$

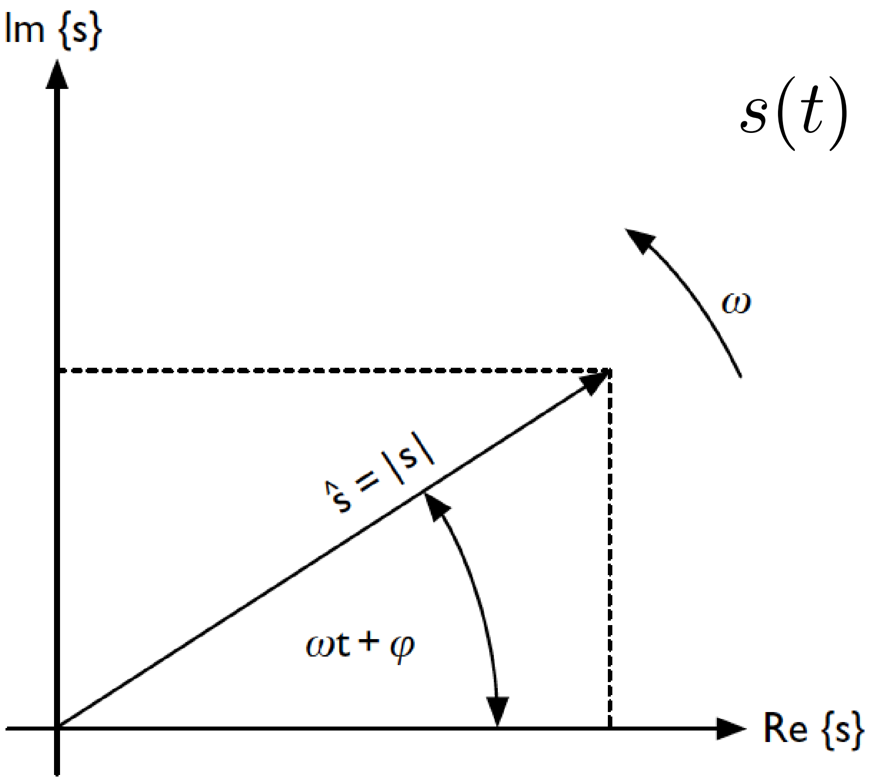


Figure 2.4 Phasor representation of a harmonic oscillation.

Demo

Kuttruff, H. (2007). *Acoustics: an introduction.* CRC Press.

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Complex numbers

Absolute value of s

$$
\begin{aligned}
|s(t)| &= \sqrt{Re\{s(t)\}^2 + Im\{s(t)\})^2} \\
&= \sqrt{Re\{\cos(\omega t + \phi)\}^2 + Im\{\sin(\omega t + \phi)\})^2}
\end{aligned}
$$

Argument of s

$$
\begin{aligned}
\angle s &= \operatorname{atan}\left(\frac{Im\{s(t)\}}{Re\{s(t)\}}\right) && \text{for Im } \{s(t)\} > 0 \\
&= \pi + \operatorname{atan}\left(\frac{Im\{s(t)\}}{Re\{s(t)\}}\right) && \text{for Im } \{s(t)\} < 0,\ Re\{s(t)\} > 0 \\
&= -\pi + \operatorname{atan}\left(\frac{Im\{s(t)\}}{Re\{s(t)\}}\right) && \text{for Im } \{s(t)\} < 0,\ Re\{s(t)\} < 0
\end{aligned}
$$

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Beats

Example of calculating with complex numbers`

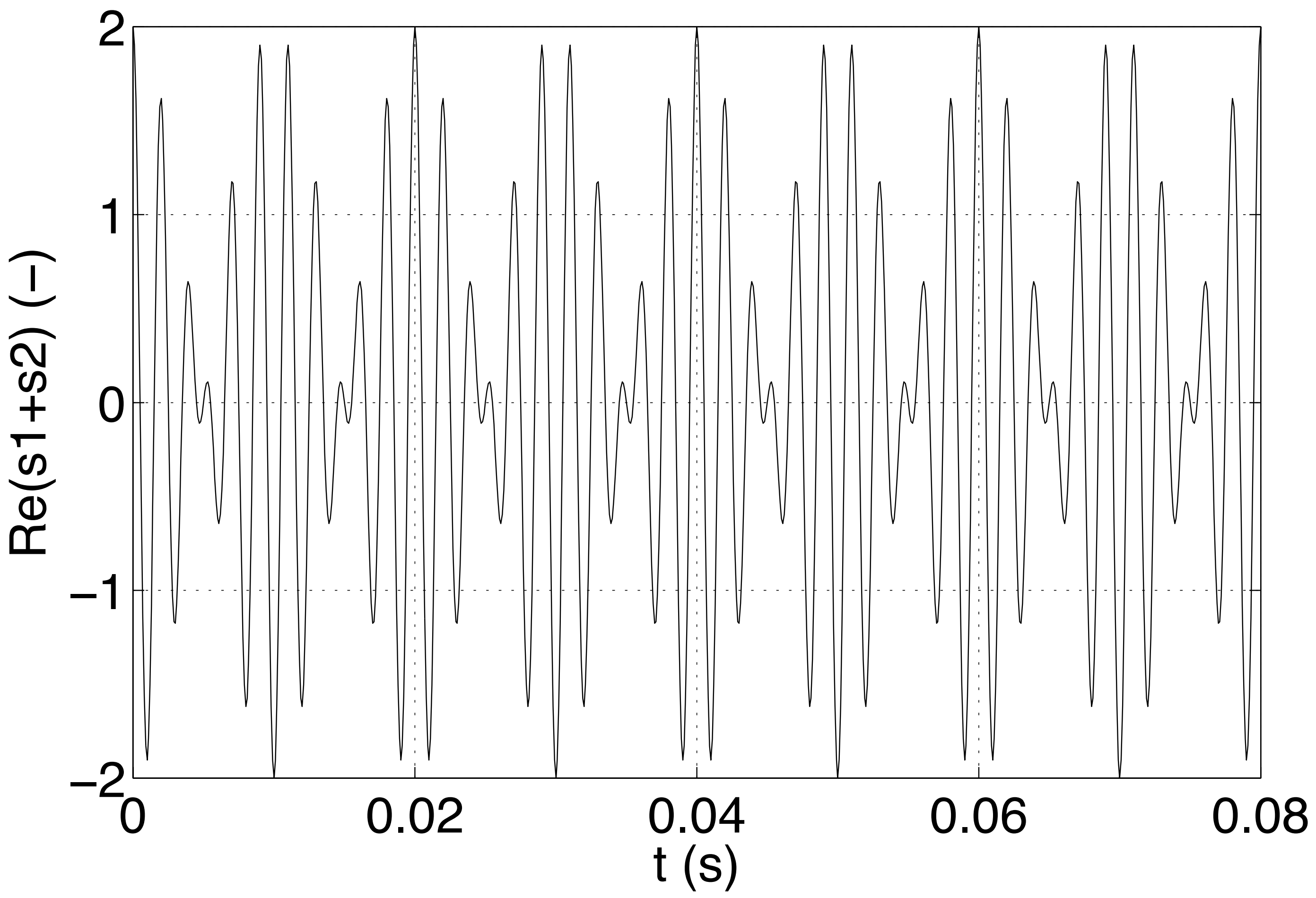
$$
\begin{aligned}
s_1(t) &= \hat{s}e^{j(\omega+\Delta\omega)t} \\
s_2(t) &= \hat{s}e^{j(\omega-\Delta\omega)t} \\
s_1 + s_2 &= \hat{s}\left(e^{-j\Delta\omega t} + e^{j\Delta\omega t}\right)e^{j\omega t} = 2\hat{s}\cos(\Delta\omega t)e^{j\omega t} \\
Re\{s_1 + s_2\} &= 2\hat{s}\cos(\Delta\omega t)\cos(\omega t)
\end{aligned}
$$

Beats

S1

S2

S1+S2



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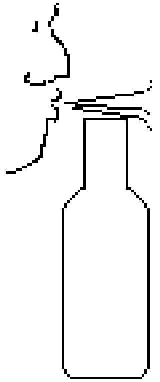
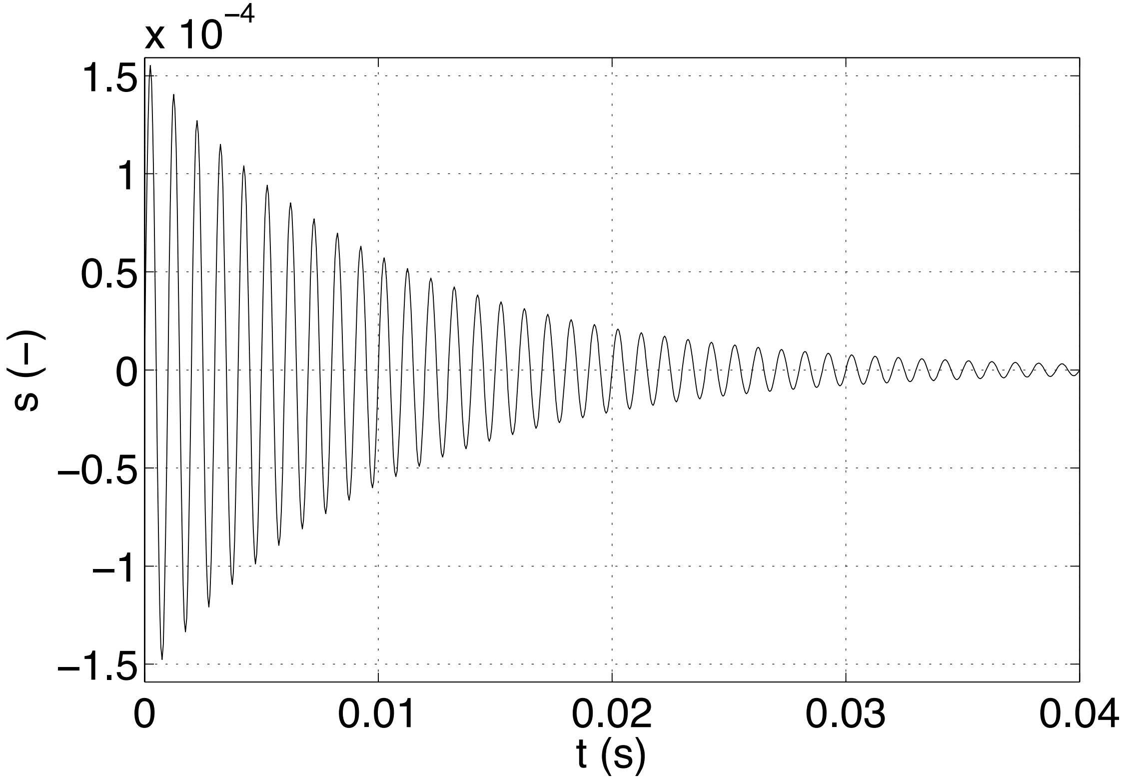
Transient response

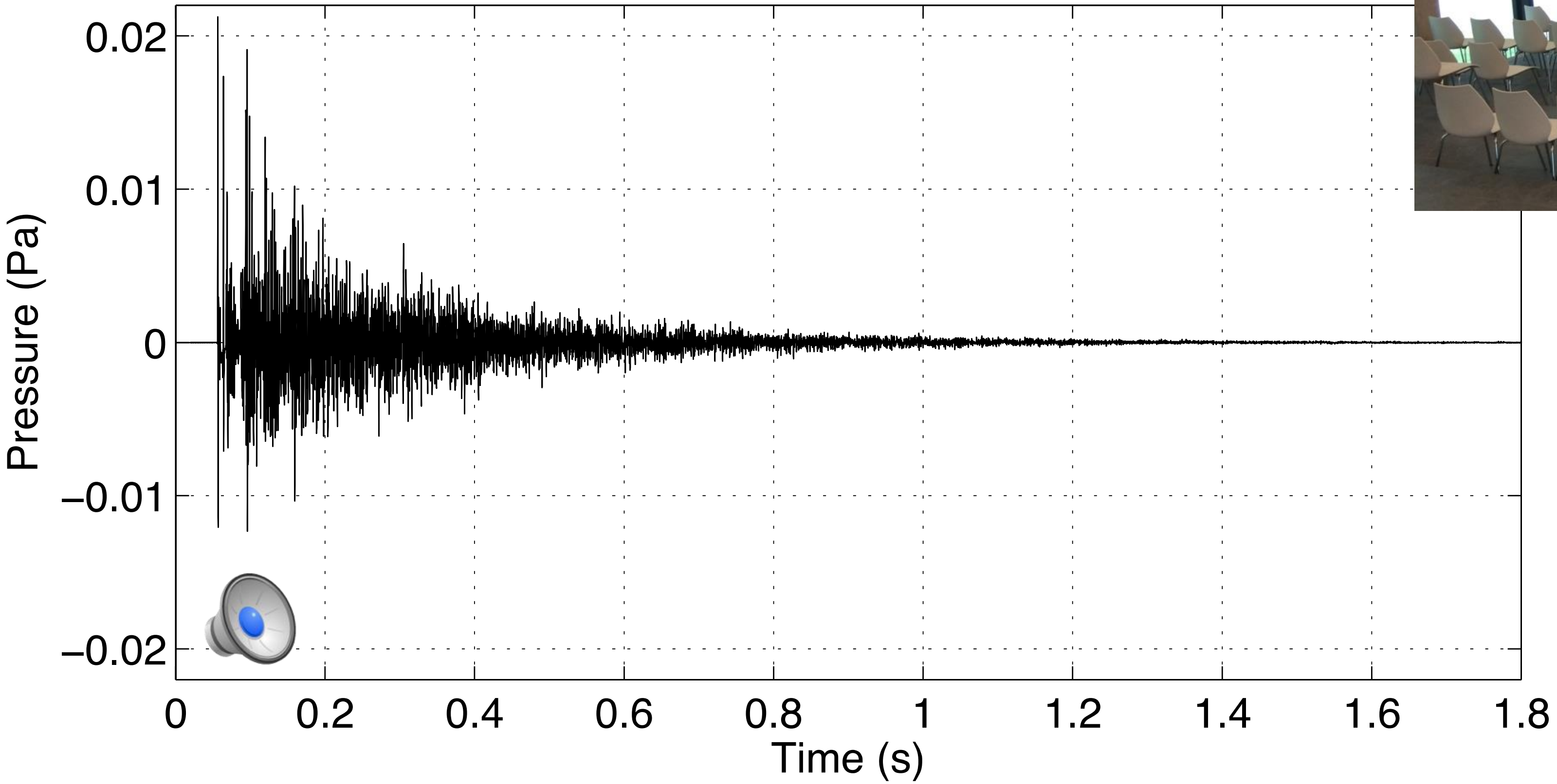




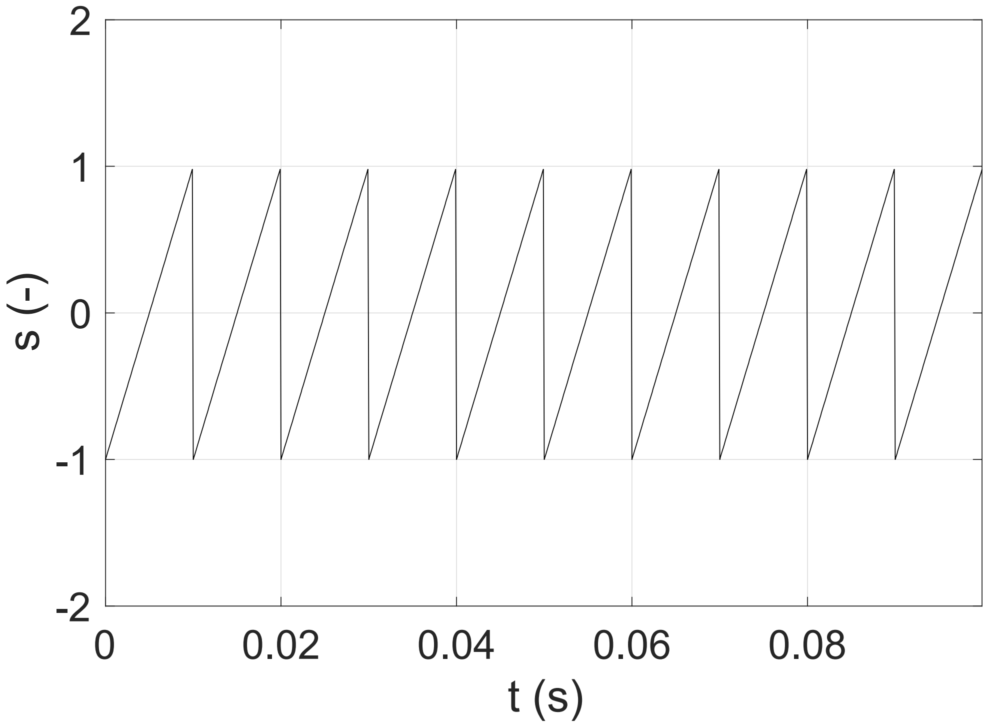
$$s(t) \quad = \quad \hat{s}e^{\delta t}e^{j(\omega t+\phi)}$$

Demo

Transient response



Periodic signals



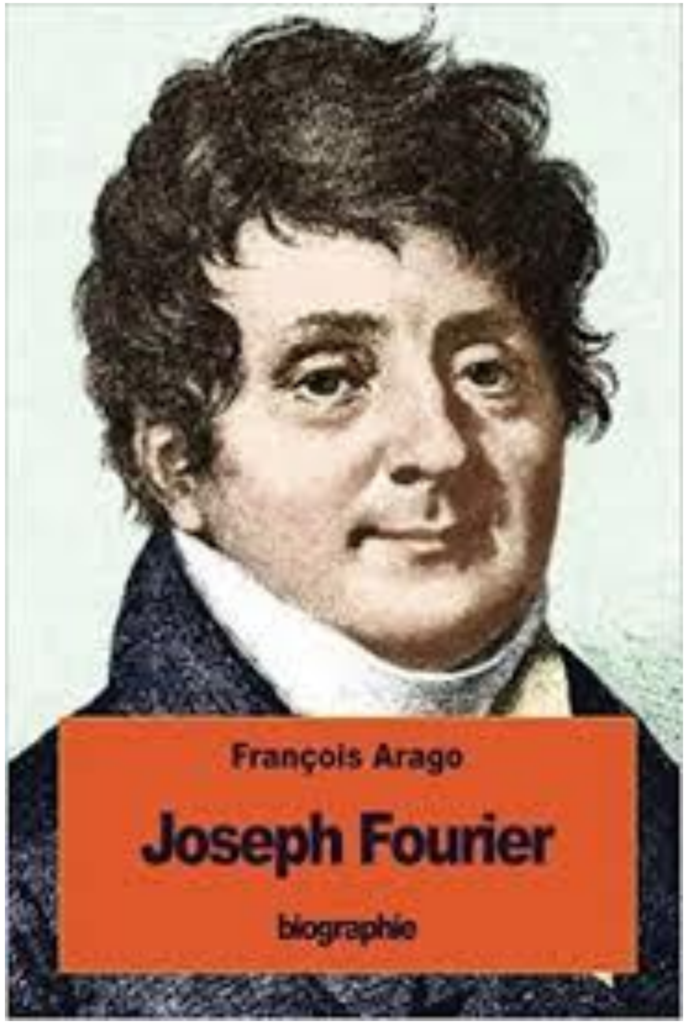
$$s(t) = \sum_{n=-\infty}^{\infty} C_n e^{j\omega_0 n t}$$

$$\omega_0 = \frac{2\pi}{T}$$

C_n = Fourier coefficients

Demo

Fourier Transform



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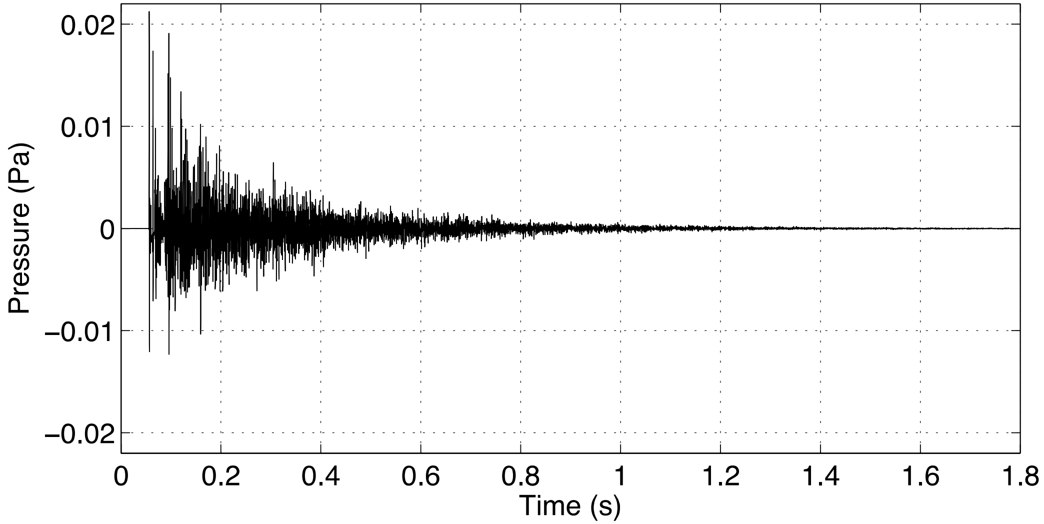
Non-periodic signals



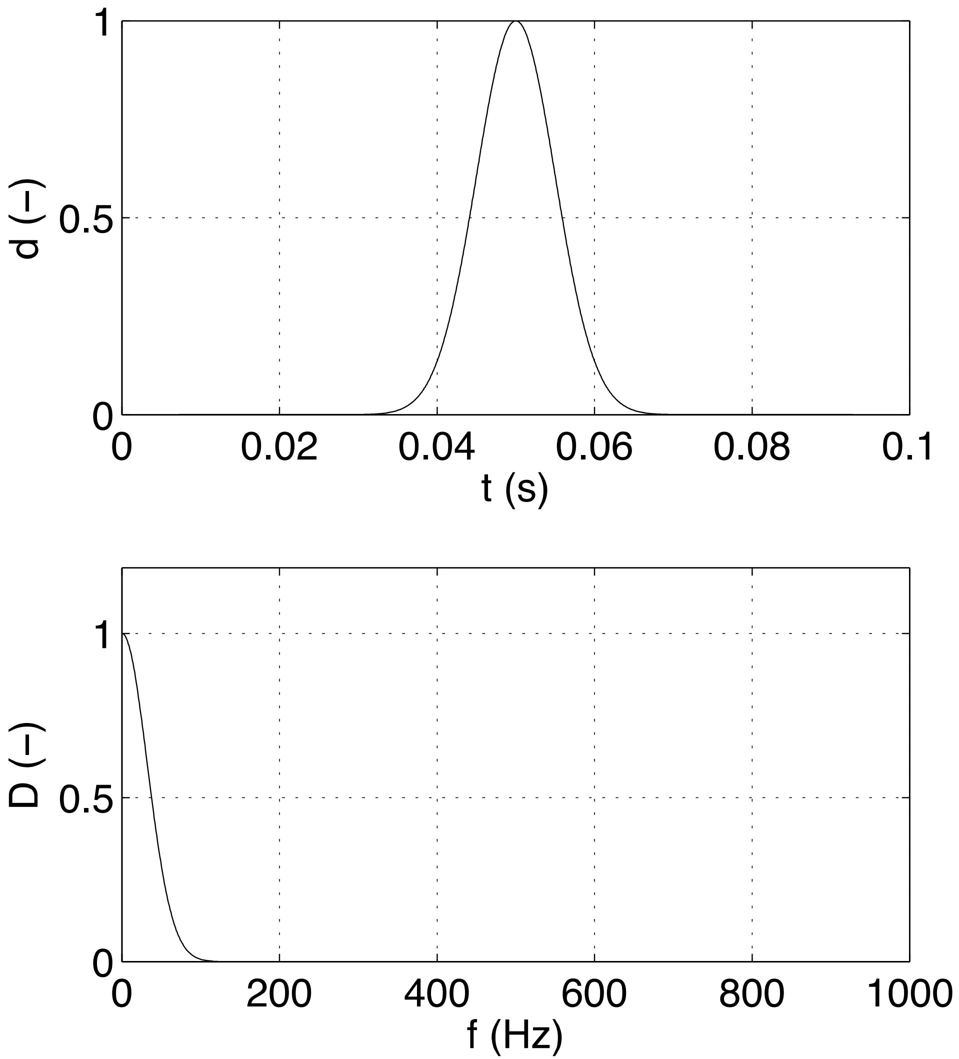
$$s(t) = \int_{-\infty}^{\infty} C(\omega) e^{j\omega t} d\omega$$

$$C(\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} s(t) e^{-j\omega t} dt$$

Fourier Transform

Demo

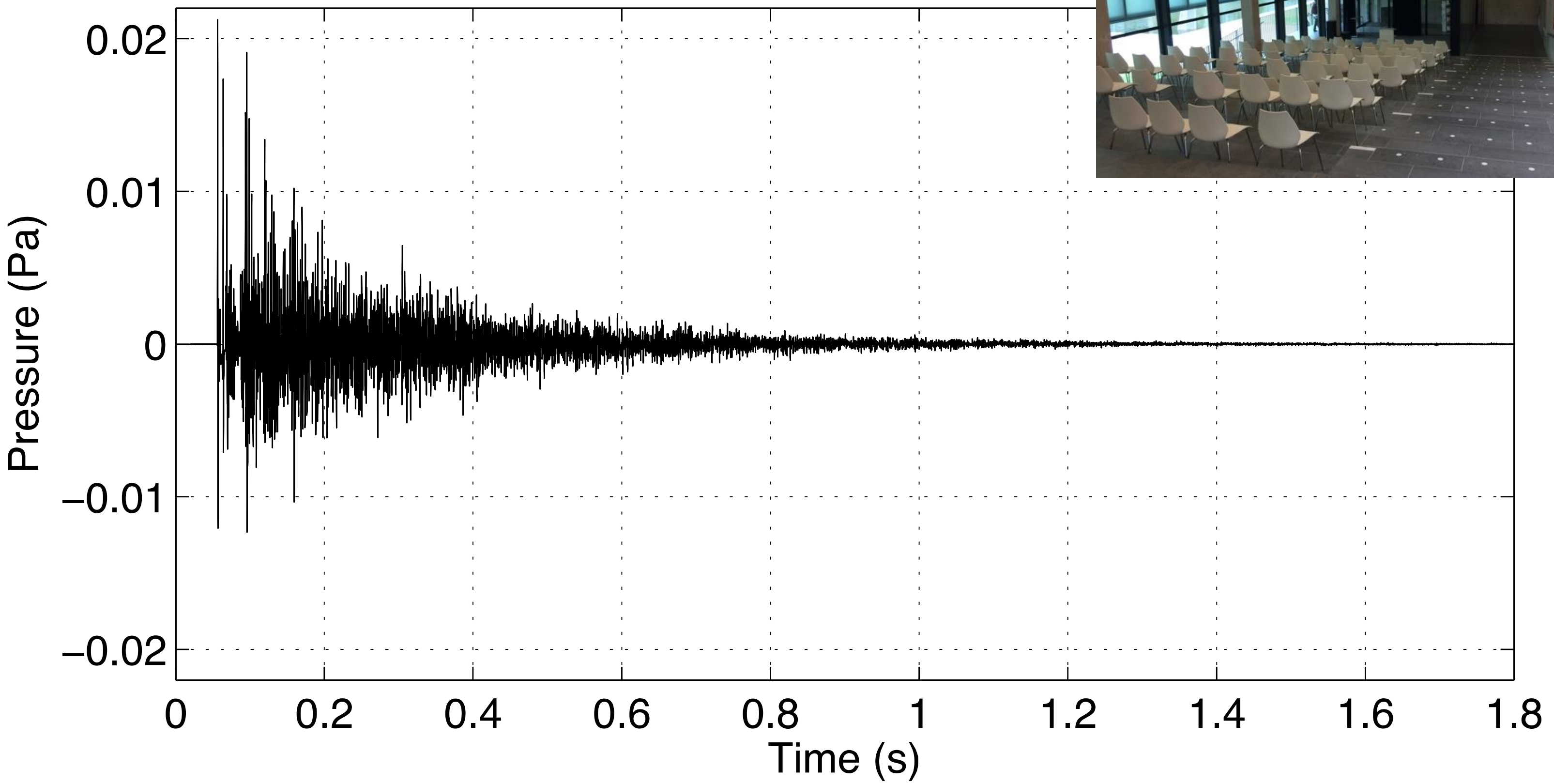
Impulsive signal properties

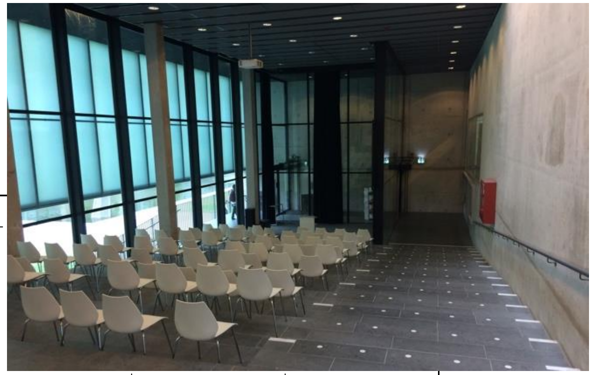


Demo

Sound pressure level

Time average of a sound signal is almost zero,
how to calculate the time-averaged level?





