Assessment procedure for floor vibrations due to walking

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The design of slender floor structures, as made in steel or composites, is often limited by the serviceability criteria. Many papers [3-12] describe the calculation of vibrations of floors. However, there is no uniform and simple method available to describe the vibrations and the level of annoyance they cause. In the period 2000-2005 an ECSC-study was performed by RWTH, SCI, ProfilArbed and TNO [1]. The goal of this study was to design a method to classify the dynamic properties of floors. Based on this study, SBR and TNO composed a Dutch guideline [2]. This guideline describes criteria on the one hand and defines a relevant quantity which should be compared with these criteria on the other hand. Subsequently, a standardized measurement protocol was described to classify floors in practice. Finally a simple design tool was deducted to estimate the class of a floor beforehand.

Key words: Floors, vibrations, nuisance, slender floor structures, criteria

1 Introduction

Floor structures made of steel or composites are designed for ultimate limit states and serviceability limit state criteria. Ultimate limit states are those related to strength and stability; serviceability limit states are mainly related to deflection. Vibrations become more and more important and are governed by stiffness, masses, damping and excitation mechanisms. The design of slender floor structures, as made in steel or composites, is often limited by the serviceability criteria, instead of the strength of the materials. Serviceability criteria, therefore, directly affect the economy of steel and composite floors. Preferably recommendations should be based on experiences from the past that allow the specifiers to refer to them independent on their specific view. Such general recommendations are also needed, because the proposals for serviceability checks so far made in the Eurocodes, e.g. in the Eurocode - Basis of Design - relate to specific loading situations as characteristic loads, frequent loads and quasi-permanent loads, which cannot be used for vibration checks. Vibration checks need specific loading situations which are correlated to the excitation mechanism.

In addition to this the structural models in the Eurocodes are mainly related to ultimate limit state checks and therefore include the base load bearing structure only. The serviceability limit state checks should be based on a realistic structural model under service loads that takes the interaction with "non load bearing" components, semi rigid effects in connections etc. into account.

Many papers [3-12] describe the calculation of vibrations of floors. However, there is no uniform and simple method available. In the period 2000-2005 an ECSC-study was performed by RWTH, SCI, ProfilArbed and TNO [1]. The goal of this study was to design a method to classify the dynamic properties of floors. Based on this study, SBR and TNO composed a Dutch guideline [2].

In the ECSC study first the internationally used guidelines and standards used to evaluate vibrations on floor were considered. These guidelines generally describe a measurement and an analysis method with results in a quantity which is to be compared with criteria. Although the described methods and criteria apply to vibrations due to external sources, they contain information about the dose-effect relation. This information was used to formulate criteria on the one hand and to define a relevant quantity which should be compared with these criteria. Subsequently, a standardized measurement protocol was described to classify floors in practice. Finally a simple design tool was deducted to estimate the class of a floor beforehand.

In this paper the aspects in the ECSC study used in the Dutch guideline are described. A guideline should contain criteria, a quantity that can be compared with the criteria and a method to calculate this quantity. In this paper therefore these three aspects are addressed: first the quantity that is used in the guideline, subsequently, the method to calculate this quantity is described and finally the criteria and their rationale are described.

2 Quantity

In order to determine a quantity which can be compared with criteria, first the quantities defined in guidelines and standards quantities are listed. Quantities indicate the effect of vibrations on people. All quantities for instance used some kind of averaging to express that short peaks are less annoying than vibration which is more or less continuous. Furthermore, all codes and guidelines use a bandpass-filter to take into account the reduced human sensitivity towards low frequency (< 10 Hz) and high frequency (>10 Hz) vibrations.

The quantity used in the ISO standard 2631-2 [2] is the root mean square value of the weighted acceleration. For transient vibrations it is unclear what time window should be assessed, i.e. should the RMS-value be obtained form a single step, multiple steps and if so how many or perhaps from measurements of an entire day.

The quantity used in BS 6472: 1992 [3] is called the vibration dose value and is given by the fourth root of the integral of the fourth power of the RMS-value of the frequency weighted acceleration. The power of 4 is used in the calculation of the vibration dose value because peak values can be particularly important with regard to damage to biological tissue.

For assessing vibration exposure the so-called vibration strength KB(t) is introduced in the German standard (DIN Norm 4150, Teil 2: 1992) [4] and Dutch Guideline (SBR richtlijn deel B, 2002) [5]. This value is a moving weighted average. For the assessment of vibrations two quantities should be checked; the maximum of the vibration strength and the assessment vibration value. The assessment vibration value takes into account the effect of the duration of the vibrations during the entire assessment period.

