1 Foundations

ELEC-E5640 - Noise Control D

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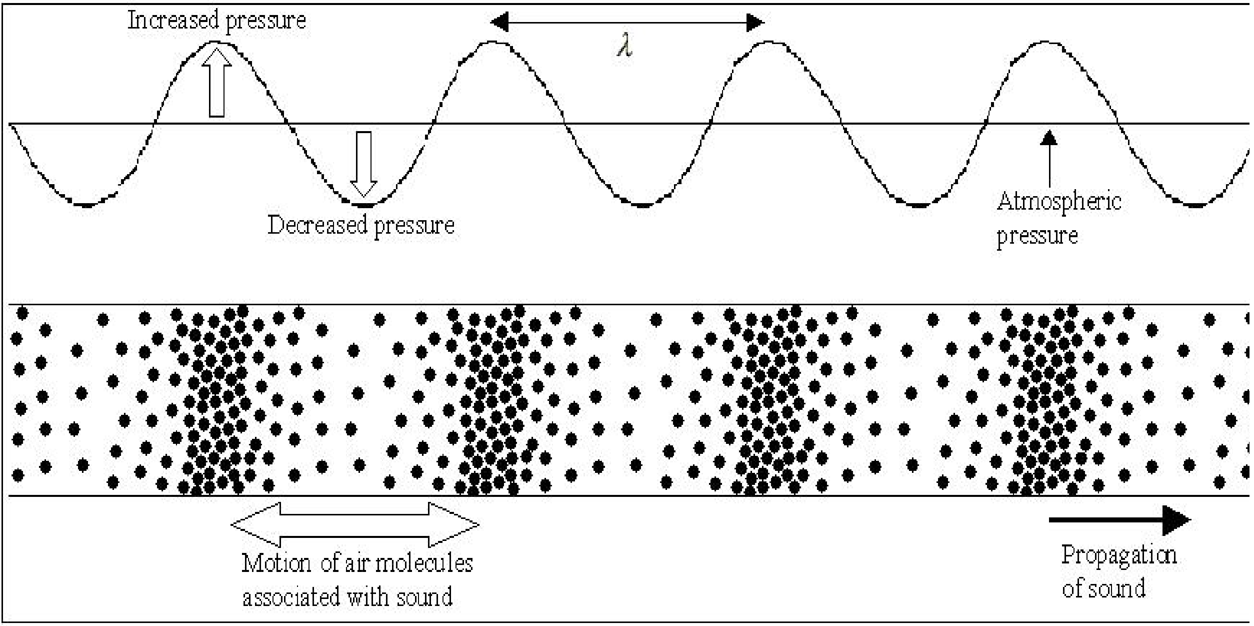
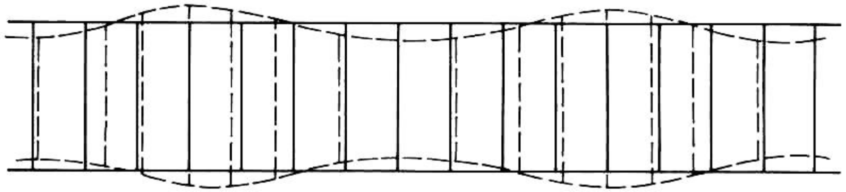
Espoo, Finland, **1st Nov 2021**

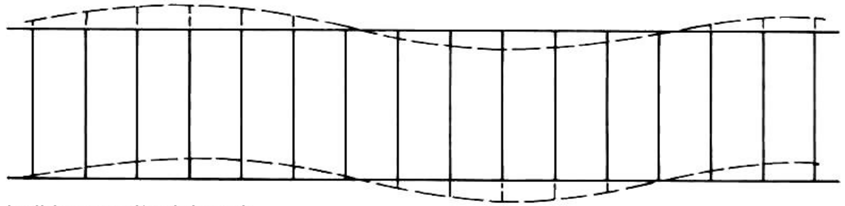
Air: longitudinal, i.e., compressional wave



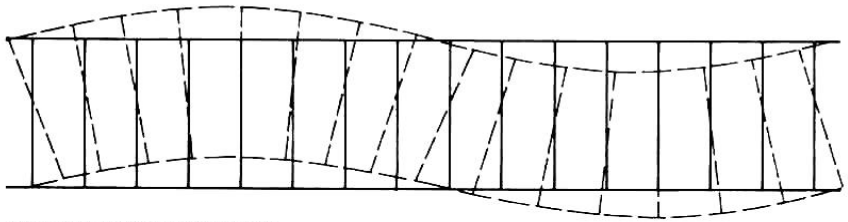
Constructions: Mainly transverse waves



Kvasipitkittäisaalto (quasi-longitudinal)



Leikkausaalto (shear)



Taivutusaalto (bending)

Poikittaisliikkeen amplitudi liioiteltu.

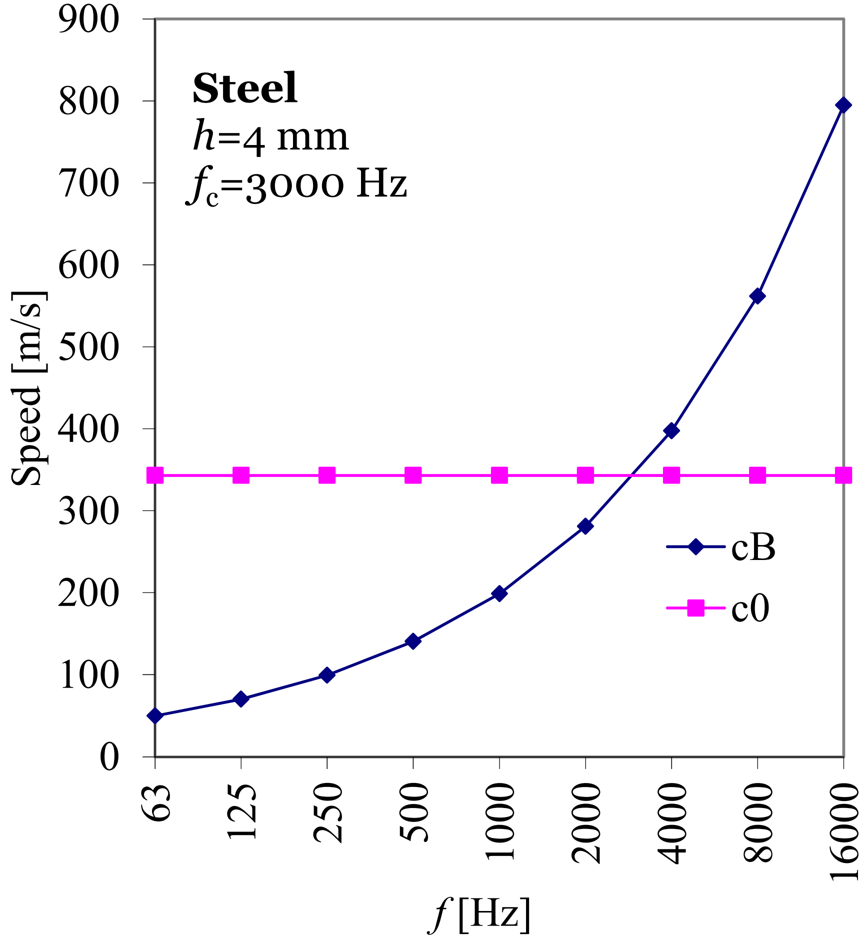
Dispersion

- Propagation speed of compressional wave in air, c_0, is <u>independent on frequency</u>

$$c_0 = 331 + 0.6 \cdot T$$

- Propagation speed of longitudinal and shear waves in solids is also frequency independent
  - E.g., steel 5790 m/s and 3100 m/s
- Propagation speed of bending wave in construction, c_B, <u>depends on frequency.</u>
- Bending wave is the waveform mostly affecting sound transmission.
- This is the main reason why noise control with materials is complex.

$$c_B = \sqrt[4]{\frac{\omega^2 B}{m'}} = \sqrt[4]{\frac{\omega^2 h^2 E}{\rho_p 12\left(1-\mu^2\right)}}$$



Descriptors of sound wave

- Time-dependent signal on angular frequency ω=2π*f*

$$p(t) = \hat{p}\sin(\omega t + \varphi)$$

- Time average for period *T* [s] is irrelevant, since:

