Psycho-vibratory evaluation of timber floors – Existent criteria, measurement protocols, analysis of objective data and determination of design indicators of vibration acceptability and vibration annoyance

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Abstract

In lightweight housing constructions containing timber floors, vibrations can be a nuisance for inhabitants. The vibrational response of wooden floor systems is thus an issue in need of being dealt with more adequately in the designing of such buildings. Studies addressing human response to vibrations are needed in order to be able to better estimate what level of vibrations in dwellings can be seen as acceptable. In the present study, measurements on five different floors were performed in a laboratory environment at two locations in Sweden (SP in Växjö and LU in Lund). Acceleration measurements were carried out while a person either was walking on a particular floor or was seated in a chair placed there as the test leader was walking on the floor. These participants filled out a questionnaire regarding their perception and experiencing of the vibrations in question. Independent of the subjective tests, acceleration measurements were also carried out, using a shaker as a source of excitation, with the aim of determining the dynamic characteristics of the floors. Also, static load tests were performed using displacement gauges in order to measure the floor deflections. The ultimate aim of the study was to develop indicators of human response to floor vibrations, specifically those regarding vibration acceptability and vibration annoyance, their being drawn based on relationships between the questionnaire responses obtained and the parameter values determined on the basis of the measurements carried out. The study first presents a literature review of the topics dealt with, a description of the measurements performed, an analysis of the objective data obtained, as well as a classification of the floors in accordance with several different serviceability criteria. Subsequently, the statistical analyses performed to extract the vibration acceptability and annoyance indicators are described, use being made there of multilevel regression. Although the sample of floors tested was small (5 altogether), certain clear trends could be noted. In particular, the first eigenfrequency (calculated in accordance with Eurocode 5) and Hu and Chui's criterion (calculated from measured quantities) proved to be the best indicators of vibration annoyance, and the Maximum Transient Vibration Value (computed on the basis of the accelerations experienced by the test subjects) to be the best indicator of vibration acceptability.

Keywords: Psycho-vibratory evaluation, Vibrations, Timber floors, Lightweight, Measurements, Serviceability criteria, Vibration annoyance, Vibration acceptability, Design indicators, Principal Component Analysis, Multilevel regression, Eurocode 5.

Sammanfattning

I lätta konstruktioner som exempelvis består av bjälklag uppbyggda av en träkonstruktion, kan vibrationer vara till besvär för boende i exempelvis flerbostadshus. Vibrationsresponsen är därmed en viktig sak som behöver behandlas adekvat vid dimensionering av sådana byggnader. Det fordras studier som beskriver människans störningsgrad beroende på vibrationer så att det är möjligt att korrekt värdera vilken vibrationsnivå som kan betraktas som acceptabla i lägenheter. I denna studie så gjordes vibrationsmätningar på fem olika golvkonstruktioner av trä (avsedda för flerbostadshus) i laboratoriemiljöer på två olika ställen i Sverige (SP i Växjö och LU in Lund). Accelerationsmätningar gjordes medan en person, antingen gick på golvet eller satt i en stol medan den ansvarige för provningarna gick på golvet. Försökspersonerna fyllde i ett frågeformulär som innehöll frågor som skulle ge svar på deras upplevelse av vibrationerna. Oberoende av de subjektiva testerna så gjordes accelerationsmätningar medan en shaker användes som excitationskälla. Syftet med dessa mätningar var att bestämma dynamiska egenskaper hos de olika golven. Även tester med statisk last genomfördes samtidigt som golvets nedböjning mättes med hjälp av speciella nedböjningsmätare. Det huvudsakliga syftet med hela studien var att utveckla indikatorer som kan beskriva mänsklig påverkan av vibrationer i golv, i synnerhet sådana indikatorer som beskriver acceptans av vibrationsstörningar. Indikatorerna har tagits fram genom att studera förhållande mellan svaren från frågeformulären och de parametervärden som bestämts på basis av genomförda mätningar. Studien presenterar först en litteraturstudie av de uppgifter som behandlats, en beskrivning av genomförda mätningar, en analys av erhållna objektiva data, och sedan en klassificering av de olika golven, i enlighet med olika funktionskriterium. Efter detta gjordes statistiska analyser för att erhålla människans acceptans för vibrationer samt för att beskriva indikatorer på störningsgrad, framtaget genom flernivå regression. Trots att antalet olika golv var få (5 totalt), så kunde ändå några tydliga trender noteras. Två särskilt tydliga trender kunde urskiljas, nämligen vikten av den första egenfrekvensen (beräknad i enlighet med Eurocode 5) och Hu och Chui's kriterium (beräknade från uppmätta resultat). Dessa båda visade sig vara de bästa indikatorerna för att beskriva vibrationsstörning. För att beskriva acceptans av vibrationer visade sig maximalt transient vibrations värde (beräknat på basis av accelerationen som upplevdes av testpersonerna) vara den bästa indikatorn.

Keywords: Psyko-vibrationer, Vibrationer, Träbjälklag, Lättviktskonstruktion, Mätningar, Användarvänlighet, Vibrationsstörning, Acceptans för vibrationer, Design indikatorer, Principal komponent analys, Flernivå regression, Eurocode 5.

1 Introduction

Timber floors have traditionally been designed with respect to their static load-carrying capacity and static stiffness when uniformly distributed loads are involved [1]. This criterion has proved to not be sufficient in regard to vibration serviceability, however, for timber constructions in particular, complaints by inhabitants there being frequent, even when present-day building code regulations are met [2].

In 1994, Swedish building regulations authorised the construction of wooden multi-storey buildings. This led to an increasing demand for open planning in both residential and office buildings, involving use of long-span floor structures. Wood is high both in strength and in stiffness in relation to its weight, making it possible to build very long spans, especially with use of glue-laminated (glulam) timber. However, slender floor constructions involving long spans have low resonance frequencies that, in combination with low damping, are easily excited by such human activities as walking, running and jumping. Since humans are very sensitive to the vibrations thus produced, floors of this sort are often regarded as annoying. Accordingly, obtaining adequate indicators of human response to vibrations in slender or lightweight structures dynamically excited by human activities is of considerable importance.

In the present work, in efforts to assess how floor vibrations are perceived under various conditions, psycho-vibratory tests of five different prefabricated floor structures were carried out in a laboratory environment at two different locations in Sweden (Lund University – referred to here as LU – and the SP Technical Research Institute of Sweden – referred to as SP). A total of 60 persons participated in the tests conducted (31 persons at LU and 29 at SP). The floors in question were presented to the subjects in random order. The tests were divided into two parts: a "seated subtest" in which the subject was seated in a chair placed on the floor and experienced the vibrations created by a person who was walking on the floor, and a "walking subtest" in which the subject was asked to walk on the floor, being able in so doing to experience vibrations this produced. A questionnaire concerning different subjective attributes was presented to the subjects after each subtest. During the psycho-vibratory tests, objective measurements were also carried out on the floors in order to assess accelerations experienced by the subjects that could eventually be compared with their answers given in the questionnaires. The accelerations were measured at several points on the surface of the floors during the "walking subtest", and on the chair when the "seated subtest" was carried out. In addition, in order to assess certain measurable physical properties of the floors, i.e. properties not dependent on the subjects, static and dynamic tests were carried out separately.

Analysing the data from the questionnaires and comparing it with the accelerations experienced by the subjects, as well as with the objective non-subject-dependent measures obtained, enabled design indicators of different subjective attributes (vibration acceptability and vibration annoyance) to be determined. Therefore, the present study aims at obtaining more thorough knowledge of the relationship between perceived vibrational discomfort and certain objective engineering parameters.

The present investigation is divided in the report into three main parts, the sections and subsections having a consecutive numbering throughout the report. The first part is designated as *Part I*, and reviews the criteria currently applied to the vibration serviceability of timber floors, describes the measurement protocols employed, analyses the objective data obtained and presents a classification of the floors in terms of several serviceability criteria in present use. *Part II*, in turn, describes efforts made to determine indicators of vibration acceptability and vibration annoyance by combining the outcomes (i.e. subjects' questionnaire responses and objective parameters) stemming from both locations. To this end, use was made of multilevel regression. Multilevel regression, not yet in wide use, appears to be a suitable statistical method for modelling repeated measures data in which inter-individual differences in rating are substantial. Finally, *Part III* presents the overall conclusions.

Part I
Existent criteria and measurements

2 Literature Review

A summary of research in the area of human response to floor vibrations, as well as a compilation of the serviceability criteria found applicable to timber constructions nowadays will be presented here first.

2.1 Factors affecting human response to floor vibrations

Extensive research in the area of human perception of whole-body vibration, and human response to such vibration has been carried out. According to [3], human response to whole-body vibration can be divided into five categories: (i) degraded comfort, (ii) interference with activities, (iii) impaired health, (iv) occurrence of motion sickness and (v) perception of low-magnitude vibration. In the case of vibration in buildings, human response to it can be said to consist of annoyance and of a reduction in comfort.

Due to the complexity, sensitivity and variability of the human body, there are no clearly stated limits for acceptable vibration levels that are used in buildings nowadays but simply certain guidelines that have been developed [3]. The response of a human to vibration not only depends upon a large number of variables but is also highly subjective. For instance, people differ in how they react in response to what are nominally the same vibration levels (reflecting inter-subject differences in this respect), and a given person may respond differently to a particular level or type of vibration under differing circumstances (intra-subject differences) [4].

More specifically, one can say that human response to whole-body vibration depends both on psychological and on physiological variables. Thus, characteristics of the vibration, i.e. its amplitude, frequency, duration and direction, may very well influence the perception of it as much as age, gender, posture, fitness, type of activity being performed, attitude, expectations, context or motivation do [4].

Moreover, if humans are subjected to vibrations for too long a time, there is the risk of health problems being involved. According to [5], long-term high-intensity whole-body vibrations can result in an increased health risk for the lumbar spine and the connected nervous system of the segments affected. The digestive system, the genital/urinary system, and the female reproductive organs are also assumed to be affected, although the probability of this can be regarded as being lower. Such effects have only been investigated in the case of seated persons, no corresponding research having been carried out on standing or recumbent persons thus far. It has also been found that it normally takes several years for the health changes involved to occur.

2.2 Criteria for human perception of structural vibrations

Pioneering work in the field of human perception of vibration is that of Reiher and Meister [6], in which human sensitivity to vibrations was investigated. Ten test persons were exposed to vertical and to horizontal steady-state vibrations while standing or lying on a platform, the frequencies ranging from 5 to 100 Hz and the amplitudes from 0.01 mm to 10 mm. Subjects' reactions were classified and were labelled in categories extending from "barely perceptible" to "intolerable". The perception threshold was reached at a constant value of the product of amplitude (displacement) and frequency, and thus at a constant vibration velocity. A vibration perception scale was proposed on the basis of these findings. The scale was eventually modified in [7] to make it applicable as well to vibrations due to walking impact, its being observed that for transient vibrations the main factor affecting human beings was that of damping, variations in amplitude and in frequency having little effect. It was suggested that if the amplitude scale is increased by a factor of ten the original Reiher-Meister scale can be seen as applicable to floor systems having less than 5 percent critical damping. The resulting modified Reiher-Meister scale is shown in Figure 1.

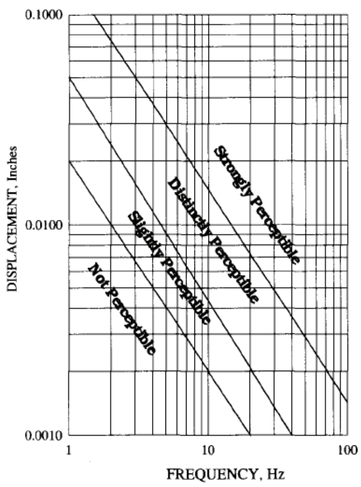


Figure 1: Modified Reiher-Meister Scale [7].

In [8], transient vibrations from a single-frequency component were investigated. A number of 40 persons standing in a room with a floor $4.9 \times 8.5\ \mathrm{m}^2$ in size were exposed to vertical vibrations created by a shaker of varying frequency, peak amplitude and damping. The vibrations involved (including both damped and undamped ones) were then rated on a 1-5 scale extending from "imperceptible" to "severe". Statistical analyses were carried out for identifying possible relationships between the response rate and various parameters. For damped vibrations, the following equation was proposed as predicting the response rate R_{WP}:

$$R_{WP} = 5.08 \left(\frac{f u_{max}}{\zeta^{0.217}} \right)^{0.265} \tag{1}$$

where f is the frequency, u_{max} the peak displacement in inches and ζ the damping ratio. The following equation was proposed for predicting the response to undamped vibrations:

$$R_{WP} = 6.82 \left(f u_{max} \right)^{0.24} \tag{2}$$

values for R_{WP} ranging from 1 to 5, labelled respectively as following: 1 "imperceptible", 2 "barely perceptible", 3 "distinctly perceptible", 4 "strongly perceptible" and 5 "severe vibration".

The investigations performed also showed the product of the frequency and the displacement to be constant and the transient vibrations of a given frequency and peak displacement to become progressively less perceptible as the damping was increased.

A vibration criterion for the degree of acceleration and damping appropriate for quiet human occupancies such as residential buildings and offices was developed in [9]. As the damping increases, the steady-state response produced by walking becomes a series of transient responses, resulting in a less significant response. A human perception scale for the degree of damping required was presented as a function of the product of initial displacement and the frequency in [10], the same parameters as in [8] being used.

In [1], springiness and vibrations in timber floors and steel floors were investigated in a laboratory environment with use of subjective rating tests, 15 persons taking part. A rating of different timber test floors in comparison with a reference floor was also carried out. The tests on laboratory timber floors showed both a reduction in the length of the span and the existence of a ceiling to have a positive effect in terms of subjective judgements of the degree of vibration, but the use of glue to fix the deck to the joists to have little effect in this respect. It was also pointed out that the spacing between adjacent natural frequencies should be one of at least 5 Hz in order to prevent annoyance.

Field tests were carried out and vibration ratings were collected in [11]. Human perception here was found to not be correlated with either peak acceleration, filtered peak acceleration, RMS acceleration, the fundamental frequency or the product of the fundamental frequency and peak acceleration. In [12], it was reported that in terms of the subjective assessments made, none of the structural modifications investigated there except for those of a reduction in joist depth and the introduction of rubber inserts, resulted in any improvement in dynamic serviceability.

There are several different standards concerning human perception of structural vibrations that are or have been employed, the three most prominent ones being the following.

2.2.1 ISO 2631-1:1997

The International Standard ISO 2631-1:1997 [5], (*Vibration and shock – Evaluation of human exposure to whole-body vibration – Part 1: General requirements*) provides guidelines on how to perform vibration measurements, what to report, and how to evaluate the results obtained, these guidelines being used to standardise reporting and to simplify comparisons. Although this standard is provided with three annexes containing suggestions, as well as current information on the possible effects of vibrations on health, comfort and perception, and motion sickness, it does not present any vibration exposure limits for whole-body vibrations.

2.2.2 ISO 2631-2:1989

This older version of the standard just referred to [13] has been cancelled and been replaced with the newer edition [14]. In the earlier version, tentative vibration serviceability limits were given in the form of base curves for the vibration magnitudes that cause approximately the same degree of annoyance. The base curves were to be used together with multiplication factors, taking into consideration the time of day and the type of occupied space involved (office, residential, etc.). In the latest edition of the standard, these base curves have been withdrawn, the reason given being the following: "Guidance values above which adverse comments due to building vibration could occur are not included anymore since their possible range is too widespread to be reproduced in an International Standard" [14].

2.2.3 ISO 2631-2:2003

The second part of the ISO standard 2631 [14] (*Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration – Part 2: Vibration in buildings – 1 Hz to 80 Hz –*) is applicable to the evaluation of vibrations in buildings with respect to matters of comfort and annoyance of occupants. No limit values are stated, due to the considerable differences in the research findings concerning this that have been reported. Instead, methods of measurement and evaluation concerned with whole-body vibrations in buildings have been suggested in order to encourage a uniform approach to the collection of data. A frequency weighting W_m (coincident with the W_k as defined in [5]) is recommended for use, irrespective of the measurement posture of an occupant (its being sufficient to simply consider vibrations in the direction having the highest frequency-weighted magnitude).

