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Acoustics (VTAN01) – Vibrations in buildings

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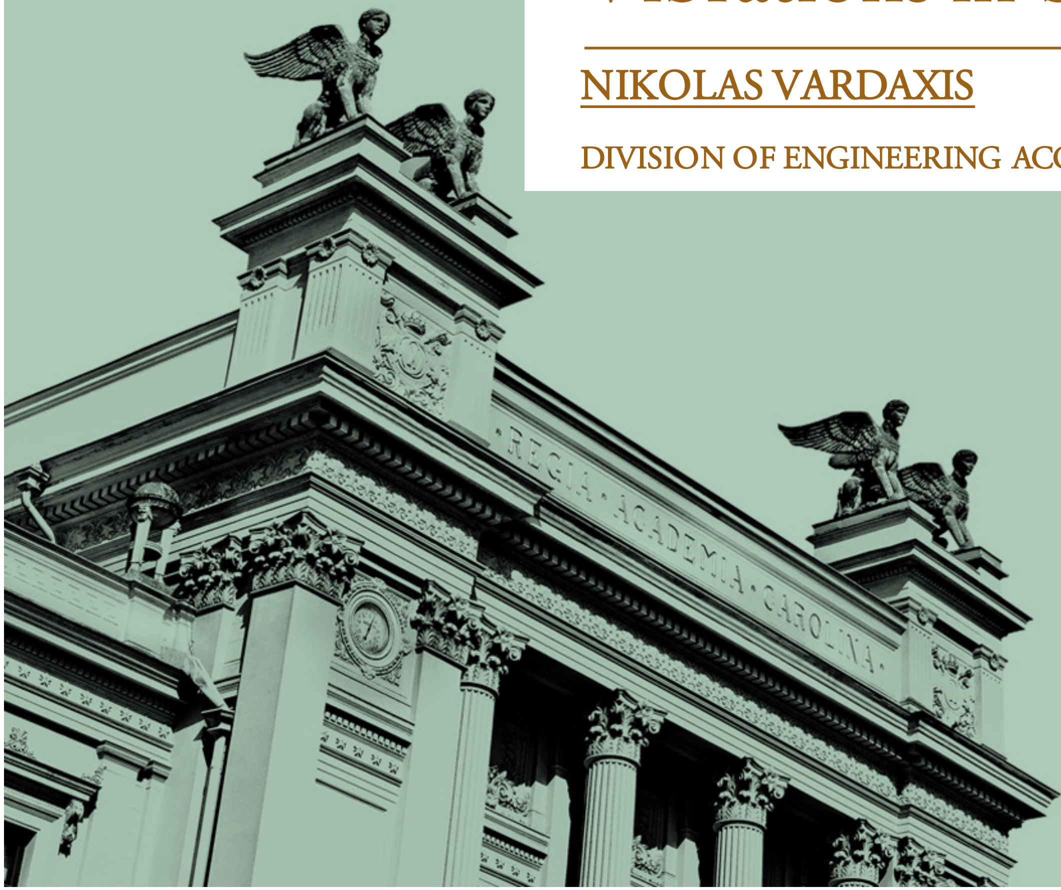


Outline

Introduction

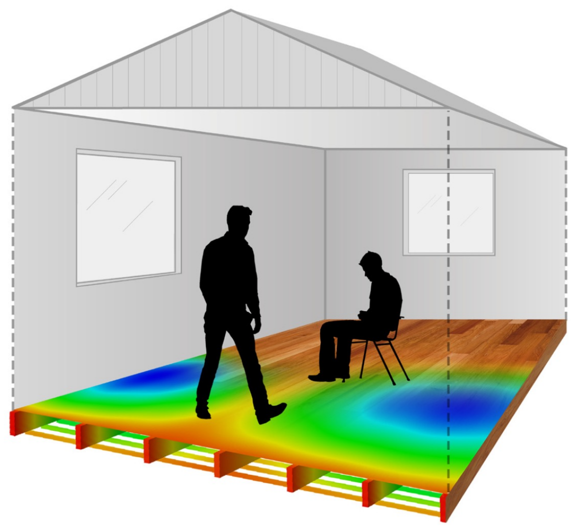
Structural Dynamics (SDOF / MDOF)

Floor Vibrations

Summary

Introduction (I)

- A very broad definition…
  - Acoustics: *what can be heard…*
  - Vibrations: *what can be felt… (below 20 Hz)*
- Hard to distinguih between both domains
- Consequences of floor vibrations:
  - Nuisance to building users
    - » Risk of health problems (during long exposure)
  - Damage to fixtures and fittings
    - » In very extreme cases: damage to building structure



Source: J. Negreira (2016)

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Outline

Introduction

Structural Dynamics (SDOF / MDOF)

Floor Vibrations

Summary

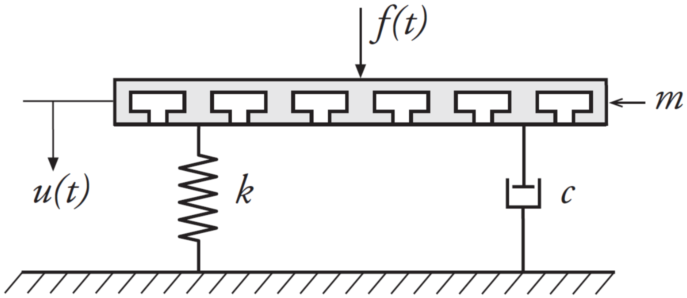
Structural dynamics – Introduction

- Types of systems
  - Discrete: finite number of DOFs needed
    - » System of ordinary differential equations
    - » Depending on the number of DOFs:
      - SDOF
      - MDOF
  - Continuous: infinite number of DOFs
    - » System of differential equations with partial derivatives

NOTE: Degrees of freedom (DoF): number of independent displacement components to define exact position of a system
NOTE2: The presented theory assumes linearity

SDOF – Single-degree-of-freedom system

- Mass-spring-damper system (e.g. a floor)



$$m\ddot{u}(t)+c\dot{u}(t)+ku(t)=f(t)$$

Inertial force | Damping force | Elastic force | Applied force

  - *u(t)* obtained by solving the PDE together with the initial conditions
    - Solution = Homogeneous + Particular

$$u(t)=u_p(t)+u_h(t)$$

$f(t)=f_0\cos(\omega t)$ | $f(t)=0$

<u>NOTE:</u> Damping is the energy dissipation of a vibrating system

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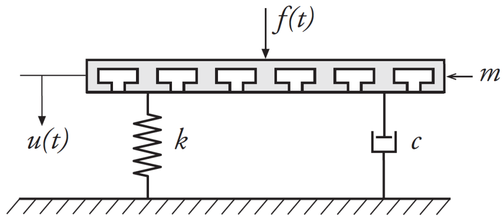
SDOF solutions

- Solution of undamped SDOF (c=0): $m\ddot{u}(t) + ku(t) = f(t)$

$$u(t) = \frac{f_0/k}{1-\left(\frac{\omega}{\omega_n}\right)^2}\cos(\omega t) + A_1\cos(\omega_n t) + B_1\sin(\omega_n t)$$

Particular solution

Homogeneous solution



$$\omega_n = \sqrt{k/m}$$

Natural frequency

- Solution of damped SDOF (c≠0): $m\ddot{u}(t) + c\dot{u}(t) + ku(t) = f(t)$

$$u(t) = \frac{(f_0/k)\cos(\omega t - \alpha)}{\sqrt{(1-\beta^2)^2 + (2\zeta\beta)^2}} + e^{-\zeta\omega_n t}\left[A_2\cos(\omega_D t) + B_2\sin(\omega_D t)\right]$$

Particular solution

Homogeneous solution

$$\beta = \omega/\omega_n$$

$$\alpha(\omega) = \tan^{-1}\left(\frac{2\zeta\beta}{1-\beta^2}\right)$$

$$\zeta = \frac{c}{c_{cr}} = \frac{c}{2m\omega_n}$$

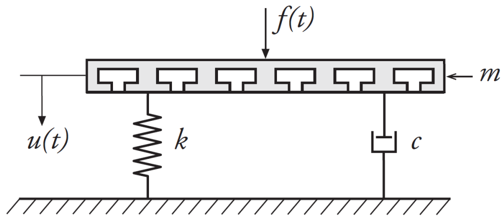
$$\omega_D = \omega_n\sqrt{1-\zeta^2}$$

NOTE: A_1 and A_2 calculated from the initial conditions

SDOF solutions

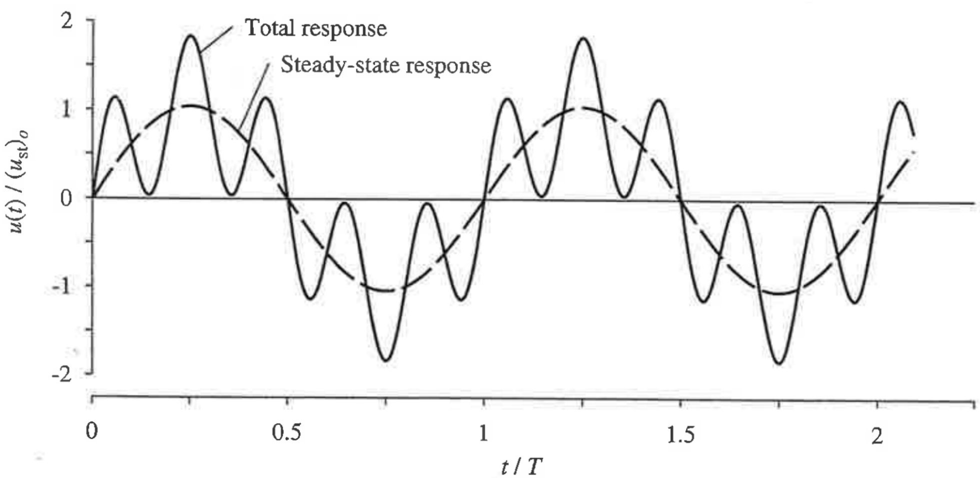
- Solution of undamped SDOF (c=0): $m\ddot{u}(t) + ku(t) = f(t)$

$$u(t) = \underbrace{\frac{f_0/k}{1-\left(\frac{\omega}{\omega_n}\right)^2}\cos(\omega t)}_{\text{Particular solution}} + \underbrace{A_1\cos(\omega_n t) + B_1\sin(\omega_n t)}_{\text{Homogeneous solution}}$$



$$\omega_n = \sqrt{k/m}$$

Natural frequency



NOTE: A_1 and A_2 calculated from the initial conditions

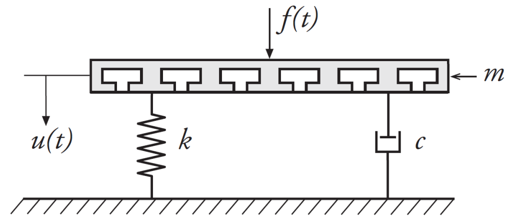
SDOF solutions

- Solution of <u>damped SDOF</u> (c≠0): $m\ddot{u}(t) + c\dot{u}(t) + ku(t) = f(t)$

$$u(t) = \frac{(f_0/k)\cos(\omega t - \alpha)}{\sqrt{(1-\beta^2)^2 + (2\zeta\beta)^2}} + e^{-\zeta\omega_n t}\left[A_2\cos(\omega_D t) + B_2\sin(\omega_D t)\right]$$

