11 Vibration and shock

ELEC-E5640 - Noise Control P

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Basic quantities and concepts

- Displacement s [m]

$$\mathbf{s}(t) = \hat{s} e^{i(\omega t + \varphi_s)}$$

- Velocity v(t) and acceleration a(t) depend on each other by:

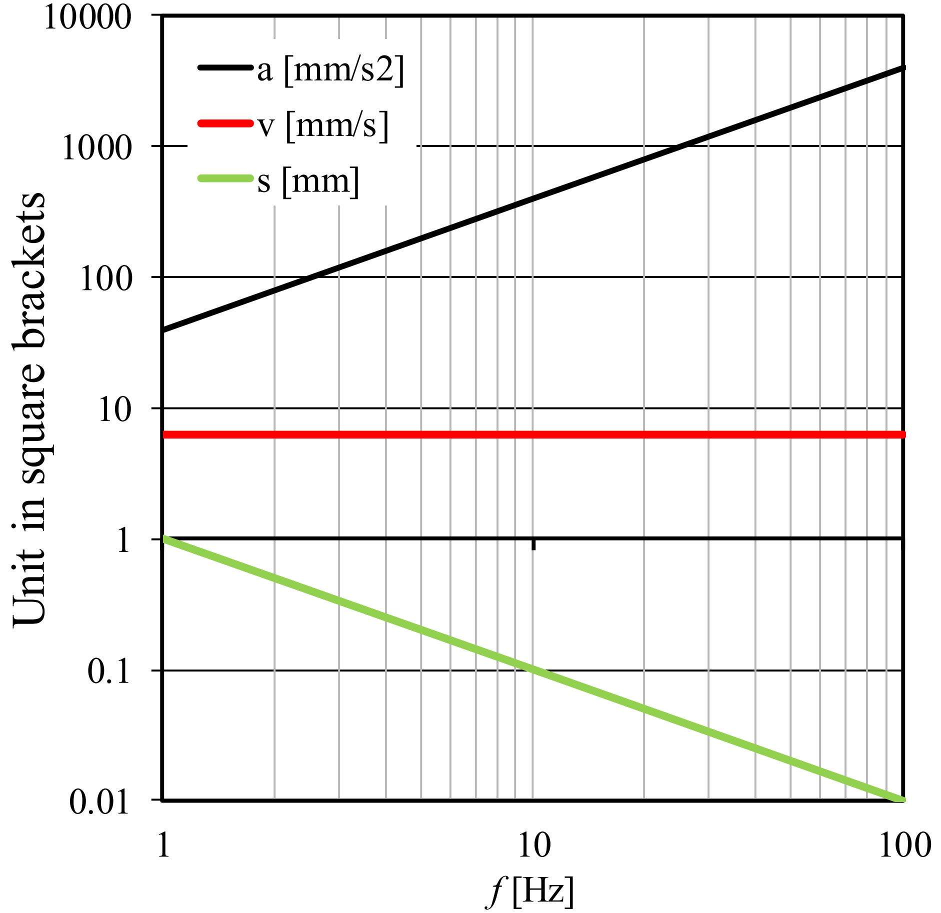
$$\mathbf{a}(t) = \frac{d}{dt}\mathbf{v}(t) = \frac{d^2}{dt^2}\mathbf{s}(t)$$

- **Vibration** = time-dependent movement of a solid surface
- **Shock**= vibration exceeding the threshold of noticeability
- **Structure borne noise** = vibration-induced audible sound originating from the surface
- **Rattle** = vibration-induced audible sound originating from an artifact touching the vibrating surface

Inter-relationships between *a*, *v* and *s*

- Measurements are often conducted for acceleration since displacement measurements often fall below background noise at high frequencies
- Figure depicts the spectrum of the same signal for the three different quantities

$$\mathbf{a} = i\omega\mathbf{v} = -\omega^2\mathbf{s}$$



Levels

- Levels are determined from the RMS values.

- **Displacement level**
  - s_0=1 pm

$$L_d = 10\lg\frac{\tilde{s}^2}{s_0^2} = 20\lg\frac{\tilde{s}}{s_0} \quad [\mathrm{dB}]$$

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

- **Velocity level**
  - v_0=1 nm/s

$$L_v = 10\lg\frac{\tilde{v}^2}{v_0^2} \quad [\mathrm{dB}]$$

$$\tilde{v} = \sqrt{\frac{1}{T}\int_0^T s^2(t)dt}$$

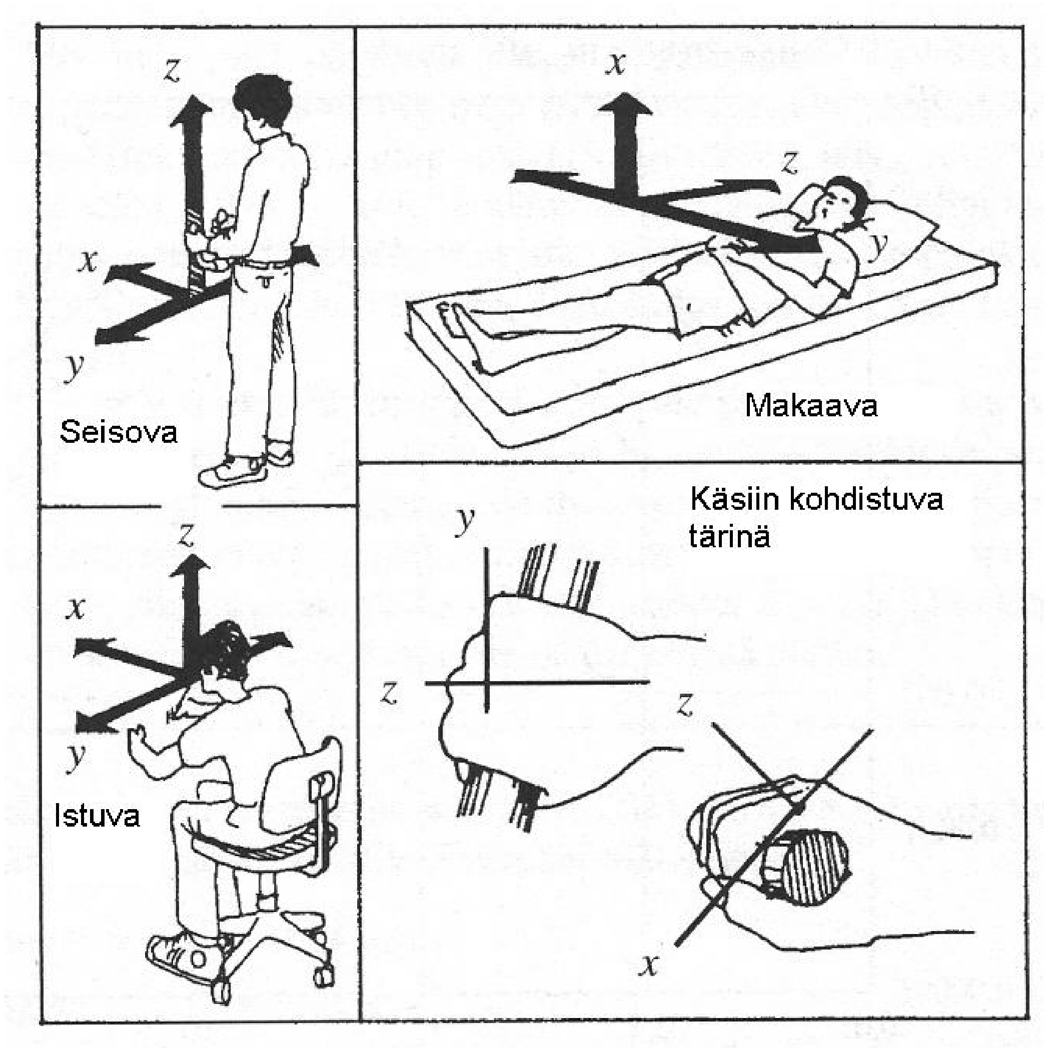
- **Acceleration level**
  - a_0=1 μm/s^2

