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Acoustics VTAN01
13. RECAP

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Learning outcomes

- Definition of sound
- Harmonic oscillations and complex notation
- Acoustic variables and levels
- Addition of correlated and uncorrelated sources
- Frequency domain representation

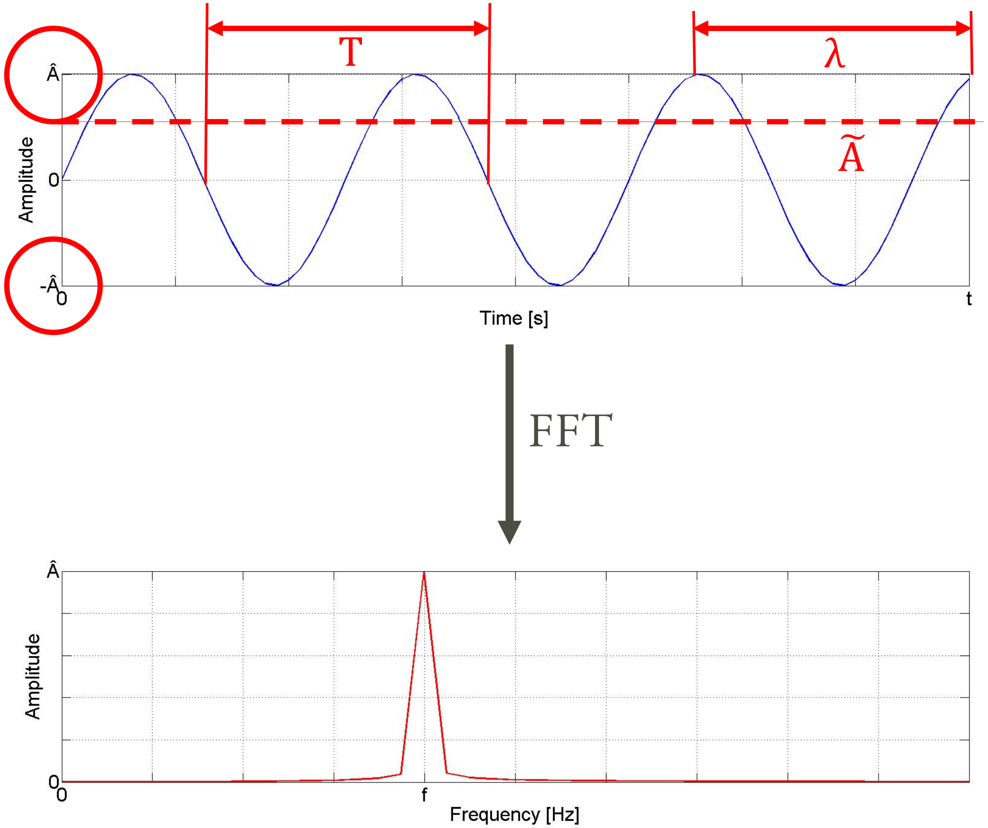
Time & frequency domains (I)

Harmonic signal: $y(t) = \hat{A}\sin(\omega t) = \hat{A}\cos(\omega t + \varphi) = \hat{A}\sin(2\pi f \cdot t)$

- Amplitude: $\hat{A}$
- Period [s]: $T = {}^{1}/_{f}$
- Frequency [Hz]: $f = {}^{1}/_{T}$
- Wavelength [m]: $\lambda = cT = {}^{c}/_{f}$
- Propagation Speed [m/s]: $c = f\lambda$

  NOTE: $c \neq v$
- Effective value (RMS):

$$A_{RMS} = \tilde{A} = \sqrt{\frac{1}{\Delta t}\int_{t_0}^{t_0+\Delta t} y^2(t)\,dt}\,, \quad \tilde{A}_{\substack{\text{harmonic}\\ \text{signal}}} = {}^{\hat{A}}/_{\sqrt{2}}$$



- Frequency domain

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Complex notation

- Equivalent description: $p(t)=\hat{A}\cos(\omega t+\varphi)$

$$p(t)=\mathrm{Re}\left[Ae^{-i(\omega t+\varphi)}\right]=\mathrm{Re}\left[\underline{A}e^{-i\omega t}\right]$$

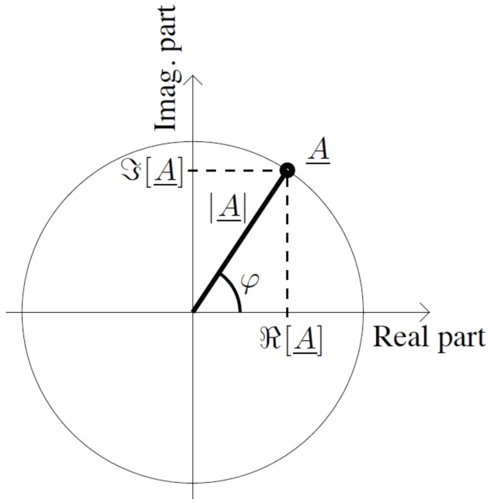
where the complex amplitude is defined as: $\underline{A}=Ae^{i\varphi}$

and $e^{i\varphi}=\cos(\varphi)+i\sin(\varphi)$

- The peak value and initial phase are

$$A=|\underline{A}|$$

$$\tan(\varphi)=\frac{\mathrm{Im}[\underline{A}]}{\mathrm{Re}[\underline{A}]}$$

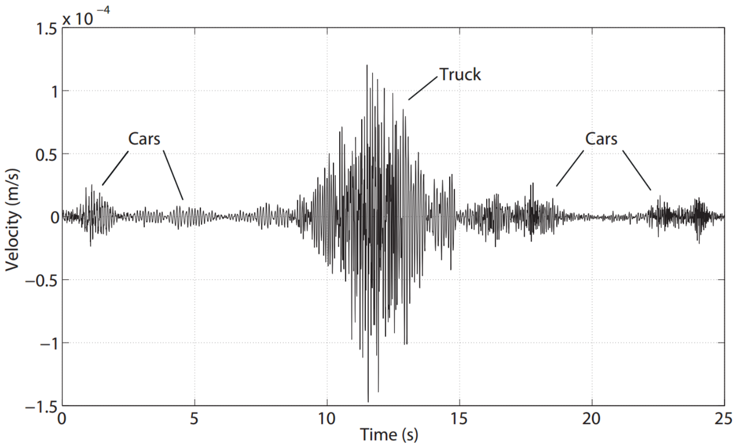


NOTE 1: The complex number "*i*" is sometimes also expressed as "*j*"

