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COMFORT ANALYSIS OF LIGHTWEIGHT FLOOR SYSTEM

Sander Zegers[1], Frans van Herwijnen[1]

[1]Faculty of Architecture, building and planning, department of structural design and construction technology, Technical University of Eindhoven, 5600 MB, Netherlands
s.f.a.j.g.zegers@bwk.tue.nl

Abstract

During the past 60 years, floor systems used in housing and office-buildings in the Netherlands were mostly made of concrete or other similar materials. These floor systems, which can be characterized as heavy, normally posed little problems concerning vibrations. In recent years, in light of sustainable construction methods, there has been a trend to reduce the use of materials and thus build lighter. In addition, building-users nowadays are more critical with regard to the comfort of the building. Light-weight floor structures are often found to be susceptible to unacceptable vibrations. The vibrations are caused by dynamic actions such as persons walking or washing machines vibrating. If one of the natural frequencies of the floor system, usually the first natural frequency, is close to the frequency of these actions, problems occur. Besides the natural frequency other properties influence the perception of a lightweight floor system such as damping.
This paper describes the structural parameters that influence vibration comfort. A quality measure is used to compare the measures, based on the velocity of the structure subject to vibration, which includes human sensitivity for vibration of different frequency. A detailed study will be presented on the effect of these measures and guidelines on practical application of the results are given. It will be shown that mass has no influence on the comfort of a beam.

1. INTRODUCTION

Floor systems used in the Netherlands are mainly heavy monolithic concrete structures. The typical weight is approximately 600-800 kg/m^2. This means that a lot of material is used to construct a typical floor system. Considering sustainable building aims, this way of building is not preferable. One of the main aims of sustainable building is to reduce material consumption by the building industry. However using lighter floor systems introduces new problems to solve that did not exist with the heavy weight floor systems.

One of the major problems concerns the susceptibility to vibration. Vibrations can be introduced by a number of actions, most importantly walking or jumping people and machines such as washing machines. In this paper the vibration caused by walking people will be further investigated.

The Dutch building code [1] gives a value for the minimal value for the first natural frequency: 3 Hz. This value proved to be sufficient for the heavier floor systems but resulted in complaints in case of lighter weight floor systems. A guideline [2] has been developed specifically for the situation of walking people on light weight floor systems. This guideline classifies floor systems by a comfort value, called OS-RMS$_{90}$, which is based on the velocity of the vibration caused by walking people. Previous studies, [3], [4] and [5] have provided insight in the effects of geometry and boundary conditions on the first natural frequency of a floor system modelled as a beam.

In this paper these insights will be further developed. First a method for calculating the first natural frequency and the method used for classification will be discussed. This is followed by presenting the method used to analyse the influence of the parameters on the comfort classification for a floor system.

2. NATURAL FREQUENCY

In this paper a floor system will be modelled as a single beam. The schematization as a single beam with end supports allows for an analytical approach [3, 4]. In this model several parameters are taken into consideration, as shown in Figure 1.

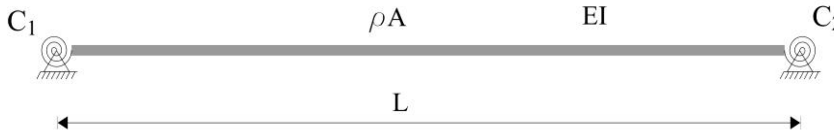

Figure 1, Mechanical scheme of floor system

Where:

L	[m]	: Length of the beam between the supports
EI	[Nm^2]	: Bending stiffness of the beam
ρA	[kg/m’]	: Mass per unit length, acting as a distributed load
C_{1-2}	[Nm/rad]	: Spring hinge at left and right support respectively

The above structure can be calculated by an explicit function by first calculating two parameters, u_1 and u_2, both depending on the geometry and boundary conditions:

$$u_1 = \frac{C_1 L}{EI}\,\text{rad}^{-1}, \quad u_2 = \frac{C_2 L}{EI}\,\text{rad}^{-1} \tag{1}$$

These two parameters can be used to calculate the value $\tilde{R}$ that is a measure for the first natural frequency [3].