The Norwegian standard NS 8179 [6] takes the 95% upper bound value to asses annoying vibrations. The 95% upper bound value is, assuming a lognormal distribution.

Floor vibrations are mostly assessed on the basis of RMS-values or progressive effective values. As far as RMS-values are concerned no guidance is given on the assessing time to be considered. For the determination of the progressing effective value an assessing time of 0.125s is used according to DIN 4150-2 and SBR.

For continuous signals, apart from the applied filter, there will be no differences between the effective value and the RMS-value when choosing an appropriate time or assessing interval. For walking loads the significant part of the signal for both measures will be near the most severe footfall loading resulting in the highest floor response. It therefore seems reasonable to choose the assessing time interval near this step (instead of the time interval of 0.125s which appears to be chosen from a practical point of view). A fixed time interval of for example 0.5s (corresponding to the average walking frequency) would lead to an assessment in which not even an entire step, exactly one step or more then one step is taken into account dependent on the person walking.

Since in the response spectrum, when using modal analysis, single steps cannot be distinguished when using a random walking or loading signal, it would also be convenient to base predictions of the floors response on one step loading signals. From this practical point of view taking into account exactly one step (from peak to peak) results in an unambiguous measure, i.e. there will not be any discussion on where the 0.5s window would have to start on the recorded time trace.

Because of years of experience worldwide using RMS-values (as is used in ISO standard 2631-2 for instance) and the rather small differences between the two measures it is proposed here to adopt the RMS-value assessed form footstep to footstep (the one step RMS-value) as a measure for assessing annoying floor vibrations. For assessing measured time signal this measure can be assessed unambiguously whereas for prediction purposes it sets the boundary conditions for loading functions to be applied.

However, vibrations caused by one footstep depend on both the floor and the person walking on it, particularly, his weight, his pace frequency and his type of soles are important aspects. To judge the comfort of a floor system, the most objective method is to invite over a hundred people with different length, weights etc. For all people the response of the floor i.e. the RMS-value can be measured. This method, however perfect, is not very practical because a large amount of people is necessary for each test. In order to overcome this problem a measurement and assessment protocol that on the one hand is easy to perform without busloads of people but on the other hand give good results is required. The assessment protocol should therefore reflect the average and the scatter of peoples feeling of discomfort due to various vibration levels. The measurement should give an indication of the range of vibration levels due to a large group of people walking on a floor, including thin people, thick people, fast walking people, slow walking people, people on high heels etc. It would be over conservative to use the absolute maximum of all these combinations. In this study it was chosen to use the 90% upper limit of the RMS-values of the response due to one footstep of a large number of people to be the quantity to compare with the criteria. The 90% upper limit is chosen because it compares with the reliability index β =1.8 that is prescribed in the Dutch building codes for serviceability limit states.

3 Method

As mentioned, ideally for each measurement an enormous number of people should be asked to walk on a floor. Since this is not very practical a method based on a transfer function is introduced. A transfer function describes the dynamic properties of the floor independent of the load on the floor. This transfer function is combined with a load that represents the large number of people to calculate the 90% upper limit of the one step

RMS-value. The concept of the spectral approach for determination of reactions is shown in Figure 1.

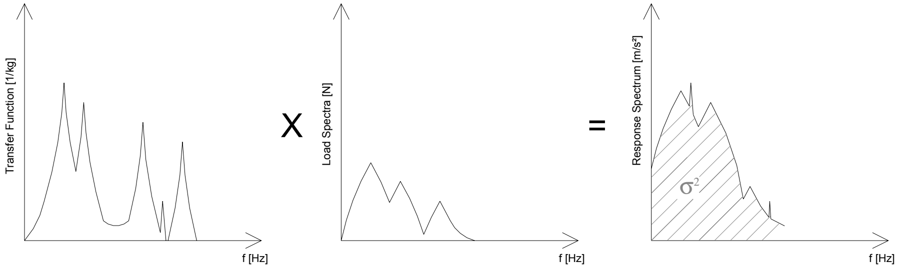

Figure 1: Conceptual overview of the spectral approach

- The input is the power spectral density function for walking induced loading. This input represents the load of a person walking on the floor.
- The transfer function should be determined by means of measurement or calculated using the dynamic properties of the system (damping, natural frequencies and mode shapes).
- The input spectrum is multiplied with the transfer function to obtain the power spectral density function of the response. The response depends on the input and the dynamic properties of the system. Both are taken into account.
- The integration of the response spectrum (the area under the curve) leads to the variance of the response.
- The variance of the response is a measure for the RMS-value

3.1 ***Transfer function***

There are two ways to determine the transfer function: by means of measurement or calculation. To determine a transfer function via measurement a dynamic force should be applied on the floor. This force should contain all frequencies between 3 and 30 Hz because this frequency range is of importance in floor vibrations. The response of the floor has to be measured. The force can be applied in several ways. In this paper only the heel drop method is described.

