Floor vibrations in Practice and Research

Classification of human induced floor vibrations

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Floor Vibrations

Floors are the interface between people and the buildings they use

Floors are the only type of structural sub-system that users of buildings cannot avoid having physical contact with

Requirements set on floors:
Vibration performance,
Acoustic performance,
Static stiffness,
Safety for collapse,
Fire safety,
Visual and economic performance.
Useful distinctions:

**Springiness** is associated with the sensation of self-generated floor deflection and vibration from a single footstep during the time of contact between the foot and floor surface.

**Vibrational disturbances** are caused by footfalls on a floor that are associated with motion induced by persons other than the observer.

Sven Ohlsson (1988)
Floor types

1. Low frequency floors
   natural frequency < 8 Hz, span normally over 10 m
   Weight over 300 kg/m²

2. High frequency floors
   natural frequency > 8 Hz, weight less than 300 kg/m²

3. Floating floors
   - These may increase local deformations
   + These may distribute point loads to several floor beams
Floor natural frequency [Hz]

\[ f_0 = \frac{\pi}{2l^2} \sqrt{\frac{(EI)_l}{m}} \]

2 support, one way action

\[ f_0 = \frac{\pi}{2l^2} \sqrt{\frac{(EI)_l}{m}} \cdot \sqrt{1 + \left[ 2 \left( \frac{l}{b} \right)^2 + \left( \frac{l}{b} \right)^4 \right] \frac{(EI)_b}{(EI)_l}} \]

4 supports, two way action

Two supporting beam structures together

\[ f_0 = \frac{1}{\sqrt{\frac{1}{f_{0,l}^2} + \frac{1}{f_{0,L}^2}}} \]
7.3.3 Residential floors

(1) For residential floors with a fundamental frequency less than 8 Hz \(f_1 \leq 8\) Hz a special investigation should be made.

(2) For residential floors with a fundamental frequency greater than 8 Hz \(f_1 > 8\) Hz the following requirements should be satisfied:

\[
\frac{u}{F} \leq a \text{ mm/kN} \tag{7.3}
\]

and

\[
v \leq b^{(f_1 \zeta^{-1})} \text{ m/(Ns²)} \tag{7.4}
\]

where:

- \(u\) is the maximum vertical deflection caused by a vertical concentrated static force \(F\) applied at any point on the floor, taking account of load distribution, where \(k_{act} = 0.0\);
- \(v\) is the unit impulse velocity response, i.e. the maximum initial value of the vertical floor vibration velocity (in m/s) caused by an ideal unit impulse (1 Ns) applied at the point of the floor giving maximum response. Components above 40 Hz may be disregarded;
- \(\zeta\) is the modal damping ratio.

NOTE: The recommended range of limiting values of \(a\) and \(b\) and the relationship between \(a\) and \(b\) is given in Figure 7.2. Information on National choice may be found in the National annex.
\[ f_1 = \frac{\pi}{2 \ell^2} \sqrt{\frac{(EI)_e}{m}} \]  

(7.5)

where:

- \( m \) is the mass per unit area in kg/m²;
- \( \ell \) is the floor span, in m;
- \( (EI)_e \) is the equivalent plate bending stiffness of the floor about an axis perpendicular to the beam direction, in Nm²/m.

(5) The value \( \nu \) may, as an approximation, be taken as:

\[ \nu = \frac{1}{m b \ell + 200} \]  

(7.6)

where:

- \( \nu \) is the unit impulse velocity response, in m/(Ns²);
- \( n_{40} \) is the number of first-order modes with natural frequencies up to 40 Hz;
- \( b \) is the floor width, in m;
- \( m \) is the mass, in kg/m²;
- \( \ell \) is the floor span, in m.

The value of \( n_{40} \) may be calculated from:

\[ n_{40} = \left( \left( \frac{40}{f_1} \right)^3 - 1 \right) \left( \frac{b}{\ell} \right)^4 \left( \frac{(EI)_e}{(EI)_{b}} \right)^{0.25} \]  

(7.7)

where \( (EI)_b \) is the equivalent plate bending stiffness of the floor about an axis parallel to the beams, where \( (EI)_{b} < (EI)_e \).
Walking force