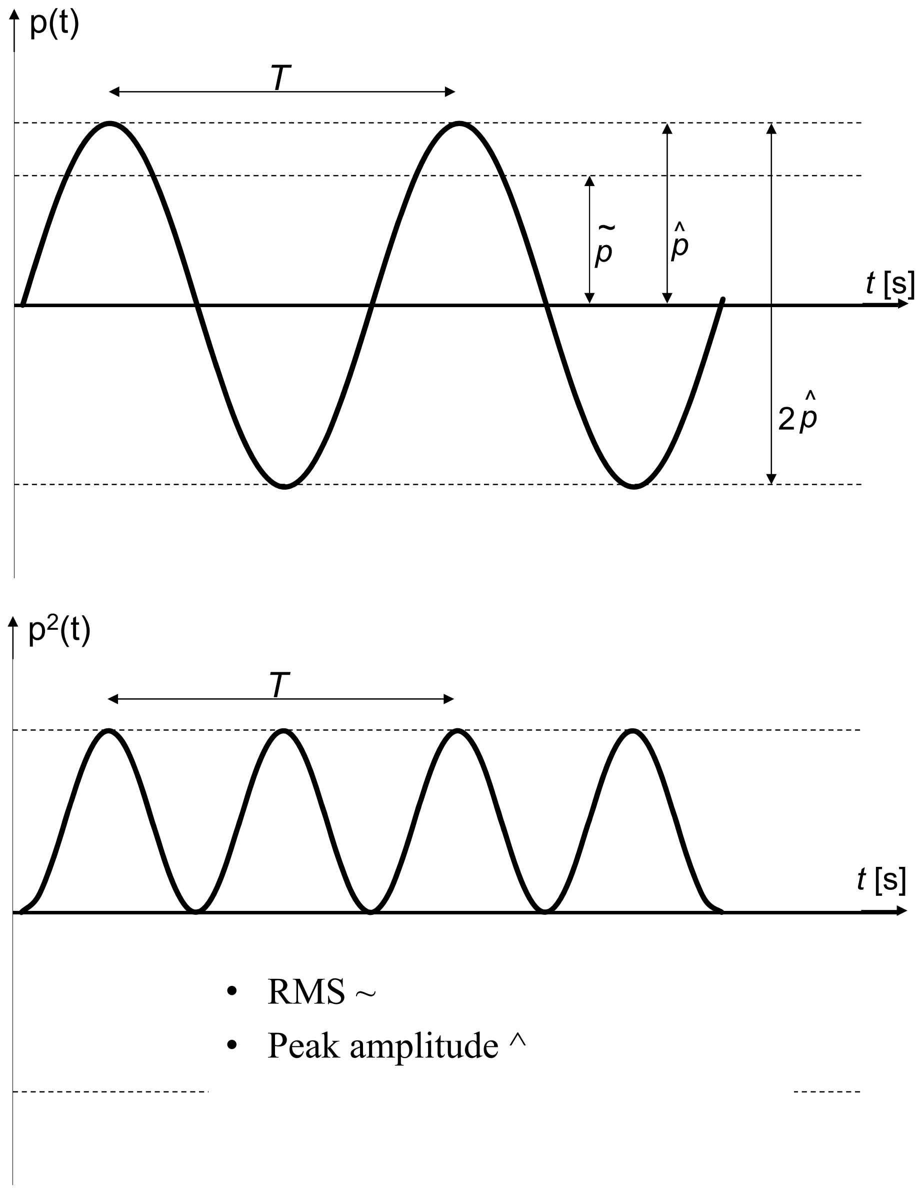
$$\overline{p} = \frac{1}{T}\int_0^T p(t)dt = \xrightarrow[T\to\infty]{} 0$$

- Root mean square (RMS) for period T is relevant:

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

- *p* [Pa] is sound pressure
- *t* [s] is time
- *f* [Hz] is frequency
- *T* [s] is time duration

$$f = \frac{1}{T}$$



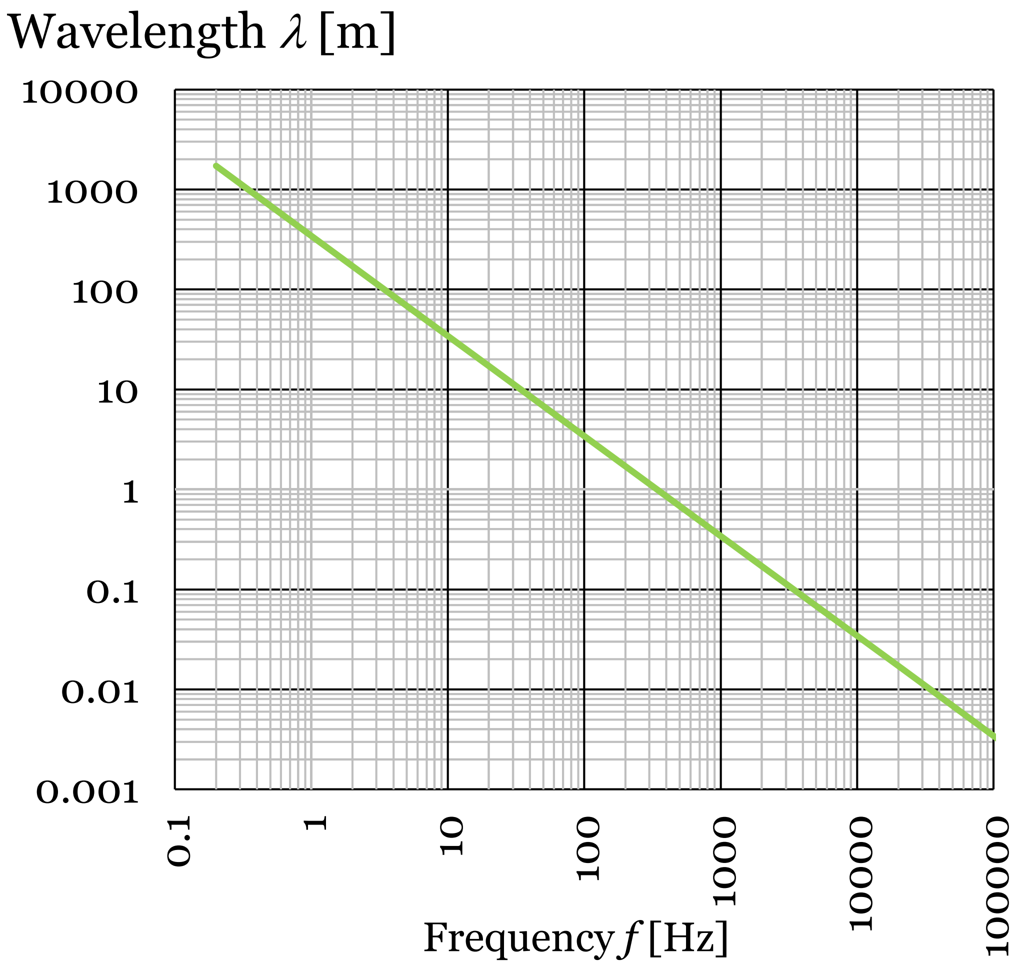
- RMS ~
- Peak amplitude ^

Frequency f [Hz] and wavelength λ [m]

- c_0 phase speed [m/s]
  - c_0 =343 m/s in air in room temperature
- f frequency [Hz]
- λ wavelength [m]

$$c = f\lambda \quad \Leftrightarrow \quad \lambda = \frac{c}{f}$$

$$c_0 = 331 + 0.6 \cdot T$$

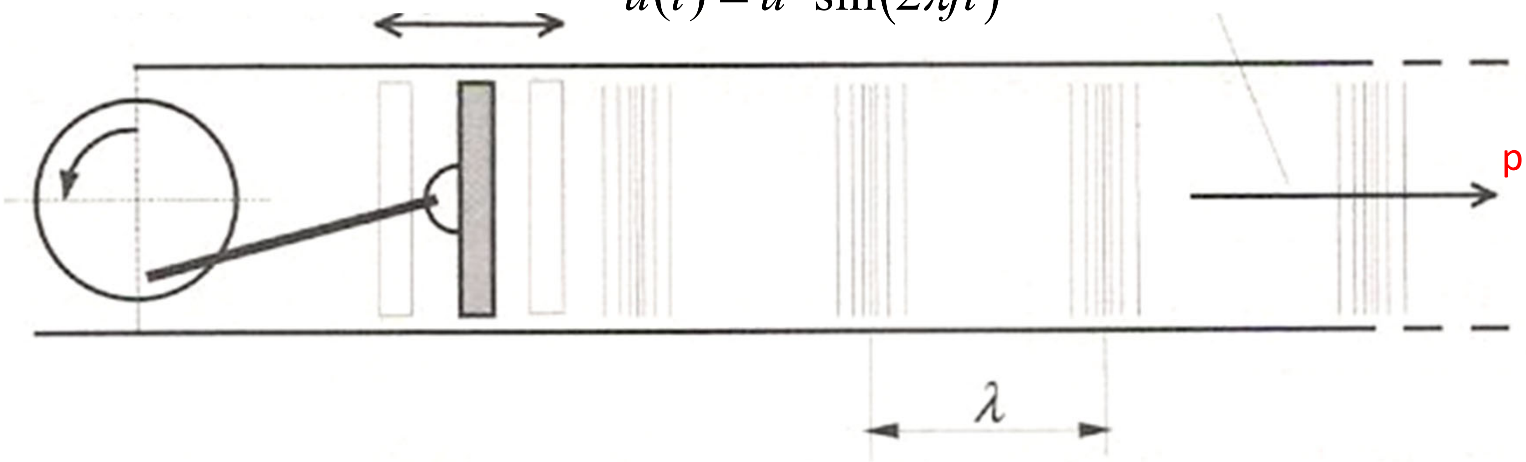


Particle velocity *u*

- sound is longitudinal vibration of air in the direction of propagation
- u is the the velocity [m/s] of particles in back and forth vibration in the media
- u is not the same as phase speed c (i.e., propagation speed)