The principle of the heel drop test is simple. An adult drops his heels on the floor to make the floor vibrate. The force imposed on the floor is measured with load cells. The response of the floor is measured with either acceleration sensors or velocity sensors. Figure 2 shows the feet of an adult who stands on a small platform.

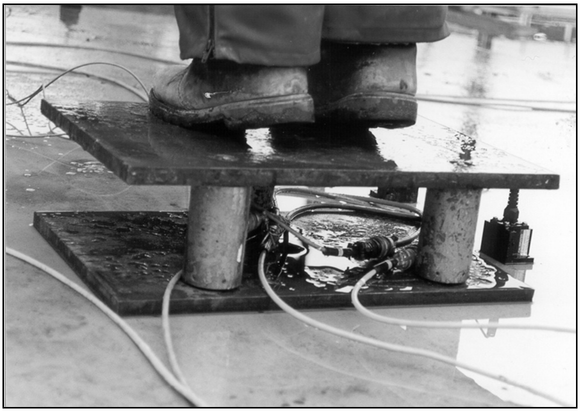

Figure 2: Load source heel drop, measured with load cells

The platform consists of three load cells between two metal plates. This test gives good responses particularly at low frequencies. The measured signals are forces and either accelerations or velocities. If accelerations are measured, the signals should be integrated to obtain velocities. The transfer function and correlations should be determined from the input and response signals in the frequency domain. The correlation should be higher than 0.8. If the correlation is lower the measurement might be performed badly or under difficult circumstances. An option is to improve the circumstances and repeat the measurement.

Instead of using a measurement, the transfer function can be generated by means of calculation as well. In order to predict the dynamic behaviour of a floor a dynamic analysis should be carried out. This can for instance be a dynamic Finite Element Method computation or by means of simple design rules. In [1] and [2] several design rules are given. In general, if a floor is not too complex, the first mode of a floor determines its dynamic behaviour due to walking. This behaviour then only depends on the mass, the first Eigen frequency and the damping of a floor. If these properties of the floor can be estimated, the measured transfer function can be replaced by the transfer function of a damped-mass-spring system.

3.2 ***Footfall loading***

To estimate the response due to an infinitively large group of people walking on a floor, RWTH measured the load of people walking directly [1]. They used these measurements to determine a relation between load, pace frequency and weight. RWTH concluded that footfall loading can be normalized by a person's mass. The normalized footfall was modelled with an 8th order polynomial. The constants in this polynomial depend on the pace frequency. Figure 4 shows the load due to single footsteps calculated according to the polynomials. With these modelled steps the footfall loading due to all different kind of people walking can be simulated.

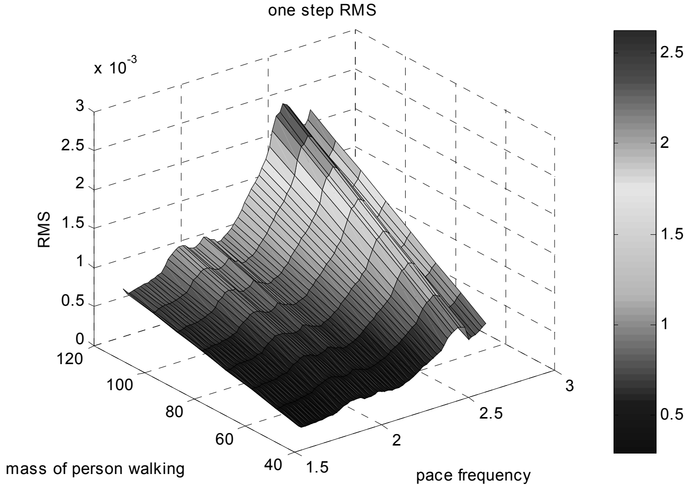

Figure 3: Response (OS-RMS) (in m/s) as a function of body mass (in kg) and pace frequency (in Hz)