$$\tilde{R} = \frac{0.78457(u_1 + u_2) + 0.15976(u_1 u_2) + \pi}{0.19981(u_1 + u_2) + 0.03377(u_1 u_2) + 1} \tag{2}$$

The first natural frequency can be calculated by the following function:

$$f_e = \frac{\tilde{R}^2_{(L,EI,C_1,C_2)}}{2\pi L^2}\sqrt{\frac{EI}{\rho A}} \quad \text{[Hz]} \tag{3}$$

3. OS-RMS$_{90}$

The OS-RMS$_{90}$ stands for 90% upper confidence One-Step-Root-Mean-Square value. This value is based on the velocity of the vibration, so a lower value indicates a better comfort. This method is explained in [2] and consists of three stages. First the transfer function of a floor structure has to be determined, which describes the response of the floor structure to a load. The transfer function can be found by experiments or numerical simulation. Secondly a theoretical walking function is defined and is dependent on the pace frequency and the persons' mass. Every combination of pace frequency and mass has a certain probability of occurring. The third stage consists of calculating the response of the floor system to the theoretical walking function.

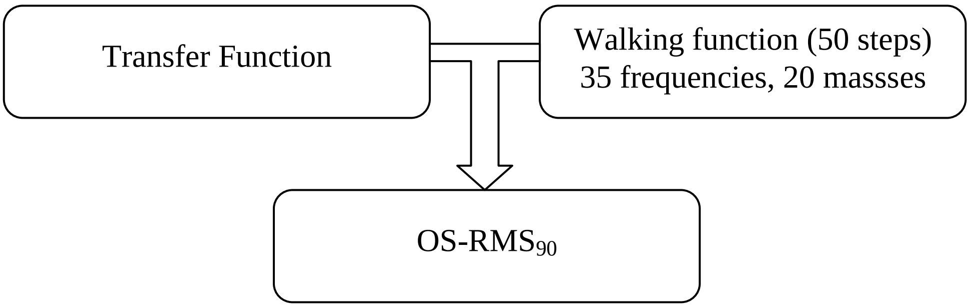

Figure 2, Flowchart determination of the OS-RMS$_{90}$-value

This method is most suitable as it incorporates the specifics of walking people which results in a bigger excitation of the floor at certain frequencies, consistent with actual walking people. In Figure 3 a graphical representation of the walking function is shown.

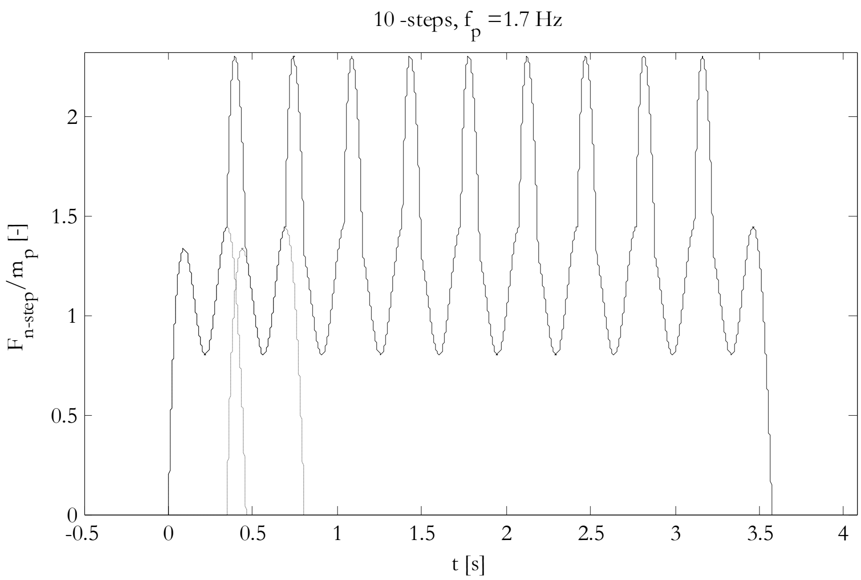

Figure 3, Walking function for 10 steps, with force: $F_{n\text{-step}}$ [N] and person mass: m_p [N]

4. COMFORT ANALYSIS

The influence of changing parameters on the OS-RMS_{90} value is of great interest because it gives an indication of the actual comfort level of a certain design. Understanding the influence on this comfort level by changing certain parameters can help to efficiently design floor systems for better comfort. A numeric model will be used to obtain the vibration characteristics of the floor system. This model will be identical to the theoretical model and is shown in Figure 4.