harmonic vibration of particles
around the zero position

$$u(t) = \hat{u} \cdot \sin(2\pi f t)$$



propagation direction

1-dimensional wave propagation in air

- Reflection-free sound field:

$$p(x,t) = \rho_0 c_0 u_x(x,t)$$

  - p [Pa] is the pressure
  - u_x [m/s] is the particle velocity in x-direction
  - x [m] is position
  - t [s] is time
  - ρ_0**=1.204 kg/m³** is density of air in 20 °C
- Propagation speed in air is called the *phase speed* c_0

$$c_0 = 331 + 0.6 \cdot T$$

  - T [°C] is the temperature
- At 20 °C → $\mathbf{c_0}$**=343 m/s**
- Z_x is the specific acoustic impedance of the medium in x-direction:

$$Z_x = \frac{p(x,t)}{u_x(x,t)}$$

- In air at 20 °C: $\boldsymbol{Z_0} = \rho_0 c_0 \approx$ **413** kg/m^{2}s

Level quantities

- Levels are always based on RMS values except peak sound pressure level L_{peak}

- **Sound pressure level, SPL** p_0=20 μPa

- **Sound power level, SWL** W_0=1 pW

- **Sound intensity level, SIL** I_0=1 pW/m^2

- The unit is decibel [dB].
- Levels are nearly always used in noise control.
- The reason is that the range of absolute values is several decades - The use of difficult expressions, such as 2E-5 Pa, is avoided by decibels.
- Decibel values can be more easily displayed, understood and regulated.
- Human resolution of loudness differences is 1 dB.

$$L_p = 10\lg\frac{\tilde{p}^2}{p_0^2} \quad [\mathrm{dB}]$$

$$L_W = 10\lg\frac{\tilde{W}}{W_0} \quad [\mathrm{dB}]$$

$$L_I = 10\lg\frac{\tilde{I}}{I_0} \quad [\mathrm{dB}]$$

$\lg = \log_{10}$

Sound power and sound intensity

- **Sound power *W*** [W] of a source is the sound energy produced by the source per time unit [J/s].
- ***W*$_x$** can be obtained by integrating the pressure *p* and particle velocity ***u*** over the surface *S* perpendicular to x:

$$W_x = \int_S \mathrm{I}_x dS = \int_S p \cdot \mathrm{u}_x dS$$

Particle velocity can be determined using Euler's equation where two phase-matched pressure microphones A and B separated by a spacer Δr are needed.

$$u_x = -\frac{1}{\rho_0 \Delta r} \int \left(p_B - p_A \right) dt$$

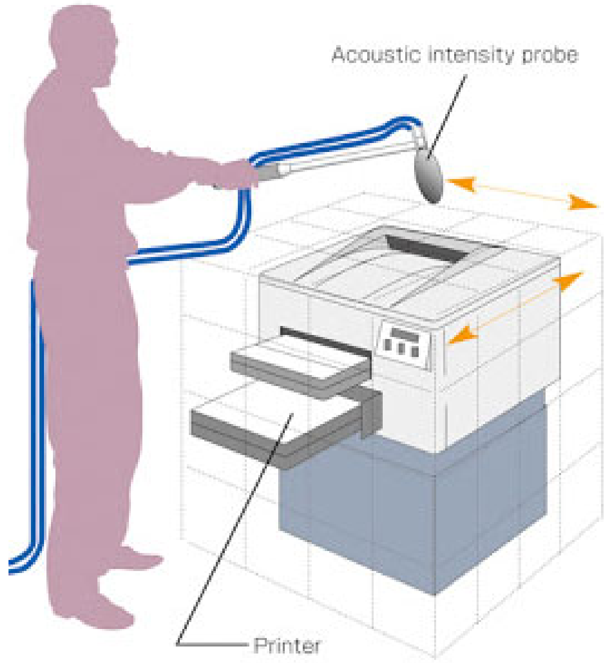
- **Sound intensity *I*** [W/m^2] is the sound power per surface unit:

$$\bar{I} = \frac{\overline{W}}{S}$$

$$I_n = \overline{p \cdot u_n} = -\frac{1}{2\rho_0 \Delta r} \overline{(p_A + p_B) \int (p_B - p_A) dt}$$

Sound power level, SWL

- Sound power level [dB] of a sound source in direction x can be determined by $$L_{W_x} = L_{I_x} + 10 \cdot \log_{10} S_x$$
  - L_{Ix} [dB re 1 pW/m^2] is the logarithmic mean sound intensity level at the measurement surface S_x perpendicular to x
  - S_x [m^2] is the area of the measurement surface enclosing the sound source.
- S consists usually of 5 sub-surfaces S_i and related sound intensity levels, L_i.
  - +x, -x, +y, -y, and z
- Then, the sound power level is calculated by the logarithmic sum of sub-surfaces' sound power levels $L_{W,i}$.
- In free field, the sound pressure level is equal with sound intensity level, and L_I can be replaced by L_p.
- SWL can be determined in also in rooms using L_p but it requires a correction due to reverberation (Sec. 3).



$$L_{tot} = 10 \lg \sum_{i=1}^{N} 10^{L_i/10}$$

Interference of two sound pressures

- Sound pressure level (SPL):

$$L_p = 10\lg\frac{\tilde{p}^2}{p_0^2} \quad [\mathrm{dB}] \qquad \tilde{p} = \sqrt{\frac{1}{T}\int_0^T p^2(t)dt}$$

- RMS of two pressures p_1 and p_2 is obtained by summing:

$$\tilde{p}_{tot}^2 = \frac{1}{T}\int_0^T p_{tot}^2(t)dt = \frac{1}{T}\int_0^T [p_1(t) + p_2(t)]^2 dt =$$

$$= \tilde{p}_1^2 + \tilde{p}_2^2 + \frac{2}{T}\int_0^T p_1(t)p_2(t)dt$$

Three cases of interference

$$L_p = 10 \lg \frac{\tilde{p}^2}{p_0^2} \quad [\mathrm{dB}]$$

1. **Uncorrelated sources**: $p_1(t) \neq p_2(t)$
   - the most usual situation
   - Two equal levels lead to 3 dB increment

$$\boxed{L_{p,tot} = 10 \lg \left(10^{L_{p,1}/10} + 10^{L_{p,2}/10} \right)}$$

2. **Correlated sources, identical phase**:
   - E.g., 2 point sources closer than λ/10 from each other
   - Two equal levels lead to 6 dB increment
   - E.g., -6 dB correction is made to environmental noise measurements close to ground

$$p_1(t) = p_2(t)$$

$$L_{p,tot} = 10 \lg \frac{4\tilde{p}_1^2}{p_0^2} = L_{p,1} + 6 \ \text{ dB}$$

3. **Correlated sources, reversed phase**:
   - E.g., active control of sound

$$p_1(t) = -p_2(t) \qquad L_{p,tot} = -\infty$$

Interference of uncorrelated sources - applications

- Interference of multiple sources
- Background noise correction
- Calculation of octave band values from one-third octave bands
- Calculation of total values within a certain frequency range from one-third octave or octave bands
- Calculation of equivalent sound pressure level