<table>
<thead>
<tr>
<th></th>
<th>F [Hz]</th>
<th>V [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slow walk</td>
<td>1.7</td>
<td>1.1</td>
</tr>
<tr>
<td>Normal walk</td>
<td>2.0</td>
<td>1.5</td>
</tr>
<tr>
<td>Slow run</td>
<td>2.5</td>
<td>3.3</td>
</tr>
</tbody>
</table>
\[ F(t) = Q \left[ 1 + \sum_{n=1}^{\infty} \alpha_n \sin(2\pi nt + \phi) \right] \]

\[ Q = 765 \text{[N]} \]
\[ n = 1, f = 2 \text{Hz}, \alpha_n = 0.4, \phi = 0 \]
\[ n = 2, f = 4 \text{Hz}, \alpha_n = 0.2, \phi = \frac{\pi}{2} \]
\[ n = 3, f = 6 \text{Hz}, \alpha_n = 0.06, \phi = \frac{\pi}{2} \]

\( F_0 = 200 \text{[N]} \)

\( F(t) \) is the force component at time \( t \), where \( Q \) is the force, \( n \) is the harmonic number, \( f \) is the frequency, and \( \alpha_n \) and \( \phi \) are the amplitude and phase of the \( n \)th harmonic, respectively.
Vibration on floors

- Low frequency, $f < 9$ Hz
  - weight over 300 kg/m²
  - Span usually over 10 m

- High frequency floors, $f > 9$ Hz
  - weight below 300 kg/m²
  - Span usually below 10 m

- Resonance vibrations

- Shocks induced on floors

- Limitation on acceleration of vibrations

- Limitation on the static deflection (velocity response of a unit impulse)

According to Eurocode 5: $f_0 > 8$ Hz
Resonance vibration

Deformation (dynamic/static)

\[ M \ddot{x} + C \dot{x} + K x = F_0 \cos \omega t \]

Frequency ratio (Load frequency/ natural frequency of the floor)
Laastason reunat vapaat

![Graph showing step frequency and acceleration](image)
Heel impact (walking) $a_o$

Continuous vibration $a_o$ (average peak accel.)

Walking vibration (12% damping)

Walking vibration (6% damping)

Walking vibration (3% damping)

Continuous vibration (10 to 30 cycles)

Frequency of Motion (Hz)

Peak acceleration $a_o$ (% g)
Table 1. The vibration classification of floors based on the intensity of the vibration.

<table>
<thead>
<tr>
<th>Body perception</th>
<th>Vibration of articles</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>The vibrations are usually imperceptible.</td>
</tr>
<tr>
<td></td>
<td>1 The clinking of glassware and the leaf movements of a plant are usually imperceptible.</td>
</tr>
<tr>
<td>B</td>
<td>The vibrations are barely perceptible.</td>
</tr>
<tr>
<td></td>
<td>2 The clinking of glassware is usually imperceptible and the leaf movements are barely perceptible.</td>
</tr>
<tr>
<td>C</td>
<td>The vibrations are perceptible. Base class</td>
</tr>
<tr>
<td></td>
<td>3 The clinking of glassware is barely perceptible. The leaf movements perceptible</td>
</tr>
<tr>
<td>D</td>
<td>The vibrations are clearly perceptible.</td>
</tr>
<tr>
<td></td>
<td>4 The clinking of glassware the leaf movements are clearly perceptible.</td>
</tr>
<tr>
<td>E</td>
<td>The vibrations are strongly perceptible.</td>
</tr>
<tr>
<td></td>
<td>5 The clinking of glassware and the leaf movements of a plant are strongly perceptible</td>
</tr>
</tbody>
</table>
Table 2. Proposal for vibration classes in office and residential buildings.

<table>
<thead>
<tr>
<th>Class</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>Normal class for vibrations transferred from another apartment. Special class for vibrations inside one apartment.</td>
</tr>
<tr>
<td>B2</td>
<td>Lower class for vibrations transferred from another apartment. Higher class for vibrations inside one apartment</td>
</tr>
<tr>
<td>C3, base class</td>
<td>Normal class for vibrations inside one apartment.</td>
</tr>
<tr>
<td>D4</td>
<td>Lower class for vibrations inside one apartment. For example attics and holiday cottages.</td>
</tr>
<tr>
<td>E5</td>
<td>Class without restrictions.</td>
</tr>
</tbody>
</table>
Table 3. Tentative acceptance limits for vibration classes.