$$L_a = 10\lg\frac{\tilde{a}^2}{a_0^2} \quad [\mathrm{dB}]$$

$$\tilde{a} = \sqrt{\frac{1}{T}\int_0^T s^2(t)dt}$$

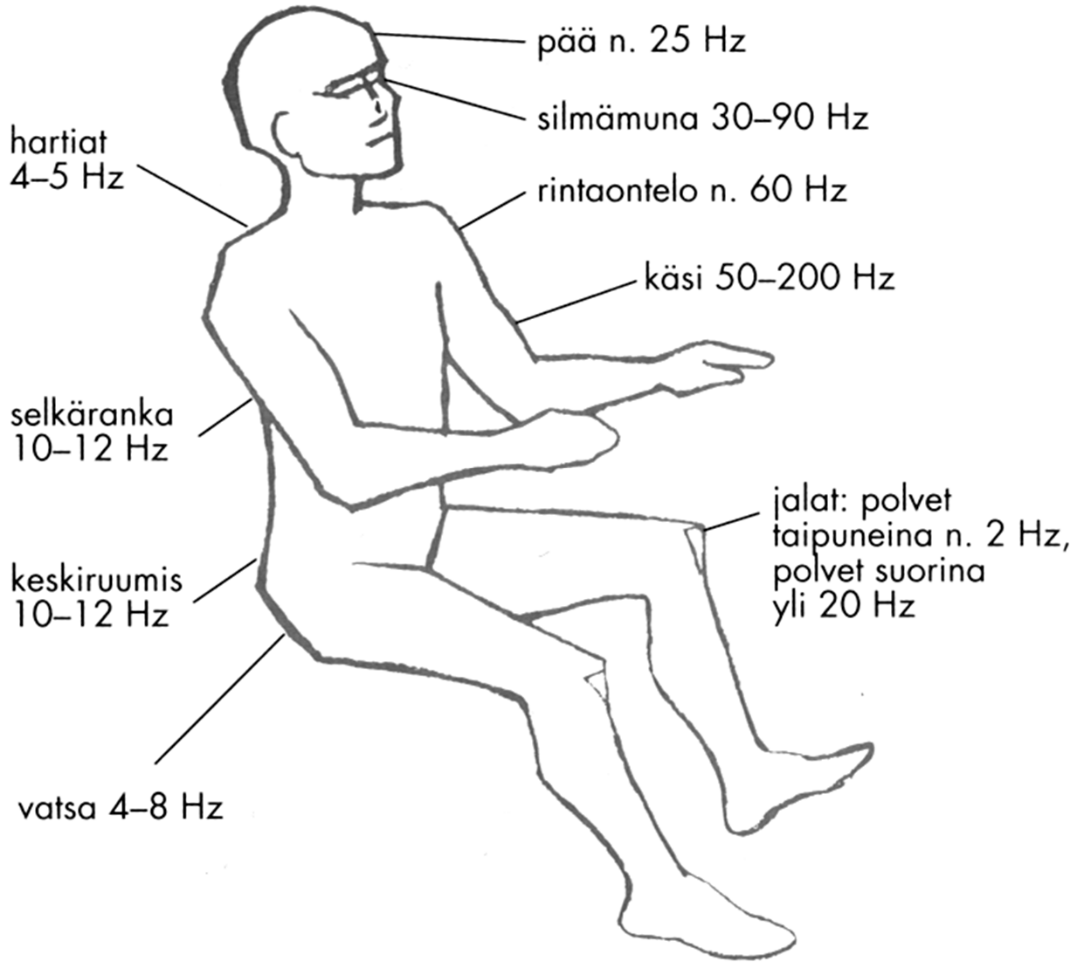
Shock measurements

- 3D-transducers



Human body resonances

- Airborne sound and vibrating bodies (ground, items) cause resonances in the body
- Noticeable resonances due to airborne sound presuppose SPLs at least 40 dB above the hearing threshold
- On the other hand, noticeable human body resonances due to shock often occur without audible sensations
- Nausea 100-500 mHz
- Long-term exposure to shock can result in adverse health effects



Declaration of vibration: vehicles and machinery - 2006/42/EC

- The instructions must give the following information concerning vibrations transmitted by the machinery to the hand-arm system or to the whole body:
  - the vibration total value to which the **hand-arm** system is subjected, if it exceeds **2,5 m/s2**. Where this value does not exceed 2,5 m/s2, this must be mentioned,
  - the highest root mean square value of weighted acceleration to which the **whole body** is subjected, if it exceeds **0,5 m/s2**. Where this value does not exceed 0,5 m/s2, this must be mentioned.
  - the uncertainty of measurement.
- Where harmonised standards are not applied, the vibration must be measured using the most appropriate measurement code for the machinery concerned.
- The operating conditions during measurement and the measurement codes used must be described.

- Decision of the government 400/2008 and 2006/42/EC
- http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2006:157:0024:0086:en:PDF

Protection of employees against vibration - 2002/44/EC

For hand-arm vibration:

(a) the daily exposure limit value standardised to an eight-hour reference period shall be 5 m/s^2;

(b) the daily exposure action value standardised to an eight-hour reference period shall be 2,5 m/s^2.

For whole-body vibration:

(a) the daily exposure limit value standardised to an eight-hour reference period shall be 1,15 m/s^2 or, at the choice* of the Member State concerned, a vibration dose value of 21 $m/s^{1,75}$;

(b) the daily exposure action value standardised to an eight-hour reference period shall be 0,5 m/s^2 or, at the choice* of the Member State concerned, a vibration dose value of 9,1 $m/s^{1,75}$.

*Choices are not applied in Finland.

'hand-arm vibration': the mechanical vibration that, when transmitted to the human hand-arm system, entails risks to the health and safety of workers, in particular vascular, bone or joint, neurological or muscular disorders;

'whole-body vibration': the mechanical vibration that, when transmitted to the whole body, entails risks to the health and safety of workers, in particular lower-back morbidity and trauma of the spine.

- Government decree 48/2005
- 2002/44/EC: http://eur-lex.europa.eu/resource.html?uri=cellar:546a09c0-3ad1-4c07-bcd5-9c3dae6b1668.0004.02/DOC_1&format=PDF

Shock exposure measurement

- Equivalent value for each direction in time T is first determined in each direction:

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

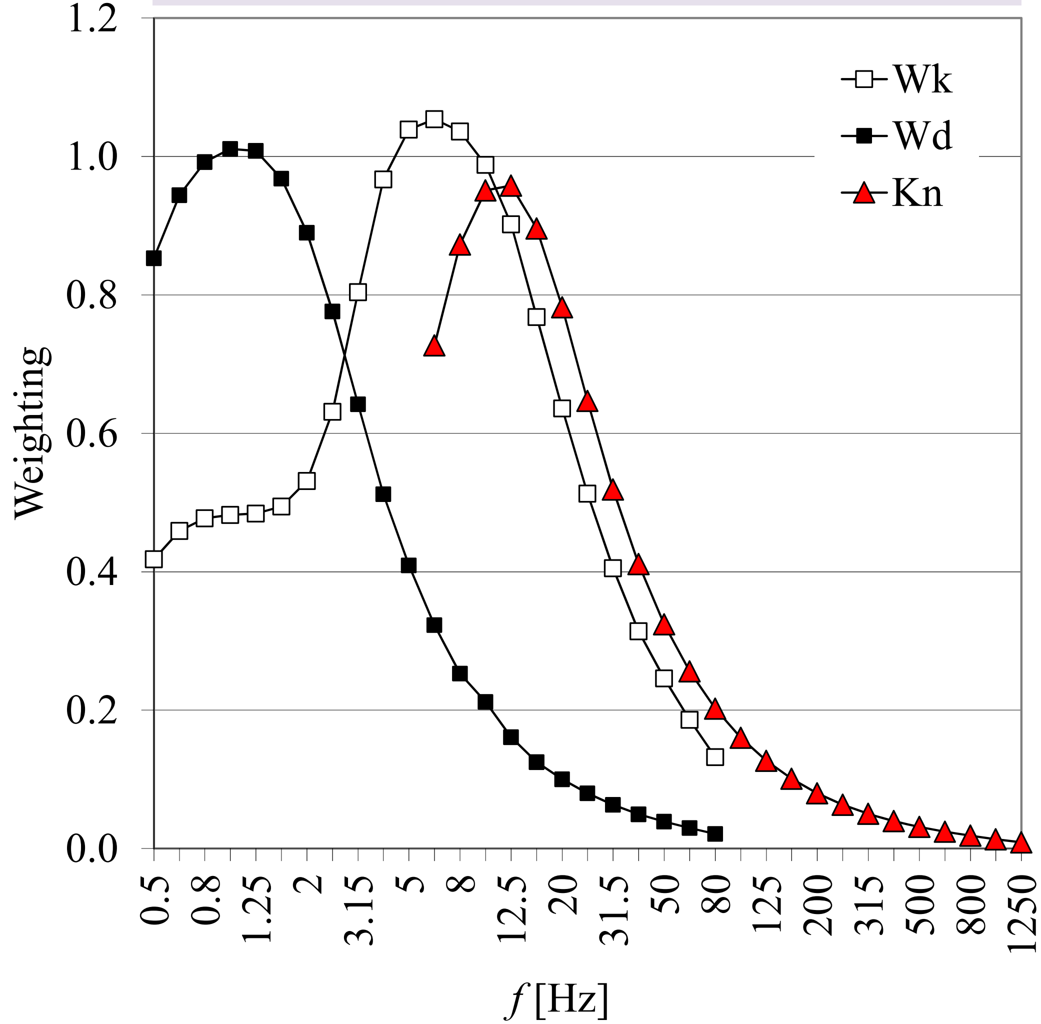
- Weighting of each direction (3 alternatives) in spectrum space:

$$\tilde{a}_w = \sqrt{\sum_{n=1}^{3}(W_n \tilde{a}_n)^2}$$

- Weighting of hand-arm vibration:

$$\tilde{a}_{h,w} = \sqrt{\sum_{n=1}^{3}(K_n \tilde{a}_{h,n})^2}$$

K_n - Hand-arm vibration (ISO 5349)
W_k - Whole-body vibration, horizontal (ISO 2631-1)
W_d - Whole-body vibration, vertical (ISO 2631-1)



Determination of vibration exposure

- All working phases of the employee are determined using short-term measurements. Short-term measurements are used since the measurement disturbs working.
- Thereafter, the exposure for each phase is determined.
- If the weighting has been applied directly to the signal, the exposure is estimated from the result of separate measurement period i by

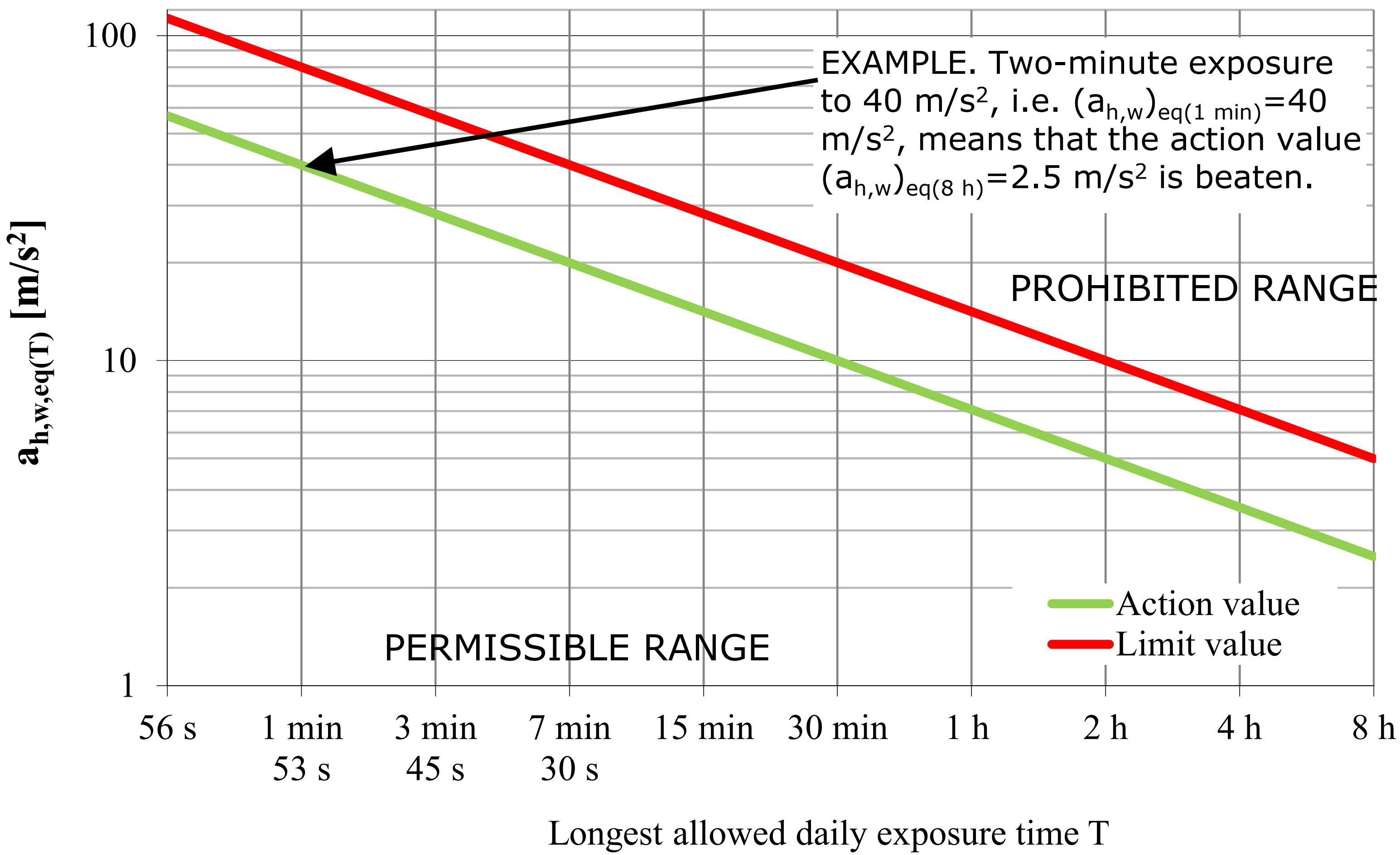
$$\tilde{a}_{h,w,eq(8)} = \sqrt{\frac{1}{T_8}\int_0^{\tau} a_{h,w}^2(t)\,dt}$$

$$\sum_{i=1}^{N} t_i = T_8 = 8\,h \qquad = \sqrt{\frac{1}{T_8}\sum_{i=1}^{N} a_{h,w,i}^2 t_i}$$

- 3D-transducer is installed to measure the vibration of the hand correctly.
- A separate bar was installed in this special case.