$$L_{tot} = 10\lg\sum_{i=1}^{N} 10^{L_i/10}$$

$$= 10\lg\left(10^{L_1/10} + 10^{L_2/10} + \ldots + 10^{L_N/10}\right)$$

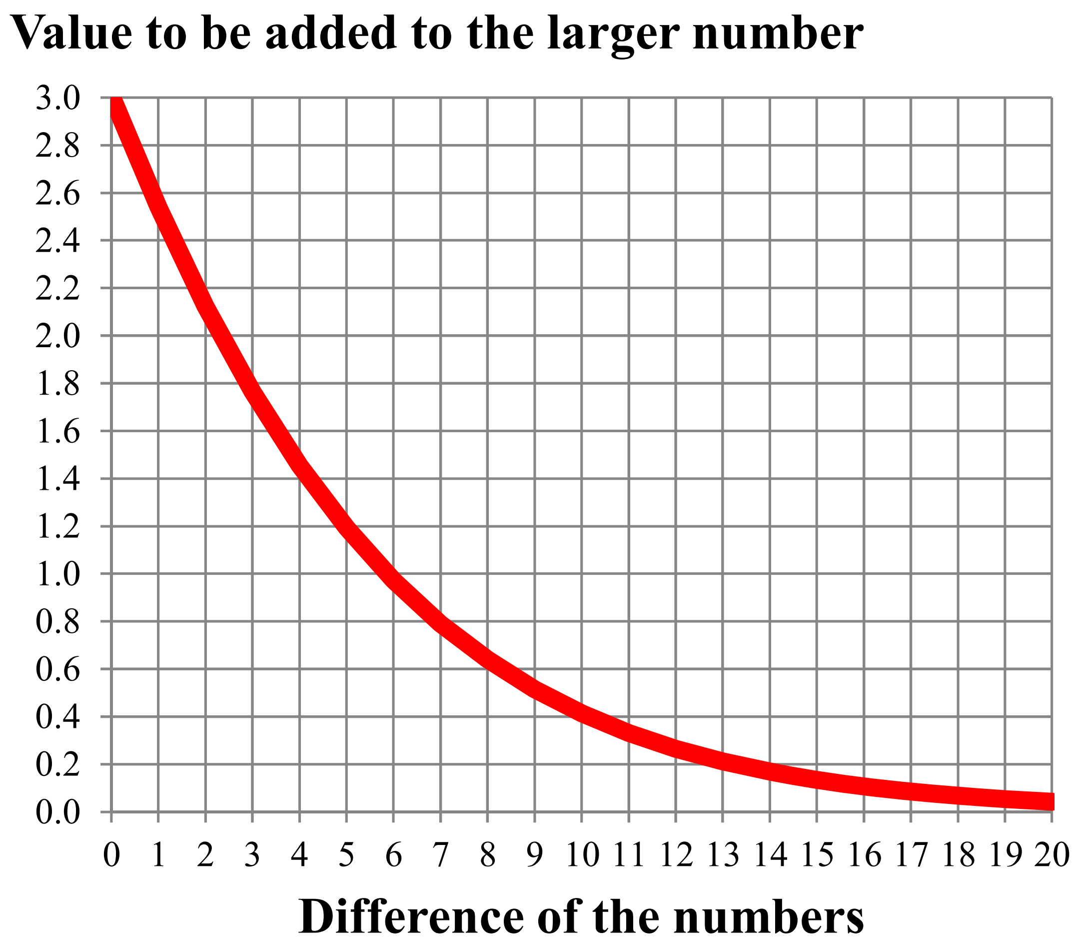
Uncorrelated sources: dB-rules

$$L_{p,tot} = 10\lg\left(10^{L_{p,1}/10} + 10^{L_{p,2}/10}\right)$$

Same levels: + 3 dB
(0 + 0) dB = 3 dB
(15 + 15) dB = 18 dB

Remote levels: stronger remains
(0 + 20) dB = 20 dB
(80 + 100) dB = 100 dB

Close levels: use the equation
(0 + 10) dB = 10.5 dB
(0 + 6) dB = 7 dB
(0 + 2) dB = 4 dB
(0 + 1) dB = 2.5 dB



Uncorrelated sources: background noise correction

- Background noise level must always be known during measurements
- Background noise originates from external noise sources
- Measurement apparatus itself (electric noise) can be an important source of background noise in low-level measurements
  - Usual background noise is + 5 dB with microphones
- If the SPL of the sound source under investigation is $\boldsymbol{L_{p,1}}$ and the SPL of background noise is $\boldsymbol{L_{p,2}}$, the total level, $\boldsymbol{L_{ptot}}$, is the sum of two uncorrelated sources:
- The SPL of the source under investigation is determined by measuring $\boldsymbol{L_{p,tot}}$ and $\boldsymbol{L_{p,2}}$ by shutting down the source under investigation:

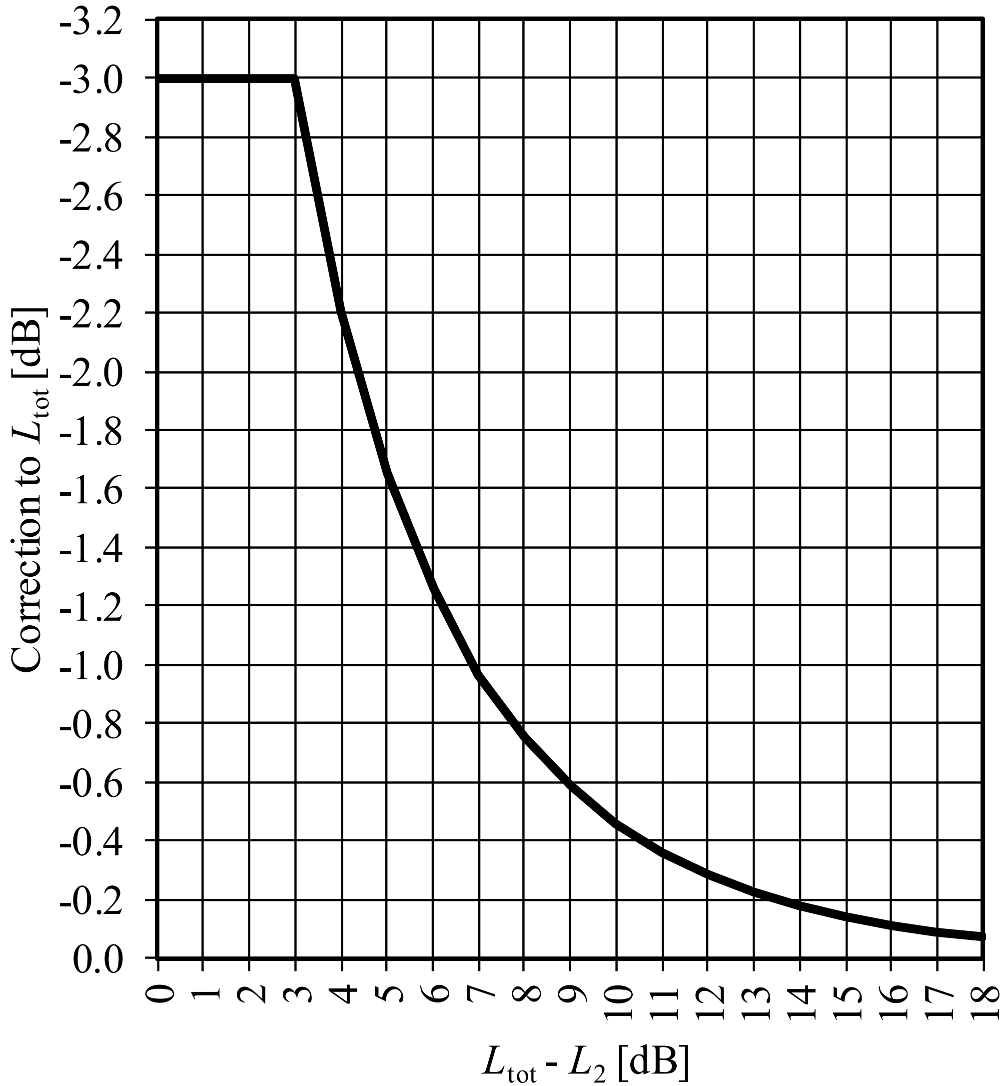
$$L_{p,tot} = 10\lg\left(10^{L_{p,1}/10} + 10^{L_{p,2}/10}\right)$$

$$L_{p,1} = 10\lg\left(10^{L_{p,tot}/10} - 10^{L_{p,2}/10}\right)$$

Background noise correction diagram

$$L_{p,1} = 10\lg\left(10^{L_{p,tot}/10} - 10^{L_{p,2}/10}\right)$$

- The correction is used in **survey and engineering** measurements when $L_{\mathrm{p,tot}}$ - L_2 is within 3 – 15 dB.
  - If $L_{\mathrm{p,tot}}$ - L_2 < 3 dB, the correction is always -3 dB and the result is marked as an underestimate of the true value.
- The correction is used in **precision** measurements when $L_{\mathrm{p,tot}}$ - L_2 is within 6 – 15 dB.
  - If $L_{\mathrm{p,tot}}$ - L_2 < 6 dB, the correction is always -1.2 dB and the result is marked as an underestimate of the true value.



