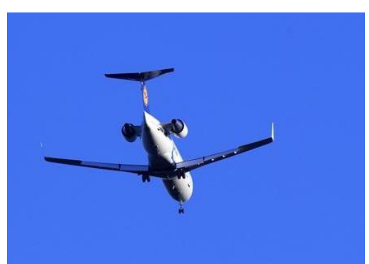
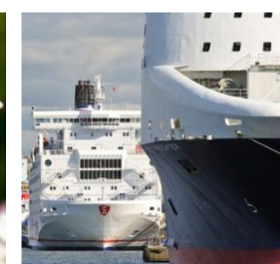
TRAFIKVERKET
SWEDISH TRANSPORT ADMINISTRATION

Vibration serviceability of floor systems

2020-02-04

Johan Jonsson





Outline

Vibration serviceability

Vibration source

Vibration path

Receiver

Performance evaluation

Design criteria – for what?

Strength
- safety

Deflection
- function, appearance, surface material, secondary structures etc. *But not for vibration!*

Vibration
- discomfort / annoyance / safety

Noise
- discomfort / annoyance

What is vibration serviceability?

The two ”limit states”:

Ultimate limit state (ULS)

– make sure that the structure does not collapse

Serviceability limit state (SLS)

– structural performance when in use

If you exceed SLS, then you exceed the structural specification!

The first step towards the assesement of vibration serviceability of a civil engineering structure of whatever kind is to identify and characterise the following three factors:

- the vibration source
- the transmission path, *i.e.* mass, stiffness and damping properties of the structure
- the receiver

A Pavic, Editoral, Structures & Buildings, 159, October, 2006

Two definitions

Vibration - caused by somebody or something other than a person who is disturbed by them

Springiness – a disturbing sensation due to the deflection and vibration at the point of application of footstep by one and the same person

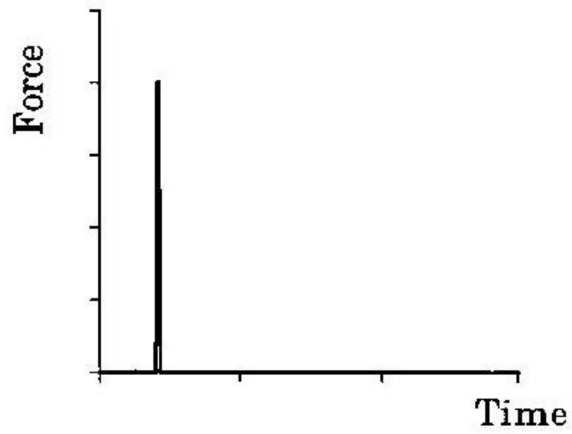
The vibration sorce

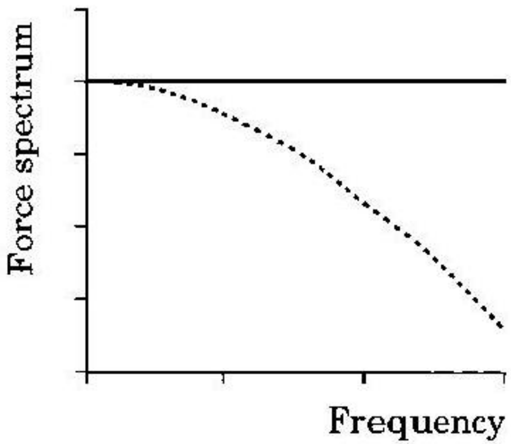
People

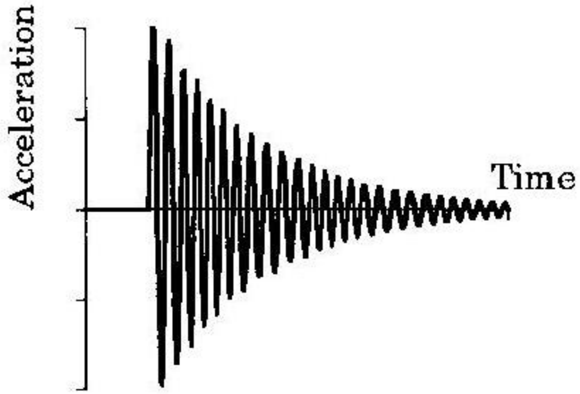
Machinery

Traffic

Impulsive force







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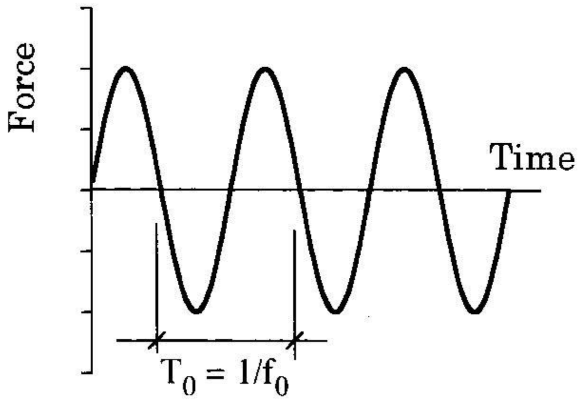
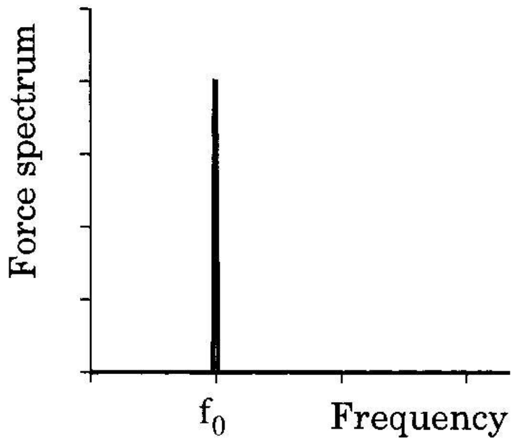
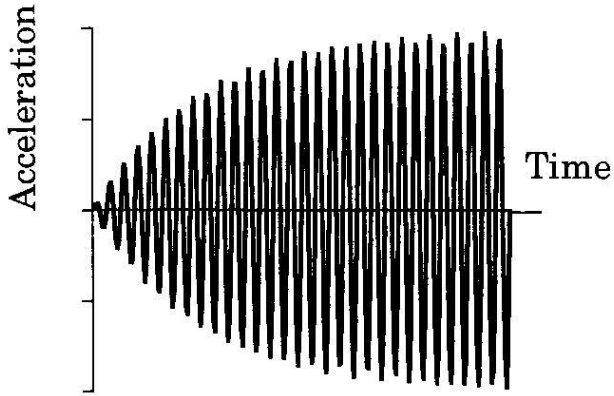
Harmonic force







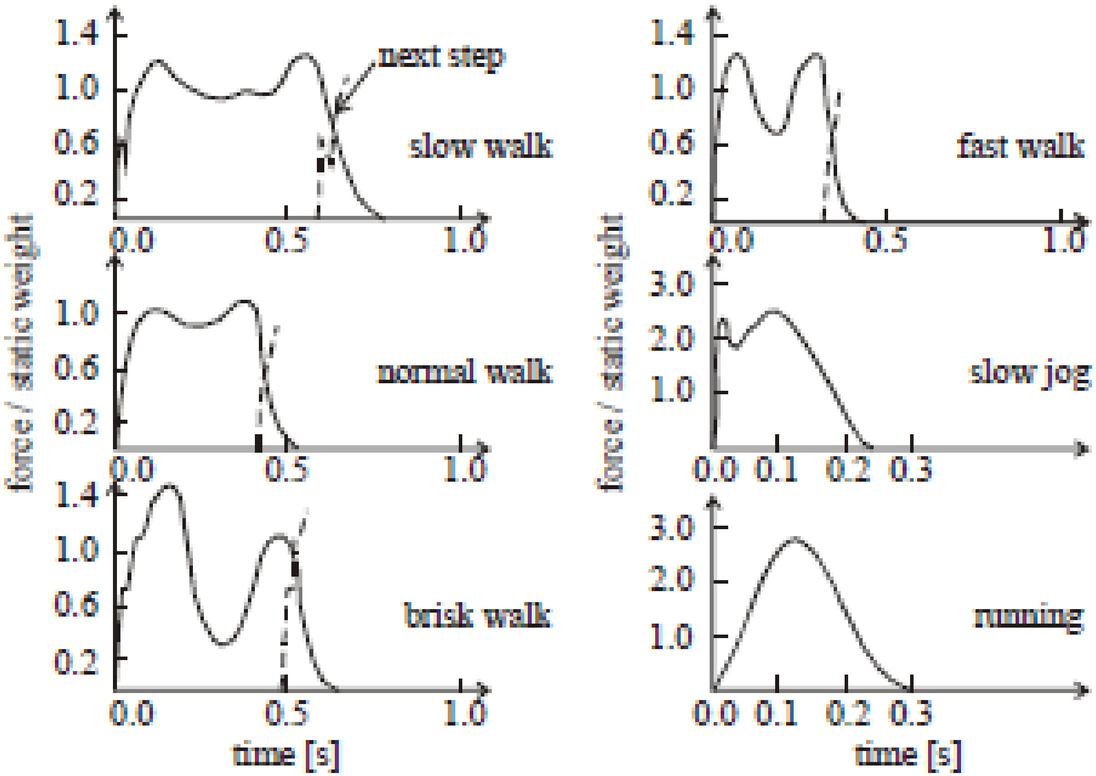
The vibration sorce

People

Machinery

Traffic

Single person force measurement - general shape



Wheeler, 1982

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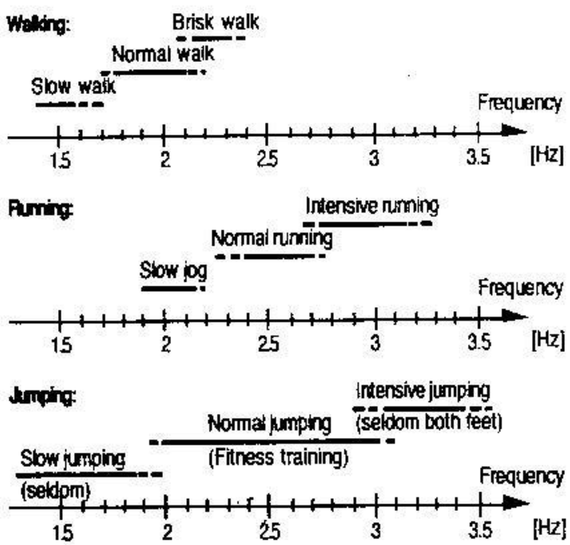
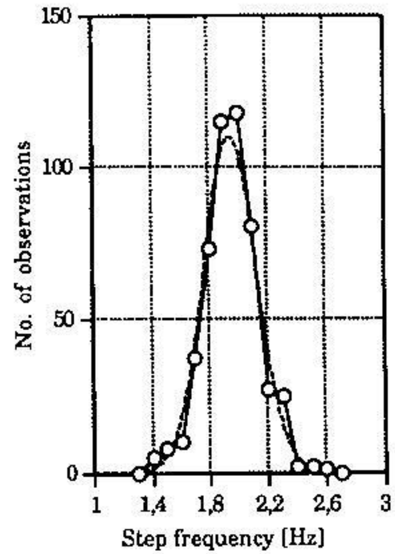
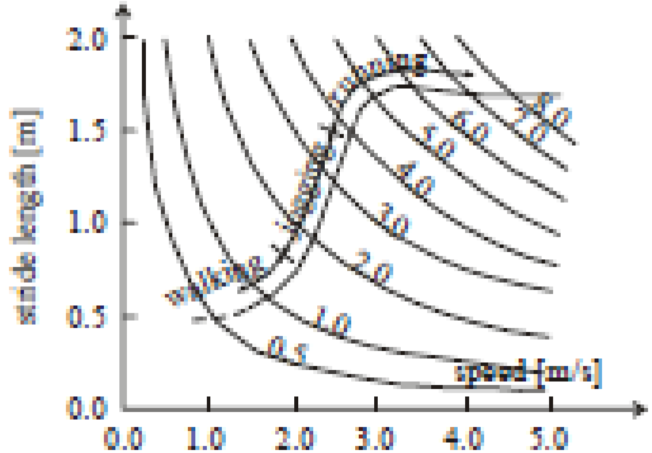
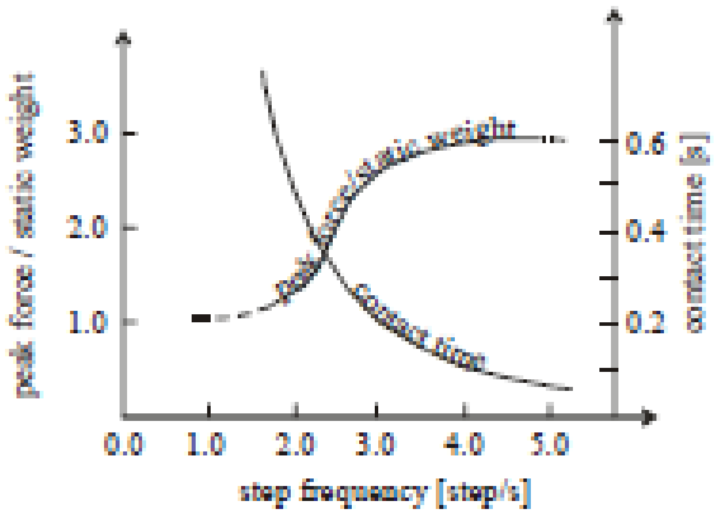
Frequency intervals