2002/44/EC limit and action values

Longest allowed daily exposure time T when the action value or limit value is beaten



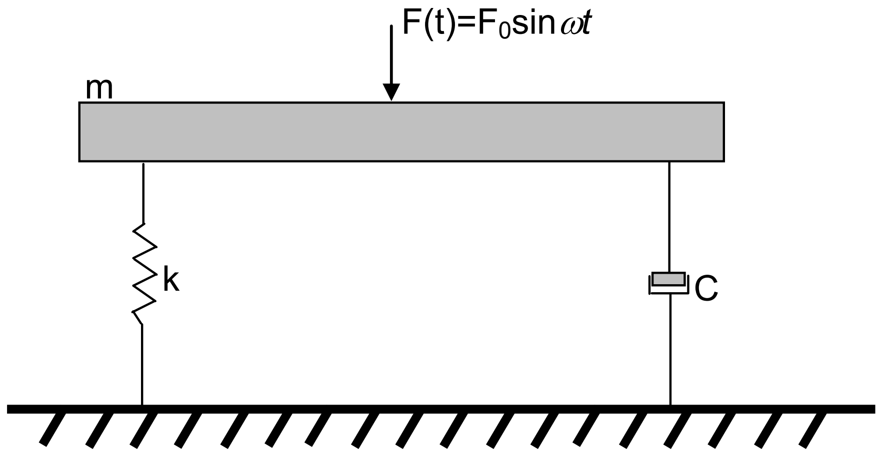
Vibration control programme - 2002/44/EC

Once the exposure action values are exceeded, the employer shall establish and implement a **programme** of technical and/or organisational measures intended to reduce to a minimum exposure to mechanical vibration and the attendant risks, taking into account in particular:

a) other working methods that require less exposure to vibration;
b) the choice of appropriate work equipment of better ergonomic design;
c) the provision of auxiliary equipment that reduces the risk of injuries caused by vibration, such as vibration isolated seats that effectively reduce whole-body vibration and handles which reduce the vibration transmitted to the hand-arm system;
d) appropriate maintenance programmes for equipment;
e) the design and layout of workplaces and workstations;
f) adequate information and training to instruct workers to use work equipment correctly and safely in order to reduce their exposure;
g) limitation of the duration of the exposure;
h) appropriate work schedules with adequate rest periods;
i) the provision of clothing to protect exposed workers from cold and damp.

Vibration isolation

Vibration isolation



- Equation of motion for a vibrating mass m:

$$m\frac{d^2x}{dt^2}+kx+C\frac{dx}{dt}=F(t)$$

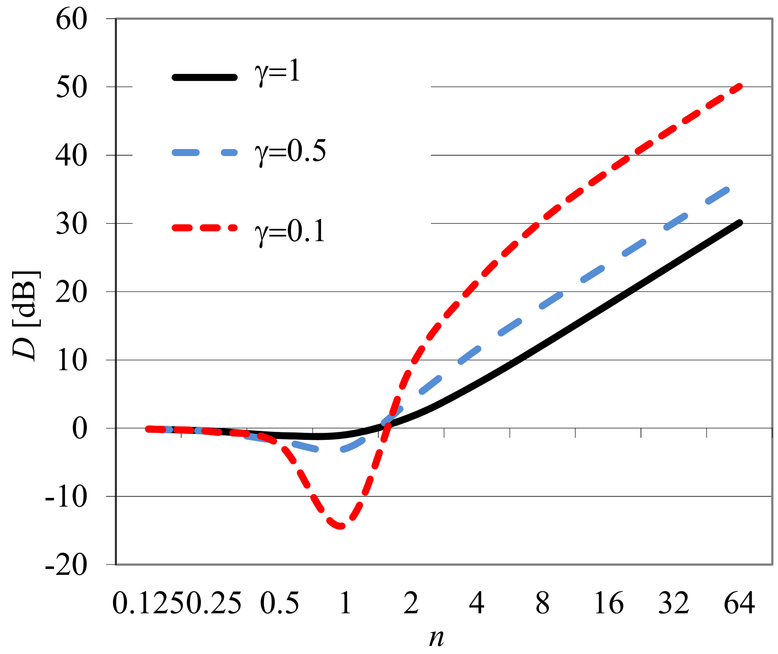
  - m [kg] is the mass of the system
  - k [N/m] is the spring constant (i.e. dynamic stiffness)
  - C [Ns/m] is the spring damping coefficient.
- If C=0, the resonance frequency becomes:

$$f_0=\frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

- Frequency-dependent isolation, D [dB], is

$$D=10\lg\left[\frac{(2\gamma n)^2+(1-n^2)^2}{1+(2\gamma n)^2}\right] \qquad \gamma=\frac{C}{2\sqrt{km}}$$

  - γ is the loss factor (value range is 0─1, usually 0.20)
  - $n=f/f_0$



Deflection Δx

- The deflection Δx [m] means the displacement of the spring when the mass m is inserted.
- It depends on the mass of the system and spring constant k:

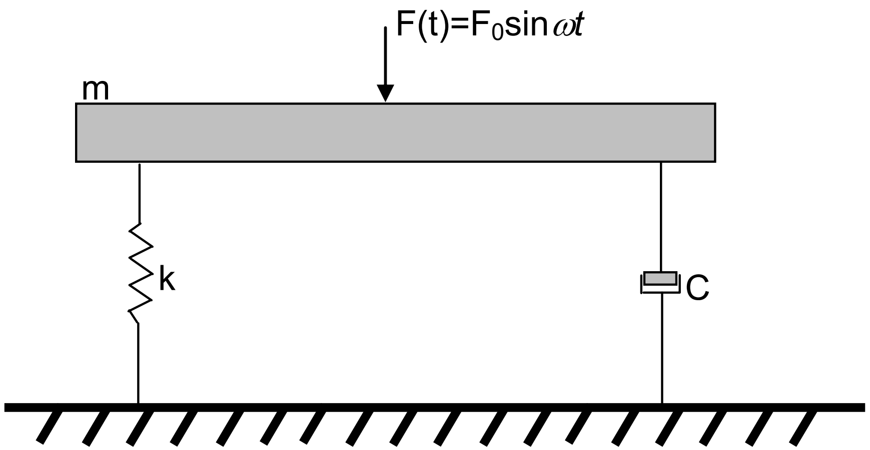
$$k\Delta x = mg$$

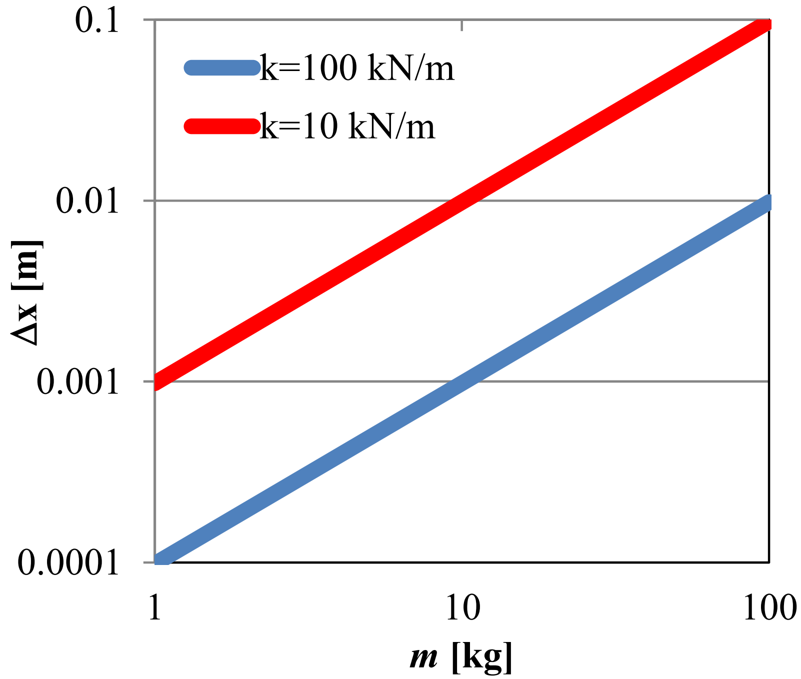
- Resonance frequency f_0 [Hz] is

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{g}{\Delta x}} \approx \frac{1}{2\sqrt{\Delta x}}$$