In [15], it was concluded that the frequency weighting of the ISO standard 2631-2 [14] and the overall weighted amplitude value obtained succeed well in describing the degree of annoyance felt regarding a single sinusoidal vibration, but that they are less accurate in regard to a vibratory signal involving only a limited number of discrete frequencies. To overcome these difficulties, a prediction model was developed in which both the overall weighted amplitude and the fundamental frequency are taken account of. This model, proposed in [15], is as follows:

Sinusoidal case:
$Annoyance = -1.26 + 0.39 \cdot weighted\ total\ amplitude$

Multiple Frequency case:
$Annoyance = -3.17 + 0.43 \cdot weighted\ total\ amplitude + 0.24 \cdot fundamental\ frequency$

Amplitude given in [mm/s^2] RMS, frequency in [Hz]
The frequency weighting: done according to ISO2631-2:2003

Interpretation:
if $Annoyance \leq 4$, the floor is acceptable
if $Annoyance > 4$, the floor is unacceptable

2.3 Design criteria to minimise annoying vibrations in floor systems

2.3.1 Criteria-limiting point-load deflections

The earliest attempts to provide some degree of control over vibration problems in timber floors involved limiting the static deflection of joists under uniformly distributed load conditions so as to ensure the floor stiffness being sufficient [16]. For instance, the traditional $L/360$ deflection limit (L being the span of the floor) was in broad use for a considerable period of time. A numerical investigation performed in [17] led to an improved stiffness-based criterion for floor vibration serviceability being developed, one that limited the midspan deflection of the floor system to 1 mm for a point load of 1 kN, independent of the span. In [18], another stiffness-based criterion, one incorporated into the National Building Code of Canada and requiring that the static deflection produced by a 1 kN load at midspan be limited to $8.0/\mathrm{L}^{1.3}$, and also that it not be greater than 2 mm for spans ranging from 3 to 6 m in length, was employed.

If the same traditional design criteria for deflection, making use of static response parameters, are employed, vibration serviceability is not guaranteed [19]. As a consequence, research aimed at gaining an understanding of the factors that affect human response to floor vibrations has increased ever since and has paved the way for the development of design approaches for studying the dynamic parameters involved.

2.3.2 Criteria for limiting-point load deflection, for velocity due to unit impulse, and for RMS velocity

Criteria taking account of several different modes of vibration as well as of modal damping, of limiting-point load deflection, of the velocity due to a unit impulse and of the RMS velocity, can be found in [1] and [20]. The development of these criteria was based on measurements of floors and subjective evaluation of their vibration performance, mainly in single-family houses. Three types of limits are to be noted: (i) the floor system needs to have a flexibility of no more than 1.5 mm/kN in the case of a concentrated load located at midspan; (ii) for floors with a fundamental frequency greater than one of 8 Hz, the values of the velocity due to a unit impulse (h'_{max}) and of a damping coefficient ($\sigma_0 = f_1\zeta$ [Hz]) need to fall within a given region of the graph $h'_{max} = f(\sigma_0)$ in order to ensure that the performance achieved will be acceptable (Figure 2); and (iii) the root-mean-square velocity for steady-state vibration needs to be less than tabulated values as given for acceptable floor systems. Actually, the use of such tabulated values has never been proposed, the recommendation being that one instead compare the root-mean-square velocity with corresponding values for similar floor constructions that show acceptable vibration performance. Yet values of this sort have never been available either. Rather, the first two criteria, namely (i) and (ii), have provided the basis for the vibration serviceability criteria in Eurocode 5 [21].

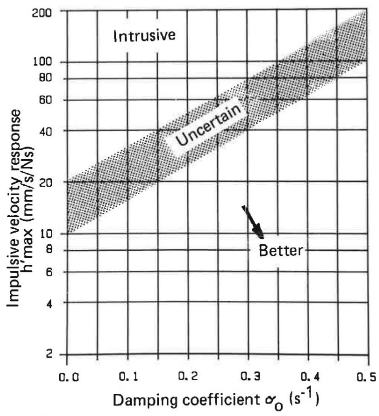


Figure 2: A preliminary proposal for classifying the response of a floor construction in terms of impact load [20].

2.3.3 Criteria limiting the fundamental frequency and the frequency-weighted RMS acceleration

The design criterion developed in [22] requires that the fundamental frequency of a floor be greater than 8 Hz, and that the frequency-weighted root-mean-square acceleration obtained during the first second of vibration be less than 0.45 m/s^2 when loaded by a specific impulse. The first part of the criterion is determined by the stiffness and the mass of the floor system, whereas the second part is a function of the damping that takes place. Theoretically, therefore, it is necessary that the designer estimate the damping of the floor structure at the time that designing is carried out. Since doing this is virtually impossible, however, due to the damping of the timber floors varying considerably depending upon the construction type selected, and the techniques and workmanship employed, methods requiring that damping calculations be performed may not be practical for design engineers to utilise.

2.3.4 Criteria limiting the fundamental frequency

The investigation performed in [19] suggests that if the stiffness of a floor is sufficient to maintain the fundamental frequency of the floor system at a level above that of 15 Hz in the case of unoccupied floors, and above 14 Hz in the case of occupied floors, the furniture or whatever and the persons involved being included, acceptable levels of vibration will be obtained.

The work presented in [15] is in opposition to the latter reference, as it shows that human perception of vibration is strongly affected by the composition of the vibration signal in terms of the number of frequency components involved and their mutual amplitude relationships. Thus, in line with [15], it can be argued that the multiple natural frequencies inherent in a floor need to be taken account of in determining the design rules to be followed. This is in agreement with the criteria for design rules proposed in [1] and [23] (in which it is suggested that up to the 8$^{\text{th}}$ harmonic should be taken account of), its contradicting many presently used floor design criteria that often rely on the fundamental frequency alone.

2.3.5 Criteria limiting the fundamental frequency and point-load deflection

In [24], rules for the design of floors with "high-" and with "low-" requirements and those with "no-" requirements, resulting in the fundamental frequency being maintained at above a level of 8 and of 6 Hz for "high-" and for "low-" requirement floors, respectively, were proposed. A stiffness criterion is also specified there (such that the deflection due to a static load of 2 kN is to be less than the limit value w_{limit}, the size of which depends upon the requirements that apply to the floor in question).

Suggested criteria and limiting values for the classifying of floors into five different classes (A-E) are proposed in [25]. It was found there that the point load deflection and the fundamental frequency are two of the best indicators of vibration performance in the case of lightweight floors.

2.3.6 A criteria-limiting combination of parameters

The approaches just mentioned are semi-empirical in nature, their providing satisfactory solutions for the particular categories of floors for which the methods were developed. None of them appear to work entirely satisfactorily when applied to other types of floors, however [16]. In [26], a new design method consisting of a vibration-controlled criterion and a calculation method for determining the criterion parameters were developed. The design criterion states that if the ratio (fundamental frequency)/(1 kN deflection)$^{0.44}$ of an unoccupied floor is larger than 18.7, the floor is most likely satisfactory for the occupants.

In [27], the ratio of the peak acceleration achieved by walking, to the force of gravity, is used as a design guideline, its value depending upon the use to which the building is to be put. Its value given as

$$\frac{a_p}{g} = \frac{P_0 e^{-0.35 f_n}}{\beta W} \leq \frac{a_0}{g} \tag{3}$$

where P_0 is a constant applied force (0.29 kN for floors and 0.41 kN for footbridges), f_n the fundamental frequency of the floor structure, β the damping ratio, W the floor's effective weight, a_0/g the tabulated acceleration limit and a_p/g the estimated peak acceleration (in units of g).

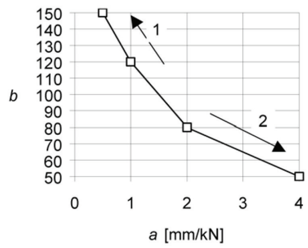


Figure 3: Recommended range of the relationship between a and b: 1 better performance, 2 poorer performance.

2.3.7 Eurocode 5

The methods presented in [1] and [20] served as the basis for the vibrational serviceability criteria developed in Eurocode 5 [21]. The Eurocodes are a set of harmonised technical rules developed by the European Committee for Standardisation for the structural design of construction work carried out within the European Union.

Specifically, the design of timber structures is dealt with in EC5-1-1 and in the serviceability limit state design guidelines regarding floor-vibration performance. The design criteria are applicable to residential wood-based plate-type floors with a fundamental frequency greater than 8 Hz, in which the human sensitivity is related to the effects of the vibration amplitude and velocity caused by the dynamic footfall forces involved [28]. If the fundamental frequency of the floor is lower than this, a special investigation of the floor in question is needed.

The effects are divided into low- and high-frequency ones. The low-frequency contributions that come from step actions are dealt with by a static criterion that limits the deflection caused by a static point load applied at the point on the floor that results in a maximum vertical deflection. The high-frequency effect is a consequence of the heel impact actions that occur, its being taken account of by use of a dynamic criterion that limits the maximum initial value of the vertical floor vibration velocity caused by an ideal unit-impulse load. Three points must thus be checked on:

- The fundamental frequency of the floor, f_1, should be at least 8 Hz in order for the floor to be regarded as a high-frequency one (otherwise a special investigation of it is needed), the requirement thus being that

$$f_1 \geq 8 \text{ Hz} \tag{4}$$

- The maximum instantaneous vertical deflection, w, due to a single force should be less than a deflection of a varying size a (see Figure 3 regarding a):

$$\frac{w}{F} \leq a \text{ [mm/kN]} \tag{5}$$

- The maximum initial value of the vertical floor vibration velocity, v, produced by an impulse of 1 [N·s], applied at the point on the floor giving the maximum response

– where components above 40 Hz can be disregarded – should verify the inequality (see the dimension b in Figure 3):

$$v \leq b^{(f_1\zeta-1)} \text{ [m/Ns}^2\text{]} \tag{6}$$

where F is a vertical concentrated static force applied to any point on the floor, taking account of the load distribution, and ζ is the modal damping ratio (a value of 1 % is recommended in [21] unless some other value has been found to be more appropriate).

For more detailed information regarding Eurocode 5 calculations, see Section 5.3.1.

2.3.8 Design tools

Various numerical methods, the finite element method, for example, are sometimes used as design tools nowadays for checking on the serviceability of floors of different types, in line with the development of commercial solutions in the form of different softwares. Often highly versatile, they can enable floors to be very much improved and various criteria described above to be verified during the design phase. Examples of the use of such tools are to be found in [29], [30] and [31].

3 The floors tested

In the present investigation, five separate floors (shown in Figures 4 - 8) differing one from another but each of a type used frequently in residential buildings, the suppliers of each playing an active role in the Swedish construction market, were tested in a laboratory environment. Due to differences between them in the structural conceptions they embodied (box-floor-type, surface-floor-type), they can differ in design, in their dimensions and in various construction features. Although the floors differed in their vibration properties, the range in vibration performance they represented was not large at all, each of them being known from earlier to display fairly good vibration performance in a normal building environment. This could make it difficult for the persons participating in the testing conducted to distinguish clearly between the floors in terms of their vibration performance. Table 1 shows the manufacturers of the floors together with the labelling used in the investigation, the design features of the floors being listed in Table 2.

Table 1: Suppliers of the floors and the labels given them.

Supplier	Label
Moelven Töreboda	A
Martinssons Byggsystem	B
Lindbäcks Bygg	C
Masonite Beams	D
Masonite Lättelement	E

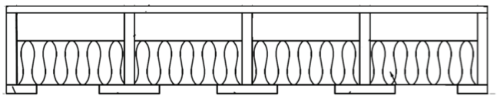


Figure 4: Moelven Töreboda.

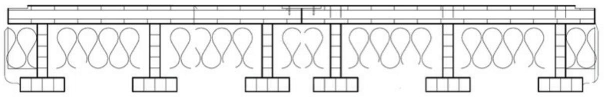


Figure 5: Martinssons Byggsystem.

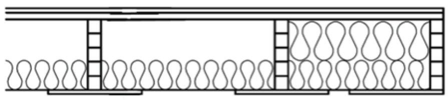


Figure 6: Lindbäcks Bygg.

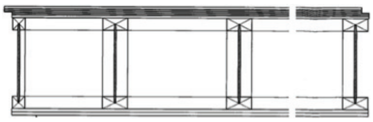


Figure 7: Masonite Beams.

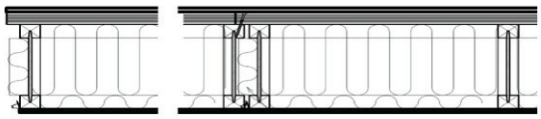


Figure 8: Masonite Lättelement.

During the tests, each floor was simply supported on two sides by glulam beams having dimensions 90×180 mm^2. The glulam beams, in turn, were supported by studs at a centre-to-centre distance from one another of 600 mm. These studs were stabilised by use of plywood slabs, and they were bolted to the concrete floor of the laboratory, as shown in Figure 9. In attaching the floor elements to the supporting beams, the floor suppliers' instructions were followed. A floor resting on its supports is shown in Figure 10.

Figure 9: Floor supports used.

Figure 10: Floor supports joined to a glulam beam by means of a tie plate, the floor resting on top. In this case, the floor is required to rest on top of an elastomer, blue in colour in the picture, according to the manufacturer's instructions.

Table 2: Floor design, all sizes in [mm].

Feature/Label	A	B	C	D	E
Length [m]	6800	8500	3700	7966	8100
Width [m]	4800 (2x2400)	4800 (4x1200)	2400	4804 (2x2402)	4848 (2x2424)
Flooring	-	-	13 mm gypsum boards	-	13 mm gypsum boards
Sheating	33 mm Kerto Q511	73 mm CLT	22 mm chipboards	43 mm plyboard	43 mm plyboard
Beams	Web: Kerto S80 51x360 s587 Flange: Kerto S16 45x300	Web: Glulam C40 42x220 s400 Flange: Glulam C40 42x180	Web: Glulam 42x225 s600 Flange: Plywood 12x300	Web: Masonite beam HB 350 C24 s480 Flange: 45x98	Masonite beam H300 C24 s585 Flange: 45x45
Remarks	-	-	-	Beam in one of the long sides H350 C24 Flange width: 45	Tension flange 0.7 mm perforated steel sheet
Strutting	2 rows of beams Kerto S75 52x360 L_1=2392 L_2=4362	-	-	2 rows of Masonite beams H350 K24 L_1=3079 L_2=6079	2 rows of Masonite beams H300 K24 L_1=3079 L_2=6079
Junction (between floor elements)	WT-T screw 6.5x130 s300 every second from left and right element respectively	Plywood strip 12x160 P30 screwed with WFR 4x50 s125	-	Glued with SikaBond-540 Chipped nails 34x45 s300	Overlapping plyboard screwed with 5x90 s300
No. Elements	2	4	1	2	2
Ceiling	-	-	-	2x13 mm gypsum board	13 mm gypsum board

4 Measurement procedures

4.1 Non-subject-dependent measurements

Prior to the subjective psycho-vibratory testing that was carried out, objective measurements of each of the five floors were performed in order to determine the values for various static and dynamic parameters for each of them, those of subfloor and floortop deflections, eigenfrequencies, eigenmodes and modal damping ratios. These parameters were used to classify the floors in terms of various criteria taken up in the literature review, use being made here both of methods proposed in Eurocode 5 [21], and of methods employed by Hu and Chui [26] and by Dolan *et al* [19], as taken up in Section 5.3. The parameters assessed on the basis of the objective measurements that were taken were also used in the statistical analysis to determine which parameters were correlated most closely with vibration acceptability and with vibration annoyance (see *Part II* of the report).

4.1.1 Eigenmodes, eigenfrequencies and damping ratios

Dynamic tests were carried out in order to measure the eigenfrequencies and damping ratios of the floors and determine the mode shapes involved. Excitation was performed by use of a shaker driven by a pseudo-random signal, the strength of it being measured by a force transducer attached to the floor by a wood screw and to the shaker by a threaded rod. The vertical floor accelerations were measured by accelerometers located at ten separate points placed within one quadrant of the floor area. The test setup is shown in Figure 11.

For frequencies of up to 40 Hz, the eigenfrequencies, damping ratios ζ [%], mode shapes and modal density, n_{40}, were extracted from the measured frequency response functions (FRFs) using the Matlab toolbox *VibraTools Suite* [32]. In order to extract the aforementioned parameters, a poly-reference time domain method [33] was used for determining the poles and the modal participation factors, a least-squares frequency-domain method then being employed to fit estimates made to the measured data. Also, the impulse velocity response was calculated from the driving point mobility.