Matsumoto *et al.*, 1972

Wheeler, 1982

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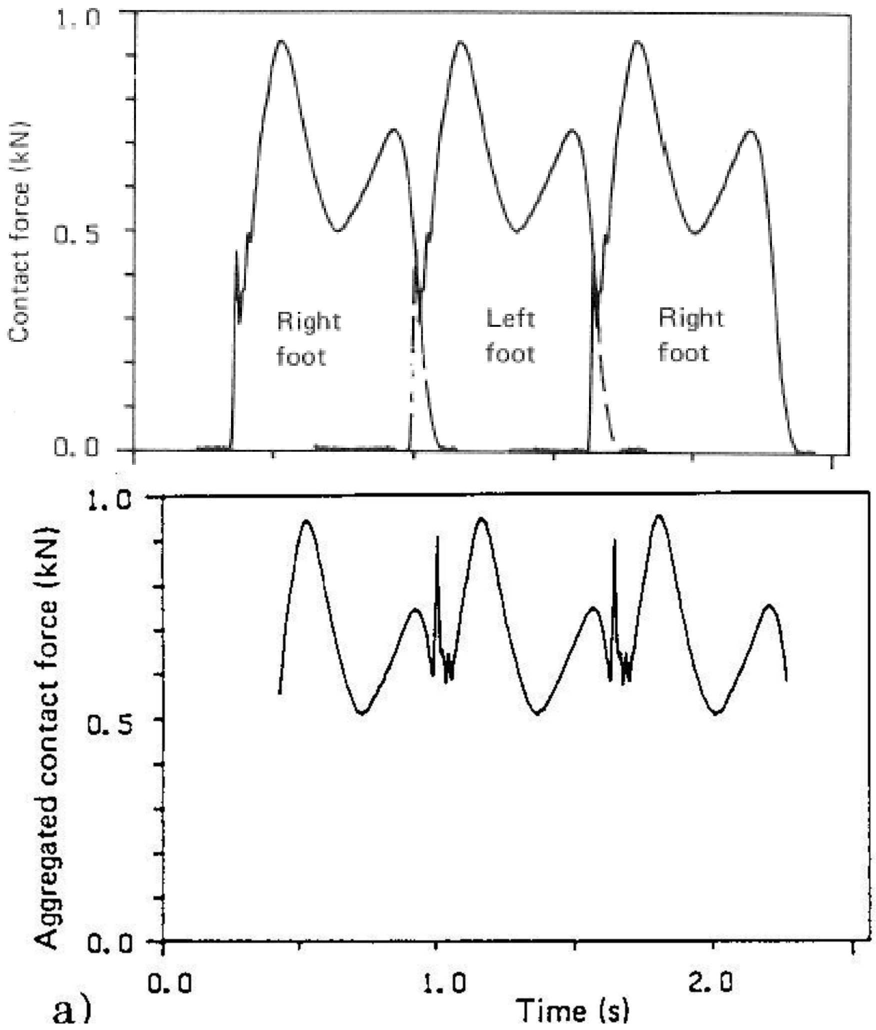
Fotstep force generated by people



Contact force due to each Foot generated by a person walking

Adding contributions of both feet gives resultant footstep force due to walking person

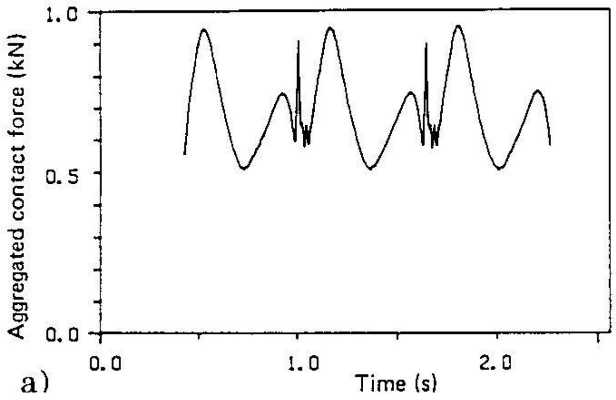
Ohlsson, 1982

Dynamic forces from walking people

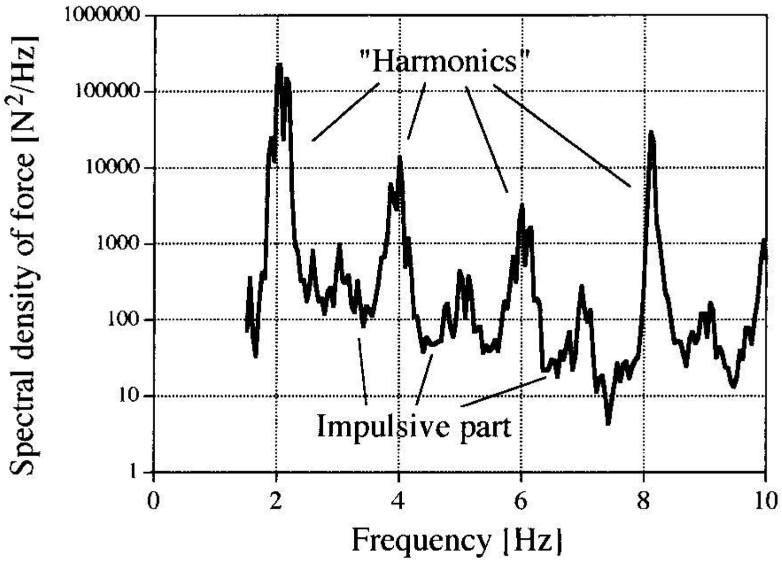
Impact – steady-state

Frequency components

Magnitude



Ohlsson, 1982



Eriksson, 1994

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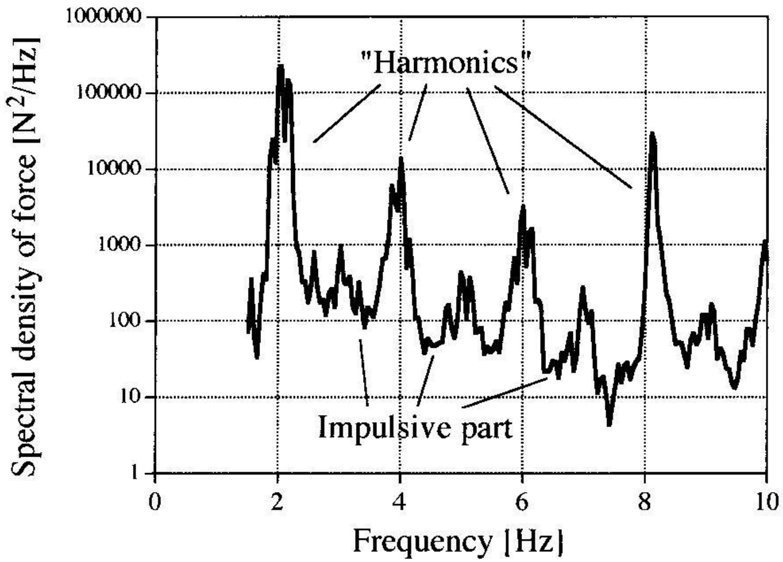
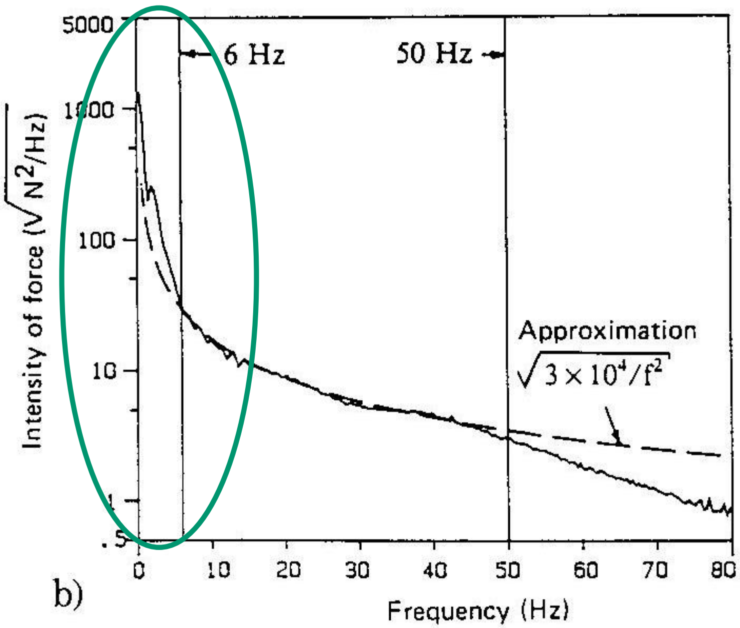
Force modelling

Continuous walking force



Eriksson, 1994

Single step force



Ohlsson, 1982

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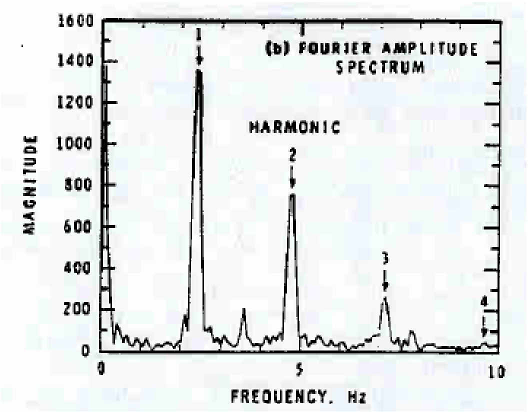
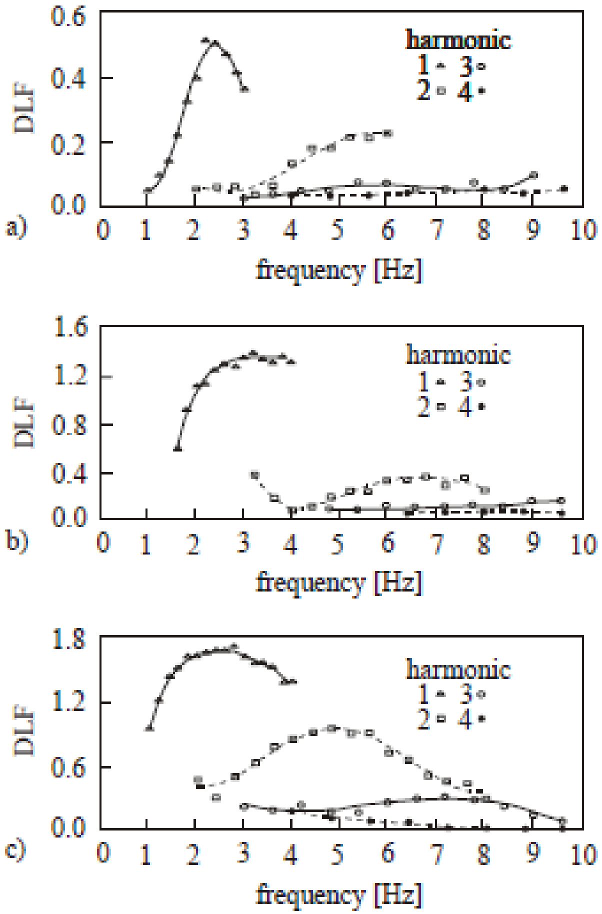
Force modelling

Time domain

$$F(t) = P\left(1 + \sum_{n=1}^{N} \alpha_n \sin\left(n2\pi f t + \phi_n\right)\right)$$





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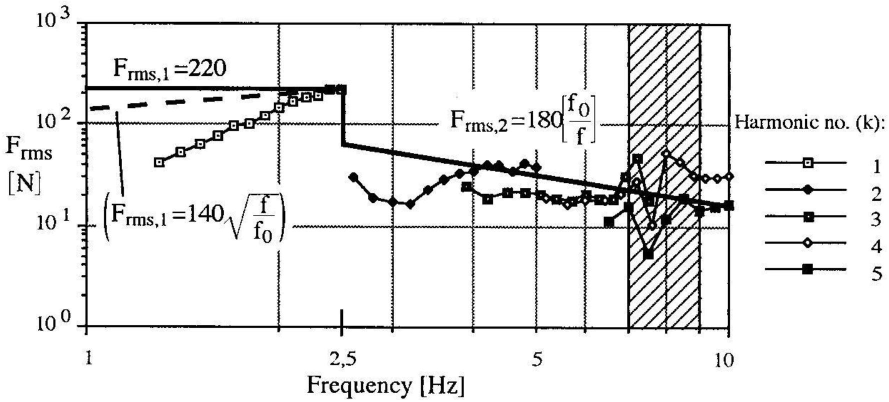
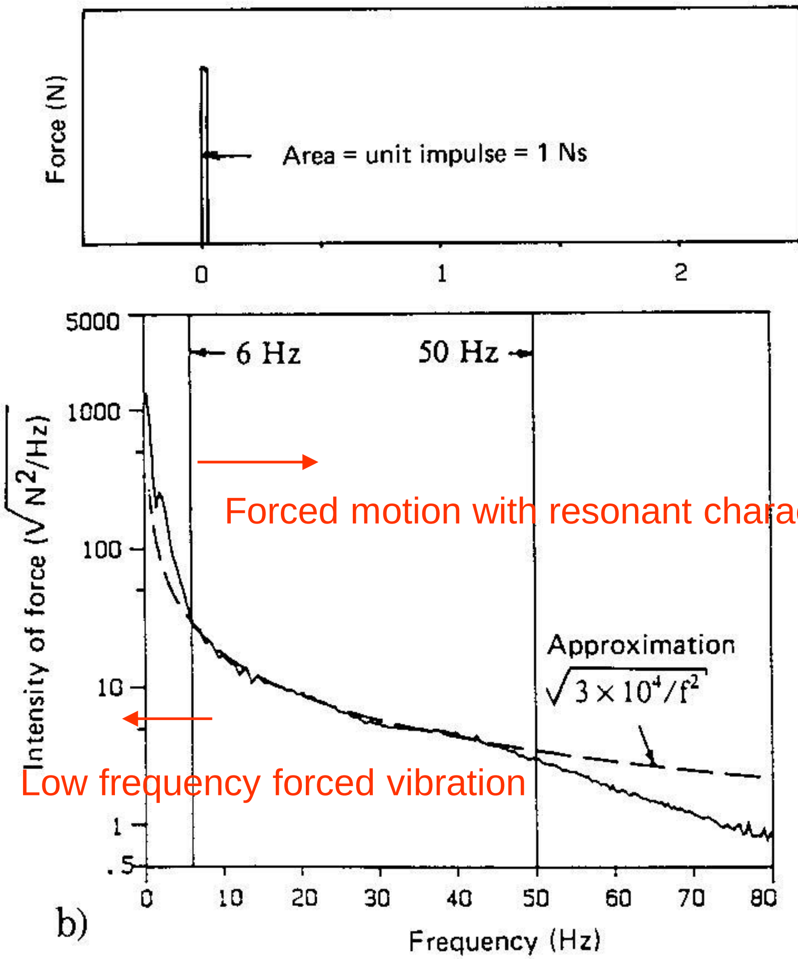
Force models for walking

