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Modelling of the People induced vibration of structures and „vice – versa”

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INTRODUCTION

- Several structures such as theatres, concert halls, dance floors, meeting rooms and footbridge, are designed to hold ***large numbers of human occupants***.
- The aesthetic demands of designers and recent advances in material and fabrication technologies have enabled the design and construction of stylish, ***light and slender long span structures***.
- Consequently, the modern structures have become ***flexible*** and prone to human induced vibrations.
- Hence, vibration serviceability issues have arisen whereby the structures may be excited by occupying humans to ***discomforting or disturbing levels of vibration***.

INTRODUCTION

- Correct design of structure has to face two different issues: the ***dynamic load*** induced by the motion of the occupants and the ***modification of the modal dynamic parameters*** of the structure due to the presence of the crowd.
- Those aspects are grouped in the so- called ***"human – structure interaction"*** .
- The modern trend in structure design to realize more slender structures results in an ***increase of stands flexibility***, i.e., in lower natural frequencies of the structures, approaching the typical range of induced loads.
- The coupling of these two aspects can lead to ***dangerous vibrations*** of the stands, both in terms of people's comfort and structure serviceability.

INTRODUCTION

- Suspension bridge (1980): 209,5m span.
- Measured dynamic properties:
  vertical 0,537 Hz
  transversal 0,342 Hz
  longitudinal 0,586 Hz.

SOME EARLY CASES OF EXCESSIVE VIBRATIONS IN STRUCTURE

- Probably the oldest report of noticeable vibrations in footbridges was made by Stevenson (1821): severe vibrations due to a marching regiment crossing over a bridge, indicating very early a need to consider human - induced dynamic loads in bridge design.
- Only 10 years after Stevenson's observations, a ***bridge collapse in Broughton*** was caused by marching soldiers.
- One of the earliest reported incidents of excessive lateral vibrations induced by crowds are dated back to the late 1950s, one involving a ***road/railway bridge in China*** (the Wuhan Yangtze Bridge) in 1957 (Sun and Yuan, 2008) and another one involving a ***pedestrian suspension bridge*** in Kiev following its opening in 1958 (Blekherman, 2005).

SOME EARLY CASES OF EXCESSIVE VIBRATIONS IN STRUCTURE

- Several large road bridges around the world have suffered from this problem during exceptional crowd events:
- The 120 year old ***Brooklyn Bridge in New York City*** swayed remarkably when traversed by crowds of pedestrians during a power blackout, leading to several complaints from concerned citizens.
- The first assessment of lateral crowd induced excitation was offered by Petersen (1972), who observed strong lateral vibrations of a ***steel arch footbridge at Erlach in Germany***, during crossing of about 300-400 pedestrians.
- The vibrations occurred on the 110 m long main span of the bridge at frequency around 1.1 Hz and were explained as a consequence of a lateral sway of the centre of gravity of the human body occurring at half the pacing frequency, resulting in resonant vibrations and a synchronization of the step with the oscillation of the bridge (Bachmann, 1992).

SOME EARLY CASES OF EXCESSIVE VIBRATIONS IN STRUCTURE

- One of the most cited incidents of excessive lateral vibrations occurring in the last century is related to the ***Toda Park Bridge in Toda City, Japan*** (T-Bridge) (Fujino et al., 1993; and Nakamura and Fujino, 2002).
- The bridge is a cable - stayed bridge with the overall length of 179 m divided into a main span (134 m) and a side span (45 m). The frequency of the fundamental vibration mode was reported in the range 0,9 – 1,0 Hz depending on the level of congestion.

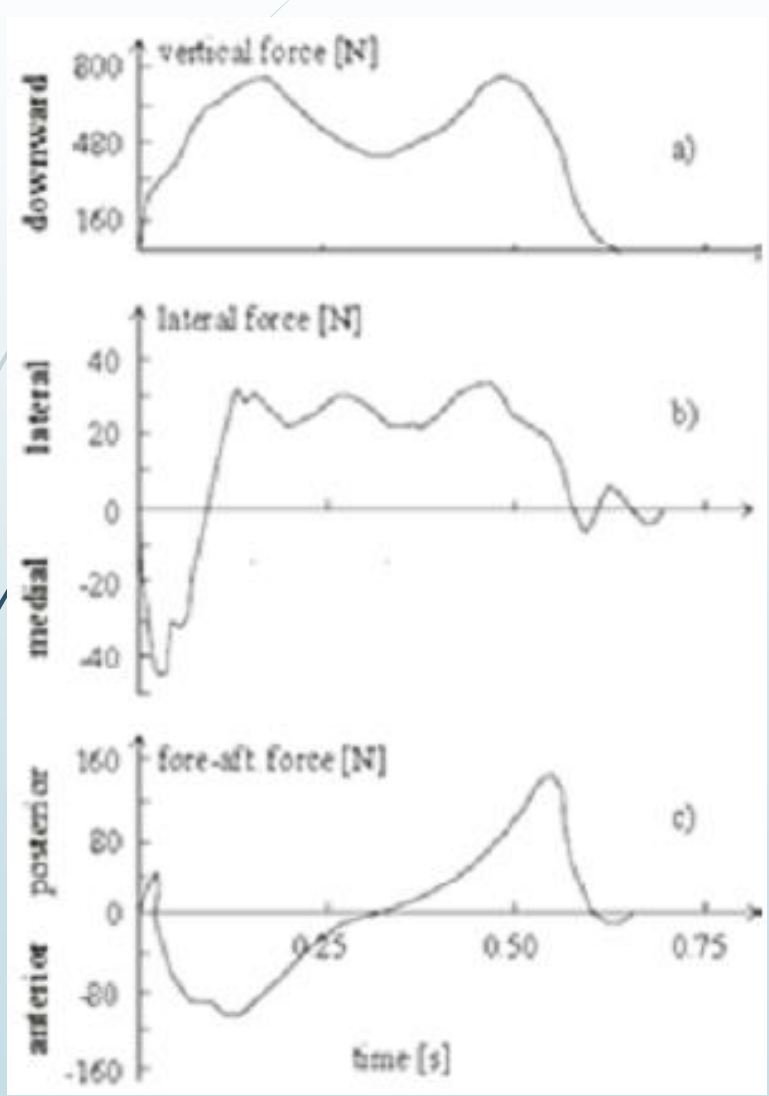
THE LONDON MILLENNIUM BRIDGE

- The London Millennium Bridge connects St. Paul's Cathedral with the Tate Modern Gallery.
- The bridge is a shallow suspension bridge in three spans; a south span of 108 m, a central span of 144 m and a north span of 81 m.
- A very light superstructure.

THE LONDON MILLENNIUM BRIDGE

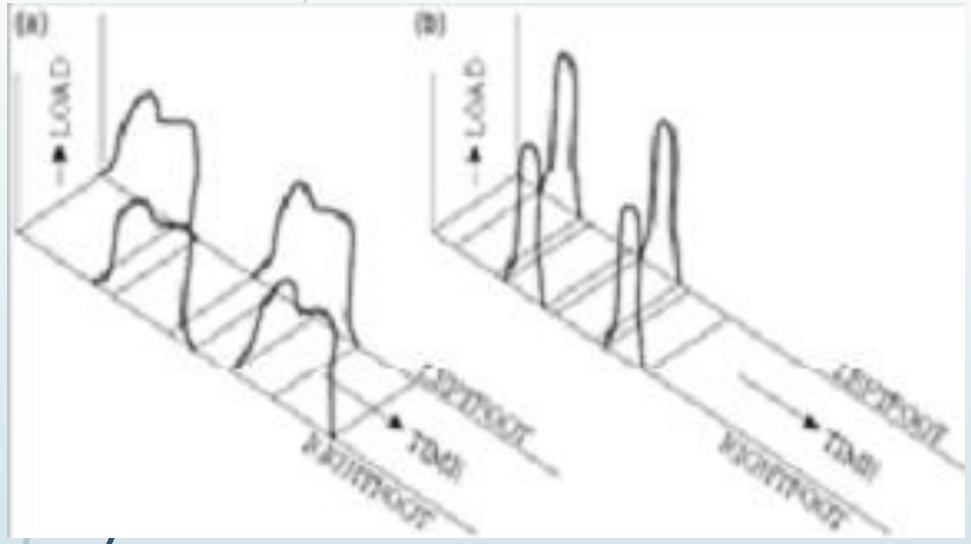
- Opening day (10/06/2000): up to 2000 people on the deck at any one time.
- Large amplitude vibrations in four different vibration modes were reported; on the Southern span at a frequency of around 0,8 Hz, at the central span in the first and second lateral vibration modes at 0,48 Hz and 0,95 Hz, respectively, and more rarely on the Northern span at a frequency of around 1 Hz.

HUMANS AS VIBRATION SOURCE FOR STRUCTURES



- During walking, a pedestrian produces a dynamic time varying force which has components in all three directions: vertical, horizontal - lateral and horizontal – longitudinal (Bachmann and Ammann, 1987).
- the vertical component of the force is regarded as the most important of the three forces because it has the highest magnitude.
- Other types of human-induced forces important for footbridges are due to running and some forms of deliberate vandal loading (jumping, bouncing or horizontal body swaying).

HUMANS AS VIBRATION SOURCE FOR STRUCTURES



- In ***walking***, foot has continuous contact with the ground with frequency range 1,6 to 2,4 Hz.
- In ***running***, foot has discontinuous contact with frequency range 2 to 3,5.
- Conventionally, for normal walking, frequency may be described by a ***Gaussian distribution*** with 2 Hz average and about 0.20 Hz standard deviation (from 0.175 to 0.22).
- Recent studies and conclusions drawn from recent testing have revealed even lower mean frequencies, around 1,8 Hz – 1,9 Hz.

HUMANS AS VIBRATION SOURCE FOR STRUCTURES

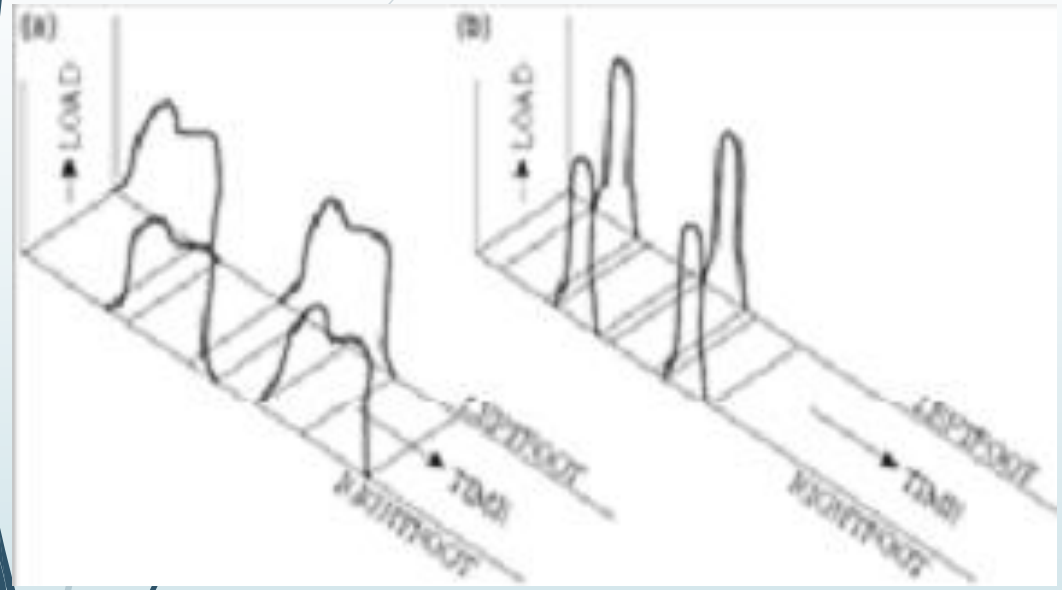
- The ***periodic function F(t)***, may therefore be resolved into a ***Fourier series***, that is a constant part increased by an infinite sum of harmonic forces. The sum of all unitary contributions of the terms of this sum returns the total effect of the periodic action.