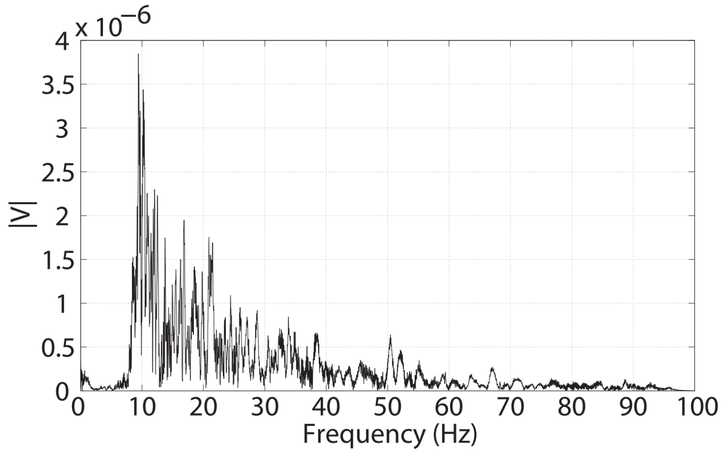
NOTE 2: $\varphi_{\cos}=\varphi_{\sin}-\frac{\pi}{2}$

Time & frequency domains (II)

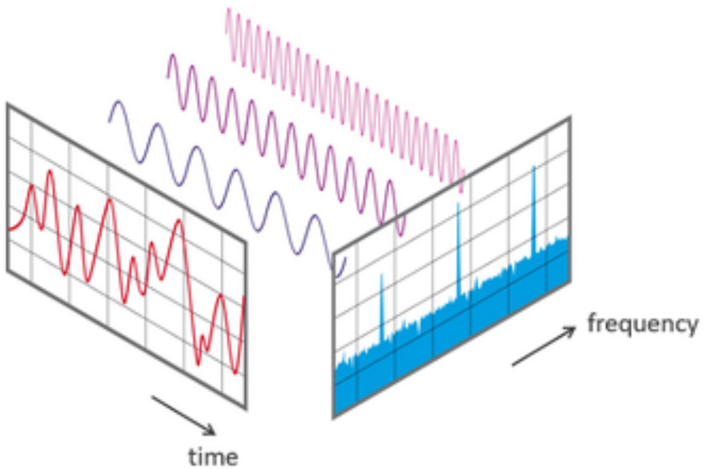
- A more complex time signal (traffic load)