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Sound pressure level

$$L = 20 \cdot \log_{10}\left(\frac{\tilde{p}}{p_b}\right)$$

p_b Reference sound pressure, $2 \cdot 10^{-5}$ Pa

$$\tilde{p} = \sqrt{\frac{1}{t_0}\int_0^{t_0} p(t)^2 dt} = \frac{\hat{p}}{\sqrt{2}}$$

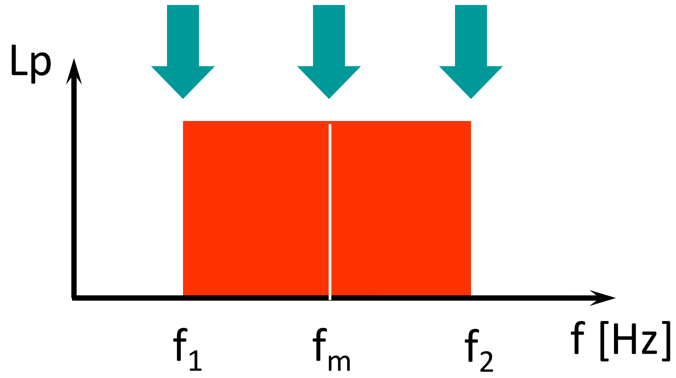
Sound pressure level difference between two signals

$$\Delta L = 20 \cdot \log_{10}\left(\frac{\tilde{p}_1}{\tilde{p}_2}\right) dB$$

Octave bands

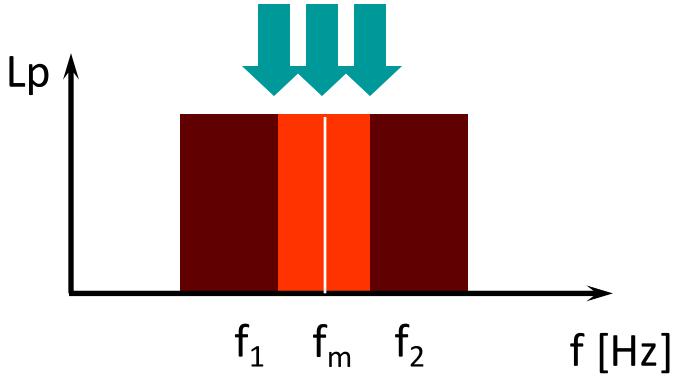
Octave bands

Example 1 kHz octave band	f_m = 1000 Hz f_1 = 707 Hz f_2 = 1414 Hz



1/3 Octave bands

Example 1 kHz 1/3 octave band	f_m = 1000 Hz f_1 = 890 Hz f_2 = 1122 Hz



Octave bands

Lower Band Limit [Hz]	Centre Frequency [Hz]	Upper Band Limit [Hz]
44	63	88
88	125	177
177	250	355
355	500	710
710	1000	1420
1420	2000	2840
2840	4000	5680
5680	8000	11,360

Murphy, E., & King, E. (2014). *Environmental noise pollution: Noise mapping, public health, and policy*. Newnes.

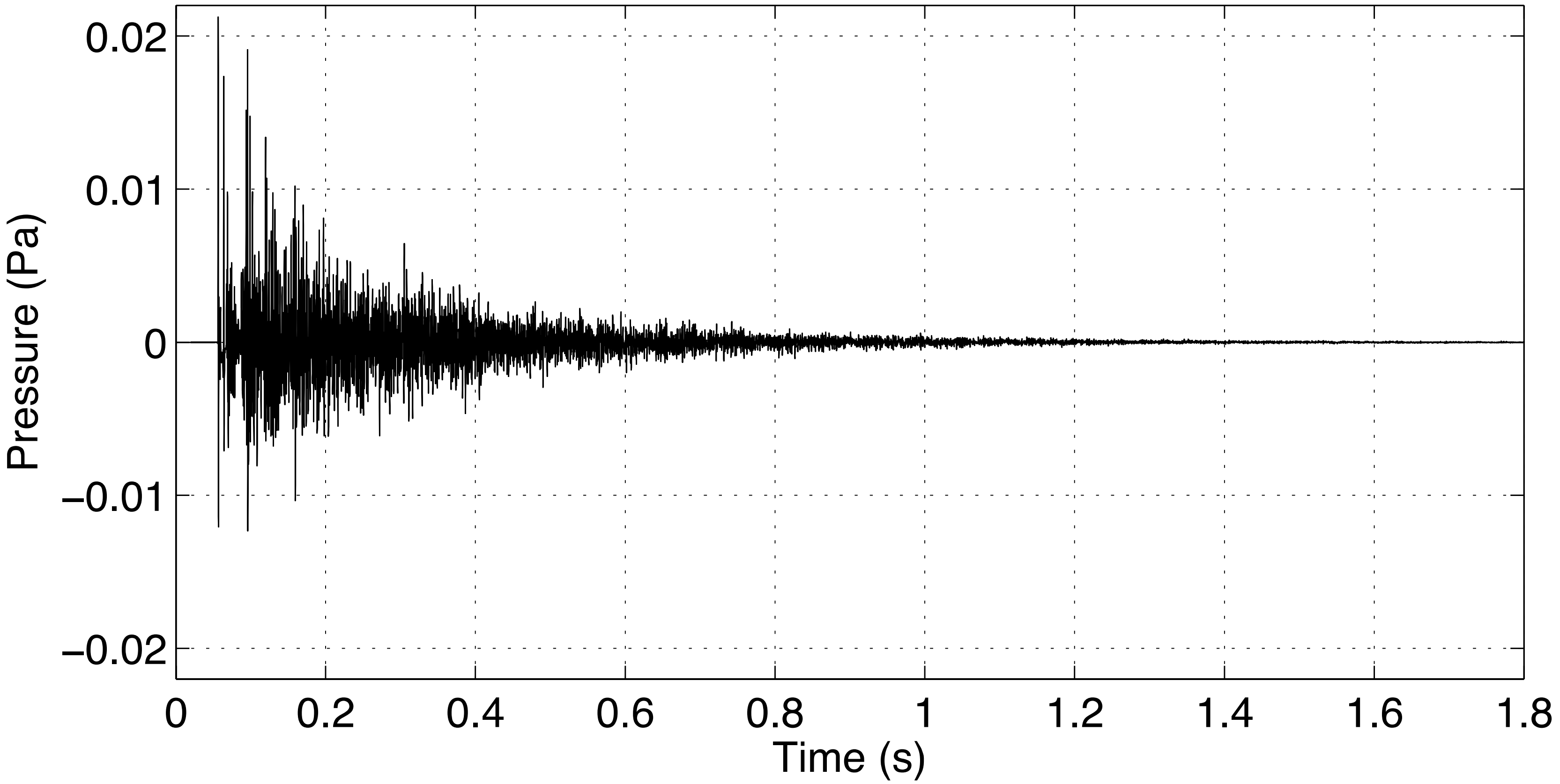
Octave bands

$$L_{p,1/3octave,j} = 10\log_{10}\left(\frac{\sum_{i=1}^{i=N_j} p_{eff}^2\left(f_{j,i}\right)}{p_{ref}^2}\right) \text{ [dB]}$$

$$= 10\log_{10}\left(\sum_{i=1}^{i=N_j} 10^{\frac{L_p\left(f_{j,i}\right)}{10}}\right) \text{ [dB]}$$

j = 1/3 octave band index [-]
i = frequency number within 1/3 octave band [-]
N_j = number of frequencies in 1/3 octave band j [-]

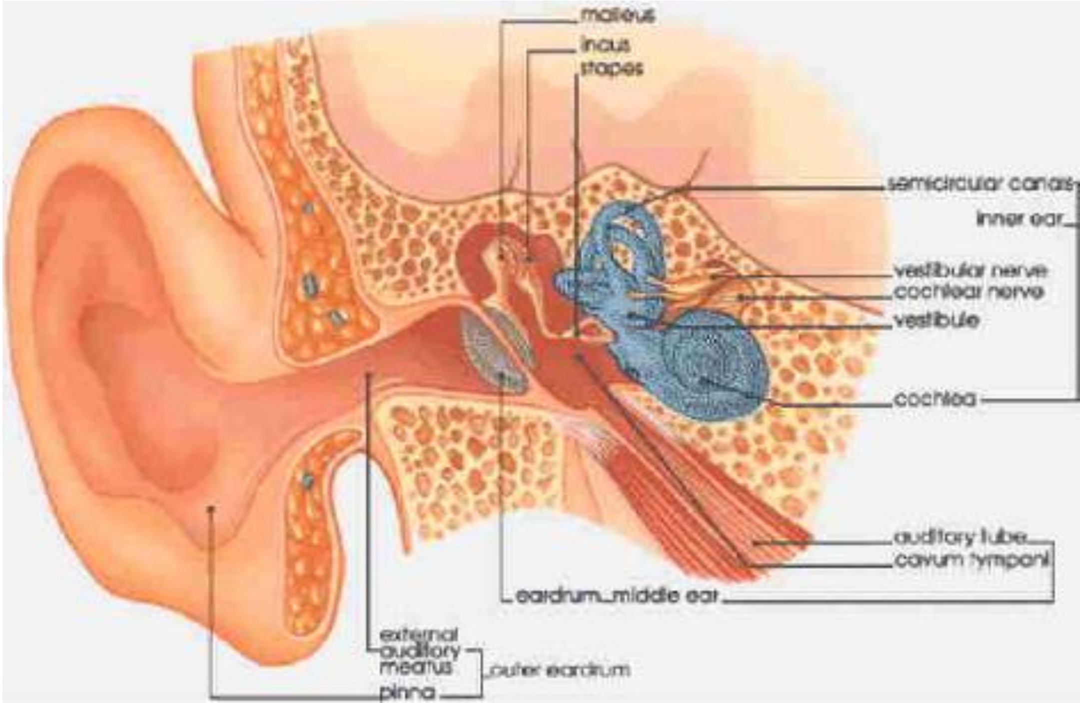
Non-periodic signals



Demo

Our hearing

- 20 - 20000 Hz
- Averages fluctuating sound pressure levels
- Can distinguish time patterns
- Not equally sensitive to all frequencies
- Resolution in time and angle (1 degree)?



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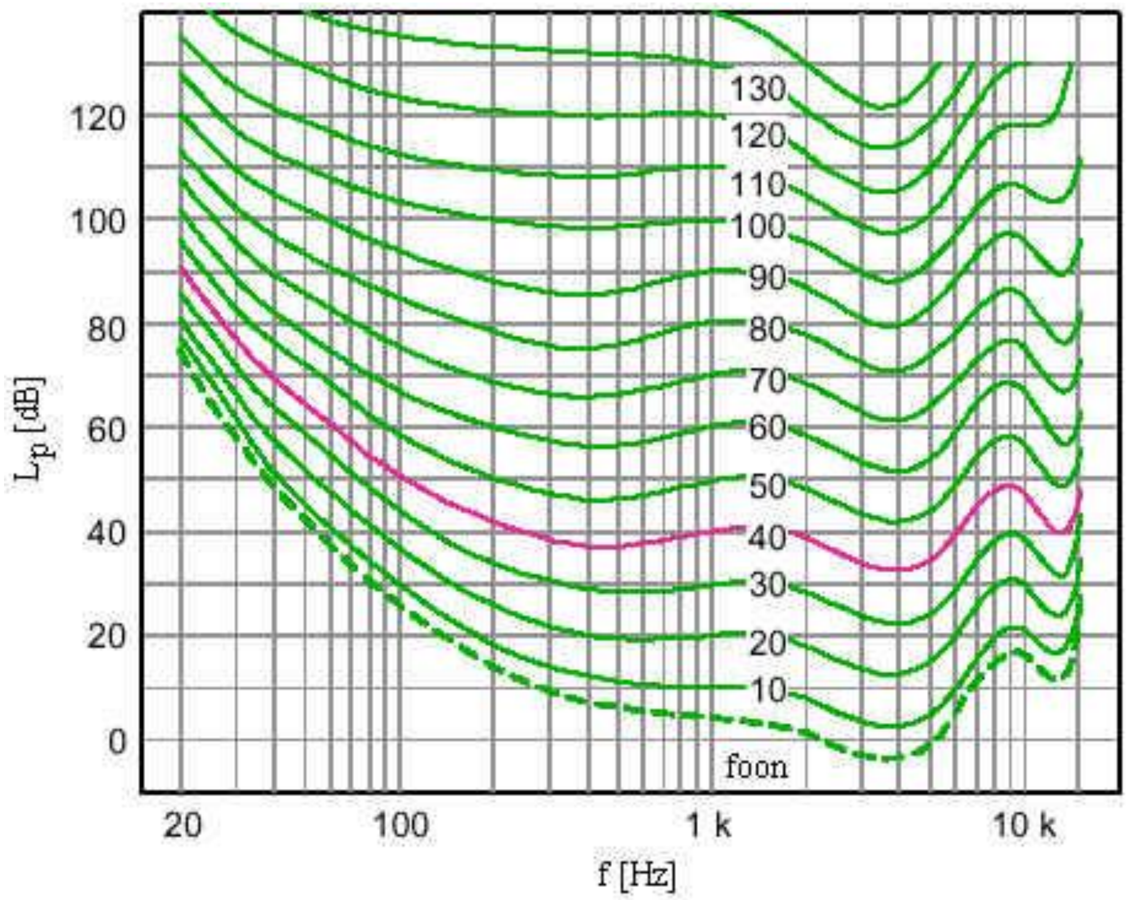
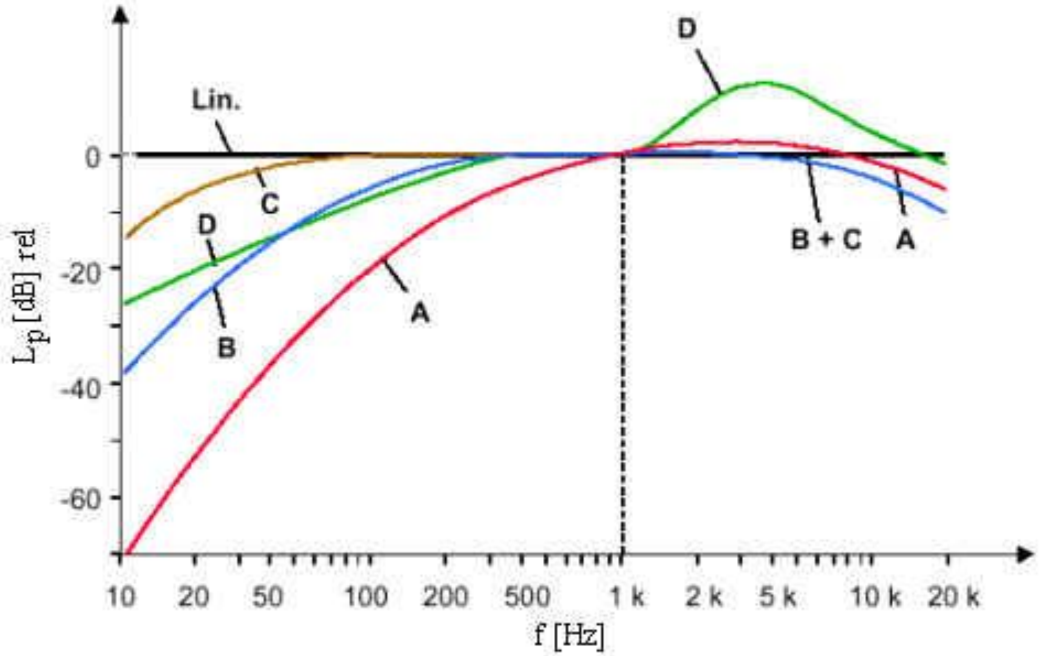
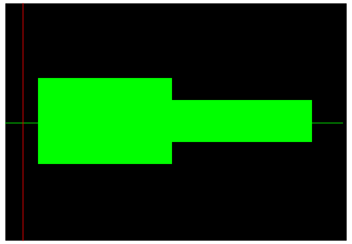
Isophone curves and weighting





Audible dB differences

Step



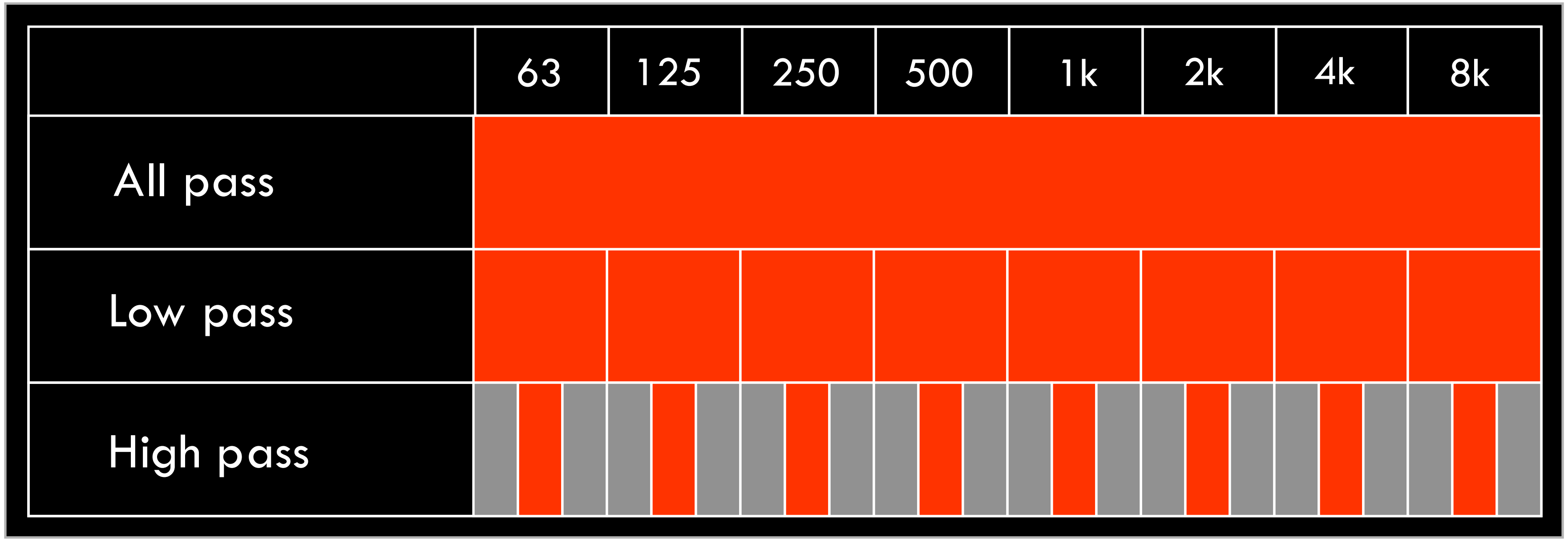
	Sine	Noise	Music
0.0 dB			
-0.5 dB			
-1.0 dB			
-1.5 dB			
-2.0 dB			
-2.5 dB			
-3.0 dB			

	Extra Music
-5.0 dB	
-10.0 dB	

High and low pass filtering

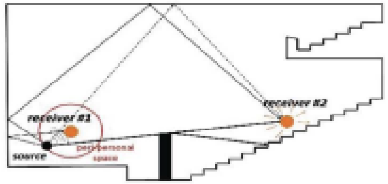
	63	125	250	500	1k	2k	4k	8k
All pass								
Low pass								
High pass								

High and low pass filtering



Influence of binaural hearing on signals

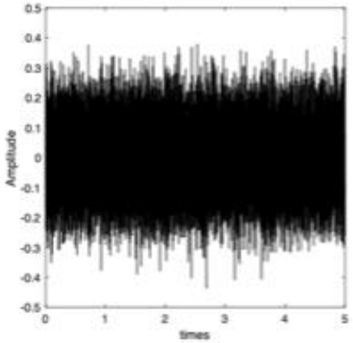
Source

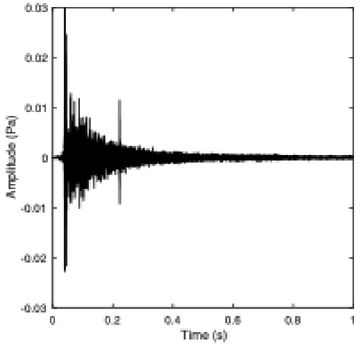


Sound propagation

Listener

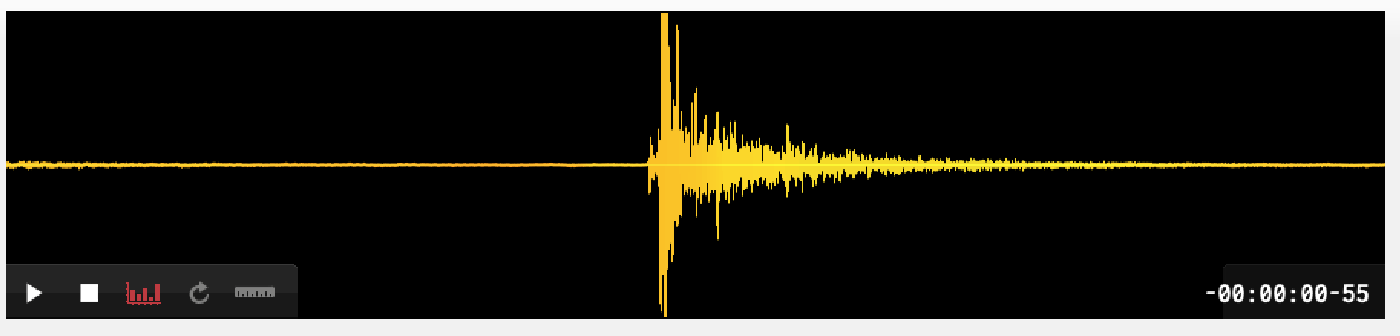
characterization

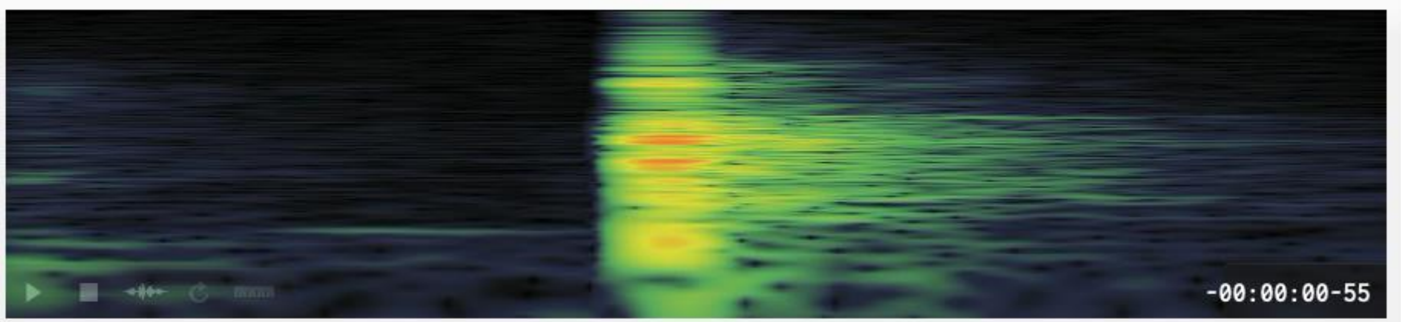




Influence of binaural hearing on signals

Hand clap





https://freesound.org Mikael Fernström

Binaural hearing

Binaural hearing uses two main acoustic cues: interaural time difference (ITD) and interaural level difference (ILD)

- ITD is the delay between both ears. It is efficient for low frequencies (below 850 Hz). It is due to the envelope of the signal reaching the two ears. It can be reminded that a sound coming from the side at 90° has an ITD of 0.6 ms. When the source is situated in the front (azimuth 0°), the so-called front target, the ITD is 0 ms.

- ILD is related to the intensity reaching the two ears. The signal is more or less attenuated by the head shadow. This effect is mostly perceptible with high frequencies (above 3 kHz). ILD is 0 for the front target.