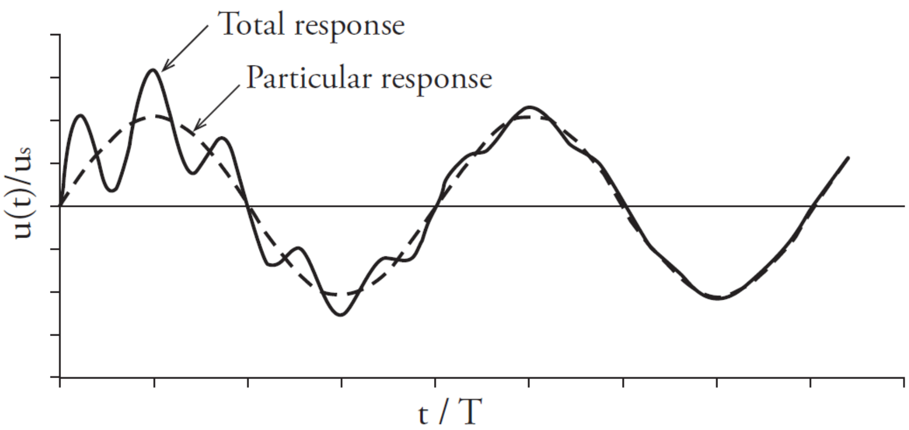
Particular solution

Homogeneous solution



$$\omega_n = \sqrt{k/m}$$

Natural frequency



<u>NOTE:</u> *After some time:* $u(t) \approx u_p(t)$

Total response of a damped system subjected to a harmonic force,

$$\beta = \omega/\omega_n$$

$$\alpha(\omega) = \tan^{-1}\left(\frac{2\zeta\beta}{1-\beta^2}\right)$$

$$\zeta = \frac{c}{c_{cr}} = \frac{c}{2m\omega_n}$$

$$\omega_D = \omega_n\sqrt{1-\zeta^2}$$

<u>NOTE:</u> A_1 and A_2 calculated from the initial conditions

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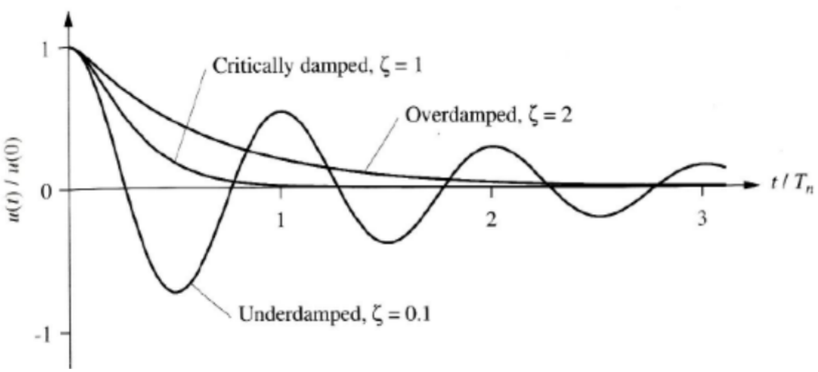
Notes on SDOFs (I)

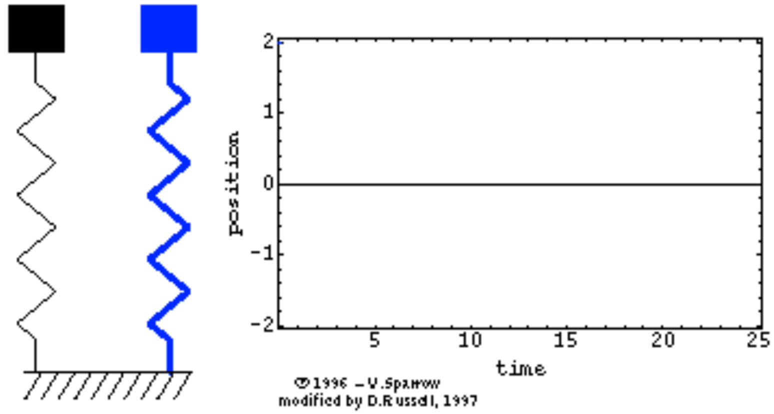
- Eigenfrequency: frequency of oscillation when the system is left to free-vibration (after having set it into movement)
  - Undamped: $\omega_n = \sqrt{k/m}$
  - Damped: $\omega_D = \omega_n \sqrt{1-\zeta^2}$

- Damping ratio [%]: $\zeta = \frac{c}{c_{cr}} = \frac{c}{2m\omega_n}$
  - c_{cr} lowest damping where mass exhibits no oscillation when displaced from equilibrium

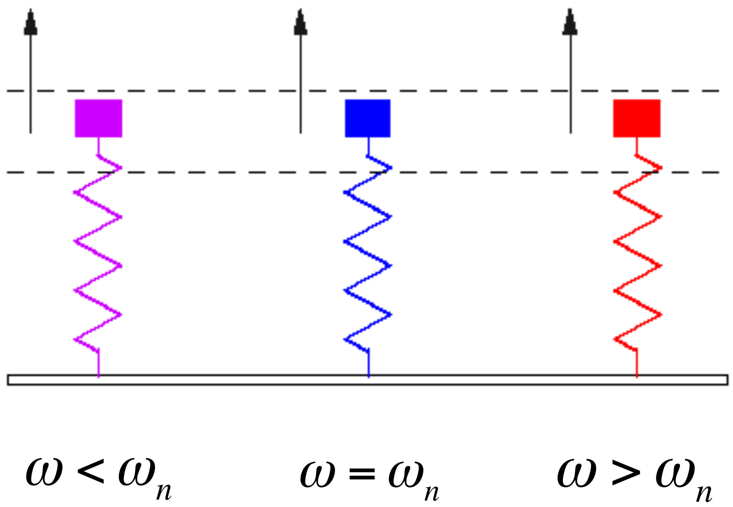


Notes on SDOFs (II)

- Ex:
  - Without damping
  - With damping

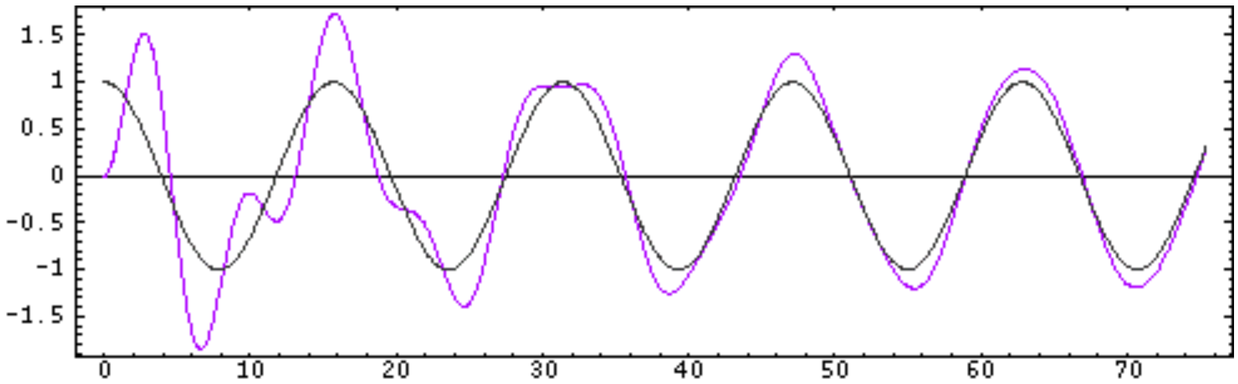


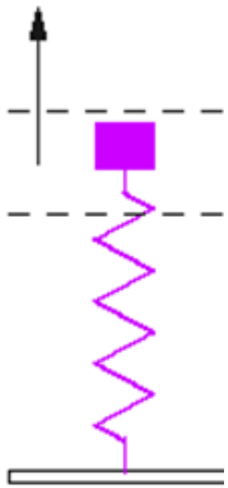
- Different driving freqs



SDOF – Low frequency excitation ($\omega < \omega_n$)

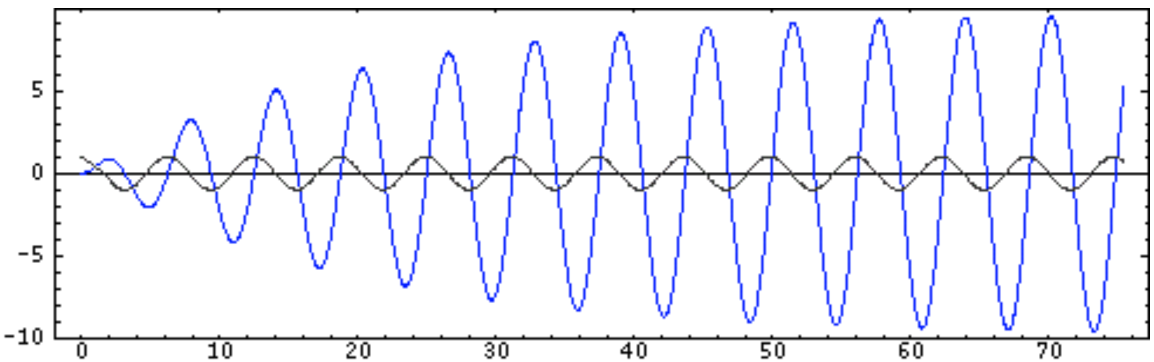
- The spring dominates
  - Force and displacement in phase

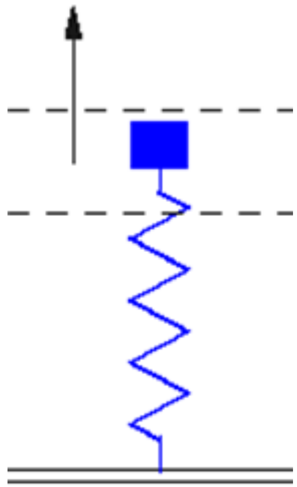




SDOF – Excitation at resonance freq. ($\omega = \omega_n$)