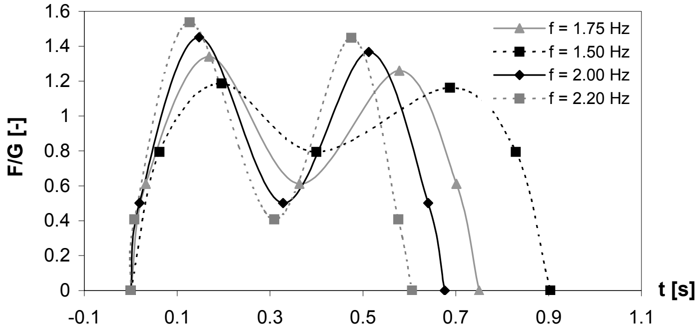

Figure 4: Vertical loads for several pace frequencies

3.3 **Response**

The simulated footfall loading depends on mass and walking frequency. With this information the one step RMS-value due to all realistic combinations of pace frequency and mass can be calculated using the concept of Figure 1.

The distribution of mass over the Dutch people was obtained from the Dutch Bureau of statistics [7]. To gain insight in the distribution of pace frequencies, a measurement was performed at the entrance of the TNO building. A statistical distribution of frequencies was based on these measurements (see Figure 5).

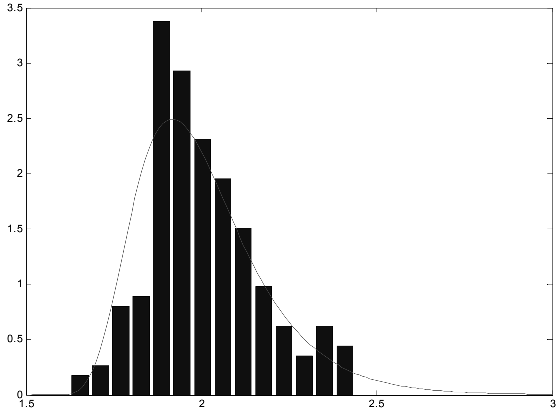

Figure 5: Fitted (shifted 1.5 Hz) lognormal distribution of pace frequencies (in Hz)

Given the transfer function and (statistical distributions of) the footfall load and body mass, the OS-RMS$_{90}$ can be calculated. Of course very many combinations of weight, pace frequency and transfer function have to be calculated before one can estimate the 90% upper value of the OS-RMS. The calculations have been carried out using the computer code PROBOX [17]. Probox is a generically applicable probabilistic toolbox that can be linked to any computer code and consist of many probabilistic calculations such as Monte Carlo sampling and FORM. In this case the option Numerical Integration is used, while the transfer functions were analysed with Matlab.

4 Simplified calculations

Often the dynamic behaviour of the floor is dominated by its first mode. Figure 6 gives an example of a measured transfer function together with a fitted transfer function of a one-mass-spring-damper system. In this case the one-mass-spring-damper system represents the dynamic behaviour of the floor almost perfectly between 3 and 80 Hz. This range is important in this study. In that case, the relevant parameters (first Eigen frequency, modal mass and damping) can then be extracted from the transfer function. The floor is then considered to behave as a damped one-spring-mass system, defined by mass, Eigen frequency and damping. In that case the OS-RMS$_{90}$ is defined by:

- the parameters of the floor: mass, Eigen frequency and damping,
- the distributions of people mass and pace frequency and footfall loading.