$$F(t) = G_0 + G_1 \sin 2\pi f_m t + \sum_{i=2}^{n} G_i \sin\left(\sin 2\pi i f_m t - \varphi_i\right)$$

- where:

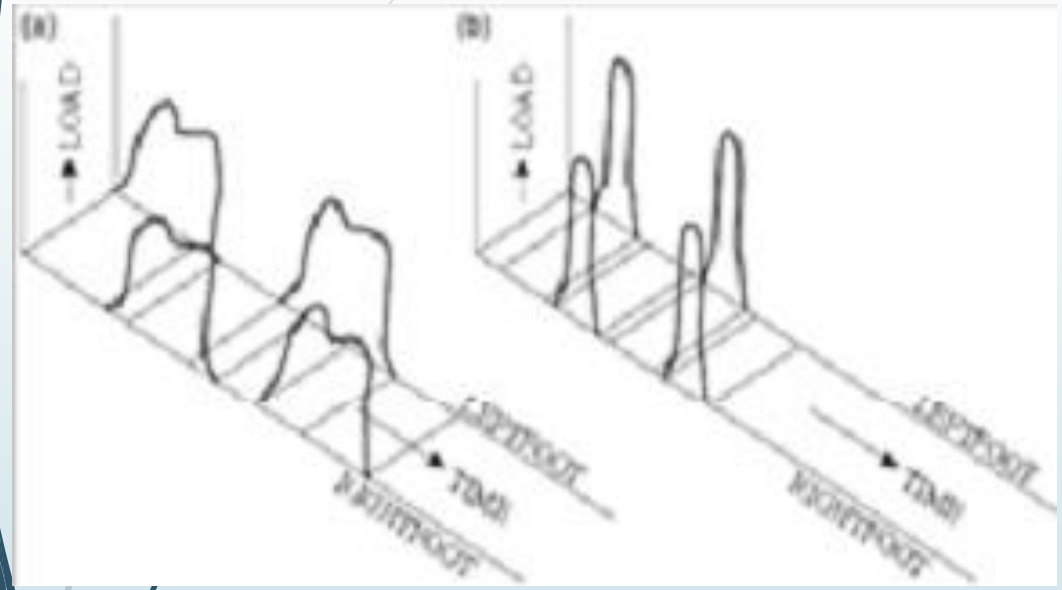
  G_0 – static force (pedestrian weight), G_1 – first harmonic amplitude, G_i – ith harmonic amplitude, f_m – walking frequency, φ_i – phase angle of the i^{th} harmonic in relation to the first one, n – numbers of harmonic taken itno account.

HUMANS AS VIBRATION SOURCE FOR STRUCTURES



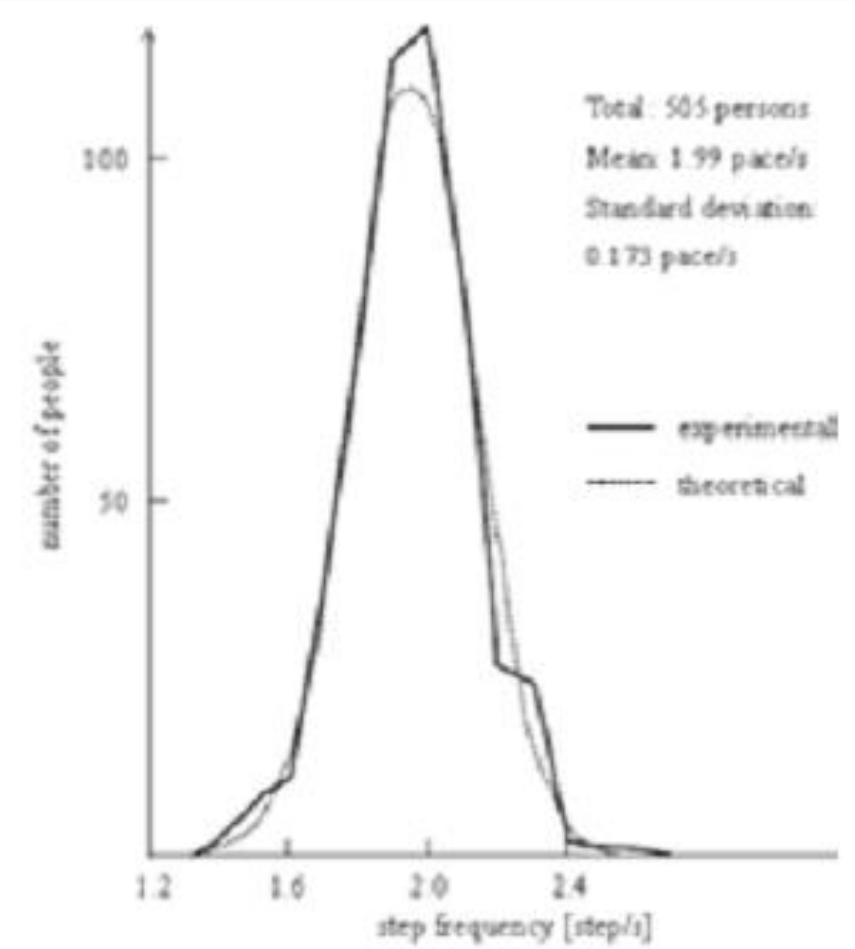
- ***Walking*** is generally characterized as regular predominantly horizontal human body motion where by at least one foot is in contact with the ground at all times, in the general frequency range of 1,4 – 2,2 Hz.
- In addition to vertical loads generated by the raising and lowering of the body centre of mass, horizontal loads arise from friction and weight-shifting. Though these horizontal loads are rarely significant individually, on a large scale (e.g., crowds) or for an unbraced structure they could prove critical.

HUMANS AS VIBRATION SOURCE FOR STRUCTURES



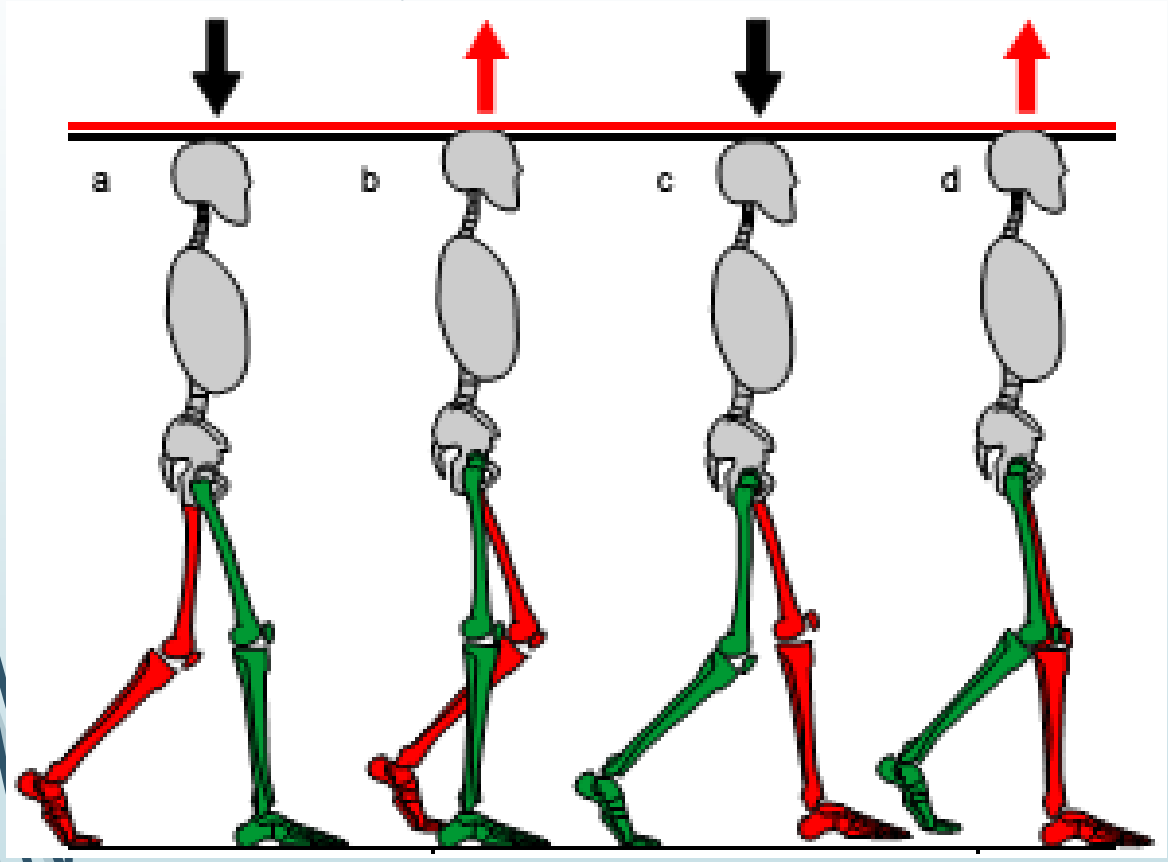
- ***Running*** is a similar activity to walking, but performed at a faster rate which results in brief periods where neither foot is in contact with the floor.
- Due to the haste of the activity, the load histories for running do not necessarily show the plateau between impact and take-off that represents the load spreading or rolling of the feet found in walking.
- Instead, running may be modeled as a series of pulses featuring single distinct peaks.

HUMANS AS VIBRATION SOURCE FOR STRUCTURES



- A reliable statistical description of normal walking frequencies was first given by Matsumoto et al. (1972 and 1978) who investigated a sample of 505 persons.
- They concluded that the frequencies followed a normal distribution with a mean pacing rate of 2,0 Hz and standard deviation of 0,173 Hz.

HUMANS AS VIBRATION SOURCE FOR STRUCTURES



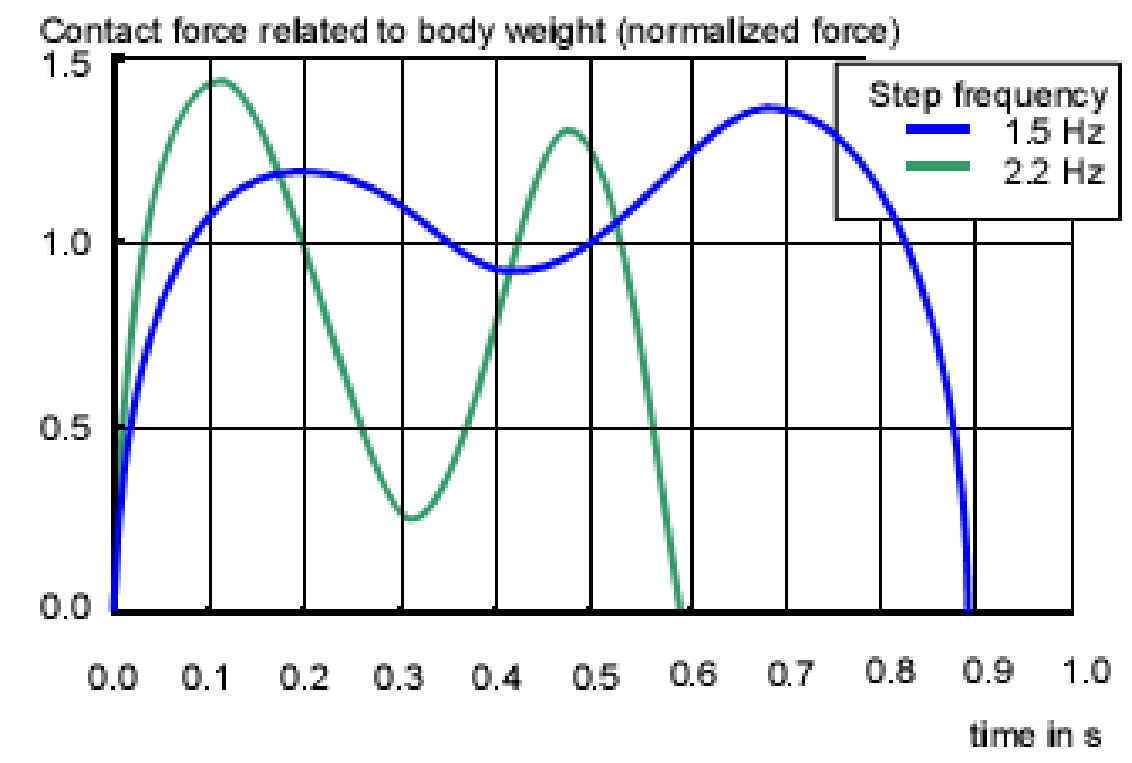
a) The right foot touches the ground with the heel. This is the starting point of the contact forces.

b) The right leg is stretched; it transmits the full body weight.

c) Rocking: the right foot rocks while the left leg swings forward.

