Human Vibration
Hand-arm Vibration

Long-term exposure can cause white-finger or dead-finger syndrome

Symptoms:
- Tingling
- Numbness
- Blanching
- Over-reaction to coldness
Whole-body Vibration

Long-term exposure can cause severe damage especially to the lumbar region of the spine

Short-term symptoms:
- Fatigue
- Headache
- Slower reactions
- Nausea
- Insomnia
Mechanical Models of the Human Body

Whole body
- Shoulder girdle (4 - 5 Hz)
- Chest wall (50 - 60 Hz)
- Abdominal Mass (4 - 8 Hz)
- Lung volume
- Lower arm
- Spinal column (axial mode) (10 - 12 Hz)
- Legs (Variable from ca. 2 Hz with knees flexing to over 20 Hz with rigid posture)

Hand-arm
- Eyeball, intraocular structures (ca. 25 Hz)
- Head (axial mode) (20 - 30 Hz)
- Hand grip (50 - 200 Hz)
Transmission of Vibration through the Body

Acceleration Ratio

Frequency, Hz

0 0.5 1.0 1.5 2.0 2.5

1 2 5 10 20 40

Head
Shoulder
Thorax

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Standards for Human Vibration

ISO 2631-1:1997
“Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration,
Part 1, General Requirements”.

ISO 5349-1986
“Mechanical vibration - Guidelines for the measurement and the assessment of human exposure to hand-transmitted vibration.”
Evaluation Method: Rating

Max. 1 Hour exposure allowed in this example

Rating curves

1/3 - octave Spectrum

Acceleration

1 Hour
2 Hour
4 Hour

Frequency, Hz

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Evaluation Method: Weighting

Motion sickness

Acceleration dB

Hz

Whole body

x, y

z

Hand-arm

0.02 0.05 0.1 0.2 0.5 1 2 5 10 20 50 100 200 500 1k

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Using the Weighing Method in Practice

Measurement → Weighting → Display

Frequency, Hz

106.2 dB

L_{Aeq}

L_{Ls} (Inst.)

L_{LPk} (MaxP.)

L_{LFMax}

Overload

Elapsed Time 00:00:53
Measurement Directions

Whole-Body

"Handgrip" position

Basicentric coordinate system

Biodynamic coordinate system
Categories of Whole-Body Vibration

- **Motion sickness**, in ships or vehicles with very soft suspension systems
  - 0.1 to 0.63 Hz

- **Whole-body vibration** in vehicles or on platforms
  - 1 to 80 Hz

- **Whole-body vibration** in buildings
  - 1 to 80 Hz
Measure in the Vertical Direction In Buildings
Hand-Arm Vibration Weighting

![Graph showing acceleration in dB vs. frequency (Hz)]

- **8 Hz**
- **16 Hz**

**Axes:**
- **Y-axis:** Acceleration (dB)
- **X-axis:** Frequency (Hz)

**Grid:**
- The graph includes a grid with labeled frequencies and acceleration levels.

**Legend:**
- Blue line at 0 dB
- Red line showing the weighted acceleration curve.
Vibration Amplitude

Vibration Level

Acceleration, $a$

Velocity, $v = \frac{a}{2\pi f}$

Displacement, $d = \frac{a}{2\pi f^2}$

Frequency
Descriptive Parameters

Amplitude

\[ a_{\text{RMS}} \]

\[ a_{\text{Peak}} \]

\[ T \]
Characteristics of Vibration – RMS

Root Mean Square:
Exponential average
Time Constant: 1s = slow, 1/8s = fast
The “Energy Equivalent” Acceleration, $a_{eq}$

Energy Equivalent Acceleration:

$$a_{eq}(T) = \sqrt{\frac{1}{T} \int_{0}^{T} a_{RMS}^2 \, dt}$$
Max. Peak and Crest Factor

Crest Factor

\[ C.F. = \frac{\text{Max. Peak}}{a_{\text{RMS}}} \], \hspace{1cm} \[ C.F. = \frac{\text{Max. Peak}}{a_{\text{eq}}} \]

\[ T = 60 \text{ s} \]
m/s² or Decibels?

Acceleration
m/s²

100
10
1
0.1
0.01

160
140
120
100
80

Acceleration
dB
re. 10⁻⁶ m/s²
### m/s² or Decibels?