Example 1.1

Measured level of wind turbine noise and background noise is 37 dB.
The background noise is 35 when the turbines are turned off.
How the level of wind turbine noise is declared in the report?

$L_{p,tot}$ [dB]	
$L_{p,2}$ [dB]	

Equivalent SPL

- Regulated values of SPL concern usually the equivalent SPL during a time period *T*.
- Equivalent level is the same as energy-based time-average.
- Equivalent level is notated by $L_{\mathrm{eq,T}}$.
  - E.g., $\mathrm{L}_{\mathrm{Aeq,07\text{-}22}}$
- Equivalent level is determined by:

$$L_{eq,T} = 10\lg\left(\frac{1}{T}\int_0^T \frac{p^2(t)}{p_0^2}dt\right) \quad \mathrm{dB}$$

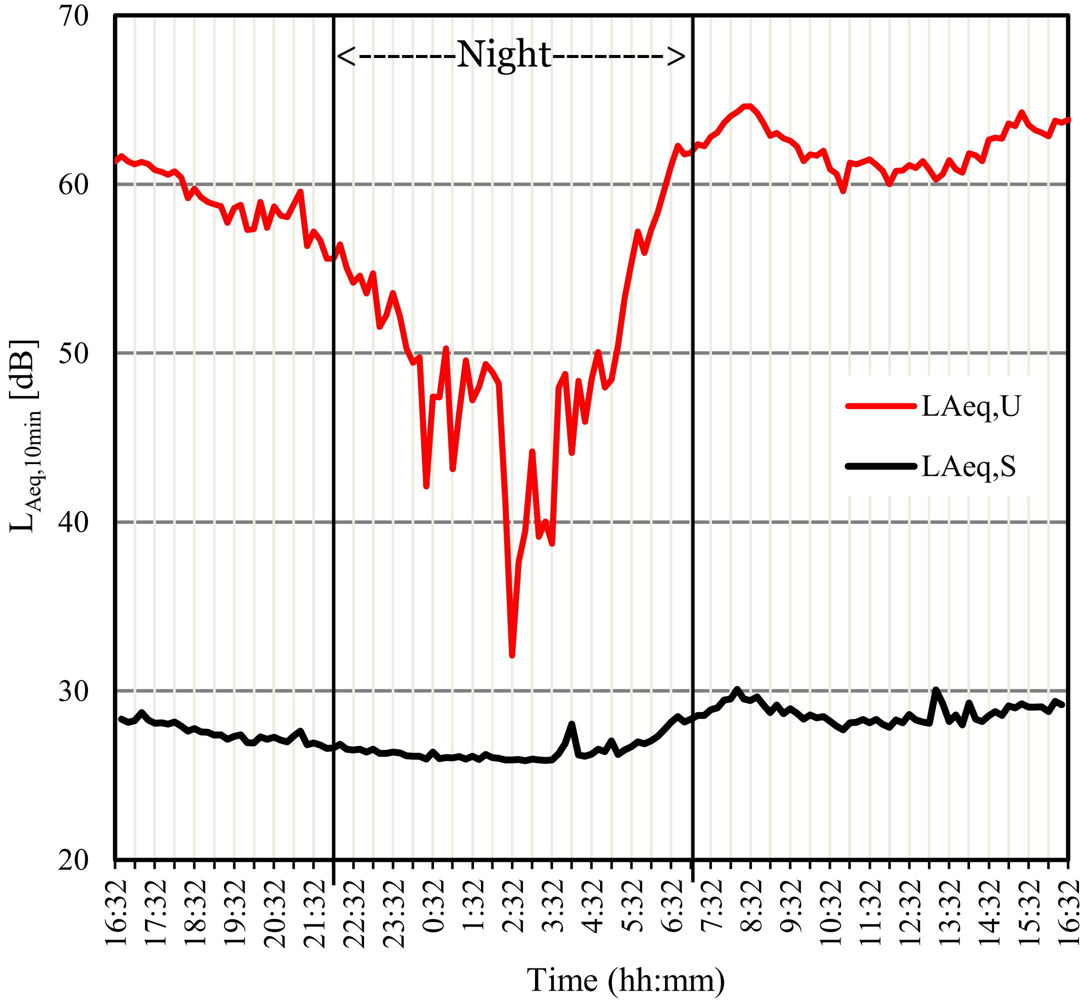
- The discrete form is:
- It can be determined both for SWL (emission) and SPL (immission).
- For example, road traffic noise varies over daytime hours and equivalent level requires the knowledge of the whole day.

$$L_{eq,T} = 10\log_{10}\left[\frac{1}{\sum_{i=1}^{N} T_i}\sum_{i=1}^{N} T_i \cdot 10^{L_{eq,T_i}/10}\right]$$

Example – measurement of road traffic noise

- Figure shows the SPL as a function of $L_{Aeq10\ min}$, i.e., using 10-min averages
  - S: Microphone in sleeping room
  - U: Outdoors (on the facade, -6 dB corrected)
- 15 hour equivalent level for daytime and 9-hour equivalent level for night time are shown in Table

	$L_{Aeq,07\text{-}22}$ [dB]	$L_{Aeq,22\text{-}07}$ [dB]
U	62	54
S	29	27



Example 1.2

Industrial plant produced the following noise levels at a distance of 700 m based on a single measurement.
Calculate the equivalent level for the daytime period 07 - 22.

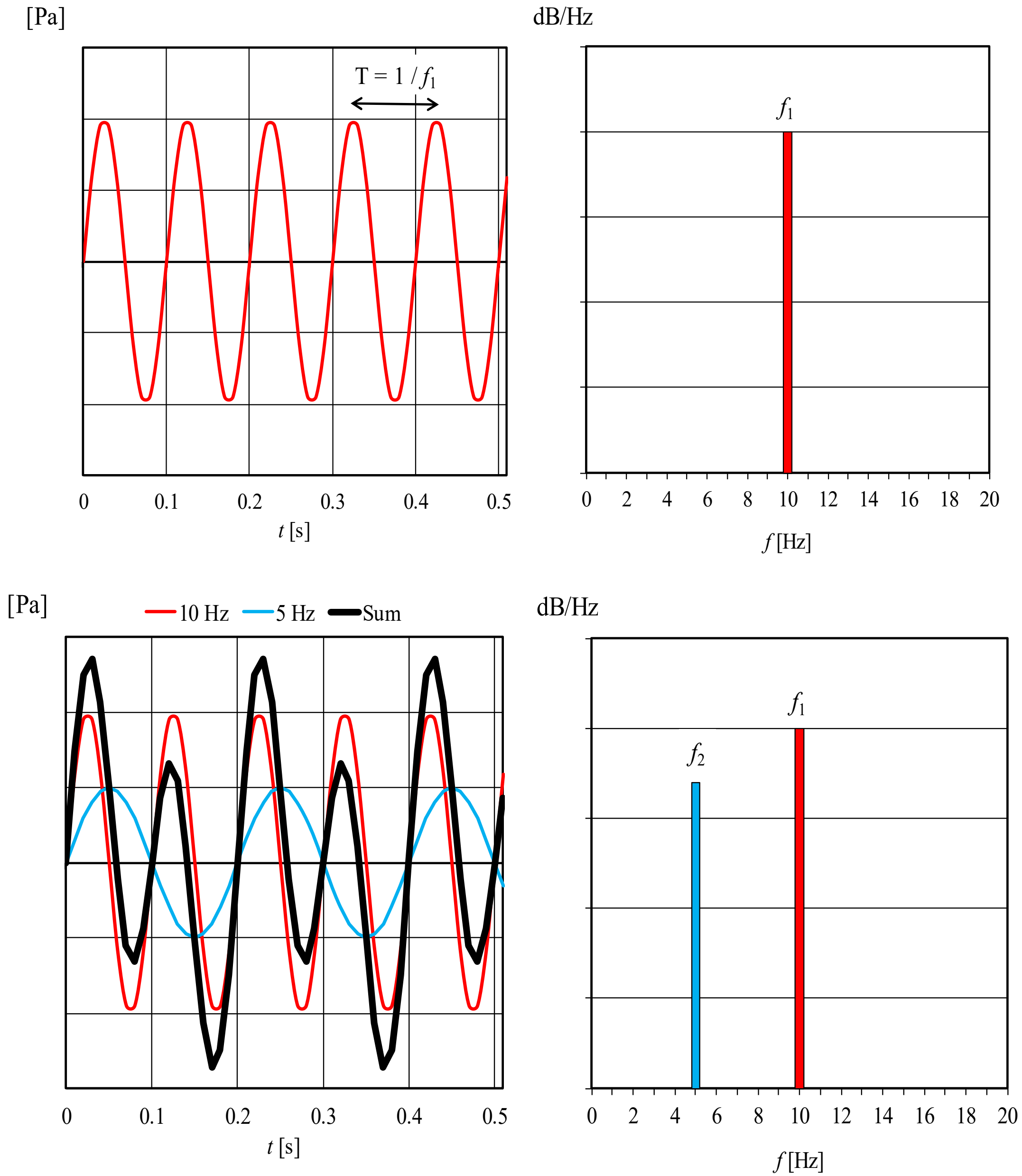
i	Time	Activity	$L_{A,eq}$ [dB]
1	07-15	Production	64
2	15-22	No production	40