FFT

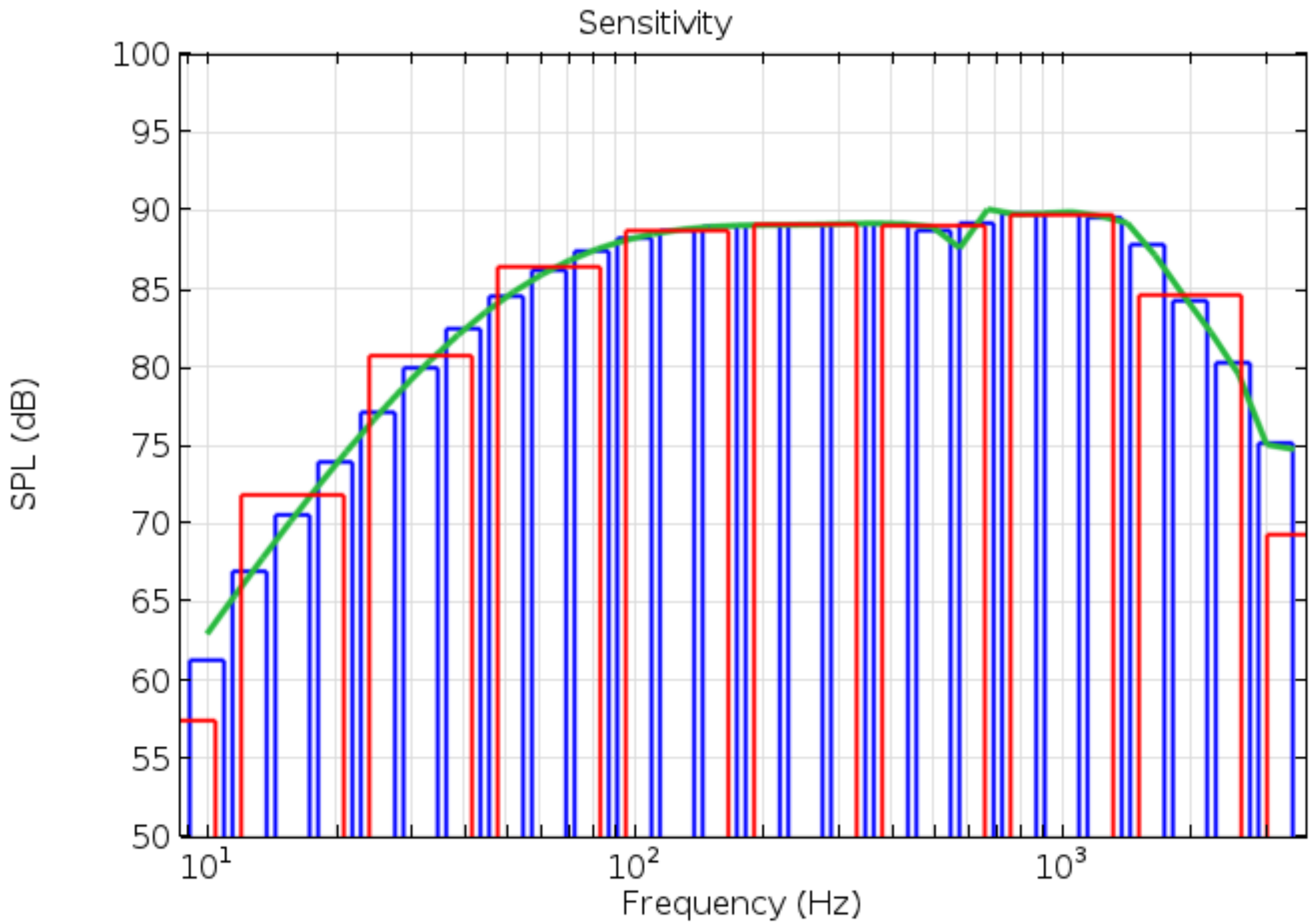


- Narrow band analyses
  - Impractical, time-consuming
  - Octave & 1/3 octave bands



NOTE: Spectrum (any magnitude plotted against frequency)

Time & frequency domains (II)



Frequency responses:

Narrow band

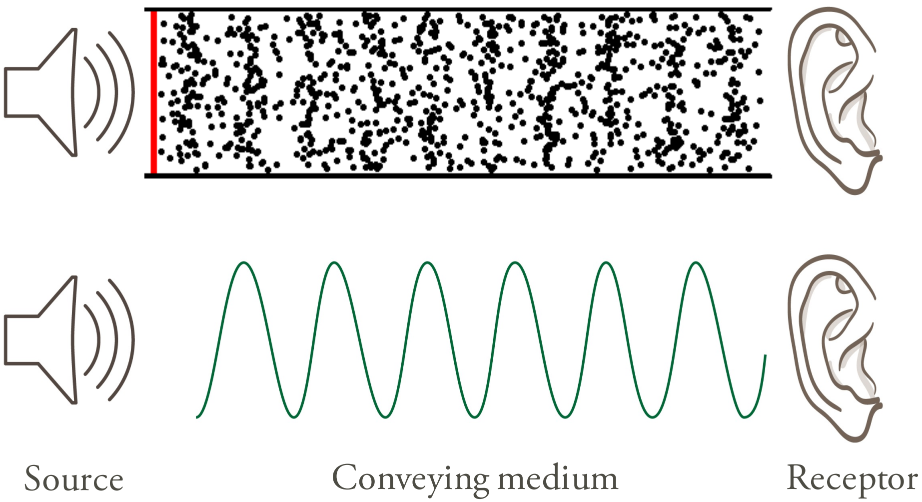
Octave bands

1/3 octave bands

[www.comsol.com/blogs/new-octave-band-plot-for-acoustics-simulations-in-version-5-2/]

Hearing process

- Pressure waves
- For a sound to be perceived
  - Frequency: 20 Hz – 20 kHz
  - Sound pressure level (SPL): frequency dependent
- Inner ear detects: $\Delta p \in [20\ \mu Pa, 200\ Pa]$ → wide range
  - Use of logarithmic scale (in decibels)



The decibel (dB) & SPL

- Logarithmic way of describing a ratio
  - Ratio: velocity, voltage, acceleration…
  - Need of a reference

- Sound pressure level (SPL / L_p)

$$L_p = 10\log\left(\frac{\tilde{p}^2}{p_{ref}^2}\right) = 20\log\left(\frac{\tilde{p}}{p_{ref}}\right)$$

$$\tilde{p} = \tilde{p}(f) \equiv \text{RMS pressure}$$
$$p_{ref} = 2\cdot 10^{-5}\ \text{Pa} = 20\ \mu\text{Pa}$$
$$p_{atm} = 101\,300\ \text{Pa}$$
$$p_{tot}(t) = p_{atm} \pm p(t)$$

  - $\tilde{p}$ measured with microphones
  - Frequency response of human hearing changes with amplitude

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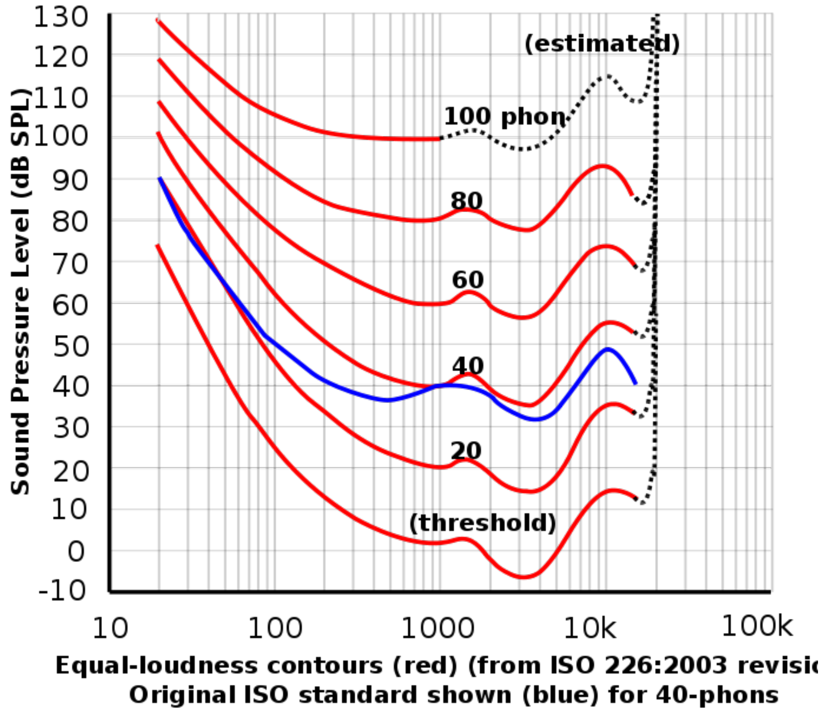
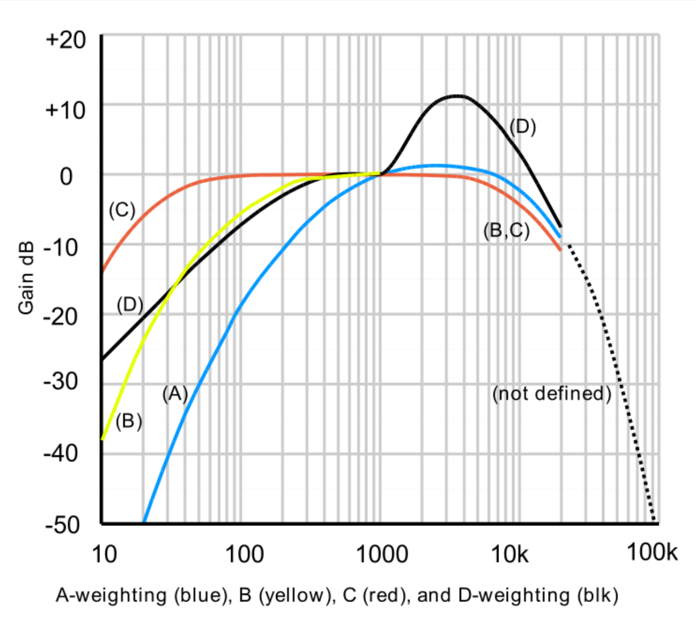
Frequency weightings