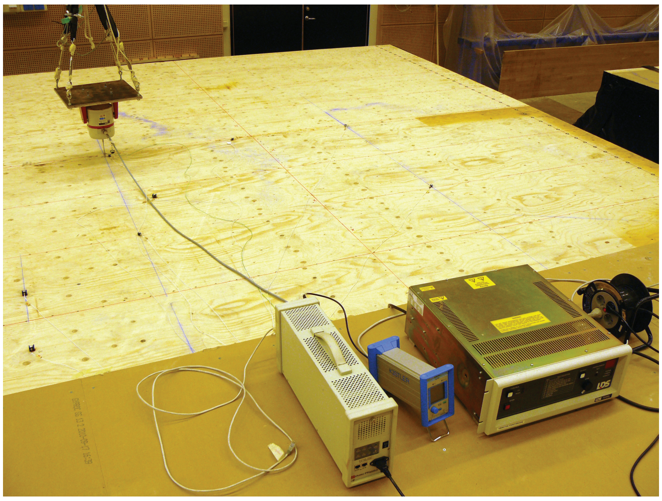


Figure 11: Shaker, accelerometers and other equipment used for the measurements.

4.1.2 Subfloor deflection

In order to classify the floors in terms described by Hu and Chui [26] and in Eurocode 5 [21], the midspan deflection produced by a static point load of 1 kN was measured. The deflection measurement procedure was based on that proposed in [34].

The displacement gauge was fastened to a reference system consisting of a magnetic stand that was attached to a metal weight hung from an overhead crane. The loading was performed by a person weighing approximately 80 kg who stood with his feet straddling the measurement point, facing in the direction of the floor-load-bearing beams. The deflection was averaged from five measurements performed in the same way for each of the floors in order to ensure good repeatability. The deflection produced by a 1 kN point load, $d_{1,m}$, was then obtained by extrapolation.

4.1.3 Floortop deflection

The floortop deflection, i.e. the deflection on the sheating of the floor, was measured. For each of the wooden floors (A to E), two displacement gauges were placed on the upper surface of the floor in question, the first one located at the midpoint of the floor and the second one placed 0.6 m from it (see Figure 12). The gauges were fixed to a reference system consisting of a metallic portal frame (moved from one floor to another) that remained motionless during recordings. This setup was the same for each of the floors.

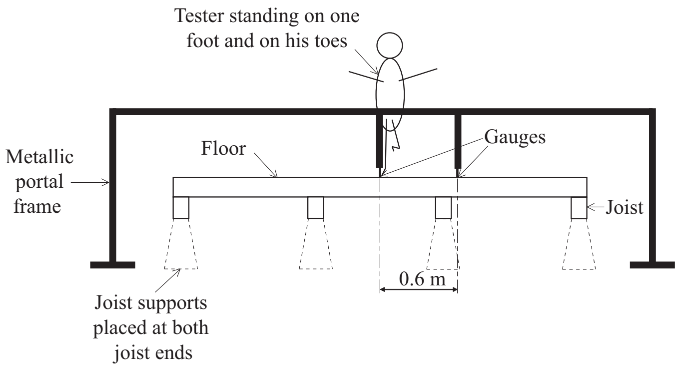


Figure 12: Side view of the floortop deflection measurement setup.

The measurement procedure was based on that proposed in [25]. The midpoint was loaded by the tester's weight of approximately 80 kg. The displacement time histories were recorded by both gauges while the tester was standing on his toes of one foot in the middle of the floor (see Figure 12). Three trials were carried out for each floor, in order to ensure a good repeatability. The maximum displacement recorded by the one gauge was subtracted from that recorded by the other, the resulting difference being extrapolated in the manner proposed in [25] so as to obtain the floortop deflection, $d_{2,m}$, produced by a 1 kN point load.

4.2 Subject-dependent measurements

The subject-dependent measurements made during the subjective tests that were carried out were obtained both at LU and at SP. A total of 60 persons differing in age and gender (31 at LU and 29 at SP) participated in the tests. All of them performed the following tasks on each floor, the tasks at both locations being the same, the five different floors being presented to each subject in random order:

- Seated subtest: the subject was first seated in a chair placed at the observation point in question (located 0.6 m from the midline of the floor, see Figure 13), he or she gazing in the direction of the walking line. The experimenter walked along the walking line at a step velocity of about 2 Hz, back and forth between the two limits indicated by the red lines in Figure 13, his passing the observation point three times. Three accelerometers were used during the test, the first one placed on the floor between the feet of the subject, the second one placed under the chair seat, and the third one placed on the backrest of the chair (marked by crosses in Figure 13). Although the acceleration would normally be measured on the upper surface of the seat [5], in this case it was placed beneath the seat so as to not create discomfort for the test person. A situation similar to this was investigated in [15], its being shown there that the transmissibility, i.e. the gain between the one way of measuring and the other – under the seat versus on top of it – both types of measurements being performed by a seated person, was approximately 1.0, showing that this alternative also works properly.

- Walking subtest: after the seated subtest was completed, the chair was removed and the subject was asked to walk in a rather free manner along the walking line, between the two limits marked by the red lines in Figure 13. No other specific instruction was given to the subject concerning his or her way of walking. Five accelerometers were placed along the walking line to measure the floor vibrations (their locations being marked by crosses in Figure 13).

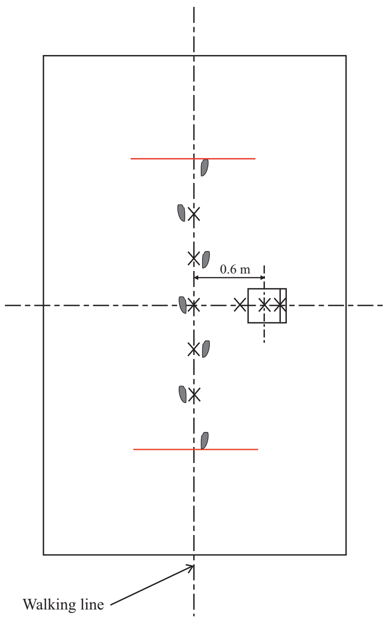


Figure 13: Measurement setup.

Figure 14 shows a subject performing the seated and the walking test, respectively.

After each completion of the one subtest or the other for a given floor, subjects were asked, as to describe, through filling in a questionnaire, their experiences of the floor in question in terms of various subjective attributes, there being one such questionnaire to be filled out following the seated subtest and another following the walking subtest. The questionnaires of this sort used at *LU* were not identical with these used at *SP*, the questionnaires for use in the two organisations having been developed separately, yet questions concerning certain matters of central interest – primarily matters of whether one is annoyed by vibrations and whether or not one considers the level of vibration present to be acceptable – were either exactly the same or rather similar in both cases, which led to a merging of the questionnaire results of this character in reporting the results here. The reasoning behind this merging of results and the methods involved are taken up in the *Part II* of this report.

Figure 14: Measurement pictures showing the seated (left) and the walking (right) subtest.

For the seated subtest at LU, subjects were asked about noise annoyance, vibration annoyance, vibration acceptability and springiness. For the walking subtest, subjects were asked about vibration annoyance, vibration acceptability and springiness. The definition of springiness given to the subjects was “resistance of a material to a shock”. In response to questions concerning noise annoyance and vibration annoyance evaluation, subjects were asked to express a judgment on a 11-point numerical scale ranging from “0” (“not at all annoyed”) to “10” (“extremely annoyed”). In response to questions concerning springiness, subjects were asked to express a judgment on a 11-point numerical scale ranging from “0” (“very bad”) to “10” (“very good”). Finally, regarding vibration acceptability, subjects were requested to express a dichotomic judgment: “acceptable” or “not acceptable”.

For the seated subtest at SP, subjects were asked about noise annoyance, vibration annoyance and vibration acceptability. They were also asked to describe in their own words their perceptions while the test leader was walking. For the walking subtest there, the subjects were asked about springiness, annoyance and acceptability. They were also asked to describe in their own words their experiencing of the floor response while walking on the floor. The definition of springiness given to the subjects here was “the resilience or flexibility of the floor under a step”. Finally, subjects there were asked to judge how they experienced the floor vibrations, as well as the quality of the floors, and whether they would accept having such vibrations in a living room in a new residential building. Subjects’ answers to all these questions were to be given on a six-point categorical scale, for instance “definitely not acceptable”, “not acceptable”, “barely acceptable”, “acceptable”, “fully acceptable”, “acceptable with any reservations whatever”. Subjects were also asked to rank the floors on a scale from the one they would prefer most to have at home to the one they would prefer least.

For each subtest and floor, the time histories of acceleration obtained in each of the accelerometers were recorded simultaneously during testing. The objective parameters extracted for each subject during the subjective testing carried out are presented in the following.

4.2.1 Overall frequency-weighted RMS accelerations

For each accelerometer, the frequency-weighted RMS (Root-Mean-Square) acceleration, a_w, was computed in accordance with Equation (7) (see standard [5], section 6.4.2),

$$a_w = \left[\sum_i \left(W_{m,i} a_i \right)^2 \right]^{\frac{1}{2}} \tag{7}$$

where $W_{m,i}$ are the weighting factors for the different third-octave bands i of the acceleration spectrum, as given in Annex A of the standard [14], and a_i are RMS values computed for the different third-octave bands i of the acceleration spectrum.

An overall frequency-weighted RMS acceleration was determined finally on the basis of the root-sum-of-squares of the frequency-weighted RMS accelerations as computed for the different accelerometers (see standard [5], section 8.2.3).

4.2.2 Overall frequency-weighted RMS velocities

In addition, for each accelerometer, velocity time histories were determined by integration on the basis of the acceleration time histories. The frequency-weighted RMS velocity, v_w, was computed then as

$$v_w = \left[\sum_i \left(K_{b,i} v_i \right)^2 \right]^{\frac{1}{2}} \tag{8}$$

where $K_{b,i}$ are the weighting factors for the different third-octave bands i of the velocity spectrum, as given in the standard [35], and v_i are the RMS values computed for the different third-octave bands i of the velocity spectrum.

In the end, an overall frequency-weighted RMS velocity was determined from the root-sum-of-squares of the frequency-weighted RMS velocities computed for the different accelerometers (see standard [5], section 8.2.3).

Note that the frequency-weighted RMS values are highly dependent upon the time window for analysis. Accordingly, this time window needs be chosen carefully and be stated in connection with the results. In the present case, frequency-weighted RMS values were computed using a time window corresponding to only one of the three "walking lines" (a "walking line" is defined as one completed stroll along the floor in the one direction or the other). Thus, the periods of time in which the subject just stood on the floor, not creating any noticeable vibrations, or moved by simply turning around, were not taken into account in the computations. Had such periods of time been taken into account, the frequency-weighted RMS values could well have been markedly reduced.

4.2.3 Maximum Transient Vibration Value ($MTVV$)

For each accelerometer, the maximum transient vibration value was computed by use of Equation (9) (see the standard [5], section 6.3.1).

$$MTVV = max \left[a_w(t_0) \right] \tag{9}$$

where $a_w(t_0)$ is defined as follows:

$$a_w(t_0) = \sqrt{\frac{1}{\tau}\int_{t_0-\tau}^{t_0} [a_w(t)]^2\, dt} \tag{10}$$

where $a_w(t)$ is the instantaneous frequency-weighted acceleration, τ is the integration time for the running average (1 second in the present case), t is the time and t_0 is the observation time. A Matlab code was created here in order to be able to calculate $MTVV$. With use of that code, the entire duration of the recording swept over, a one-second window being employed. Each of the computed $a_w(t_0)$ values was saved. The output produced, i.e. $MTVV$, is the "worst" (i.e. the maximum) of these values. In the end, an overall $MTVV$ was determined on the basis of the root-sum-of-squares of the $MTVV$s computed for the different accelerometers (see the standard [5], section 8.2.3).

5 Results

5.1 Non-subject-dependent objective parameters

5.1.1 Eigenmodes, eigenfrequencies and damping ratios

The eigenfrequencies, eigenmodes and modal damping ratios up of to 40 Hz were extracted (as described in Section 4.1.1), fairly close agreement of the *LU* and the *SP* results and good reproducibility of the measurements being obtained. It was thus concluded that the floors were mounted in a similar way at both locations, allowing the data to be used interchangeably, measurements at both locations thus theoretically providing basically the same results. The results obtained at *SP* are presented in Tables 3 and 4.

Table 3: Measured eigenfrequencies below 40 Hz, i.e. n_{40}.

Floor Label	Mode number [Hz]											n_{40}
	1	2	3	4	5	6	7	8	9	10	11	
A	16.3	17.7	18.3	30	36	-	-	-	-	-	-	5
B	9.9	10.5	11.1	17.3	24.2	27.8	29.5	33.7	36.6	38.9	39.6	11
C	24.3	26.1	36	-	-	-	-	-	-	-	-	3
D	8.8	9.9	14	22.7	24	28.3	31.7	37	-	-	-	8
E	8.2	12	20.2	25.9	28.4	34.1	-	-	-	-	-	6

Not surprisingly, floor C, with the shortest span, has the highest fundamental frequency, whereas floors B, D and E, with the longest spans, have the lowest fundamendal frequencies. Also, floor C has the lowest value for n_{40}, whereas floors B and D have the highest values for n_{40}. In examining the modal damping ratios for the three first eigenmodes, one can note that floor C has the strongest damping properties, whereas floor B has the weakest damping properties.

Table 4: Measured modal damping ratios below 40 Hz, i.e. ζ_i [%].

Floor Label	Modal damping ratio, ζ_i [%]										
	1	2	3	4	5	6	7	8	9	10	11
A	1.6	1.5	1.5	8	5	-	-	-	-	-	-
B	0.7	1.1	0.9	1.2	1.1	1.4	1.6	1	1.2	2.1	1.3
C	2.3	2.6	5	-	-	-	-	-	-	-	-
D	1.8	2.1	2.2	2	2	1.5	1.6	2	-	-	-
E	1.1	1.8	3.5	2.6	3.2	4	-	-	-	-	-

5.1.2 Floor deflections

The subfloor deflection, $d_{1,m}$, and the floortop deflection, $d_{2,m}$, were measured as described in Sections 4.1.2 and 4.1.3, respectively. The results are shown in Table 5.

The deflection $d_{1,m}$ appears to covary with $d_{2,m}$. For instance, floor A (the rigidity of which is among the highest, see Table 7) has the lowest subfloor and floortop deflection, whereas floor B has both the highest subfloor and floortop deflection.

Table 5: Measured subfloor deflection produced by a 1 kN load $d_{1,m}$ and floortop deflection $d_{2,m}$.

Floor	A	B	C	D	E
$d_{1,m}$ [mm/kN]	0.260	0.660	0.560	0.530	0.440
$d_{2,m}$ [mm/kN]	0.101	0.529	0.335	0.320	0.230

5.2 Subject-dependent objective parameters

The 2.5%, 50% and 97.5% percentiles for a_w, v_w and $MTVV$ for the seated test, for all floors and subjects, are given in Table 6. The parameter a_w appears to strongly covary with v_w and $MTVV$. Floors A and C have the lowest median values of a_w , v_w and $MTVV$, whereas floors B, D and E have the highest median values of a_w , v_w and $MTVV$. The dispersion of the a_w, v_w and $MTVV$ values for each of the floors is large. This high degree of dispersion may have come about through the large differences in weight between those participating in the test (extending from 50.7 to 140 kg). Indeed, subjects differing appreciably in weight have been found to differ in the levels of acceleration and velocity of vibration they experience [3]. This dispersion may also be due to differences between subjects in their manner of walking.

Table 6: Percentiles of weighted parameters for each of the floors for the subjects as a whole, in the seated subtest.