Frequency analysis

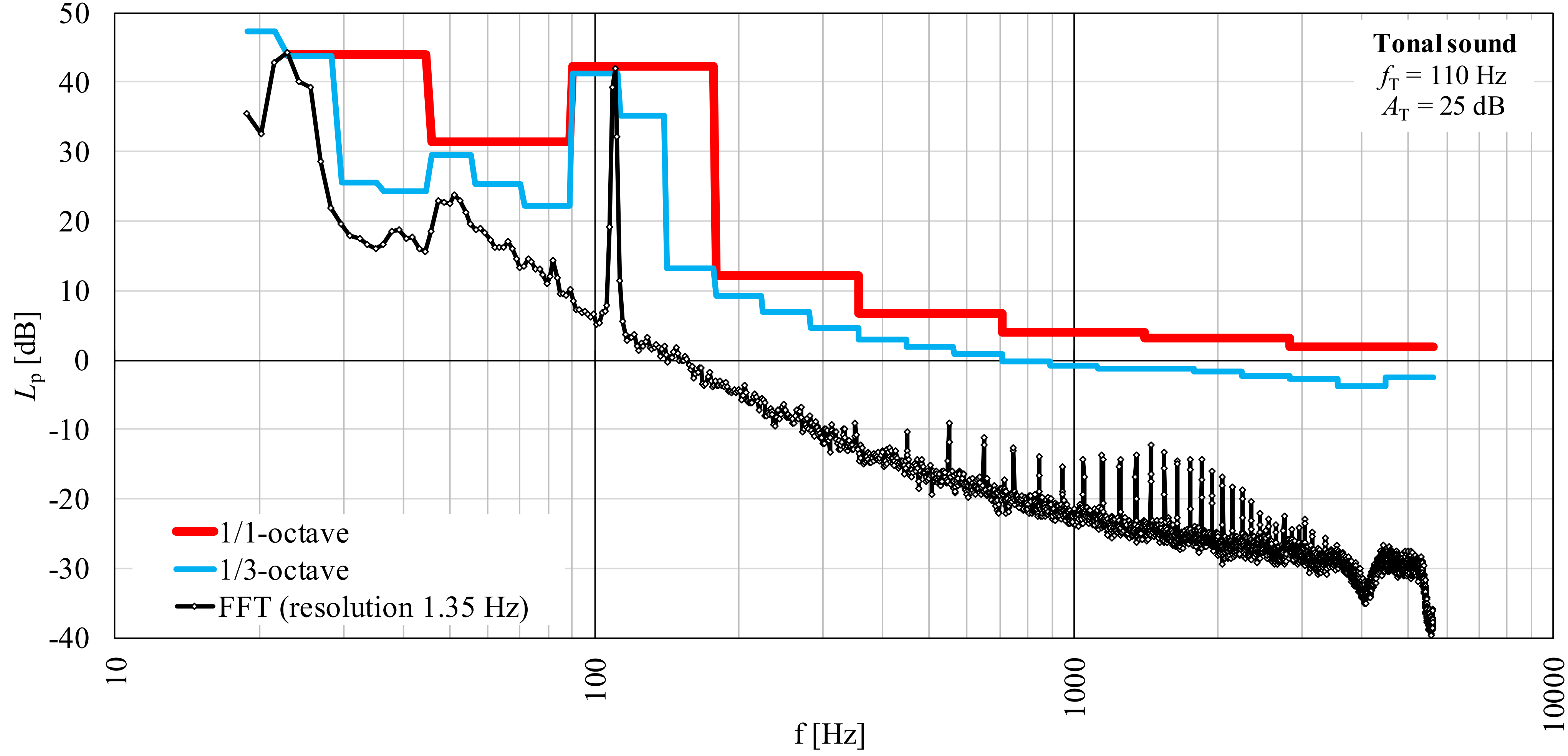
- Periodic signal can be presented as a sum of harmonic signals using Fourier series:

$$p(t) = \sum_{n=1}^{N} \hat{p}_n \cos(2\pi n f_0 t + \varphi_n)$$

- where p^ is the peak pressure of component n and $f_0=1/T$. Terms $n*f_0$ are harmonic multiples and σ_n is the phase difference of the component.
- FFT-analysis (Fast Fourier Transform) can be used to determine the amplitude of each frequency.

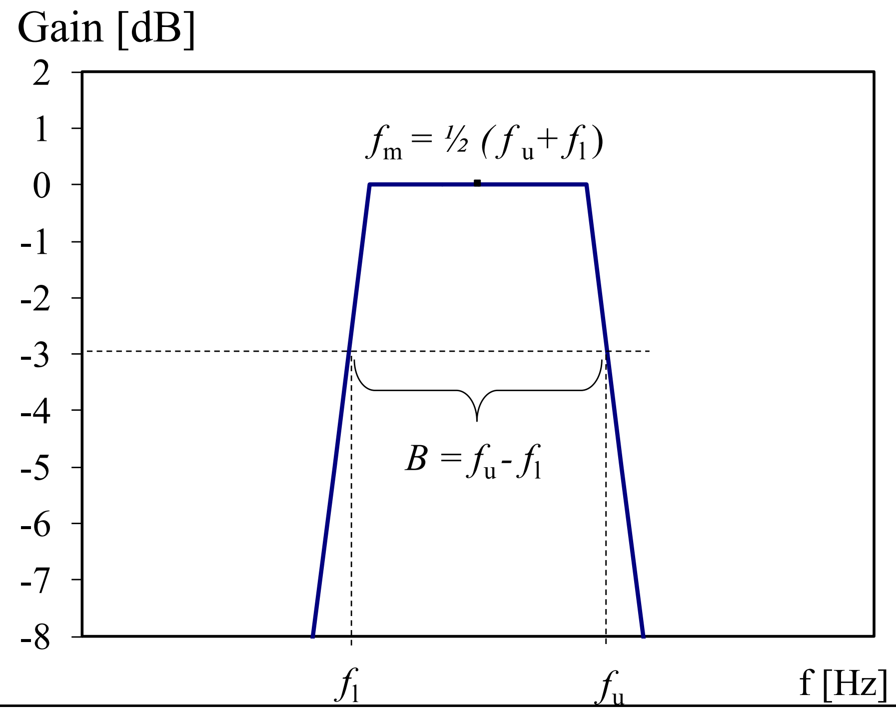


Frequency analysis



Frequency analysis

- **Fast Fourier Transform FFT analysis**
  - Narrow-band analysis
  - Constant bandwidth in Hz is used over the whole frequency range
  - FFT is applied in noise control when specific tones need to be identified
- **Percentage band analysis**
  - mainly used in noise control
  - logarithmic bandwidth
  - One-third octave bands, 20, 25, ..., 20000 Hz
  - Octave bands: 31.5, 63 ... 16000 Hz
  - For example $\boldsymbol{f_m}$**=100 Hz**:
    - f_l=89 Hz
    - f_u=112 Hz
    - B=23 Hz



	1/1-octave filter	1/3-octave filter
Lower frequency limit	$f_l = f_m / \sqrt{2}$	$f_l = f_m / \sqrt[6]{2}$
Upper frequency limit	$f_u = \sqrt{2} f_m$	$f_u = \sqrt[6]{2} f_m$
Bandwidth	$B = f_u - f_l$	$B = f_u - f_l$
Middle frequency	$f_m = \sqrt{f_l f_u}$	$f_m = \sqrt{f_l f_u}$