- Resonance frequency determines the deflection:

$$\Delta x = \frac{1}{4 f_0^2}$$



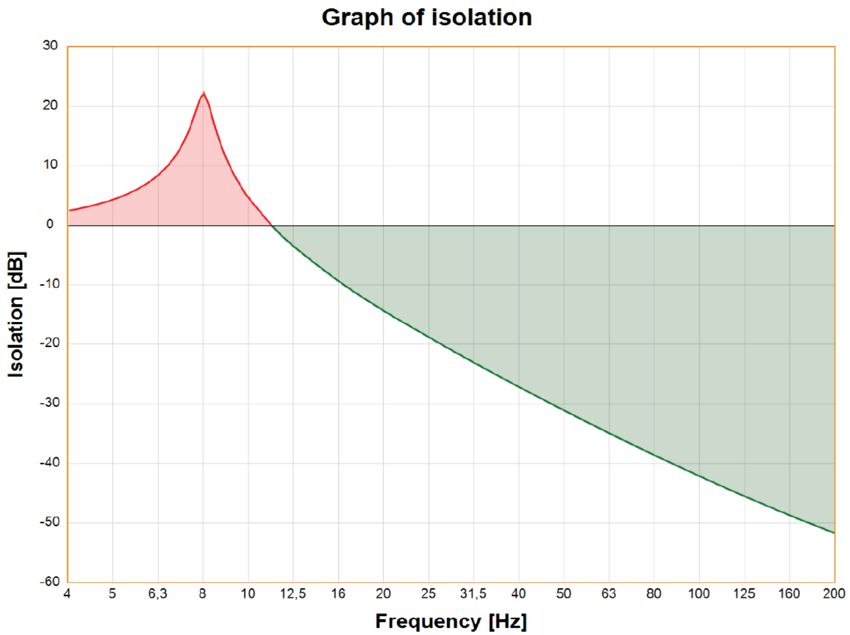


Dimensioning in practice

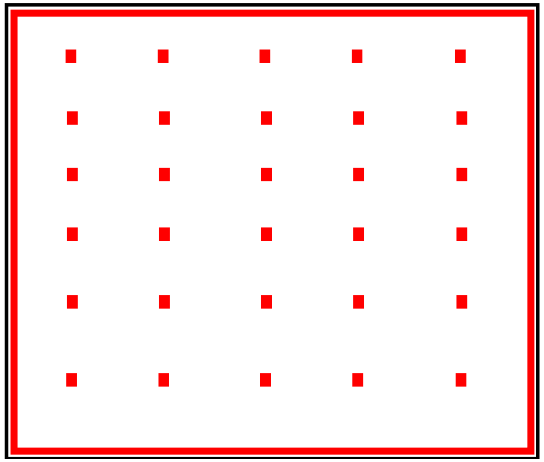
http://www.getzner.com/en/user-area/freqcalc/

Dimensioning of new reverberation rooms in Turku

- Floor, walls and ceiling are made of 160 mm steel-reinforced concrete
- Walls are installed on the edges of the floor and ceiling over the walls
- Sylodyn ND 50 mm is used under the floor to isolate structure-borne noise from the building body to reach low background noise
- **Strip** of width 100 mm on the edges of the room (2700 kg/m load)
- Several pads of 85x85 mm in the middle cc 600 mm (400 kg/m2 load)
  - 27 pieces per 10 m2.
  - distance to the strip is 300 mm.
- Deflection is approximately 4 mm
- System resonance is approximately 8 Hz. That is suitable since the purpose is to eliminate sounds above 18 Hz (20 Hz one-third octave band).



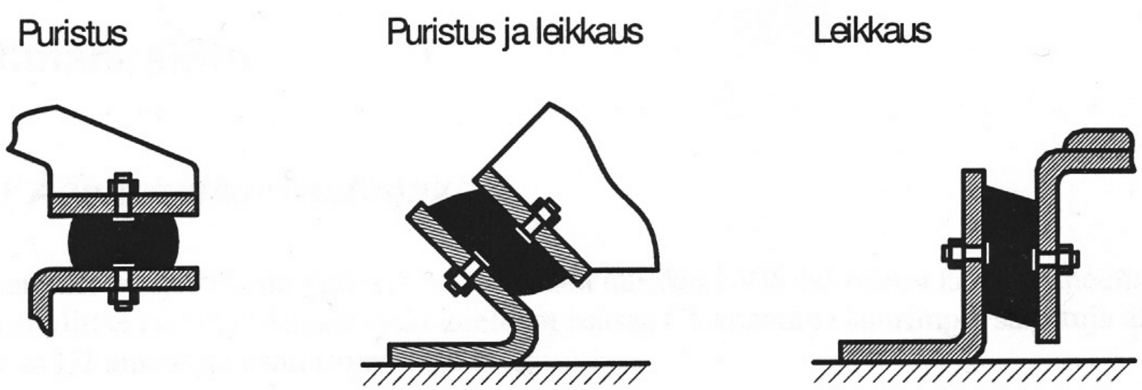
Frequency	Isolation
4 Hz	2,5 dB / -34%
5 Hz	4,3 dB / -65%
6,3 Hz	8,4 dB / -164%
8 Hz	22 dB / -1154%
8 Hz	21,9 dB / -1141%
10 Hz	4,7 dB / -72%
12,5 Hz	-3,3 dB / 31%
16 Hz	-9,6 dB / 67%
20 Hz	-14,4 dB / 81%
25 Hz	-18,7 dB / 88%
31,5 Hz	-23 dB / 93%
40 Hz	-27,3 dB / 96%
50 Hz	-31,1 dB / 97%
63 Hz	-34,9 dB / 98%
80 Hz	-38,7 dB / 99%
100 Hz	-42,1 dB / 99%
125 Hz	-45,4 dB / 99%
160 Hz	-48,8 dB / 100%
200 Hz	-51,7 dB / 100%



Isolator types

Figure: Kylliäinen, 2006

- Elastomeric isolators
  - Lowest resonance 6-20 Hz
  - Easy installation
  - 100 year duration (polyurethan)
  - Sensitive to chemicals
  - Internal damping
- Metal springs
  - Lowest resonance 1.5 Hz
  - Internal damping is low
  - Installation is difficult
  - Everlasting



Dimensioning of vibration isolators

- Determine the lowest frequency, $\boldsymbol{f_s}$, of the stimulus that should be isolated.
  a) Isolators below a source: e.g. the rotation speed of the machine.
  b) Isolators below a room or a house to be protected: the lowest frequency where isolation shall be achieved.
- The mass of the isolated piece
  a) Machine
  b) Room
- System's resonance $\boldsymbol{f_0}$ shall be $0.5 \cdot \boldsymbol{f_s}$ at most
- Determine the maximum deflection Δx by