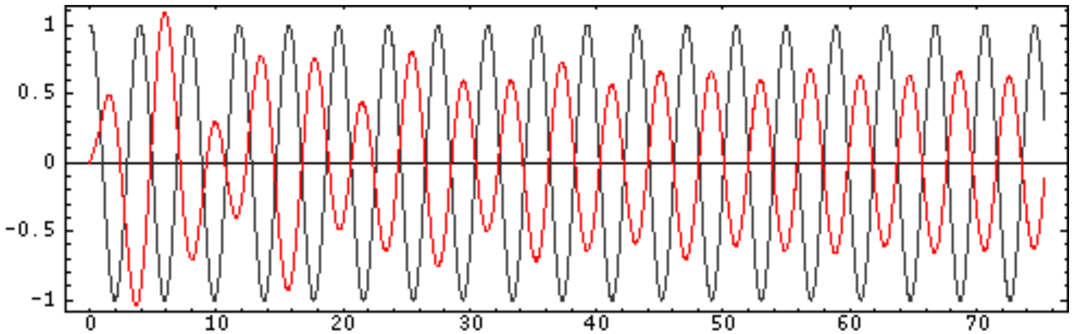
- Damping dominates
  - Phase difference = 90° or π
- If no (or little) damping is present:
  - The system collapses

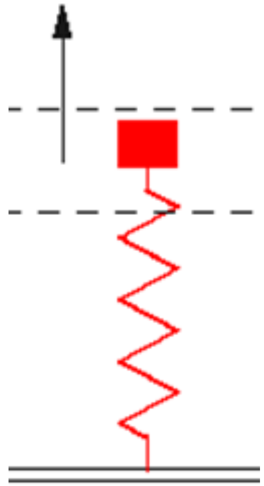




SDOF – High frequency excitation ($\omega > \omega_n$)

- The mass dominates
- Force and displacement in counter phase:
  - Phase difference = 180° or π



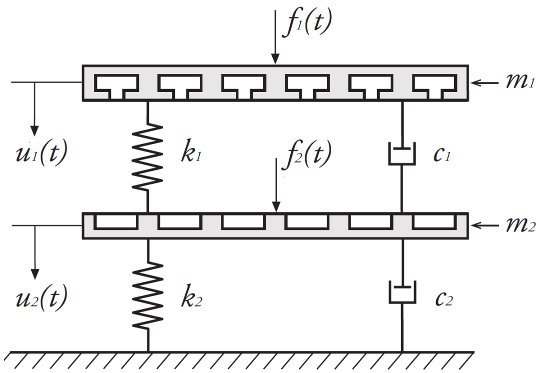


Example: SDOF eigenfrequency and eigenmode.

MDOF – Multi-degree-of-freedom systems

- In reality, more DOFs are needed to define a system → MDOFs
  - Continuous systems → often approximated by MDOFs

- Multi-degree-of-freedom system (Mass-spring-damper)



$$\mathbf{M}\ddot{\mathbf{u}}(t) + \mathbf{C}\dot{\mathbf{u}}(t) + \mathbf{K}\mathbf{u}(t) = \mathbf{f}(t)$$

$$\mathbf{M} \in \mathbb{R}^{n\times n}$$
$$\mathbf{K} \in \mathbb{R}^{n\times n}$$
$$\mathbf{C} \in \mathbb{R}^{n\times n}$$
$$\mathbf{f}(t) \in \mathbb{R}^{n\times 1}$$
$$\mathbf{u}(t) \in \mathbb{R}^{n\times 1}$$

  - Solution process: similar as in SDOFs (particular+homogeneous),
    - » Here just focus (for the sake of simplicity) in the homogeneous solution of the undamped system → natural frequencies and modes of vibrations

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MDOF – Homogeneous solution of the undamped system

$$\mathbf{M}\ddot{\mathbf{u}}(t) + \mathbf{K}\mathbf{u}(t) = \mathbf{0}$$

$$\begin{aligned} \mathbf{u}(0) &= \mathbf{u}_0 \\ \dot{\mathbf{u}}(0) &= \mathbf{v}_0 \end{aligned}$$

The undamped modes form an orthogonal basis, i.e. they uncouple the system, allowing the solution to be expressed as a sum of the eigenmodes of the free-vibration SDOF system

$$\mathbf{u}(t) = \sum_{j=1}^{n} q_j(t)\phi_j$$

$$q_j(t) = A_n \cos(\omega_n t) + B_n \sin(\omega_n t)$$

A_n and B_n are constants of integration determined by the IC

$$\left[-\omega_n^2 \mathbf{M}\phi_j + \mathbf{K}\phi_j\right] q_j(t) = \mathbf{0}$$

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MDOF – Homogeneous solution of the undamped system

- Last equation can be satisfied in two ways:
  - Trivial solution $q_j(t)=0$ (no movement)
  - Through the ω_n and mode shapes satisfying the eigenvalue problem

$$\begin{tikzcd}
 & \left[\mathbf{K} - \omega_n^2 \mathbf{M}\right] \phi_j = 0 \arrow[dl] \arrow[dr] & \\
\left|\mathbf{K} - \omega_n^2 \mathbf{M}\right| = 0 \arrow[r] & \omega_n \arrow[r] & \phi_j
\end{tikzcd}$$

- Structure disturbed from static equilibrium → oscillates freely at ω_n
- Associated to each ω_n there is a mode shape
  - A structure has an unlimited number of ω_n.
    - » If e.g. FEM is used: there are as many ω_n and mode shapes as DOFs

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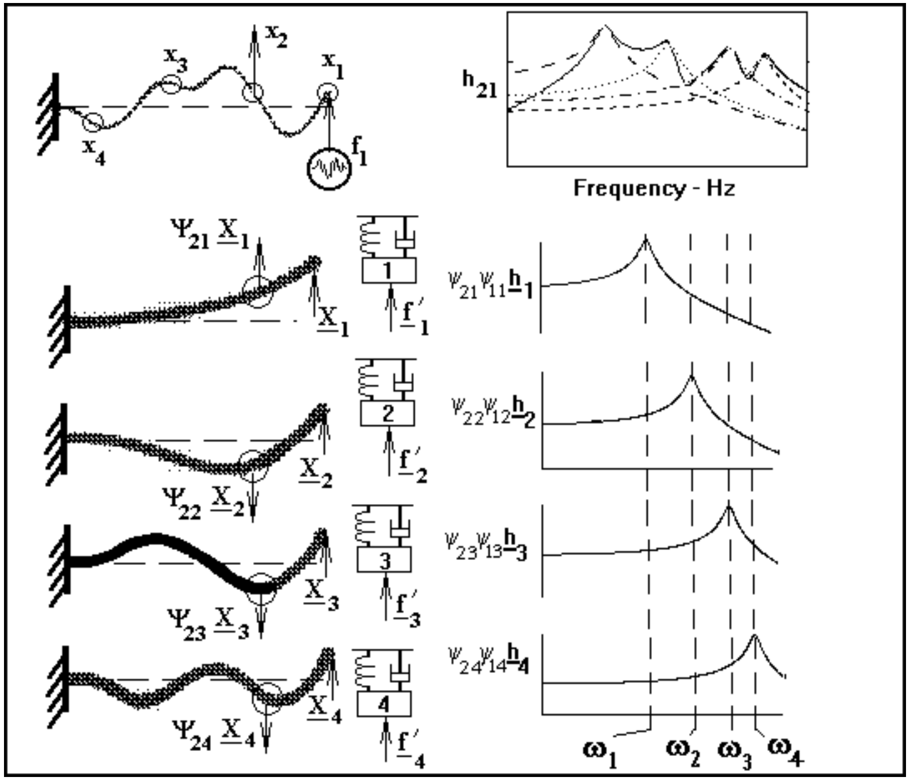
MDOF – Note on modal superposition

- *"The undamped modes form an orthogonal basis, i.e. they uncouple the system, allowing the solution to be expressed as a sum of the eigenmodes of the free-vibration SDOF system"*



Source: http://signalysis.com

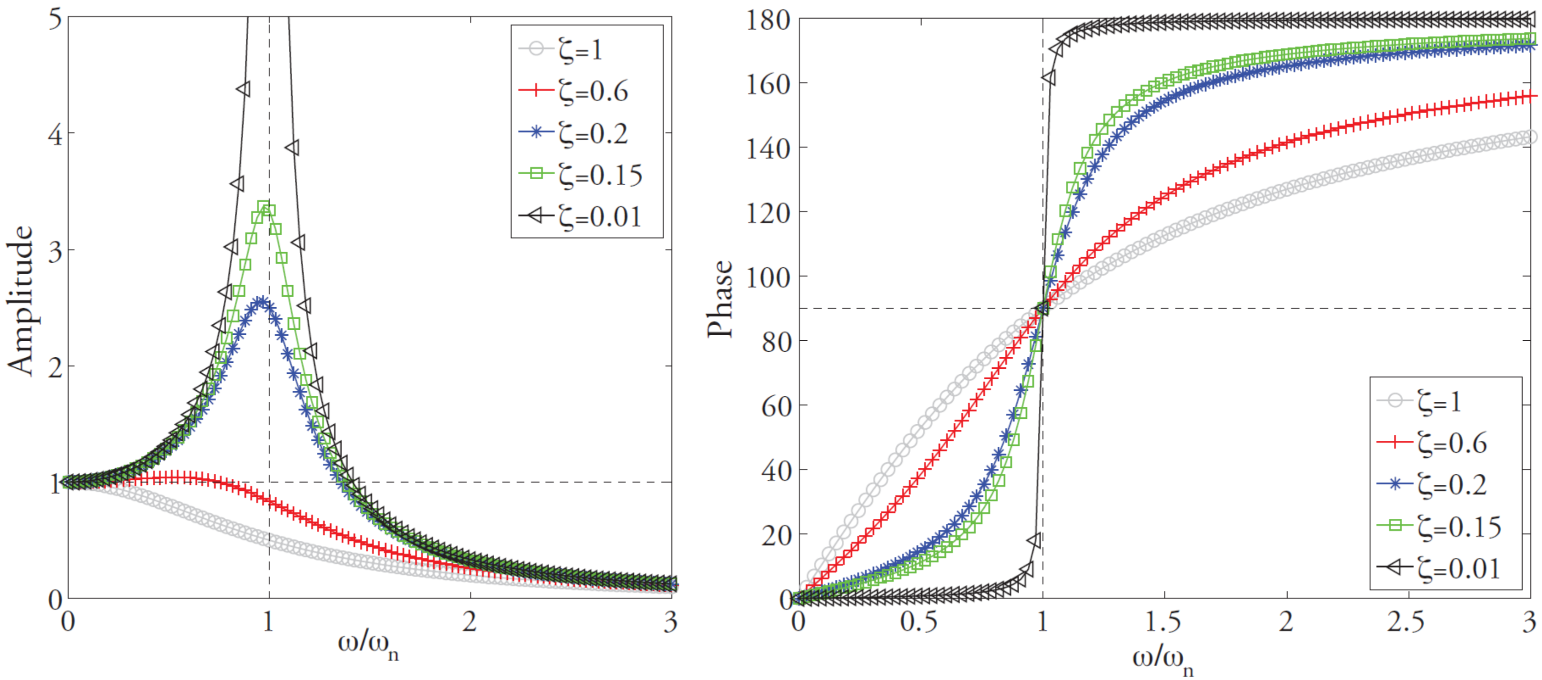
$$\mathbf{u}(t) = \sum_{j=1}^{n} q_j(t)\phi_j$$

$$q_j(t) = A_n \cos(\omega_n t) + B_n \sin(\omega_n t)$$

Resonance & Eigenmodes

Examples:

- Earthquake design
- Bridges
- Modes of vibration: Plate & 2-MDOF



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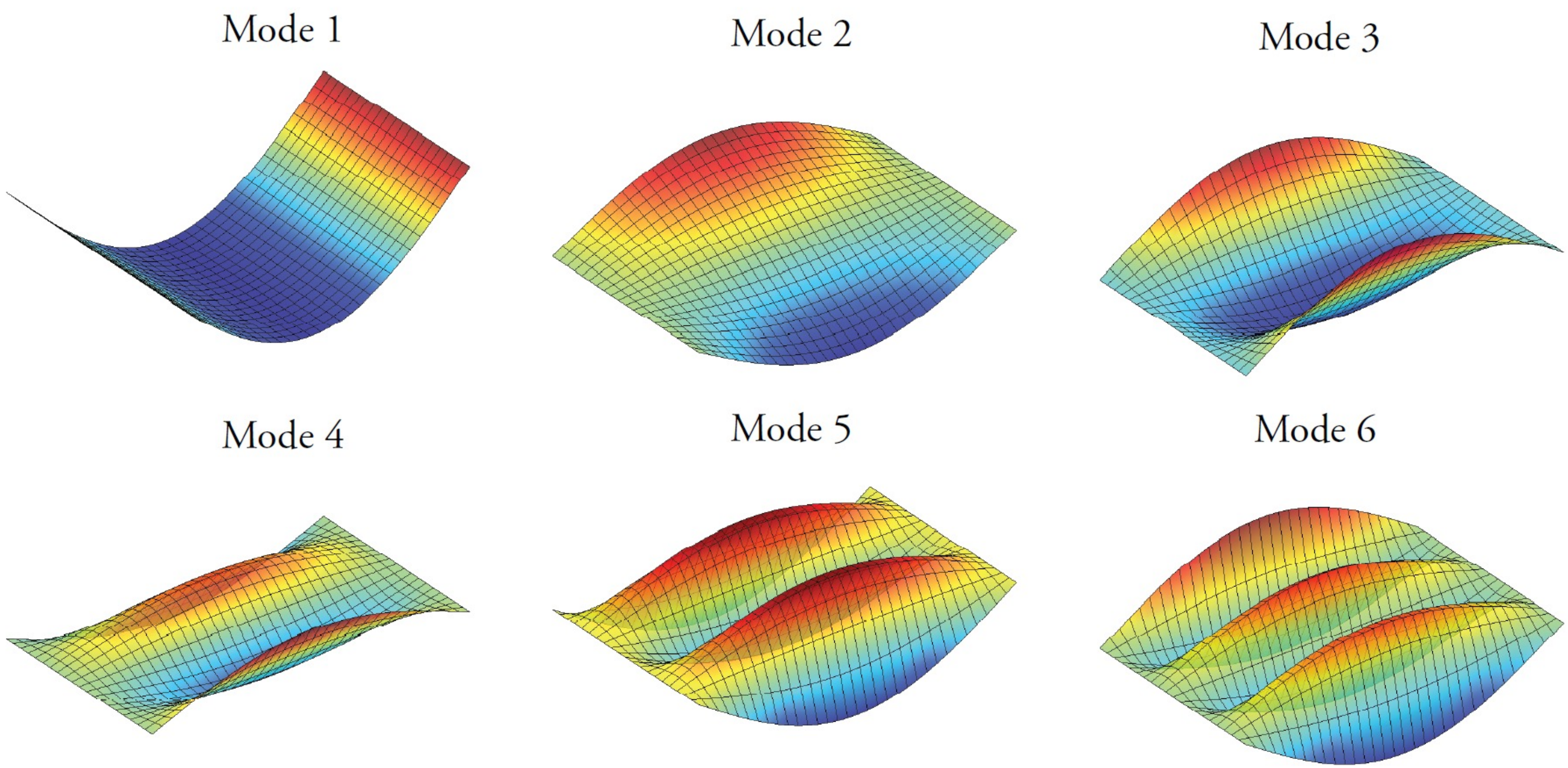
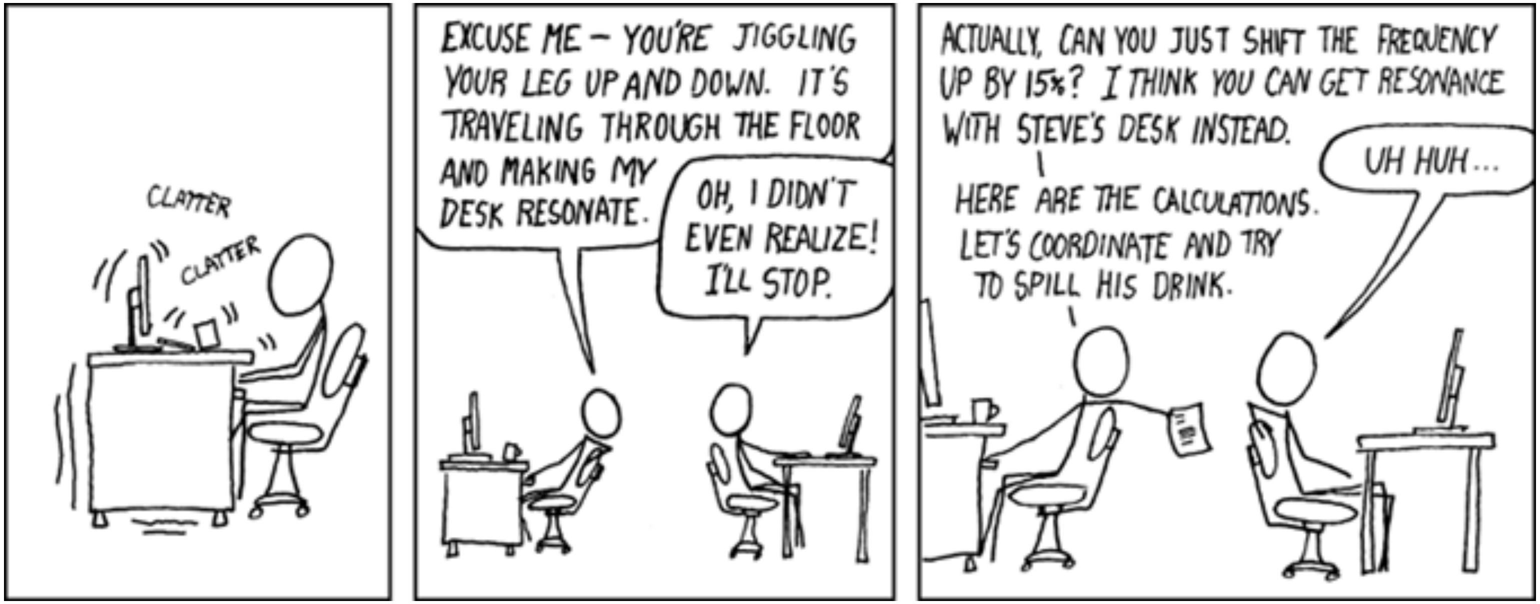
Mode shapes – Example floor



NOTE: In floor vibrations, modes are superimposed on one another to give the overall response of the system. Fortunately it is generally sufficient to consider only the first 3 or 4 modes, since the higher modes are quickly extinguished by damping.

… resonance and modes are indeed "present" daily



Source: steelconstruction.info

Outline

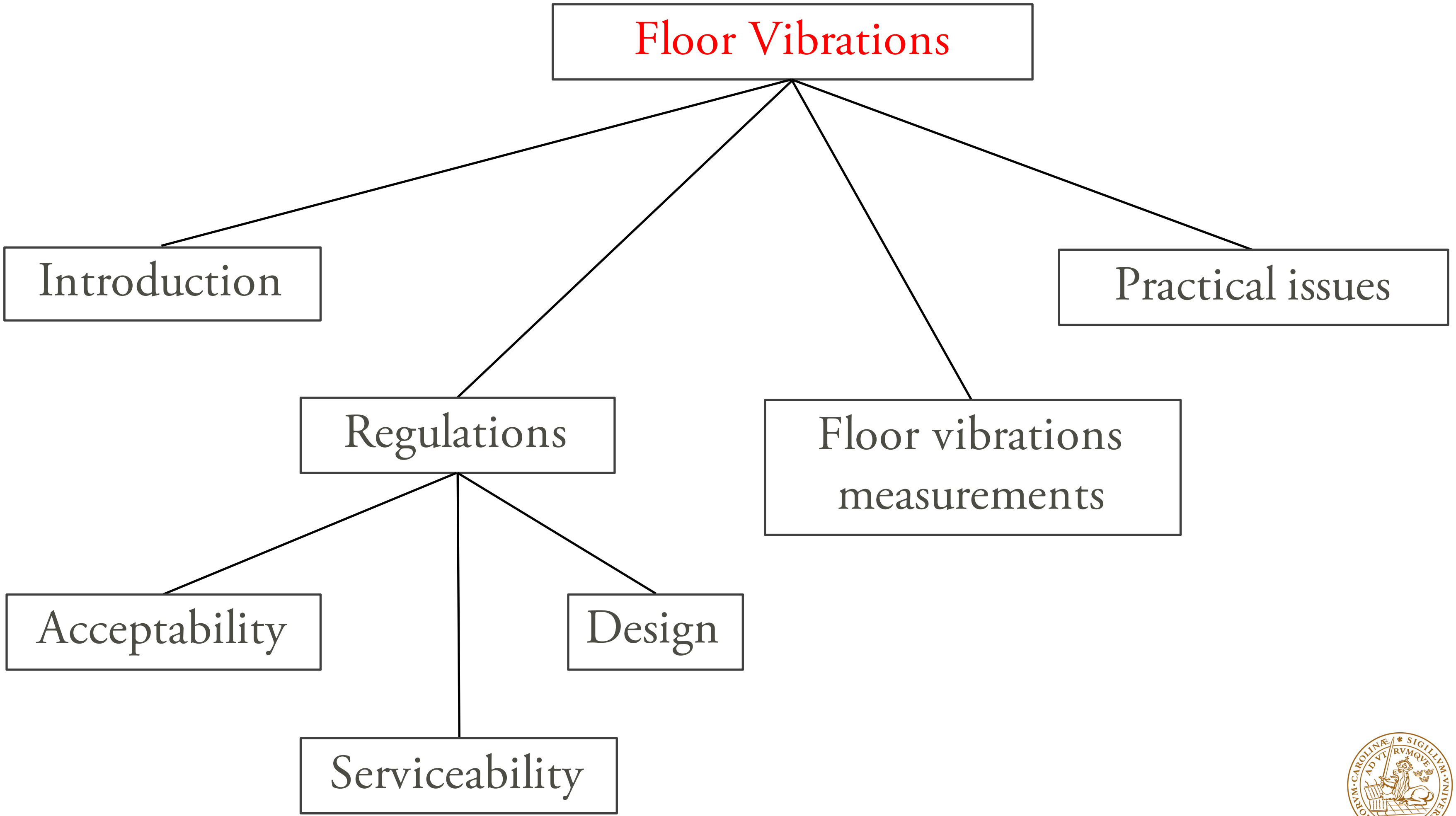
Introduction

Structural Dynamics (SDOF / MDOF)