Middle frequencies f_m and frequency ranges of standard frequency bands

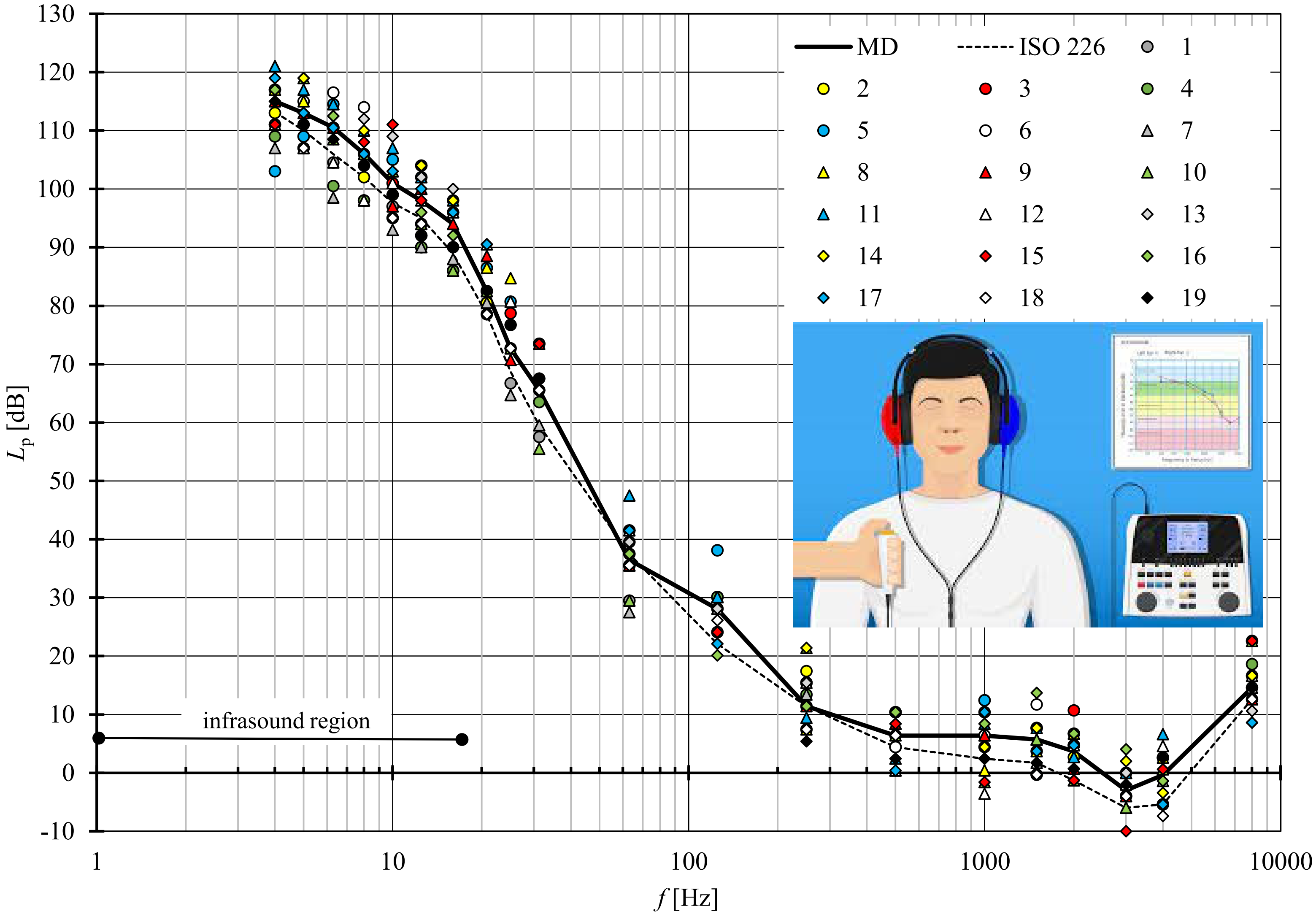
- Each row represents one third-octave band.
- Color is an octave band.
- Nominal frequencies of the octave bands are bolded.

f_m	1/3-octave range	1/1-octave range
1.6	1.41 - 1.78	
2	1.78 - 2.24	1.41 - 2.82
2.5	2.24 - 2.82	
3.15	2.82 - 3.55	
4	3.55 - 4.47	2.82 - 5.62
5	4.47 - 5.62	
6.3	5.62 - 7.08	
8	7.08 - 8.91	5.62 - 11.2
10	8.91 - 11.2	
12.5	11.2 - 14.1	
16	14.1 - 17.8	11.2 - 22.4
20	17.8 - 22.4	
25	22.4 - 28.2	
31.5	28.2 - 35.5	22.4 - 44.7
40	35.5 - 44.7	
50	44.7 - 56.2	
63	56.2 - 70.8	44.7 - 89.1
80	70.8 - 89.1	
100	89.1 - 112	
125	112 - 141	89.1 - 178
160	141 - 178	

f_m	1/3-octave range	1/1-octave range
200	178 - 224	
250	224 - 282	178 - 355
315	282 - 355	
400	355 - 447	
500	447 - 562	355 - 708
630	562 - 708	
800	708 - 891	
1000	891 - 1120	708 - 1410
1250	1120 - 1410	
1600	1410 - 1780	
2000	1780 - 2240	1410 - 2820
2500	2240 - 2820	
3150	2820 - 3550	
4000	3550 - 4470	2820 - 5620
5000	4470 - 5620	
6300	5620 - 7080	
8000	7080 - 8910	5620 - 11200
10000	8910 - 11200	
12500	11200 - 14100	
16000	14100 - 17800	11200 - 22400
20000	17800 - 22400	

Hearing threshold

- HT is the lowest SPL that person can hear
- HT is determined by audiologists in 125-8000 Hz
  - Survey: > 20 dB HL
  - Precision: > 0 dB HL
- Scientific research can study hearing more precisely:
  - Down to -15 dB
  - Down to 4 Hz