Floor	Percentile	a_w [m/s^2]	v_w [m/s]	$MTVV$ [m/s^2]
A	0.025	0.001	0.00004	0.004
	0.50	0.012	0.00030	0.034
	0.975	0.026	0.00070	0.054
B	0.025	0.003	0.00010	0.011
	0.50	0.054	0.00140	0.150
	0.975	0.144	0.00341	0.291
C	0.025	0.001	0.00005	0.003
	0.50	0.021	0.00060	0.058
	0.975	0.041	0.00110	0.091
D	0.025	0.003	0.00009	0.012
	0.50	0.055	0.00140	0.151
	0.975	0.116	0.00320	0.242
E	0.025	0.003	0.00010	0.009
	0.50	0.063	0.00160	0.163
	0.975	0.116	0.00331	0.292

5.3 Classification of the floors

5.3.1 Floor classification according to Eurocode 5 [21]

The degree to which the design guidelines given in Eurocode 5 [21] (see Section 2.3.7) were met was also investigated, for the calculated data, in line with instructions given in [28]. The calculations were carried out under the assumption that the floor was unloaded, i.e. that only the weight of the floor and other permanent actions need to be taken into account. For the individual materials of the floor structures, the mean values for the modulus of elasticity involved were employed, these being provided by the material suppliers. In calculating the flexural rigidity in the span direction, $(EI)_l$, composite action between the floor sheathing and the floor joists was assumed to occur on each of the floors. In calculating the corresponding flexural rigidity in the cross-joist direction $(EI)_b$, however, only the contribution from the floor sheathing was taken into account. The fact of not considering the positive effect of strutting between joists when calculating $(EI)_b$ means that the rigidity of the floors A, D and E is underestimated somewhat, since two rows of strutting are present in each of them. On the basis of the results of laboratory tests, the rotational rigidity $(EI)_T$ was assumed to be equal to $(EI)_l/500$ in the finite element (FE) analysis and hand calculations. Table 7 gives the physical properties of the floors.

For a rectangular floor having overall dimensions of $L \times B$, simply supported along all four edges and having timber beams with span of L, the fundamental frequency f_1 can be calculated in an approximate manner as

$$f_1 = \frac{\pi}{2L^2}\sqrt{\frac{(EI)_l}{m}} \tag{11}$$

where m is the mass per unit area given in [kg/m^2], L is the floor span given in [m], and

$(EI)_l$ is the equivalent plate bending stiffness of the floor about an axis perpendicular to the beam direction given in [N·m^2/m].

For floors having a fundamental frequency of more than 8 Hz, as calculated by use of Equation (11) (this is the case for all of the floors under study here), the requirements to be satisfied are the following:

- Low-frequency effects: the requirement given in Equation (5) needs to be met. The deflection value produced by a point load of 1 kN, w, given in [mm], as calculated using Equation (12), must not exceed the limit, a, given for each country in the National Annex. In the Swedish National Annex, the deflection limit a is equal to 1.5 mm, no consideration being taken of the floor span.

$$w = \frac{1000 k_{dist} l_{eq}^3 k_{amp}}{48(EI)_{joist}} \tag{12}$$

  In calculating the deflection produced by a point load, w, account is taken of only a single joist. The effect of load sharing between joists is taken account of by use of the following reduction factor k_{dist}:

$$k_{dist} = max\left\{k_{strut}\left[0.38 - 0.08\ln\left[\frac{14(EI)_b}{s^4}\right]\right]; 0.30\right\} \tag{13}$$

  where $(EI)_{joist}$ is the stiffness of a single joist in [N·mm^2], $(EI)_b$ is the flexural rigidity in the cross-joist direction as given in [N·mm^2/m], s is the spacing between joists in as given in [mm] and the factor k_{strut} takes the effect of strutting into account. If a single row or several rows of strutting exist, the value of k_{strut} is set to 0.97 (floors A, D and E), in the case of no strutting the value being equal to 1 (floors B and C). The parameter l_{eq} is the equivalent span of the floor joists in [mm], which equals here the span of the floor joists, since each of them is simply supported. In addition, k_{amp} is an amplification factor that takes into account the effects of shear deformations, its being equal to 1.05 for simply supported timber joists (floors A, B and C) and to 1.15 for simply supported glued thin webbed joists (floors D and E).

- High-frequency effects: when an impulse force of 1 [N·s] is applied to the centre of the floor in a manner simulating heel impact, the unit impulse velocity response v needs to comply with Equation (6), the value of v being given by Equation (14), and the value of b being set to 100 in the Swedish National Annex. For the relationship between a and b, see Figure 3. The value of v can, as an approximation, be taken as

$$v = \frac{4(0.4 + 0.6n_{40})}{(mBL + 200)} \tag{14}$$

  where v is the unit impulse velocity response given in [m/(N·s^2)], n_{40} is the number of first-order modes having eigenfrequencies of up to 40 Hz, B is the floor width in

[m], m is the mass per unit area in [kg/m^2] and L is the floor span in [m]. The value of n_{40} can be calculated as

$$n_{40} = \left[\left(\left(\frac{40}{f_1} \right)^2 - 1 \right) \left(\frac{B}{L} \right)^4 \frac{(EI)_l}{(EI)_b} \right]^{0.25} \tag{15}$$

where $(EI)_b$ is the equivalent plate bending stiffness of the floor about an axis parallel to the beams, given in [N·m^2/m]. Note that $(EI)_b < (EI)_l$.

For purposes of verification, eigenfrequencies of up to 40 Hz were also calculated for each of the floors, as displayed in Table 8, using the Matlab FE toolbox *Calfem* [36]. The mode shapes for floor D are shown, as an example, in Figure 15.

Table 7: Stiffness parameters (EI) (longitudinal – l –, transversal – b –, rotational – T – and single joist), floor geometry – the width of the exterior supports not being taken into account – (L length and B width) and mass m of the floors.

Floor	$(EI)_l$ [N·m^2/m]	$(EI)_b$ [N·m^2/m]	$(EI)_T$ [N·m^2/m]	$(EI)_{joist}$ [N·mm^2]	L [m]	B [m]	m [kg/m^2]
A	2.65E+07	5.99E+03	5.30E+04	1.56E+13	6.7	4.8	60
B	1.94E+07	2.06E+05	3.88E+04	0.77E+13	8.4	4.8	67
C	1.81E+06	2.40E+03	3.62E+03	0.11E+13	3.7	2.4	43
D	1.05E+07	2.91E+04	2.09E+04	0.50E+13	8.0	4.8	48
E	1.06E+07	2.62E+04	2.11E+04	0.62E+13	8.0	4.8	53

Table 8: Calculated eigenfrequencies of the different floors, obtained using the Matlab toolbox *Calfem* [36].

Floor Label	Mode number [Hz]											n_{40}
	1	2	3	4	5	6	7	8	9	10	11	
A	23.3	23.4	23.9	24.9	26.8	29.9	34.4	-	-	-	-	7
B	11.9	12.1	15.2	26.8	-	-	-	-	-	-	-	4
C	23.5	23.7	24.6	27.8	35.2	-	-	-	-	-	-	5
D	11.5	11.6	12.6	16.3	24.1	36.0	-	-	-	-	-	6
E	10.9	11.1	11.9	15.2	22.2	32.8	-	-	-	-	-	6

A summary of the calculations and requirements, as stated in [21] for the five floors under study, is presented in Table 9. All of the requirements are fulfilled for each of the floors.

It should be pointed out that there is still concern regarding both the accuracy of the proposed damping ratio ζ and the procedures for calculating n_{40}. This also raises serious doubts regarding the accuracy of the simplified procedures used for calculating the impulse velocity response v. Specifically, it is stated in [31] that the current EC5-1-1 design criteria do not adequately address issues concerning the dynamic response of timber flooring systems and their associated vibrational problems. Reconsideration of the design criteria is thus called for.

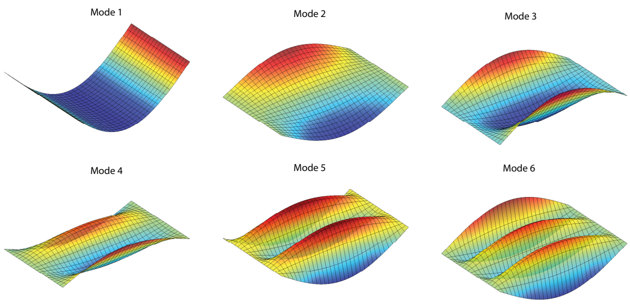


Figure 15: Eigenmodes for Floor E calculated with Calfem.

Table 9: Calculations in terms of Eurocode 5 [21].

		Low frequency effects					High frequency effects					Requirements		
Floor	f_1 [Hz]	k_{strut}	k_{amp}	k_{dist}	w [mm]	a [mm]	n_{40}	v [mm/N·s^2]	v_{limit} [mm/N·s^2]	b	ζ [%]	$f_1 > 8$ Hz	$w/F \leq a$	$v \leq b^{(f_1\zeta-1)}$
A	23.5	0.97	1.05	0.396	0.167	1.5	7	8.54	29.18	100	1	✓	✓	✓
B	12.0	1	1.05	0.300	0.501	1.5	3	3.18	17.36	100	1	✓	✓	✓
C	23.5	1	1.05	0.300	0.498	1.5	4	19.19	29.57	100	1	✓	✓	✓
D	11.5	0.97	1.15	0.488	0.730	1.5	5	6.39	16.97	100	1	✓	✓	✓
E	11.0	0.97	1.15	0.300	0.593	1.5	5	6.12	16.58	100	1	✓	✓	✓

5.3.2 Floor classification according to Hu and Chui [26]

The criterion for floor vibration acceptability proposed in [26] states, regarding unoccupied floors, that if the ratio of the fundamental frequency, f_1, to the deflection due to a 1 kN point load, d_1, expressed as $r_{HC} = [f_1/d_1{}^{0.44}]$, is larger than 18.7, the floor in question is most likely satisfactory for occupants. In such a case, the criterion has been evaluated both with use of the measured first eigenfrequency and deflection as well as with use of the first eigenfrequency and deflection, as assessed on the basis of calculations.

The formulae used in the design method employed are based on the ribbed-plate theory. The floor stiffness parameters should then be calculated, taking account of the semi-rigid connections between the joist and the sheathing, the torsional rigidity of the joists and the sheathing stiffness in both the span and the across-joist directions. In addition, performance-enhancement-related construction details such as between-joist bridging, strong-back and strapping, are accounted for in the formulae presented in [26]. The deflection $d_{1,c,HC}$ in [m] due to a static point load P of 1 kN at the centre of the floor was calculated as

$$d_{1,c,HuChui} = \frac{4P}{LB\pi^4} \cdot \sum_{m=1,3,5...} \sum_{n=1,3,5...} \frac{1}{\left(\frac{m}{a}\right)^4 D_x + 4\left(\frac{mn}{ab}\right)^2 D_{xy} + \left(\frac{n}{b}\right)^4 D_y} \tag{16}$$

where P is in [N], L is the floor span in [m], B is the floor width in [m], D_x is the system flexural rigidity along the span direction in [N·m^2/m], D_y is the system flexural rigidity in the cross-joist direction in [N·m^2/m] and D_{xy} is the sum of the shear rigidity of the multi-layered floor deck and the torsion rigidity of the floor joist. To ensure convergence of the calculations, it is recommended to use three terms for $m = 1, 3, 5$ and eighteen terms for $n = 1, 3, 5...35$.

The fundamental frequency $f_{1,c,HC}$ in [Hz] of a floor system was calculated as follows:

$$f_{1,c,HC} = \frac{\pi}{2\sqrt{\rho}} \sqrt{\left(\frac{1}{L}\right)^4 D_x + 4\left(\frac{1}{LB}\right)^2 D_{xy} + \left(\frac{1}{B}\right)^4 D_y} \tag{17}$$

where ρ is the mass per unit area in [kg/m^2]. Table 10 presents the results regarding the classification of the floors. In that table, the acceptability rate is the percentage of the participants who would accept the floor for their own houses. A value of 50% for acceptability can be considered as the threshold for a floor being acceptable.

Table 10: Classification of the floors according to Hu and Chui [26]. The subindex m denotes measured values whereas c indicates calculated values. In the last row, the percentages of subjects who considered the floor vibrations acceptable during the seated subtest are presented. It is often considered 50% of acceptability as the threshold for a floor being "acceptable".

Floor label	A	B	C	D	E
$f_{1,m}$ [Hz]	16.3	9.9	24.3	8.8	8.2
$d_{1,m}$ [mm]	0.26	0.66	0.56	0.53	0.44
$f_{1,c,HC}$ [Hz]	23.3	12.6	23.7	11.6	11.1
$d_{1,c,HC}$ [mm]	0.29	0.28	0.89	0.61	0.62
$r_{HC,m}$	29.5	11.9	31.4	11.6	11.8
$r_{HC,c}$	40.1	22.3	24.7	14.5	13.7
$r_{HC,m} > 18.7$	✓	×	✓	×	×
$r_{HC,c} > 18.7$	✓	✓	✓	×	×
Acceptability [%]	56.7	30.0	58.3	35.0	25.0

Albeit the criterion computed from the calculated data fails to correctly describe the vibration acceptability for floor B, the criterion does accurately portray the vibration acceptability for the measured data. The mismatch for floor B may be due to the fact that it has a high cross-joist rigidity, due to the thick cross-laminated timber (CLT) plate there and the fact that the model proposed in [26] assumes lower cross-joist rigidity.

5.3.3 Floor classification according to Dolan *et al.* [19]

The design criterion presented in [19] states that if the stiffness of the floors is sufficient to mantain the fundamental frequency of the floor system at a level above 15 Hz for unoccupied floors, and above 14 Hz for occupied floors (i.e. including furniture and/or persons), an acceptable level of vibration will be obtained. The fundamental frequency, f_1, of the joists and the girders alone can be estimated using

$$f_1 = \frac{\pi}{2}\sqrt{\frac{gEI}{WL^3}} \tag{18}$$

where g is the acceleration due to gravity – equal to 9.81 [m/s^2] –, E the modulus of elasticity in [Pa], I the moment of inertia of the joist alone in [m^4] (without consideration of the composite action with the subflooring), W the weight of the floor system supported by the joist, given in [N], and L is the floor span in [m]. The weight, W, is taken as being simply the weight of the joist plus the weights of the subflooring and the finished flooring that are supported by a joist. The ceiling, floor covering, furniture, and other occupancy weights are not to be included in W. The same restrictions apply when calculating the fundamental frequency of the girder.

If the floor system includes joists and girders, the fundamental frequency can be estimated using the Dunkerly equation:

$$f_1 = \sqrt{\frac{f_{joist} f_{girder}^2}{f_{joist} + f_{girder}^2}} \tag{19}$$

where f_{joist} is the fundamental frequency of the joist alone, given in [Hz], and f_{girder} is the fundamental frequency of the more flexible girder supporting the joists, also given in [Hz].

This criterion is simple to use and restricts only the stiffness of a floor system relative to its weight. Damping is not included since it cannot be effectively estimated or controlled by the designer, and if the level of damping is high, this improves the vibration performance of the system. The criterion involved also ignores any composite action between the joists and the sheathing which if present would improve performance and be effective at the low displacement amplitudes associated with vibrations. Both of these concerns have been investigated experimentally and been discussed in [19]. The results for each of the five floors can be seen in Table 11.

Table 11: Classification according to Dolan *et al* [19]. The subindex m denotes measured values, c indicates calculated values and D stands for Dolan.

Floor Label	A	B	C	D	E
$f_{1,m}$ [Hz]	16.3	9.9	24.3	8.8	8.2
$f_{1,c,D}$ [Hz]	15.9	6.1	21.9	2.9	2.2
$f_{1,m} > 15$ Hz	✓	×	✓	×	×
$f_{1,c,D} > 15$ Hz	✓	×	✓	×	×
Acceptability [%]	56.7	30.0	58.3	35.0	25.0

The criterion based on both the measured and the calculated fundamental frequencies appear able to predict the acceptability from the subjects standpoint. Despite this, it is our belief that the failure of the formulae involved to take account of composite actions between parts when the bending stiffness is calculated can lead to results being too conservative in predictions made on the basis of these calculations.

6 Discussion

For all of the floors, the degree to which the requirements proposed by Eurocode 5 [21] were met was checked. In fact, all of the floors met the requirements stated in EC5-1-1.

This is not very surprising, however, since Eurocode 5 regulates the structural design of construction work carried out in the European Union and all of the floors under study were ones of a type used in real buildings there. Also, the requirements stated in EC5-1-1 were drawn up on the basis of measurements and subjective ratings made in lightweight timber houses, which happens to be our working scenario.

In addition, in considering the value of 50 % acceptability (i.e. half of the participants being ready to accept the floor within their own house) as the threshold for a floor being "acceptable", it was found that the Hu and Chui [26] criterion works well for the measured data here, since it matches the acceptability results for all of the floors under study here. A match with the calculated data, however, fails for floor B, since the degree of acceptability for subjects cannot be predicted there. This is probably due to the assumption in the analytical formulae proposed that the connections between joists and sheathing be semi-rigid, whereas floor B has rigid connections and a high level of across-joist rigidity due to the thick CLT layer on the surface of it.