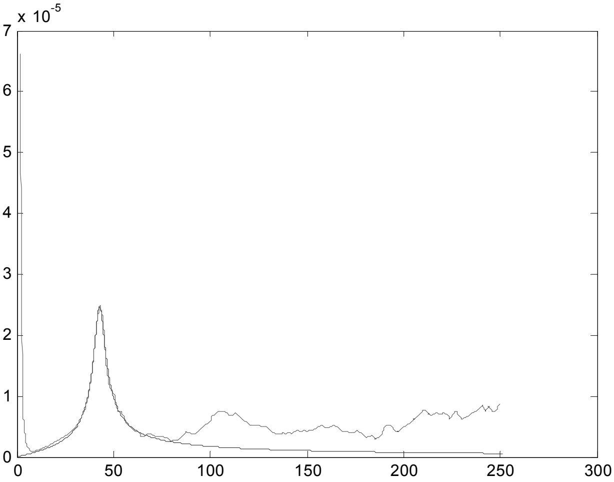

Figure 6: Example of a measured and fitted transfer function

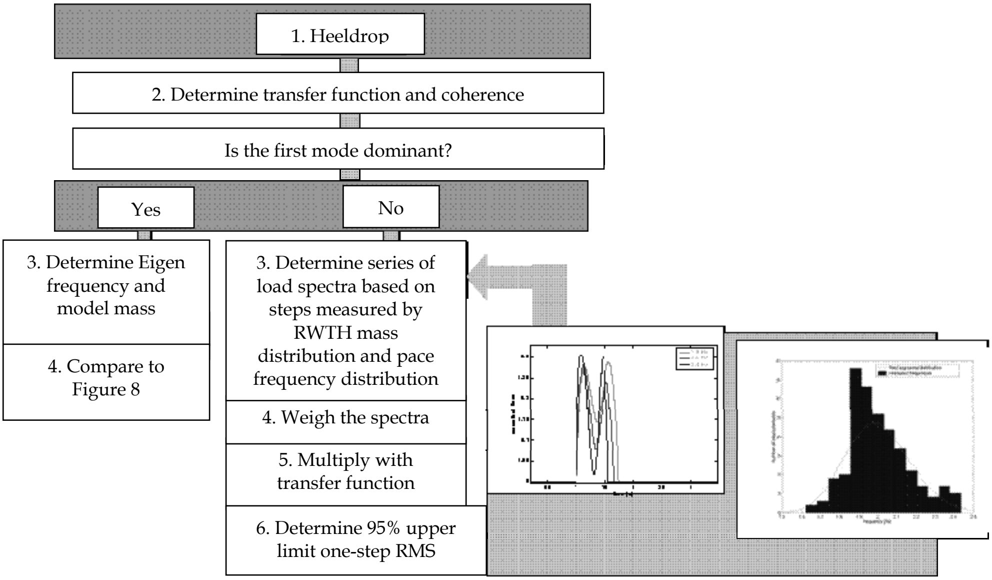

Figure 7: Total assessment procedure

Since all parameters are defined, the response (OS-RMS$_{90}$) given these parameters can be calculated using Probox. This can be carried out for a large number of combinations of mass, Eigen frequency and damping. The results of these calculations was presented graphically. When the graphs are used, calculations are not necessary. An example of these graphs is shown in Figure 8. Of course this procedure is not only valid for measured transfer functions. One can also estimate the transfer function based on the characteristics of the floor.