<table>
<thead>
<tr>
<th>Acc.dB (re. 10⁻⁶ m/s²)</th>
<th>80</th>
<th>100</th>
<th>120</th>
<th>140</th>
<th>160</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hand-arm</strong></td>
<td><img src="image1.png" alt="Hand-臂" /></td>
<td><img src="image2.png" alt="Hand-臂" /></td>
<td><img src="image3.png" alt="Hand-臂" /></td>
<td><img src="image4.png" alt="Hand-臂" /></td>
<td><img src="image5.png" alt="Hand-臂" /></td>
</tr>
<tr>
<td><strong>Whole body in vehicles</strong></td>
<td><img src="image6.png" alt="Airplane" /></td>
<td><img src="image7.png" alt="Train" /></td>
<td><img src="image8.png" alt="Vehicle" /></td>
<td><img src="image9.png" alt="Vehicle" /></td>
<td><img src="image10.png" alt="Vehicle" /></td>
</tr>
<tr>
<td><strong>Whole body in buildings</strong></td>
<td><img src="image11.png" alt="Building" /></td>
<td><img src="image12.png" alt="Building" /></td>
<td><img src="image13.png" alt="Building" /></td>
<td><img src="image14.png" alt="Building" /></td>
<td><img src="image15.png" alt="Building" /></td>
</tr>
<tr>
<td><strong>Acc.m/s²</strong></td>
<td>0.01</td>
<td>0.1</td>
<td>1</td>
<td>10</td>
<td>100</td>
</tr>
</tbody>
</table>

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Basic Instrumentation for Weighted Measurements

Accele-
rometer

DeltaTron
Amplifier

Input
Filter

Weighting

Amplifier

Level
Analyzer

Channel
1(X)

Multiplexer

Channel
2(Y)

Channel
3(Z)

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Transducer for Whole-body Vibration

Rubber disc

Tri-axial Accelerometer
Mounting the Transducer – Whole Body
Whole-body Vibration in Buildings
Directional Considerations

Weighted Acceleration Sum:

\[ \text{WAS} = \sqrt{(1.4a_x)^2 + (1.4a_y)^2 + a_z^2} \]
Calculation of the Working Day Dose

\[
\text{Dose} = \left( \frac{t_1}{\tau_1} + \frac{t_2}{\tau_2} + \frac{t_3}{\tau_3} \right) \times 100\%
\]

\(t = \text{Elapsed time}\)

\(\tau = \text{Allowed time}\)
Example of Dose Calculation:

<table>
<thead>
<tr>
<th>Work Type</th>
<th>Elapsed Time $t$ (hours)</th>
<th>$a_{eq}$ m/s²</th>
<th>Allowed Time $\tau$ (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>0.7</td>
<td>2.5</td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
<td>1.3</td>
<td>0.9</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>0.3</td>
<td>8</td>
</tr>
</tbody>
</table>

$$Dose = \left( \frac{2}{2.5} + \frac{0.5}{0.9} + \frac{1}{8} \right) \times 100\% = 148\%$$
Approximated Exposure Evaluation

Requirement: \( a_{eq} \leq a_0 \)

\[
a = \begin{cases} 
2.8 \text{ m/s}^2 & (z) \\
2.0 \text{ m/s}^2 & (x, y)
\end{cases}
\]

\( t_0 = 10 \text{ min} \)

\[
t_{allowed} = \left( \frac{a_0}{a_{eq}} \right)^2 \times t_0 \quad (1)
\]

Dose = \( \frac{t_{elapsed}}{t_{allowed}} \times 100\% \) \quad (2)
Mounting the Transducer – Hand Arm

Accelerometers should be rigidly attached to the tool, but not interfering with normal operation.
Mounting Adaptors – Hand Arm

Hand-adaptor

Handle adaptor

Handle adaptors and hand-adaptors are used when rigid mounting to the tool is not possible.
Coordinate Systems

The hand adaptor measures in the biodynamic coordinate system

The handle adaptor measures in the basicentric coordinate system
Directional Considerations for Hand-Arm

For hand-arm vibration it is often necessary to measure in all three directions to find the worst one.
Type of Adaptor

Handle adaptor

Hand-adaptor
Cables are fixed down, often with tape, so that there is minimal cable-induced vibration in the measurement system.
Exposure Evaluation

Risk of getting vascular disorders (White finger syndrome)