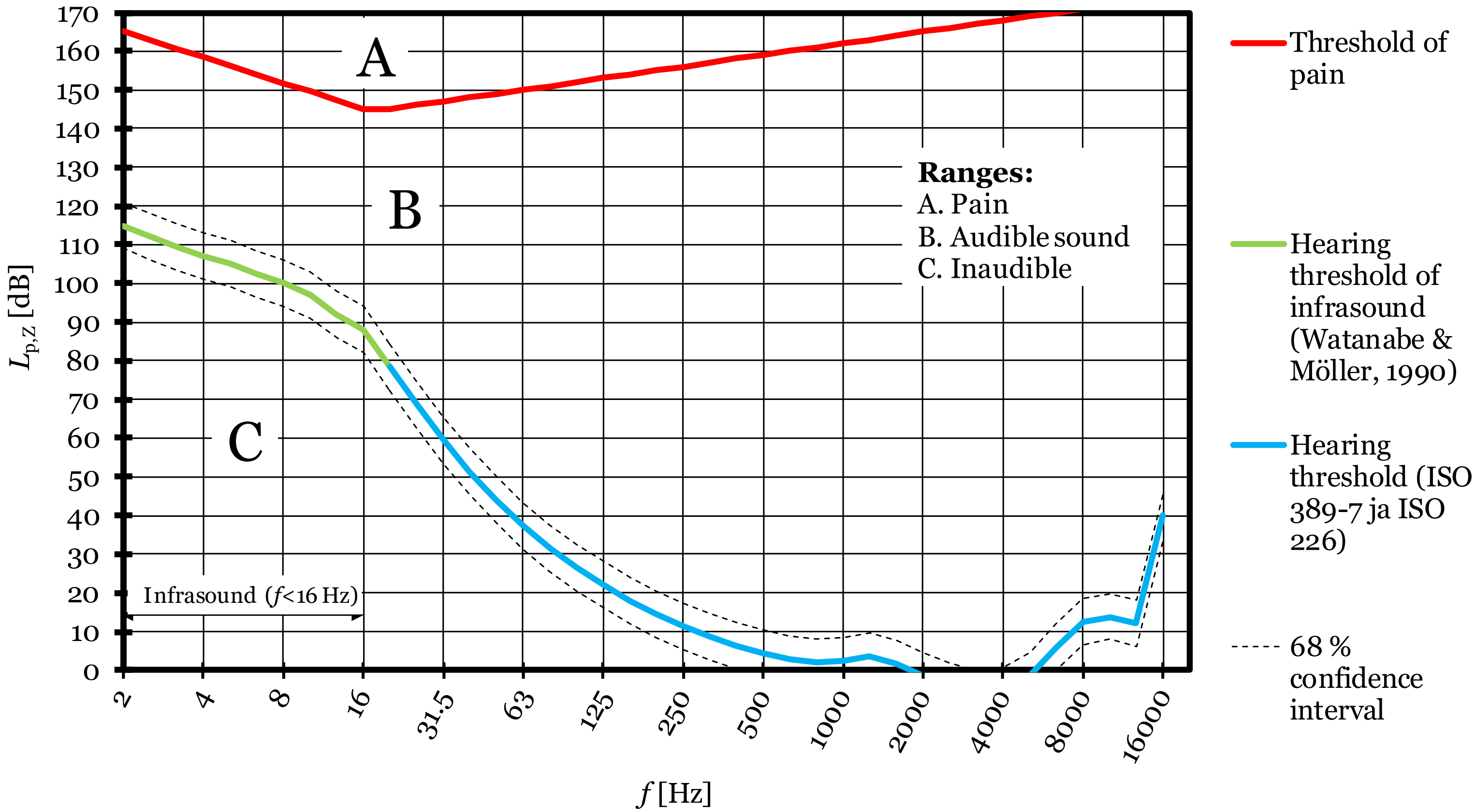


- Recent study shows that
  - HT can be determined also for infrasound region, down to 4 Hz,
  - Individual differences are 15-20 dB

Rajala and Hongisto (2021) Submitted for publication

Hearing threshold

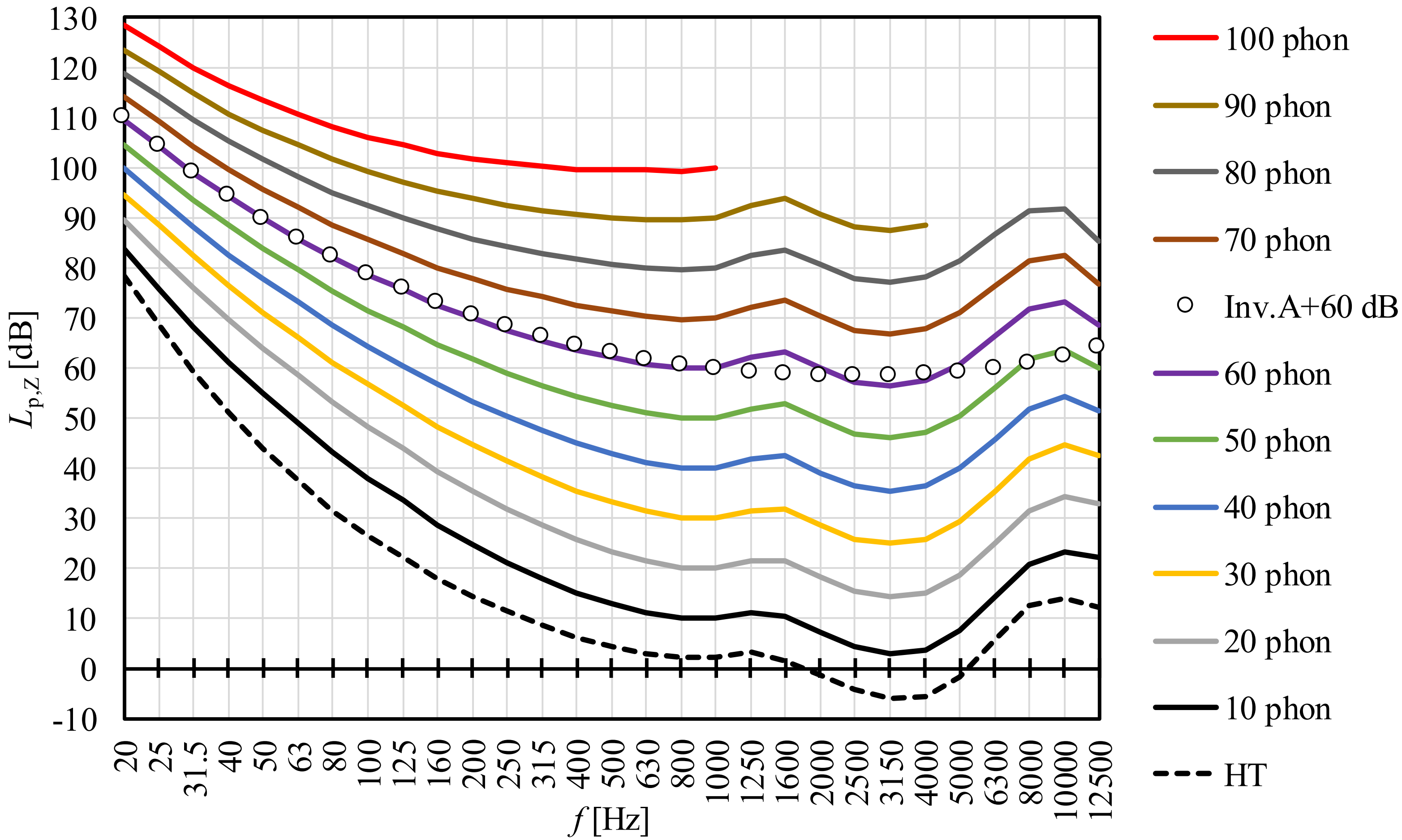
- The lowest audible SPL
- HT is standardized within 20 - 20.000 Hz
- Threshold SPL for infrasound 1 - 20 Hz is given by e.g. Watanabe & Møller (1990).
- The curves are valid for young normal hearing people
- 32% of individuals' thresholds are beyond the dashed lines



Hongisto, **Turun ammattikorkeakoulu,** 2017
http://julkaisut.turkuamk.fi/isbn9789522166531.pdf

Equal loudness contours of ISO 226 (loudness)

- Equal loudness contours have been determined by listening experiments
- A-weighting attempts to weight the frequencies 20-20000 Hz according to their relative loudness sensations at 60-phon curve
- C-weighting seems not to follow any of these curves but it is often used to describe loud impulse noise and low frequency noise. (Why?)



A- and C-weighting tables (IEC 61672:2003)

- A-weighted SPL, $L_{A,n}$, of a linear level $L_{Z,n}$, at frequency band f_n is obtained by

$$L_{A,i} = L_{Z,i} + A_i$$

- The total A-weighted SPL of N frequency bands is obtained by

$$L_A = 10\log_{10}\sum_{i=1}^{N} 10^{L_{A,i}/10}$$

- Octave band values are bolded.

i	f_n [Hz]	A_i [dB]	C_i [dB]
1	20	-50.4	-6.2
2	25	-44.7	-4.4
3	**31.50**	**-39.4**	**-3.0**
4	40	-34.6	-2.0
5	50	-30.2	-1.3
6	**63**	**-26.2**	**-0.8**
7	80	-22.5	-0.5
8	100	-19.1	-0.3
9	**125**	**-16.1**	**-0.2**
10	160	-13.4	-0.1
11	200	-10.9	0.0
12	**250**	**-8.6**	**0.0**
13	315	-6.6	0.0
14	400	-4.8	0.0
15	**500**	**-3.2**	**0.0**
16	630	-1.9	0.0
17	800	-0.8	0.0
18	**1000**	**0.0**	**0.0**
19	1250	0.6	0.0
20	1600	1.0	-0.1
21	**2000**	**1.2**	**-0.2**
22	2500	1.3	-0.3
23	3150	1.2	-0.5
24	**4000**	**1.0**	**-0.8**
25	5000	0.5	-1.3
26	6300	-0.1	-2.0
27	**8000**	**-1.1**	**-3.0**
28	10000	-2.5	-4.4
29	12500	-4.3	-6.2
30	**16000**	**-6.6**	**-8.5**
31	20000	-9.3	-11.2

Example: Road traffic noise

- *Z*-curve is the unweighted SPL
  - Z-weighting is zero weighting
- Total weighted value (Z, A, or C) is obtained from the energy-based sum of all one-third octave band values

- Noise level meter always determines the total value using range 20-20000 Hz.
- Range of interest can, however, be narrower in many applications:
  - speech applications: 100-10000 Hz
  - environmental noise: 20-5000 Hz
  - occupational noise: 20-20000 Hz

$$L_A = 10 \log_{10} \sum_{i=1}^{N} 10^{L_{A,i}/10}$$