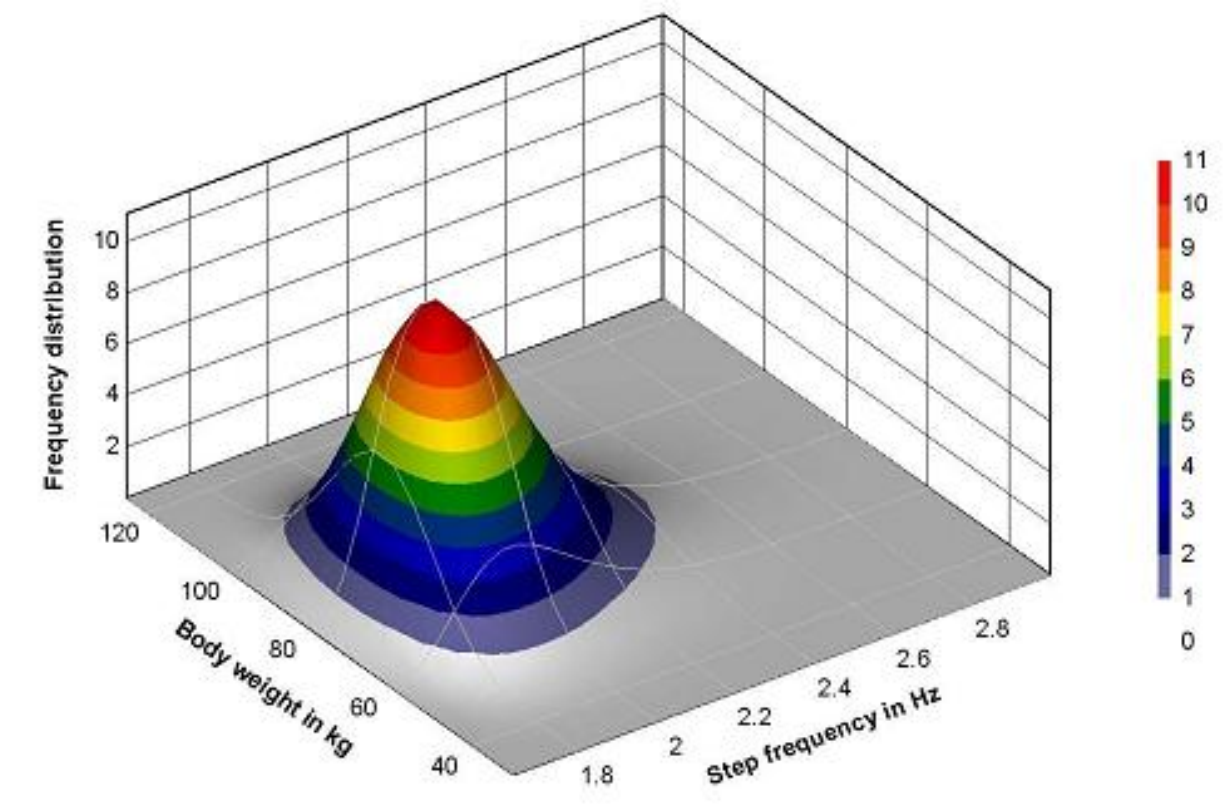
d) The left foot touches the ground while the right leg swings forward.

HUMANS AS VIBRATION SOURCE FOR STRUCTURES



- An example for the time history of the contact forces for two different step frequencies, where the amplitudes are normalized by relating them to the body weight G of the person.

HUMANS AS VIBRATION SOURCE FOR STRUCTURES



- Frequency distribution of body mass and step frequency for a population of data of 700.

FORCE MODELLING

- To successfully apply the measured dynamic forces in design it is necessary to model them analytically.
- Two types of such models can be found:
  - Time – domain models and
  - Frequency domain models.
- Time-domain models are more common.
- Mathematical modelling of human - induced dynamic forces is a complicated task because:
  - There are many different types of human - induced forces and some of them change not only in time but also in space
  - Dynamic force generated by a single person is essentially a narrow-band process which is not well understood and therefore difficult to mathematically model
  - The influence of the number of persons as well as their degree of synchronization/correlation is difficult to generalize.

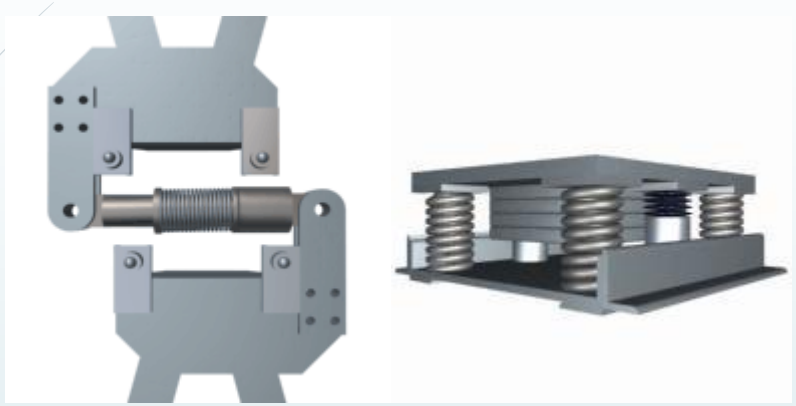
FORCE MODELLING: TIME – DOMAIN FORCE MODELS

- Time - domain models for walking and running are based on an assumption that both human feet produce exactly the same force and that the force is periodic. The assumption of perfect repetition is also frequently used in modeling of vandal loading generated by a single person and small groups.
- ***Deterministic force models***: each periodic force Fp(t) with a period T can be represented by a Fourier series.
- ***Probabilistic Force Models***: A more detailed probabilistic approach to the walking force model is based on the fact that a person will never produce exactly the same force-time history during repeated experiments. In the case of two persons it is even more so. For a single person force, which is still assumed to be periodic, randomness, can be taken into account by probability distributions of person's weight, pacing rate and so on. For several people, the probability distribution of time delay between people who perform a particular activity can be added.

VIBRATION REDUCTION TECHNIQUES FOR STRUCTURES

- ***ABSORBING DAMPER***
- In mechanical dampers the structure's oscillation damping is achieved by springs or elastic pieces.
- In hydraulic dampers - by liquids, oil or gas.
- Hydraulic or viscous damper is made of hydraulic cylinder, surrounding a piston, the head of which forms two chambers. A relative motion applied to the actuator results in a pressure difference between the two chambers, creating a potential for flow and energy dissipation.

VIBRATION REDUCTION TECHNIQUES FOR STRUCTURES

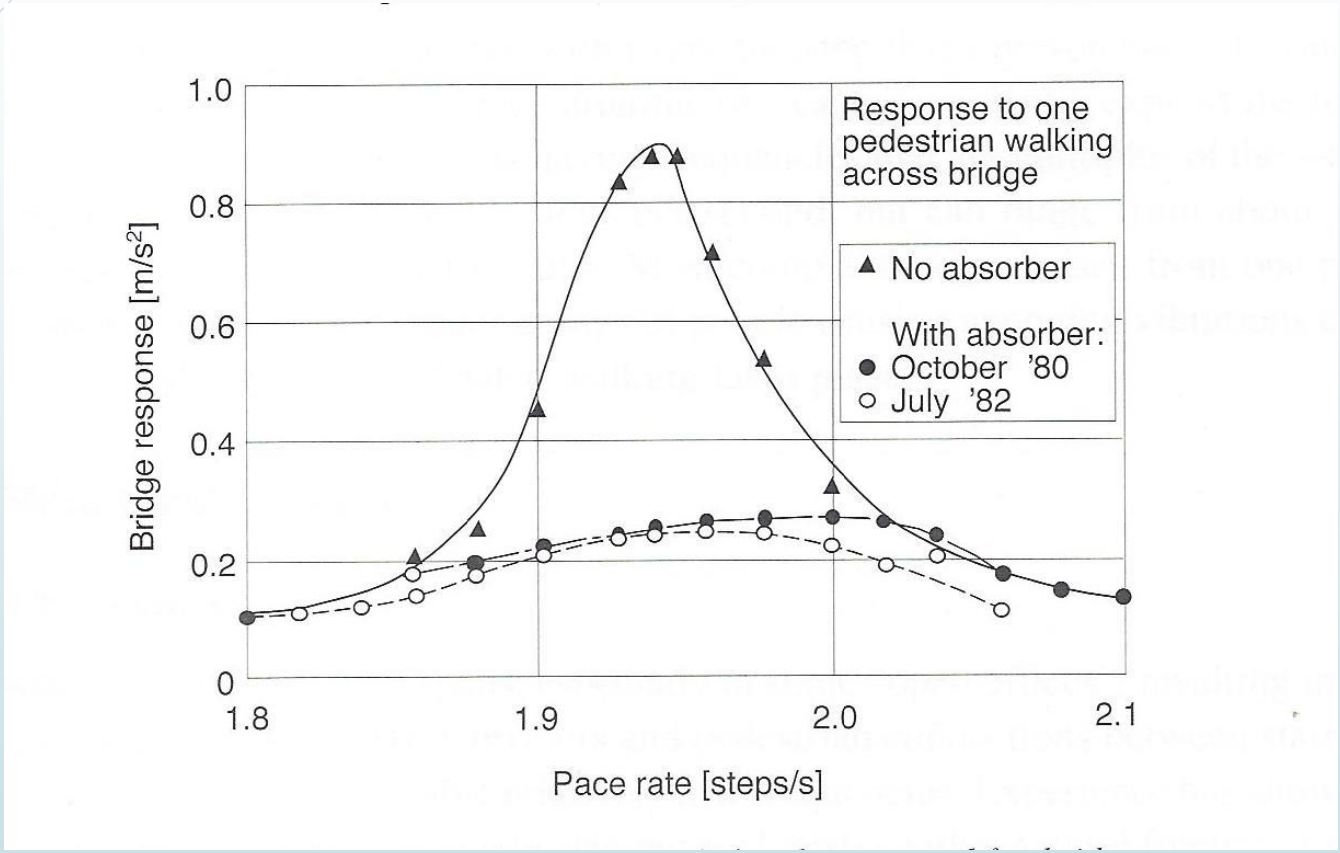


- ***TUNED MASS DAMPER (TMD)***
- TMD is a device absorbing vibrations by vibration of the self- mass.
- A TMD consists of a mass-spring damper system which is attached to the structure and carefully tuned with the structure's vibration characteristics.
- When the counterweight of the damper moves in one direction as the structure moves in the other, the damping of the structure's oscillation is achieved.

