Acoustics lesson 1

Steve Vanlanduit
Departement of Mechanical Engineering
Building Z, room ZW113
E-mail: steve.vanlanduit@vub.ac.be
Consult

• For any remark/question/complaint/etc. Concerning the **Bruface** program ‘Electromechanical Engineering’
• During the ‘Acoustics and vibrations’ lectures
• By e-mail: [steve.vanlanduit@vub.ac.be](mailto:steve.vanlanduit@vub.ac.be)
• After appointment (room ZW113)
Acoustics and vibrations Course overview

- **Acoustics**, S. Vanlanduit, 4 lectures,
  - Tuesday 10-12AM weeks 1-4
- **Vibrations part 1**, A. Preumont, 9 lectures
  - Thursday 2-4PM, weeks 1-8
- **Vibrations part 2**, P. Guillaume, 5 lectures,
  - Tuesday 10-12AM week 5-7 and Friday 8-10h weeks 8+9
- **Labs**
- **Exercices**
Overview:
- Physics of sound
- Hearing
- Measurement of sound
- Acoustics in enclosed spaces
- Transmission of sound
- European legislation
Environmental noise
Noise on the workfloor

Source: Belgian Fund for Professional deseases (FBZ)
Introduction

Sound sources
Overview:
- Physics of sound
- Hearing
- Measurement of sound
- Acoustics in enclosed spaces
- Transmission of sound
- European legislation
Basic physics of sound

Definition of sound:
- Longitudinal waves in a medium (air, water)
- Pressure variations (sound pressure in Pa, Bar, atm)
- Frequencies: 20Hz-20kHz
Basic physics of sound

The ‘dB’ scale

Sound pressure level (SPL):

\[ L_p = 10 \log_{10} \frac{p^2}{p_0^2} \]
Basic physics of sound

Pressure – dB conversion factors:

- $10 \times 4 = 40$ dB
- $10 \times 3 = 30$ dB
- $10 \times 2 = 20$ dB
- $10 ¥ 1 = 10$ dB
- $10 ¥ 0.3 = 3$ dB
Basic physics of sound

\[ L_p = 20 \log \frac{p}{p_0} \text{ dB re } 20 \mu \text{Pa} \]

\( p_0 = 20 \mu \text{Pa} = 20 \times 10^{-6} \text{ Pa} \)

Ex. 1: \( p = 1 \text{ Pa} \)

\[ L_p = 20 \log \frac{1}{20 \times 10^{-6}} \]
\[ = 20 \log 50 \, 000 \]
\[ = 94 \text{ dB} \]

Ex. 2: \( p = 31.7 \text{ Pa} \)

\[ L_p = 20 \log \frac{31.7}{20 \times 10^{-6}} \]
\[ = 20 \log 1.58 \times 10^{-6} \]
\[ = 124 \text{ dB} \]
Basic physics of sound
Basic physics of sound

Logarithmic frequency division

- Octave bands
- Tertz bands
Basic physics of sound

Propagation of sound

Simplified sound sources:
- Plane source $\rightarrow$ plane sound wave
- Line source $\rightarrow$ cylindrical sound wave
- Point source $\rightarrow$ spherical wave
Basic physics of sound

The plane wave equation:

\[
\frac{\delta^2 u}{\delta x^2} = \frac{1}{c^2} \frac{\delta^2 u}{\delta t^2}
\]

Solution:

\[
u(t, x) = \text{Re}(U_0 e^{i\omega t} e^{-\frac{x}{c}i\omega})
\]

\[
k = \frac{2\pi}{\lambda} = \frac{\omega}{c}
\]

\[
f\lambda = c
\]
Basic physics of sound

The speed of sound:

• Gasses

\[ c = \sqrt{\frac{\gamma P}{\rho}} = \sqrt{\gamma RT} \]

• Solids

\[ c = \sqrt{\frac{E}{\rho}} \]

