DESIGN GUIDE FOR FLOOR VIBRATIONS

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INTRODUCTION

In the past, the demand for flexible use of commercial and administrative buildings was leading to a request for floors with long spans. These expectations have been met by the development of innovative construction techniques, e.g. composite floor systems as well as pre-stressed hollow core slabs. This trend has been supported further by the use of modern, high strength materials. Hence serviceability criteria, such as deflection limits and the vibration behaviour, define in the first instance the design of these new, slender constructions.
While deflection limits are regulated in the relevant standards, the vibration comfort of slabs is not clearly defined. A directed design with regard to floor vibrations is presently not possible. In addition, a generally accepted method for the reliable prediction of the action effects for vibrations, in general expressed in accelerations or velocities, are not available.
This paper presents a design guide comprehending a simple design method for floors in reference to human induced vibrations [1]. Comfort criteria for vibrations are defined in relation to the use of the floor. Further a simple design method for prediction of vibration intensity of floors due to human induced vibrations to check these criteria is introduced. The content of this work has been developed and validated in the scope of the RFCS-project "Vibrations of Floors" [2].

1 COMFORT CRITERIA FOR FLOOR VIBRATIONS

The perception of vibrations by persons and the individual feeling of annoyance depend on several aspects. Although the perception of vibrations is a very individual sensation a number of parameters influencing this reaction could be identified:

- The current activity of the considered person is of relevance for its perception of vibrations - persons working in the production hall in a factory have a different perception of vibrations from those working in an office or surgery;
- Age and health of affected people may affect the annoyance level of vibrations;
- Posture of the people such as standing, laying or sitting;
- The relation of the person to the source of excitation (are the vibrations expected or unforeseen);
- Frequency and amplitude of the vibration.

These parameters have been reviewed and assigned to perception classes recommended for different utilization of floors, see *Table 1*. These perception classes represent the targeted design recommendations with regard to floor vibrations and thus the comfort criteria. The design values for classification are based on the ISO 10137 [5] however they have been adapted according to the European partners' experiences drafted in the project "Vibrations of Floors" [2].

Table 1. Classification of floor utilizations in respect to perception classes

Class	Utilization of floor: Critical workspace	Health	Education	Residential	Office	Meeting	Retail	Hotel	Industrial use	Sports
A	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended
B	Critical	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended
C	Not recommended	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended
D	Not recommended	Critical	Critical	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended
E	Not recommended	Not recommended	Not recommended	Critical	Critical	Critical	Critical	Critical	Recommended	Recommended
F	Not recommended	Not recommended	Not recommended	Not recommended	Not recommended	Not recommended	Not recommended	Not recommended	Critical	Critical

Recommended (green) · Critical (yellow) · Not recommended (red)

2 DYNAMIC SLAB PROPERTIES

2.1 General

The dynamic behaviour of floors depends basically on the mass, stiffness and damping of the floor. The ratio between stiffness and mass determines the natural frequency of the floor. Natural frequencies in a range of step frequencies induced by pedestrians walking on the floor can become critical. In *Fig. 1* the frequency distribution of the step frequency of 200 persons passing the entrance hall of the TNO-administration building in Delft is shown.

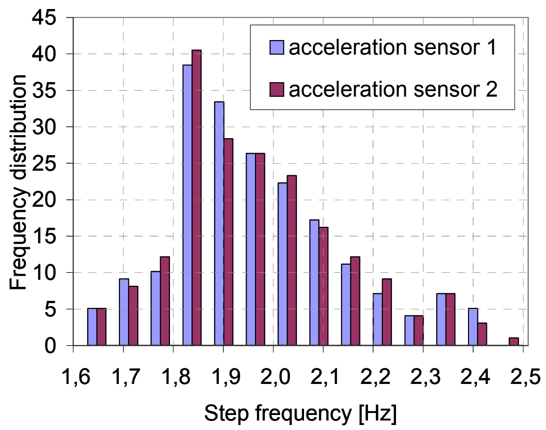


Fig. 1. Frequency distribution of the step frequencies [2]

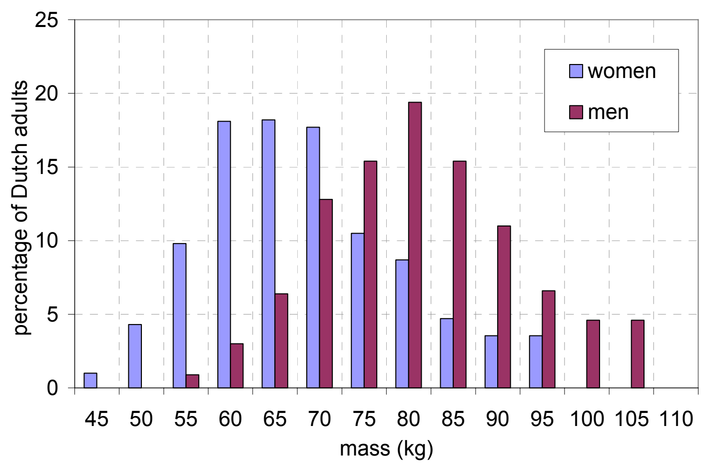


Fig. 2. Frequency distribution of the exciter mass (pedestrians)