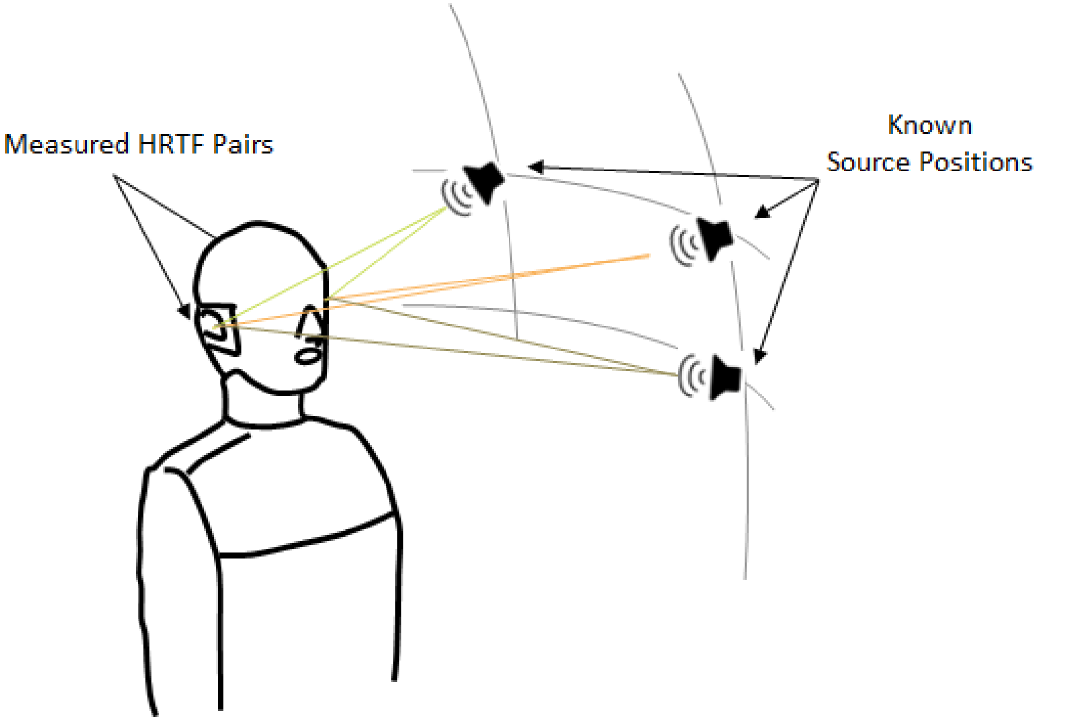
(Doerbecker and Ernst, 1996; Francart et al., 2011):

https://www.sciencedirect.com/topics/medicine-and-dentistry/binaural-hearing

Binaural hearing

Head Related Impulse Response (or Transfer Function), HRIR (or HRTF)

- Frequency dependency
- Directivity



https://www.mathworks.com/help/audio/ref/interpolatehrtf.html

Binaural hearing

HRTF spectrum

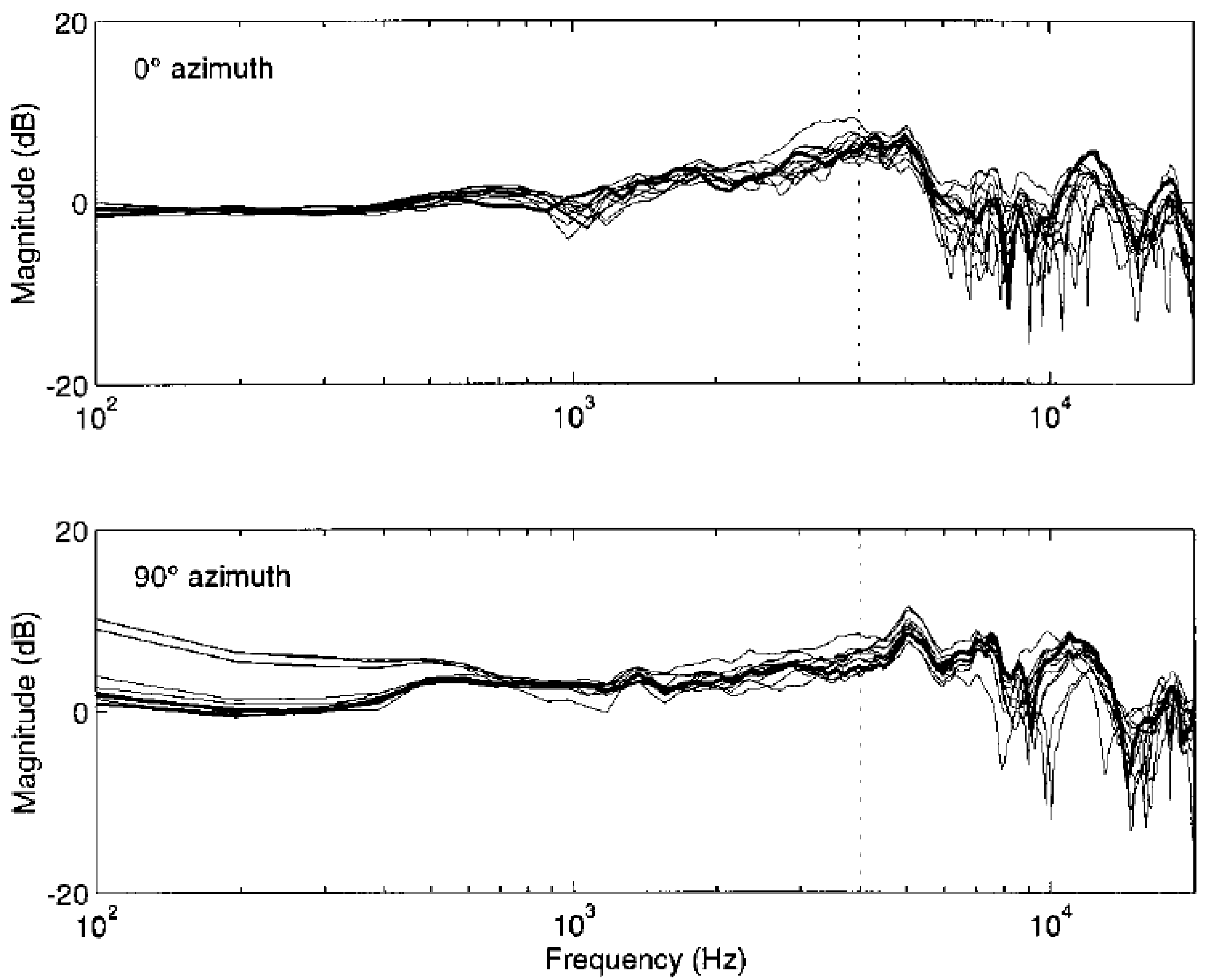
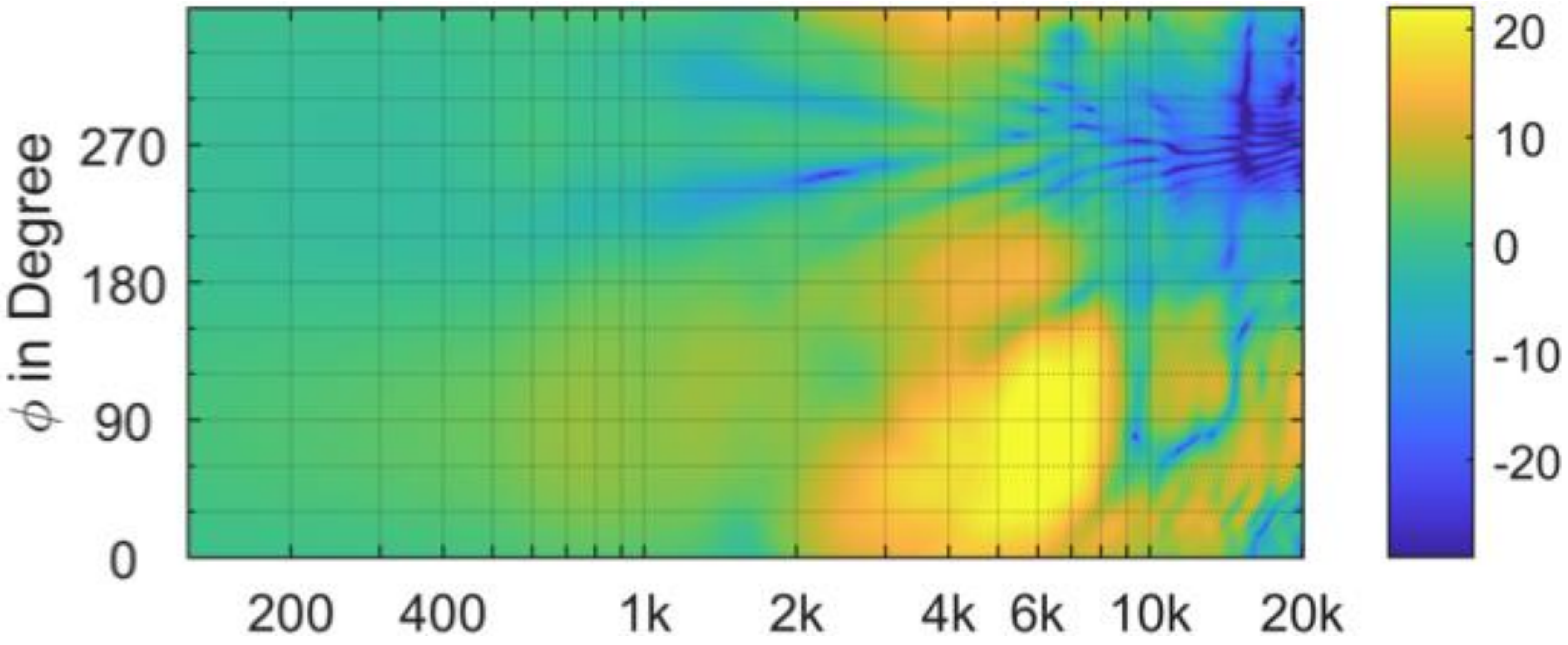


FIG. 1. Examples of 12 individual HRTFs (thin lines) and the general HRTF (heavy line) for the right ear in two different azimuth angles. The dotted vertical line marks the upper frequency of 4 kHz employed in the present study.

Drullman, R. and Bronkhorst, A.W., 2000. Multichannel speech intelligibility and talker recognition using monaural, binaural, and three-dimensional auditory presentation. *The Journal of the Acoustical Society of America*, *107*(4), pp.2224-2235.

Binaural hearing

Measured left ear horizontal plane HRTF



Braren, H. and Fels, J., 2020. A High-Resolution Head-Related Transfer Function Data Set and 3D-Scan of KEMAR. Institute for Hearing Technology and Acoustics, RWTH Aachen University, Technical report.

Tutorial time

Record and analyse your sounds with a Matlab mlx script
Try different sounds

- **An impulsive signal (hand clap or tongue click)**
- **A sustained vowel**
- **The background sound in the room**

Inspect the time signals, spectra with your neighbour and discuss

.mlx file

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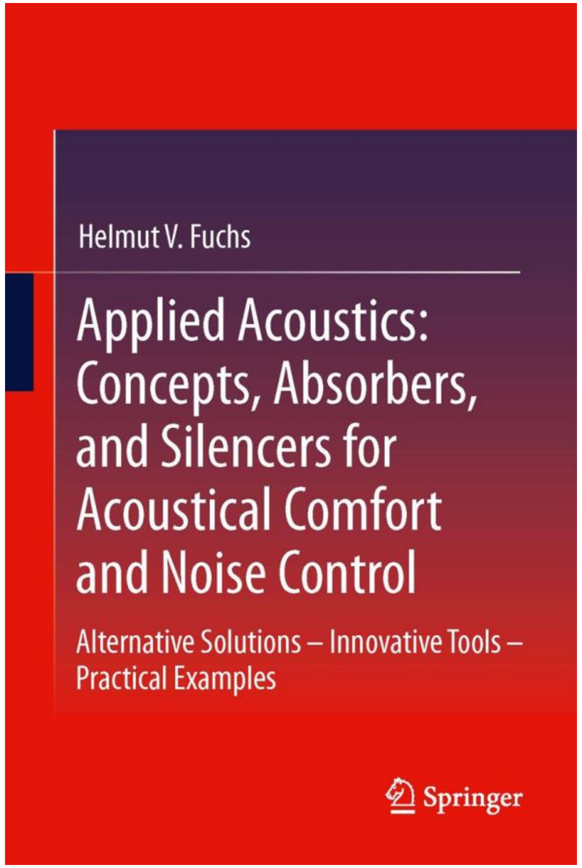
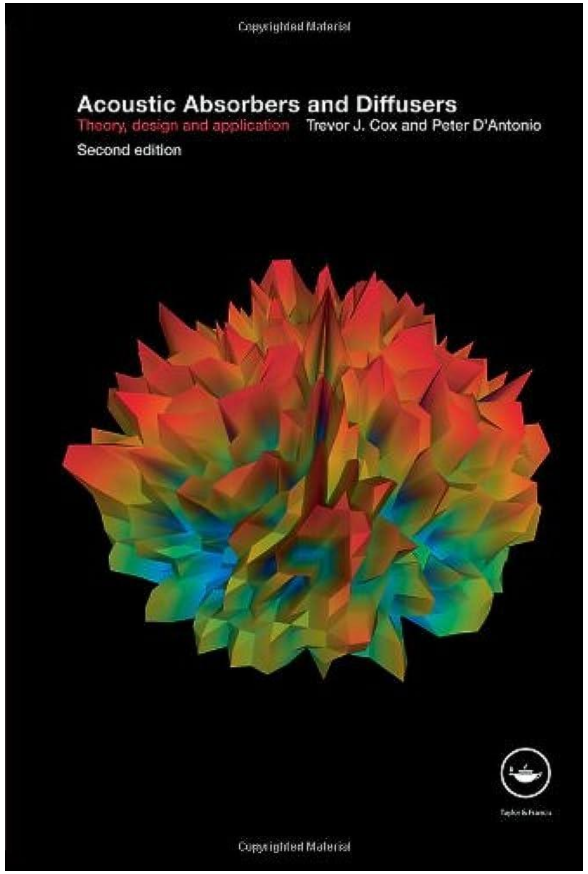
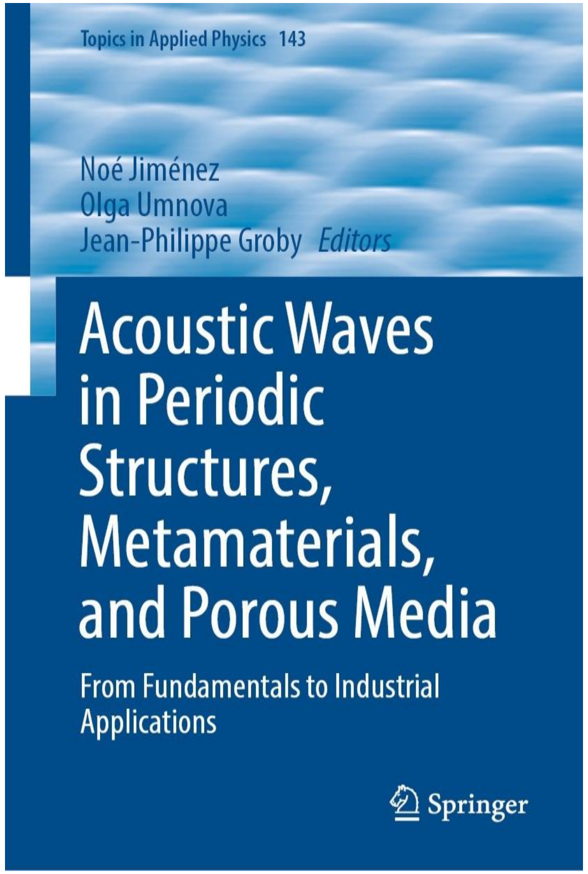
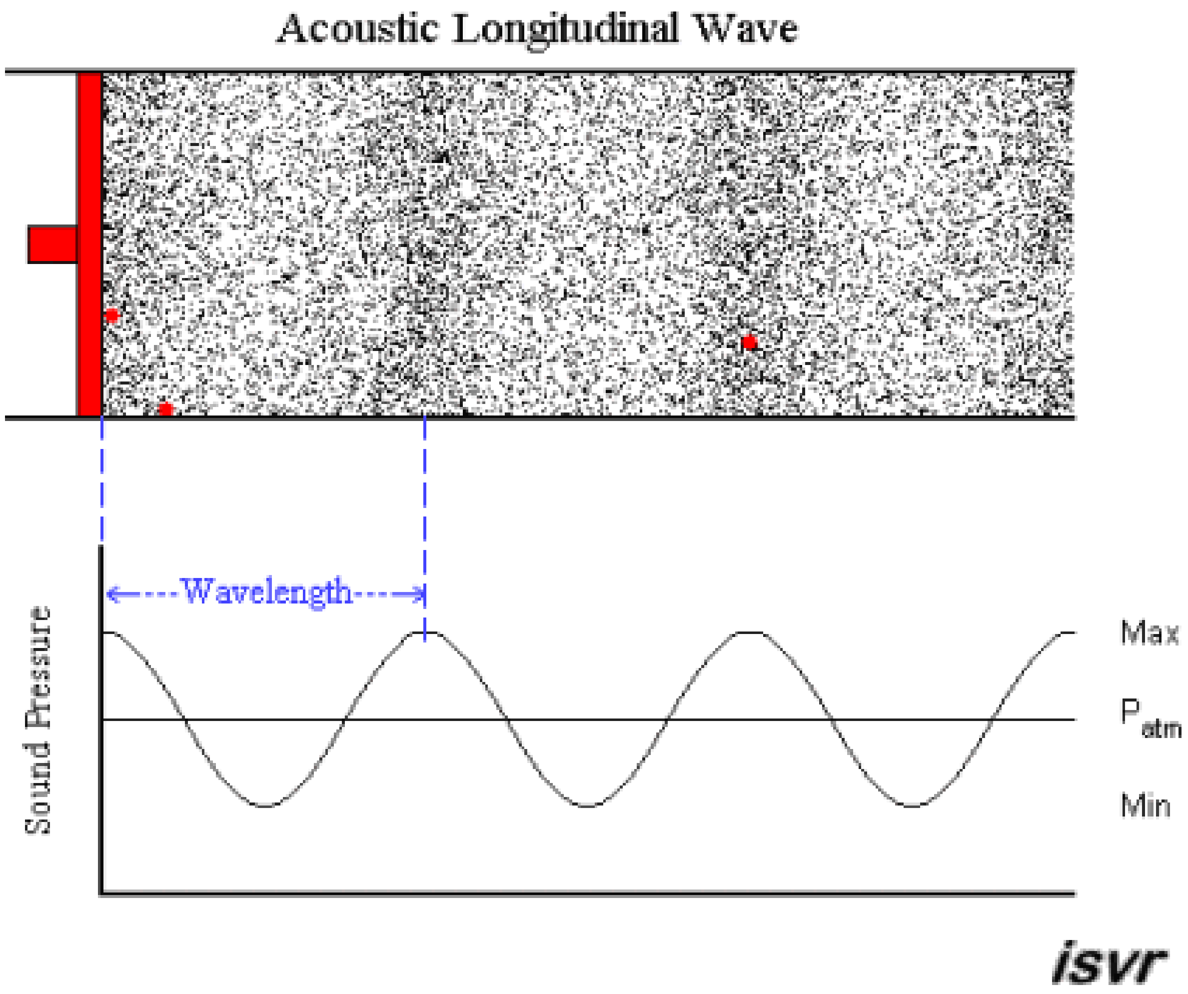
Books on acoustic materials







One dimensional sound propagation



http://resource.isvr.soton.ac.uk/spcg/tutorial/tutorial/Tutorial_files/Web-basics-nature.htm

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SEA

EAA

One dimensional sound propagation

http://www.haines.com.au

1D Wave Equation in fluids (as air)

Assumptions

- No viscous effects
- No mean flow effects
- Temperature fluctuations but no heat flow (adiabatic conditions)
- Amplitudes of acoustic variables are small (pressure amplitude < 1 Pa) such that linearization applies
- We consider the molecular macro scale, i.e. not at molecule level

- + relation between pressure and density $p = c^2 \rho$

$$\frac{\partial^2 p}{\partial x^2} = \frac{1}{c^2} \frac{\partial^2 p}{\partial t^2}$$

Harmonic waves: solution to 1D wave equation

$$p(x,t) = Ae^{j(\omega t - kx)}$$

$$k = \frac{\omega}{c}$$ wavenumber

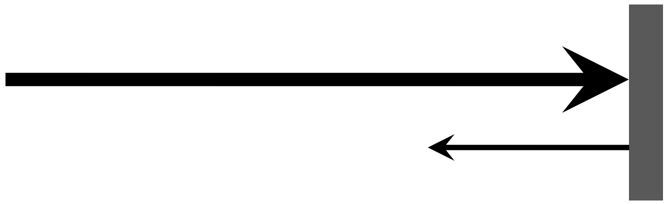
$$v_x(x,t) = Be^{j(\omega t - kx)}$$

Impedance of air

$$Z_0 = \rho_0 c = \frac{p}{v_x}$$

There is also a running wave in the other direction

Solution to 1D wave equation with boundary



$$p(x,t) = p_i + p_r = A\left(e^{j(\omega t - kx)} + Re^{j(\omega t + kx)}\right)$$

With *R* the complex reflection coefficient of the boundary

$$R(f) = \frac{Z_n(f) - 1}{Z_n(f) + 1}$$

Z_n = normalized surface impedance, depends on material

Solution to 1D wave equation with boundary

R can be a complex number (value between -1 and 1 real and imaginary), which leads to amplitude and phase effects of the reflected sound

Demo with sound field in front of boundary changing the amplitude and phase of the reflection coefficient

Demo

Demo with sound field in front of boundary changing the amplitude of the surface impedance

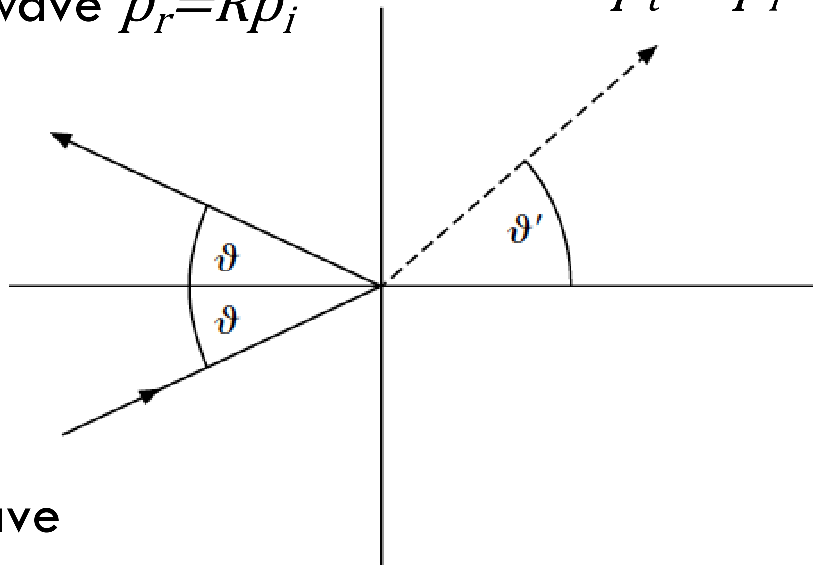
Demo

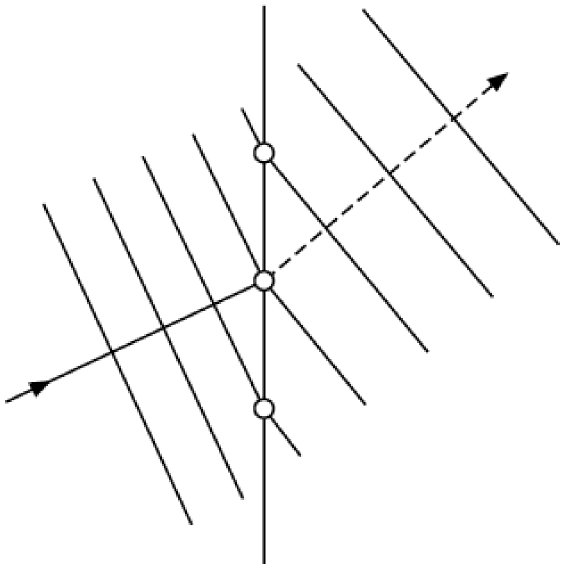
Reflection in 2D: plane waves

Plane wave reflection coefficient

Transmitted wave
$p_t = T p_i$

Reflected wave $p_r = R p_i$





Incident wave
p_i

Kuttruff, H. (2007). *Acoustics: an introduction*. CRC Press.

Reflection in 2D (plane surface)

Plane wave reflection coefficient

$$R(f) = \frac{Z_n(f)\cos(\theta) - \cos(\theta')}{Z_n(f)\cos(\theta) + \cos(\theta')}$$

$$\frac{c}{\sin(\theta)} = \frac{c'}{\sin(\theta')}$$

$$\alpha = 1 - \lfloor R \rfloor^2$$

Absorption coefficient α :

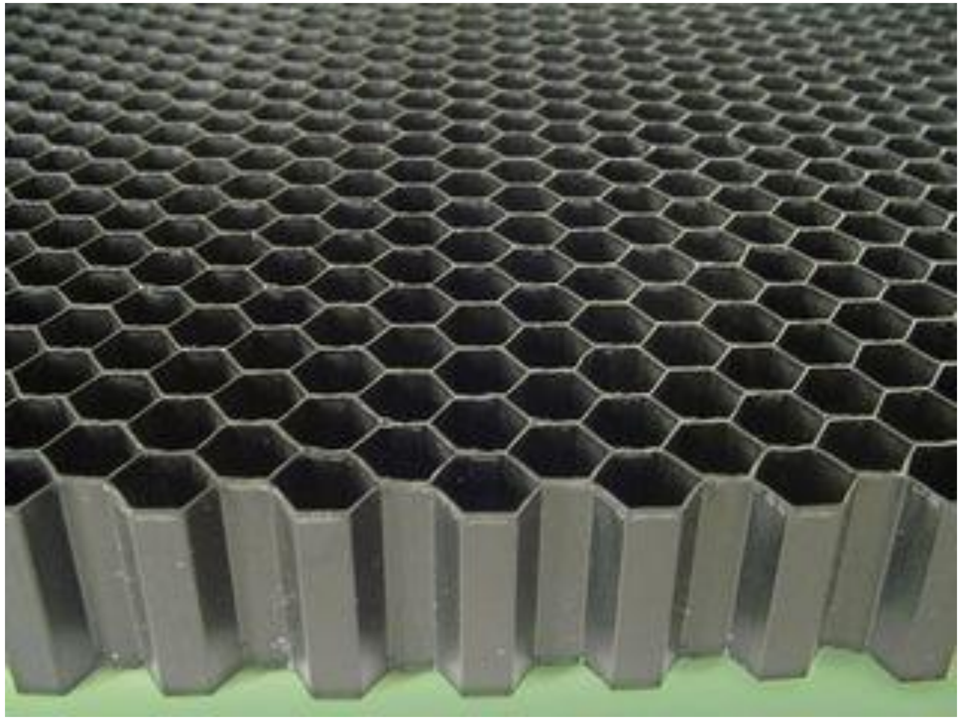
- is real value between 0 a 1
- does not contain phase information of the reflected sound

Demo

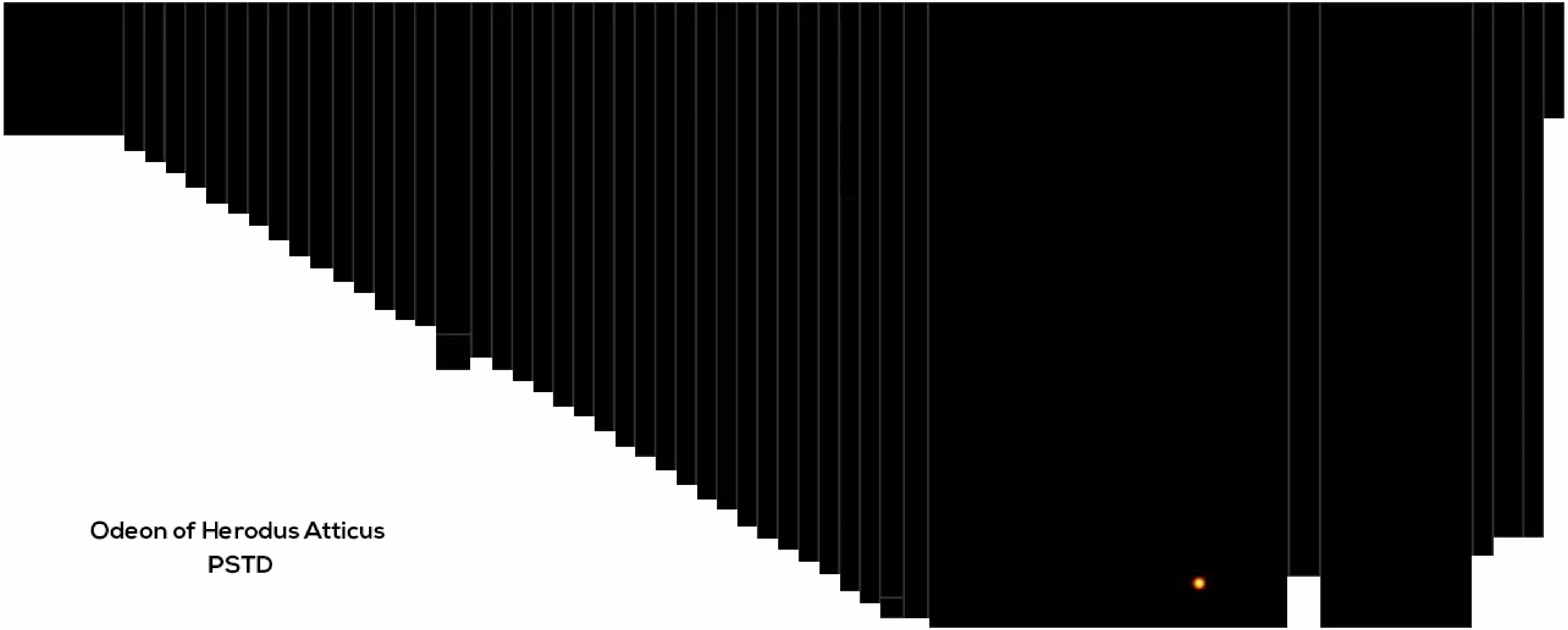
Reflection in 2D (plane surface)

Locally reacting medium

$$R(f) = \frac{Z_n(f)\cos(\theta) - 1}{Z_n(f)\cos(\theta) + 1}$$



Reflection in 2D: cylindrical waves



openpstd.org

Cylindrical and spherical wave reflection coeff.