4.1 Methodology

For this parameter study for each parameter a range of values is determined that are of interest in building practice. The focus of this research is on office and housing buildings. Each parameter is examined individually by only changing this parameter while keeping the other parameters at the standard value. These values are given in Table 1, and are further discussed afterwards.

Table 1, Overview parameters

Parameter	unit	description	Min	Max	Standard
L	[m]	Length of the beam	5	12	8,5
EI	[Nm^2]	Bending stiffness of the beam	$9{,}09\text{x}10^6$	$5{,}1\text{x}10^8$	$2{,}5\text{x}10^8$
ρA	[kg/m’]	Mass per unit length	50	400	225
C1, C2	[Nm/rad]	Rotational stiffness at supports	0	$1\text{x}10^8$	0

Parameter L
The parameter L describes the length of the single span of the floor system. Typical spans in buildings are ranging from a minimal of 5 meters to a maximum of 12 meters.

Parameter ρA
This parameter describes the mass per unit length. Traditionally wooden floors are the lightest (ca 50 kg/m^2) in normal practice. As this paper focuses on lightweight floor systems a maximum value is assigned as 400 kg/m^2. This compares to a concrete floor of approximately 160 mm. For this analysis a beam with a width of one meter is modelled

Parameter EI
This parameter describes the bending stiffness of the floor system. For this analysis the values for the stiffness are chosen so that the first natural frequency ranges from 2 Hz to 15 Hz, when using the standard values for the other parameters. This frequency range corresponds with natural frequencies found in practice. Calculating parameters u_1 and u_2 we find $u_1=u_2=0$. Substituting these values in equation (2) we find $\tilde{R}=\pi$. Combining this value for $\tilde{R}$ and equation (3) we can calculate the range for the parameter EI.

Parameter C_1 and C_2
These parameters describe the amount of rotation stiffness of the supports. The extremes for these parameters are unconstrained respectively fixed. The unconstrained condition corresponds to a value of 0 while the fixed condition corresponds with a value of ∞. The completely fixed condition will not be practical to achieve, and previous examination of the influence of this parameter [3] learns that a maximum value for $C_{1,2} = 10^8$ Nm/rad gives nearly the same results as a completely fixed support. For this parameter the standard value is chosen to be $C_{1,2} = 0$.

4.2 Numeric Model

To calculate the effect of the parameters on the comfort of the floor system a model of a beam is used and calculated with the finite element model program ANSYS. A total of 21 nodes are used for the beam, and a total of 10 sub nodes per element are used to get a more accurate vibration response. A simple BEAM element is used, while for element 1 and 22 COMBIN14 elements. A modal analysis is performed where the first 10 modes are used.

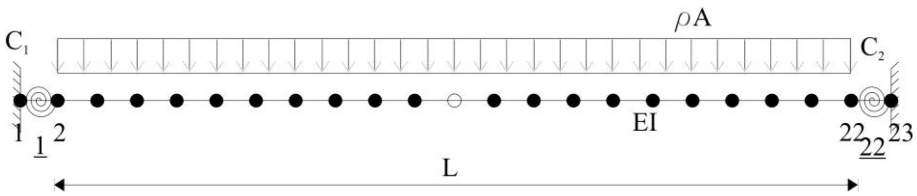

Figure 4, Numeric model

A stepping force is applied to the middle node in the model, in Figure 4 represented by the non-filled node. The force applied has an arbitrary value of 1000 N for the duration of ¼T, see Figure 5. The duration of the applied force is important for comparing the results obtained. If the duration of the force exceeds ¼T the amplitude of the vibration will be reduced and will depend on what time the force will be removed. In case the duration of the applied force is ≤ ¼T the amplitude has a direct relation to the duration. Equation (3) is used to find the analytical response which is used to find the accurate natural frequency and thus the duration for applying the force.