The harmonic excitation of a floor depends further on the size of the floor, as several foot steps are required until the floor starts vibrating. The guideline presented in this paper assumes that the length of the floor is reasonably large for harmonic excitation to occur.

While the influence of the stiffness of the floor is confined to the natural frequency, the mass of the floor affects additionally the dynamic behaviour of the floor. The ratio between the mass of the exciter to the mass of the excited floor is a significant parameter for the dynamic response of the

floor. The sensitivity to floor vibrations increases with increasing ratio of exciter mass and floor mass. The exciter mass is a pedestrian whose representative weight distribution is given in *Fig. 2*.
The excited mass is defined as modal mass of the floor. Each frequency of the floor corresponds to a modal mass. Simplified modal mass can be described as the mass participating in the vibration mode considered.
Modern floors with large spans are light-weight constructions with a low stiffness. The low stiffness leads to low natural frequencies while the low weight to an increase in the ratio of the exciter mass to the excited mass. Therefore the assessment of the vibration of floors may become essential.
Furthermore damping has an important influence on the vibration behaviour of the floor. The damping properties are not only dependent on the structure, but also on the finishes and use of the premises. Thus separation walls, ceilings under the floor, free floating floors or swimming screeds affect the damping properties significantly.
Appropriate damping values can be taken from *Table 2*. The system damping D is obtained by summing up the appropriate values. In the evaluation of the dynamic floor characteristics also a realistic fraction of imposed load should be considered in the mass of the floor. Experienced values for residential and office building are 10% to 20% of the imposed load.

Table 2. Estimation of the floors' damping

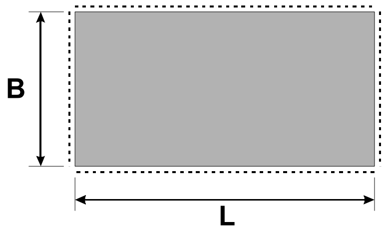
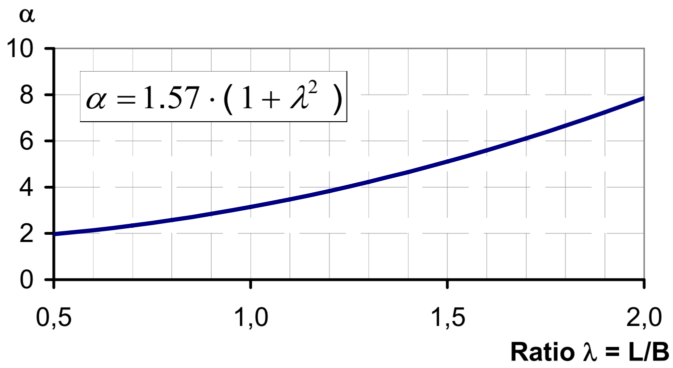
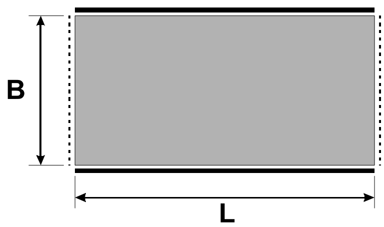
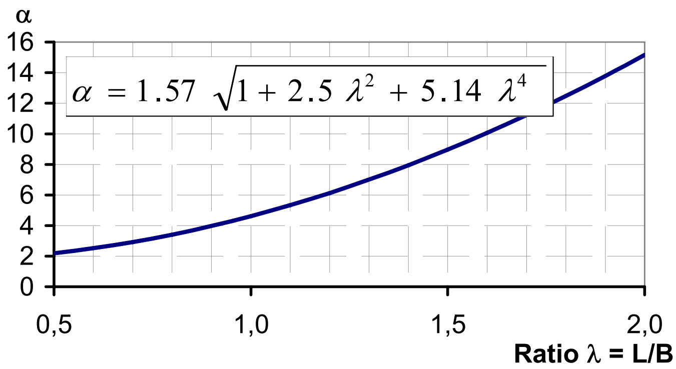
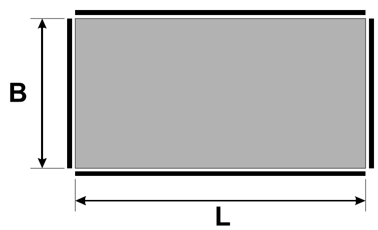
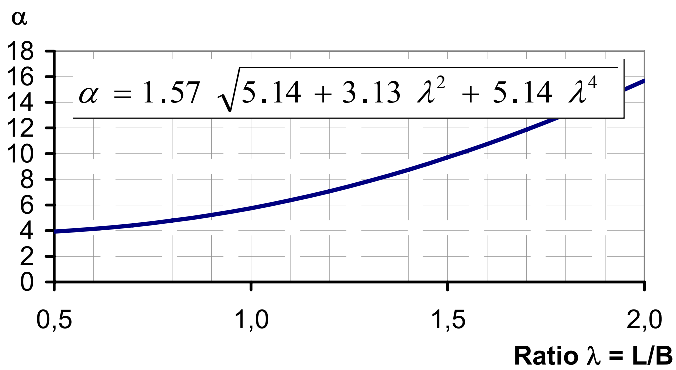
Type	Damping (% of critical damping)
Structural damping D_1	
Wood	6%
Concrete	2%
Steel	1%
Composite (Steel-Concrete)	1%
Damping due to furniture D_2	
Traditional office for 1 to 3 persons with separation walls	2%
Paperless office	0%
Open plan office	1%
Library	1%
Residential	1%
Schools	0%
Gymnastic rooms	0%
Damping due to finishes D_3	
Ceiling under the floor	1%
Free floating floor	0%
Swimming screed	1%
Total damping $D = D_1 + D_2 + D_3$	