<table>
<thead>
<tr>
<th>MEDIUM</th>
<th>TEMPRATURE (C)</th>
<th>SOUND SPEED (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>helium</td>
<td>0</td>
<td>972</td>
</tr>
<tr>
<td>air</td>
<td>0</td>
<td>331</td>
</tr>
<tr>
<td>air</td>
<td>20</td>
<td>340</td>
</tr>
<tr>
<td>water</td>
<td>0</td>
<td>1402</td>
</tr>
<tr>
<td>water</td>
<td>20</td>
<td>1482</td>
</tr>
<tr>
<td>sea water</td>
<td>20</td>
<td>1522</td>
</tr>
<tr>
<td>iron</td>
<td>0</td>
<td>5130</td>
</tr>
<tr>
<td>brass</td>
<td>0</td>
<td>4700</td>
</tr>
<tr>
<td>copper</td>
<td>0</td>
<td>3560</td>
</tr>
<tr>
<td>gold</td>
<td>0</td>
<td>3240</td>
</tr>
</tbody>
</table>
Basic physics of sound

Wave equation solutions for simplified sources:

Plane wave:

\[ p(t, x) = Ae^{i\omega t}e^{-\frac{x}{c}i\omega} \]

Spherical wave:

\[ p(t, r) = \frac{A}{r}e^{i\omega t}e^{-ikr} \]

Cylindrical wave:

\[ p(t, r) \approx \frac{A}{\sqrt{r}}e^{i\omega t}e^{-ikr} \]
Basic physics of sound

**Point source**

- $r: L_p$
- $2r: L_p - 6 \text{ dB}$

**Line source**

- $r: L_p$
- $2r: L_p - 3 \text{ dB}$

**Plane source**

- $r: L_p$
- $2r: L_p$
Basic physics of sound

Types of sound signals:

- Periodic
- Stochastic
- Impulse
Basic physics of sound

Spectral analysis:

[Graphs showing different sound waves and their frequency spectra.]
Basic physics of sound

Spectral analysis:
Basic physics of sound

The acoustic impedance:

Acoustic impedance

\[ z = \frac{p}{v} \]

MKS unity:

\[ \frac{kg}{m^2 s} = \text{rayl} \]

For plane waves:

\[ z = \rho c \]

In air:

\[ z = 400 \text{ Rayl} \]
Use of impedance:

- Acoustic absorption: \[ a = \frac{4z_1}{z_2} \]

- Resonators

See lesson 2
Basic physics of sound

RMS value:

\[ p_{\text{eff}} = \sqrt{\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} p(t)^2} \]

Equivalent sound level:

\[ L_{\text{eq}} = 10 \log \left( \frac{1}{T} \int_0^T \frac{p^2}{p_{\text{ref}}^2} \, dt \right) \]

\[ L_{\text{eq}} = 10 \log \left( \frac{1}{N} \sum_{n=1}^{N} 10^{L_n/10} \right) \]

\[ L_{\text{dn}}: \]

\[ L_{\text{dn}} = 10 \log \left[ \frac{1}{24} \left( \int_{7 \, \text{A.M.}}^{10 \, \text{P.M.}} 10^{L/10} \, dt + \int_{10 \, \text{P.M.}}^{7 \, \text{A.M.}} 10^{(L+10)/10} \, dt \right) \right] \]
Basic physics of sound

Adding two dB values:

\[ L_p = 10 \log(10^{L_{p1}/10} + 10^{L_{p2}/10}) \]

Example:

\[ L_1 = 55 \text{ dB} \]
\[ L_2 = 51 \text{ dB} \]
\[ \Delta L = 4 \text{ dB} \]
\[ L_+ = 1.4 \text{ dB} \]
\[ L_t = 55 + 1.4 = 56.4 \text{ dB} \]
Basic physics of sound

Correlated – uncorrelated sources:

1. Coherent source:
   \[ \text{RMS}^2(\text{totaal sound}) \neq \text{RMS}^2(\text{source1}) + \text{RMS}^2(\text{source2}) \]

2. Incoherent sources:
   \[ \text{RMS}^2(\text{totaal sound}) = \text{RMS}^2(\text{source1}) + \text{RMS}^2(\text{source2}) \]
Basic physics of sound

Sound Power in Watt:
- ‘energy flux through a closed surface’
- Sound power level $L_W$ in dB:
  \[ L_W = 10\log\left(\frac{W}{W_0}\right) \text{ with } W_0 = 10^{-12} \text{ Watt} \]