VIBRATION REDUCTION TECHNIQUES FOR STRUCTURES

- ***ACTIVE TUNED DAMPER***
- This type of vibration absorbers can suppress and tune the vibrations over a range of frequencies by incorporating a variable stiffness element that can be adjusted in real-time.
- ***STRUCTURAL OR PHYSICAL DAMPING***
- It consists of local or total structural modifications by changing mainly the stiffness or the mass of a structure.
- Such as local strengthening of members, introducing of additional beams in the cross-sections, installing a stiffer hand rail by truss or solid wall construction, intermediate piers, additional hangers, ties or cables can be mentioned.
- By these measures the natural frequencies could be changed, leading to frequency tuning of the bridge structures.

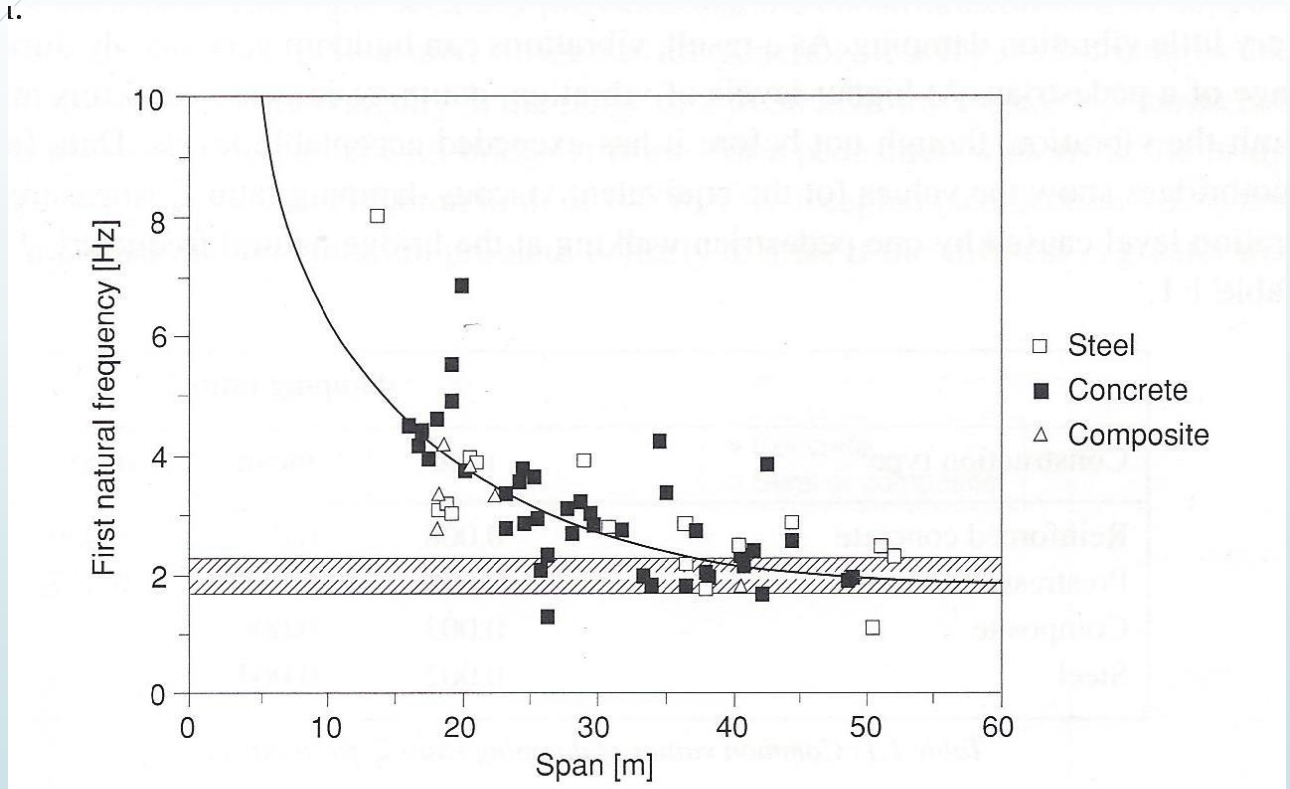
VIBRATION REDUCTION TECHNIQUES FOR STRUCTURES



LESSONS LEARNED

- Human - structure interaction is an important aspect of human - induced vibrations.
- Human induced vibration in structure has serviceability problem rather than safety.
- Vibration induced in structure play a significant role in comfort of human present on it.
- Footbridges which exhibit vibration serviceability problems are low - frequency flexible structures with natural frequencies within the normal walking frequency range.
- In such a situation, walking near to resonant frequency is expected to generate the highest level of response.
- However, the walking force is not perfectly periodic and it could be attenuated due to interaction between the structure and the pedestrian.

JUST TO REMEMBER



Footbridge fundamental frequency as a function of span

What about the "vice – versa"?

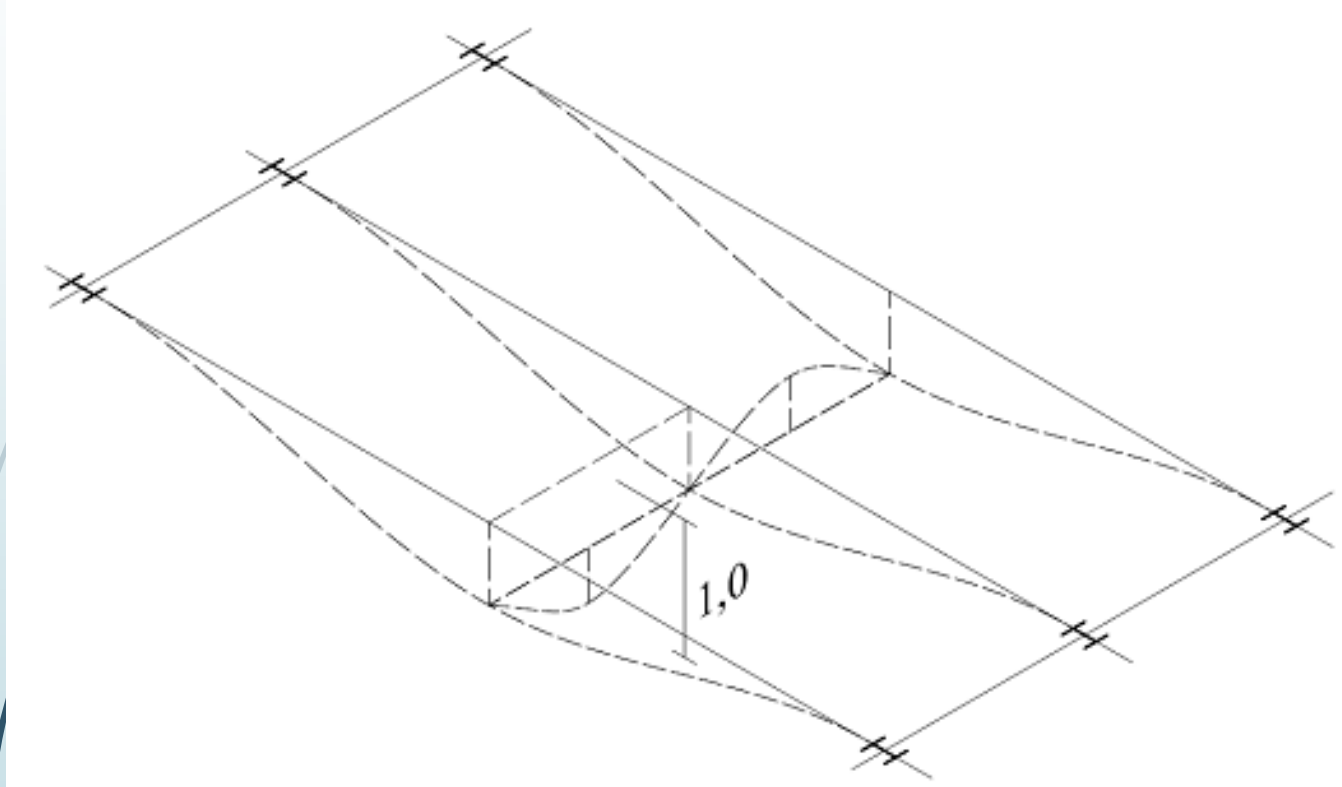
Design of floor structures for human induced vibrations

- Sustainability requires multi-storey buildings built for flexible use concerning space arrangement and usage.
- In consequence large span floor structures with a minimum number of intermediate columns or walls are of interest.
- Modern materials and construction processes, e.g. composite floor systems or prestressed flat concrete floors with high strengths, are getting more and more suitable to fulfill these requirements.
- These slender floor structures have in common, that their design is usually not controlled by ultimate limit states but by serviceability criteria, i.e. deflections or vibrations.

Design of floor structures for human induced vibrations

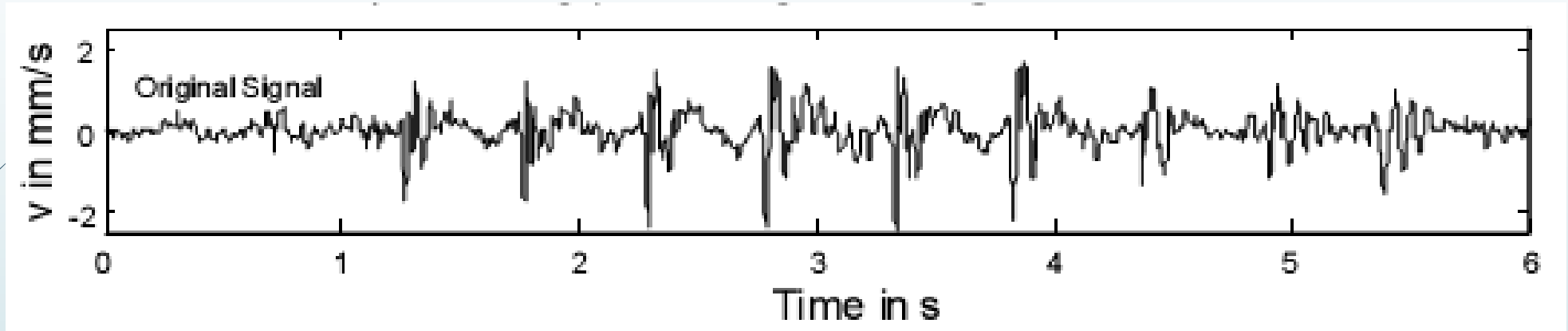
- Filigree slab with ACB-composite beams (office building)
- It is spanning one way over 4.2 m between main beams. Its overall thickness is 160 mm. The main beams are Arcelor Cellular Beams (ACB).
- For the main beams with a span of 16.8 m ACB/HEM400 profiles made of material S460 have been used.