2.2 Determination of the Relevant Floor Properties

The determination of the dynamic floor properties specified above is an unusual task for designers of buildings in their daily practice. Therefore design guidance has been elaborated for the determination of the natural frequency and corresponding modal mass of floors. In this design guide [1], straightforward aids for the manual calculation applied to simple, regular static systems as well as guidance for the evaluation using FEA calculations is given.
In *Table 3* a selection of manual formulas for the determination of the first natural frequency (acc. to [4]) and the modal mass of isotropic plates for different supporting conditions are presented.

For the application of the given equations it is assumed that no lateral deflection at any edges of the plate occurs.
Further manual formulas for orthotropic plates (e.g. composite slabs) as well as general rules and approximation methods for the determination of the dynamic properties are included.

Table 3. Simple determination of the natural frequency and modal mass of isotropic plates

Support condition	Frequency; Modal mass
clamped (solid line) hinged (dotted line)	$f = \frac{\alpha}{L^2}\sqrt{\frac{E\,t^3}{12 \cdot m\,(1-\upsilon^2)}}$; $M_{mod} = \beta \cdot M_{tot}$
	 $\beta \approx 0{,}25$ for all λ
	 $\beta \approx 0{,}20$ for all λ
	 $\beta \approx 0{,}17$ for all λ

E Young Modulus in N/m²
t Plate thickness in m
m Specific mass of the floor including finishes and a fraction of the imposed load in kg/m²
υ Poisson ratio
M_{tot} Total mass of floor including finishes and a representative fraction of the imposed load in kg

3 ASSESSMENT OF COMFORT

A design value used to calculate a response of the floor is OS-RMS$_{90}$. This value covers the response velocity of the floor for a significant step with the intensity of 90% of people's steps walking normally – called the "one step root mean square 90", see *Fig. 3*. It is a root mean square of the velocity determined as follows:

$$v_{RMS} = \sqrt{\frac{1}{T}\int_0^T v(t)^2 \, dt} \approx \frac{v_{Peak}}{\sqrt{2}} \quad (1)$$

where T is the investigated period of time.