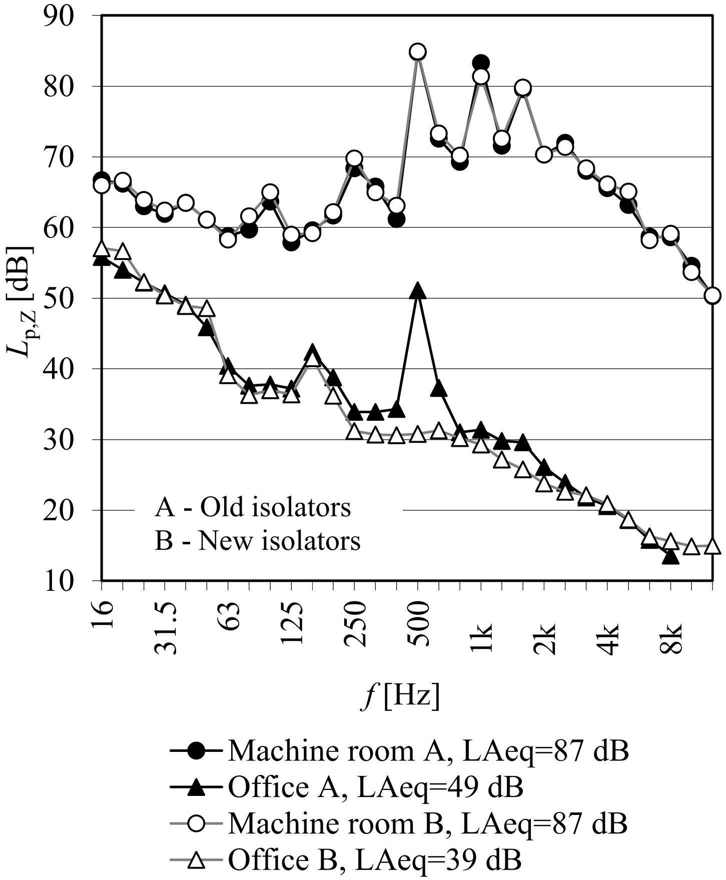
$$\Delta x = \frac{1}{4 f_0^2}$$

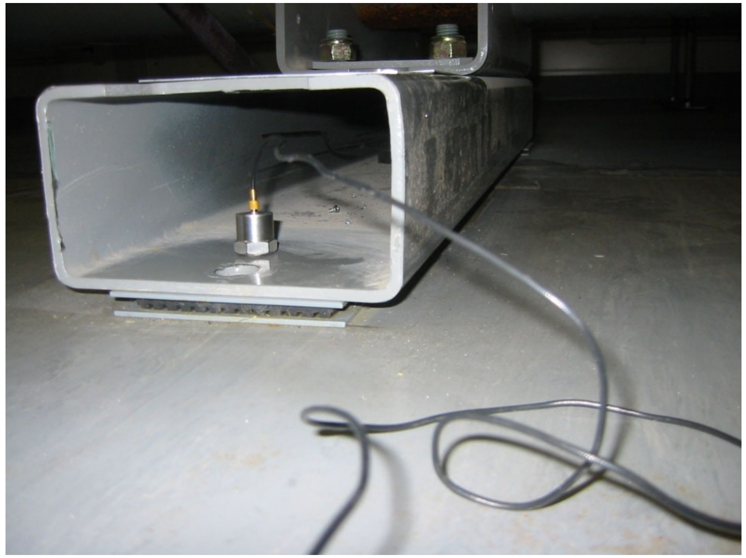
- Consult the isolator supplier who will ask these same questions and suggests alternative solutions.

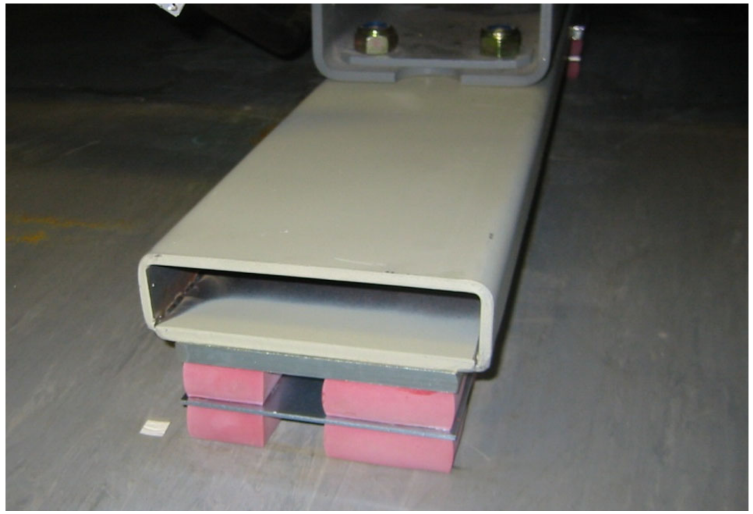
EXAMPLE: Vibration isolation

- Compressor noise could be heard in the office room
- below the machine room
- Isolator below the compressor rail was 1 mm thick: Δx<0.01 mm and f_0>300 Hz
  - Upper figure:
- New isolators were installed which provided sufficiently high Δx and lower f_0
  - Lower figure

$$f_0 = \sqrt{\frac{1}{4\Delta x}}$$







Vibration in buildings

Sources:
- Heavy road traffic, light vehicles in bumpy roads
- Railway
- HVAC

Vibrating components
- Whole building
- Building element
- Rattle due to a vibrating building element

Impacts
- Reduction of residential comfort: sleeping and concentration
- Fear or concern about structural damage and/or reduced real estate value.

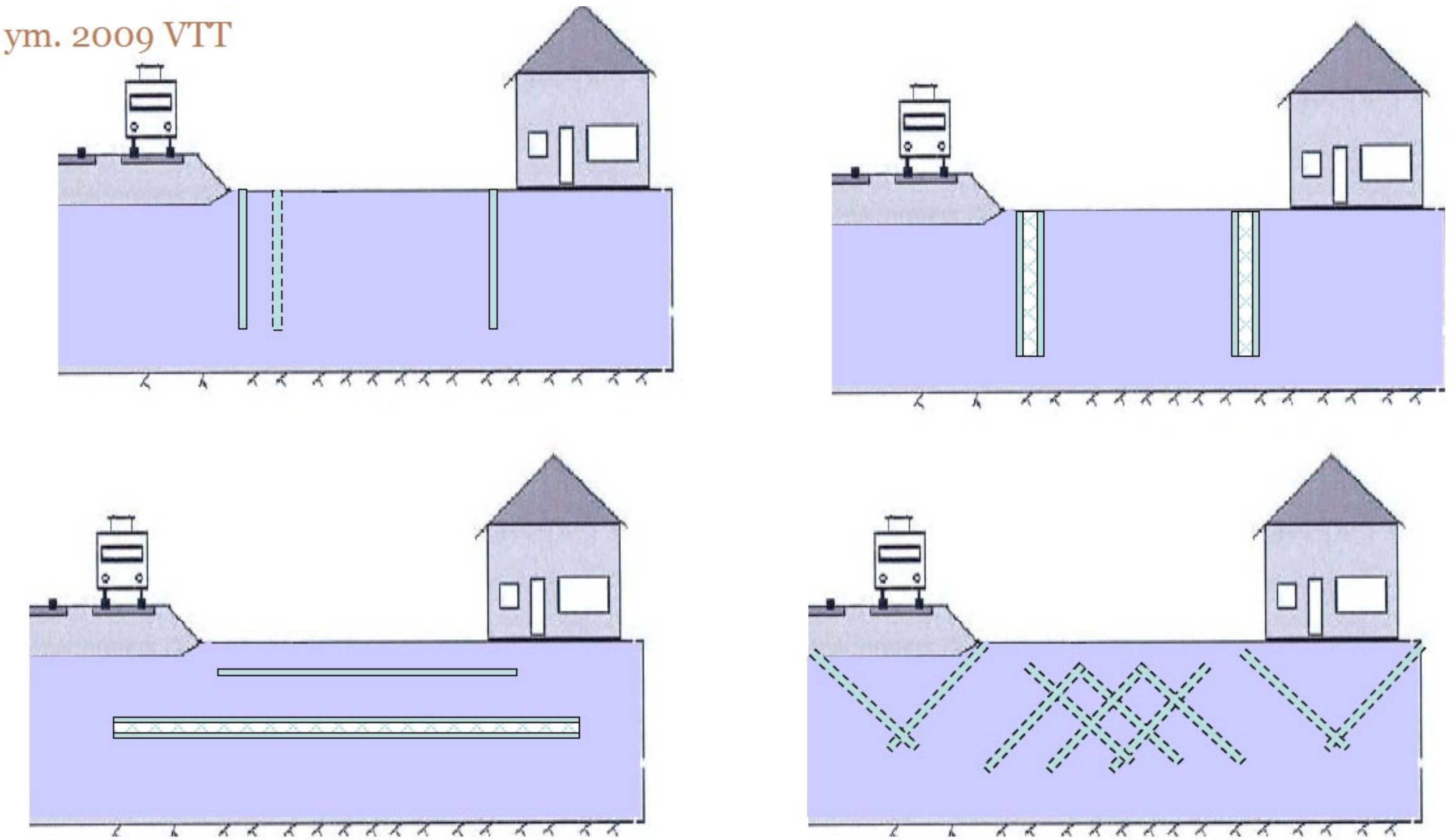
Other
- Changes in residential comfort precede structural damage. The latter is rare.
- Individual differences in vibration sensation and tolerance are large.
- Rattle may increase the concern.