- Frequency response of human hearing changes with amplitude
- How to relate the objective measure to the subjective experience of sound?



Frequency weightings

- Filters and calculation



$$L_{weighted} = 10 \log \left(\sum 10^{\frac{(L_n + weighting)}{10}} \right)$$

Frekvens [Hz]	A-filter [dB]	B-filter [dB]	C-filter [dB]
10	-70.4	-38.2	-14.3
12.5	-63.4	-33.2	-11.2
16	-56.7	-28.5	-8.5
20	-50.5	-24.2	-6.2
25	-44.7	-20.4	-4.4
31.5	-39.4	-17.1	-3.0
40	-34.6	-14.2	-2.0
50	-30.2	-11.6	-1.3
63	-26.2	-9.3	-0.8
80	-22.5	-7.4	-0.5
100	-19.1	-5.6	-0.3
125	-16.1	-4.2	-0.2
160	-13.4	-3.0	-0.1
200	-10.9	-2.0	0
250	-8.6	-1.3	0
315	-6.6	-0.8	0
400	-4.8	-0.5	0
500	-3.2	-0.3	0
630	-1.9	-0.1	0
800	-0.8	0	0
1000	0	0	0
1250	0.6	0	0
1600	1.0	0	-0.1
2000	1.2	-0.1	-0.2
2500	1.3	-0.2	-0.3
3150	1.2	-0.4	-0.5
4000	1.0	-0.7	-0.8
5000	0.5	-1.2	-1.3
6300	-0.1	-1.9	-2.0
8000	-1.1	-2.9	-3.0
10000	-2.5	-4.3	-4.4
12500	-4.3	-6.1	-6.2
16000	-6.6	-8.4	-8.5
20000	-9.3	-11.1	-11.2

Frequency weightings (I)

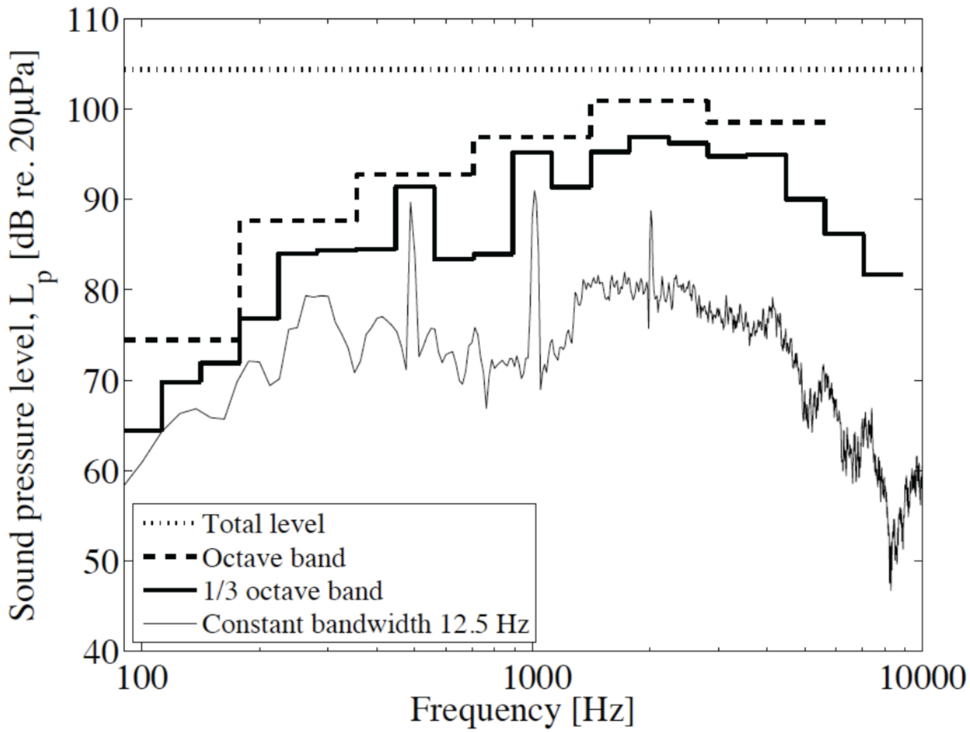
- Correlate objective sound measurements with subjective human response
  - A-weighting [dB(A)/dBA]: designed to reflect the response of how the human ear perceives noise, i.e. 20 Hz-20 kHz
    - » Only really accurate for relatively quiet sounds and pure tones?
    - » Low frequency noise is suppressed (wind turbine noise?)
  - C-weighting [dB(C)/dBC]: developed for high level aircraft noise
  - Z-weighting: zero frequency weighting (un-weighted values)
  - B-weighting: covers the mid-range between the A- and C-weighting
  - D-weighting: designed for use when measuring high level aircraft noise

Fallen into disuse

*Filters are defined in the standard IEC 61672

Frequency bands

- A sound in the frequency domain may be looked at in several ways.
  - Narrow bands;
  - Third-octave bands;
  - Octave bands;
  - Total value.