Design of floor structures for human induced vibrations



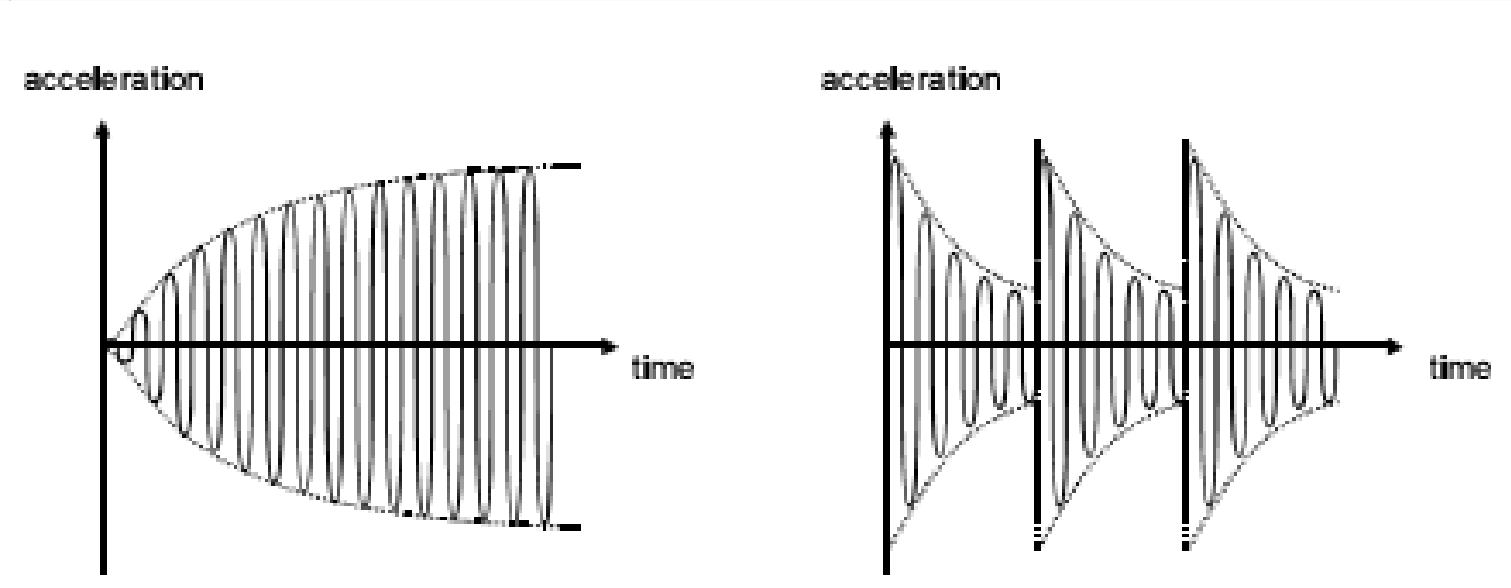
- Mode shape expected for the part of the floor considered corresponding to the first eigenfrequency.

Design of floor structures for human induced vibrations



- Typical velocity time history measured at a representative point of a floor structure excited by a walking person.

Design of floor structures for human induced vibrations

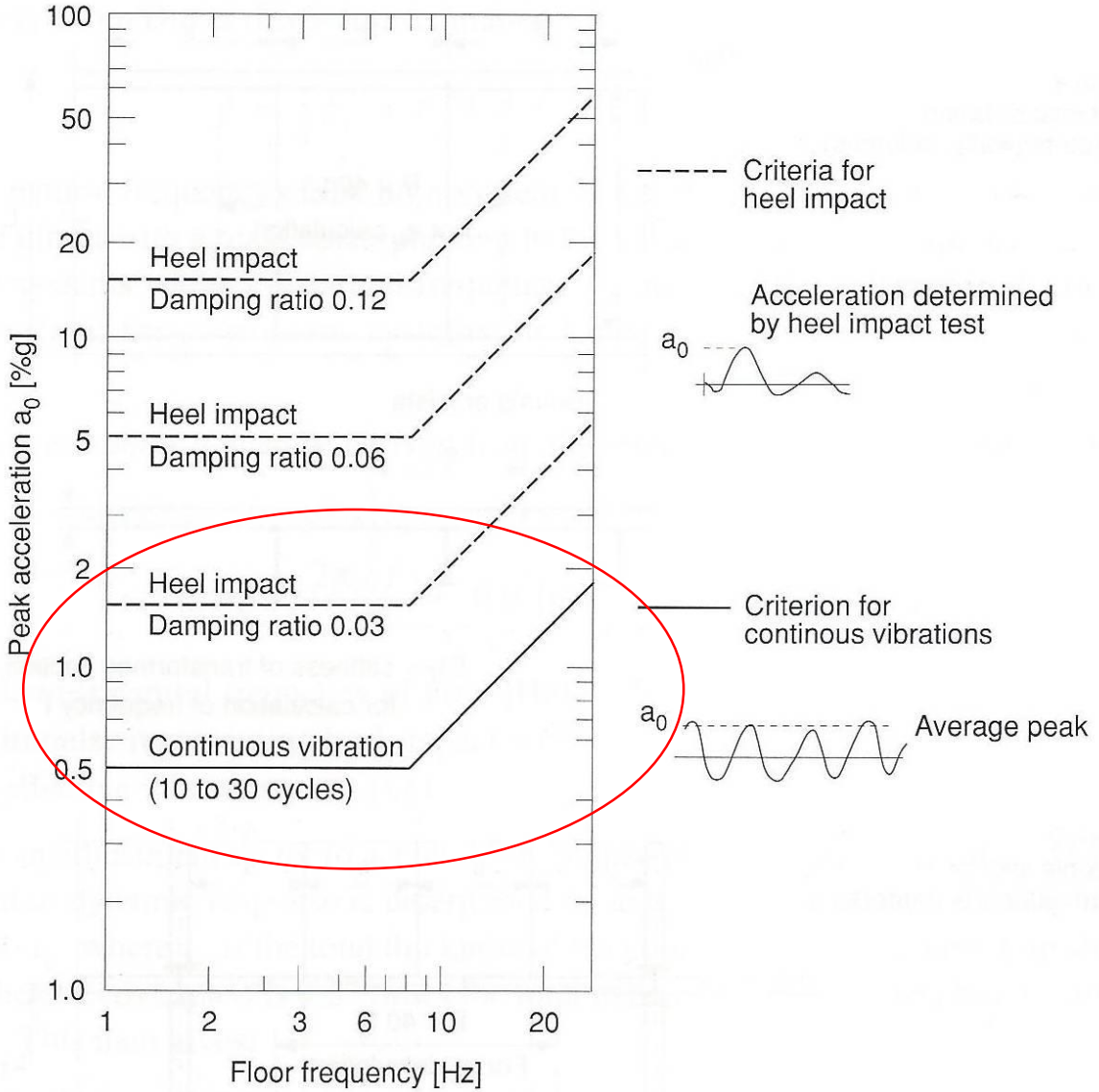


- Possible envelopes of dynamic responses of a floor to regular excitation: a) resonant response, b) transient response.

Design of floor stru

Simple design rule

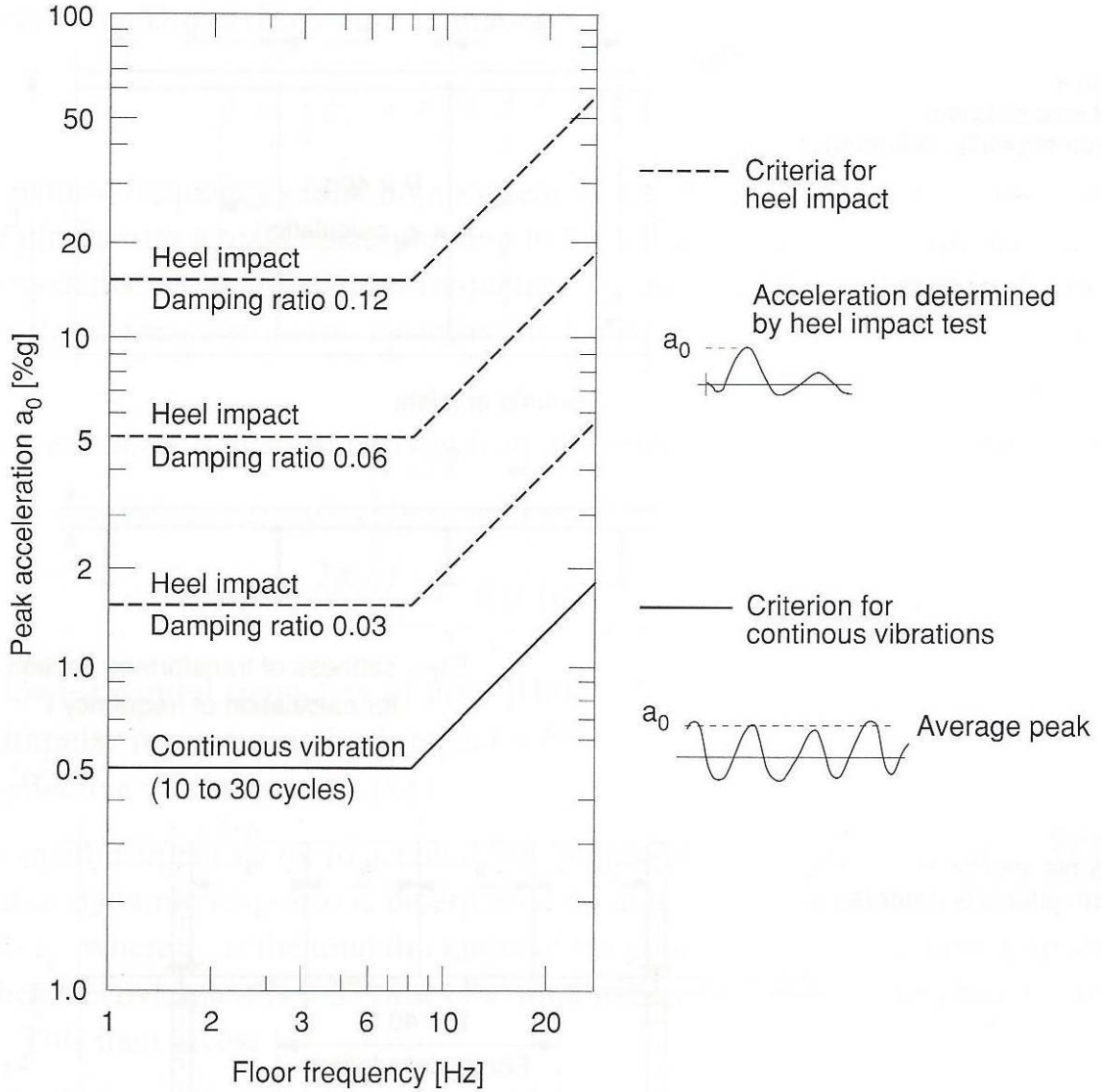
- ***High tuning method***
- Since the annoying vibrat
  natural frequency of the
  the walking forces, the pr
  away from each other →
- For highly damped floors
  should be above the frerc
  Hz.
- For floors with low dampi
  be above the frequency c
- ***Natural frequency of***