Lower frequency



Forced motion with resonant character

Higher frequency



Forced motion with resonant character

Low frequency forced vibration

Ohlsson

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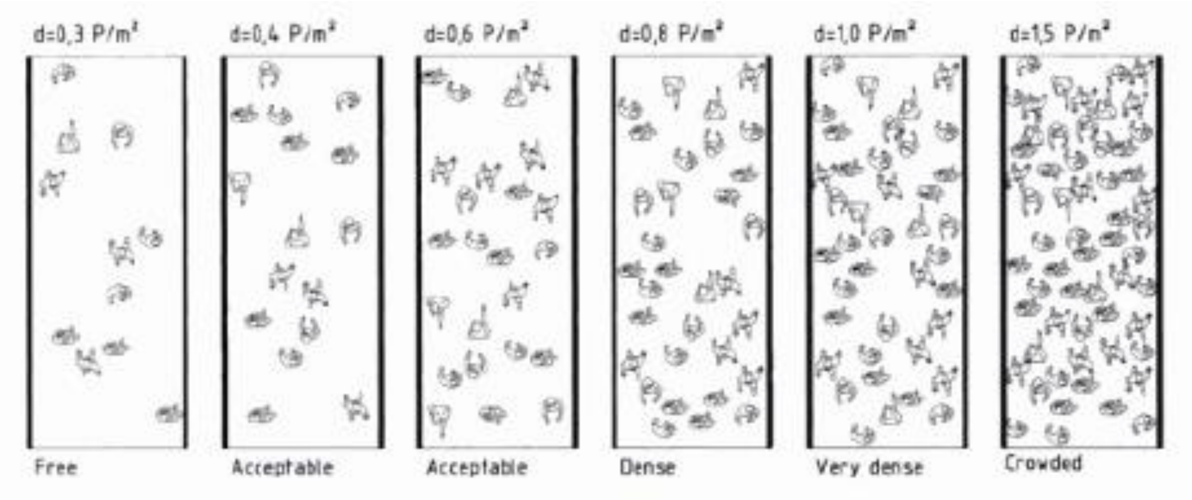
Force modelling

Pedestrian density & correlation

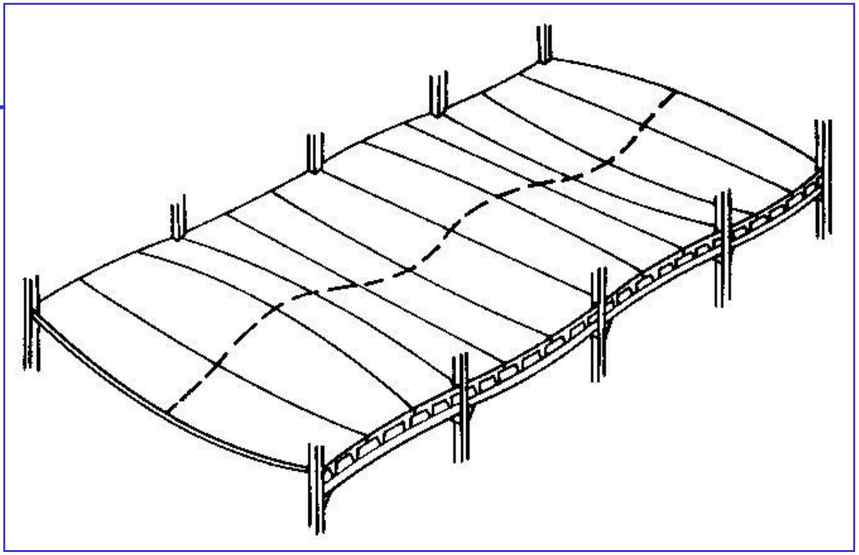


after Oeding

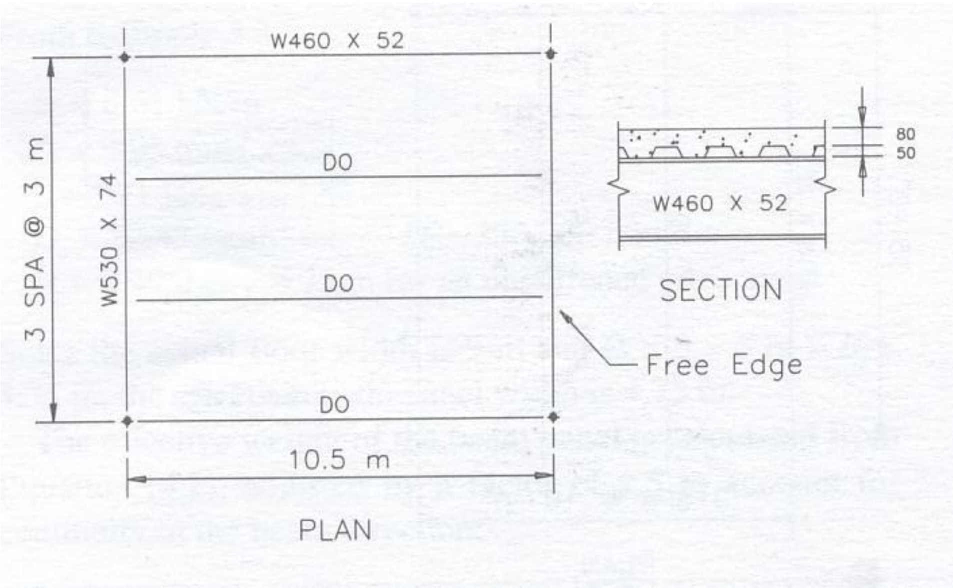
- Syncronisation
- one, small group, stream
- Impact on modal mass

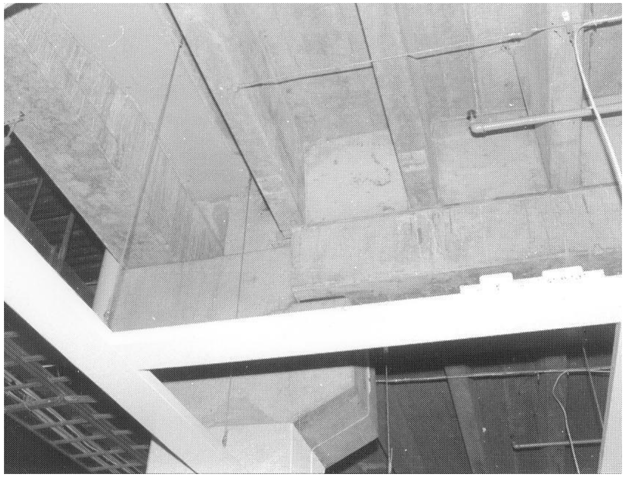
The transmission path

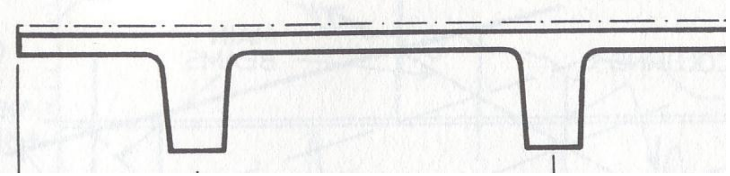
- Floor vibration

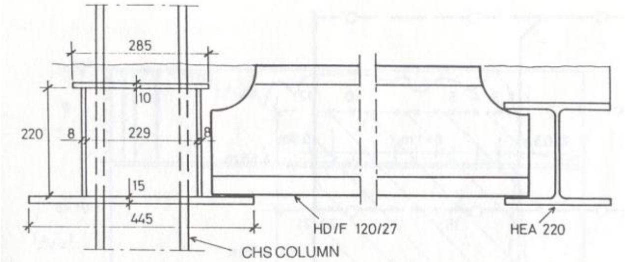


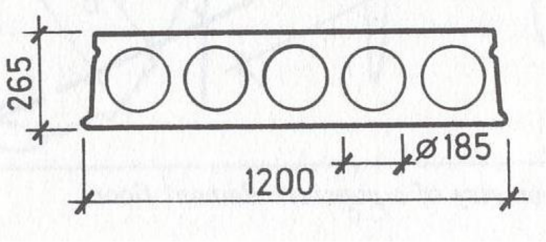
Typical design of steel/concrete floors



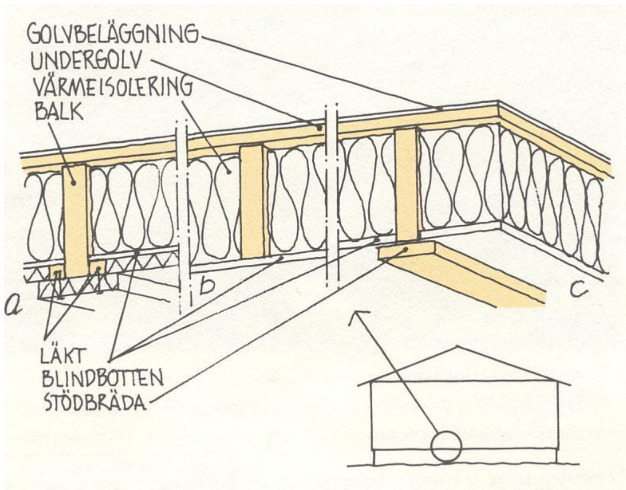


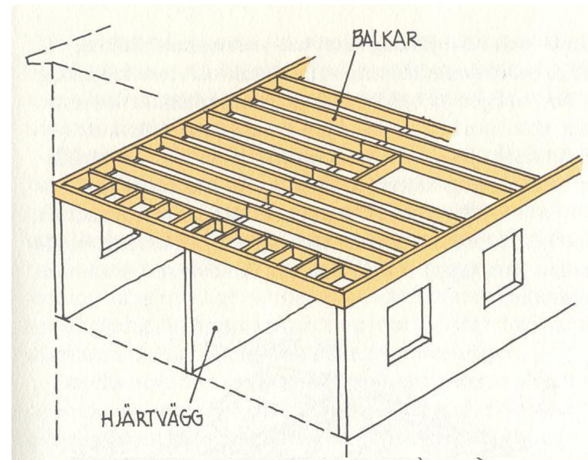


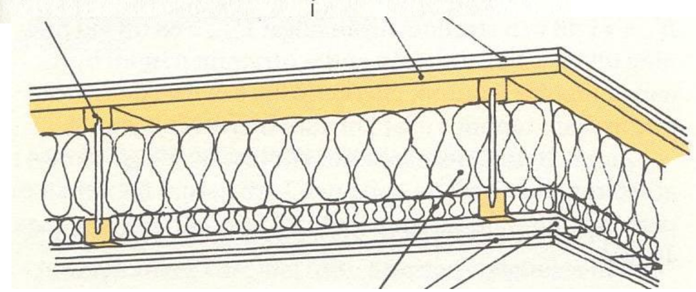


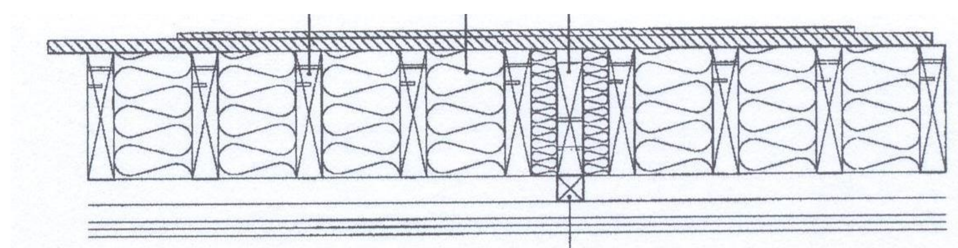


Typical design of timber floors

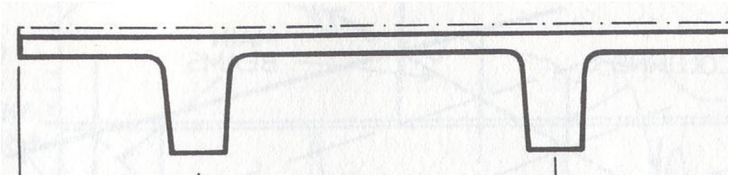


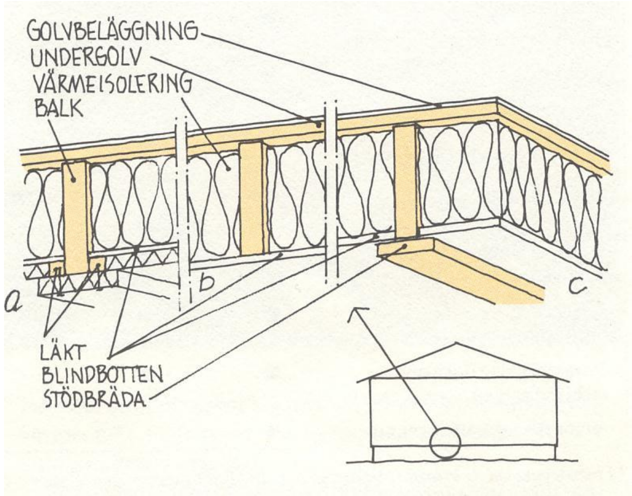






Similarities?