Octave and 1/3-octave bands

If f_n is the cut-off lower frequency and f_{n+1} the upper one, the ratio of the band limits is given by:

$$\frac{f_{n+1}}{f_n} = 2^k$$

where k=1 for full octave and k=1/3 for one-third octave band

ISO 266 Standard Frequencies for Acoustic Measurements		
ISO Band numbers	**Octave band center frequency**	**One-third octave band center frequencies**
1	1.25 Hz	
2, 3, 4	2 Hz	1.6 Hz, **2 Hz**, 2.5 Hz
5, 6, 7	4 Hz	3.15 Hz, **4 Hz**, 5 Hz
8, 9, 10	8 Hz	6.3 Hz, **8 Hz**, 10 Hz
11, 12, 13	16 Hz	12.5 Hz, **16 Hz**, 20 Hz
14, 15, 16	31.5 Hz	25 Hz, **31.5 Hz**, 40 Hz
17, 18, 19	63 Hz	50 Hz, **63 Hz**, 80 Hz
20, 21, 22	125 Hz	100 Hz, **125 Hz**, 160 Hz
23, 24, 25	250 Hz	200 Hz, **250 Hz**, 315 Hz
26, 27, 28	500 Hz	400 Hz, **500 Hz**, 630 Hz
29, 30, 31	1000 Hz	800 Hz, **1000 Hz**, 1250 Hz
32, 33, 34	2000 Hz	1600 Hz, **2000 Hz**, 2500 Hz
35, 36, 37	4000 Hz	3150 Hz, **4000 Hz**, 5000 Hz
38, 39, 40	8000 Hz	6300 Hz, **8000 Hz**, 10000 Hz
41, 42, 43	16000 Hz	12500 Hz, **16000 Hz**, 20000 Hz

NOTE 1: Convert octave band to 1/3-octave band level reduction of -4.771dB for each 1/3 octave band:

$$L_p = 10\log\left(\frac{1}{3}\right)$$

NOTE 2: Octave band level of three 1/3-octave band levels:

$$L_{oct} = 10\log\left(\sum_{i=1}^{3} 10^{\frac{L_{p,i}}{10}}\right)$$

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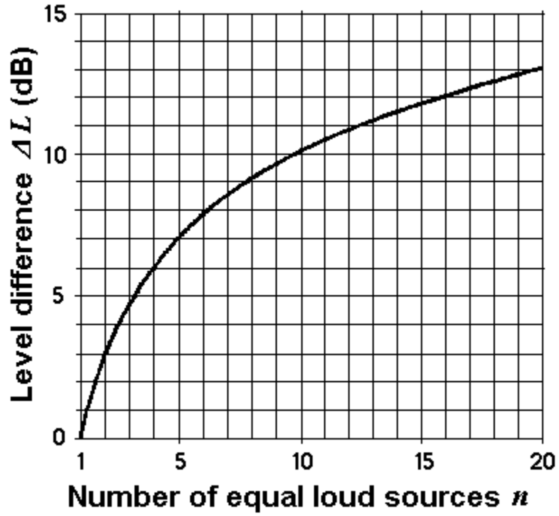
Summation of noise

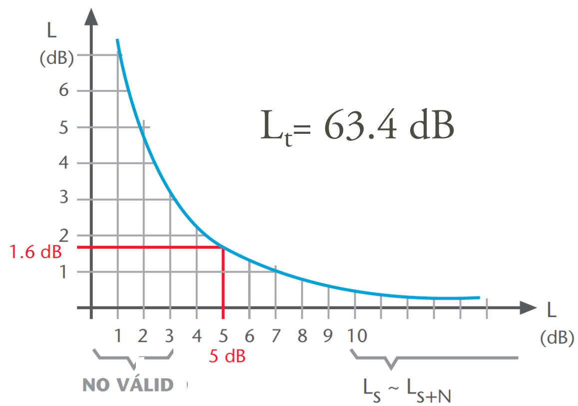
- Graphical methods
  - Adding equally loud incoherent sources
  - Adding two different sources
    - » e.g. L_1=61 dB / L_2=55 dB

L_t= 62 dB

$$L_{p,tot} = 10\log\left(\sum_{n=1}^{N} 10^{\frac{L_{p,n}}{10}}\right)$$



  - Substracting two different sources
    - » e.g. L_{S+N}=65 dB / L_N=60 dB



L_t= 63.4 dB

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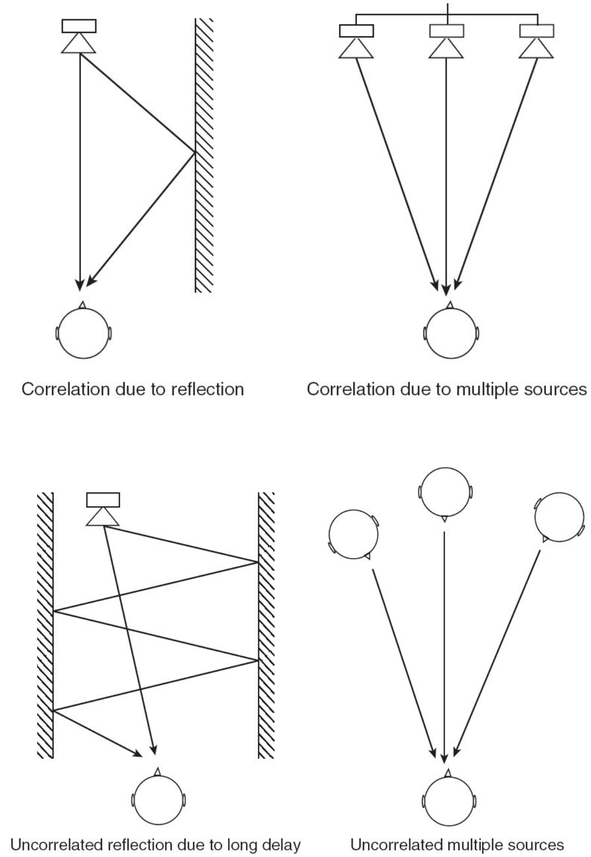
Summation of noise (I)