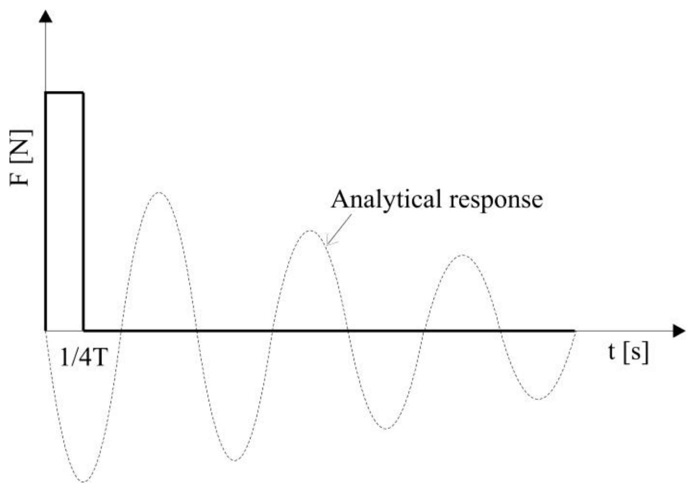

Figure 5, Applied force

A constant damping factor is used of ζ=2%. This value lies between the damping factor for steel and concrete floor structures, 1% and 4% respectively found in literature [2].

5. RESULTS

It is of great interest how changing the parameters influence the comfort value OS-RMS$_{90}$. This influence is presented with the use of four graphs. The first graph, Figure 6, plots the OS-RMS$_{90}$ comfort value as a percentage of the OS-RMS$_{90}$ found using the standard values for the parameters, against the natural frequency of the beam. The natural frequency is also influenced by changing one of the parameters.

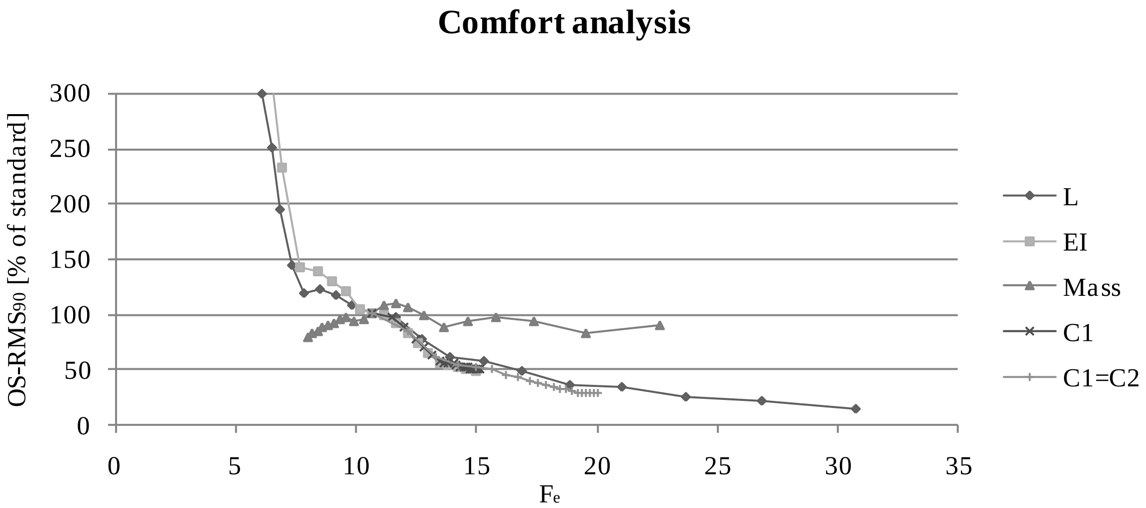

Figure 6, Results OS-RMS$_{90}$ vs. natural frequency

It can be seen that all parameters except the mass parameter follow approximately the same curve. This is the result of the fact that an increase in mass results in a lower natural frequency, which would lead to a higher OS-RMS$_{90}$, while the increase in mass has an opposite effect on the effective velocity. These effects cancel each other out mostly, only small fluctuations around 100% can be seen, see Figure 6. All the other parameters have these two effects as well, but they work in the same direction.