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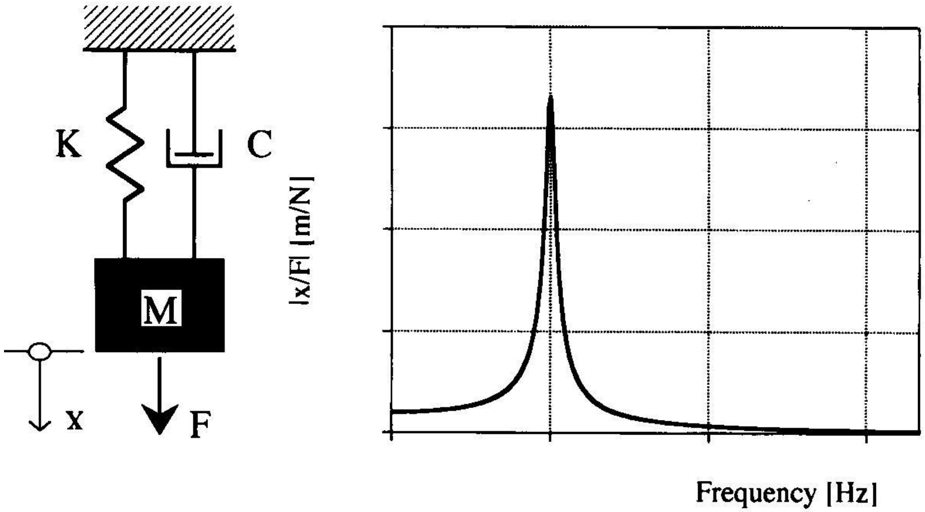
Single degree of freedom system



the transmission path, *i.e.* mass, stiffness and damping properties of the structure

Theory on black board

Theory

<u>Single degree of freedom system</u>

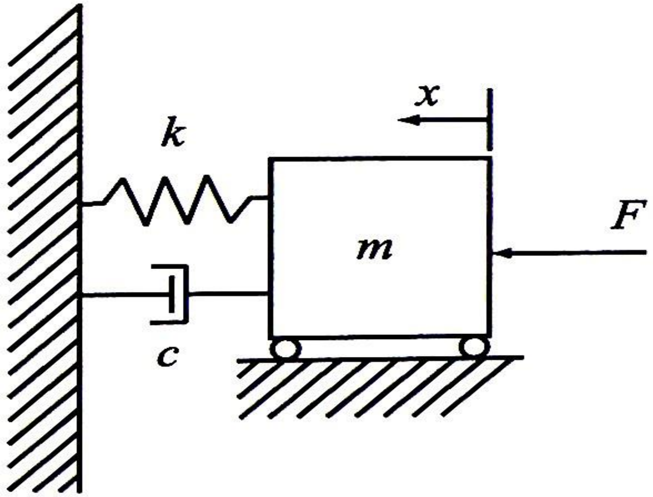
F = F(t)

m = mass

k = spring

c = viscous damping

x = x(t) displacement



The equation of motion:

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

$$|\hat{x}| = \frac{\hat{F}}{k\sqrt{(1-\beta^2)^2 + (2\xi\beta)^2}}$$

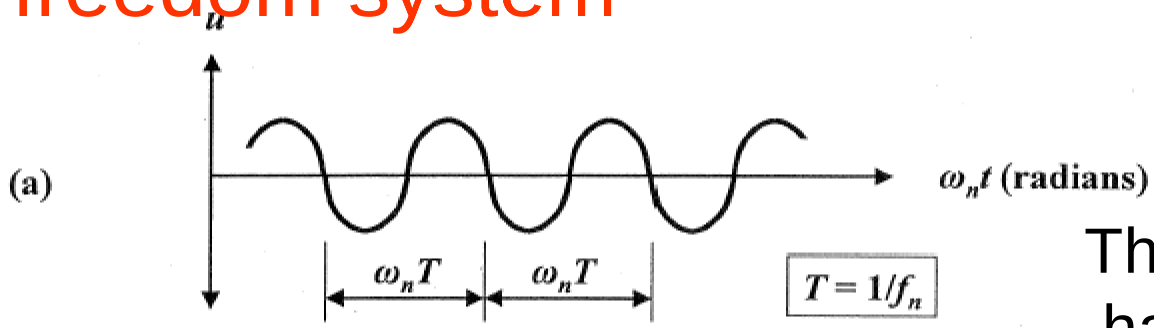
Solution:

$$x(t) = \hat{x}e^{j\omega t} \rightarrow \frac{dx(t)}{dt} = j\omega\hat{x}e^{j\omega t} \qquad \frac{d^2x(t)}{dt^2} = -\omega^2\hat{x}e^{j\omega t}$$

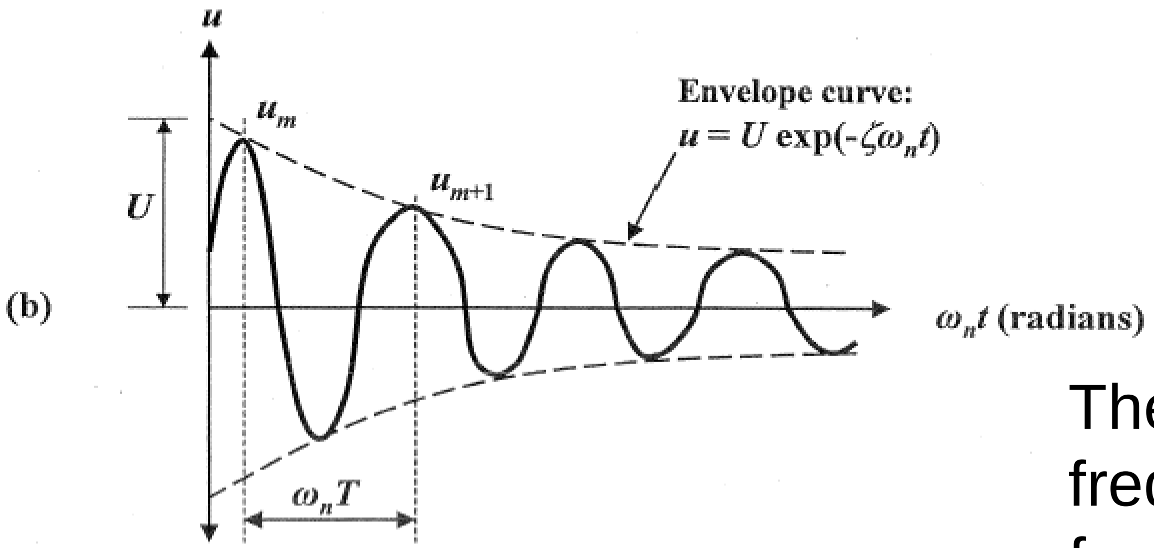
$$\beta = \omega/\omega_0 \qquad \omega_0 = \sqrt{\frac{k}{m}}$$

$$\xi = c/c_{cr} \qquad c_{cr} = 2\sqrt{km}$$

Time-history responses for single degree of freedom system



The period T of simple harmonic motion

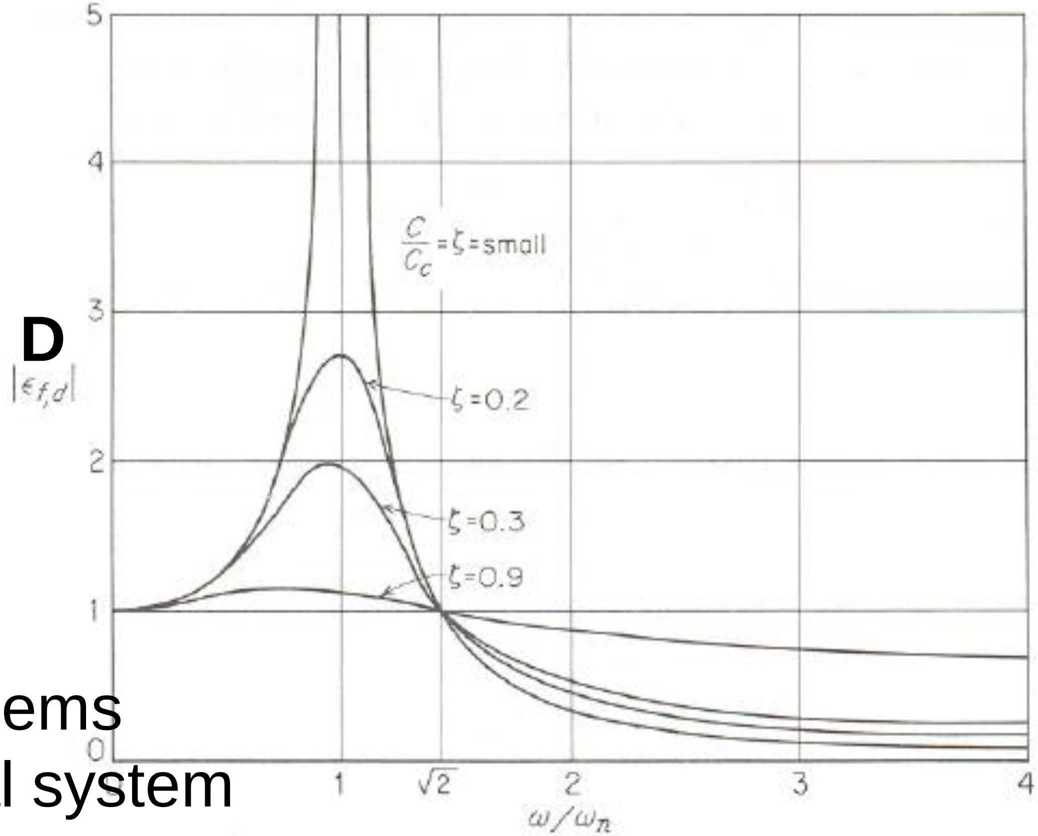


The angular natural frequency for
free damped oscillation

Dynamic amplification factor, D

D is the ratio of the vibration amplitude to the static displacement

D

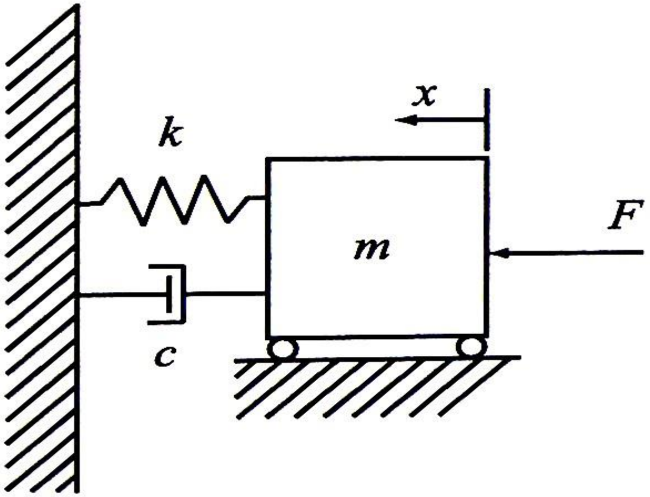


Practical strategy for minimising vibration problems is to ensure that structural system has high natural frequency

Theory (cont'd)

Dynamic amplification factor

$$D = \frac{1}{\sqrt{\left(1-\beta^2\right)^2 + \left(2\xi\beta\right)^2}}$$



$$\beta \approx 1 \Rightarrow D \approx \frac{1}{2\xi}$$

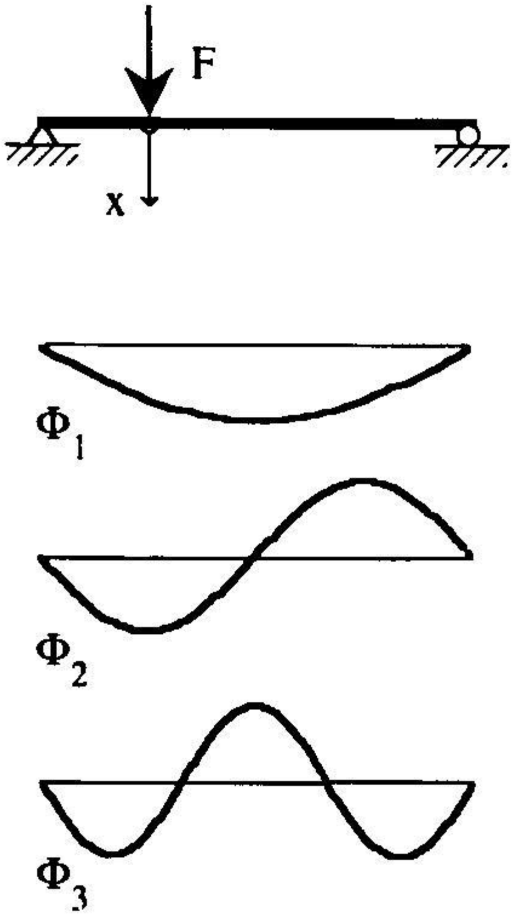
ξ = 0.04 $\rightarrow$ D = 12.5 !!

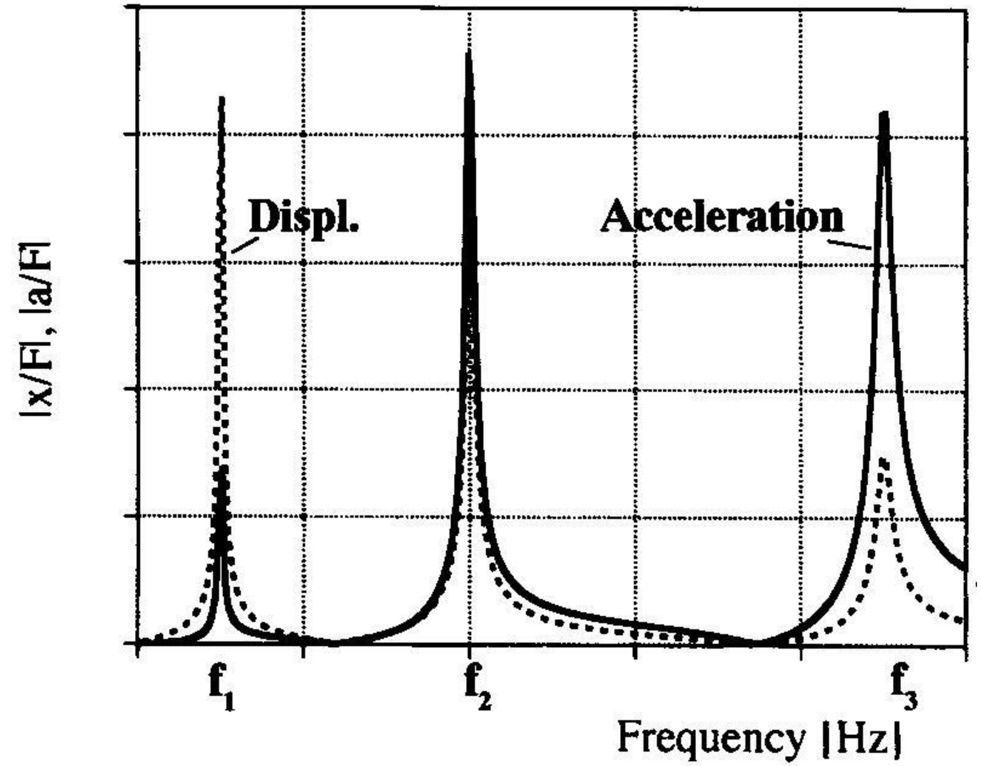
$$D_{\max} = \frac{1}{2\xi\sqrt{1-\xi^2}} \quad for \quad \beta = \sqrt{1-2\xi^2}$$