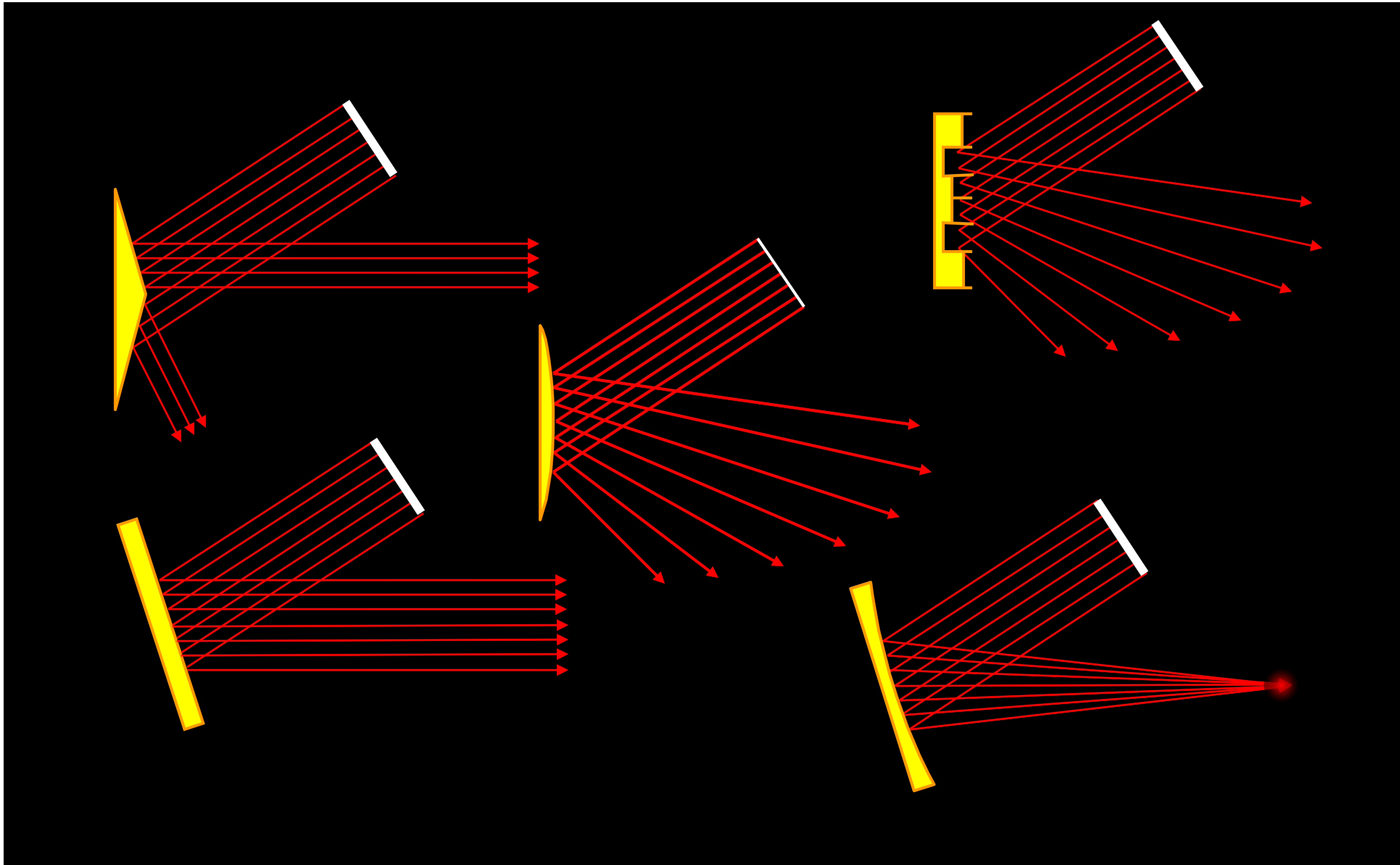
Cylindrical wave reflection coefficient can be found in

F. P. Mechel, A line source above a plane absorber, Acoust. Acta Acoust. 86 (2000) 203–215.

Spherical wave reflection coefficient

$$
\begin{aligned}
R_{\text{sph}} &= R + (1-R)F(w) \qquad \text{sphe} \\
F(w) &= 1 - j\sqrt{\pi}e^{-w^2}\operatorname{erfc}(jw) \qquad \text{l} \\
w &\approx \frac{1}{2}(1-j)\sqrt{kr_2}(\cos(\theta) + \frac{1}{Z}) \\
R &\approx R_{\text{sph}} \quad \text{if} \quad |w| > 4
\end{aligned}
$$

Surface types



Surface types

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Porous material

Important for a porous material:
- Flow resistivity
- Thickness
- Porosity

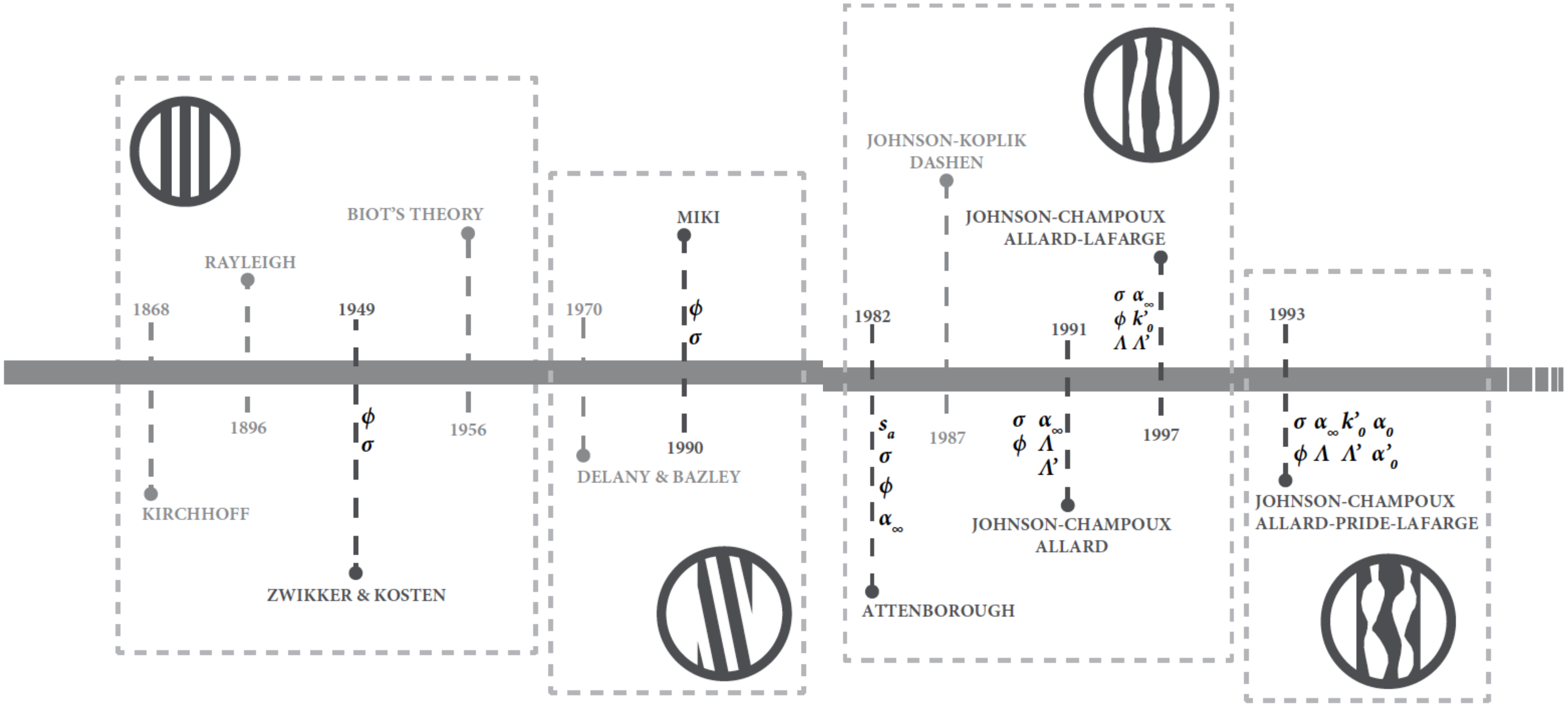
Wavenumber and specific impedance of a simplified porous material (according to Kuttruff, H. (2007). Acoustics: an introduction). Values within one pore

$$k' = \frac{\omega}{c}\sqrt{1 - \frac{j\sigma\Xi}{\rho_0\omega}}$$

$$Z' = Z_0\sqrt{1 - \frac{j\sigma\Xi}{\rho_0\omega}}$$

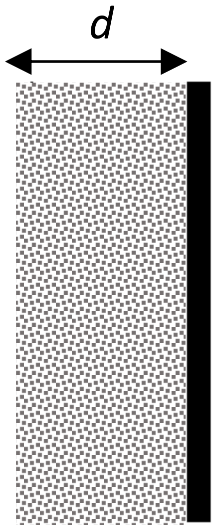
Demo

Porous materials



Botterman, B., (2016), WWCB: characterizing, modelling and optimizing the sound absorption of wood wool cement boards, MSc. Thesis, TU/e

Porous material on a hard boundary



Porous material

$$Z = -jZ' \cot(k'd)$$

Impedance of porous layer with rigid backing at distance d

Demo

Porous sheet on a hard boundary

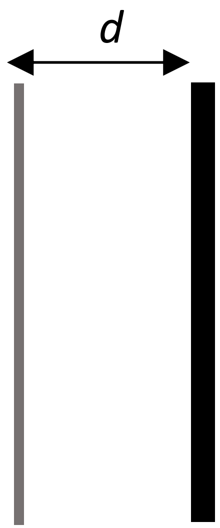
Porous sheet

$$Z = r_s - jZ_0 \cot(kd)$$

Impedance of porous sheet on air layer with rigid backing at distance d

Demo

Solid sheet on a hard boundary



Solid sheet

http://www.melfoamacoustics.com

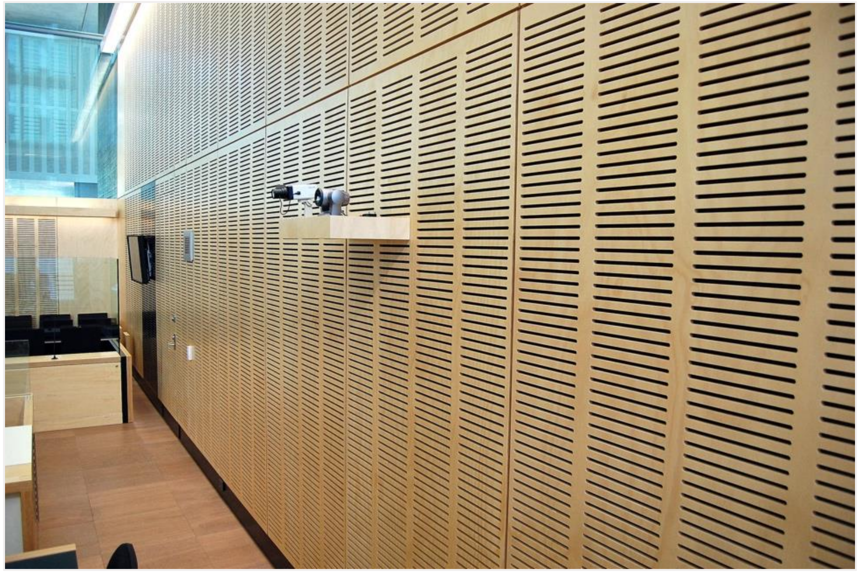
$$Z = j\omega m' - jZ_0 \cot(kd)$$

Impedance of non-porous sheet on air layer with rigid backing at distance d

Demo

Perforated sheet on a hard boundary

Perforated sheet



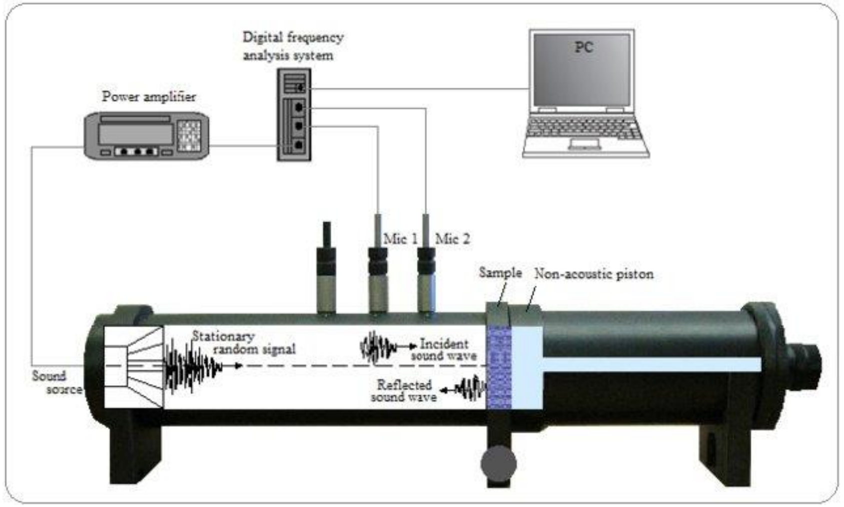
$$Z = r + j\omega m'_a - jZ_0 \cot(kd)$$

Impedance of perforated sheet on air layer with rigid backing at distance d, with m'_a the mass of the moving air in the pores and r the resistance due to friction from the movements in the pores

Demo

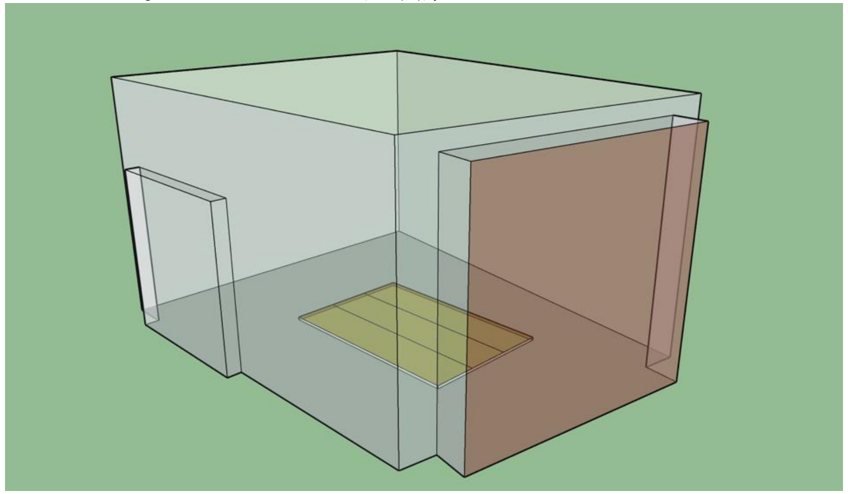
Determining surface impedance/sound absorption

Lab measurements



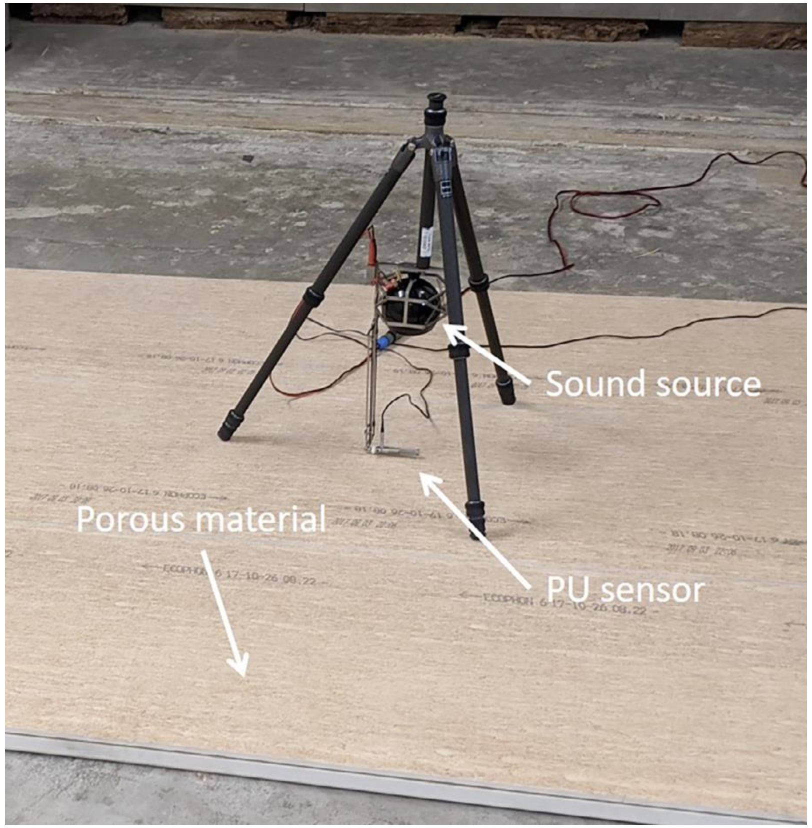
Çelikel, D.C. and Babaarslan, O., 2017. Effect of bicomponent fibers on sound absorption properties of multilayer nonwovens. *Journal of engineered fibers and fabrics*, 12(4), p.155892501701200403.

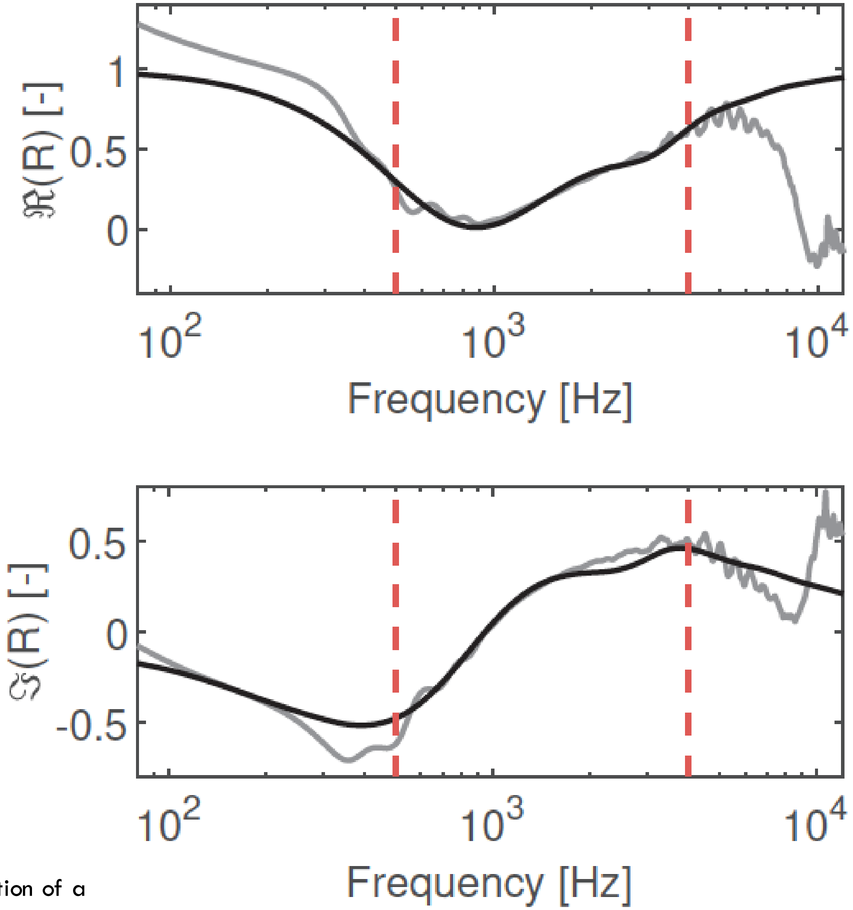
Baltazar Briere



Determining surface impedance/sound absorption

In-situ approach





de La Hosseraye, B.B., Hornikx, M. and Yang, J., 2022. In situ acoustic characterization of a locally reacting porous material by means of PU measurement and model fitting. Applied Acoustics, 191, p.108669.

Metamaterials as sound absorption

https://www.youtube.com/watch?v=JUi3qK32mf0

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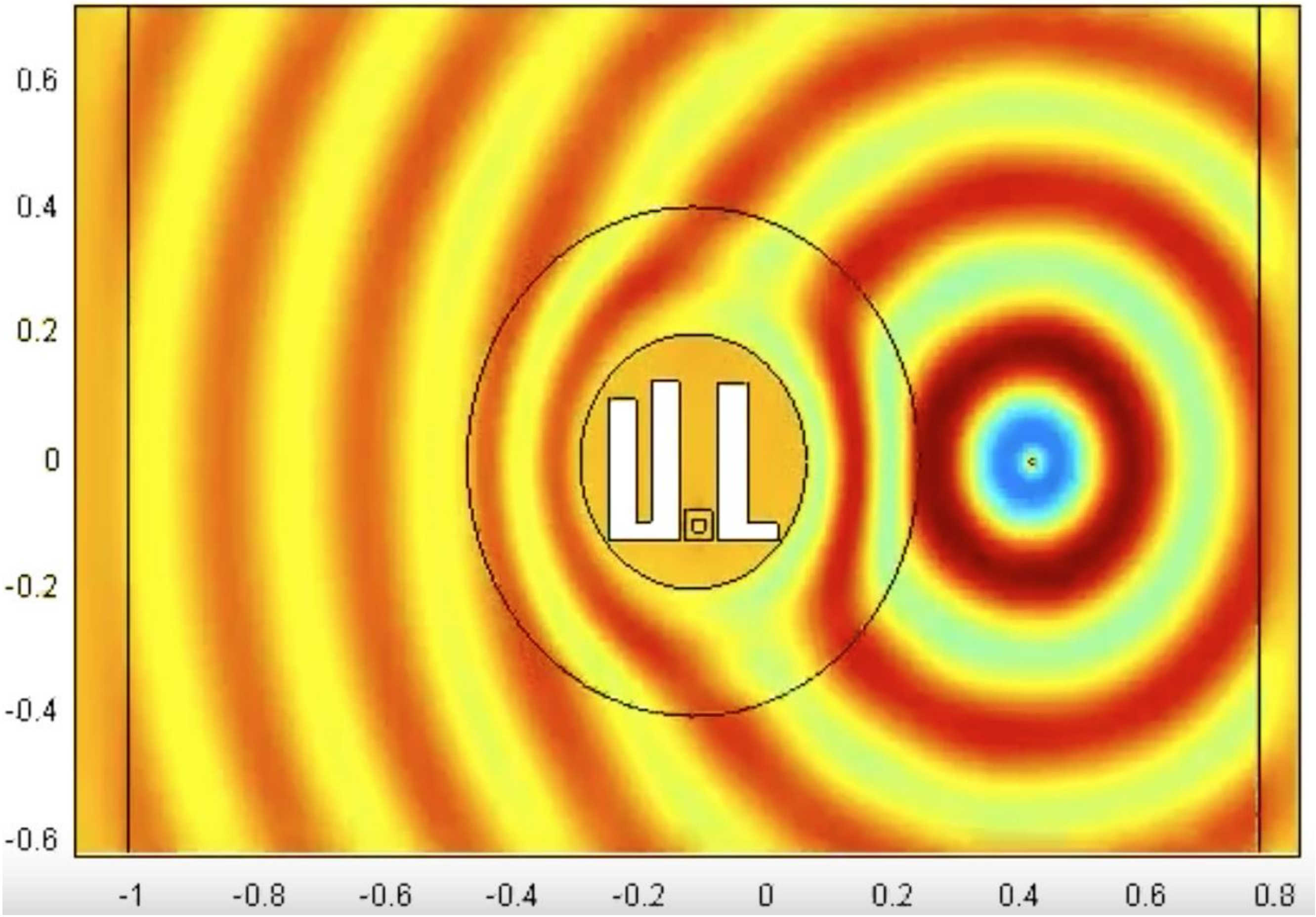
Metamaterials as sound absorption



Sébastien Guenneau of Liverpool University, UK

Metamaterials as sound absorption

Acoustic metamaterials

- Artificial material (not occuring in nature)

- Consisting of meta-atoms (typically periodic)

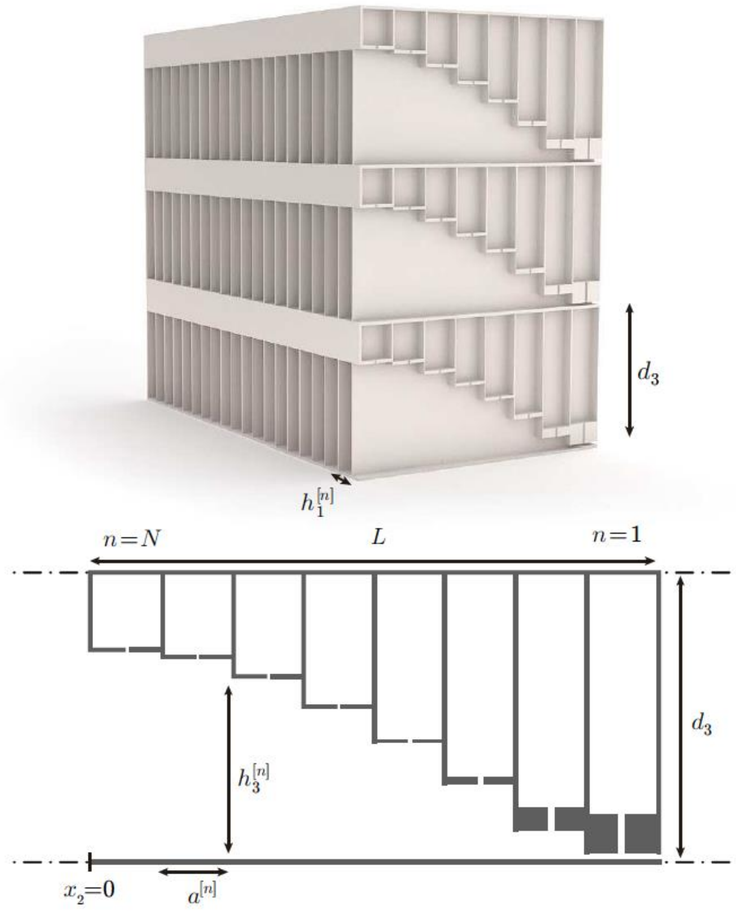
- Dimensions much smaller than wavelength

- Exhibiting behavior not encountered in nature

- … materials designed to control, direct, and manipulate sound waves

Metamaterials as sound absorption

Example: Rainbow-trapping absorbers

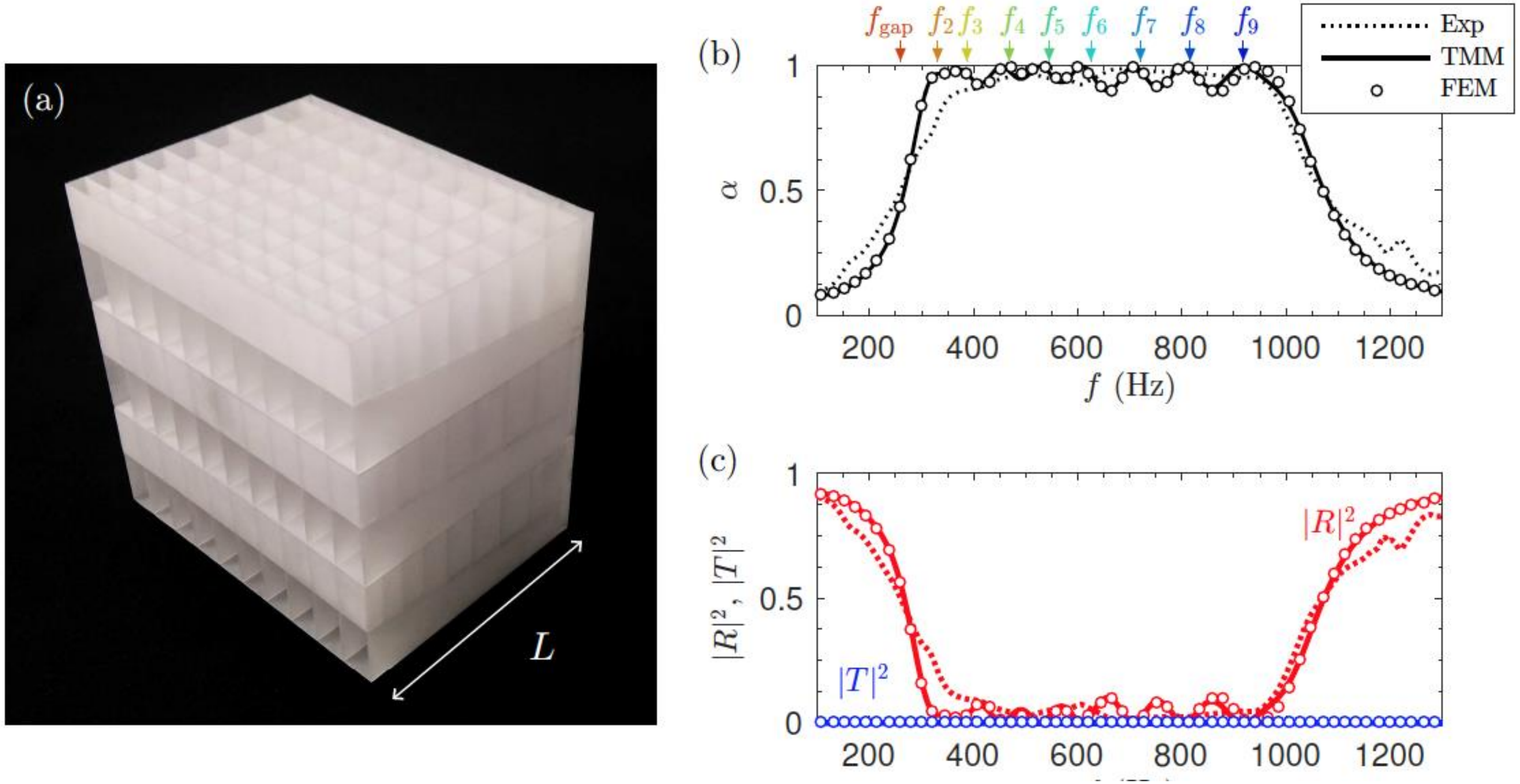


Jiménez, N., Romero-García, V., Pagneux, V. and Groby, J.P., 2017. Rainbow-trapping absorbers: Broadband, perfect and asymmetric sound absorption by subwavelength panels with ventilation. *arXiv preprint arXiv:1708.03343*.