Design of floor stru

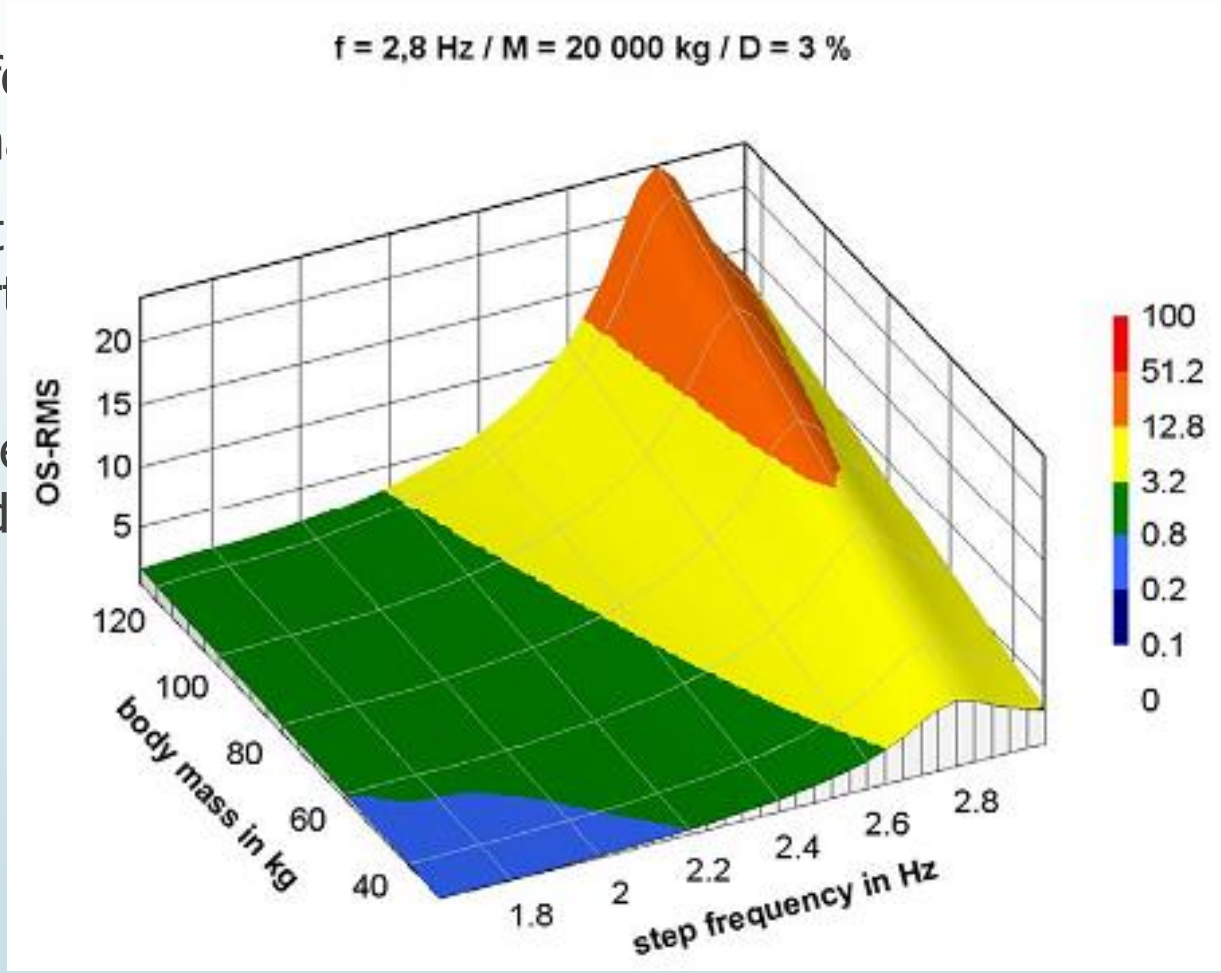
Simple design rule

- ***Heel impact method***
- The heel impact consists
  and suddenly dropping th
- The prosedure can be us
  floors for acceptability ag



Comfort assessment of the floor structures

- The purpose of the comf
  that vibrations are so sm
- This comfort assessment
  reflects both, the comfor
  the floor structure.
- **OS-RMS**-value : "one st
  the step frequency and d



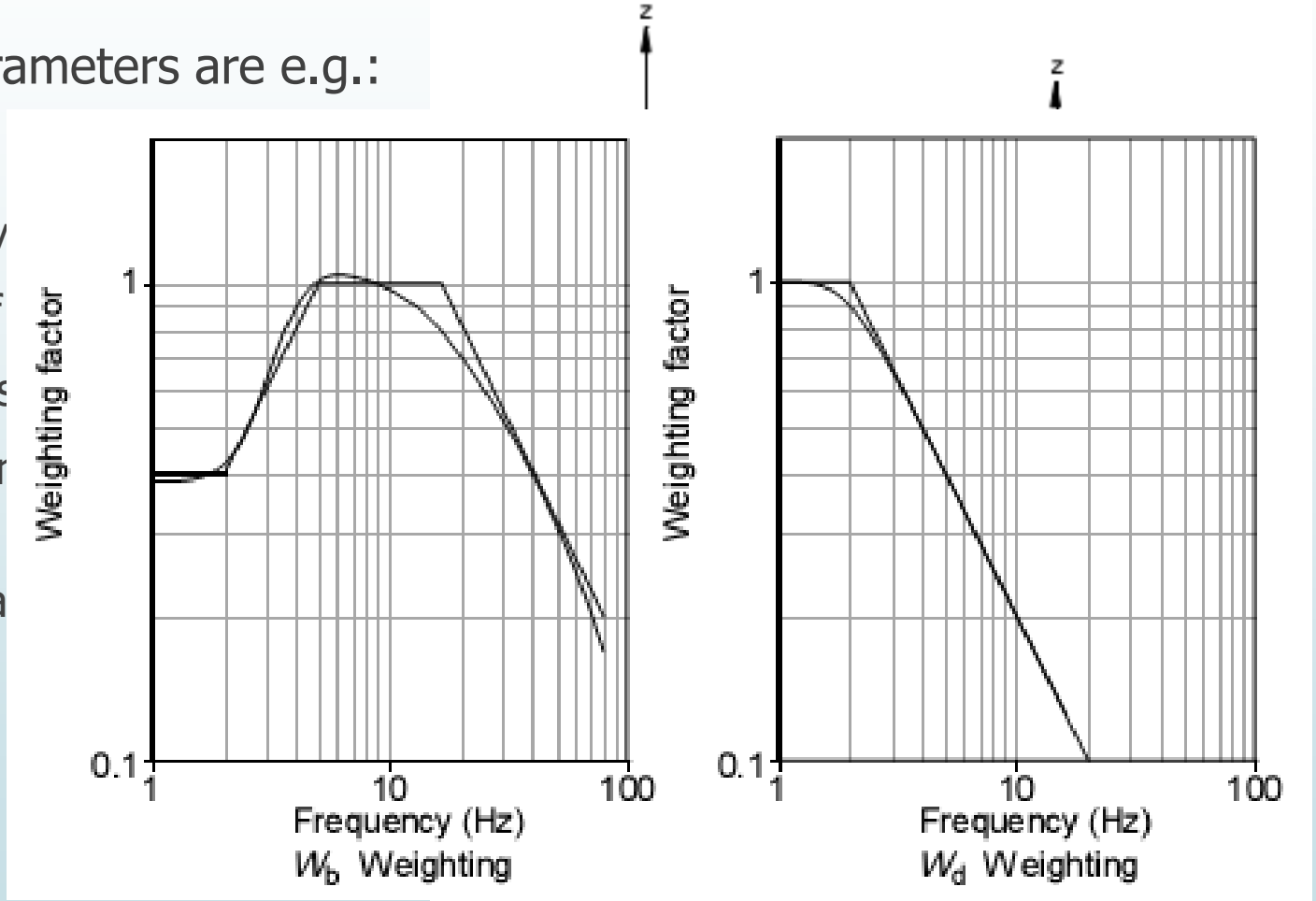
Comfort assessment of the floor structures

- The limits for the OS-RMS -values for comfort are based on various standards for standardizing human perception.

- In general, the perception and the individual judgment, whether vibrations are disturbing or not (discomfort), are based on the same criteria but can lead to different limits, as certain persons can detect vibrations without being discomforted by them.

Comfort assessment of the floor structures

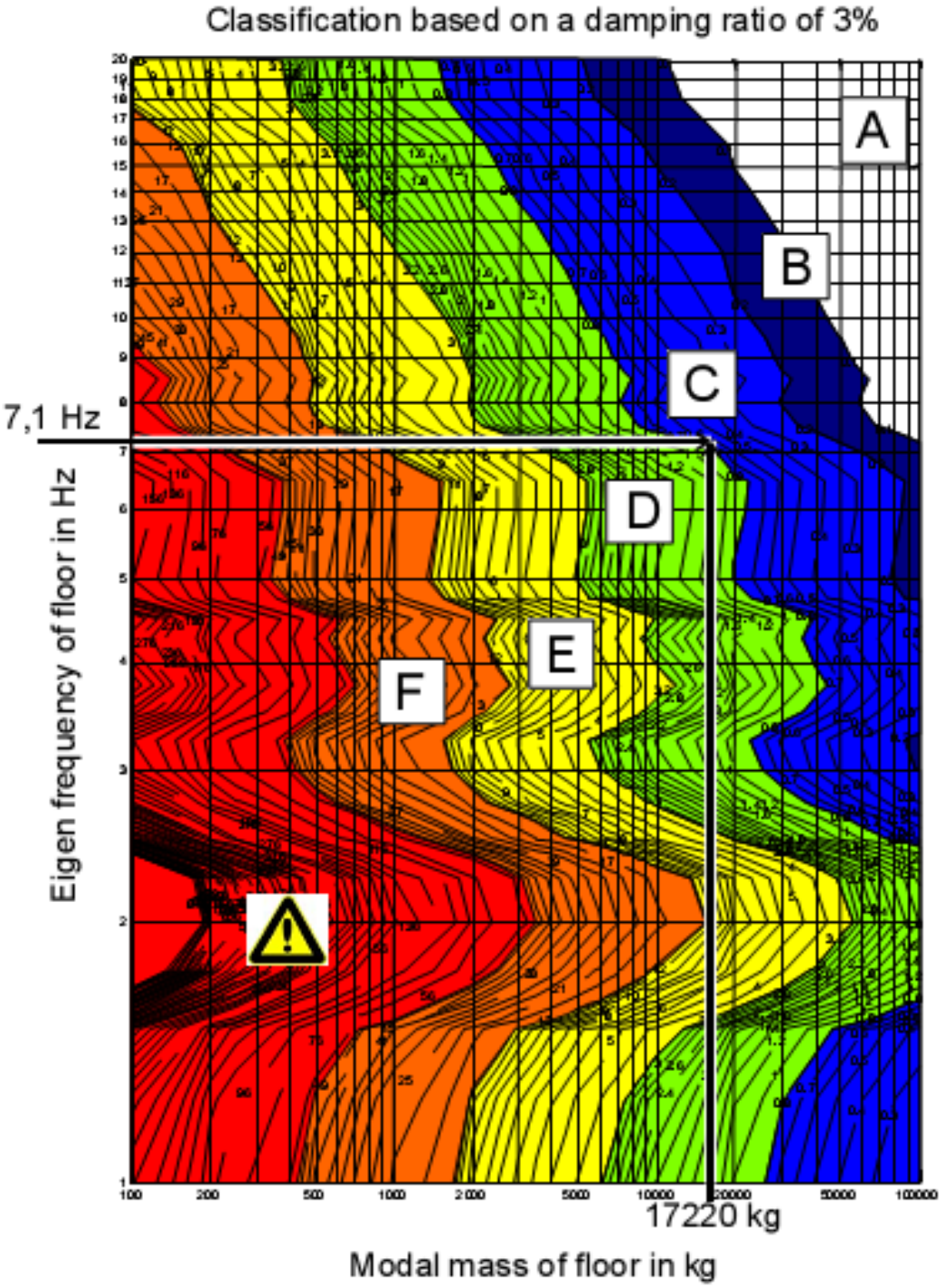
- The governing parameters are e.g.:
  - momentary activ
  - age and state of
  - posture of the us
  - Relation betweer not),
  - Frequency and a function).



Comfort assessment of the fl

Class	$OS\text{-}RMS_{90}$		Usage of the floor structure									
	Lower limit	Upper limit	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



Comfort assessment of the floor structures

Description	Frequency range 1 to 10 Hz Peak acceleration (mm/s^2)	Frequency range 10 to 100 Hz Peak velocity (mm/s)
Just perceptible	34	0,5
Clearly perceptible	100	1,3
Disturbing/unpleasant	550	6,8
Intolerable	1800	13,8

- An indication of human perceability thresholds for vertical harmonic vibrations (person standing).