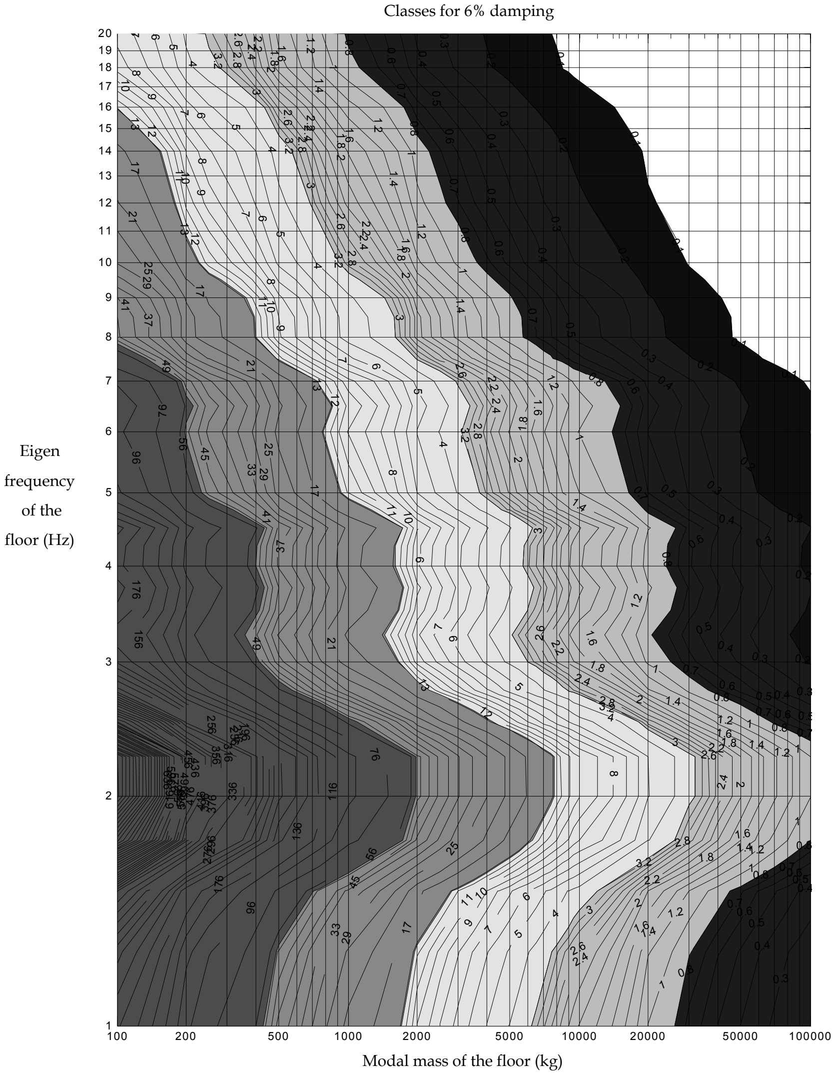

Figure 8: Example of an OS-RMS$_{90}$ response computed by Probox

5 Criteria

Several floor vibration criteria are summarized in Table 1. Although both RMS-values and effective values are presented comparisons can be made assuming the RMS-value is taken over a small time interval (< 1s) which is the case when taken as one step peak, i.e. from footstep to footstep. As stated previously all the standards and guidelines described previously are based on vibrations from external sources (such as for example trains) and often apply to continuous vibrations. It is reasonable to assume that when a continuous signal is equally annoying as a transient signal (for instance one footfall) the peak value of the transient signal is higher then that of the continuous signal. This corresponds to reactions in practice where people often complain that the continuously swaying and slowly decaying of the floor is more annoying then one single decaying step. In other words the peak value of a single step can be higher than the limit value for continuous vibrations but still cause equal or less annoyance.

Table 1: Floor vibration criteria (in mm/s)

	Residential				Office				Critical working area			
	Day		Night		Day		Night		Day		Night	
	Low	Up	Low	Up	Low	Up	Low	Up	Low	Up	Low	Up
ISO 2631-2	0.2	0.4	0.14	0.14	0.4	0.4	0.4	0.4	0.1	0.1	0.1	0.1
DIN 4150-2	0.15	3.0	0.1	0.2	0.4	6	0.3	0.6	0.1	3.0	0.1	0.15
SBR	0.2	0.8	0.2	0.4	0.3	1.2	0.3	1.2	0.1	0.1	0.1	0.1
NS 8176	0.1	0.6	0.1	0.6	-	-	-	-	-	-	-	-

On the basis of this it seems reasonable to adopt the values in Table 2 for assessing one step RMS-values. The classes in this table were coupled to the function of the floor as shown in Table 3 gives help for the application of the classes. It may depend on different circumstances (e.g. expected comfort) if a higher class is adequate for a specific building or not.

6 Example

In Rotterdam a floor with a span of 4.6 m and a width of 9 m was used in an apartment building. The floor is supported by steel C-sections. On top of the C-sections a Lewis c and an anhydrite layer was placed. To calculate the Eigen frequency of the floor the sections, the Lewis sheet and the anhydrite are assumed to move as one unit. The Eigen frequency, calculated according to NEN 6702, with a mass of 1,25 kN/m² is 13.4 Hz. The modal mass is calculated based on the normalized bending. The modal mass was 995 kg. Besides these calculations, the Eigen frequency and the damping were measured in situ. The measured Eigen frequency was 14.2 Hz and the damping was 6.5%. The measured Eigen frequency corresponds very well with the calculated one. The small difference between the two values might be due to assumptions about the support of the floor or material properties. The OS-RMS_{90} based on the calculated or measured Eigen frequency, modal mass and the measured damping is either 1.7 or 1.9 according to Figure 8. The floor therefore is class D.

Table 2: Limit values for the OS-RMS_{90} in mm/s

Class	Lower boundary	Upper boundary
A	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

Table 3: Minimal classes as a function of floor usage

Function of the floor	Class
Residential	D
Prison	D
Industrial	E
Hotel	D
Sport	E
Retail	D
Meeting	D
Health	C
Critical workspace	A
Office	D
Education	C
Other	D

7 Conclusion

In the period 2000-2005 an ECSC-study was performed by RWTH, SCI, ProfilArbed and TNO. This study led to a method to classify the annoyance due to people walking on a floor. With this method a floor can be classified using measurements or prediction. Figure 8 presents the total procedure.

For floors that can be described as a one-mass-spring-damper system, given the boundaries of the OS-RMS$_{90}$ in Table 2 and the pre-calculated response graphs in shown in Figure 8, one can directly read the response class. This makes it quite easy to predict floor vibrations.

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