The applicability of Dolan *et al*'s criterion [19] was examined. It was observed that these guidelines could be applied and that they worked properly with use of the measured data for each of the five floors included in the study. Nonetheless, although the criteria worked properly as well for the calculated data, the fact that the composite action that occurs is not accounted for in the formulae proposed for use there means that the calculations underestimate the fundamental frequency, which could lead to the results obtained being unrealistically conservative.

Part II
Determination of design indicators

7 Methods

This section presents the methods used for merging the subjective data stemming from two separate though closely related studies, that at SP and that at LU (see section 7.1), and for analysing the merged data obtained (see section 7.2).

7.1 Merging the subjective data

Of the rather many questions posed to subjects either at the SP location or at the LU location, only two of them were considered to be equivalent in the sense that the subjects' answers to them at the two locations could be combined. These two questions concerned vibration annoyance and vibration acceptability, respectively.

At SP, the vibration annoyance question was: "How do you experience the vibrations when I walk on the floor?". The response scale was a six-point verbal one, having the following alternatives: "not at all disturbing", "barely disturbing", "a little disturbing", "disturbing", "very disturbing", "extremely disturbing". The vibration acceptability question was: "Considering a newly-built residential building: do you experience the vibrations that occur as?". The response scale was again a six-point verbal one, having the following alternatives: "definitely not acceptable", "not acceptable", "barely acceptable", "acceptable", "fully acceptable", "definitely acceptable". The questions and the answers were both in Swedish, and are translated here to English. At LU, the vibration annoyance question was "Imagine that you live in a newly-built multi-storey building equipped with this floor, you are seated on a chair and another person is walking by: what number from 0 to 10 best shows how much you are bothered, disturbed or annoyed by the floor vibrations?". The response scale was an eleven-point numerical one, the numbers ranging from 0 to 10. Two labels, "not at all" and "extremely", were attached to the respective ends of the scale, at 0 and 10. The vibration acceptability question was "Imagine that you live in a newly built multi-storey building equipped with this floor, you are seated on a chair and another person is walking by: do you find the floor vibrations acceptable?". The two response alternatives were "Yes, acceptable" and "No, not acceptable". The questions and answers were available both in English and in Swedish.

One can note that both the vibration annoyance and the vibration acceptability questions were posed at each of the two laboratories in a situation in which the test person was seated in a chair placed on the floor in question while the test leader was walking by. Since the two studies differed in the response scale used regarding both vibration annoyance and vibration acceptability, the issue arose of how to merge the subjective data coming from the two locations, at SP and LU.

For the vibration annoyance question, the responses from both data sources could be translated into scores ranging from 0 to 100. This translation procedure is based on the assumption that the different response categories available divide up the range extending from 0 to 100 into equally spaced intervals [37]. The general rule followed here for assigning a particular score on the 0 to 100 scale is that described by [38]:

$$score\,(0\,\text{to}\,100) = 100(i - \frac{1}{2})/m \tag{20}$$

where m is the number of categories ($m = 6$ in the SP study, and $m = 11$ in the LU study) and $i = 1,....,\ m$ is the rank number of a given category, starting with the lowest response category. After this translation, the scores ranging from 0 to 100 from both studies could be merged.

Regarding the vibration acceptability question, in the SP study the responses were translated into dichotomic responses in accordance with the following rules: the responses "definitely not acceptable" and "not acceptable" were transformed into the response "no, not acceptable", and the responses "barely acceptable", "acceptable", "fully acceptable" and "definitely acceptable" were transformed into the response "yes, acceptable". After this transformation, the dichotomic responses from both studies could be merged.

7.2 Data analysis

The data analysis aimed at assessing relationships between the subjective data and the objective parameters involved, as well as at finding a satisfactory indicator for each of the two subjective attributes (vibration annoyance and vibration acceptability), that is, an objective parameter that best explains the subjective data. To this end, use was made of multilevel regression (see section 7.2.2).

The large amount of non-subject-dependent objective parameters available made it impossible to determine by means of multilevel regression analysis the relationships between each and every one of these objective parameters, on the one hand, and the subjective data, on the other. Thus, a preliminary analysis based on Principal Component Analysis (PCA) was carried out first, in order to select beforehand a small number of objective parameters that could best explain the subjective data (see section 7.2.1).

7.2.1 Preliminary selection of relevant non-subject-dependent objective parameters

Vibration annoyance data The merged vibration annoyance scores ranging from 0 to 100 were analyzed using linear PCA, or more specifically the MDPREF model [39]. This model provides a multidimensional space in which the floors are represented by points and the subjects by unit vectors passing through the origin. These entities are located in such a way that the projections of the points on the vectors are in maximal agreement with the subjects' scores. A vector endpoint represents the point of maximum vibration annoyance of the subject in question. In order to identify the vibratory features of the floors able to affect vibration annoyance, the non-subject-dependent objective parameters were fitted into the space as non-normalized vectors, using a PREFMAP procedure [40]. An objective parameter vector then points in a direction such that the projections of the points on the vector are in maximum agreement with the values of the objective parameter. The length of the vector, which is equivalent to the linear correlation coefficient between the projections and the values of the objective parameter, indicates the quality of representation of the objective parameter in the space [41].

The non-subject-dependent objective parameters that were fitted are presented in Table 12. Their values for each of the floors are shown in *Part I* of the report.

Vibration acceptability data The merged binary responses were analyzed using logistic PCA, a tool especially well suited for analyzing binary data. More specifically, the model proposed by [42] was employed. Similarly, this model provides a multidimensional space consisting of a configuration of floor points and of subject vectors passing through the origin. For convenience sake, the subject vectors were normalized *a posteriori*. A vector endpoint represents the point of maximum acceptability for the subject in question. In order to identify the vibratory features of the floors that could affect vibration acceptability, the objective parameters were also fitted into the space as non-normalised vectors by use of a PREFMAP procedure.

Again, all objective parameters shown in Table 12 were fitted.

Symbol	Objective parameter
$d_{1,m}$	Measured subfloor deflection
$d_{1,c,EC5}$	Calculated subfloor deflection, according to Eurocode 5
$d_{1,c,HC}$	Calculated subfloor deflection, according to Hu and Chui
$d_{2,m}$	Measured floortop deflection
$n_{40,m}$	Measured number of modes below 40 Hz
$n_{40,c,EC5}$	Calculated number of modes below 40 Hz, according to Eurocode 5
$n_{40,c,FEM}$	Calculated number of modes below 40 Hz, obtained by use of Calfem simulations
$f_{1,c,EC5}$	Calculated first eigenfrequency, according to Eurocode 5
$f_{1,c,FEM}$	Calculated first eigenfrequency, obtained by use of Calfem simulations
$f_{1,c,HC}$	Calculated first eigenfrequency, according to Hu and Chui
$f_{1,c,D}$	Calculated first eigenfrequency, according to Dolan *et al.*
$f_{1,m,v}$	Measured first eigenfrequency in the SP study
v_m	Measured impulse velocity response
$v_{c,EC5}$	Calculated impulse velocity response, according to Eurocode 5
η_1	Measured damping ratio for the first eigenmode
η_2	Measured damping ratio for the second eigenmode
m	Mass
$(EI)_l$	Longitudinal stiffness of the load-bearing beams
$(EI)_b$	Transverse stiffness of the load-bearing beams
$r_{HC,c}$	Hu and Chui's criterion, as calculated from the calculated quantities $f_{1,c,HC}$ and $d_{1,c,HC}$
$r_{HC,m}$	Hu and Chui's criterion, as calculated from the measured quantities $f_{1,m,v}$ and $d_{1,m}$

Table 12: List of non-subject-dependent objective parameters.

7.2.2 Determination of an indicator of vibration annoyance and vibration acceptability

In efforts to find an adequate indicator of vibration annoyance and one of vibration acceptability, a regression analysis involving the vibration annoyance and the acceptability responses, on the one hand, and the relevant appearing objective parameters, on the other, was carried out. More specifically, for analyzing the repeated measures data that were collected, use was made of multilevel regression models, within a Bayesian framework. Although this regression method has been used for meta-analysis of *in situ* noise annoyance studies earlier [37], it appears to not yet have been used for modelling subjective data collected under laboratory conditions. Multilevel regression has advantages over classical regression for the modelling of repeated measures data. Notably, multilevel regression formulation complies strictly with the hierarchical structure of repeated measures data that consists of observations nested within individuals. It thus takes account of the fact that the observations are not independent. For an introduction to multilevel regression models, the reader is referred to the textbooks of Gelman and Hill [43] and Hox [44].

In carrying out the regression analysis here, a two-level random-intercept-only model (one which includes no explanatory variable at the occasion level) was first fitted to the subjective responses (either vibration annoyance or vibration acceptability responses). This model provides a baseline for comparisons with models that include occasion-level predictors, its for this reason being referred to henceforth here as a "null" model.

Following this, for each of the subjective attributes, objective parameters were inserted successively into two-level models as occasion-level predictors. For each objective parameter, two models, the one with a fixed regression slope and the other with a random regression slope, were tested. For each objective parameter, these two models were compared with the corresponding null model in order to check, for each of the objective parameters considered, to what extent it could account for the subjective responses obtained.

Finally, for each subjective attribute, the models of interest, each including an objective parameter thought to be able to account to some extent for the subjective responses obtained, were compared with one another. These comparisons aimed at determining which indicator is best, this being the one provided by the model making it possible to best explain the subjective responses obtained.

Note that the objective parameters tested are divided into two groups: (i) those determined on the basis of the measurements carried out separate from the subjective testing and which do not vary across individuals, these being referred to as non-subject-dependent objective parameters, and (ii) those determined on the basis of the measurements carried out during the subjective testing and that vary across individuals, these being referred to as subject-dependent objective parameters (see *Part I* of the report).

Model specification A two-level random-intercept-only model (one that included no explanatory variable at the occasion level) was first fitted to the data in question. For the vibration annoyance data, this null model ($M0$) can be written as follows:

$$\begin{aligned} Y_{fi} &= (\beta_{00} + u_{0i}) + e_{fi} \\ u_{0i} &\sim N(0, \sigma^2_{u_0}) \text{ , for } i = 1, ..., I \\ e_{fi} &\sim N(0, \sigma^2_e) \text{ , for } i = 1, ..., I \text{ and } f = 1, ..., F \end{aligned} \tag{21}$$

where Y_{fi} is the vibration annoyance score obtained for floor f and individual i, F is the number of floors, I is the number of individuals, β_{00} is the fixed intercept, the terms u_{0i} are (random) residual error terms (for the intercept) at the individual level, and e_{fi} are (random) residual error terms at the occasion level. The residual errors u_{0i} are assumed to have a mean of zero, and a variance $\sigma^2_{u_0}$ that is to be estimated. The residual errors e_{fi} are assumed to have a mean of zero, and a variance σ^2_e which is to be estimated.

For the vibration acceptability data (binary data), this null model ($M0$) can be written as follows:

$$\begin{aligned} logit(p_{fi}) &= \beta_{00} + u_{0i} \\ u_{0i} &\sim N(0, \sigma^2_{u_0}) \text{ , for } i = 1, ..., I \end{aligned} \tag{22}$$

where p_{fi} is the probability that the binary response Y_{fi} obtained for floor f and individual i is equal to 1 (here 1 = "acceptable") and $logit(p_{fi}) = \log(p_{fi}/(1 - p_{fi}))$.

Two-level models with a fixed regression slope were then tested. For the vibration annoyance data, these models can be written as follows:

$$\begin{aligned} Y_{fi} &= (\beta_{00} + u_{0i}) + \beta_{10} X_{fi} + e_{fi} \\ u_{0i} &\sim N(0, \sigma^2_{u_0}) \text{ , for } i = 1, ..., I \\ e_{fi} &\sim N(0, \sigma^2_e) \text{ , for } i = 1, ..., I \text{ and } f = 1, ..., F \end{aligned} \tag{23}$$

where β_{10} is the fixed slope, X_{fi} is the value of the occasion-level predictor (i.e. the objective parameter which is being tested) for measurement occasion (i.e. floor) f and individual i.

For the vibration acceptability data, these models can be written as follows:

$$\begin{aligned} logit(p_{fi}) &= (\beta_{00} + u_{0i}) + \beta_{10} X_{fi} \\ u_{0i} &\sim N(0, \sigma^2_{u_0}) \text{ , for } i = 1, ..., I \end{aligned} \tag{24}$$

Finally, two-level models with a random regression slope were tested. For the vibration annoyance data, these models can be written as follows:

$$\begin{aligned} Y_{fi} &= (\beta_{00} + u_{0i}) + (\beta_{10} + u_{1i}) X_{fi} + e_{fi} \\ \begin{bmatrix} u_{0i} \\ u_{1i} \end{bmatrix} &\sim N\left(\mathbf{0}, \begin{bmatrix} \sigma^2_{u_0} & \sigma_{u_{01}} \\ \sigma_{u_{01}} & \sigma^2_{u_1} \end{bmatrix}\right) \text{, for } i = 1, ..., I \\ e_{fi} &\sim N(0, \sigma^2_e) \text{ , for } i = 1, ..., I \text{ and } f = 1, ..., F \end{aligned} \tag{25}$$

where the terms u_{1i} are (random) residual error terms (for the slope) at the individual level. The residual errors u_{1i} are assumed to have a mean of zero, and a variance $\sigma^2_{u_1}$, which is to be estimated. The term $\sigma_{u_{01}}$ is the covariance between the residual error terms u_{0i} and u_{1i}.

For the vibration acceptability data, these models can be written as follows:

$$logit(p_{fi}) = (\beta_{00} + u_{0i}) + (\beta_{10} + u_{1i})X_{fi} \tag{26}$$
$$\begin{bmatrix} u_{0i} \\ u_{1i} \end{bmatrix} \sim N\left(\mathbf{0}, \begin{bmatrix} \sigma^2_{u_0} & \sigma_{u_{01}} \\ \sigma_{u_{01}} & \sigma^2_{u_1} \end{bmatrix}\right), \text{for } i = 1, ..., I$$

Computation Gamma distributions were used as non-informative prior distributions for the variance and the covariance parameters. The posterior distributions of the model parameters were computed using Markov Chain Monte Carlo simulations involving up to 40000 iterations. These computations were performed using the Software MLwiN© [45]. For each model parameter, a median value (i.e. a point estimate) and a 95% credibility interval were determined from its posterior distribution.

Model comparison The models were compared in terms of the following criteria:

- DIC – Deviance Information Criterion. This criterion provides a measure of out-of-sample predictive error [43]. This fit measure takes the degree of complexity of the model into account. The DIC values are not bounded; the lower the value of DIC is, the better the predictive power of the model is assumed to be. In comparing two models, differences in DIC of more than 10 may definitely rule out the model having the higher DIC value, differences of between 5 and 10 being regarded as substantial [46]. For differences in DIC of less than 5, it can be misleading to simply report the model having the lower DIC value [46].

- R_1^2 – The proportion of variance explained at the lowest level (the measurement occasion level). It is computed for the vibration annoyance data. This criterion, which provides a measure of the goodness-of-fit of the model to the data, is defined as follows [43]:
$$R_1^2 = 1 - \frac{E(V(e_{fi}))}{V(Y_{fi})} \tag{27}$$
where V represents the finite-sample variance operator, the expectation $E()$ averages over the uncertainty in the fitted model (using the posterior simulations). The quantity R_1^2 varies between 0 and 1; the closer R_1^2 is to 1, the better the goodness-of-fit of the model to the data is.

- $\hat{\Delta}$ – The proportion of risk explained at the lowest level. It is computed for the vibration acceptability data. This criterion provides a measure of the goodness-of-fit of the logistic model to the data. It is defined as follows [43, 47]:
$$\hat{\Delta} = 1 - \frac{E\left(\frac{\sum_{i=1}^{I}\sum_{f=1}^{F}\hat{p}_{fi}(1-\hat{p}_{fi})}{I \times F}\right)}{p(1-p)} \tag{28}$$

where $\hat{p}_{fi}$ are the estimated probabilities that $Y_{fi} = 1$ (i.e. "acceptable"), the expectation $E()$ averages over the uncertainty in the fitted model (using the posterior simulations), p is the sample marginal probability that $Y_{fi} = 1$ (that is, p is given by the proportion of 1's occurring in the $I \times F$ binary responses). The quantity $\hat{\Delta}$ varies between 0 and 1; the closer $\hat{\Delta}$ is to 1, the better the goodness-of-fit of the logistic model to the data is.

Thus, for vibration annoyance, the model comparisons are based on two criteria: DIC and R_1^2. For vibration acceptability, the model comparisons are likewise based on two criteria, here DIC and $\hat{\Delta}$. A given model model will only be considered to clearly outperform another model if it performs better in terms of both criteria.