- Types of sources
  - Correlated (or coherent)
    - Constant phase difference, same frequency
    - Interferences (constructive/destructive)

$$L_{p,tot} = 20 \log\left(\sum_{n=1}^{N} 10^{\frac{L_{p,n}}{20}}\right)$$

  - Uncorrelated (or incoherent)

$$L_{p,tot} = 10 \log\left(\sum_{n=1}^{N} 10^{\frac{L_{p,n}}{10}}\right)$$



The total RMS pressure: $\tilde{p}_{tot}^2 = \tilde{p}_1^2 + \tilde{p}_2^2 + \frac{2}{\Delta t}\int_{t_0}^{t_0+\Delta t} p_1(t)p_2(t)dt$

For uncorrelated sources, the 3rd term vanishes

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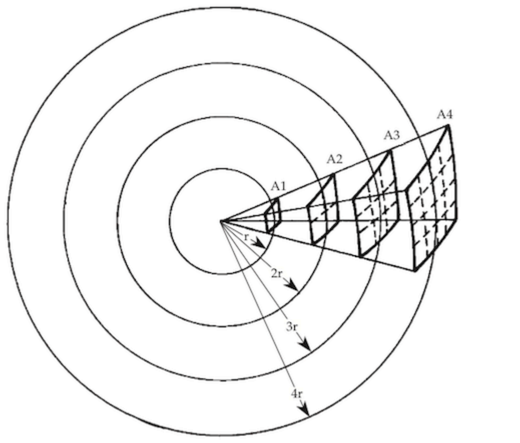
Sound (acoustic) intensity

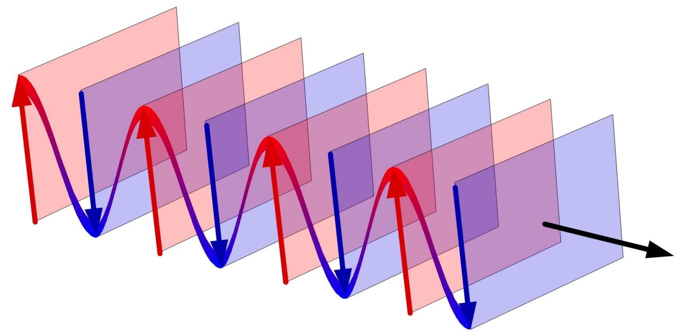
- Sound power per unit area [W/m²]
  - Vector quantity: energy flow and direction

$$I = \langle pv \rangle = \frac{1}{\Delta t}\int_0^T p(t)v(t)dt$$

  - In a free field: $I = \frac{\widetilde{p^2}}{\rho c}$; $I \propto p^2$



- Types of propagation
  - Plane: $I \equiv \text{constant}$;
  - Cylindrical: $I(r) \propto \frac{1}{r}$
  - Spherical: $I(r) \propto \frac{1}{r^2}$; $I(r) = \frac{\Pi}{4\pi r^2}$

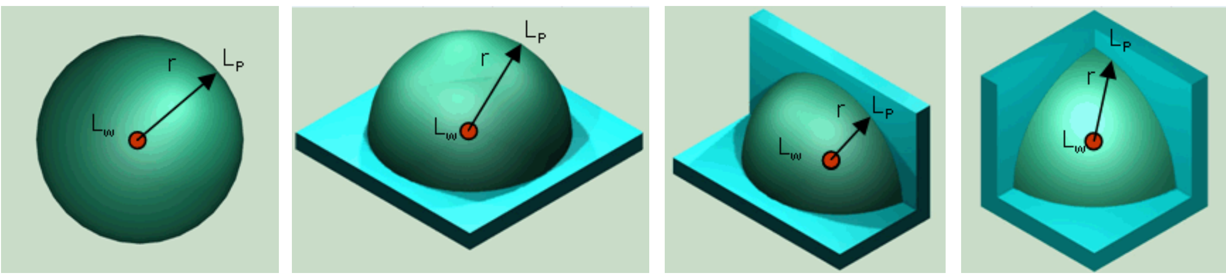


- In decibels… $L_I = 10\log\left(\frac{I}{I_0}\right)$; $I_0 = 10^{-12}\,W/m^2$

Notes / Definitions (I)

- Sound emission
  - Sound power continuously emitted from a sound source

- Sound power level (SWL / L_W / L_{Π}) or acoustic power
  - Total sound energy emitted by a source per unit time
    - » Constant regardless of the room
    - » Independent of the distance from the sound source
    - » Theoretical value
  - Units: Watts [W] or decibels [dB] (re: 10^{-12} W)



Source: www.sengpielaudio.com

$$L_W = L_p + \left|10\log\left(\frac{Q}{4\pi r^2}\right)\right|$$

- Q=1: Full sphere
- Q=2: Half sphere
- Q=3: Quarter sphere
- Q=4: Eighth sphere

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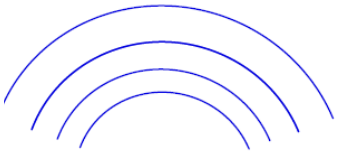
Do not mix up concepts (III)…