An again, as a reminder

Representative types of activity			Range of applicability		
Designation	Definition	Design rate (Hz)	Actual activities	Rate (Hz)	Structure type
Walking	Walking with continuous ground contact	1,6 to 2,4	Slow Normal Fast, brisk	1,7 2,0 2,3	Pedestrian structures office buildings
Running	Walking with discontinuous ground contact	2,0 to 3,5	Slow Normal Fast (sprint)	2,1 2,5 > 3,0	Pedestrian bridges and jogging tracks
Jumping	Normal to high rhytmical jumping on the spot	1,8 to 3,4	Fitness training Jazz dance	1,5 to 3,4 1,8 to 3,5	Sport halls Gymnastic training rooms

- Representative types of activities and their applicability to different actual activities and types of structures

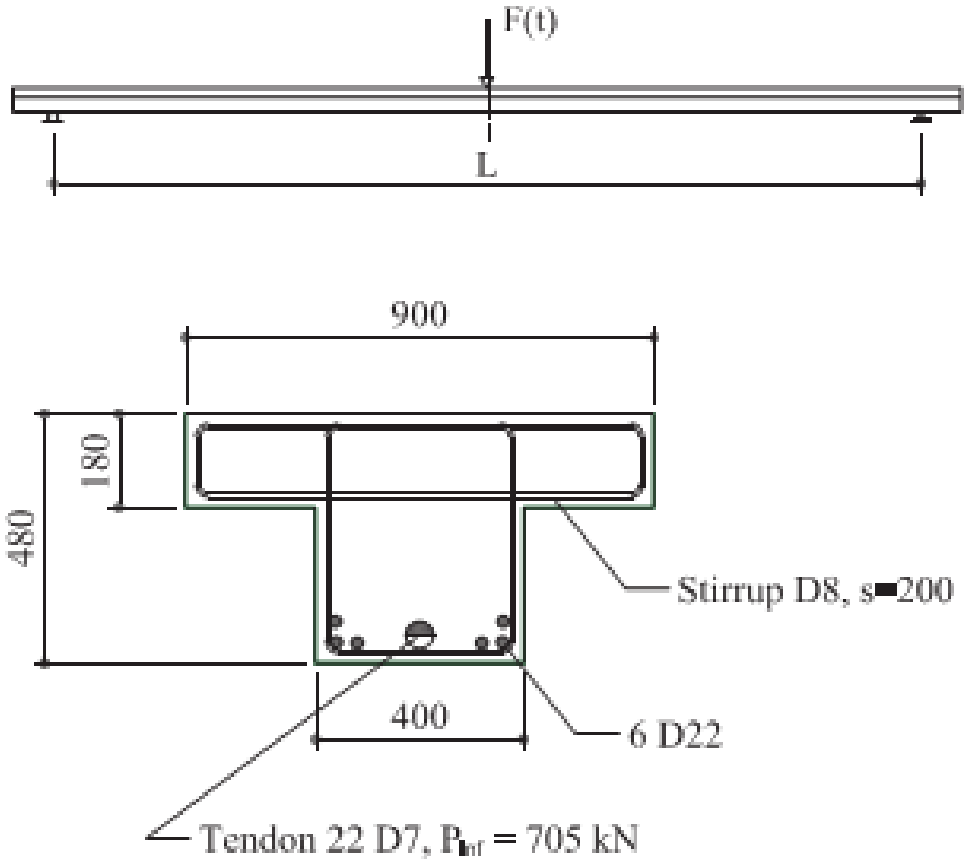
An again, as a reminder

Representative types of activity			Range of applicability		
Designation	Definition Design rate (Hz)		Actual activities Rate (Hz)		Structure type
Dancing	Approximatly equivalent to brisk walking	1,5 to 3,0	Social events with dancing	1,5 to 3,0	Dance halls Concert halls
Hand clapping	Rhitmycal hand clapping in front of one's chest	1,5 to 3,0	Concerts with enthusiastic audience	1,5 to 3,0	Concert halls and spectator galeries
Lateral body swaying	Rhytmical lateral body swaying while being seated / standing	0,4 to 0,7	Concerts, social events	0,4 to 0,7	Spectator galeries

- Representative types of activities and their applicability to different actual activities and types of structures

Example: "Jumping on a reinforced concrete beam"

- Beam

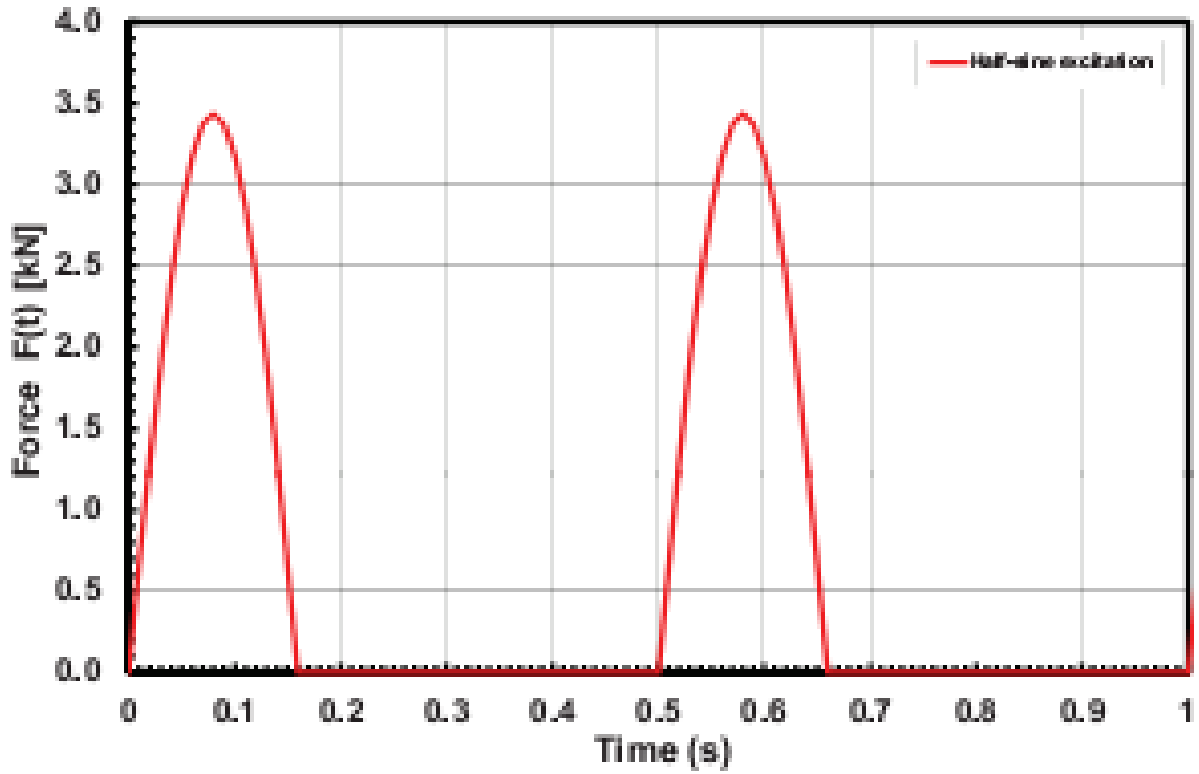


- Young's Modulus: $E = 23500\,MPa$
- Density: $\rho = 20.6\,kN/m^3$
- Bending stiffness: $EI = 124741\,kNm^2$
- Damping rate $\zeta = 0.017$
- Modal mass $M_n = 0.5 M_{tot}$
- Modal stiffness

$$K_n = \frac{\pi^4}{2} \cdot \frac{EI}{L^3}$$

Example: "Jumping on a reinforced concrete beam"

Excitation



- Jumping frequency: $f_0 = 2\text{Hz}$
- Period: $T_0 = 0.5\text{s}$
- Contact time: $t_p = 0.16\text{s}$
- Person's weight: $G = 0.70\text{kN}$
- Amplitude: $A = 3.44\text{kN}$

Example: "Jumping on a reinforced concrete beam"

- Investigated cases

Length [m]	Frequency f_n [Hz]	u_{max} [m]	$\overline{V}$ [-]
26.80	1	0.003	1.37
19.00	2	0.044	55.94
15.50	3	0.002	3.62
13.42	4	0.012	41.61
12.01	5	0.001	4.20
10.96	6	0.004	25.02

- Maximum deflections

Static: $u_{st} = \frac{G}{K_n}$

Dynamic: $u_{max} = \max(u(t))$

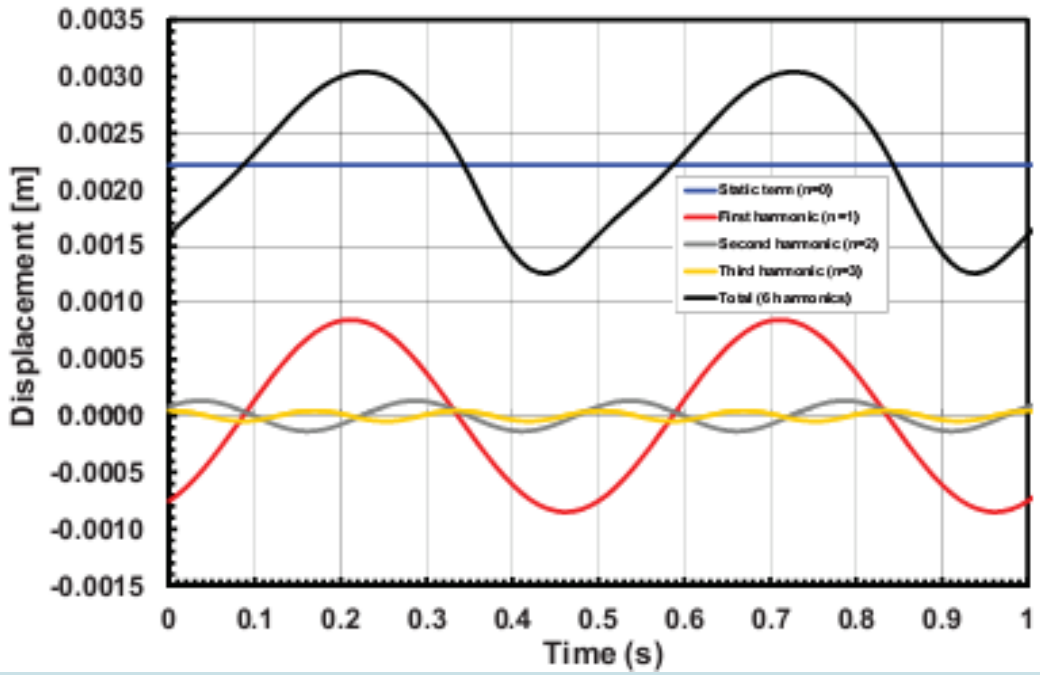
Ratio: $\overline{V} = \frac{u_{max}}{u_{st}}$

Notes:

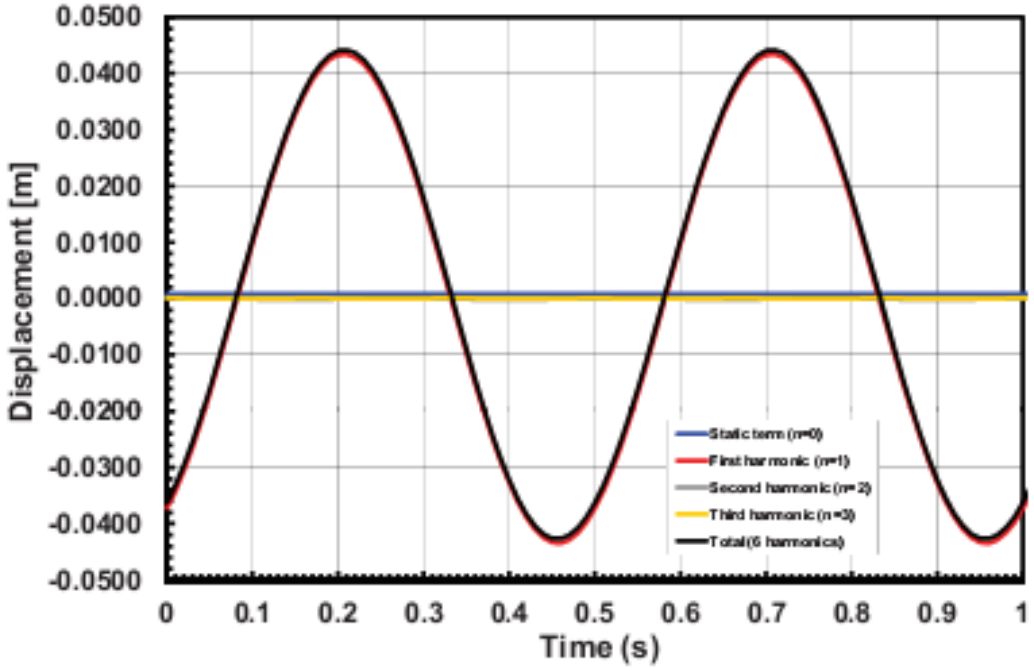
- When excitation frequency f_0 is twice as large as the natural frequency f_n of the beam, the magnification factor V is small.
- Taking into account the higher harmonics can be important!