8 Results

The results of the present study that are reported in this section are ones obtained from the analysis of the merged data by use of the methods presented in section 7.2.

8.1 Preliminary selection of relevant objective parameters

8.1.1 Vibration annoyance data

The vibration annoyance data could be represented in a 2-D MDPREF space. The two first dimensions were found to account for 73% of the total variance. The optimal dimensionality was selected by use of the Scree test method [48]. It was applied to the plot of the eigenvalues against the number of dimensions. The space is shown in Figure 16. For greater readability, only the endpoints of the subject vectors are reported there. The labels that begin with "V" designate the subjects from the SP study, and those beginning with "L" the subjects from the LU study.

Most of the endpoints of the subject vectors lie within the left-hand part of the space. This shows there to be a relatively close consensus among the subjects in terms of their responses. The average subject vector (marked in Figure 16 by a black circle), which appears in the left-hand part of the space, nearly coincides with the first dimension, indicating that consensus is basically found regarding this dimension of the space (its accounting for 50% of the total variance). Nevertheless, some endpoints are to be found elsewhere, notably in the upper and lower right-hand parts of the space. One can also note that the subject vectors in both studies are well mixed, there thus appearing to be no study effect on the vibration annoyance responses.

The $f_{1,c,EC5}$, $f_{1,c,FEM}$ and $f_{1,c,HC}$ vectors, which appear in the right-hand part of the space, are very close in position to the average subject vector. Their length (close to the unit) shows there to be a very high quality of representation ($r = 0.997$, $p = 0.001$, $r = 0.997$, $p = 0.001$, and $r = 0.994$, $p = 0.003$, respectively). Also, the $f_{1,m,v}$ and $f_{1,c,D}$ vectors, which appear in the right-hand part of the space, are likewise close in position to the average subject vector, although to a lesser extent. Their length reveals a very high quality of representation ($r = 0.993$, $p = 0.004$ and $r = 0.981$, $p = 0.015$, respectively).

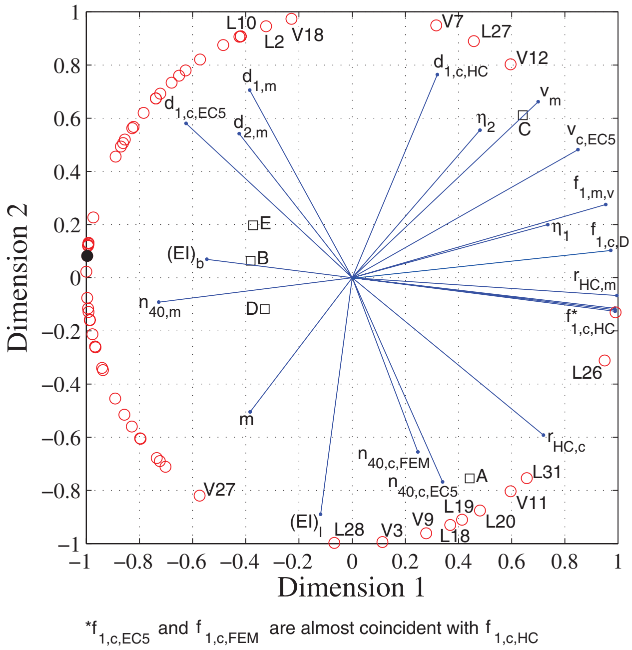


Figure 16: Vibration annoyance data – 2-D MDPREF space. □: floors; ○: endpoints of the subject vectors; ●: endpoint of the average subject vector; —: objective parameter vectors.

All in all, the first eigenfrequency is able, on the average, to explain the subjects' responses rather well. The higher the first eigenfrequency is, the lower on the average the level of vibration annoyance is. In addition, the $r_{HC,m}$ vector, which appears in the right-hand part of the space, is close in position to the average subject vector. Its length indicates it to have a very high quality of representation ($r = 0.998$, $p = 0.001$). These various observations show that Hu and Chui's criterion (calculated from measured quantities) can explain the subjects' responses on the average rather well. The higher this criterion is, the lower on the average the level of vibration annoyance is. The η_1 vector, finally, which appears in the right-hand part of the space, is close to the average subject vector, yet its somewhat shorter length indicates it to have a lower quality of representation ($r = 0.763$, $p = 0.323$), this objective parameter thus being correlated to a lesser degree with the average response.

	Vibration annoyance and vibration acceptability
Non subject-dependent indices	Calculated first eigenfrequency, obtained in accordance with Eurocode 5 ($f_{1,c,EC5}$) Hu and Chui's criterion ($r_{HC,m}$) Damping ratio for the first eigenmode (η_1)
Subject-dependent indices*	Frequency-weighted RMS acceleration (a_w) Frequency-weighted RMS velocity (v_w) Maximum Transient Vibration Value (MTVV)

*See *Part I* for further details of the procedure for calculating these indices.

Table 13: Objective parameters tested.

8.1.2 Vibration acceptability data

The vibration acceptability data were represented in a 2-D space. The space is shown in Figure 17; for greater readability, only the endpoints of the subject vectors are reported there. Again, the labels beginning with "V" designate the subjects from the SP study, and those beginning with "L" the subjects from the LU study.

Most of the endpoints of the subject vectors lie within the upper right-hand, lower right-hand and left-hand parts of the space. This dispersion shows the subjects' vibration acceptability responses to be less consensual than their vibration annoyance responses are. The average subject vector (marked by a black circle in Figure 17) appears in the lower right-hand part of the space. One can note too that the subject vectors in both studies are quite well mixed, no study effect on the vibration acceptability responses being evident, therefore.

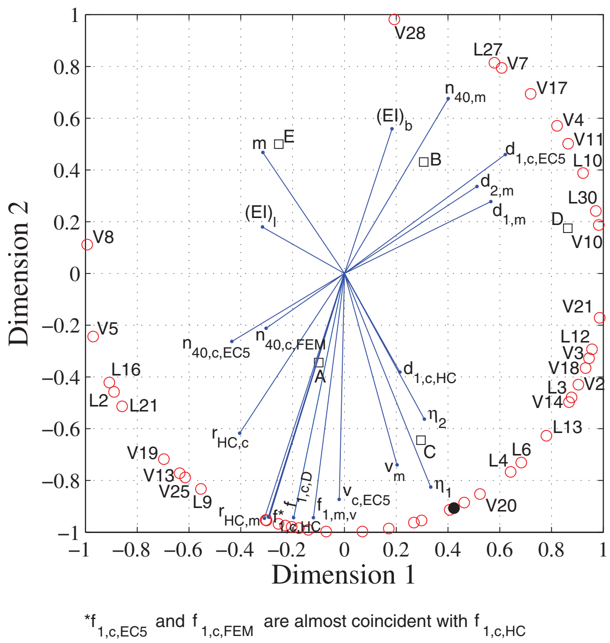


Figure 17: Vibration acceptability data – 2-D logistic PCA space. ○: endpoints of the subject vectors; ●: endpoint of the average subject vector; —: objective parameter vectors.

The η_1 vector, which appears in the lower right-hand part of the space, is very close in position to the average subject vector. Its length shows it to possess a moderate quality of representation ($r = 0.890$, $p = 0.146$). These observations show that the damping ratio for the first eigenmode appears to be able to explain the subjects' responses on the average here rather well. The higher the value of η_1 is, the greater on the average vibration acceptability is assumed to be. The $f_{1,m,v}$, $f_{1,c,EC5}$, $f_{1,c,FEM}$, $f_{1,c,HC}$ and $f_{1,c,D}$ vectors, which appear in the lower left-hand part of the space, are less close in position to the average subject vector. Their length indicates them to have a high quality of representation ($r = 0.952$, $p = 0.053$, $r = 0.986$, $p = 0.01$, $r = 0.986$, $p = 0.01$, $r = 0.982$,

$p = 0.014$, and $r = 0.965$, $p = 0.034$, respectively). These observations show that the first eigenfrequency can on the average explain the subjects' responses rather well. The higher the first eigenfrequency is, the greater on the average the vibration acceptability is assumed to be. In addition, the $r_{HC,m}$ vector, which appears in the lower left-hand part of the space, is as close in position to the average subject vector. Its length shows it to have a very high quality of representation ($r = 0.998$, $p = 0.001$). This indicates Hu and Chui's criterion (calculated from measured quantities) to be able to explain the subjects' responses on the average rather well. The higher this criterion is, the greater on the average the vibration acceptability is assumed to be.

8.1.3 Discussion

The PCA results show there to be several non-subject-dependent objective parameters that can explain the subjective data rather well.

Regarding vibration annoyance, the linear PCA results show $f_{1,c,EC5}$, $f_{1,c,FEM}$, $f_{1,c,HC}$ and $r_{HC,m}$ to be the most relevant parameters for explaining, on the average, the subjects' responses. Regarding the first eigenfrequency, it appears as though any one of the three indices $f_{1,c,EC5}$, $f_{1,c,FEM}$ and $f_{1,c,HC}$ could be selected, since each of them seems equally relevant, although $f_{1,c,EC5}$ was finally selected due its widespread use and the ease of the calculations it involves. Although η_1 appeared to be correlated with the average response to a lesser extent, this design parameter seemed to possibly also be relevant in accounting for the subjects' responses, its thus being selected as well, and $r_{HC,m}$ finally being selected too.

Regarding vibration acceptability, the logistic PCA results showed $f_{1,m,v}$, $f_{1,c,EC5}$, $f_{1,c,FEM}$, $f_{1,c,HC}$, $f_{1,c,D}$, η_1 and $r_{HC,m}$ to be the parameters most relevant on the average in accounting for the subjects' responses. As far as the first eigenfrequency is concerned, any one of the five indices that were tested could have been selected, since these appeared to be about equally relevant, yet $f_{1,c,EC5}$ was selected finally, in order to be consistent with the choice made regarding vibration annoyance, $r_{HC,m}$, and η_1 being selected as well.

8.2 Determination of indicators of vibration annoyance and vibration acceptability

All the objective parameters tested are presented in Table 13.

8.2.1 Vibration annoyance data

The null model $M0$ is shown in Table 14. Figures 18 and 19 show the differences in DIC and in R_1^2, respectively, between the null model $M0$ (taken as a reference model) and the models involving occasion-level predictors.

	Coefficient (95% CI)
Fixed part	
β_{00}	61.33 (56.73; 65.94)
Random part	
σ_e^2	387.2 (324.6; 466.2)
$\sigma_{u_0}^2$	234.3 (141.4; 383.8)
DIC	2641.2
$\boldsymbol{R_1^2}$	0.475

Table 14: Vibration annoyance – Null model $M0$. 95% CI: 95% Bayesian credibility interval; β_{00}: intercept; σ_e^2: variance of the residual errors at the occasion level; $\sigma_{u_0}^2$: variance of the residual errors u_0 (for the intercept) at the individual level; DIC: Deviance Information Criterion; R_1^2: proportion of variance explained at the occasion level.

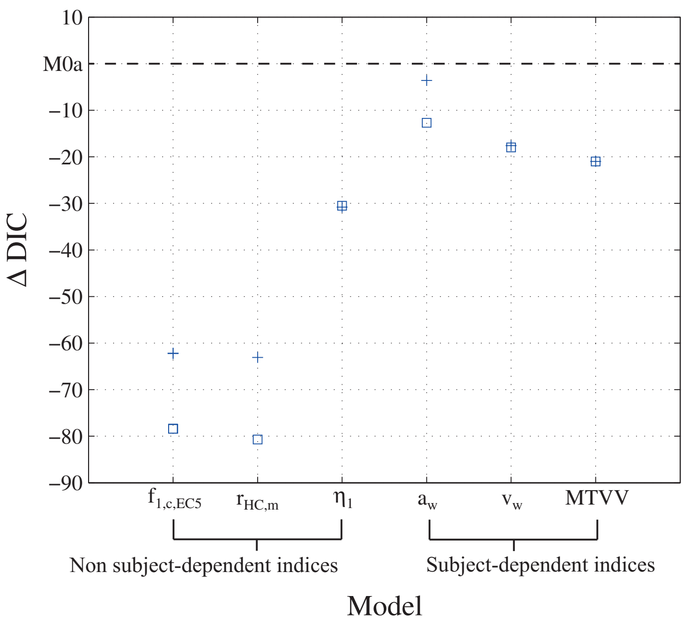


Figure 18: Vibration annoyance - Differences in DIC (ΔDIC) between null model $M0$, and the models involving occasion-level predictors. $+$: fixed-slope model; $\square$: random-slope model.

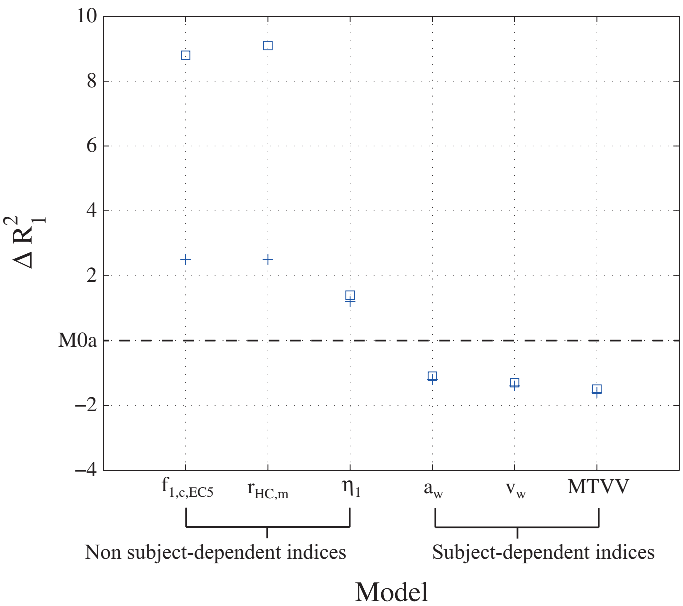


Figure 19: Vibration annoyance - Differences in R^2_1 (ΔR^2_1) between null model $M0$, and the models involving occasion-level predictors. $+$: fixed-slope model; $\square$: random-slope model.

Models involving non-subject-dependent indices Including $f_{1,c,EC5}$ in a model as an occasion-level predictor with a fixed slope enables the model's goodness-of-fit and out-of-sample predictive power to be improved ($\Delta R^2_1 = 2.5\%$ and ΔDIC $\ll$-10 as compared with the null model $M0$). Employing a fixed-slope model involving $f_{1,c,EC5}$ is thus found to outperform the null model. Making the slope random then enables the model's goodness-of-fit and out-of-sample predictive power to be improved ($\Delta R^2_1 = 6.3\%$ and ΔDIC<-10 as compared with the fixed-slope model). In regard to both criteria, therefore, the random-slope model involving $f_{1,c,EC5}$ is the one to select. It should also be emphasized that 98% of the random slopes (the median values of these) are negative. Thus, for nearly all of the subjects, vibration annoyance is negatively correlated with $f_{1,c,EC5}$, so that the lower $f_{1,c,EC5}$ is, the greater the vibration annoyance is. Thus, there is rather close consensus among the subjects in terms of the effect of $f_{1,c,EC5}$ on vibration annoyance. Accordingly, the model just described appears to definitely be the one to select. In making use of this model, $f_{1,c,EC5}$ can serve as a suitable indicator of vibration annoyance.

Including $r_{HC,m}$ in the model as an occasion-level predictor with a fixed slope enables the model's goodness-of-fit and out-of-sample predictive power to be improved ($\Delta R^2_1 = 2.5\%$ and ΔDIC $\ll$-10 as compared with the null model $M0$). A fixed-slope model in which $r_{HC,m}$ is included thus outperforms the null model. In addition, making the slope random enables a further improvement in the goodness-of-fit and the out-of-sample predictive power to be achieved ($\Delta R^2_1 = 6.6\%$ and ΔDIC<-10 in comparison with the fixed-slope model). Thus, in terms of both criteria, a random-slope model involving $r_{HC,m}$ appears to be the one to select. It should also be emphasized that 98% of the random slopes (the median values of these) are negative. For nearly all the subjects, vibration annoyance is negatively correlated with $r_{HC,m}$, such that the lower $r_{HC,m}$ is, the greater the vibration annoyance is. Thus, there is rather close consensus among the subjects in terms of the effect of $r_{HC,m}$ on vibration annoyance. It is felt that the model just described should definitely be selected. In making use of this model, $r_{HC,m}$ can represent a suitable indicator of vibration annoyance.