Floor Vibrations

Summary

Outline – Floor vibrations



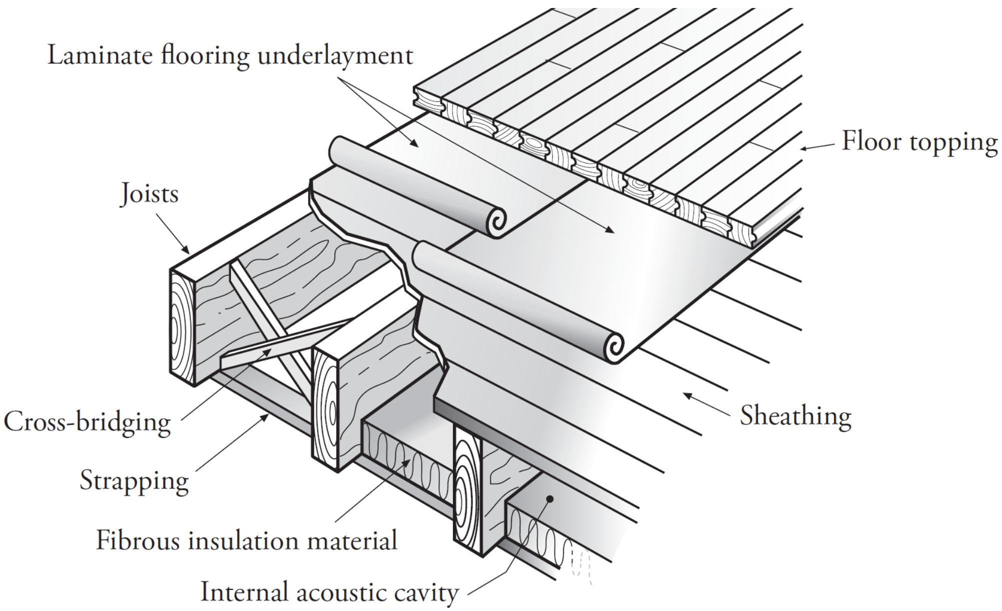
Introduction (I)

- Floor vibrations: oscillatory motion experienced by the building and its occupants during the course of day-to-day activities
  - Sources of vibrations:
    - » Human activity: walking, dancing, jumping…
    - » Vibrating machinery
    - » External forces: traffic (at ground level or underground), wind…
  - Both vertical but also horizontal
  - Consequences:
    - » Nuisance to the building users / health problems (long exposure)
    - » Damage to the fixtures and fittings
    - » (in very extreme cases) damage to the building structure

NOTE: Just low-amplitude vibrations are treated (i.e. serviceability); high-amplitude vibrations (i.e. earthquakes) are out of the scope in this course.

Introduction (II)

- Two types of floor vibrations
  - Local deflection: appears in the direct vicinity of the occupant
  - Resonant vibration: result of a lack of damping

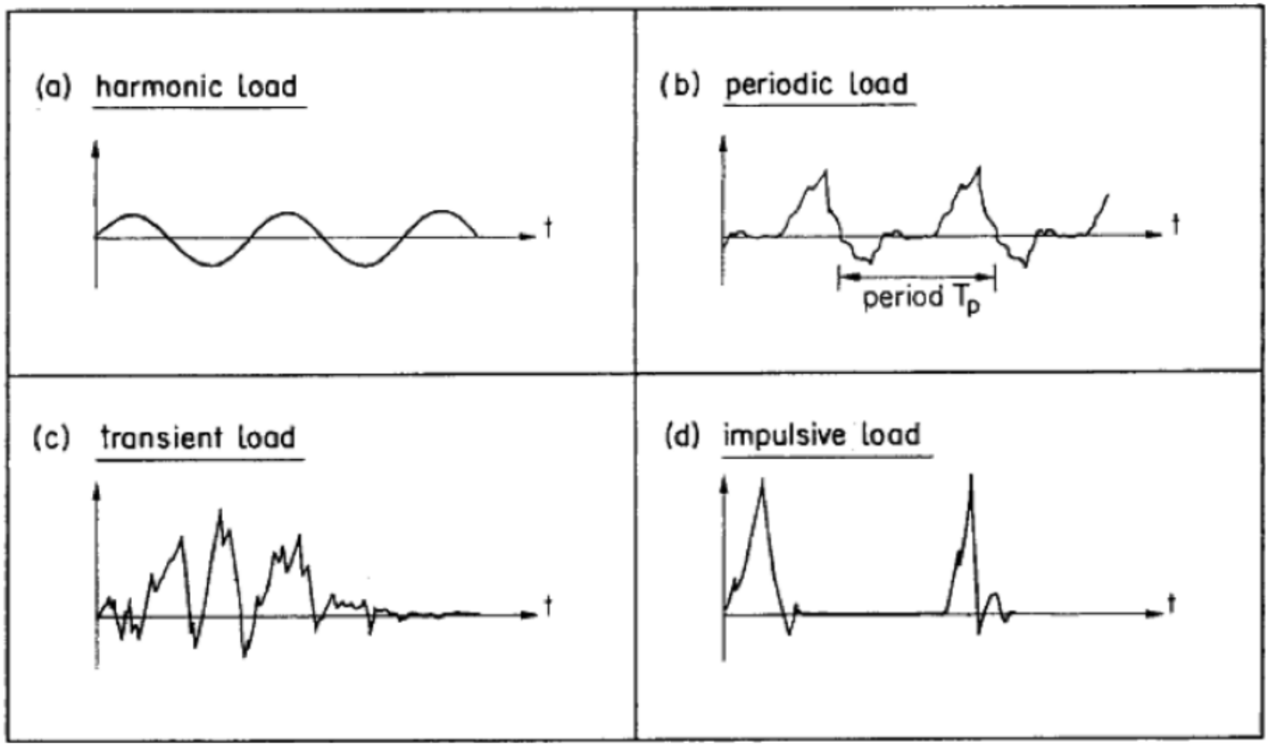


Representative Swedish wooden floor and its parts

- Dynamic parameters of floor
  - Stiffness
  - Damping
  - Mass
  - Fundamental frequency

Introduction (III)

- Vibration sources (types)



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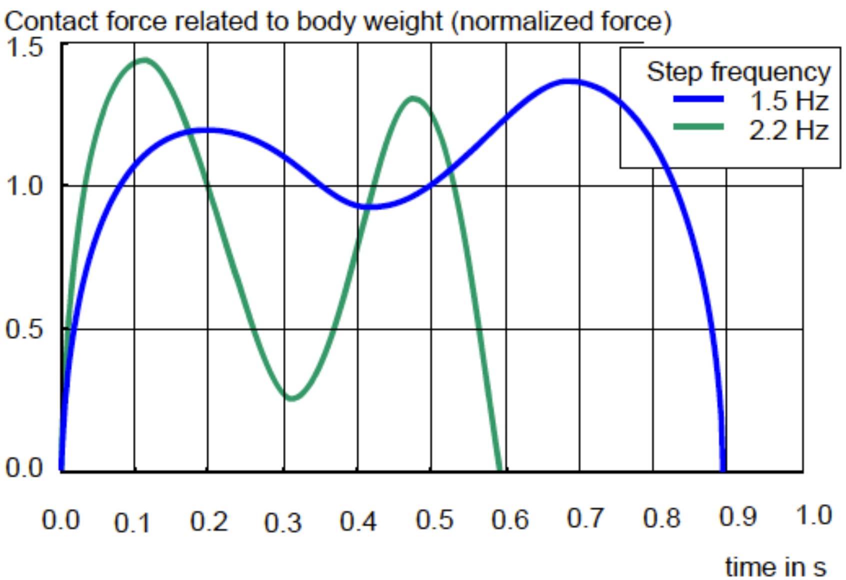
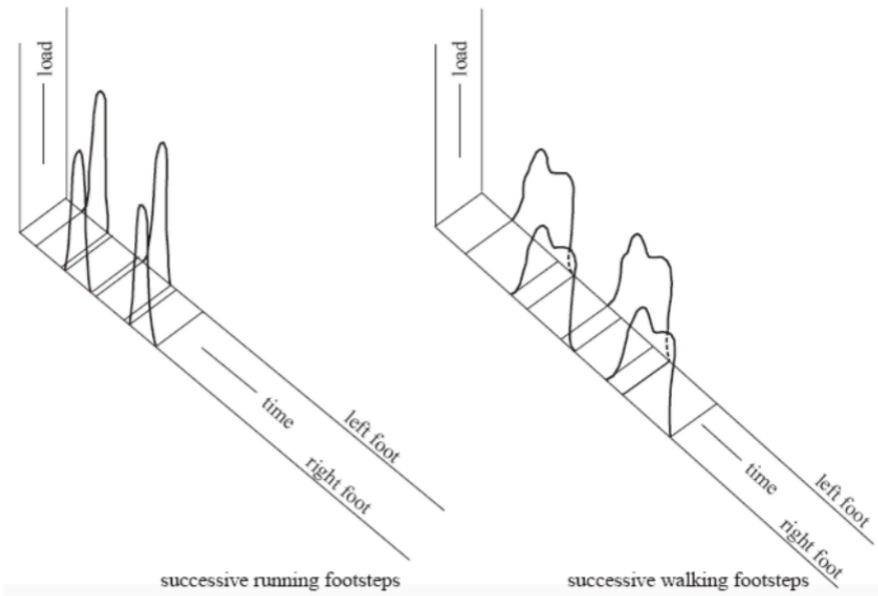
Introduction (IV)

- Typical source of complains → human induced vibrations
  - A person walking: 1.6 to 2.2Hz → resonance?