It can be shown: $and \quad \xi \leq 1/\sqrt{2}$

Usually $\xi^2 << 1$

Beam, simply supported





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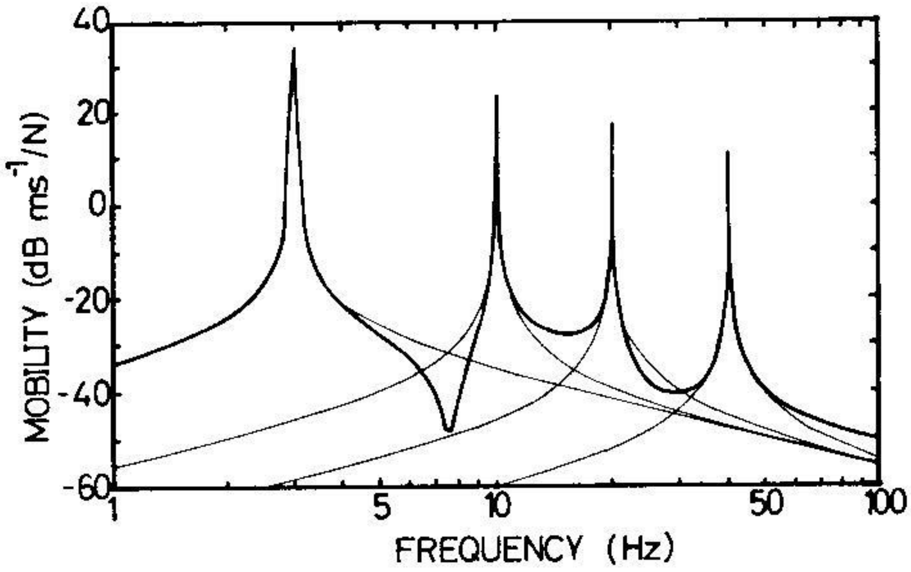
MDOF, Modal analysis

Resonance

Vibration modes

- Resonance frequency, f_n
- Modal mass, M_n
- Modal stiffness, K_n
- Mode shape, $(\phi_n(x,y))$
- Modal damping, C_n
  - Modal damping ratio,
    $\zeta_n = C_n/C_{cr}$



Isotropic plate

Isotropic plates

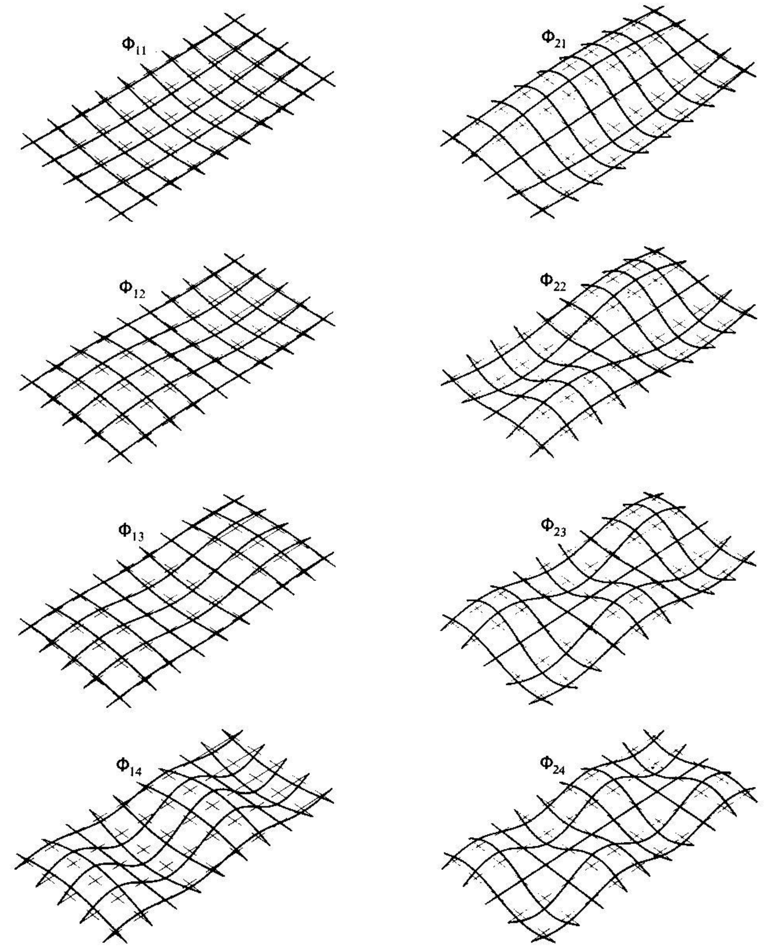
The resonance frequencies for rectangular isotropic plates simply supported along all four edges can be written as

$$f_{mn} = \frac{\pi}{2}\sqrt{\frac{D}{gL^4}}\left[m^2 + n^2\left(\frac{L}{B}\right)^2\right] \qquad \text{(A1)}$$

where m and n refer to the associated normal modes in accordance with the figure overleaf. For a unit width of the plate, the plate stiffness $D = Et^3/12\,(1-\nu^2)$ is approximately equal to EI.

Values of the expression $(m^2 + n^2(L/B)^2)$ are tabulated below for some low values of m and n.

Resonance No	L/B	1.0	0.5	0.25	0.10
f_{11}		2.00	1.25	1.06	1.01
f_{12}		5.00	2.00	1.25	1.04
f_{13}		10.00	3.25	1.56	1.09
f_{14}		17.00	5.00	2.00	1.16
f_{15}		26.00	7.25	2.56	1.25
f_{21}		5.00	4.25	4.06	4.01
f_{22}		8.00	5.00	4.25	4.04
f_{23}		13.00	6.25	4.56	4.09



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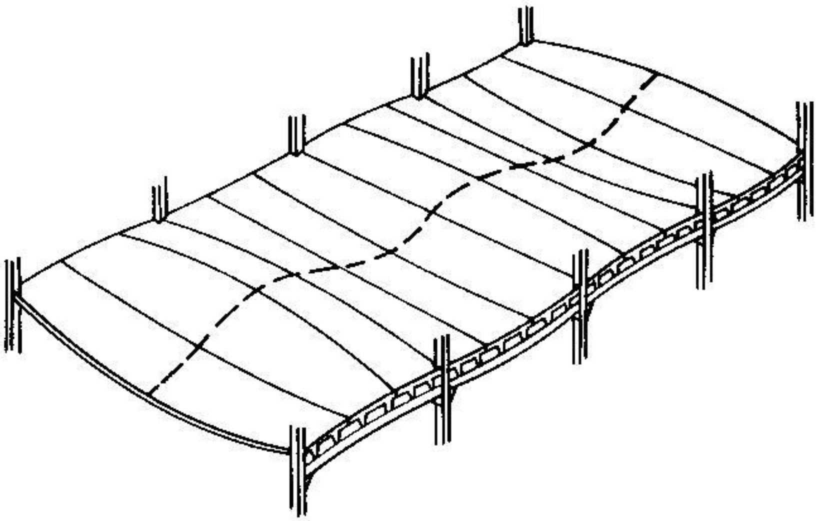
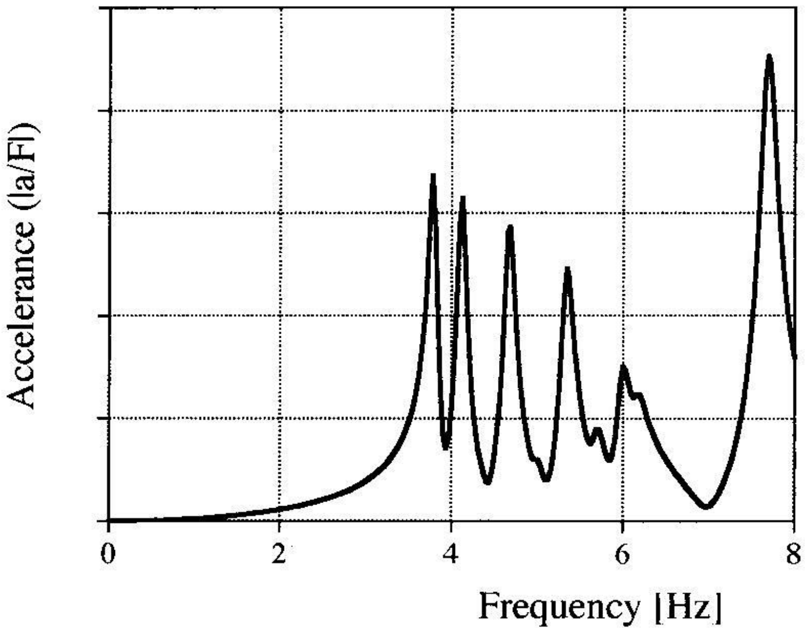
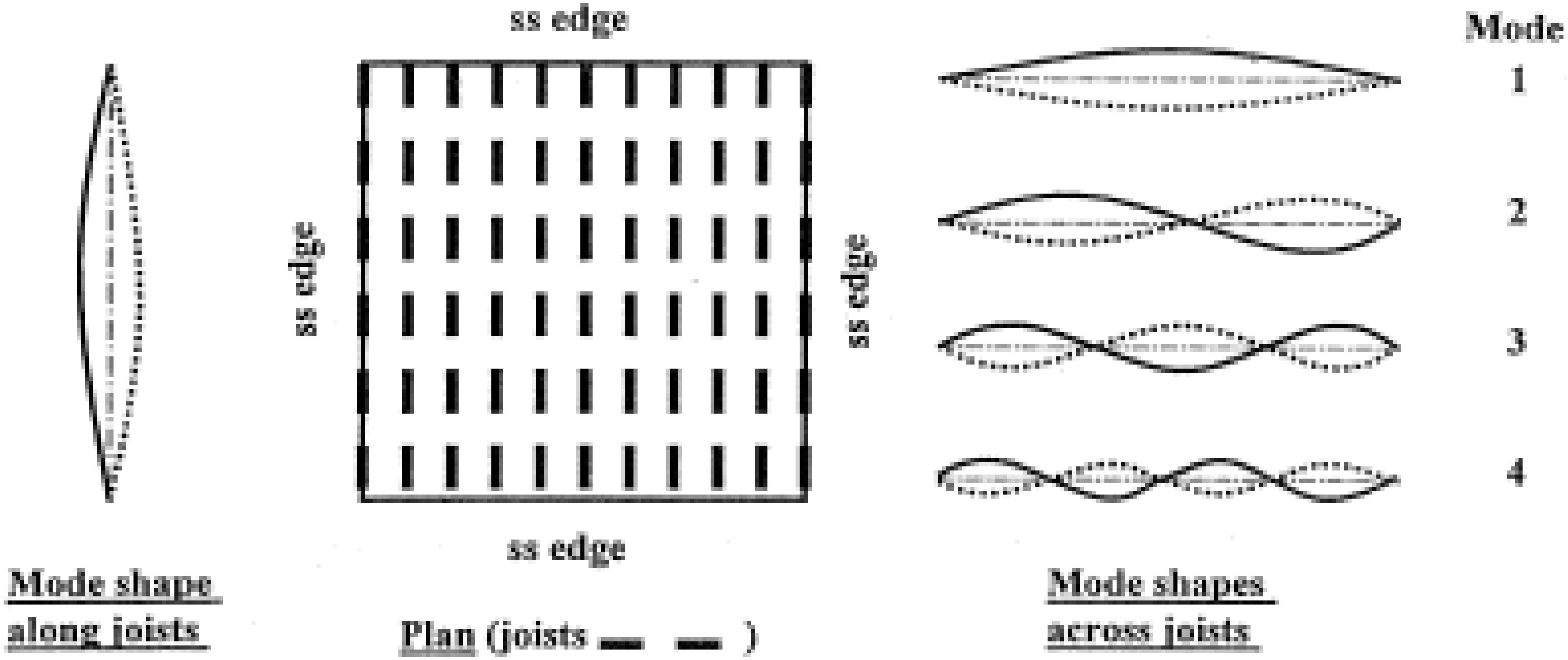
Orthotropic plate

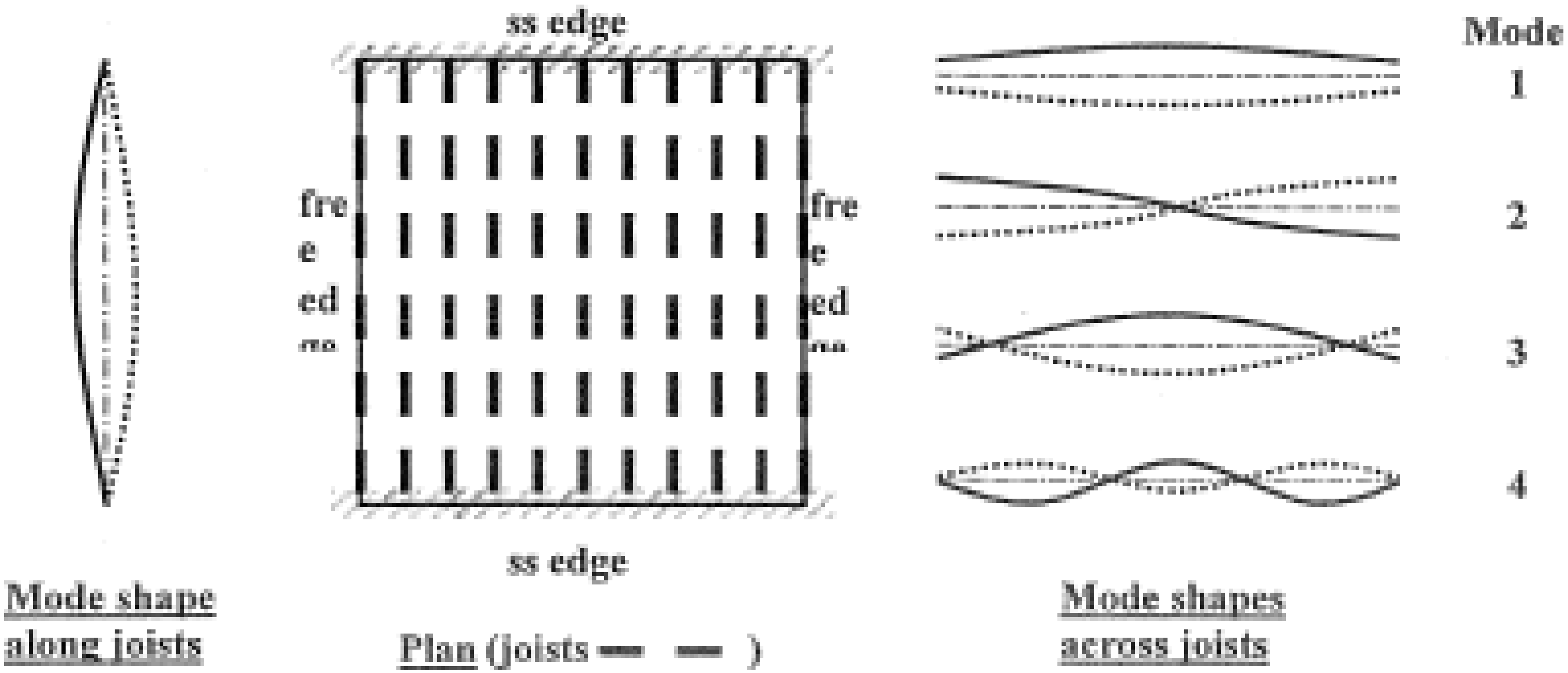




Typical mode shapes for a rectangular joisted floor / plate simply-supported (ss) on all edges



Typical mode shapes for a rectangular joisted timber floor / plate supported on two edges



The reciever

People

Vibration evaluation?