Years of exposure

50th percentile
40th percentile
30th percentile
20th percentile
10th percentile

a [m/s^2]
The 4-hour Energy Equivalent Acceleration, $a_{eq}(4)$

$$a_{eq}(4) = a_{eq}(t) \sqrt{\frac{T}{4}}$$

The 4-hour Energy Equivalent Acceleration, $a_{eq}(4)$

$$L_{eq}(4) = L_{eq(T)} + 10 \log \frac{T}{4}$$
Exposure from Several Events

\[ a_{eq}(T) = \sqrt{\frac{a_1^2 T_1 + a_2^2 T_2 + a_3^2 T_3 + \ldots}{T_1 + T_2 + T_3 + \ldots}} \]

\[ L_{eq}(T) = 10 \log \frac{T_{1 \text{ inv.log}} \frac{L_1}{10} + T_{2 \text{ inv.log}} \frac{L_2}{10} + \ldots}{T_1 + T_2 + \ldots} \]
Example of Exposure Calculations

<table>
<thead>
<tr>
<th>Work Type</th>
<th>$a_n$ m/s$^2$</th>
<th>Effective time Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.6</td>
<td>0.7</td>
</tr>
<tr>
<td>2</td>
<td>10.3</td>
<td>0.5</td>
</tr>
<tr>
<td>3</td>
<td>2.5</td>
<td>1.0</td>
</tr>
</tbody>
</table>

$$a_{eq}(T) = \sqrt{\frac{5.6^2 \times 0.7 + 10.3^2 \times 0.5 + 2.5^2 \times 1.0}{0.7 + 0.5 + 1.0}} = 6.1 \text{ m/s}^2$$

$$a_{eq}(4) = 6.1 \times \sqrt{\frac{2.2}{4}} = 4.5 \text{ m/s}^2$$

$$a_{eq}(8) = 6.1 \times \sqrt{\frac{2.2}{8}} = 3.2 \text{ m/s}^2$$
Frequency Analysis – 1/3 Octave

Note: Different signals to the analyzers
Frequency Analysis – FFT

Note: Different signals to the analyzers
Level Analysis

Level dB

Time
Statistical Analysis

Level distribution

Cumulative distribution

L_{90} = 103 dB

L_{10} = 128 dB
Example: Wheel-loader

![Diagram showing noise levels over time for health and proficiency.]
Example: Wheel-loader

1/3 Octave Spectrum

- dB
- m/s²
- Z-direction
- Hz

Suspension

- 120
- 1
- 110
- 0.315
- 100
- 0.1
- 90

1,0 2,5 6,3 16 40 63 100 Hz
Example: Helicopter

FFT Spectrum

- Main rotor blades
- Main rotor
- Tail blades
- Tail shaft

- 5.25 dB
- 10.5 dB
- 22 dB
- 33 dB
- 43 dB
- 53 dB
- 64 dB
- 71 dB
- 75 dB
- 86 dB
- 97 dB

Hz
Example: Chipping Hammer

Very high peak acceleration levels are found at the handle of the chipping hammer. Even higher levels are found at the chisel (and the operator often uses his other hand to control the chisel).
Chipping Hammer Vibration

1/3 - Octave Acceleration

- Tool body resonance
- Left Hand Resonance
- Blow frequency
- Subharmonic

Frequency (Hz)

- 4
- 16
- 63
- 250
- 1k
- 4k
- 16k
- 63k

Acceleration (m/s²)

- 130
- 140
- 150
- 160
- 170
- 180

Decibels (dB)
Example: Chain Saw

- Centre line of log:
  - 25 mm above the ground line
  - 80 mm below the ground line

- Ground line:
  - 600 mm

- Chain saw:
  - Suction valve (S)
  - Feed valve (f)
  - 25 mm
  - 80 mm
Chain Saw

Weighted 1/3-octave Spectrum

- Idling
- Sawing
- Racing
Example: Grinders

![Graph showing vibration levels and frequency]

- Oscillation frequency
- Weighted 1/3-octave Spectrum
- Graph with dB and m/s² axes
- Random distortion products
- Marked frequencies (2^{th}, 4^{th}, 8^{th} harmonics)

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Conclusion

Central Issue:
Avoid breaking occupational health legislation at lowest cost

Monitoring and Risk assessment checklist:

- Is there a problem?
- How big is the problem?
- What causes the problem?
- How do we reduce the problem?
- How do we prevent the problem?

Vibration + Time = Vibration Exposure

Vibration Exposure + Time = **Tissue Damage**

Vibration exposure is measured according to national and international standards for Hand-Arm Vibration and Whole-Body Vibration.