| Class | $a_{rms}^{2)}$ [m/s²] | $v_{max}^{2)}$ [mm/s] | $v_{rms}^{2)}$ [mm/s] | $|u_{max}|^{2)}$ [mm] | $\delta_0^{1)}$ [mm/kN] | $\delta_1^{1)}$ [mm/kN] |
|-------|-------------------------|------------------------|------------------------|-------------------------|------------------------|------------------------|
| A     | $\leq 0.03$             | $\leq 4$               | $\leq 0.3$             | $\leq 0.05$             | $\leq 0.12$            | $\leq 0.1$             |
| B     | $\leq 0.05$             | $\leq 6$               | $\leq 0.6$             | $\leq 0.1$              | $\leq 0.25$            | $\leq 0.2$             |
| C     | $\leq 0.075$            | $\leq 8$               | $\leq 1.0$             | $\leq 0.2$              | $\leq 0.5$             | $\leq 0.5$             |
| D     | $\leq 0.12$             | $\leq 10$              | $\leq 1.5$             | $\leq 0.4$              | $\leq 1.0$             | $\leq 1.0$             |
| E     | $> 0.12$                | $> 10$                 | $> 1.5$                | $> 0.4$                 | $> 1.0$                | $> 1.0$                |

1) Design criteria (load: 1 kN for u and w) to be used in design,
2) Dynamic test criteria (load: walking person) to be used in testing
Local deflection

\[ F \quad \delta_1 \]

\[ \begin{align*}
300 & \quad 300 \\
\end{align*} \]

\[ F \quad \delta_1 \]

\[ \begin{align*}
600 & \\
\end{align*} \]
Base class C3

\[ \delta + w < 1.0 \text{ mm} \]
\[ \delta < 0.5 \text{ mm} \]

Deflection due to 1 kN [mm]

Fundamental frequency [Hz]
Fundamental frequency [Hz] vs. $a_{w\text{-rms}}$ [m/s$^2$]

- **Base class C3**
- □ accepted
- × not accepted

The graph shows the relationship between the fundamental frequency and the root-mean-square acceleration ($a_{w\text{-rms}}$) for different levels of acceleration. The data points are categorized into accepted and not accepted based on the specified levels.
Fundamental frequency [Hz] vs. $u_{\text{max}}$ (mm)

- **Accepted** (squares)
- **Not accepted** (crosses)

**Base class C3**

- $u_{\text{max}}$ threshold: 0.20 mm
- Fundamental frequency range: 0 to 30 Hz

[Graph showing the relationship between fundamental frequency and maximum displacement for accepted and not accepted samples, with a threshold line at 0.20 mm]
Vibration transfer to the neighboring apartment

| Measurement                      | Source of vibration | $|u_{max}|$ | $v_{rms}$ | $a_{rms}$ | Rate of transfer to the neighboring apartment |
|----------------------------------|---------------------|--------|----------|----------|----------------------------------------------|
|                                  |                     | mm     | mm/s     | m/s²     |                                              |
| **Floor a) Fully cut**           |                     |        |          |          |                                              |
| In the same room                 | Walking             | 0,025  | 0,32     | 0,037    |                                              |
| Vibration to neighbor            | Walking             | 0,010  | 0,044    | 0,0047   | 13 %                                         |
| In the same room                 | Washing             | 0,0080 | 0,14     | 0,016    |                                              |
| Vibration to neighbor            | Washing             | 0,0078 | 0,039    | 0,0040   | 25 %                                         |
| **Floor b) Continous**           |                     |        |          |          |                                              |
| In the same room                 | Walking             | 0,018  | 0,176    | 0,020    |                                              |
| Vibration to neighbor            | Walking             | 0,0059 | 0,060    | 0,0053   | 26 %                                         |
| In the same room                 | Washing             | 0,016  | 0,12     | 0,011    |                                              |
| Vibration to neighbor            | Washing             | 0,011  | 0,065    | 0,0071   | 64 %                                         |
Conclusions on floor vibration classification

• A classification of floor quality is proposed based on vibration properties
• Benefits: consumers know what they are buying and producers what they are selling
• Different quality levels are possible:
  - high quality apartments, B
  - normal apartments, C
  - single houses, D
  - summer houses D or E
• The limit values may need adjustments as more experience is gained.
Conclusions on vibration performance of timber floors

- Dynamic performance of floors is a complex issue: a contribution of a) excitation, b) response, c) acceptability
- Design procedures are limited
- Avoidance of resonance is a prime issue
- To increase the vibration performance increase stiffness in 2-directions (increase acoustic insulation increase ’softness’)
- Timber-concrete composite floors have performed well based on experimental experience
- Vibration of floors is a common complaint of the occupant
Vibration serviceability of timber floors is a complex and important issue, but has largely been ignored.

Care must be exercised to define the dynamic system.

Modern construction materials and methods can exacerbate vibration problems

improved strength efficiency can mean lessened serviceability.

Problem floors cannot be avoided reliably using existing (simplistic) design ‘rules’

is no international agreement as yet about how to handle the issue in design codes