Receiver ⟷ Sound Pressure Level

$$L_p = 10 \log_{10} \frac{p^2}{p_o^2}$$

$$p_o = 2 \times 10^{-5} N/m^2$$

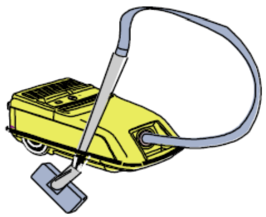
$$= 20 \mu Pa$$



Path ⟷ Sound Intensity Level

$$L_i = 10 \log_{10} \frac{I}{I_0}$$

$$I_o = 1 pW/m^2$$



Source ⟷ Sound Power Level

$$L_w = 10 \log_{10} \frac{W}{W_o}$$

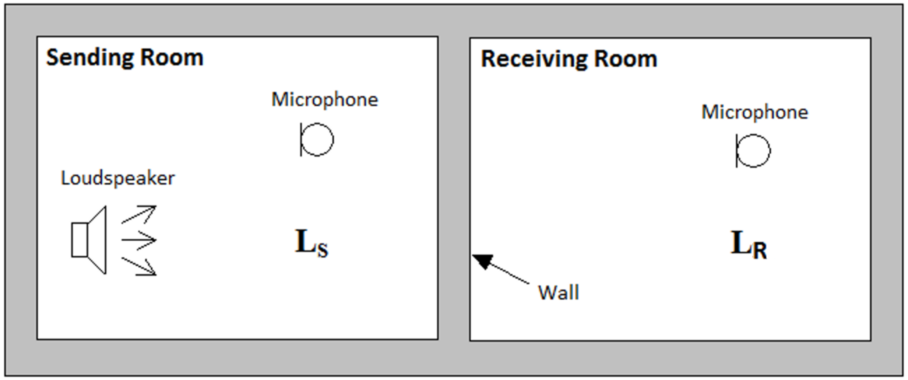
$$W_o = 1 pW$$

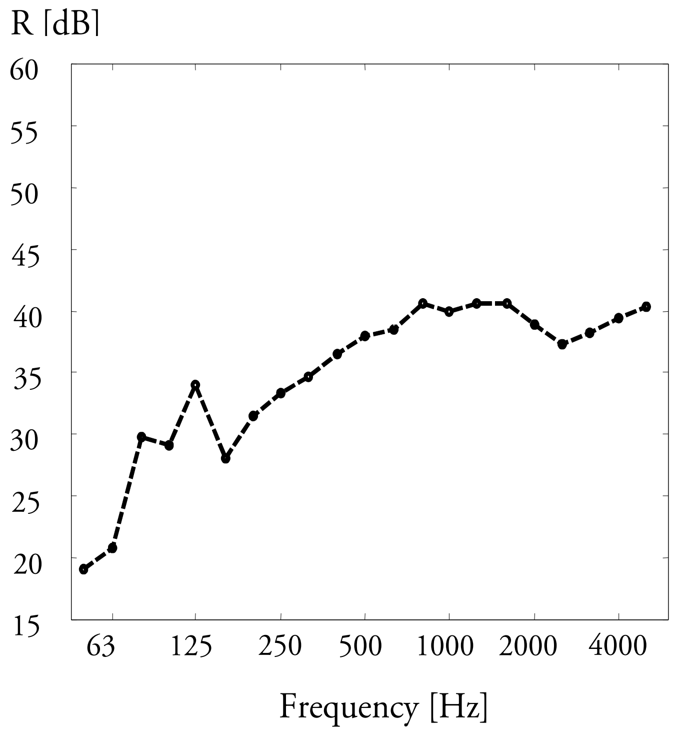
www.bksv.com, 2

Brüel & Kjær
BEYOND MEASURE

Building acoustics measurements

- Airborne sound insulation measurements (ISO standards)





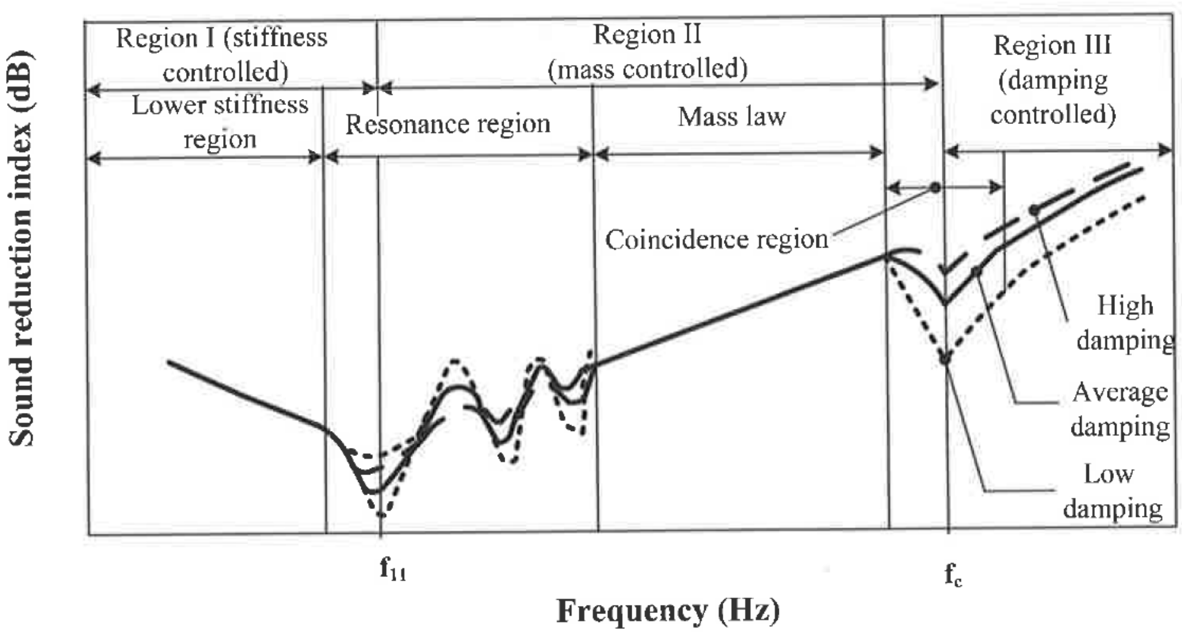
$$R(f) = L_S(f) - L_R(f) + 10\log\left(\frac{S}{A(f)}\right)$$