Source: Galanti(2011)



- Mathematically described by Fourier series

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Regulations (I)

- Floor vibrations: seviceability issue
  - Discomfort of building occupants → hard to determine
    - » Type of activity
    - » Time of day when the activity is being undertaken
    - » The type of environment where the activity is taking place
    - » The direction of the vibration
    - » The amplitude of the vibration
    - » The frequency of the vibration
    - » The source of the vibration
    - » The level of damping
    - » The duration of the exposure
  - Damage to sensitive equipment
- Human body: complex, sensitive, subjective and variable → no design limits for acceptable vibration levels in buildings (just guidelines)

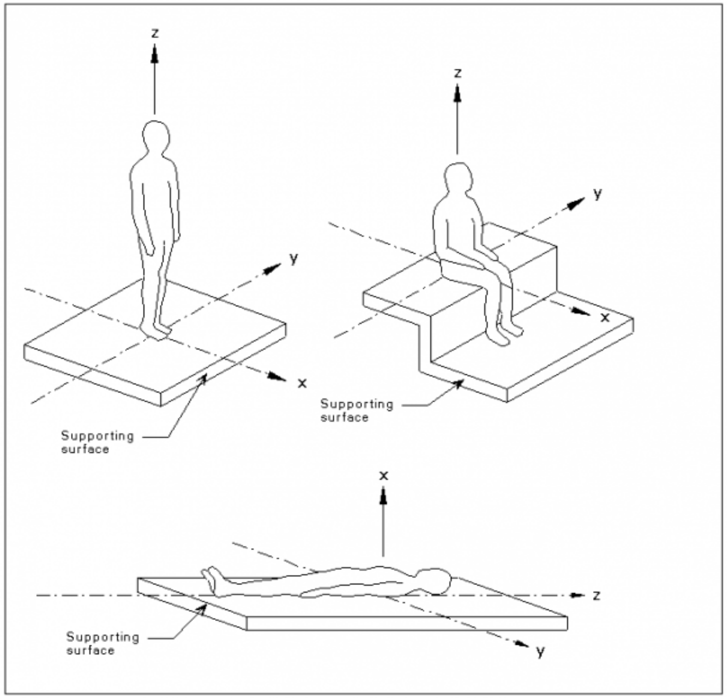
Regulations (II)

- Human perception of structural vibrations
  - ISO 2631-1:1997: guidelines on how to perform vibration measurements, what to report, and how to evaluate the results
  - ISO 2631-2:2003: methods of measurement and evaluation concerned with whole-body vibrations in buildings
- Serviceability criteria to minimize annoying vibrations in floors
  - ISO 10137:2007: recommendations on the evaluation of vibration serviceability of buildings based on Vibration Dose Values (VDV)
  - Eurocode 5: serviceability limit state design guidelines regarding floor-vibration performance (different for different structures/materials)
  - Different criteria limiting several parameters (deflection, impulse velocity, eigenfrequency…) → Research-based criteria
    - » E.g.: HIVOSS (OS-RMS$_{90}$) → See e.g. [1] for literature review

[1] *J.Negreira et al: Psycho-vibratory evaluation of timber floors - Towards the determination of design indicators of vibration acceptability and vibration annoyance.* Published in Journal of Sound and Vibration (JSV).

ISO 2631-1:1997

- Measurement guidelines of whole-body vibrations (0-80 Hz)
  - Vibrations in boats, construction workers…
  - No vibration exposure limits given
- Accelerations are to be measured
  - Measurement time: representative value
  - Different directions considered
  - Frequency weightings (direction dependent)
- Three annexes containing suggestions:
  - Possible effects of vibrations on health
  - Comfort and perception
  - Motion sickness



ISO 2631-2:2003

- Frequency range: 0-80 Hz
- Evaluation of vibration in buidings with respect to comfort / annoyance
- Overall frequency weighted acceleration values are preferred
  - Weightings coincident with the ones given in ISO 2631-1:1997
  - Sufficient to simply consider vibrations in the direction having the highest frequency-weighted magnitude
- In an older version (ISO 2631-2:1987), tentative vibration serviceability limits were given in the form of base curves for the vibration magnitudes that cause approximately the same degree of annoyance
  - Withdrawn in 2003: "Guidance values [...] are not included anymore since their possible range is too widespread to be reproduced in an International Standard"

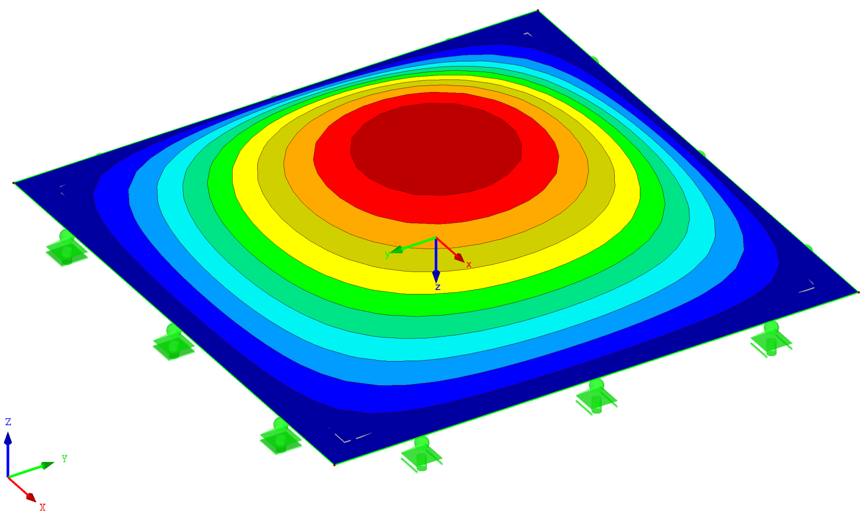
ISO 10137:2007

- Recommendations on the evaluation of serviceability against vibrations of buildings, and walkways within buildings or connecting them or outside of buildings. It covers three recipients of vibrations:
  - Human occupancy in buildings and on walkways
  - The contents of the building
  - The structure of the building
- Evaluation involves: vibration source, transmission path and receiver
- Guidelines on the evaluation of vibration serviceability of buildings based on Vibration Dose Values (VDV)
  - No phsyical meaning ($ms^{-1.75}$) → considers intermitency of walking

$$VDV = \left\{ \int_0^T \left[a_w(t) \right]^4 dt \right\}^{\frac{1}{4}}$$

Eurocode 5

- Serviceability limit state design guidelines regarding floor-vibration performance (different for different structures/materials). For wood:
  - 1st natural frequency: $f_1 \geq 8$ Hz
  - Deflection from 1 kN point load: $\frac{w}{F} \leq a$ [mm] (SS-EN: $w \leq 1.5$ mm)
  - Impulse velocity response: $v \leq b^{(f_1\zeta-1)}$ [m/Ns^2]



The previous conditions are in many cases insufficient to assure acceptable floor performance

Example of other criteria: HIVOSS

Determine dynamic floor characteristics:
Natural Frequency
Modal Mass
Damping

↓

Read off *OS-RMS₉₀* value

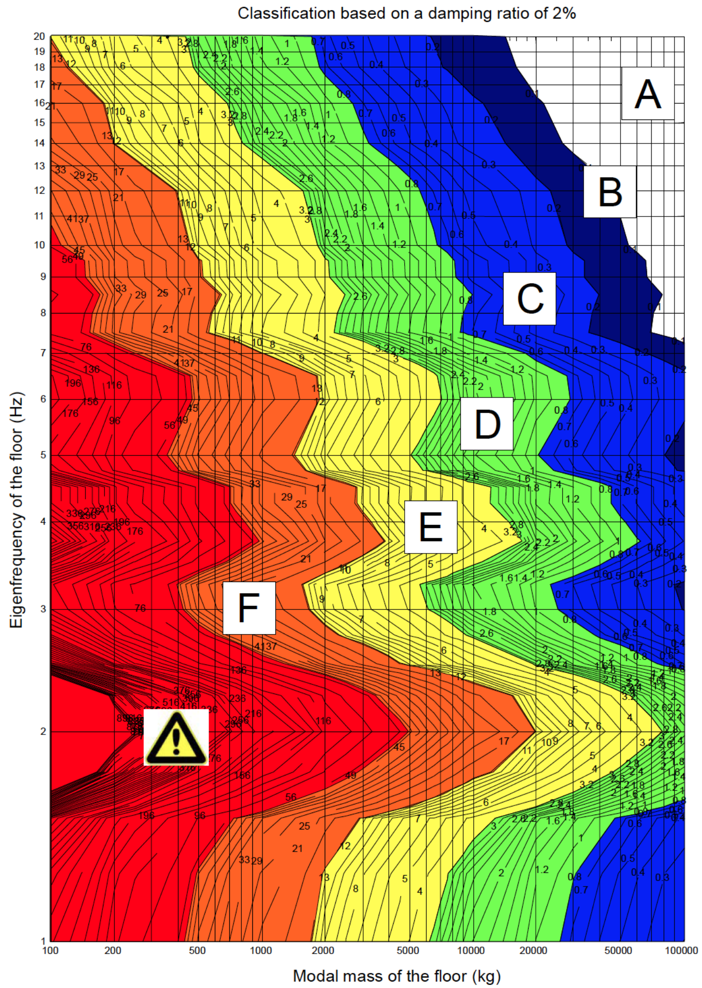
↓

Determine and verify floor class

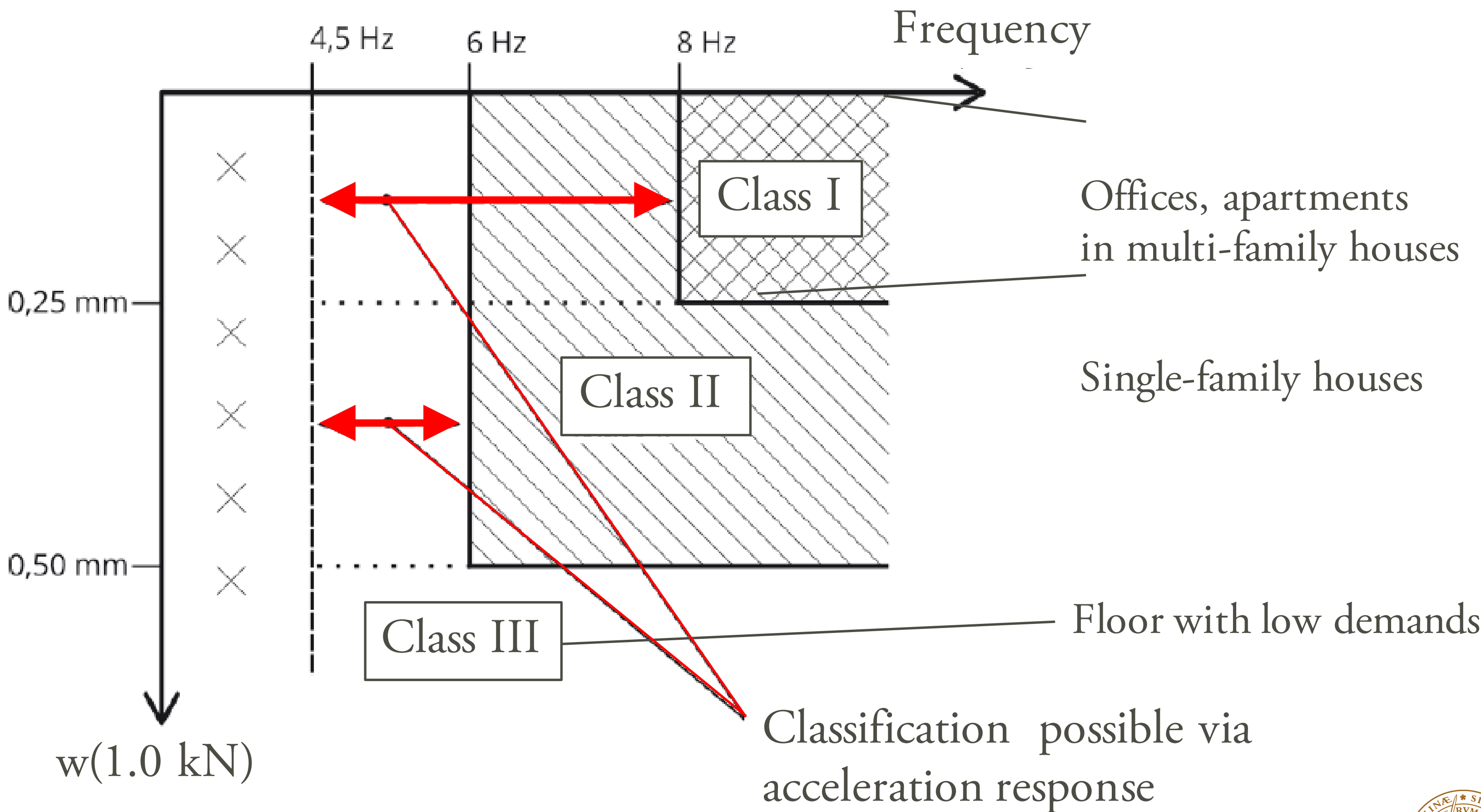
Class	*OS-RMS₉₀* Lower limit	*OS-RMS₉₀* Upper limit	Function: Critical areas	Hospitals, surgeries	Schools, training centers	Residential buildings	Office buildings	Meeting rooms	Senior citizens' Residential building	Hotels	Industrial Workshops	Sports facilities
A	0.0	0.1										
B	0.1	0.2										
C	0.2	0.8										
D	0.8	3.2										
E	3.2	12.8										
F	12.8	51.2										