Figure 7 shows the influence of the variation of the parameter value on the first natural frequency. Traditionally a design was made based on the value of the first natural frequency.

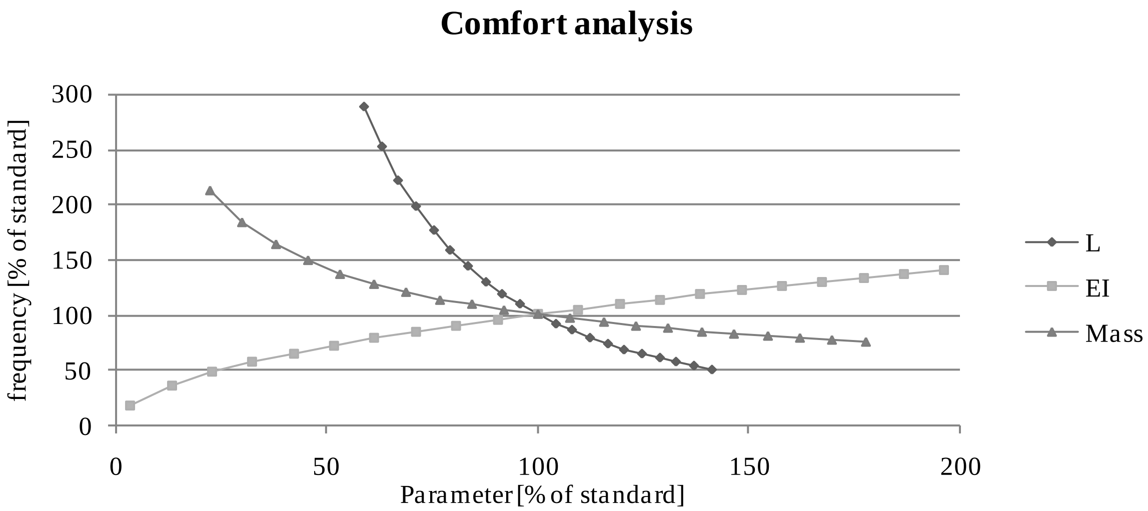

Figure 7, Results, f_e vs. % of maximal values for parameters

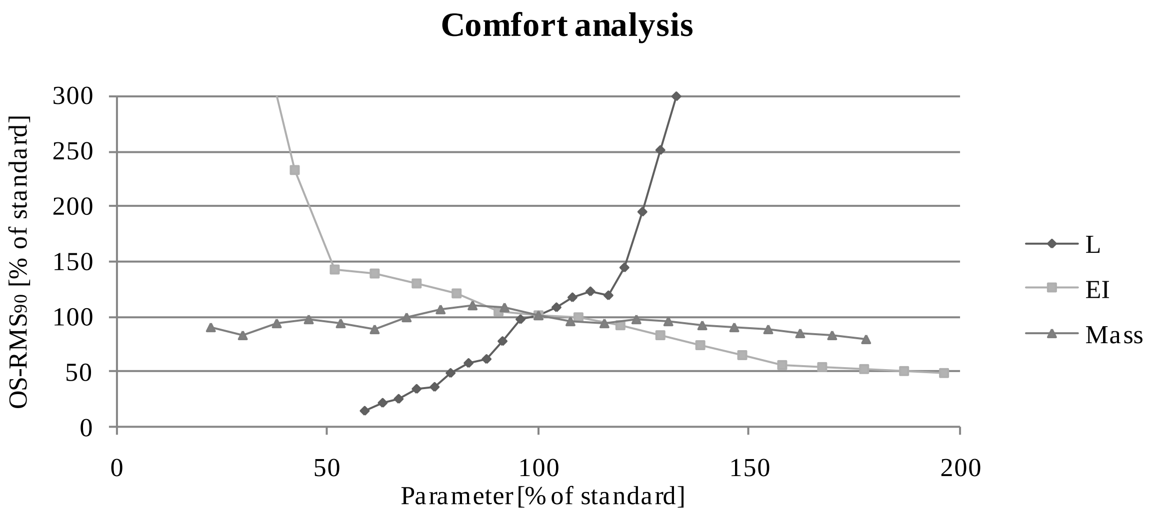

Figure 8, Results, OS-RMS$_{90}$ vs. % of standard values for parameters

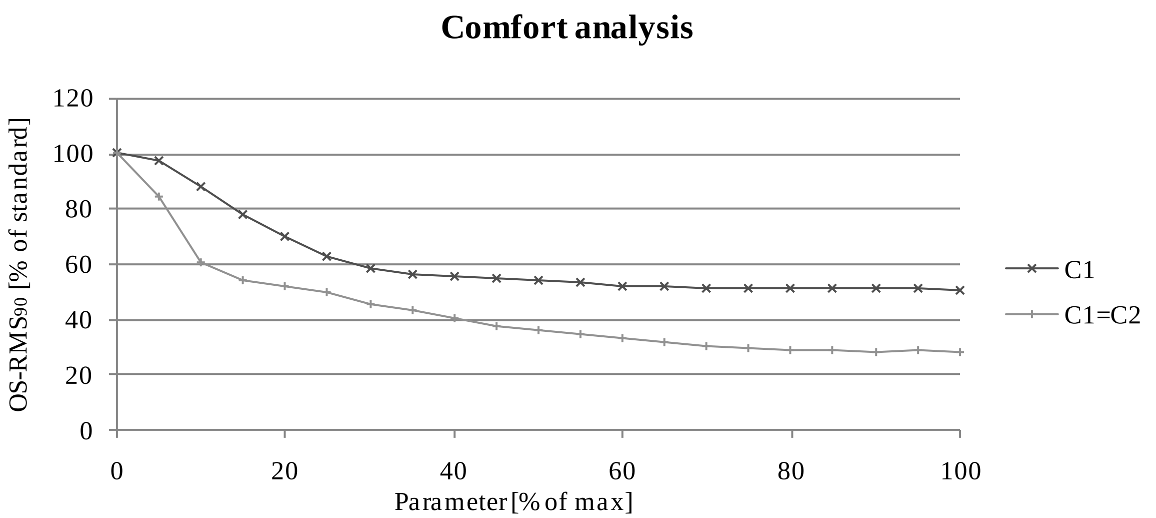

Figure 9, Results, OS-RMS$_{90}$ vs. % of maximal values for parameters

Figure 8 shows the OS-RMS$_{90}$ curve of three parameters which standard value is the average of the extreme values. At 100% on the parameter axis, the value on the OS-RMS$_{90}$ –axis represents the standard value, which is also marked as 100%. It can be seen that doubling the stiffness, EI, leads to a halving of the OS-RMS$_{90}$, while the effect of the length is much stronger. Figure 9 shows that it is possible to reduce the OS-RMS$_{90}$ to about 30% by providing some spring stiffness at the support.

Traditionally a design was made based on the value of the first natural frequency. A better measure would be to design for the OS-RMS$_{90}$-value. A table can be made where the effect of varying parameters, from the standard, on the frequency and the OS-RMS$_{90}$-value can be compared. The parameters L, EI and Mass are listed. The value presented represent the maximum positive effect in [%], i.e. a decrease for the OS-RMS$_{90}$-value and an increase for f_e.

Table 2, Comparison effect of parameters on OS-RMS$_{90}$ and natural frequency.

Parameter	OS-RMS$_{90}$$^{(1)}$	$f_e$$^{(2)}$	ratio
L	282	197	1,42
EI	787	275	2,85
ρA	90	47	1,91

$^{(1)}$ Increase in % of OS-RMS$_{90}$
$^{(2)}$ Decrease in % of f_e

6. CONCLUSIONS

In this paper an analysis is presented on the way the comfort of a floor system modelled as beam structure is influenced by the parameters that are involved.

It is shown that the use of the first frequency as a design guideline is correct as far as the general trend goes, i.e. increase of the first natural frequency leads to better comfort. However the actual comfort gained is different as indicated by the change of the first natural frequency. The OS-RMS$_{90}$-value would be a better measure.

Insight of how parameters influence the comfort of a floor structure modelled as a beam has been provided.

A relatively small increase in spring stiffness at the supports leads to about 250% increase in comfort, while a change of mass has almost no influence on the comfort.

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