Statement of results:

- $R'_w\,(C_{50\text{-}3150}\,;\,C_{tr})$
- $R_w\,(C_{50\text{-}3150}\,;\,C_{tr})$

Sound reduction index of single-leaf partitions

- **Exact method**
  - Region I: Stiffness-controlled region ($f < f_{11}$)
  - Region II: Mass-controlled region ($f_{11} < f < f_c$)
  - Region III: Damping-controlled region ($f_c < f$)



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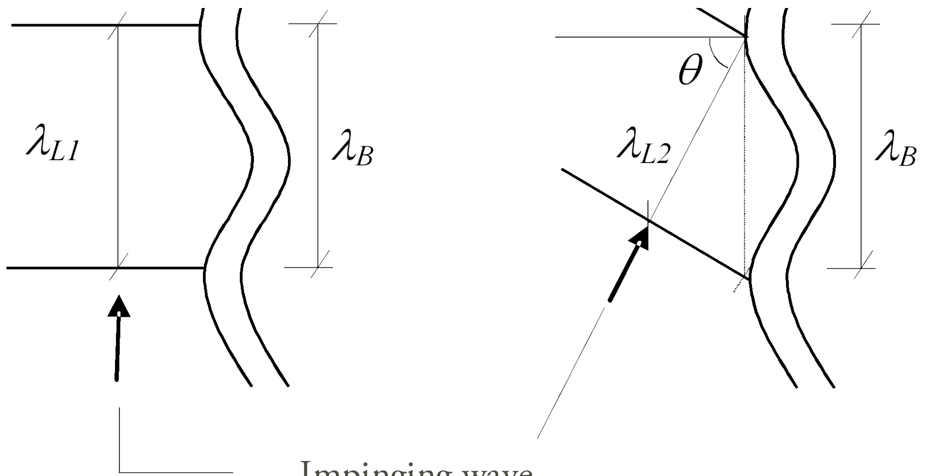
Reminder: Coincidence – critical frequency

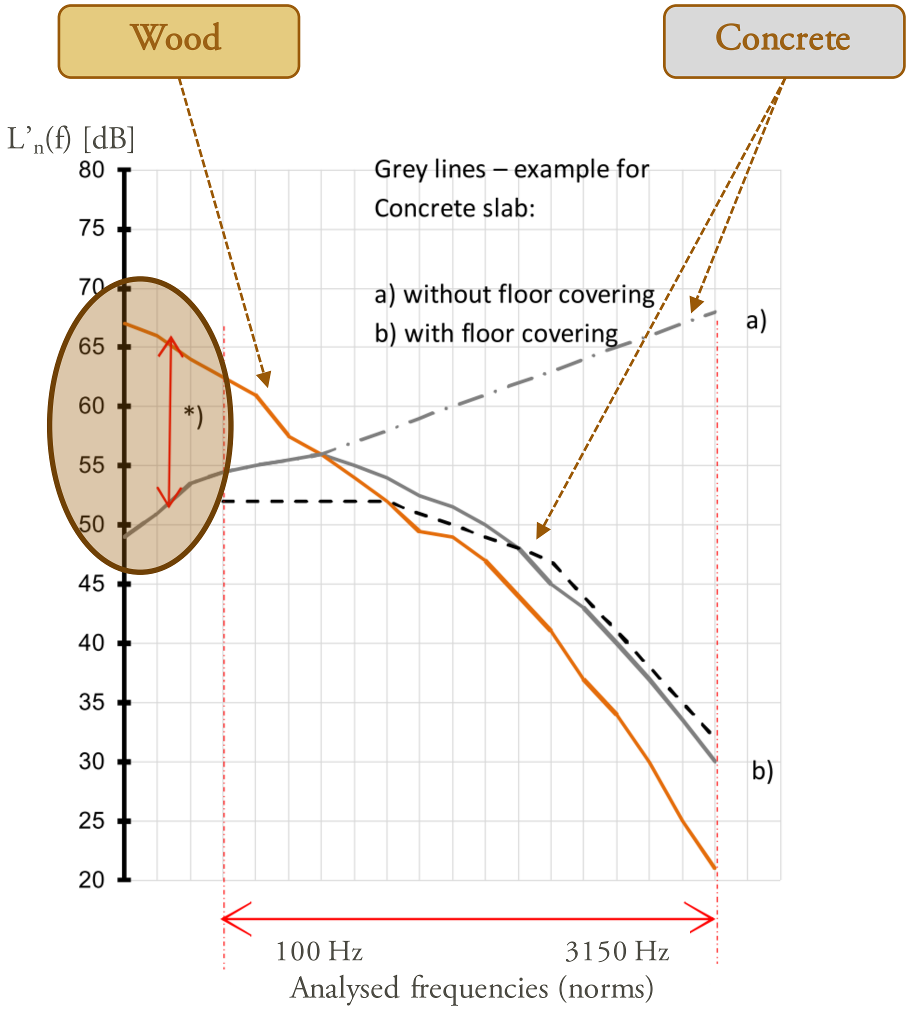


- The wavelength of a bending wave λ_B is dependent on frequency, bending stiffness and mass density

- When the wavelength of sound in air coincides with the structural wavelength → Coincidence phenomena
  - Radiation efficiency becomes very high
  - Insulation inefficiencies

Impact sound “problems”: SNQs

SNQ = Single number quantity, descriptor



Thank you for your attention!

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