Metamaterials as sound absorption

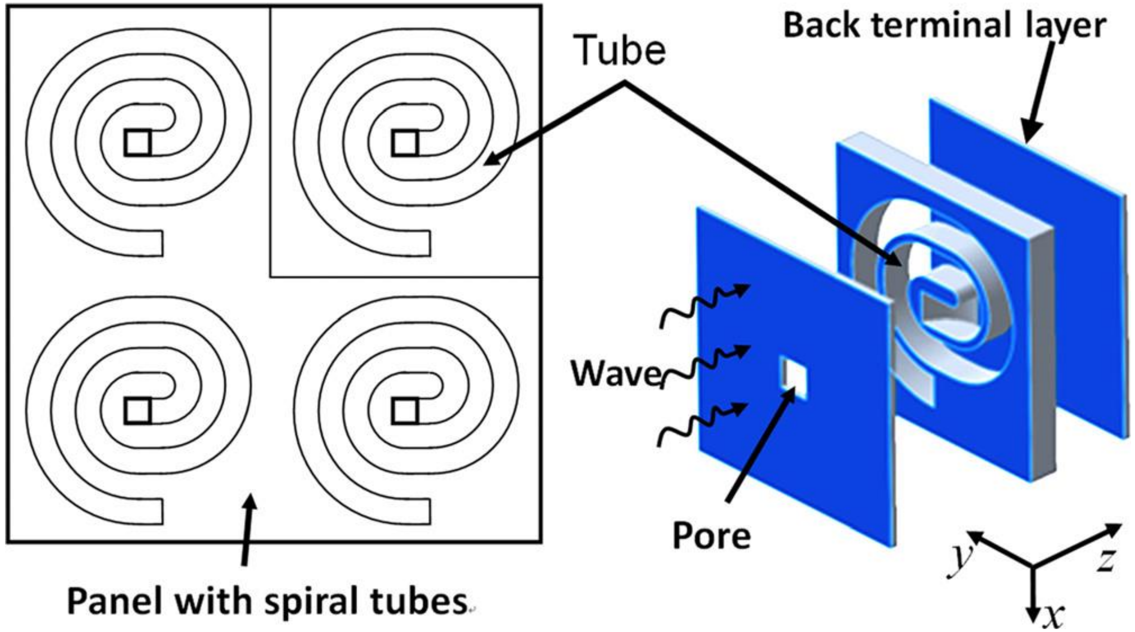
Example: Rainbow-trapping absorbers

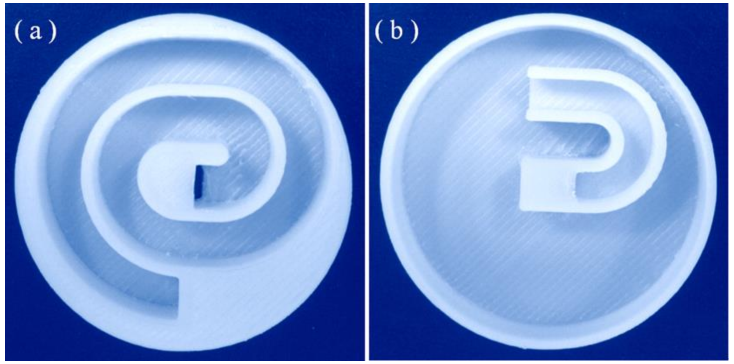
Jiménez, N., Romero-García, V., Pagneux, V. and Groby, J.P., 2017. Rainbow-trapping absorbers: Broadband, perfect and asymmetric sound absorption by subwavelength panels with ventilation. *arXiv preprint arXiv:1708.03343.*



Metamaterials as sound absorption

Example: Metaporous layer

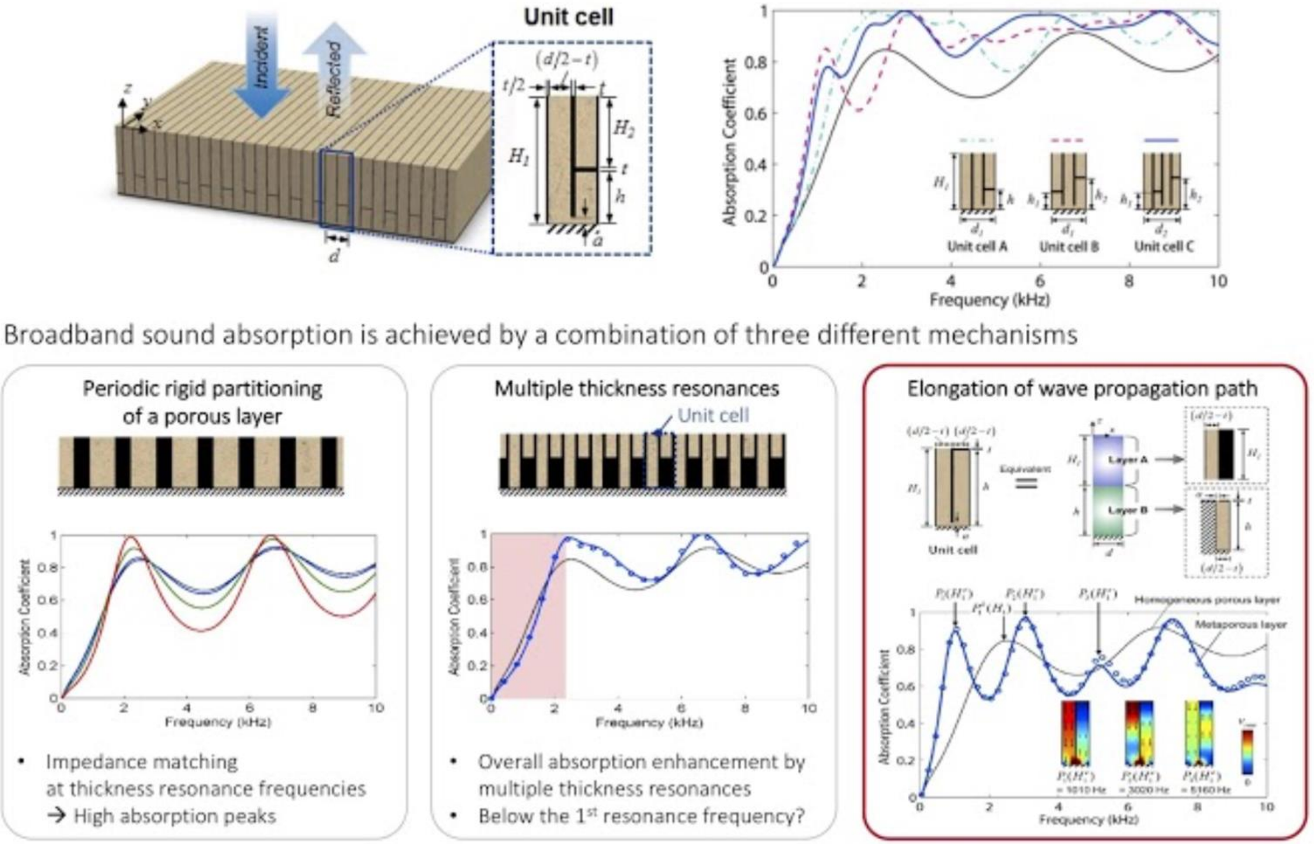




Cai, X., Guo, Q., Hu, G. and Yang, J., 2014. Ultrathin low-frequency sound absorbing panels based on coplanar spiral tubes or coplanar Helmholtz resonators. *Applied Physics Letters*, *105*(12), p.121901.

Metamaterials as sound absorption

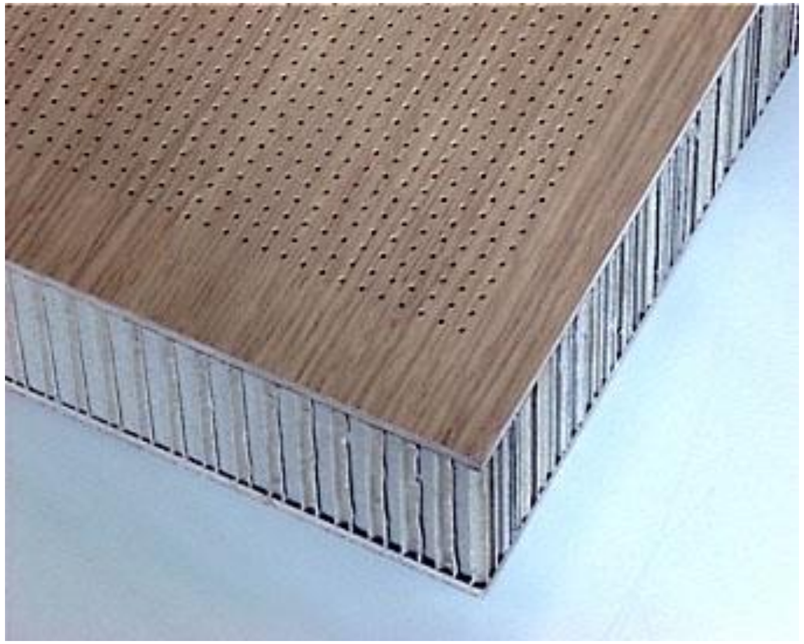
Example: Metaporous layer

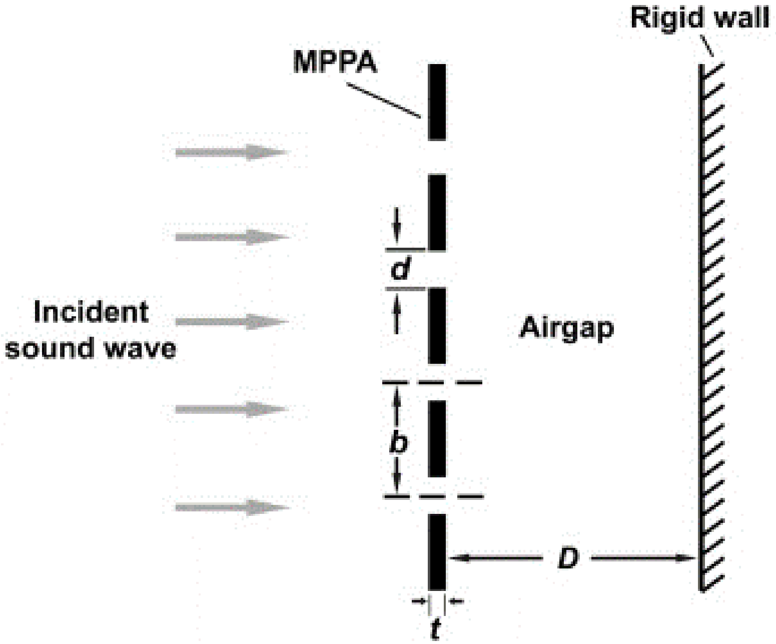


J. Yang, J.S. Lee, and Y.Y. Kim, *J. Appl. Phys*. 117, 174903 (2015)

Metamaterials as sound absorption

Example: Microperforated panel





Liu, Z., Zhan, J., Fard, M. and Davy, J.L., 2017. Acoustic properties of multilayer sound absorbers with a 3D printed micro-perforated panel. *Applied Acoustics*, *121*, pp.25-32.

Metamaterials as sound absorption

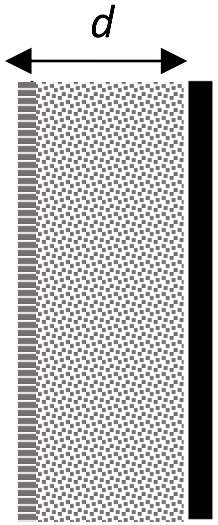
General challenges

- Thin panel with broadband damping
- Combining mechanisms (porous material + metamaterial)

Applications in terms of damping of sound

- Low frequency absorption in outdoor noise mitigation (screens, roofs)
- Damping modes in floors
- Reducing sound transmission of open windows

Tutorial



Perforated sheet

$$Z = r + j\omega m'_a - jZ_0 \cot(kd)$$

Impedance of perforated sheet on porous material layer with rigid backing at distance d, with m'_a the mass of the moving air in the pores and r the resistance due to friction from the movements in the pores.

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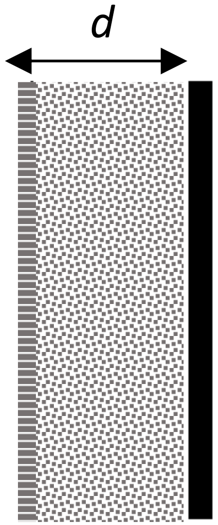
Tutorial



Perforated sheet

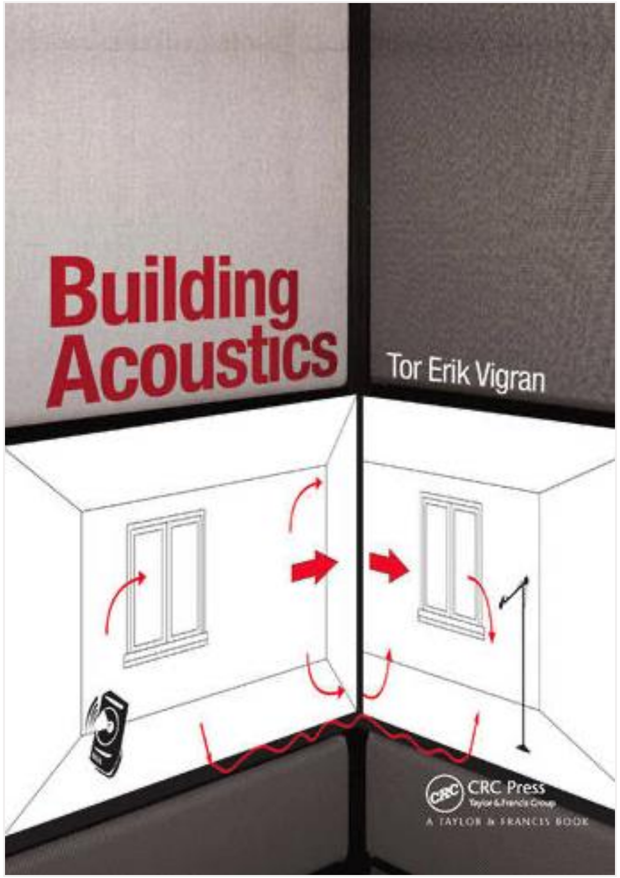
Change variables of this configuration and dicuss the changes in reflection coefficient and absorption coefficient that occur.

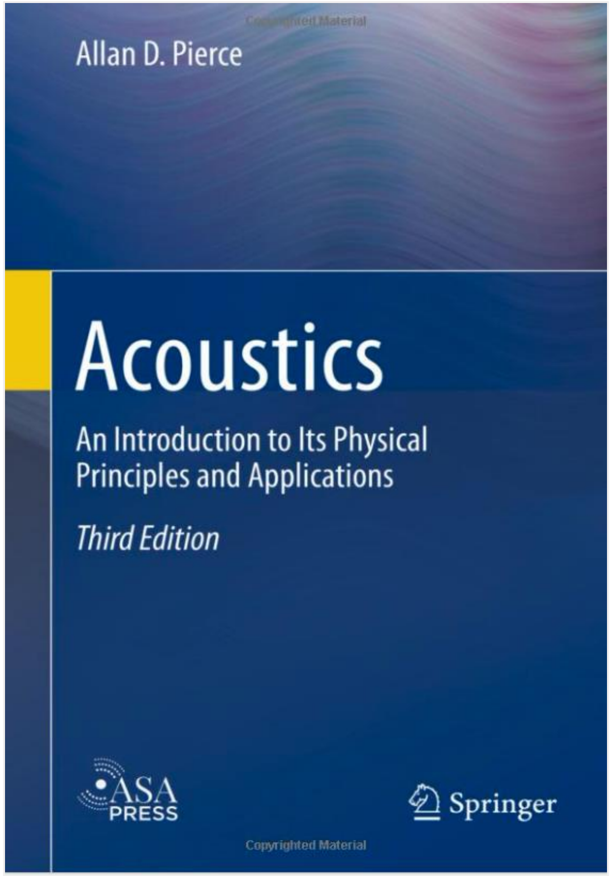
Course outline

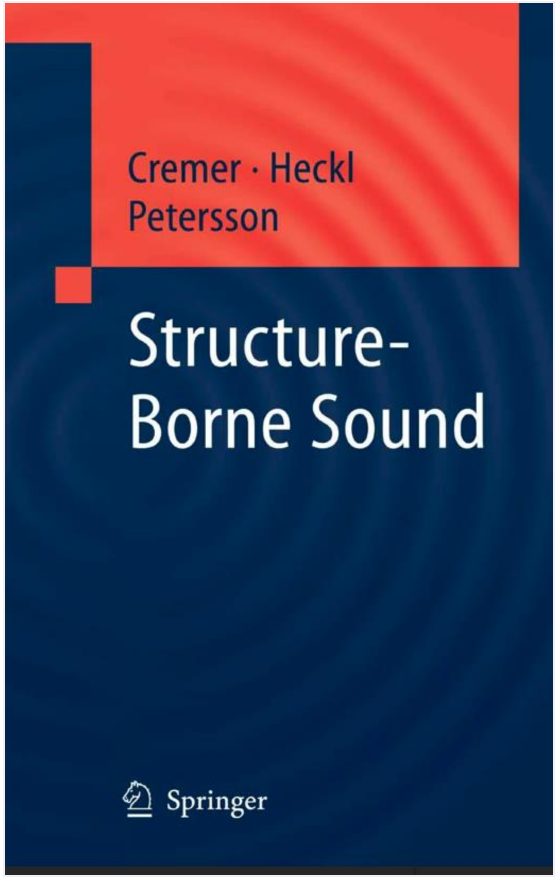
Time table / Lecture modules	TOPIC
DAY 1 - 21/06/2024	
8:30-9:00 h	Registration
9:00-10:30 h	**Lecture**: Introduction (why do we study acoustics) Basic signal properties: Period, wavelength and frequency. Definitions, and fundamental equations for propagation of sound.
10:30-11:00 h	Coffee break
11:00-12:00 h	**Lecture**: More advanced signal properties: Pure and complex sounds, frequency decomposition and sound spectrum. Acoustic quantities: levels and their manipulation, Octave bands and physiology of hearing, binaural hearing.
12:00-13:00 h	Plenary session I. Deep learning, AI and acoustics (Prof. Hamid Krim. North Carolina State University) **(All the topics)**
13:00-14:00 h	Lunch
14:00-15:30 h	**Tutorial**: Tools for acoustic analysis Recording of recorded sound Manipulation of sound
15:30-16:00 h	Coffee break
16:00-17:00 h	**Lecture**: Wave-surface interactions, 1D wave equation solution including reflection cofficient Sound absorption, types of sound absorption materials

Sound insulation

Building Acoustics books

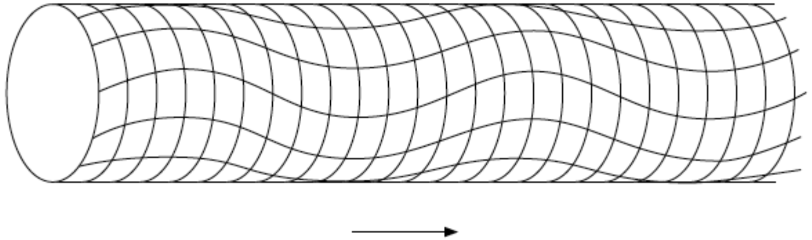




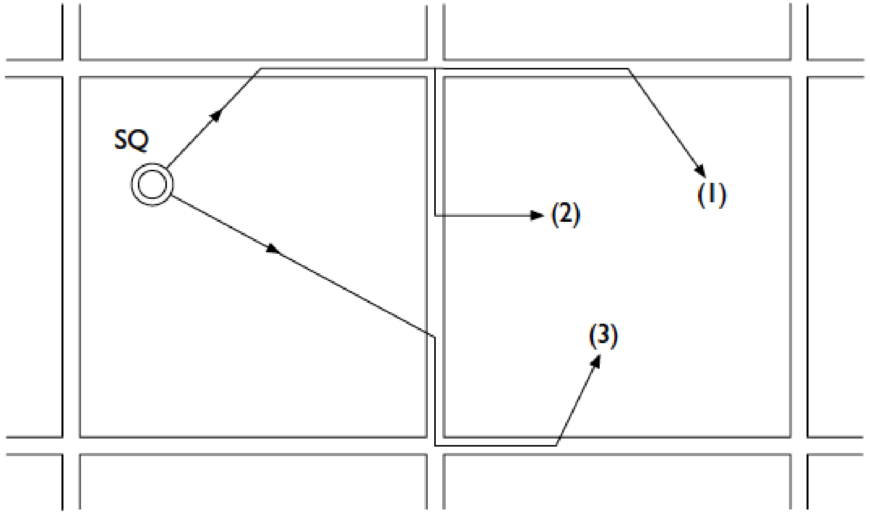


Sound insulation lecture

Sound waves in isotropic solids

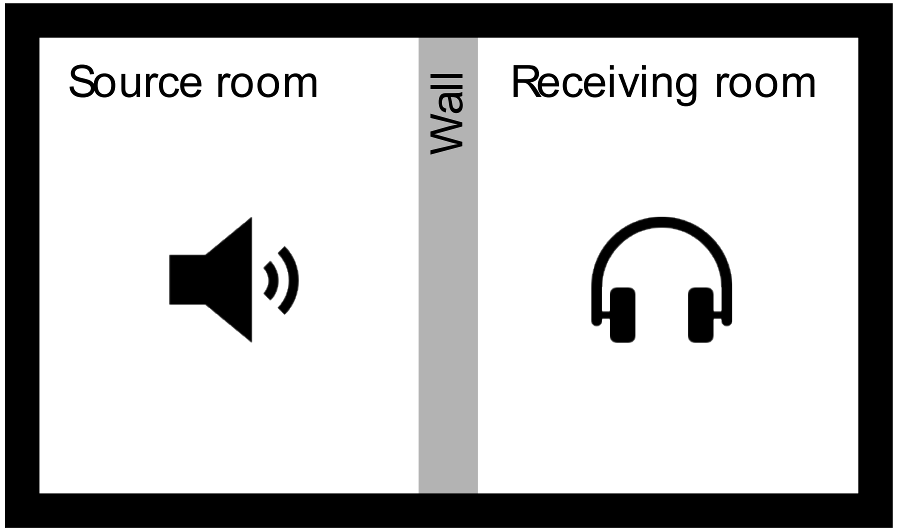


Building Acoustics



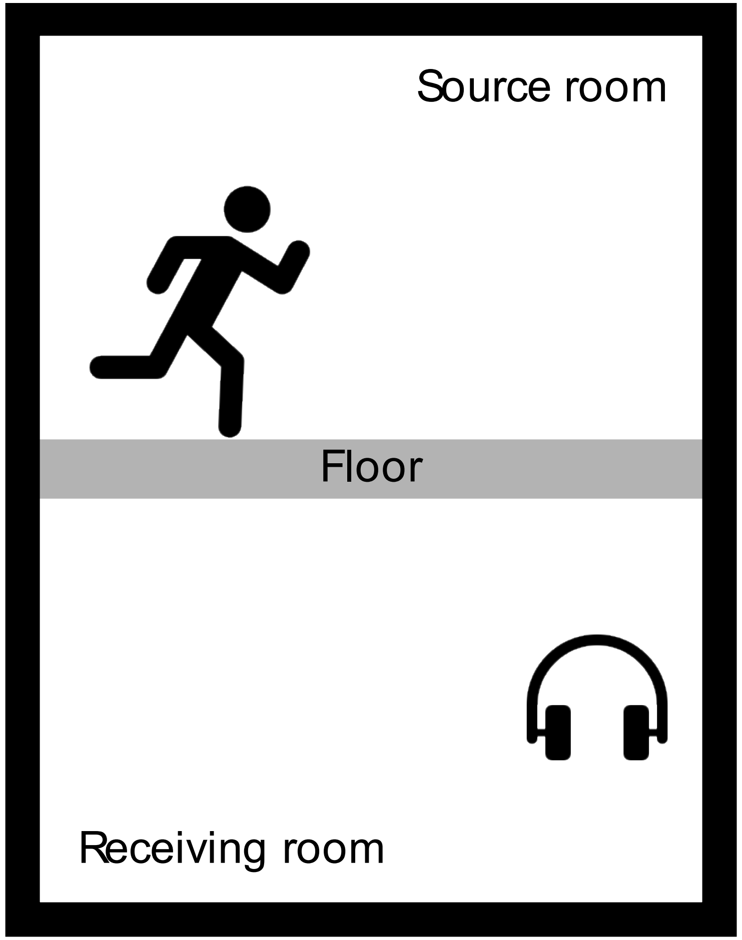
Kuttruff, H. (2007). *Acoustics: an introduction*. CRC Press.