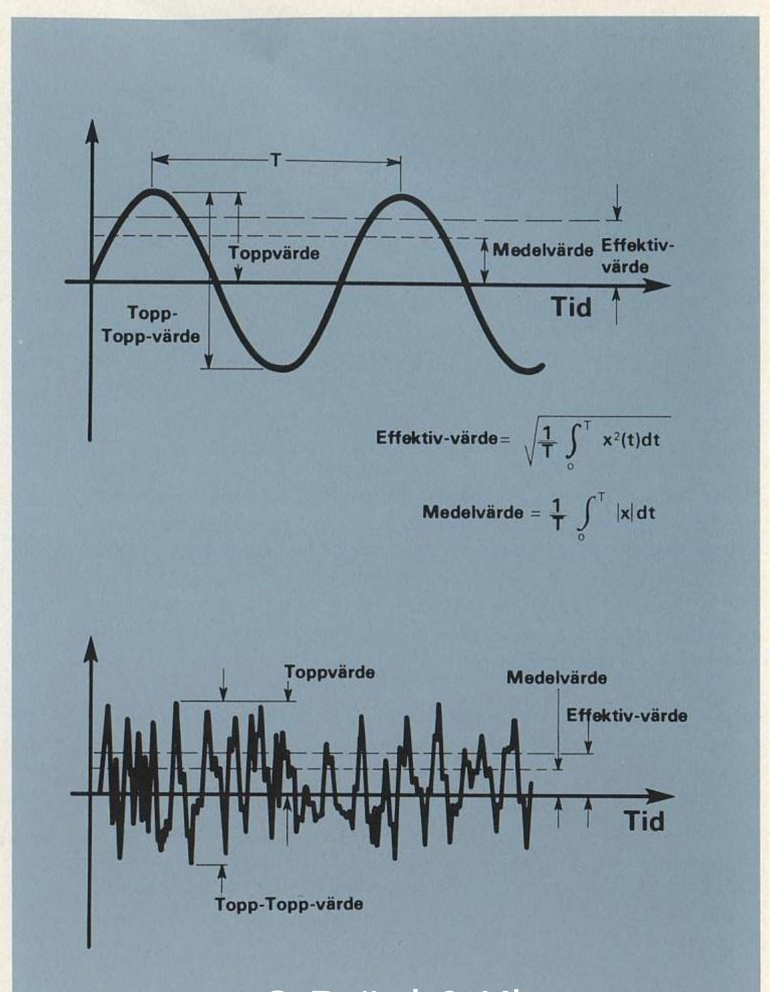
How to quantify the vibration level?

peak-to-peak: typically used when a max stress level

peak value: for transients, no information about vibration duration

mean value: of no interest

RMS value: relates to the vibration energy content



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Human perception

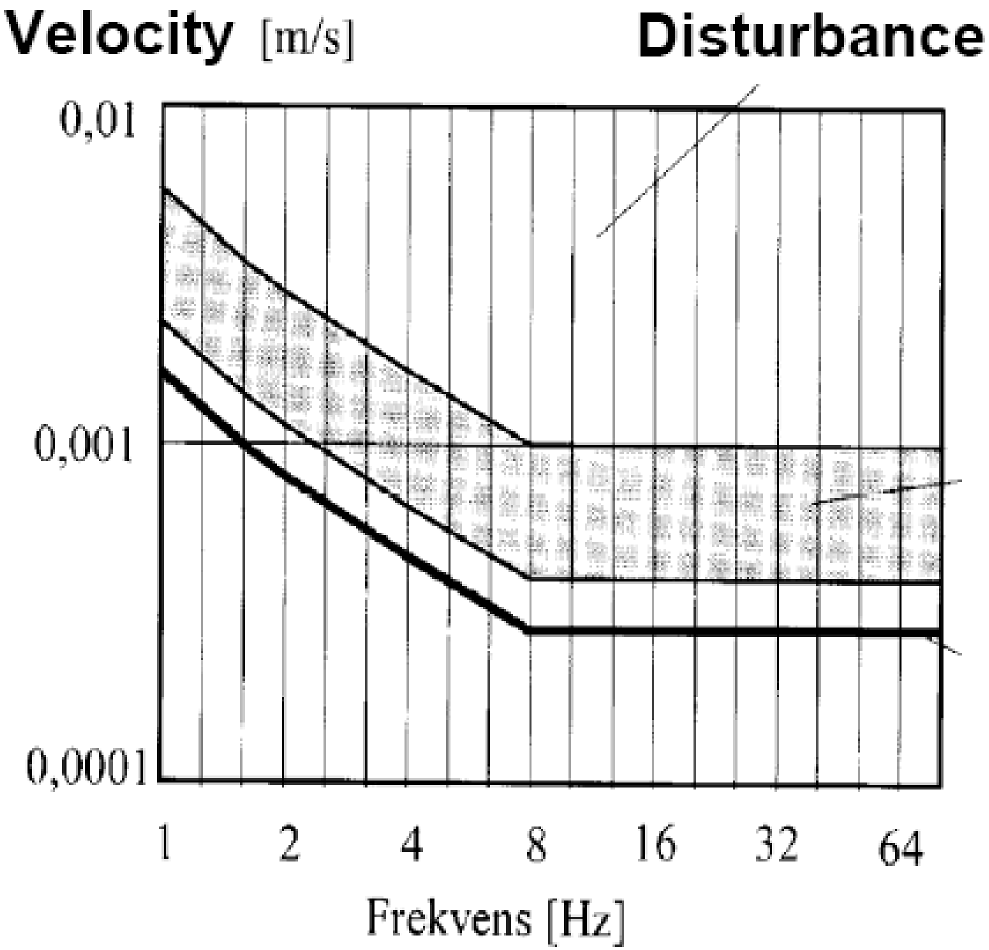
Perception of motion:

0.05 – 1.0Hz balance, motion sickness
1.0 – 8.0 Hz global body resonances
8.0 – 80 Hz complex reaction

Level of perception**:** 5 mm/s^2 @ 8Hz

Vibrations in the audible frequency range: (16 Hz –20 kHz)

Human perception of vibrations



Moderat Distur-bance

Distur-bance limit

ISO 2631-1 1985

Discomfort due to vibration

Depends on:

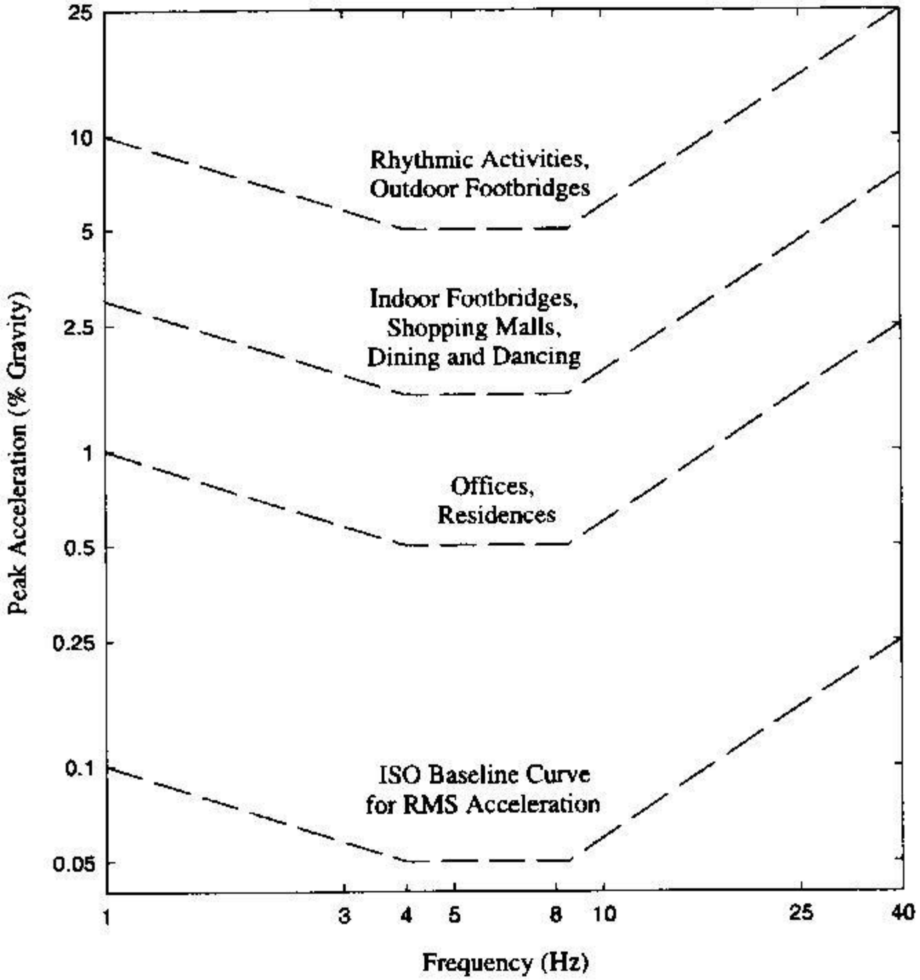
Amplitude

Frequency

Duration

Activity and ”motivat
of recipient

…and is strongly
subjective!



Murray *et al*

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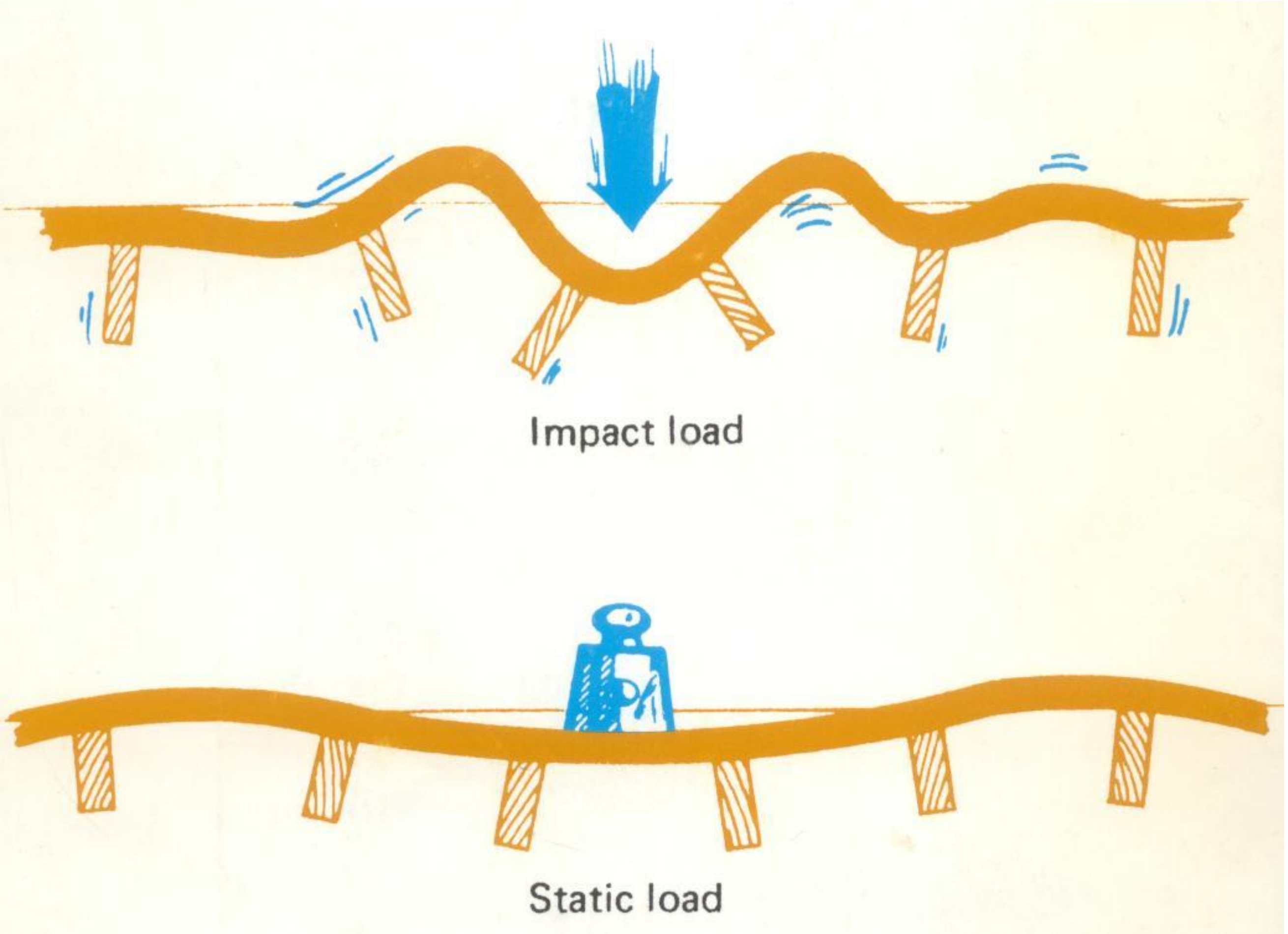
Design for statics, check for dynamics or vice versa?