Vibration control of traffic routes

- Maximization of the distance especially in areas of clay
- Smoothness maintenance
- Thick road surface
- Speed limitation
- Freight traffic is directed to routes with less residents
- Reinforcement of building foundations
- Ground barrier between source and exposure
- Vibration isolation of the building
- Vibration isolation of the source, e.g. Länsimetro
- Measurement method (In Finnish):
  - https://www.rakennustieto.fi/Downloads/RK/RK100303.pdf
  - http://www.vtt.fi/inf/pdf/tiedotteet/2004/T2278.pdf
- Example of a measurement (In Finnish: Destia, Tampere, 2014):
  - http://www.tampere.fi/ytoteto/aka/nahtavillaolevat/8430/selvitykset/tarina_runkomeluselvitys.pdf
- Ground barrier (In Finnish: Talja ym. 2009 VTT):
  - http://www.vtt.fi/inf/julkaisut/muut/2009/VTT-R-00963-09.pdf

Ground barriers

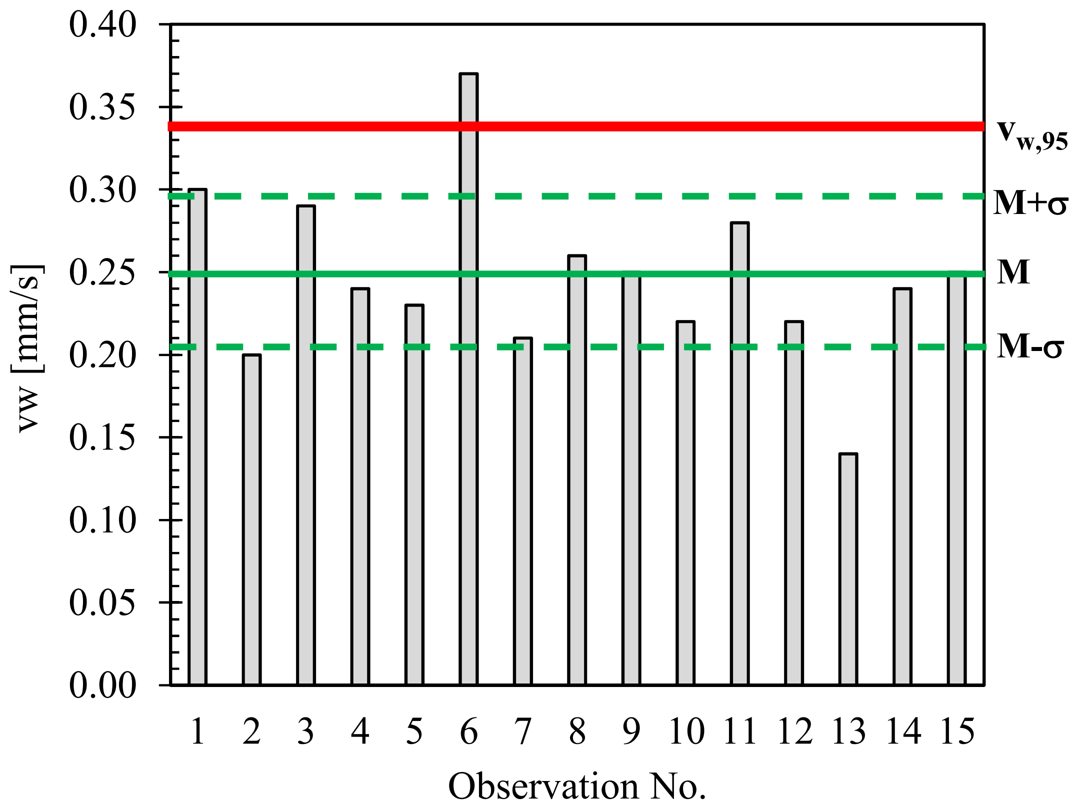
Talja ym. 2009 VTT



Kuva 7. Esimerkkjä eri tavoista muuttaa maaperän värähtelyominaisuuksia.

Measurement of traffic vibration

- The purpose is to determine the largest vibration occurrence
- Measurement in 3 dimensions
- Measurement positions:
  - Residential satisfaction is determined in the upmost floor where the floor span is the largest, or where the complaint is given
  - Constructional damage is measured from the foundations (joint of load bearing structure and foundations)
- NS 8176 recommends a one-week measurement duration during which 15 largest 1-second values are used in the analysis:
  - Mean of RMS values, $\overline{v}_W$ [mm/s] **(N=15)**
  - Standard deviation, **σ**