Inserting η_1 into the model as an occasion-level predictor with a fixed slope tends to improve the model's goodness-of-fit ($\Delta R_1^2 = 2.5\%$ in comparison with the null model M0) and makes it possible to improve its out-of-sample predictive power (ΔDIC$\ll$-10 as compared with the null model $M0$). Making the slope random does not serve to further improve the goodness-of-fit or the out-of-sample predictive power of the model, however ($\Delta R_1^2 = 0.2\%$ and ΔDIC>0 in comparison with the fixed-slope model). Thus, a random-slope model containing η_1 does not outperform a fixed-slope model containing η_1. All in all, in making use of the fixed-slope model, η_1 appears to be an adequate indicator of vibration annoyance.

Finally, one can note that a random-slope model involving $r_{HC,m}$ appears to perform as well as a random-slope model involving $f_{1,c,EC5}$ does ($\Delta R_1^2 = 0.3\%$ and ΔDIC>-5). It appears, therefore, that $r_{HC,m}$ and $f_{1,c,EC5}$ are about equally good indicators of vibration annoyance. One can also note that the random-slope models involving $f_{1,c,EC5}$ or $r_{HC,m}$ clearly outperform the fixed-slope model involving η_1, in terms both of goodness-of-fit and of out-of-sample predictive power (at least $\Delta R_1^2 = 7.6\%$ and ΔDIC $\ll$-10). Thus, $f_{1,c,EC5}$ and $r_{HC,m}$ appear to be better than η_1 as indicators of vibration annoyance.

Models involving subject-dependent indices Including a_w in a model as an occasion-level predictor with a fixed slope does not serve to improve the model's goodness-of-fit or its out-of-sample predictive power ($\Delta R_1^2 = -1.2\%$ and ΔDIC>-5 as compared with the null model $M0$). A fixed-slope model involving a_w thus does not outperform the null model. Including a_w in the model as an occasion-level predictor with a random slope enables the model's out-of-sample predictive power to be improved (ΔDIC<-10 in comparison with the null model $M0$), but it does not serve to improve its goodness-of-fit ($\Delta R_1^2 = -1.1\%$ in comparison with the null model $M0$). Thus, a random-slope model does not clearly outperform the null model. Therefore, the models involving a_w do not clearly outperform the null model, a_w thus not being an indicator of vibration annoyance.

Including v_w in a model as an occasion-level predictor with a fixed slope enables the model's out-of-sample predictive power to be improved (ΔDIC<-10 as compared with the null model $M0$), but it does not serve to improve its goodness-of-fit ($\Delta R_1^2 = -1.4\%$ in comparison with the null model $M0$). Thus, the fixed-slope model involving v_w appears to not clearly outperform the null model. Also, although including v_w in the model as an occasion-level predictor with a random slope enables the model's out-of-sample predictive power to be improved (ΔDIC<-10 as compared with the null model $M0$), it does not serve to improve its goodness-of-fit ($\Delta R_1^2 = -1.3\%$ in comparison with the null model $M0$). Therefore, a random-slope model involving v_w does not clearly outperform the null model. The models involving v_w appear to not clearly outperform the null model, v_w thus not being an indicator of vibration annoyance.

Including MTVV in the model as an occasion-level predictor with a fixed slope enables the model's out-of-sample predictive power to be improved (ΔDIC<-10 as compared with the null model $M0$), but it does not serve to improve its goodness-of-fit ($\Delta R_1^2 = -1.6\%$ in comparison with the null model $M0$). Accordingly, a fixed-slope model involving MTVV does not clearly outperform the null model. Also, although including MTVV in the model as an occasion-level predictor with a random slope enables the model's out-of-sample predictive power to be improved (ΔDIC<-10 in comparison with the null model $M0$), it does not serve to improve its goodness-of-fit ($\Delta R_1^2 = -1.5\%$ with respect to the null model $M0$). Thus, the random-slope model involving MTVV does not clearly outperform the null model. Since the models involving MTVV do not clearly outperform the null model, MTVV appears to not be a suitable indicator of vibration annoyance.

Summary Of the non-subject-dependent indices that were tested, $f_{1,c,EC5}$ and $r_{HC,m}$ were found to be the best indicators of vibration annoyance. None of the subject-dependent indices that were tested appeared to be a good indicator of vibration annoyance.

8.2.2 Vibration acceptability data

The null model $M0$ is presented in Table 15. Figures 20 and 21 show the differences in DIC and in $\hat{\Delta}$, respectively, between the null model $M0$ (taken as a reference model) and the models involving occasion-level predictors.

	Coefficient (95% CI)
Fixed part	
β_{00}	-0.491 (-0.983; -0.042)
Random part	
$\sigma^2_{u_0}$	1.92 (0.801; 4.1)
DIC	355.6
$\hat{\Delta}$	0.260

Table 15: Vibration acceptability – Null model $M0$. 95% CI: 95% Bayesian credibility interval; β_{00}: intercept; $\sigma^2_{u_0}$: variance of the residual errors u_0 (for the intercept) at the individual level; DIC: Deviance Information Criterion; $\hat{\Delta}$: proportion of risk explained at the occasion level.

Models involving non-subject-dependent indices Including $f_{1,c,EC5}$ in the model as an occasion-level predictor with a fixed slope enables the model's goodness-of-fit and out-of-sample predictive power to be improved ($\Delta\hat{\Delta} = 10.5\%$ and ΔDIC$\ll$-10 as compared with the null model $M0$). Thus, the fixed-slope model involving $f_{1,c,EC5}$ outperforms the null model. Making the slope random enables the model's goodness-of-fit and out-of-sample predictive power to be further improved ($\Delta\hat{\Delta} = 21.2\%$ and ΔDIC$\ll$-10 as

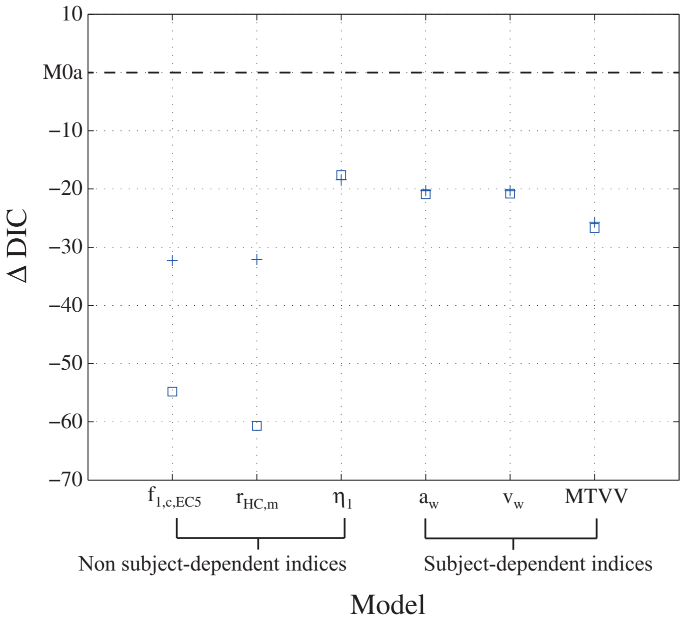


Figure 20: Vibration acceptability - Differences in DIC (ΔDIC) between null model $M0$, and the models involving occasion-level predictors. $+$: fixed-slope model; $\square$: random-slope model.

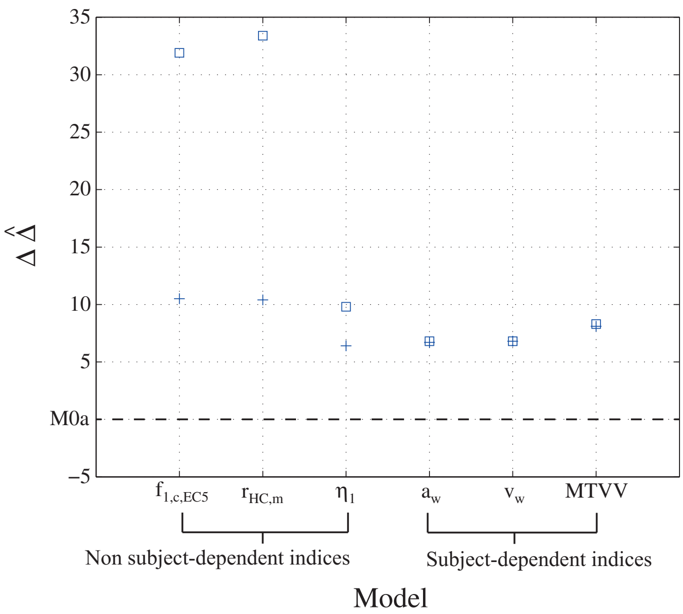


Figure 21: Vibration acceptability - Differences in $\hat{\Delta}$ ($\Delta\hat{\Delta}$) between null model $M0$, and the models involving occasion-level predictors. $+$: fixed-slope model; $\square$: random-slope model.

		Vibration annoyance	Vibration acceptability
Non subject-dependent indices	$f_{1,c,EC5}$	+++	−
	$r_{HC,m}$	+++	−
	η_1	+	+
Subject-dependent indices	a_w	−	+
	v_w	−	+
	MTVV	−	++

Table 16: Summary of the results of the multilevel regression analyses. −, +, ++, +++: comparative degrees of relevance of the objective parameters as indicators of the subjective attributes in question.

compared with the fixed-slope model). Although in terms of these two criteria the random-slope model involving $f_{1,c,EC5}$ should be selected, there is a serious problem connected with use of this model, namely that 75% of the random slopes (the median values of these) are positive, and 25% negative. Thus, for some subjects, vibration acceptability is positively correlated with $f_{1,c,EC5}$, whereas for others vibration acceptability is negatively correlated with it. The subjects thus differ regarding the effect that $f_{1,c,EC5}$ has on vibration acceptability. This model should thus not be selected here. All in all, $f_{1,c,EC5}$ is not found to be suitable as an indicator of vibration acceptability.

Including $r_{HC,m}$ in the model as an occasion-level predictor with a fixed slope enables the model's goodness-of-fit and out-of-sample predictive power to be improved ($\Delta\hat{\Delta} = 10.4\%$ and ΔDIC $\ll$-10 as compared with the null model $M0$). A fixed-slope model involving $r_{HC,m}$ thus outperforms the null model. Making the slope random enables the model's goodness-of-fit and out-of-sample predictive power to be further improved ($\Delta\hat{\Delta} = 23\%$ and ΔDIC$\ll$-10 as compared with the fixed-slope model). Thus, in terms of both of these criteria the random-slope model involving $r_{HC,m}$ should be selected. Yet, just as with the random-slope model involving $f_{1,c,EC5}$, there is a serious problem connected with the use of this model too, 69% of the random slopes (the median values of these) being positive, and 31% negative. For the same reason as before, this model too should not be selected. All in all, $r_{HC,m}$ appears to not be a suitable indicator of vibration acceptability.

Including η_1 in the model as an occasion-level predictor with a fixed slope enables the model's goodness-of-fit and out-of-sample predictive power to be improved ($\Delta\hat{\Delta} = 6.4\%$ and ΔDIC$\ll$-10 as compared with the null model $M0$). A fixed-slope model involving η_1 thus outperforms the null model. Making the slope random enables the goodness-of-fit to be improved slightly ($\Delta\hat{\Delta} = 3.4\%$ as compared with the fixed-slope model) but does not help the out-of-sample predictive power to be improved further (ΔDIC>0 as compared with the fixed-slope model). Thus, a random-slope model involving η_1 does not clearly outperform the fixed-slope model involving η_1. All in all, in making use of the fixed-slope model, η_1 may be suitable as an indicator of vibration acceptability.

Models involving subject-dependent indices Including a_w in the model as an occasion-level predictor with a fixed slope enables the model's goodness-of-fit and out-of-sample predictive power to be improved ($\Delta\hat{\Delta} = 6.7\%$ and ΔDIC$\ll$-10 as compared with the null model $M0$). Thus, a fixed-slope model involving a_w clearly outperforms the null model. Making the slope random does not serve to further improve the model's goodness-of-fit or out-of-sample predictive power ($\Delta\hat{\Delta} = 0.1\%$ and ΔDIC>-5 as compared with the fixed-slope model). The random-slope model thus does not outperform the fixed-slope model. In making use of the fixed-slope model, a_w appears able to serve as an indicator of vibration acceptability.

Including v_w in the model as an occasion-level predictor with a fixed slope enables the model's goodness-of-fit and out-of-sample predictive power to be improved ($\Delta\hat{\Delta} = 6.8\%$ and ΔDIC≪-10 as compared with the null model $M0$). Thus, the fixed-slope model involving v_w appears to clearly outperform the null model. Making the slope random does not serve to further improve either the model's goodness-of-fit or its out-of-sample predictive power ($\Delta\hat{\Delta} = 0\%$ and ΔDIC>-5 as compared with the fixed-slope model). The random-slope model thus does not outperform the fixed-slope model. In making use of the fixed-slope model, v_w may be suitable as an indicator of vibration acceptability.

Including MTVV in the model as an occasion-level predictor with a fixed slope enables the model's goodness-of-fit and out-of-sample predictive power to be improved ($\Delta\hat{\Delta} = 8.3\%$ and ΔDIC≪-10 as compared with the null model $M0$). The fixed-slope model involving MTVV thus clearly outperforms the null model. Making the slope random does not serve to further improve the model's goodness-of-fit or out-of-sample predictive power ($\Delta\hat{\Delta} = 0.2\%$ and ΔDIC >-5 as compared with the fixed-slope model). Thus, a random-slope model does not appear able to outperform the fixed-slope model. In making use of the fixed-slope model, MTVV appears able to function well as an indicator of vibration acceptability.

Finally, one can note that (i) the goodness-of-fit of the fixed-slope model involving MTVV is slightly better than that of the fixed-slope models involving a_w or v_w ($\Delta\hat{\Delta} \geq 1.3\%$), and (ii) its out-of-sample predictive power tends to be better as well (-10< ΔDIC<-5). Thus, MTVV appears to be a better indicator of vibration acceptability than a_w or v_w are.

Summary Of the various non-subject-dependent indices that were tested, it was η_1 that turned out to be the best indicator of vibration acceptability. Of the subject-dependent indices that were tested, it was MTVV that appeared to be the best indicator of vibration acceptability. MTVV appears to also be a better indicator of vibration acceptability than η_1 is. In addition, (i) the goodness-of-fit of the fixed-slope model involving MTVV is slightly better than that of the fixed-slope model involving η_1 ($\Delta\hat{\Delta} = 1.7\%$), and (ii) its out-of-sample predictive power tends to be better as well (-10<ΔDIC<-5).

8.2.3 Summary of the outcomes

Table 16 summarizes the results of the multilevel regression analyses. The "–" symbol indicates the objective parameter in question to not be a good indicator of the subjective attribute in question. The greater the number of "+" symbols is, the more the objective parameter is regarded as being relevant as an indicator of the subjective attribute in question.

The multilevel models that pertain to the best indicators – $f_{1,c,EC5}$ and $r_{HC,m}$ for vibration annoyance and MTVV for vibration acceptability – are shown in Tables 17 and 18, respectively.

	$f_{1,c,EC5}$	$r_{HC,m}$
	Coefficient (95% CI)	Coefficient (95% CI)
Fixed part		
β_{00}	83.27 (75.19; 91.33)	78.06 (71.12; 84.90)
β_{10}	-1.35 (-1.77; -0.940)	-0.872 (-1.14; -0.603)
Random part		
σ_e^2	270.4 (220.6; 333.8)	267.8 (218.3; 330.3)
$\sigma_{u_0}^2$	517.7 (249.5; 964.0)	415.9 (219.8; 742.8)
$\sigma_{u_1}^2$	0.945 (0.333; 2.09)	0.400 (0.144; 0.870)
DIC	2562.8	2560.5
$\boldsymbol{R_1^2}$	0.563	0.566

Table 17: Vibration annoyance – Random-slope models involving $f_{1,c,EC5}$ and $r_{HC,m}$ as occasion-level explanatory variables. 95% CI: 95% Bayesian credibility interval; β_{00}: fixed intercept; β_{10}: fixed slope; σ_e^2: variance of the residual errors at the occasion level; $\sigma_{u_0}^2$: variance of the residual errors u_0 (for the intercept) at the individual level; $\sigma_{u_1}^2$: variance of the residual errors u_1 (for the slope) at the individual level; DIC: Deviance Information Criterion; R_1^2: proportion of variance explained at the occasion level. The covariance between residual errors u_0 and u_1 at the individual level is not shown.