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Low-frequency and high-frequency floors

Low-frequency floors

- Lowest natural frequency below 8-10 Hz
- Harmonic force components worst
- Weight (normally) sufficient for impulsive part

High-frequency floors

- Lowest natural frequency higher than 8-10 Hz
- Normally smaller spans
- Impulsive part of force most important in combination with damping

Evaluation of high-frequency (light-weight) systems

Criteria:

- Deflection
- Springiness
- Vibration

Important parameters:

- Stiffness
- Mass
- Edges
- Transverse stiffness
- Damping

Structural flexibility

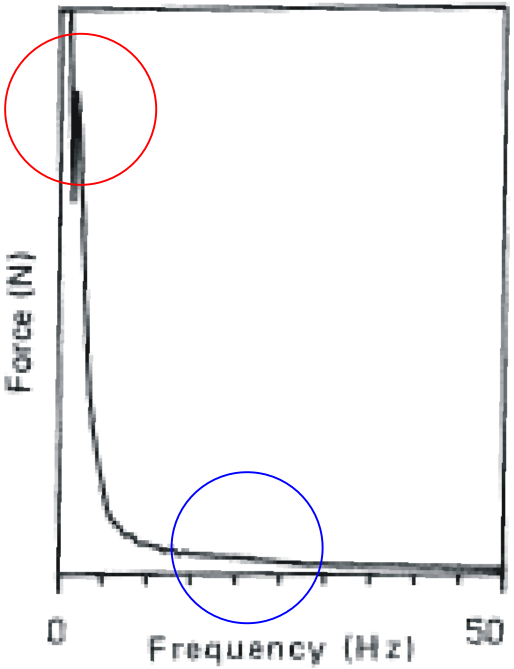

Fig. 1.1 Footstep force as a function of frequency due to a walking person

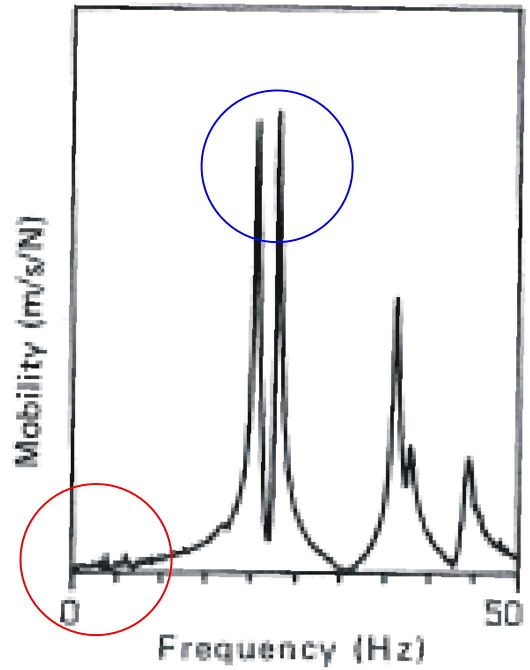

Fig. 1.2 Mobility. The peaks mark the resonance frequencies

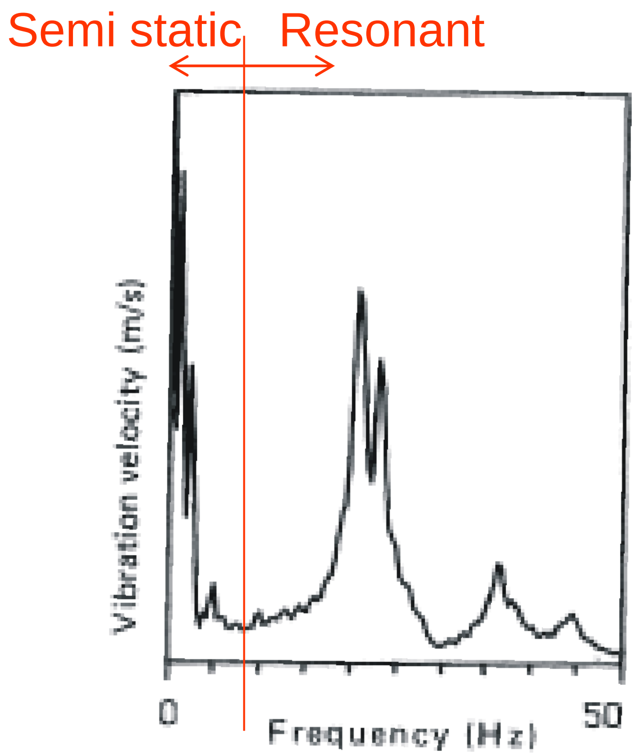

Fig. 1.3 The resulting vibration velocity

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Design criteria – high-frequency light weight floors

EN1995-1-1, ch 7

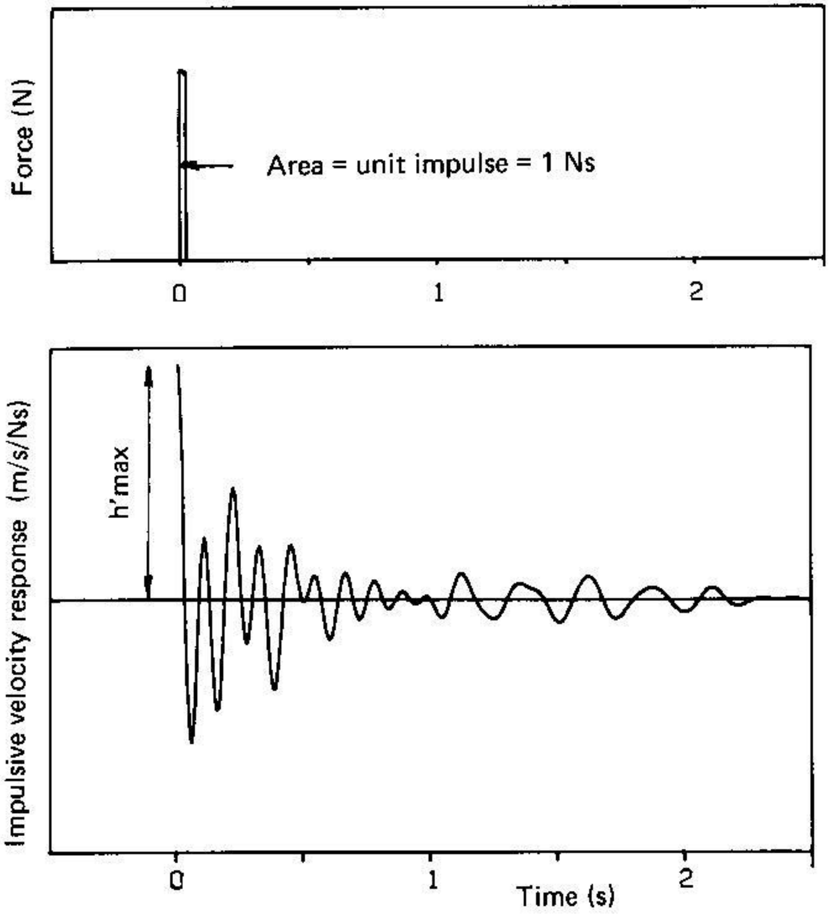
- Deflection criterion
- Impulse response criterion

(Based on Springiness and human-induced floor vibration, Swedish Council for Building Research, D12:1988)

The assessment method

Static criterion:
Deflection under 1 kN point load ~1.5 mm

Impulse response criterion:
$h'_{max} < 100^{(f_1\zeta-1)}$ m/(Ns^2)



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Acceptable impulse response

$h'_{max} = \nu < b^{(f_1\zeta-1)}$ m/(Ns^2)

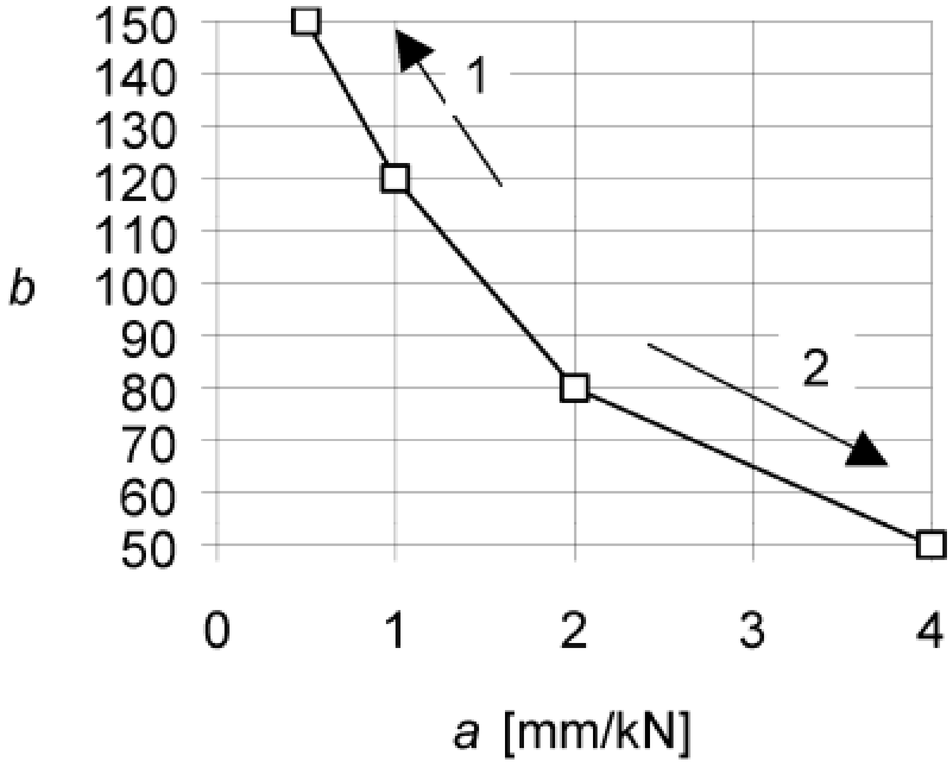
$f_1\zeta = \sigma_0$

ζ = 1% (EN1995-1-1, 7.3.1)

$$\nu = \frac{4(0,4 + 0,6\,n_{40})}{m b \ell + 200}$$

$\Rightarrow$ higher velocity acceptable if respons decays faster

(see also EN1995-1-1,7.3.3)



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Calculation of impulse response h'_{max}

The initial velocity at the point of application of the load (x_o, y_o) can be written as

$$w'_{max} = F \cdot t \cdot \sum_{n=1}^{\infty} \frac{\Phi_n^2(x_o, y_o)}{m_n} \quad \left[m/s \right] \tag{4.1}$$

The initial response due to an idealised unit impulse at the point (x_o, y_o) is thus

$$h'_{max} = \sum_{n=1}^{\infty} \frac{\Phi_n^2(x_o, y_o)}{m_n} \quad \left[\frac{m/s}{Ns} \right] \tag{4.2}$$

It has been shown that the impact loads caused by footsteps mainly excite natural frequencies < 40 Hz, and it is therefore proposed that summation should be confined to normal modes $n \leq N_{40}$:

$$h'_{max} = \sum_{n=1}^{N_{40}} \frac{\Phi_n^2(x_o, y_o)}{m_n} \quad \left[\frac{m/s}{Ns} \right] \tag{4.3}$$

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In the general case, the following operations are then required for calculation of h' max:

- Calculation of natural frequencies and associated normal modes and modal masses for resonances < 40 Hz.
- Identification of the most 'flexible' point (x_o, y_o) which gives the highest value of h' max.
- Calculation of h' max.