Recommended
Critical
Not recommended

Based on 90 percentile of the one-step root mean square ($OS\text{-}RMS_{90}$)

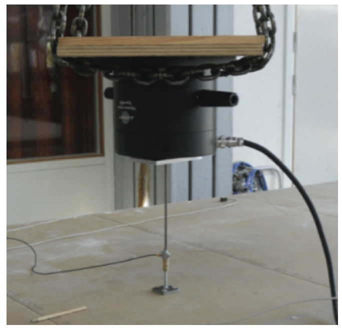


ProHolz, Hamm & Richter criterion



Experimental modal analysis (EMA) (I)

- Two main types of floor vibrations
  - Impact testing
    - » Intrumented hammer
    - » Tapping machine
    - » Rubber tire
    - » Heel-drop
    - » Japanese ball
  - Shaker testing
- Response measured with accelerometers



Experimental modal analysis (EMA) (II)

- EMA → Obtain dynamic parameters of the structure
  - Eigenfrequencies, eigenmodes, damping rations, modal mass…
  - Important to understand dynamic behaviour
    - Design decisions
    - Serviceability criteria

- Examples
  - Plate EMA (1&2)
  - Truck EMA

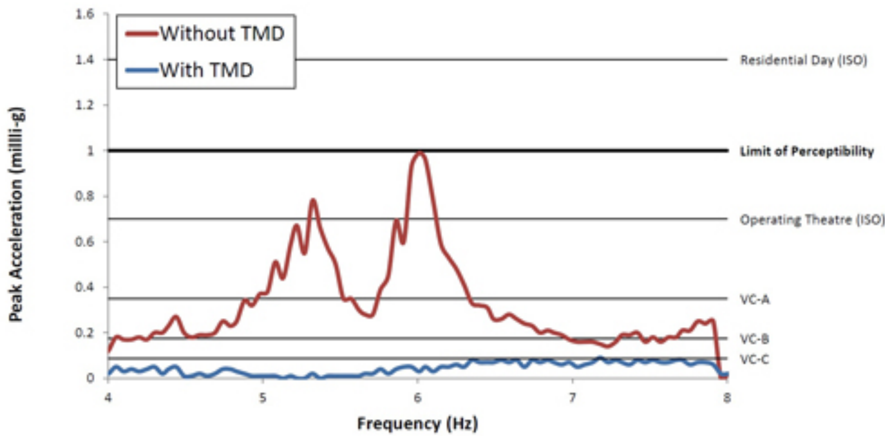
Material damping is farily easy to determine. However, damping in assembled structures is very hard to calculate due to connections, BC, etc. Measurements are very useful to that end.

Some practical design considerations

- Natural frequency different than the one of the activities to be performed
- Adding, altering or relocating partitions
- Add extra damping to floors
  - Tuned mass dampers (TMD)
  - Discrete connecting damping elements → expensive (retrofitting)
  - Use of high-damping materials (absorbers) within the construction
- Changing dimensions of the floor
  - Vary floor thickness (i.e. stiffness)
  - Modify the mass
  - Vary floor span
  - Modify beam dimensions

Tuned mass dampers TMD (example)

Source: http://labdesignnews.com



Outline

Introduction

Structural Dynamics (SDOF / MDOF)

Floor Vibrations

Summary

Summary

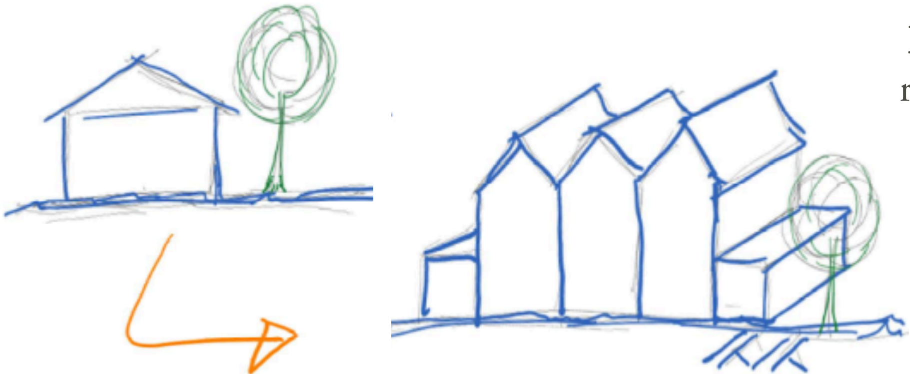
- Structural dynamics
  - SDOF
  - MDOF
- Floor vibrations
  - Regulations
  - Measurements
  - Practical issues

References (I)

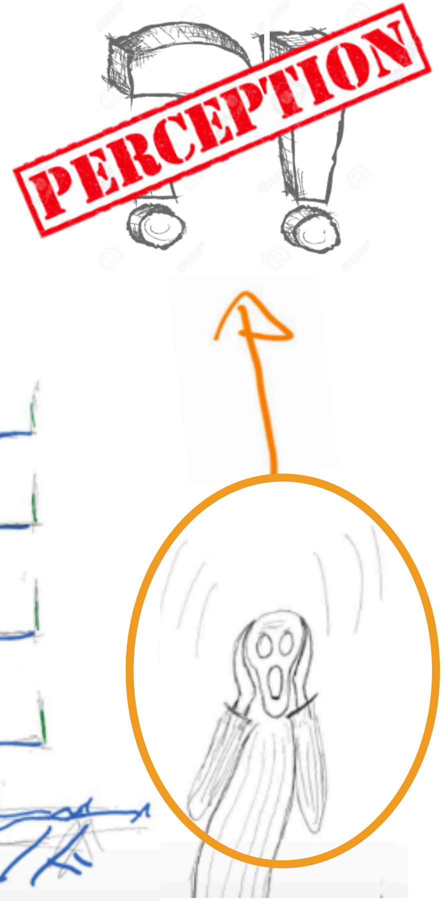
- ISO (1997), ISO 2631-1: Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration – Part 1: General requirements, International Organization for Standardization, Geneva, Switzerland.
- ISO (2003), ISO 2631-2: Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration – Part 2: Vibration in buildings (1 Hz to 80 Hz), International Organization for Standardization, Geneva, Switzerland.
- ISO (2007), ISO 10137: Bases for design of structures – Serviceability of buildings and walkways against vibrations, International Organization for Standardization, Geneva, Switzerland.
- CEN (2004), EN 1995-1-1: Eurocode 5 – Design of timber structures – Common rules and rules for buildings, European Committee for Standardization, Brussels, Belgium.
- M.Feldmann et al.,RFCS-Project: Human Induced Vibration of Steel Structures – HIVOSS: Design Guideline and Background Report,2008.

… and some “extra” info

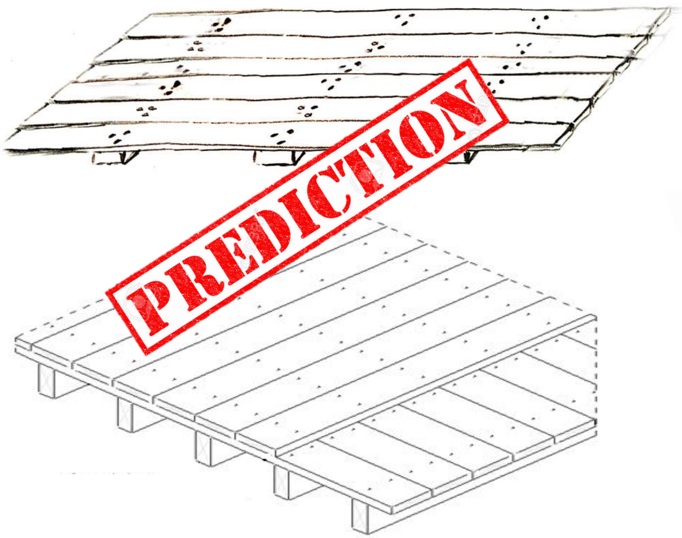
Vibroacoustic performance of wooden buildings – Overview



Design indicators: human response to floor vibrations



Computer prediction tools: foresee performance and structural modifications during design phase



AIMS:

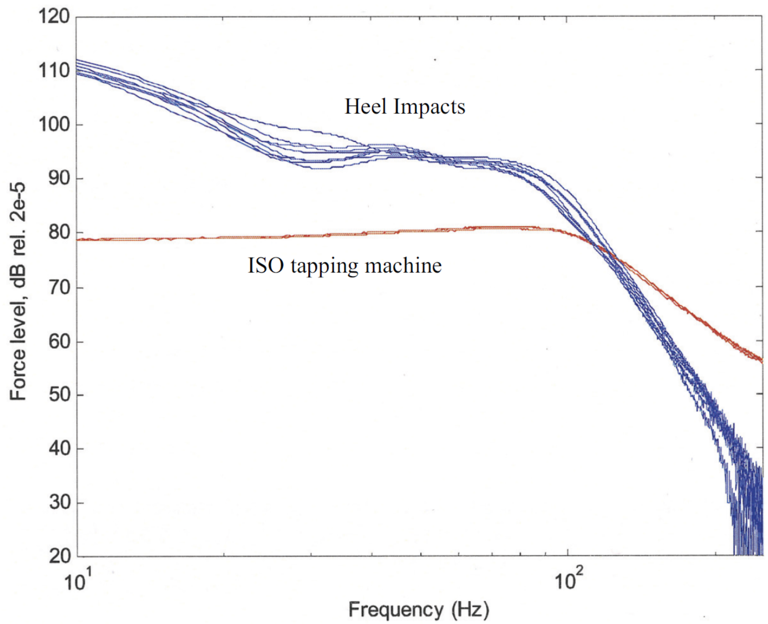
- Cost and time savings for industry
- Vibroacoustic comfort

Vibroacoustic issues in wooden buildings (I)

- Multi-storey wooden buildings allowed in 1994
  - Many advantages
    - » Lighter and cheaper
    - » High degree of prefabrication
    - » Environmental friendly
    - » Plentiful resource in Sweden
    - » …
  - Main disadvantages
    - » Disturbing vibrations
    - » Variability
    - » …

Vibroacoustic issues in wooden buildings (II)

- Current ISO standards (Sweden: 50–3150 Hz)
  - Identical for light / heavy constructions
  - Low frequencies out of the scope
    - » *AkuLite* → Statistical analyses (objective parameters & subjective ratings)
      - Impact: lower limit 20 Hz



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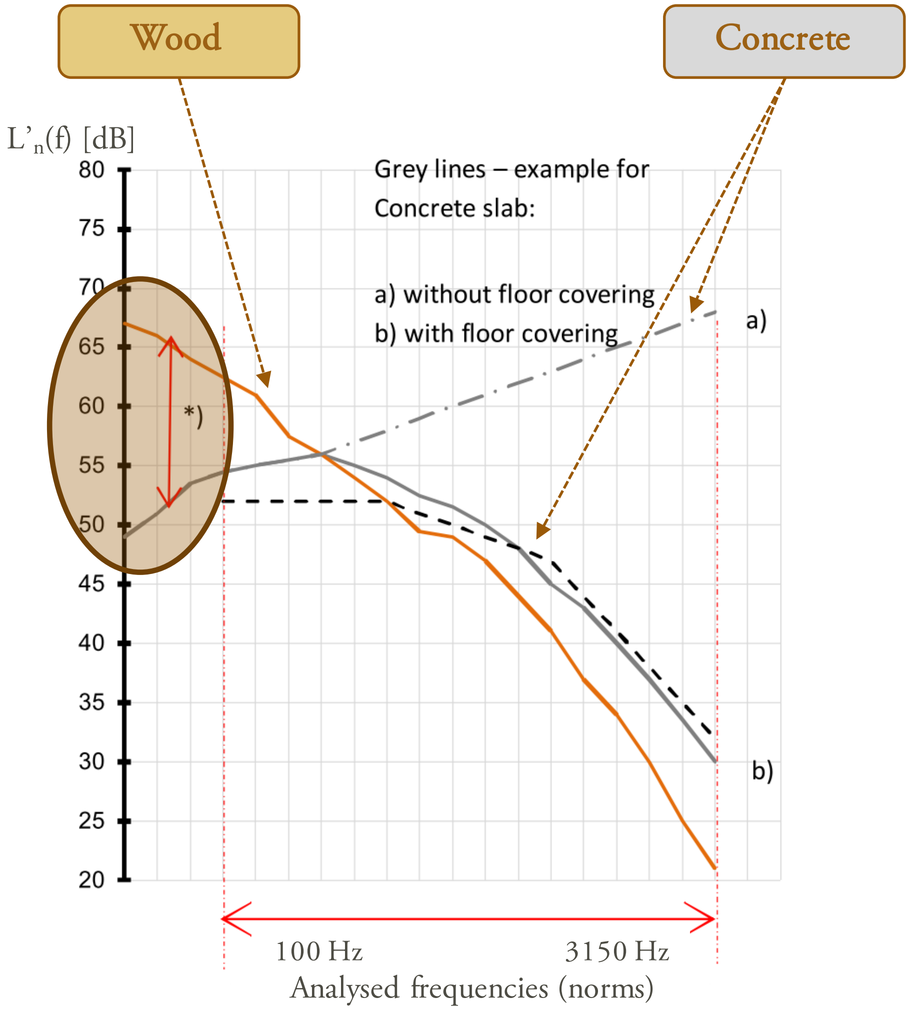
- Vibroacoustic comfort is sought → research needed in:
  - Human perception of floor vibrations
    - » Improvement of current standards (methods and evaluation procedures)
  - Prediction tools
    - » Structural modifications during design phase
      - – Inexpensive, not time-consuming

The"problem": SNQs (I)

SNQ = Single number quantity, descriptor



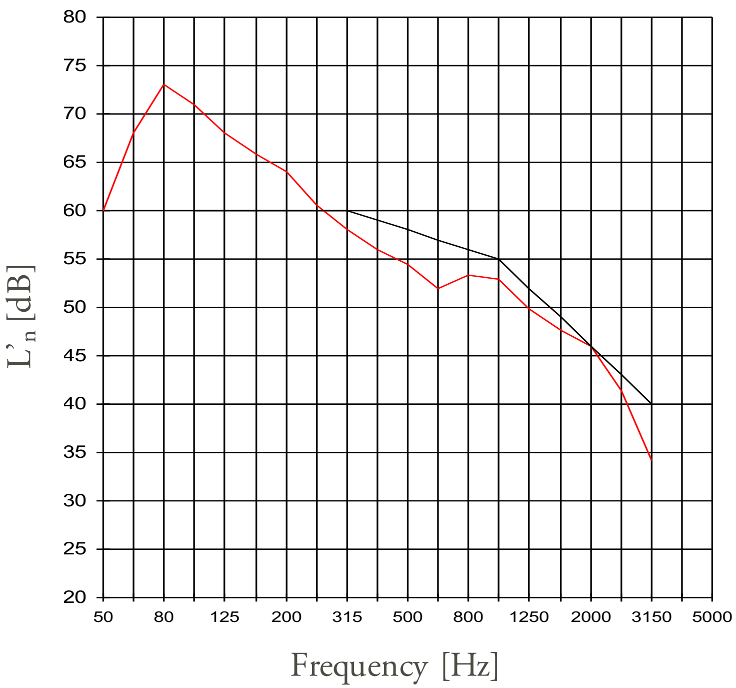
The“problem”: SNQs (II)

$$L'_{nw,\,wood} \neq L'_{nw,\,concrete}$$

(even if the SND are identical)

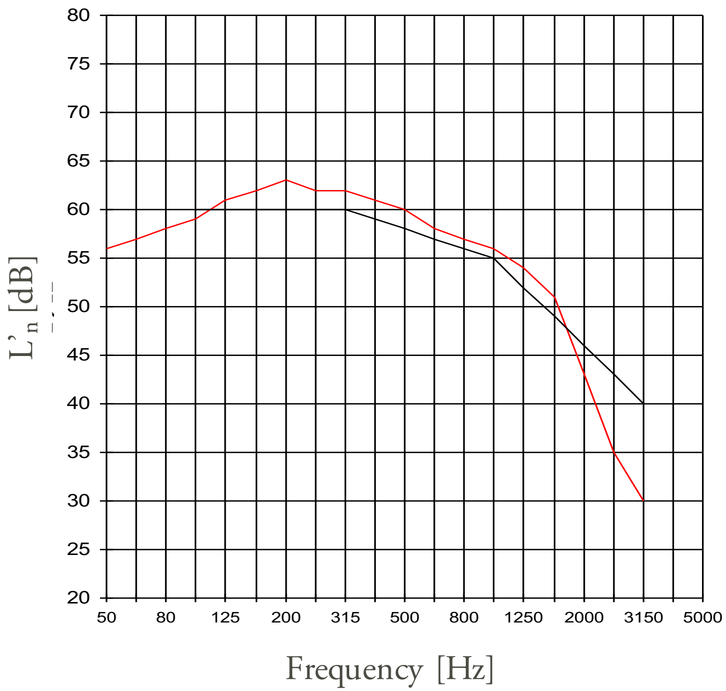
L'_{nw} =58 dB

$L'_{nw}+C_{I,50\text{-}2500}$ = 62 dB



L'_{nw} =58 dB

$L'_{nw}+C_{I,50\text{-}2500}$ = 57 dB



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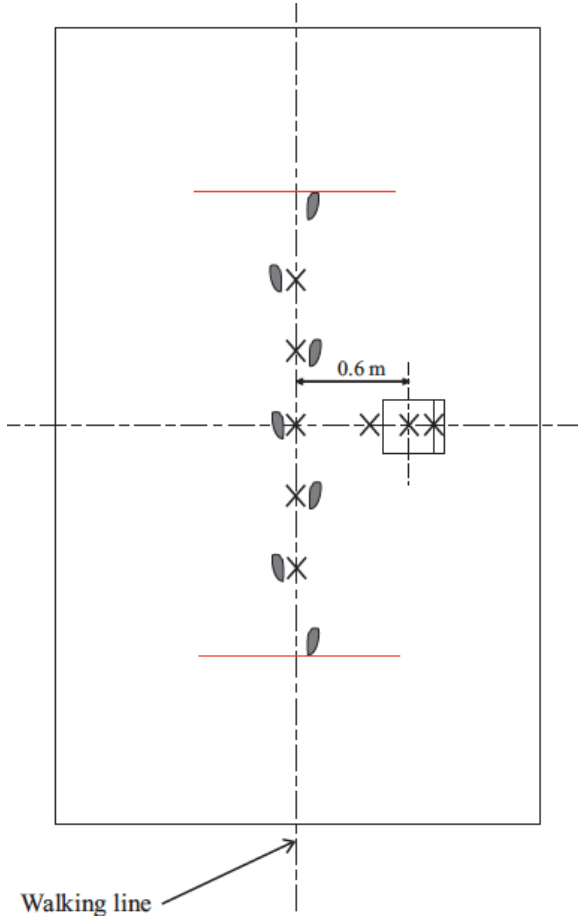
Example of design criteria investigation

- 5 prefabricated floors and 60 subjects
  - Seated test
  - Walking test
- Measurements
  - During subjective test
    - » Accelerations
    - » Questionnaires
  - Separately from subjective test
    - » Dynamic parameters (EMA)
    - » Deflections (subfloor, floortop)
- Design indicators for vibration annoyance and acceptability



J.Negreira et al: Psycho-vibratory evaluation of timber floors - Towards the determination of design indicators of vibration acceptability and vibration annoyance.
Published in Journal of Sound and Vibration (JSV).

Thank you for your attention!

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