Sound insulation



Air à solid (wall) à air

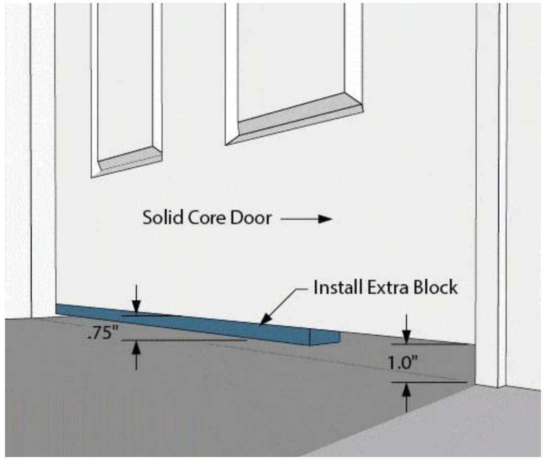
Airborne sound

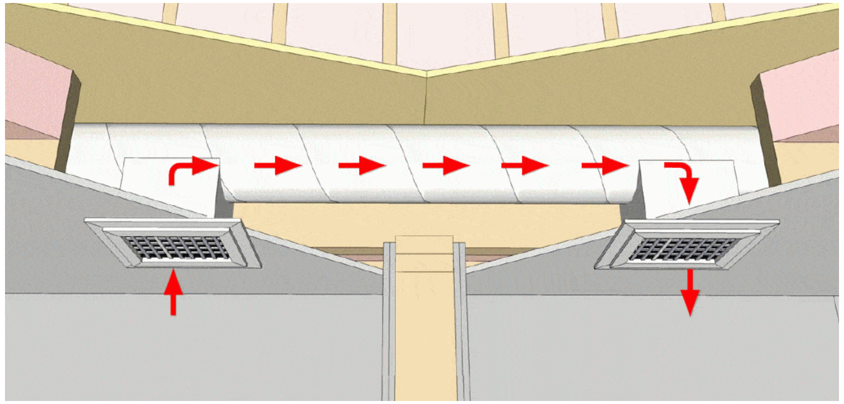


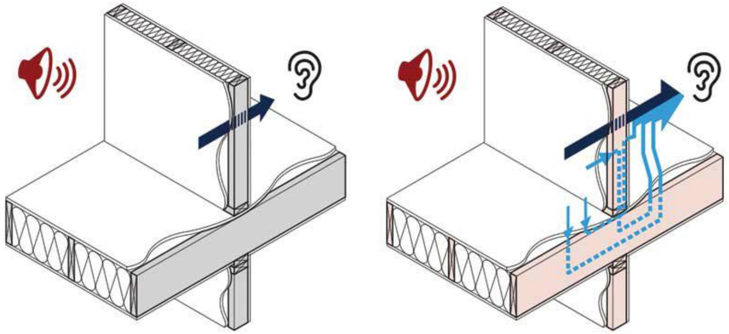
Solid (floor) à air

Structure-borne sound

Sound transfer paths

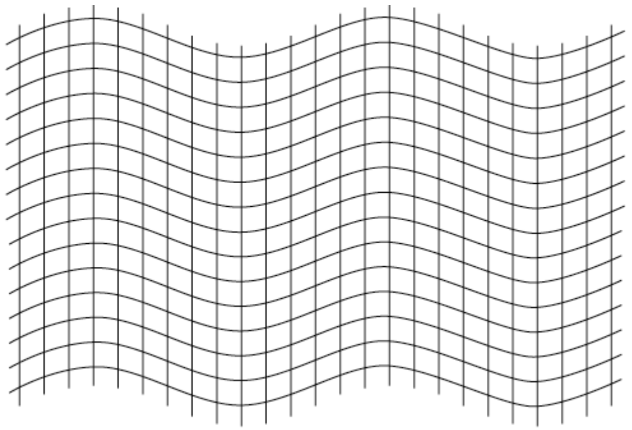




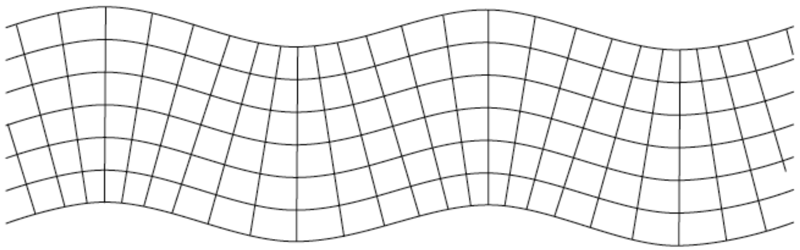


Sound waves in isotropic solids

Sound waves in unbounded solids



Waves in plates and bars



Wave propagation in solids

Wave propagation in air

Velocity components v_x, v_y, v_z [m/s] vector

Pressure p [N/m^2] scalar

Wave propagation in solids

Displacement components ξ, η, ζ [m] vector

[Elastic stresses](#)

$$\begin{pmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{pmatrix}$$

N/m^2] tensor

Wave propagation in solids

Wave propagation in air

1D wave equation -> motion of particles in direction of wave propagation

$$\frac{\partial^2 p}{\partial x^2} = \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2}$$

Wave propagation in solids

1D Wave equation -> motion of particles in direction of wave propagation

+ motion of particles perpendicular to wave propagation

$$(2\mu + \lambda)\frac{\partial^2 \xi}{\partial x^2} = \rho_0 \frac{\partial^2 \xi}{\partial t^2}$$

μ and λ are material properties

$$\mu \frac{\partial^2 \eta}{\partial x^2} = \rho_0 \frac{\partial^2 \eta}{\partial t^2}$$

$$\mu \frac{\partial^2 \zeta}{\partial x^2} = \rho_0 \frac{\partial^2 \zeta}{\partial t^2}$$

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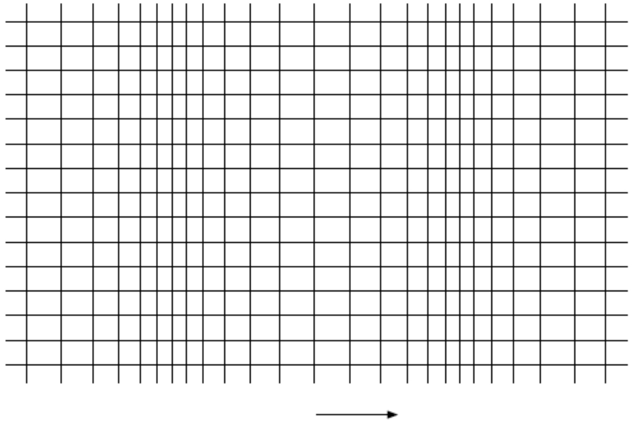
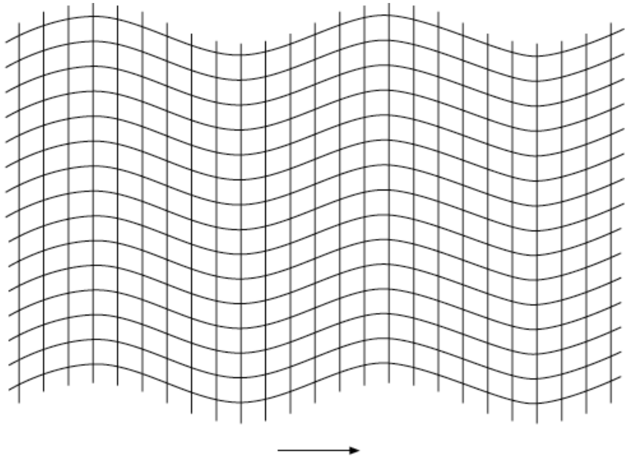
Wave propagation in solids

Longitudinal wave / compressional wave



$$(2\mu + \lambda)\frac{\partial^2 \xi}{\partial x^2} = \rho_0 \frac{\partial^2 \xi}{\partial t^2}$$

Transverse wave ('string instrument') / shear wave

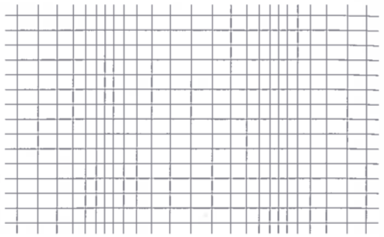


$$\mu \frac{\partial^2 \eta}{\partial x^2} = \rho_0 \frac{\partial^2 \eta}{\partial t^2}$$

$$\mu \frac{\partial^2 \zeta}{\partial x^2} = \rho_0 \frac{\partial^2 \zeta}{\partial t^2}$$

Wave propagation in solids

Longitudinal wave

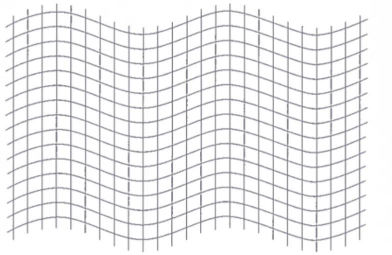


$$(2\mu + \lambda)\frac{\partial^2 \xi}{\partial x^2} = \rho_0 \frac{\partial^2 \xi}{\partial t^2}$$

Longitudinal wave speed c_L

$$c_L = \sqrt{\frac{2\mu + \lambda}{\rho_0}}$$

Transverse wave



$$\mu \frac{\partial^2 \eta}{\partial x^2} = \rho_0 \frac{\partial^2 \eta}{\partial t^2}$$

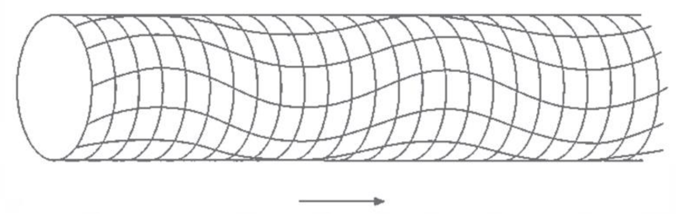
$$\mu \frac{\partial^2 \zeta}{\partial x^2} = \rho_0 \frac{\partial^2 \zeta}{\partial t^2}$$

Transverse wave speed c_T

$$c_T = \sqrt{\frac{\mu}{\rho_0}}$$

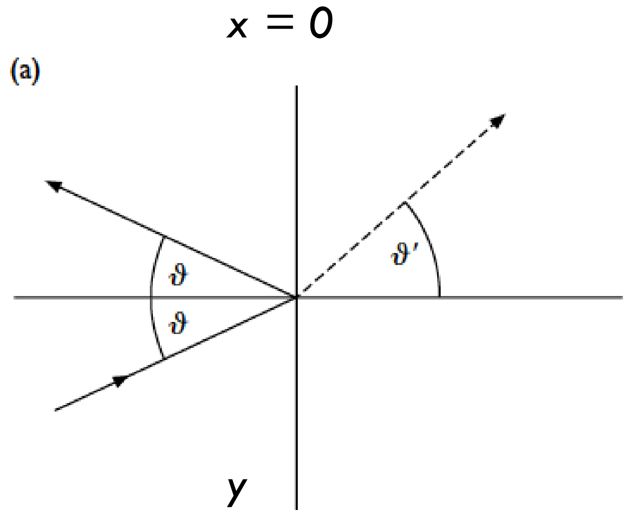
Wave propagation in solids

Special transversal wave: torsional wave



http://sciencedemonstrations.fas.harvard.edu/icb/icb.do?keyword=k16940&pageid=icb.page80865&pageContentId=icb.pagecontent606656&view=view.do&viewParam_name=indepth.html

Wave propagation in solids

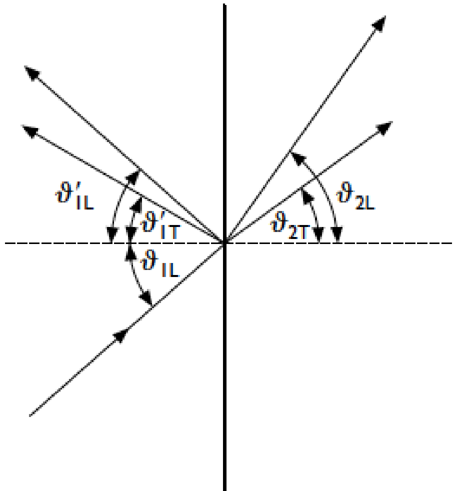


Interface of air with boundary:

Continuity of *p* and normal velocity component v_n

Two additional waves to fulfill boundary conditions (BCs)

Reflected and transmitted wave



Interface of two solid media:

Incident longitudinal wave with *x* and *y* dependency

Continuity of normal displacement component and stresses ξ, η, σ_{xx} and σ_{xy}

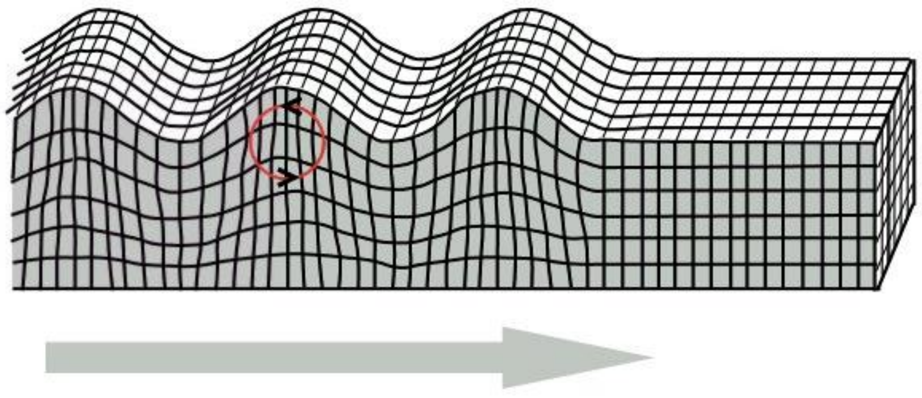
4 BCs, 4 additional waves -> wave conversion

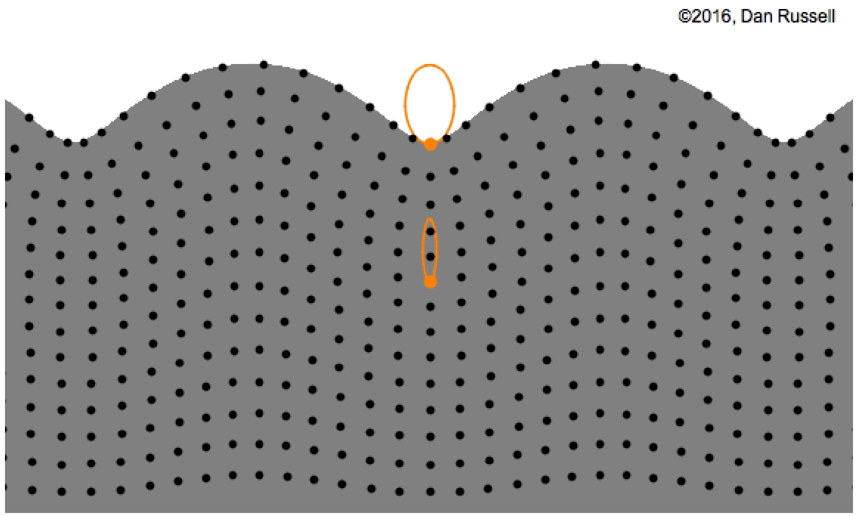
Kuttruff, H. (2007). *Acoustics: an introduction*. CRC Press.

Wave propagation in solids: interface

Rayleigh wave (surface wave), e.g. earthquake, water surface

Combination of longitudinal and transverse wave components, only close to surface.



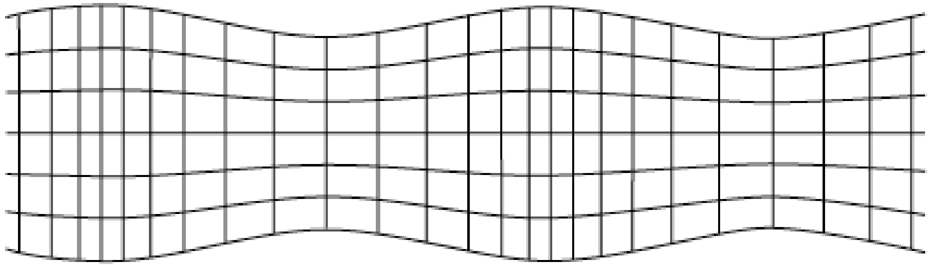


https://www.acs.psu.edu/drussell/Demos/waves/wavemotion.html

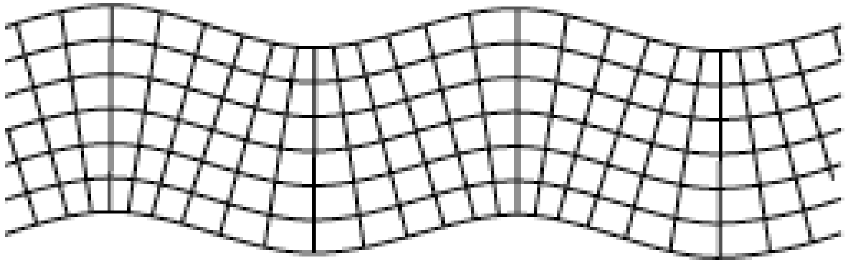
Wave propagation in plates and bars

- Most practical solids have a finite dimension
- Boundary effects play a role
- More wave types exist

Extensional waves (quasi longitudinal waves)



Bending waves



Wave propagation in plates and bars

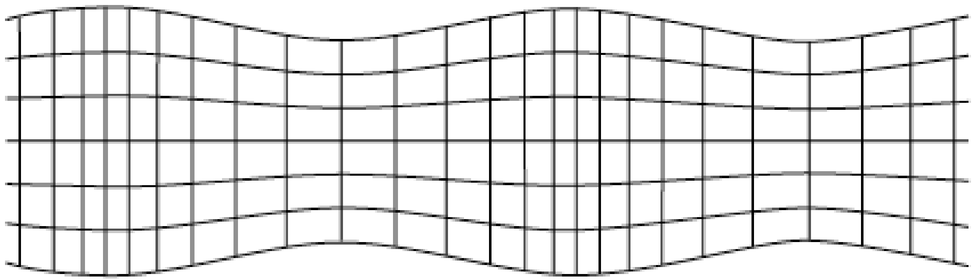
Extensional waves in plates and bars

Assumption: thin plates and bars (thickness << l)

Wave equation

Y = Young's modulus

$$\frac{\partial^2 \xi}{\partial x^2} = \frac{\rho_0}{Y}\frac{\partial^2 \xi}{\partial t^2}$$



Elastic deformation: extension and contraction

Wave propagation in plates and bars

Extensional waves in plates and bars

Extensional wave speed bar $$c_{E1} = \sqrt{\frac{Y}{\rho_0}}$$

Extensional wave speed plate $$c_{E2} = \sqrt{\frac{Y}{\rho_0(1-\nu^2)}}$$

Value of ν = Poisson's ratio $(0 < \nu < 0.5)$

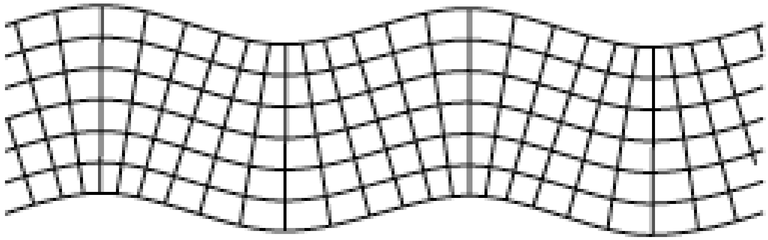
$$c_L > c_{E2} > c_{E1} > c_T$$

Wave propagation in plates and bars

Bending waves in plates and bars

Bending wave equation

$$\frac{\partial^4 \eta}{\partial x^4} + \frac{m'}{B}\frac{\partial^2 \eta}{\partial t^2} = 0$$



Bending stiffness B

$$B = \frac{d^3}{12} \cdot \frac{Y}{1 - \nu^2}$$

Solution

$$\eta(x,t) = \hat{\eta} \cdot e^{j(\omega t - k_B x)} \qquad k_B^2 = \pm\omega\sqrt{m'/B}$$

Wave propagation in plates and bars

Bending waves in plates and bars

Two travelling waves

$$(k_B)_{1,2} = \pm\sqrt{\omega} \cdot \sqrt[4]{\frac{m'}{B}}$$

Bending wave speed, depending on frequency

$$c_B = \frac{\omega}{k_B} = \sqrt{\omega} \cdot \sqrt[4]{\frac{B}{m'}}$$

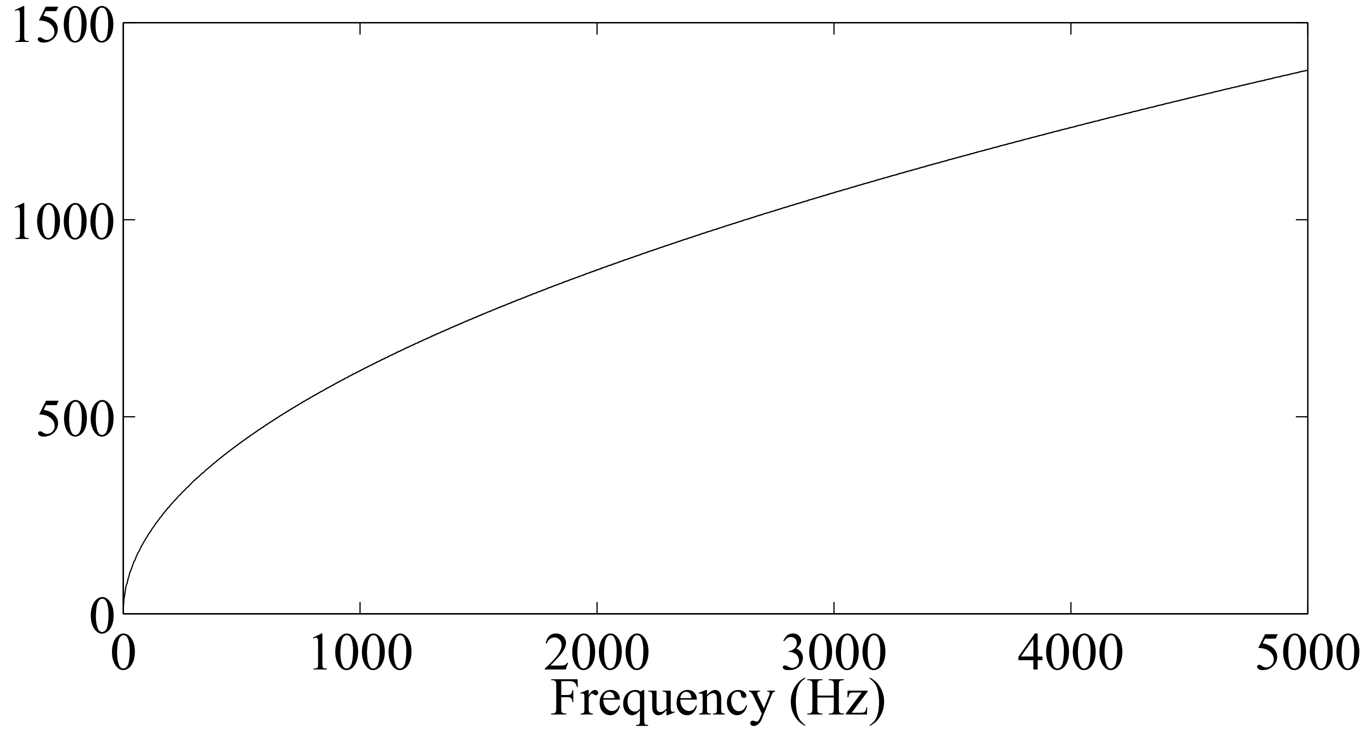
Wave propagation in plates and bars

Bending wave speed, 0.1 m brickwork

$B = 7 \cdot 10^5 \ \mathrm{Nm}^2$

$m' = 1900 \cdot 0.1 \ \mathrm{kg/m}^2$

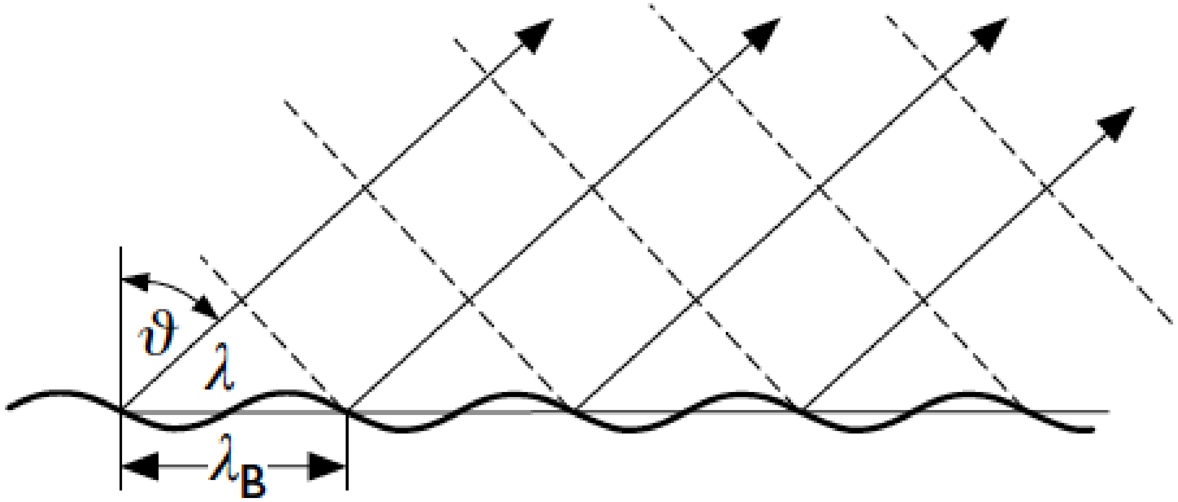
$$c_B = \frac{\omega}{k_B} = \sqrt{\omega} \cdot \sqrt[4]{\frac{B}{m'}}$$



Wave propagation in plates and bars

Sound radiation: critical frequeny is important!

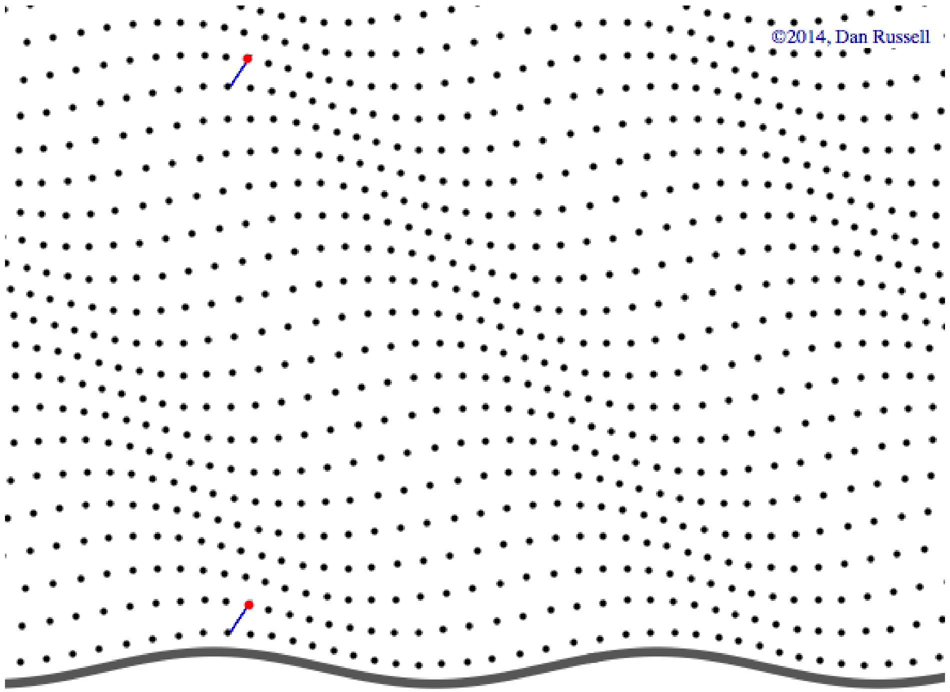
$$f_c = \frac{c^2}{2\pi}\sqrt{\frac{m'}{B}}$$



Kuttruff, H. (2007). *Acoustics: an introduction*. CRC Press.