Example: "Jumping on a reinforced concrete beam"

- Case1: f_0 = 2Hz, f_n = 1Hz

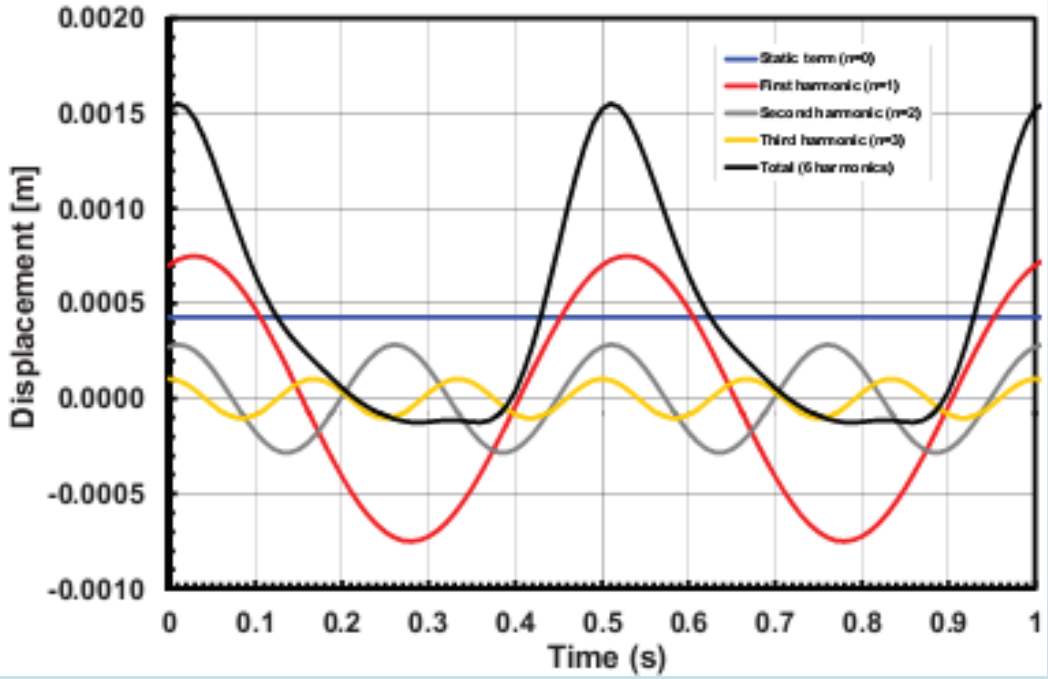


- Case 2: f_0 = 2Hz, f_n = 2Hz

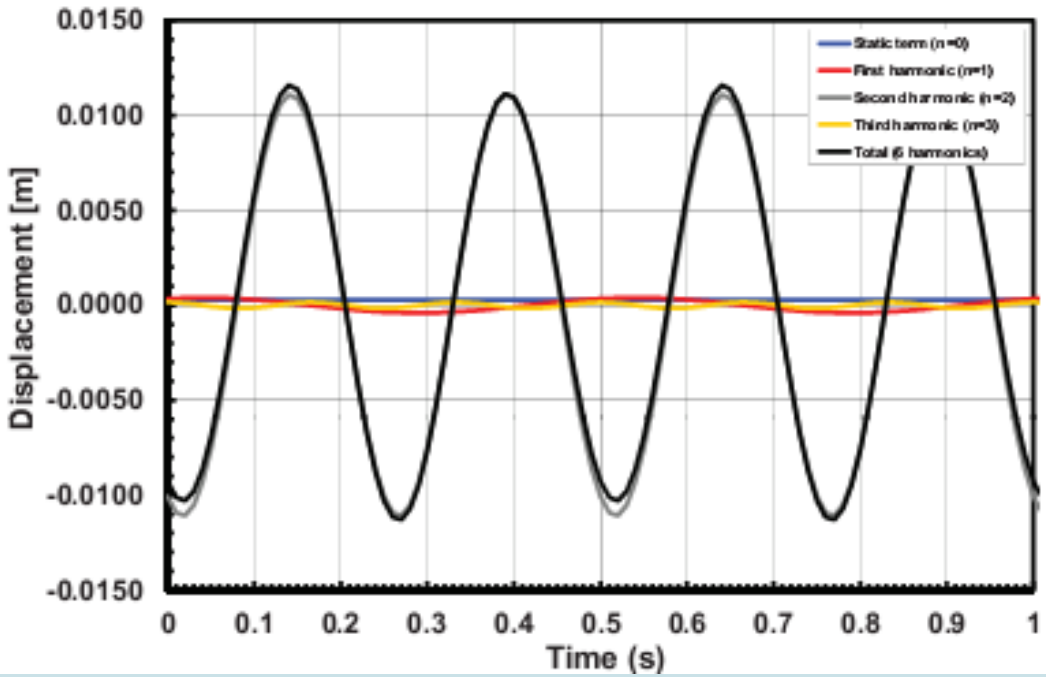


Example: "Jumping on a reinforced concrete beam"

- Case 3: $f_0 = 2Hz$, $f_n = 3Hz$

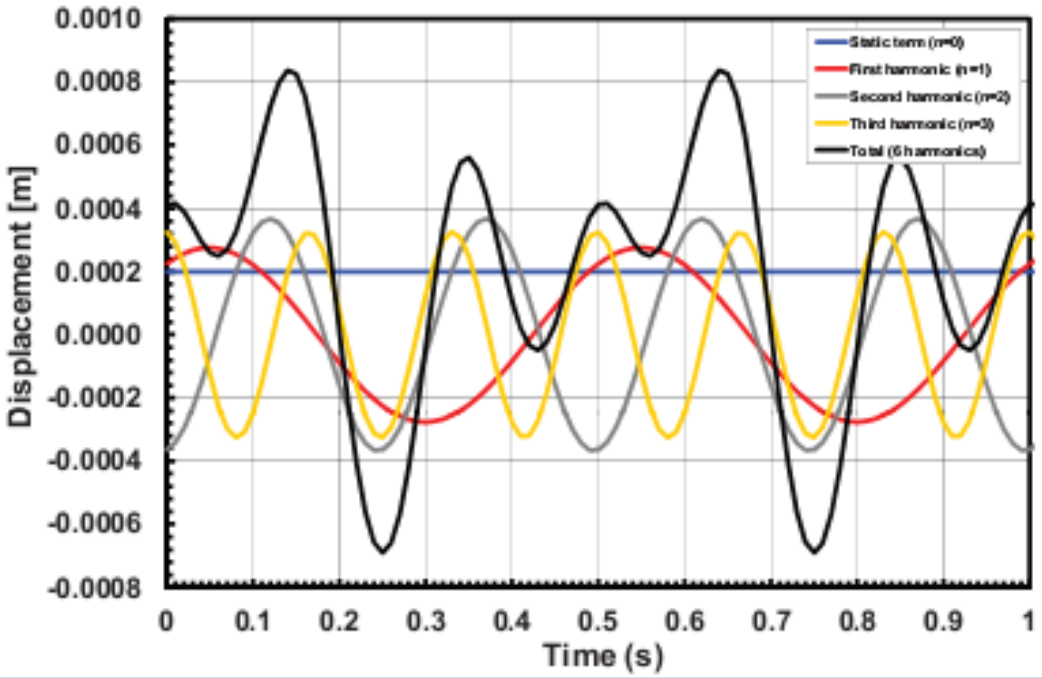


- Case 4: $f_0 = 2Hz$, $f_n = 4Hz$

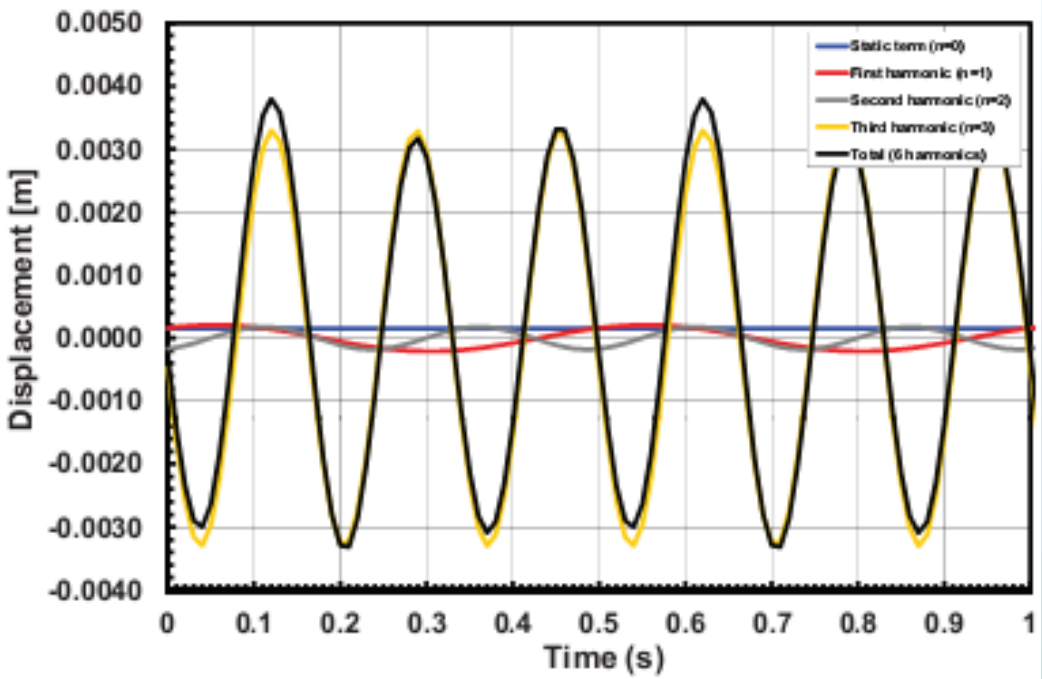


Example: "Jumping on a reinforced concrete beam"

- Case 5: f_0 = 2Hz, f_n = 5Hz



- Case 6: f_0 = 2Hz, f_n = 6Hz



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