Sound Intensity $I$ in Watt/m²:
- ‘energy flux through 1m² surface’
- Sound intensity level $L_I$ in dB:
  \[ L_I = 10\log\left(\frac{I}{I_0}\right) \text{ with } I_0 = 10^{-12} \text{ Watt/m²} \]

\[
W = \int_S I \cdot dS
\]
Basic physics of sound

Sound intensity: \[ I_{r,\text{inst}} = \frac{dE_r}{dt \, dS} \]
\[ = \frac{F_r \, dr}{dt \, dS} \]
\[ = \frac{p_t \, dS \, dr}{dt \, dS} \]
\[ = \frac{p_t \, v_r}{p_t} \]

For plane waves:
\[ I_r = p \, v_r = p_{\text{eff}} v_{\text{eff}} \]
\[ = \frac{p_{\text{eff}}^2}{\rho c} = \rho c v_{\text{eff}}^2 \]

I is a vector quantity! \[ I_r = p_{\text{eff}} v_{\text{eff}} \cos \psi \]
Basic physics of sound

Relation between power and pressure:

\[ W = \frac{4\pi r^2 p_{\text{eff}}^2}{\rho c} \]

\[ \Rightarrow p_{\text{eff}} = \sqrt{\frac{\rho c W}{4\pi r^2}} \]

Typical sound power outputs (in WATTS) and equivalent sound power levels (in dB):

<table>
<thead>
<tr>
<th>Sound source</th>
<th>Power</th>
<th>Sound power level</th>
</tr>
</thead>
<tbody>
<tr>
<td>whisper</td>
<td>$10^{-9}$</td>
<td>30</td>
</tr>
<tr>
<td>vacuum cleaner</td>
<td>$10^{-6}$</td>
<td>60</td>
</tr>
<tr>
<td>normal voice</td>
<td>$10^{-5}$</td>
<td>70</td>
</tr>
<tr>
<td>raised voice</td>
<td>$10^{-3}$</td>
<td>90</td>
</tr>
<tr>
<td>chain saw</td>
<td>1</td>
<td>120</td>
</tr>
<tr>
<td>orchestra (75 musicians)</td>
<td>10</td>
<td>130</td>
</tr>
<tr>
<td>quadripole jet exhaust</td>
<td>$10^4$</td>
<td>160</td>
</tr>
</tbody>
</table>
The hearing system
The hearing system
The hearing system
Measurement of sound

Simple instrument for sound pressure measurement:

= ‘sonometer’
Measurement of sound

IEC 651:
- Type 1
- Type 2
- Type 3
Measurement of sound

Measurement microphones

Principles:
- Piezoelectric
- Inductive
- Condenser
- Electret
Measurement of sound
Measurement of sound

\[ Q = CV \]
\[ C = \varepsilon \frac{A}{d} \]

\[ \Rightarrow V = \frac{Q}{C} = \frac{Q}{\varepsilon A} d \Rightarrow \Delta V = \frac{Q}{\varepsilon A} \Delta d \]
Measurement of sound
Measurement of sound
Measurement of sound
Measurement of sound

40 dB Equal Loudness Contour inverted and compared with A-weighting

A-weighting

$L_p$ (dB)

20 Hz 100 1 kHz 10 kHz
Measurement of sound

A, B, C en D filters \(\leftarrow (40, 70, 100, 120 \text{ dB respectively})\)

IEC 60651 (1979-01)
Measurement of sound
## Measurement of sound

### Octaves and Tertz band analysis

<table>
<thead>
<tr>
<th></th>
<th>25</th>
<th>31.5</th>
<th>40</th>
<th>50</th>
<th>63</th>
<th>80</th>
<th>100</th>
<th>125</th>
<th>160</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>250</td>
<td>315</td>
<td>400</td>
<td>500</td>
<td>630</td>
<td>800</td>
<td>1000</td>
<td>1250</td>
<td></td>
</tr>
<tr>
<td>1600</td>
<td>2000</td>
<td>2500</td>
<td>3150</td>
<td>4000</td>
<td>5000</td>
<td>6300</td>
<td>8000</td>
<td>10000</td>
<td></td>
</tr>
<tr>
<td>12500</td>
<td>16000</td>
<td>20000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Graph showing frequency response](image)

![Bar graph showing sound level](image)
Measurement of sound

Calibration Chart for Proprietary Condenser Microphone Cartridge
Type 4155
Serial No. 762849.