Talja, VTT, 2004

- **The value to be reported:**

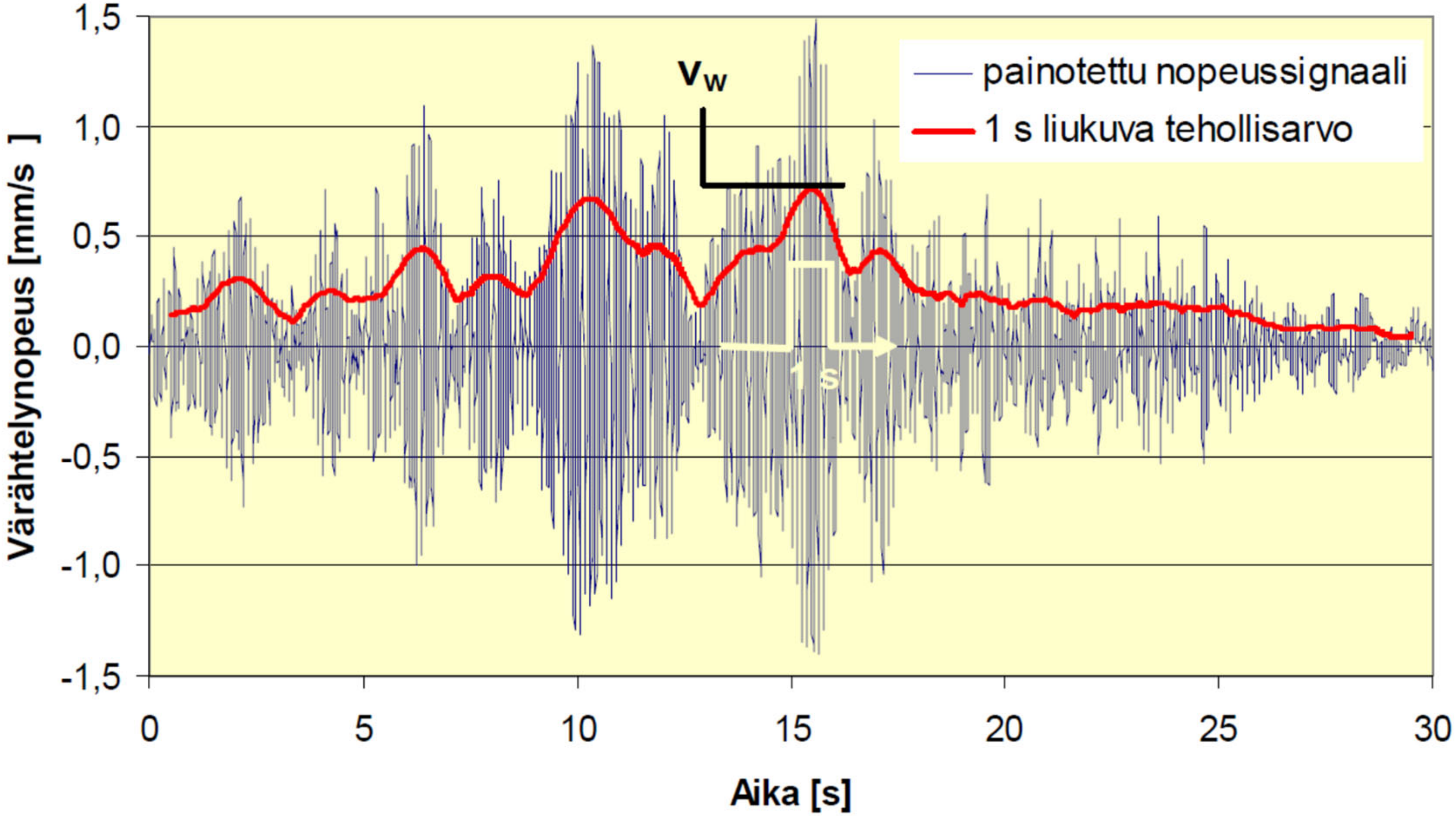
$$v_{w,95} = \overline{v}_w + 1.8 \cdot \sigma$$

Selection of an observation

Talja, VTT, 2004

- Frequency-weighted signal is considered in all three directions in 1-second periods.
- RMS value is calculated
- The largest 1-s-long RMS value is chosen

$$\tilde{v}_W$$



Kuva 7. Suurimman tehollisarvon v_w määrittäminen painotetusta nopeussignaalista.

Frequency weighting

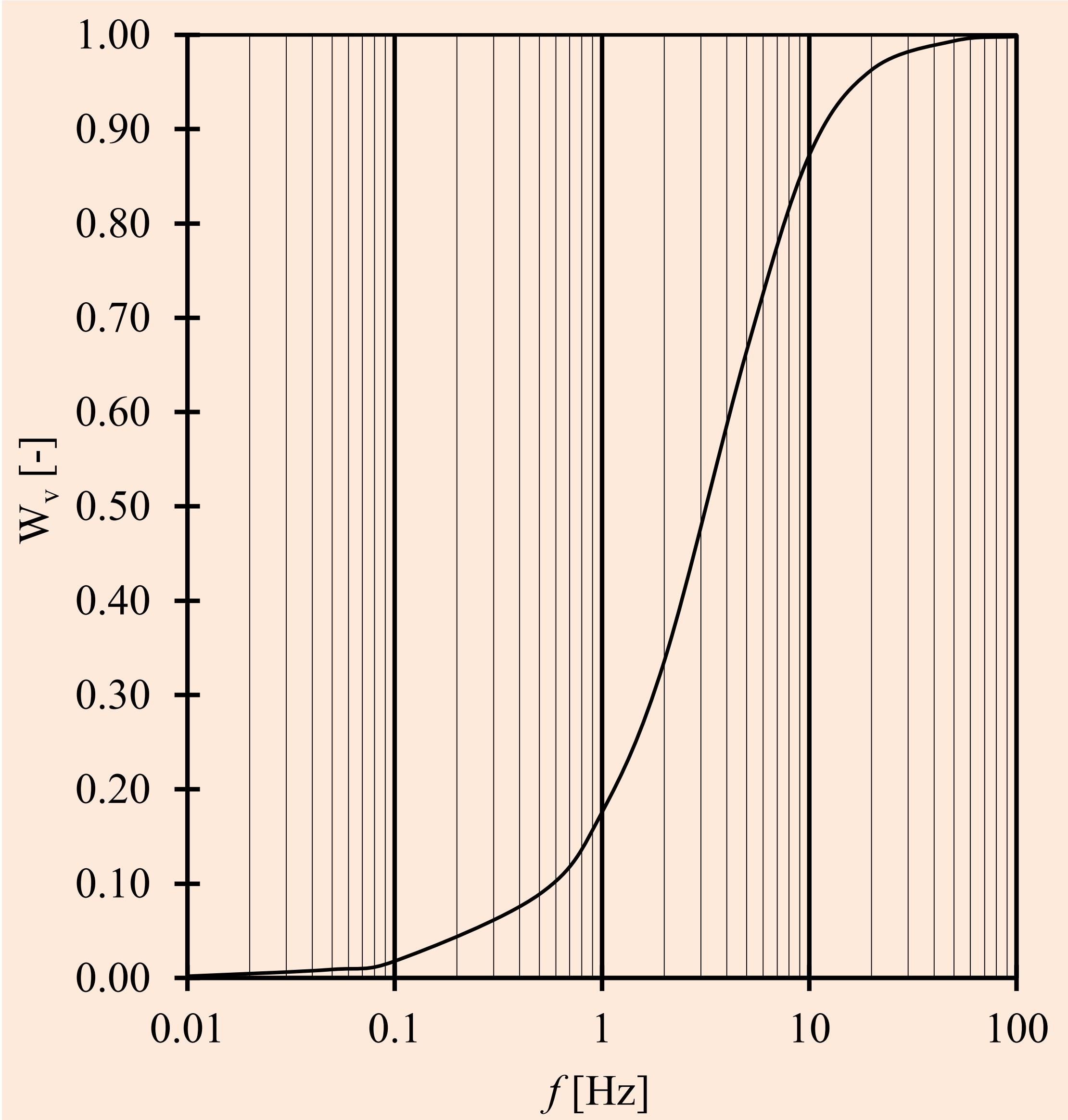
- If the analysis is made in **frequency domain** (spectrum), the largest one-second-long RMS value is obtained by summing up the weighted third-octave bands:
  - $W_{v,i}v_i$ is the weighted RMS of band i

$$\tilde{v}_W = \sqrt{\sum_i \left(W_{v,i} v_i\right)^2}$$

- Frequency-dependent weighting is made to the signal so that the result conforms with perception
- For velocity, v, weighting is

$$W_v(f) = \frac{1}{\sqrt{1 + \left(\frac{f_0}{f}\right)^2}}$$

  - where f_0=5.6 Hz.



NS 8176 recommendation for classification

- $v_{W,95}$ corresponds to the statistical maximum value during one week
  - Only 5% of observations may exceed this value.
- Recommendation concerns both day and night time

Class	Description	$v_{w,95}$ [mm/s]
A	**Very good conditions.** Vibration is seldom perceived.	**≤0.10**
B	**Good conditions.** Vibration is occasionally perceived but the levels are not annoying.	**≤0.15**
C	**Satisfactory conditions.** Approximately 15% of population perceives annoyance.	**≤0.3**
D	**Tolerable conditions.** Approximately 25% of population perceives annoyance.	**≤0.60**

$$v_{w,95} = \bar{v}_w + 1.8 \cdot \sigma$$

Talja, VTT, 2004