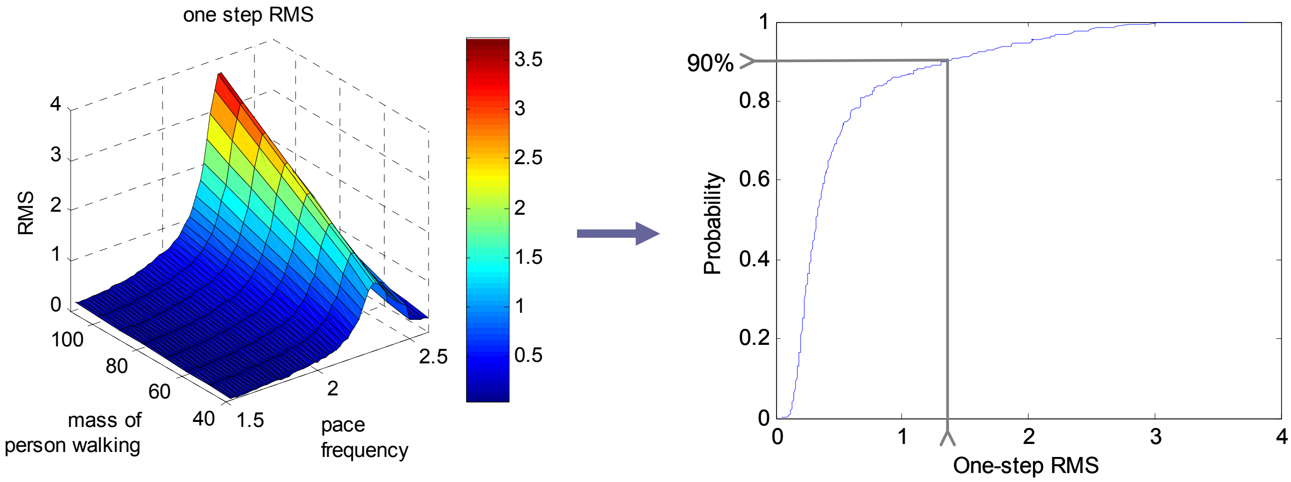


Fig. 3. The OS-RMS$_{90}$

For the comfort assessment of floors the classification introduced in chapter 1 has been included into diagrams, see *Fig. 4*. Consequently the perception classes A to F from *Table 1* can be read directly from these design diagrams. Thus input parameters for the determination of the perception class of the floor are following:

- Damping (taking into account finishes and furniture),
- Natural frequency,
- Corresponding modal mass of floor.

After the designation of these dynamic properties the designer chooses a relevant design diagram in reference to the damping of the floor.
The diagram is applied by introducing modal mass on the x-axis and corresponding frequency on the y-axis. On the intersection of the both entered values the OS-RMS$_{90}$ and the acceptance class can be read, see *Fig. 4*. Design diagrams have been elaborated for 1% up to 9% damping.
This method leads in general to conservative results when applied as single bay method using the mode related to the fundamental frequency. However, in special cases in which the modal mass for a higher mode is significantly low, also higher modes need to be considered.

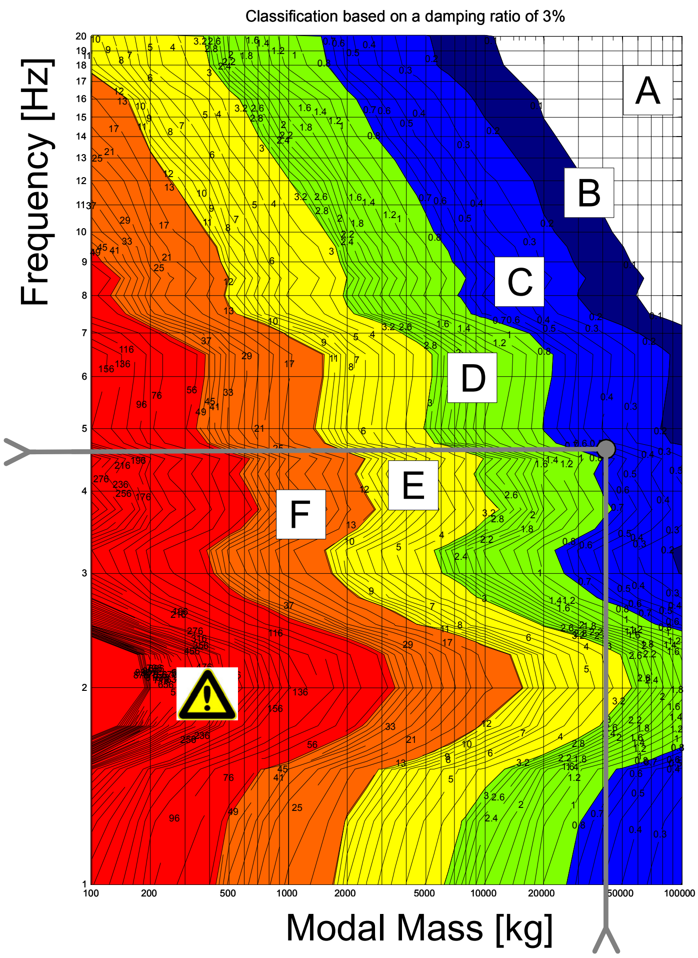


Fig. 4. Read-off of the perception class from the design diagrams (here for 3% damping)

4 SUMMARY AND ACKNOWLEDGMENT

The design guide presented in this paper [1] is a simple tool addressed to designers who do not have deep knowledge about dynamic behaviour of structures. It enables them to assess floors for human induced vibrations. The method is semi-probabilistic and the results lead to a determination of the vibration response of sensitive floors with a reliable accuracy.

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