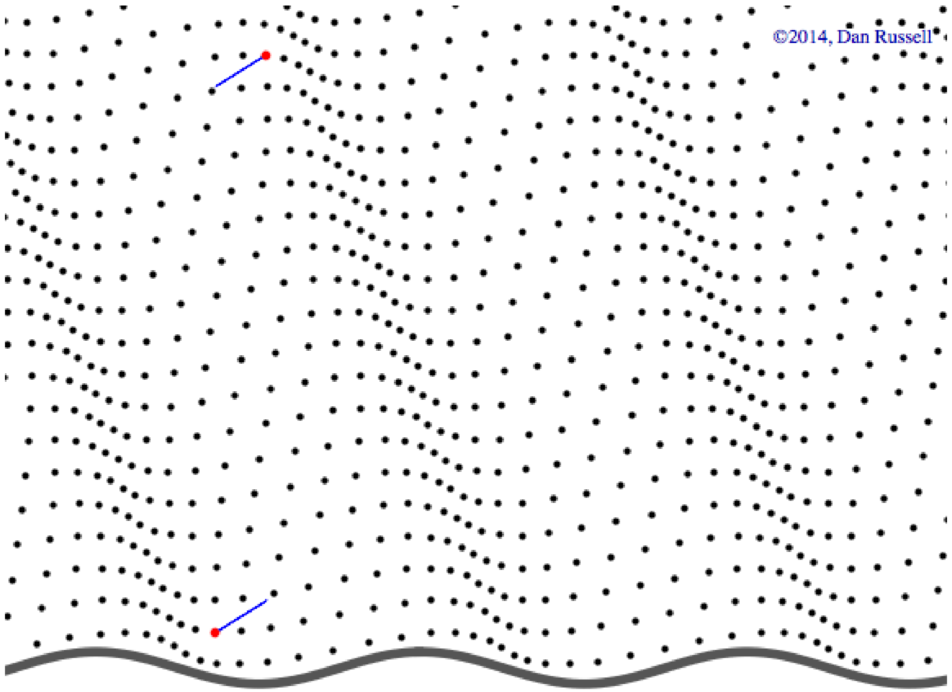
Wave propagation in plates and bars

$$c_{\mathrm{B}} = 1.5c$$



$$\theta = \arcsin\frac{1}{1.5} = 41.81^{\circ}$$

$$c_{\mathrm{B}} = 1.1c$$



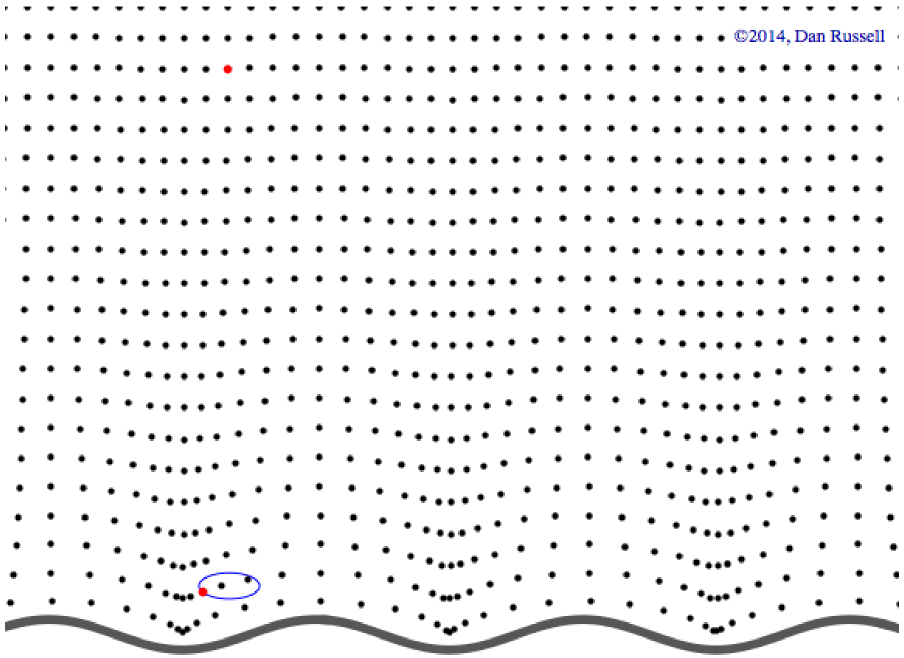
$$\theta = \arcsin\frac{1}{1.1} = 65.38^{\circ}$$

Wave propagation in plates and bars

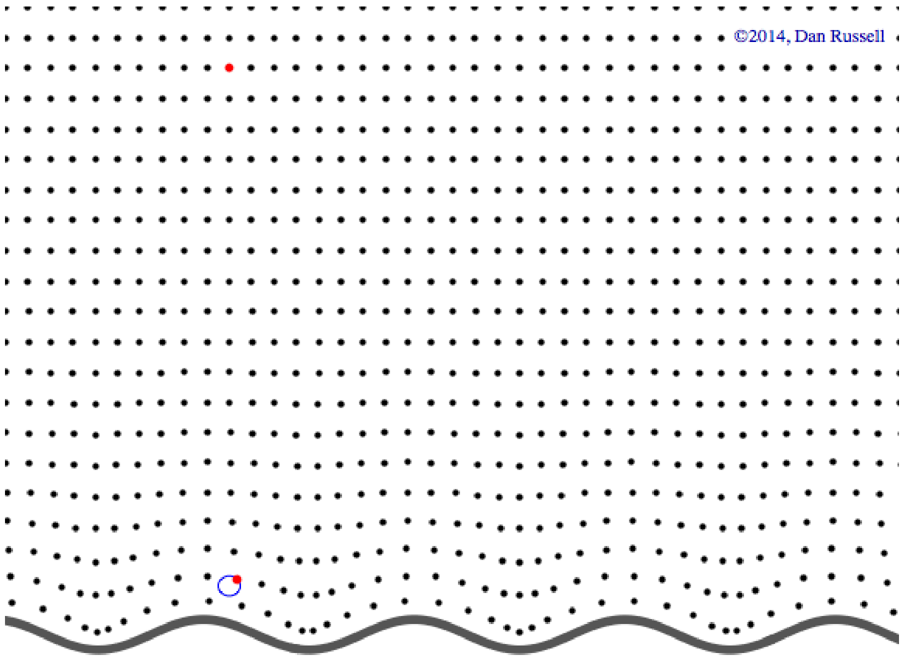
For $c_\mathrm{B} < c$ (or $\lambda_\mathrm{B} < \lambda$ or $\omega < \omega_\mathrm{c}$):

no radiation of sound

$c_\mathrm{B} = 0.95c$



$c_\mathrm{B} = 0.75c$



Wave propagation in plates and bars

Application: ice thickness

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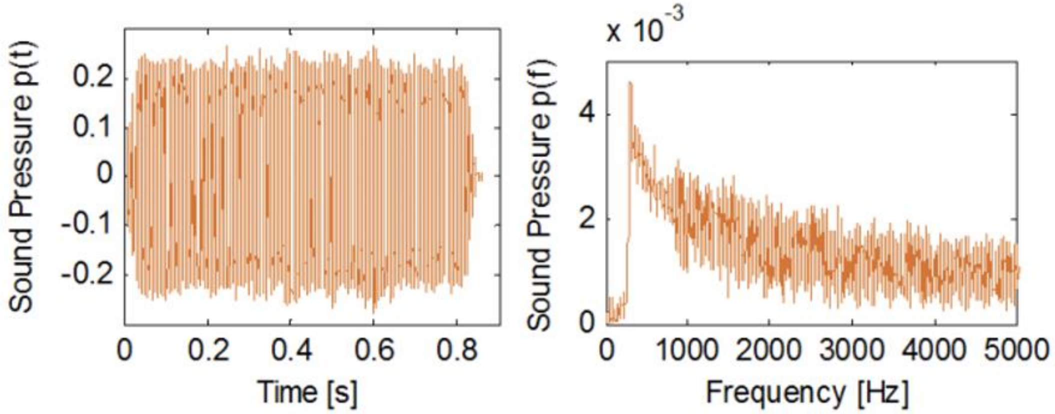
Wave propagation in plates and bars

Wave propagation in plates and bars

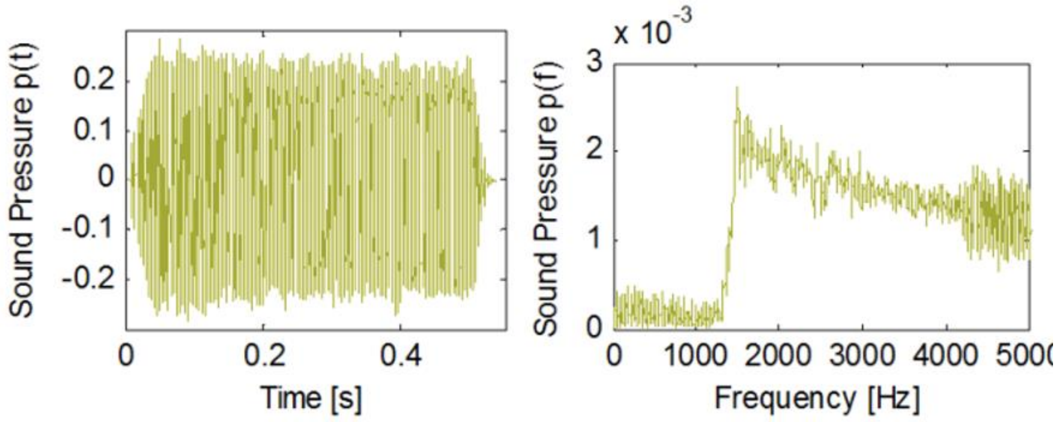
Application: ice thickness

Q. Can you estimate the thicknesses from the measure data?

Ice layer of thickness A



Ice layer of thickness B



Properties: $Y = 9.1 \times 10^9\,\mathrm{N/m^2}$

$$\rho_0 = 916.7\,\mathrm{kg/m^3}$$

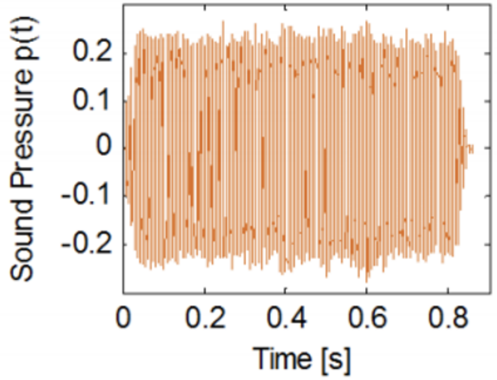
$$\nu = 0.33$$

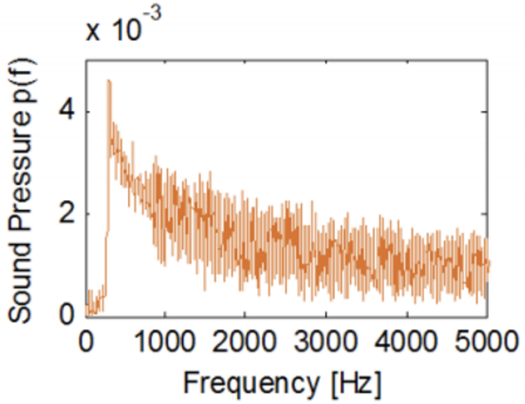
$$c = 340\,\mathrm{m/s}$$

Wave propagation in plates and bars

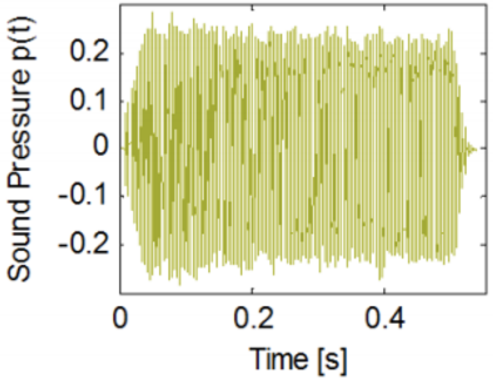
Application: ice thickness

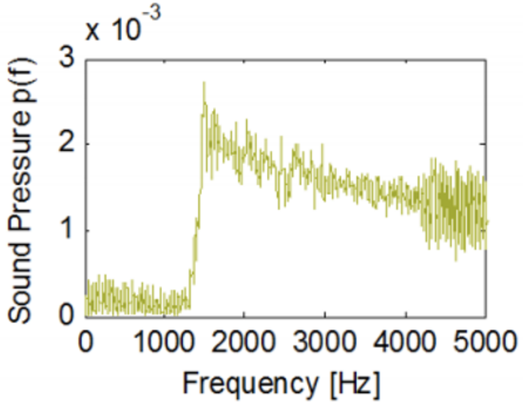
Ice layer of thickness A





Ice layer of thickness B





Critical frequency of a plate

$$\omega_c = c^2 \sqrt{\frac{m'}{B}} \quad \text{where} \begin{cases} m' = \rho_0 d \\ B = \dfrac{Y d^3}{12(1-\nu^2)} \end{cases}$$

$$\Rightarrow d = \frac{c^2}{\pi f_c} \sqrt{\frac{3(1-\nu^2)\rho_0}{Y}}$$

Estimation of the ice layer thickness

Thickness A

$$f_c = 250\,\mathrm{Hz} \quad \Rightarrow \text{thickness } d = 7.6\,\mathrm{cm}$$

Thickness B

$$f_c = 1500\,\mathrm{Hz} \quad \Rightarrow \text{thickness } d = 1.3\,\mathrm{cm}$$

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Building Acoustics

Air-borne sound insulation

Measurements
Single leaf partitions
Double leaf partitions

Measuring sound insulation

Measurements

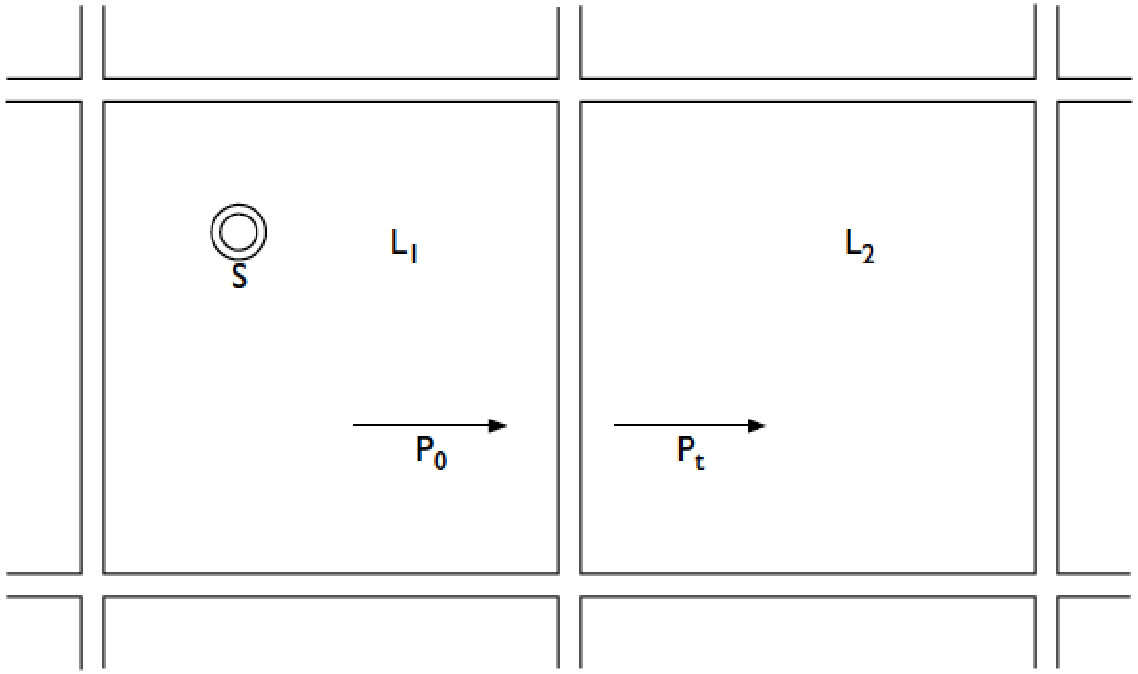
Reduction index

$$R_A = 10\log_{10}\left(\frac{I_0}{I_t}\right)$$

$$I_0 = P_0/S$$

$$I_t = P_t/S$$

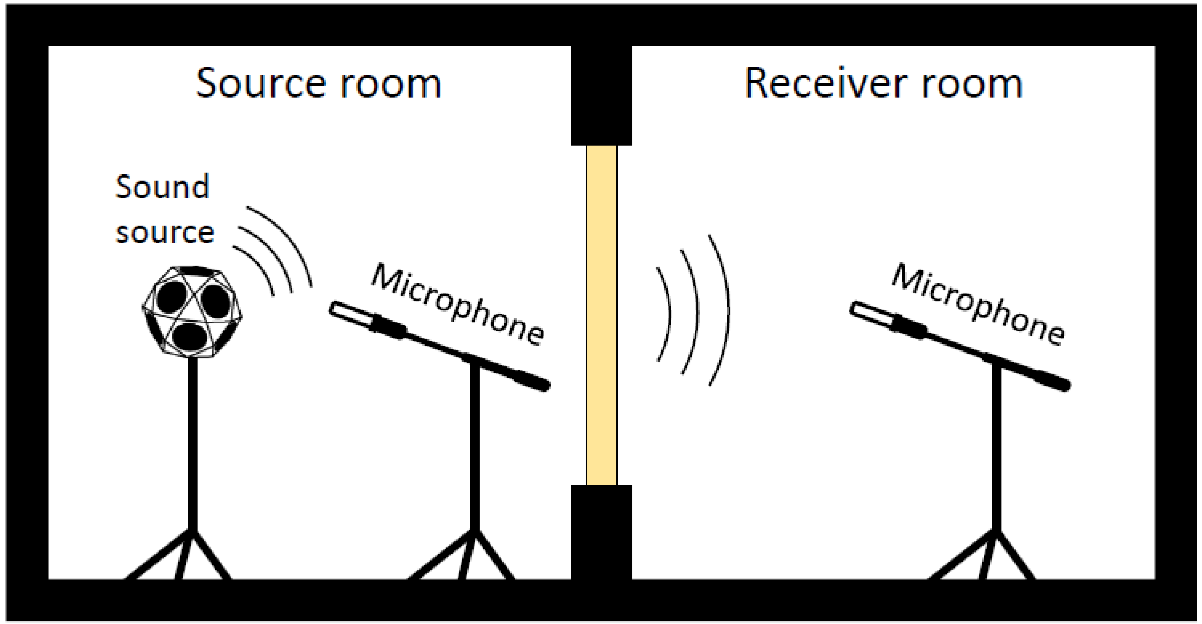
$$R_A = 10\log_{10}\left(\frac{P_0}{P_t}\right)$$



Measuring sound insulation

Measurements

Diffuse sound field



http://plus.pointblanklondon.com/government-lab-reveals-its-sonic-secrets-danny-j-lewis-investigates/

Measuring sound insulation

Measurements

Diffuse sound field: acoustic energy density *w* [J/m³] is a constant

Incident power:

$$P_0 = \frac{c}{4} S \cdot w_1$$

Power in receiver room:

power radiated by wall = power absorbed by boundaries

$$P_t = \frac{c}{4} A \cdot w_2$$

Measuring sound insulation

Measurements

Using

$$R_A = 10\log_{10}\left(\frac{P_0}{P_t}\right)$$

And relations from previous slide

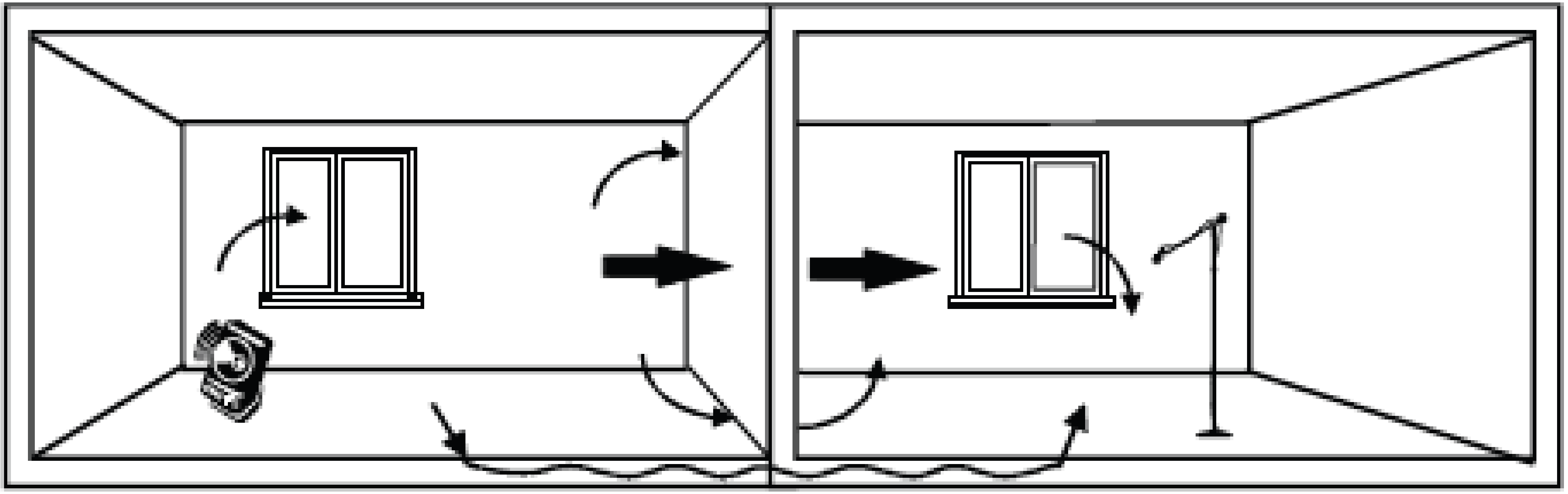
$$R_A = 10\log_{10}\left(\frac{w_1}{w_2}\right) + 10\log_{10}\left(\frac{S}{A}\right)$$

This leads to

$$R_A = L_1 - L_2 + 10\log_{10}\left(\frac{S}{A}\right)$$

Measuring sound insulation

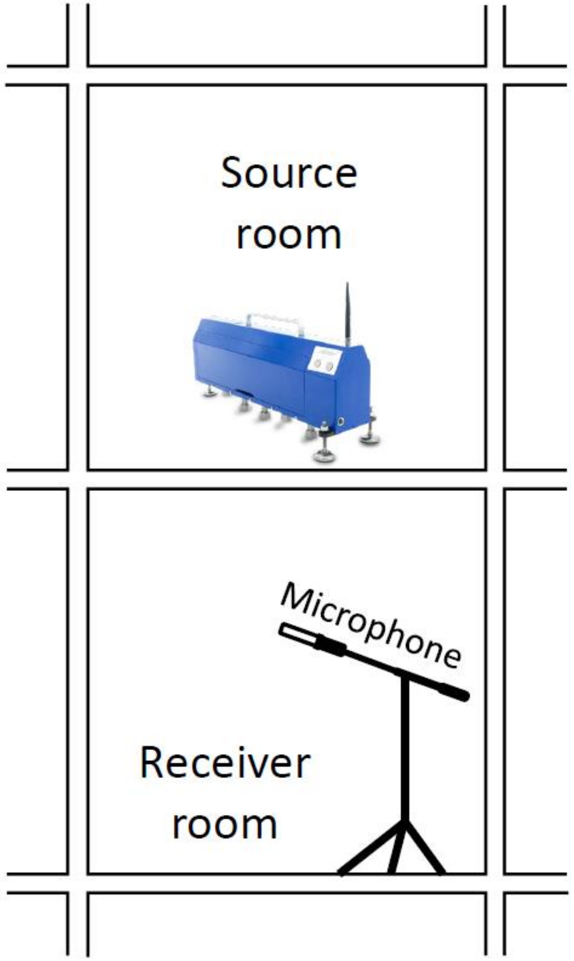
Field measurements



Vigran, Building Acoustics

Measuring sound insulation

Structure borne sound insulation



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SEA

EAA

Measuring sound insulation

Flanking sound transmission

https://acoustical-consultants.com/built-environment/noise-investigations/how-to-measure-astc-ratings-of-specific-sound-transmission-paths/

Mockup of CLT construction at University of Bologna

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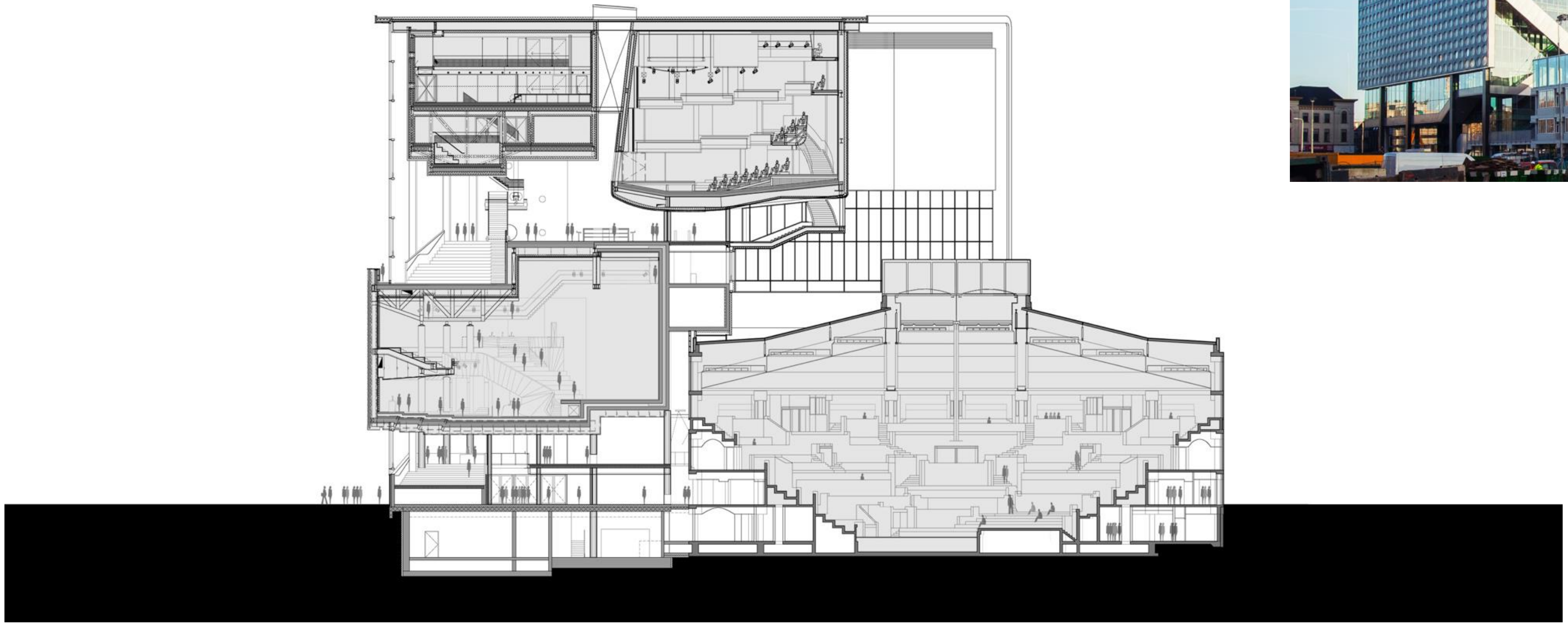
SEA