For floor constructions simply supported at all edges, first may be considered to be critical, and for this reason x_o = L/2 (midspan), see Appendix A. Further, each and every one of the modal masses m_n can be approximately put equal to one quarter of the mass of the floor construction

$$m_1 = m_2 = \ldots\ldots = m_n = gBL/4 \quad [kg] \tag{4.4}$$

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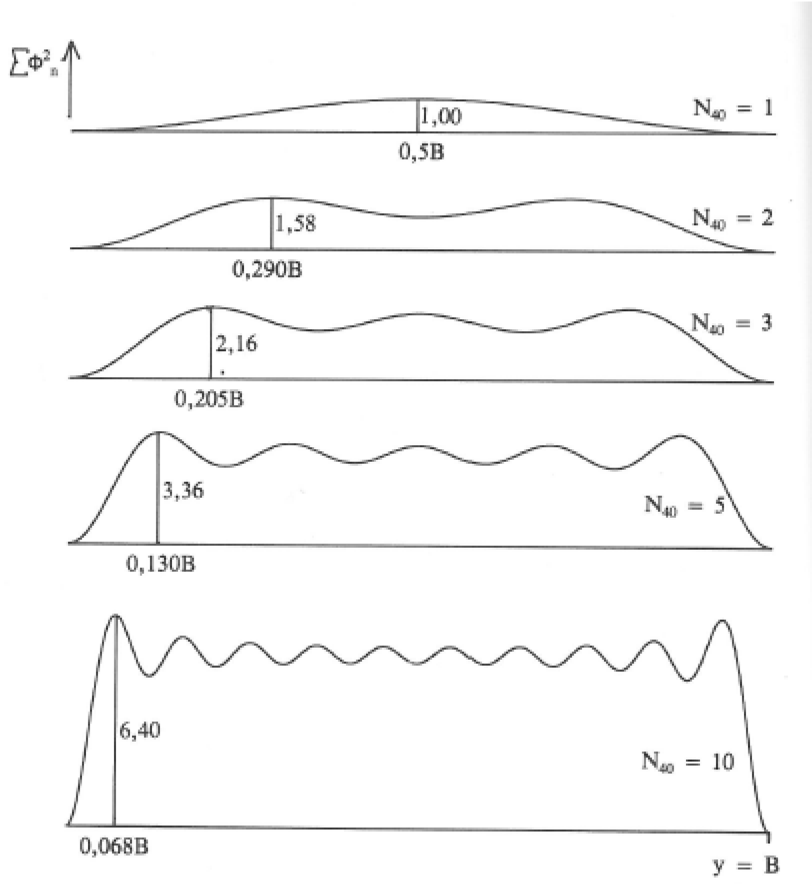
The most flexible point



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on condition that $\Phi_n max = 1$ (normalising). For this case, Equation (4.3) can be simplified to read

$$h'_{max} = \frac{4}{gBL} \cdot \left(\sum_{n=1}^{N_{40}} \Phi_n^2 \right)_{max} \qquad \left[\frac{m/s}{Ns} \right] \qquad (4.5)$$

The maximum value of the summation has been approximately calculated in Appendix B and is ≈ 0.4 + 0.6 N_{40}. We can then write

$$h'_{max} = \frac{4 \cdot (0{,}4 + 0{,}6\, N_{40})}{gBL} \qquad \left[\frac{m/s}{Ns} \right] \qquad (4.6)$$

where N_{40} can be read off the charts in Appendix A.

$$h'_{max} = \frac{4 \cdot (0{,}4 + 0{,}6\, N_{40})}{gBL + 200} \qquad \left[\frac{m/s}{Ns} \right]$$

EN1995-1-1: $N_{40} = (((40/f_1)^2 - 1) * (b/l)^4 * (EI)_l/(EI)_b)^{0,25}$

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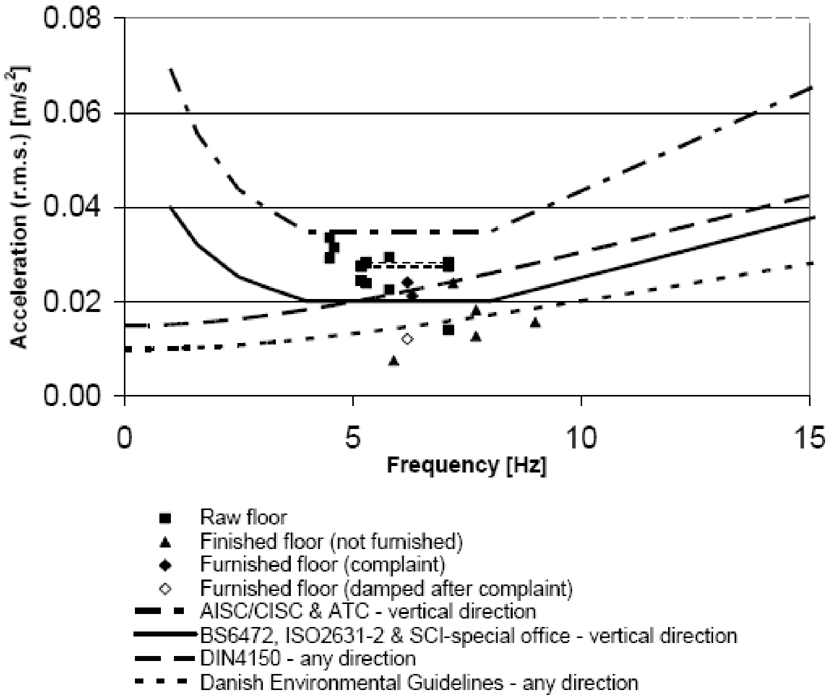
Evaluation of low-frequency floors / pedestrian bridges



Important parameters:

- Resonance frequencies
- Vibration modes (mass)
- Force model
- Annoyance criteria

Design criteria

- AISC Design Guide 11 (Murray *et al*), 1997
- SCI Design Guide (Wyatt), 1989
- Sètra – for pedestrian bridges

Coderelated acceptance levels (acceleration)

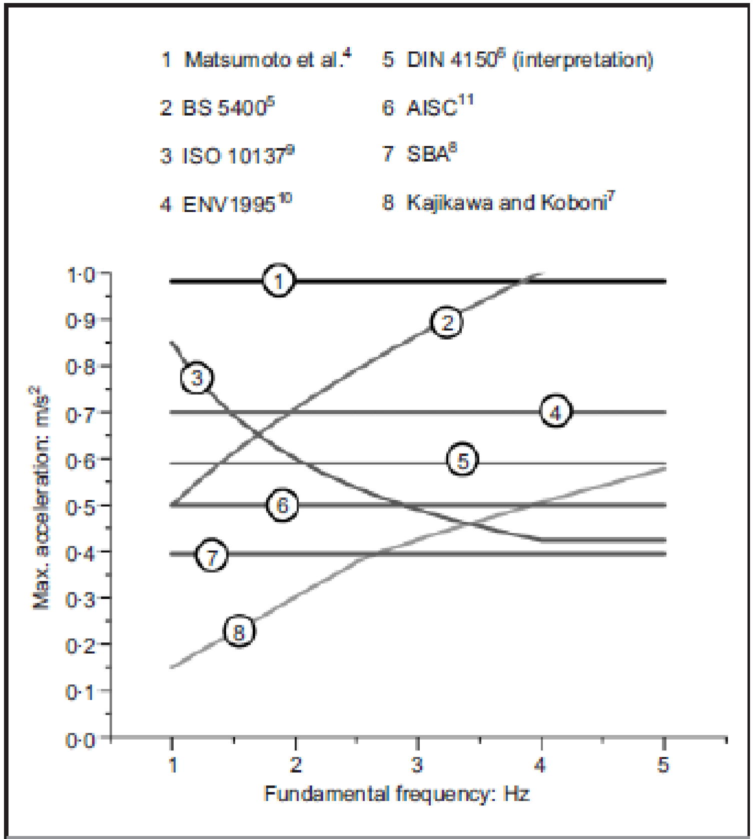


Fig. 1. Comparison of some recommended acceleration limits for the design of pedestrian bridges

Sétra

service d'Études techniques des routes et autoroutes

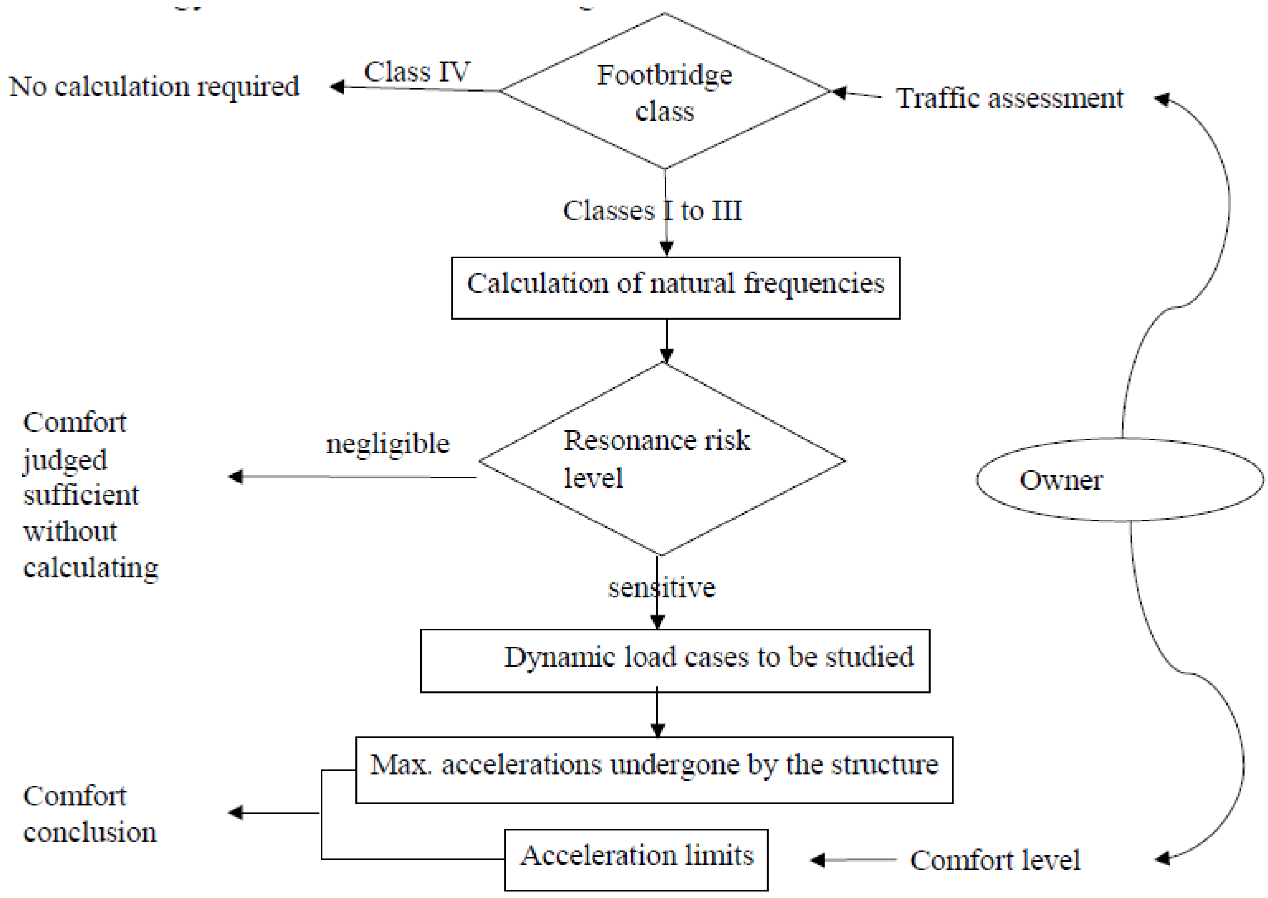
october 2006

Technical guide

Footbridges

Assessment of vibrational behaviour of footbridges under pedestrian loading

General approach – pedestrian bridges



from Sètra document

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Practical approach

Sètra & BS EN

Classification of bridge for pedestrian density and comfort level

Equivalent No of persons as design load applied on structure

Steady state response

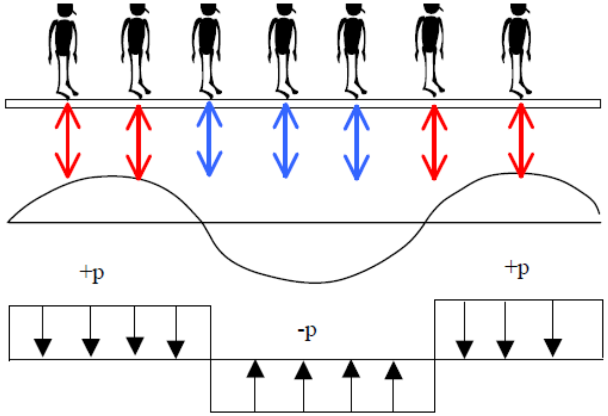
EN 1995-2

Simple approach, three cases

Comfort level: 0.7 m/s2

Based on fib, bulletin 32

Simply supported beam



from Sètra document

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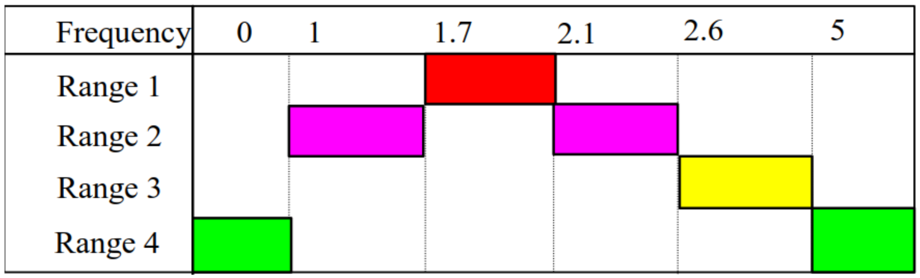
Is calculation necessary?

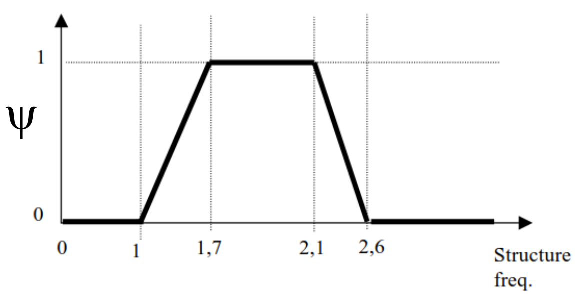
Eurocode 2 (Ref. [4])	1.6 Hz and 2.4 Hz and, where specified, between 2.5 Hz and 5 Hz.
Eurocode 5 (Ref. [5])	Between 0 and 5 Hz
Appendix 2 of Eurocode 0	<5 Hz
BS 5400 (Ref. [6])	<5 Hz
Regulations in Japan (Ref. [30])	1.5 Hz – 2.3 Hz
ISO/DIS standard 10137 (Ref. [28])	1.7 Hz – 2.3 Hz
CEB 209 Bulletin	1.65 – 2.35 Hz
Bachmann (Ref. [59])	1.6 – 2.4 Hz

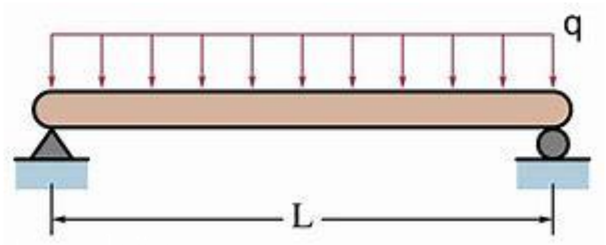
Sètra example



Class	Density *d* of the crowd
III	0.5 pedestrians/m^2
II	0.8 pedestrians/m^2

Direction	Load per m²
Vertical (v)	$d \times (280\text{N}) \times \cos(2\pi f_v t) \times 10.8 \times (\xi / n)^{1/2} \times \psi$





$$a = \frac{2q}{\pi m \xi} \qquad q = d \cdot 280 \cdot 10.8 \sqrt{\frac{\xi}{n}} \cdot \psi$$

ξ = modal damping

m = mass per meter

n = number of persons on bridge

To conclude:

Design for dynamics and check for statics.

Use simple models when possible.

Thank you for listening!

contact

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