Briel & Kjaer

Open Circuit Sensitivity 1013 mbar, 23°C and 50% R.H.
126.5 dB re 1 V/sr from 50 Hz to 125 kHz.

This Calibration is traceable to the National Bureau of Standards, Washington D.C.

Open Circuit Correction Factor:
Kocc. = 0.5 dB

Condenser Cartridge: C...16.2 μF

Frequency Response Characteristics:
The upper curve is the open circuit free field characteristic of the microphone. The lower curve is the open circuit pressure response recorded with microphone flange at 1/2"-

Conformance to Test:
Polarization Voltage: -100 V DC, rear side of chart
Frequency: 250 Hz
Relative Pressure: 1000 mbar
Relative Humidity: 40% RH
Temperature: 29°C
Date: 6-6-79 Signature: K.R.

Summary Specifications:
Outside Diameter: 0.875 & PlusMinus; 0.005
Overall Length: 4.500 & PlusMinus; 0.005

Free field
Pressure
Measurement of sound

Sound exposure level:

\[ SEL = 10 \log \left( \int_0^T 10^{L/10} dt \right) \]
Measurement of sound

Sound intensity measurement:

\[ F_x = m a \]
\[ \Rightarrow \rho \frac{\partial v_x}{\partial t} = -\frac{\partial p}{\partial x} \]
\[ \Rightarrow v_x = -\frac{1}{\rho} \int \frac{\partial p}{\partial x} dx \]

\[ I_x = \bar{p} v_x \]
\[ = -\frac{1}{2\rho \Delta r} (p_A + p_B) \int (p_A - p_B) dt \]
Measurement of sound

Limitation of the frequency range
Sound power measurement

Different possible techniques:

1. Using SPL measurements:
   \[\text{ISO 3740 series}\]

2. Using sound intensity measurements
   \[\text{ISO 9614 series}\]
Sound power measurement

ISO 3741 to 3747

Procedure:
- Choice of a surrounding surface
- SPL measurements at discrete points on the surface
  - A weighted
  - In octave or tertz bands

Variants depending on:
- Type of surface
- Acoustical environment (anechoic room?)
- Required accuracy
- Size of the source
- Background noise
- Application area, required information
Sound power measurement

ISO 3744
- Semi-anechoic, outdoor, large room
- Largest source dimension < 15m
- All types of sound
- In frequency bands
- Surrounding surface:
  - Parallelepipededum
  - Hemisphere
  - Sphere

\[ L_w = \overline{L_p} + 10 \log \frac{S}{S_0} - K_1 - K_2 \]

\[ \overline{L_p} = 10 \log \frac{1}{N} \sum_{i=1}^{N} 10^{0.1L_{pi}} \]
Comparison method: **ISO 3747**

- Accuracy $\sigma = 4$ to $5$ dB
- Fixed non-mobile machines
- In-house and outside
- No limitation on the volume of the source
- All stationary sound
- Method:

$$L_W = L'_W + (L_{pm} - L'_{pm})$$

- Power of the reference source
- Avg. SPL of unknown source
- Avg. SPL reference source
Sound power measurement

Using sound intensity:

ISO 9614: ‘Determination of sound power levels of noise sources using sound intensity’

Procedure:

- Definition of an arbitrary surrounding surface
- Measure acoustic intensity at discrete points on the surface
- Calculation of the sound power:

\[ W_i = I_{ni} S_i \]

\[ L_W = 10 \log \sum_{i=1}^{N} \frac{W_i}{W_0} \]
Sound power measurement

Advantages:

- Elimination of background noise
- In situ measurement possible
- Nearfield measurements
- Arbitrary surfaces possible

\[
\int_{S} \mathbf{I} \cdot d\mathbf{S} = 0
\]

Source not enclosed by measurement surface

Power $W$ (Watts)
Sound power measurement

Disadvantages:

- Limited frequency range
- Directivity
- Cost of the instrumentation
Sound power measurement

ISO 9614-2:

Sweep method
Major question:
- Explain the working principle of the human hearing system.
- Discuss the working principle of a sonometer and an intensity meter.
- Explain how one can measure sound power in practice.

Minor questions:
- Calculate dB level (by heart)
- Give order of magnitude of acoustical quantities