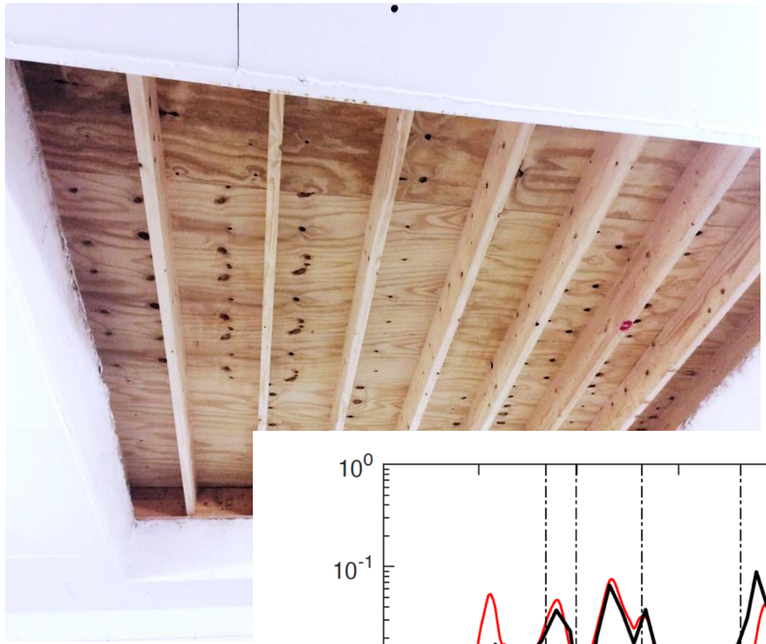
EAA

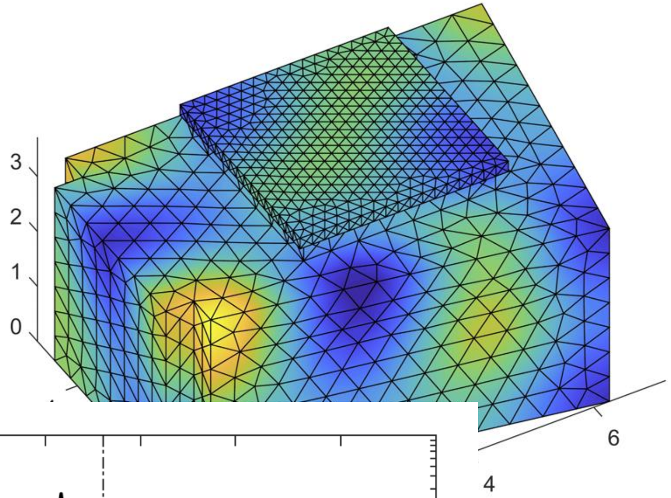
Predicting sound insulation

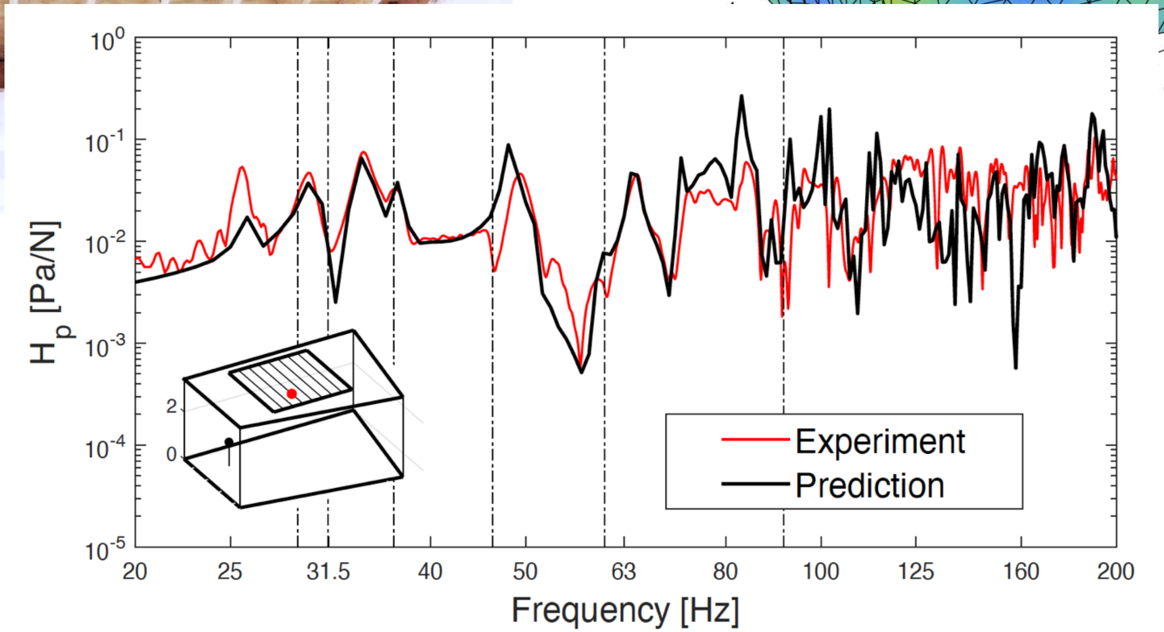


https://www.nationalestaalprijs.nl/project/muziekcentrum-tivolivredenburg

Predicting sound insulation

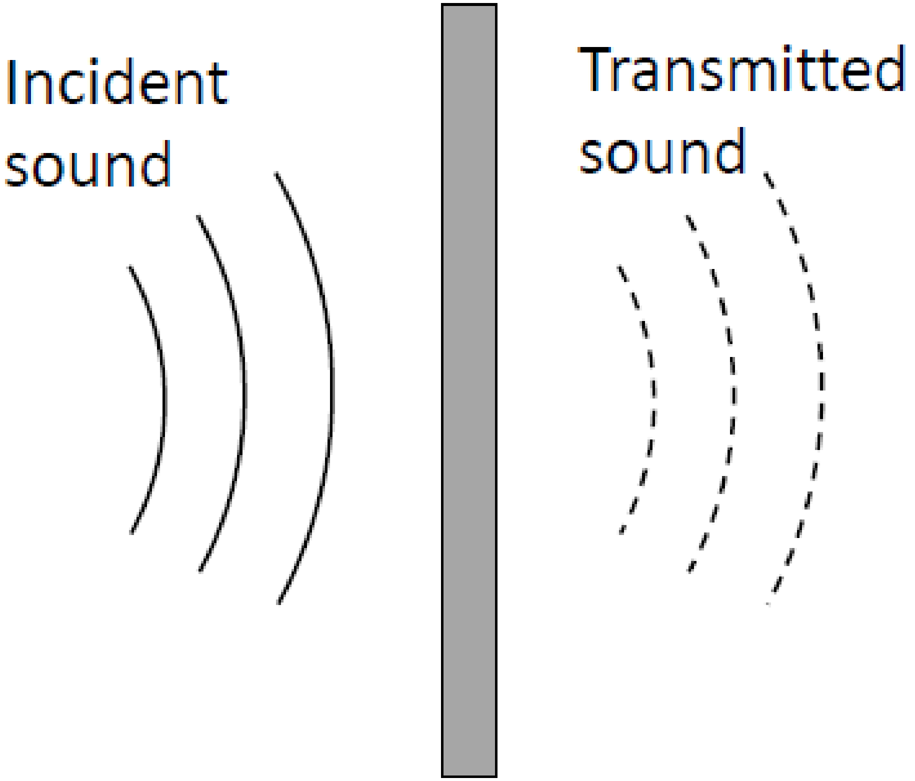






Building Acoustics: Air-borne sound insulation

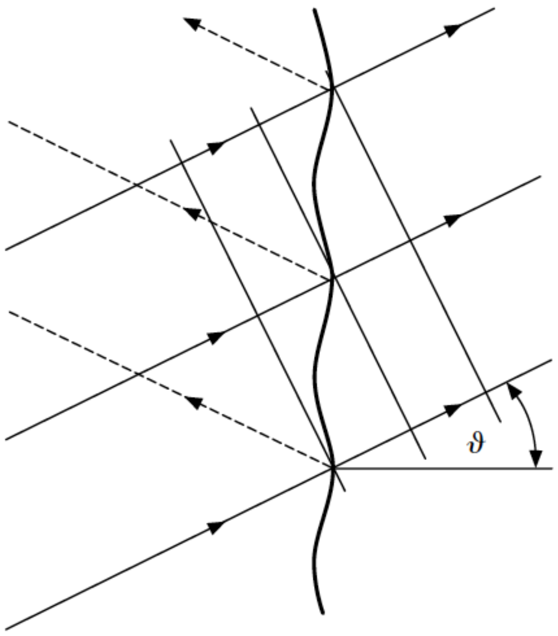
Air-borne sound insulation: Single leaf partitions



Building Acoustics: Air-borne sound insulation

Air-borne sound insulation: Single leaf partitions

Incident plane wave at thin wall



pressures at both sides of the wall

$$p_1(y) = \hat{p}(1 + R)e^{-jky\sin\vartheta} \cdot e^{j\omega t}$$

$$p_2(y) = \hat{p}Te^{-jky\sin\vartheta} \cdot e^{j\omega t}$$

displacement component in wall

$$\xi(y) = \hat{\xi}e^{-jky\sin\vartheta} \cdot e^{j\omega t}$$

Building Acoustics: Air-borne sound insulation

Air-borne sound insulation: Single leaf partitions

Bending wave equation, imposed force is pressure difference over wall

$$m' \frac{\partial^2 \xi}{\partial t^2} + B \frac{\partial^4 \xi}{\partial y^4} = p_1 - p_2$$

$$p_1 - p_2 = (-\omega^2 m' + Bk^4 \sin^4 \vartheta) \cdot \xi$$

To compute the sound reduction index, we need

$$R_A = 10 \log_{10} \left| \frac{p_i}{p_2} \right|^2$$

Building Acoustics: Air-borne sound insulation

Air-borne sound insulation: Single leaf partitions

$$p_1 - p_2 = \left(-\omega^2 m' + B k^4 \sin^4 \vartheta\right) \cdot \xi \qquad R_A = 10 \log_{10} \left| \frac{p_i}{p_2} \right|^2$$

Making use of $p_1 = p_i + p_r$ and $v_{x,i} + v_{x,r} = v_{x1} = v_{x2}$

$$R_A \approx 10 \log_{10}\left(X^2\right)$$

$$X = \frac{\omega m'}{2 Z_0} \cos(\theta) \left[1 - \frac{B \omega^2 \sin^4(\theta)}{m' c^4} \right]$$

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Building Acoustics: Air-borne sound insulation

Air-borne sound insulation: Single leaf partitions

$$\omega < \omega_c$$

$$R_A \square 10 \log_{10}\left(X^2\right)$$

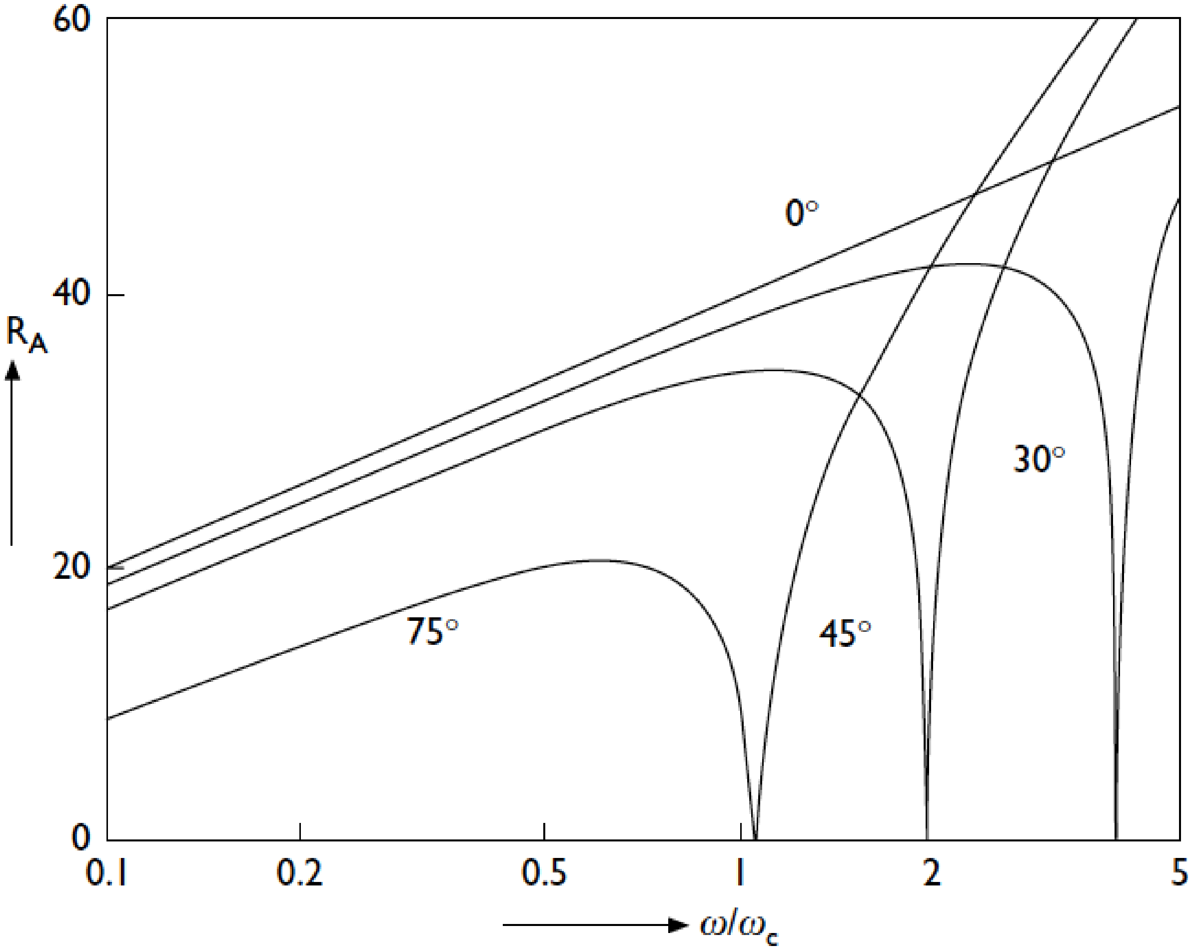
$$X = \frac{\omega m'}{2Z_0}\cos(\theta)$$

$$\omega > \omega_c$$

$$X = \cos(\theta)\frac{B\omega^3 \sin^4(\theta)}{2Z_0 c^4}$$

Building Acoustics: Air-borne sound insulation

Air-borne sound insulation: Single leaf partitions

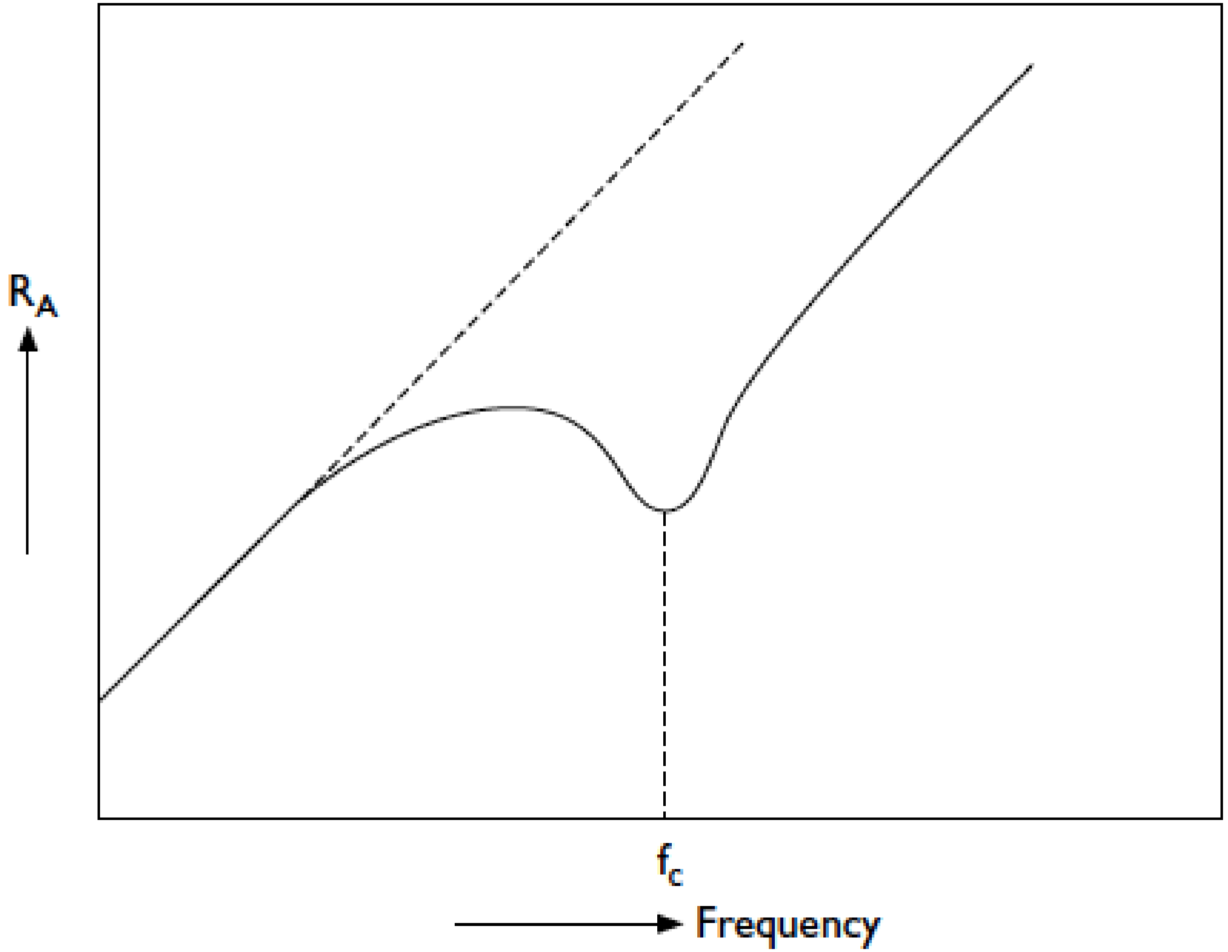


Demo

Building Acoustics: Air-borne sound insulation

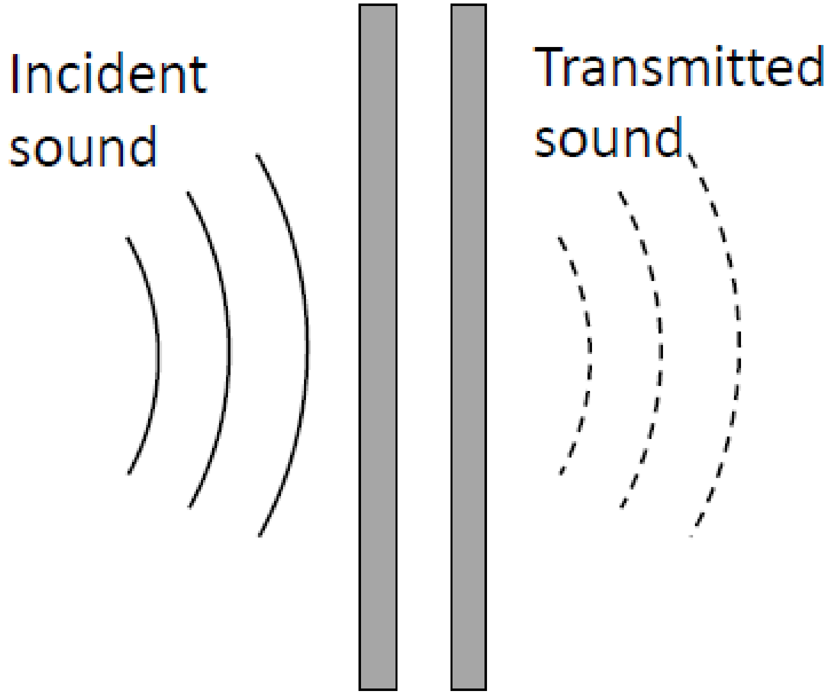
Air-borne sound insulation: Single leaf partitions

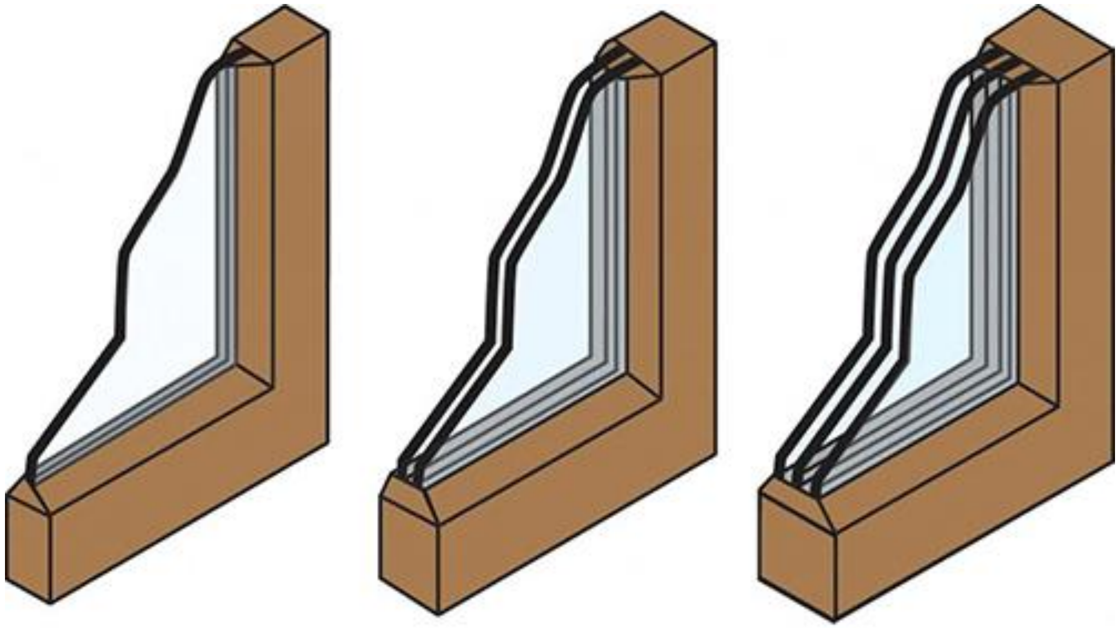
We also should include
- Damping of bending waves
- Finite dimensions of partitions
- Random incident sound waves



Building Acoustics: Air-borne sound insulation

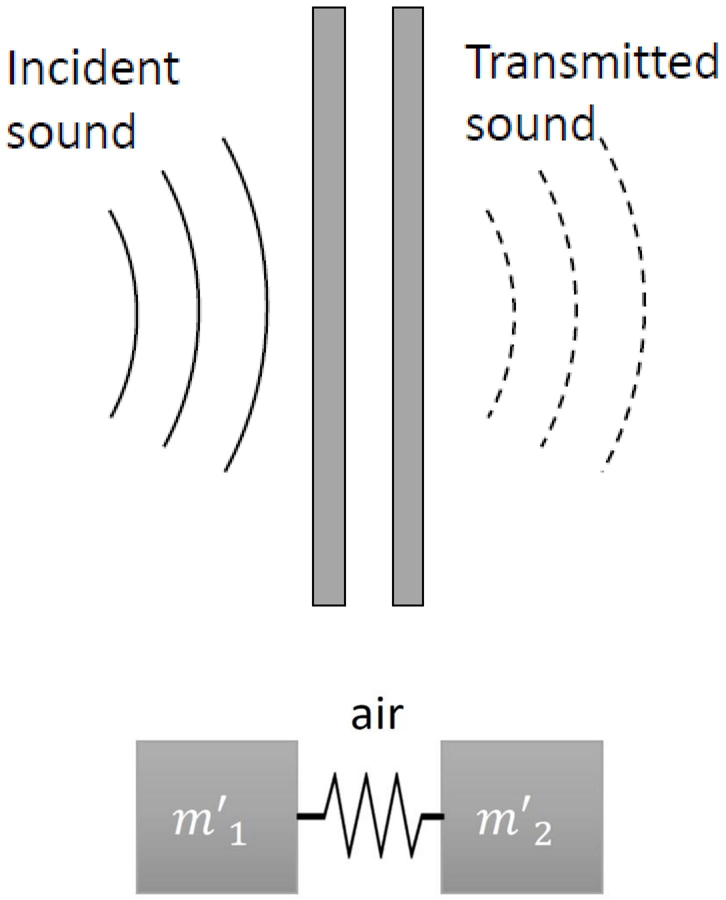
Air-borne sound insulation: Double leaf partitions





Building Acoustics: Air-borne sound insulation

Double leaf partitions



Building Acoustics: Air-borne sound insulation

Air-borne sound insulation: Double leaf partitions

For very low frequencies

The two leafs vibrate in equal phase

$$R_A \approx 20\log_{10}\left(\frac{\omega\left(m_1' + m_2'\right)}{2Z_0}\right)$$

The leafs vibrate in opposite phase at the mass-spring resonance frequency

$$\omega_0 = \sqrt{\frac{1}{n'}\left(\frac{1}{m_1'} + \frac{1}{m_2'}\right)}$$

Building Acoustics: Air-borne sound insulation

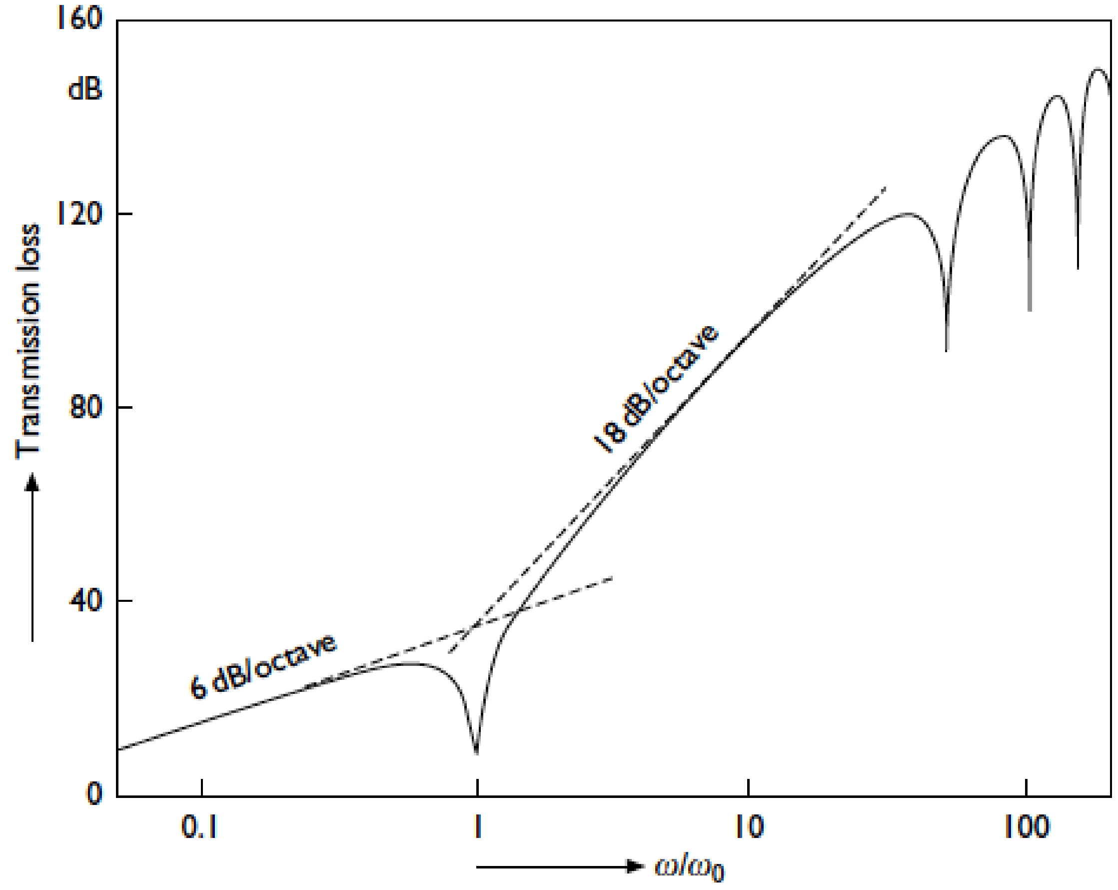
Air-borne sound insulation: Double leaf partitions

Above the mass spring resonance frequency
The two leafs vibrate in random phase

$$R_A \approx 20\log_{10}\left(\frac{\omega^3 n' m_1' m_2'}{2Z_0}\right)$$

Building Acoustics: Air-borne sound insulation

Air-borne sound insulation: Double leaf partitions



Building Acoustics: Air-borne sound insulation

Air-borne sound insulation: Double leaf partitions

We also should include

- Damping of bending waves
- Finite dimensions of partitions (mechanical coupling of leafs)
- Random incident sound waves

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Tutorial Time

Investigate the sound insulation of a wall as a function of frequency by changing:

- Mass
- Thickness
- Angle of sound wave incidence

$$f_c = \frac{c^2}{2\pi}\sqrt{\frac{m'}{B}}$$

Calculate the critical frequency of the wall

Can you recognize this frequency in the sound insulation curve?