	Coefficient (95% CI)
Fixed part	
β_{00}	0.307 (-0.296; 0.965)
β_{10}	-10.93 (-16.85; -6.11)
Random part	
$\sigma_{u_0}^2$	2.60 (1.10; 5.70)
DIC	329.9
$\hat{\Delta}$	0.341

Table 18: Vibration acceptability – Fixed-slope model involving MTVV as an occasion-level explanatory variable. 95% CI: 95% Bayesian credibility interval; β_{00}: fixed intercept; β_{10}: fixed slope for MTVV; $\sigma_{u_0}^2$: variance of the residual errors u_0 (for the intercept) at the individual level; DIC: Deviance Information Criterion; $\hat{\Delta}$: proportion of risk explained at the occasion level.

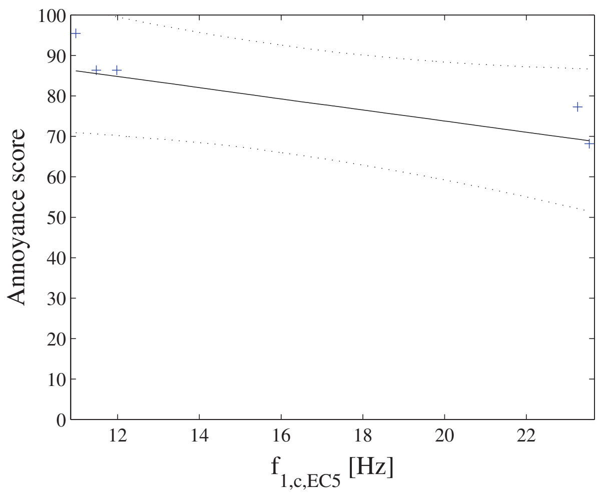
9 Discussion

Different potential indicators of vibration annoyance and of vibration acceptability were investigated. It was found that $f_{1,c,EC5}$ and $r_{HC,m}$, i.e. two non-subject-dependent objective parameters, were the best indicators for vibration annoyance, and that MTVV, i.e. a subject-dependent objective parameter, was the best indicator for vibration acceptability. Note that the damping ratio for the first eigenmode also turned out to be an important parameter in connection with both vibration acceptability and vibration annoyance. As [49] has indicated, studies carried out in the 1960s by Wiss, Lenzen and Hurz suggested damping to also be important. Indeed, increased exposure time is thought to lead to an increase in vibration annoyance. Sufficient damping reduces the duration of exposure to the effects of each step taken by a person walking on the floor, so that walking is perceived then to a lesser degree as involving a continuous vibrational disturbance. In the present study, neither vibration acceptability nor vibration annoyance was found to be correlated with floor deflection. This result contradicts both traditions and current regulations. Notably, [49] reported that already in 1840 Thomas Tredgold recommended making use of deflection limits. [25] also suggested that floor deflection is related to vibrational discomfort. In the present study, certain dynamic parameters, specifically $f_{1,c,EC5}$, $r_{HC,m}$ and MTVV, were shown to be more closely correlated with vibration discomfort than floor deflection was. This result seems not illogical at all, since floor deflection is a measure of floor stiffness alone, whereas the dynamic behavior of a floor also depends upon the mass inertia of the floor.

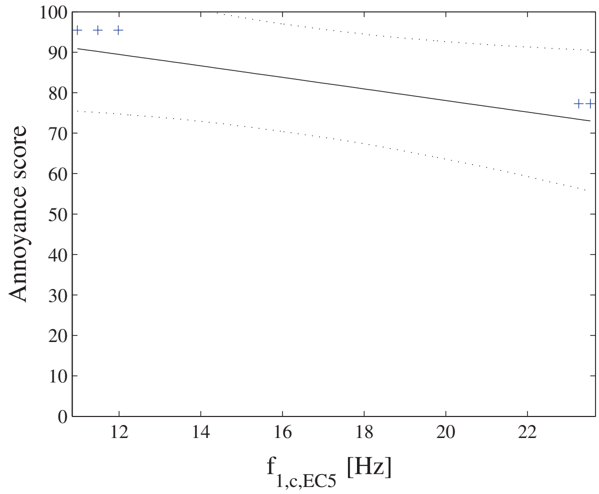
As regards vibration acceptability, MTVV may not be practical to use in connection with design guidelines for manufacturers regarding the vibration serviceability of timber floors, since it implies that already at the design phase one needs to deal directly with walking excitation and measurement of the accelerations experienced by subjects. In fact, for random-slope models involving $f_{1,c,EC5}$ or $r_{HC,m}$, the goodness-of-fit and the out-of-sample predictive power turned out to be highest in connection with vibration acceptability. It was also observed, however, that the effect of these parameters on vibration acceptability varied considerably from subject to subject, which thus precluded their being good indicators of vibration acceptability. This corroborates the results of logistic PCA showing subjects' vibration acceptability responses to be less consistent from one subject to another than the subjects' vibration annoyance responses are. Large inter-individual differences in acceptability ratings have also been observed by [50], who studied subjective responses to aircraft noise in terms of noise annoyance and noise acceptability. Finding indicators of vibration annoyance to not represent adequate indicators of vibration acceptability, and *vice versa*, is not illogical, in view of the fact that the two subjective attributes involved are not perfectly (negatively) correlated. Indeed, a multilevel regression analysis of vibration annoyance (taken as the dependent variable) and vibration acceptability was carried out here. The proportion of variance explained at the occasion level, i.e. R_1^2, was found to be equal to 0.759, which is not particularly high.

Figures 22, 23 and 24 show, for the two vibration annoyance models (involving $f_{1,c,EC5}$ and $r_{HC,m}$, respectively) and the vibration acceptability model (involving MTVV), the individual regression lines[1] of two subjects, together with their 95% credibility interval.

[1] For the vibration annoyance models, the individual regression lines were computed as follows: $(\beta_{00} + u_{0i}) + (\beta_{10} + u_{1i})\, f_{1,c,EC5_f}$ and $(\beta_{00} + u_{0i}) + (\beta_{10} + u_{1i})\, r_{HC,m_f}$. For the vibration acceptability model, the individual regression lines were computed as follows: $(\beta_{00} + u_{0i}) + \beta_{10}\, MTVV_{fi}$.

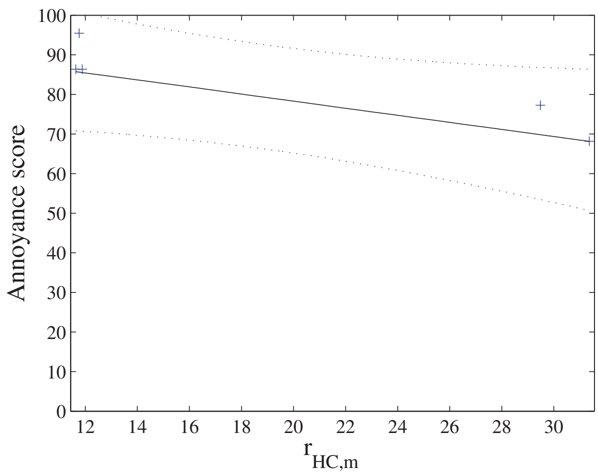


(a) Subject n°8.

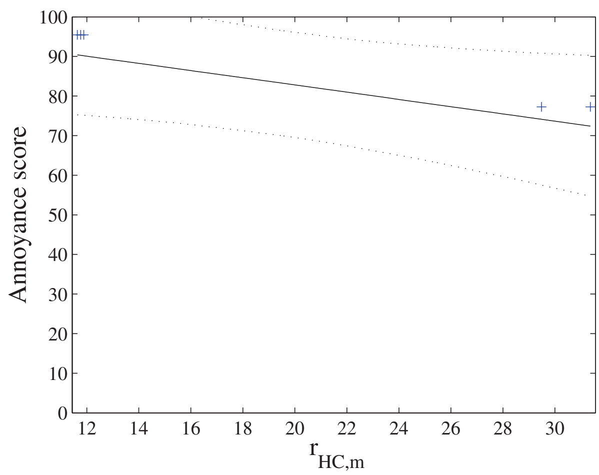


(b) Subject n°17.

Figure 22: Vibration annoyance model involving $f_{1,c,EC5}$ – Individual regression lines for two subjects. —: median value; – –: lower and upper limits of the 95% credibility interval;+: actual scores.

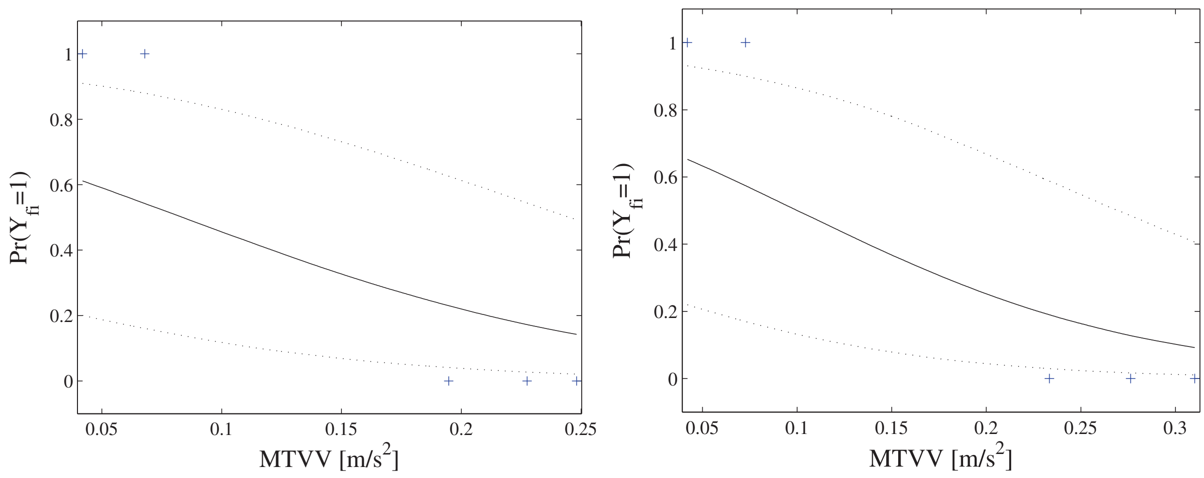


(a) Subject n°8.



(b) Subject n°17.

Figure 23: Vibration annoyance model involving $r_{HC,m}$ – Individual regression lines for two subjects. —: median value; – –: lower and upper limits of the 95% credibility interval;+: actual scores.



(a) Subject n°7.

(b) Subject n°15.

Figure 24: Vibration acceptability model involving MTVV – Individual regression lines for two subjects. —: median value; – –: lower and upper limits of the 95% credibility interval;+: actual binary responses.

It can be seen that, even though $f_{1,c,EC5}$ and $r_{HC,m}$ on the one hand, and $MTVV$ on the other, turned out to be the best indicators of vibration annoyance and vibration acceptability, respectively, the uncertainty regarding the individual regression lines remains substantial. In accordance with this, the goodness-of-fit of the three models was found to be only moderate ($R_1^2 = 0.563$ and $R_1^2 = 0.566$, and $\hat{\Delta} = 0.341$, see tables 17 and 18). Nevertheless, certain trends can be noted.

For one thing, the first eigenfrequency may be an important objective parameter in connection with vibration annoyance. The lower it is, the higher the individual annoyance scores tend to be. Figure 25 shows the overall regression line[2] ($\beta_{00} + \beta_{10}\, f_{1,c,EC5}$) and its 95% credibility interval, for the vibration annoyance model involving $f_{1,c,EC5}$. It can be noted that, on the average, the floor vibrations are not experienced as annoying (with scores < 58.3[3]) for an $f_{1,c,EC5}$ value (median value) of greater than 18.5 Hz. Taking account of the uncertainty regarding the overall regression line, this threshold value may lie somewhere between 15 and 22 Hz. This interval includes the threshold value advanced by [19], that of 15 Hz, for preventing wooden floor vibrations from being annoying.

Secondly, Hu and Chui's criterion may be an important objective parameter for vibration annoyance as well. The lower this criterion is, the higher the individual annoyance scores tend to be. Figure 26 shows the overall regression line ($\beta_{00} + \beta_{10}\, r_{HC,m}$), together with its 95% credibility interval, for the vibration annoyance model involving $r_{HC,m}$. One can observe that, on the average, for an $r_{HC,m}$ value (median value) of greater than 23, the floor vibrations are not experienced as annoying (with scores < 58.3). Taking account of the uncertainty regarding the overall regression line, this threshold value may

[2]The overall regression line provides the predicted values for an "average" subject.

[3]This score corresponds to the category "disturbing" of the six-point verbal scale used in SP study.

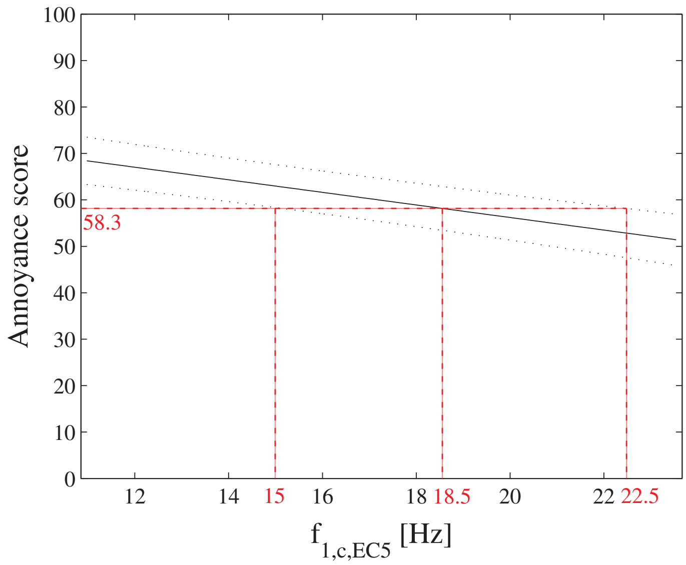


Figure 25: Vibration annoyance model involving $f_{1,c,EC5}$ – Overall regression line. —: median value; – –: lower and upper limits of the 95% credibility interval.

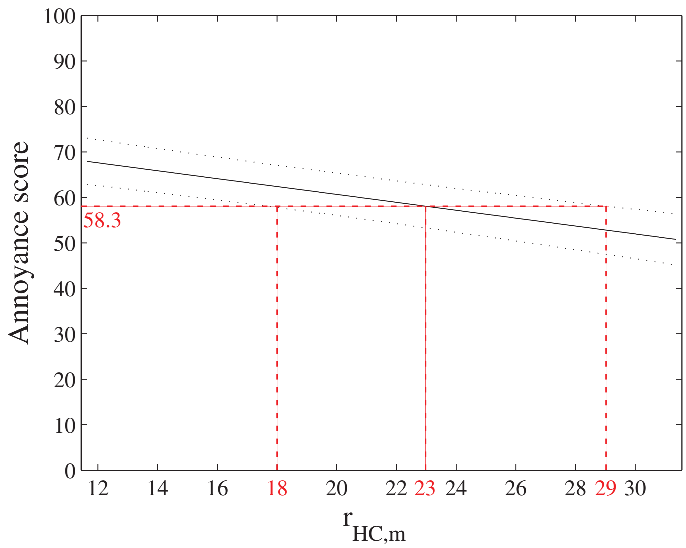


Figure 26: Vibration annoyance model involving $r_{HC,m}$ – Overall regression line. —: median value; – –: lower and upper limits of the 95% credibility interval.

lie somewhere between 18 and 29. This interval includes the threshold value advanced by [26], that of 18.7, above which floors can be considered to most likely be regarded by occupants as being satisfactory.

Thirdly, MTVV turned out to be the best indicator of vibration acceptability. The lower MTVV is, the more vibrations are judged to be acceptable. Figure 27 shows the overall regression line ($\beta_{00}+\beta_{10}\,MTVV$), together with its 95% credibility interval, for the vibration acceptability model. One can observe that, on the average, the floor vibrations are judged to be acceptable ($Pr(Y_{fi}) > 0.5$) for an MTVV value (median value) of 0.03 m/s^2 or less. Taking account of the uncertainty regarding the overall regression line, this threshold value can be extended to 0.08 m/s^2. No study claiming MTVV to be an adequate indicator of vibration acceptability has been reported in the literature. [25], notably, used the RMS velocity, v_{rms}, to draw up a vibrational classification of high-frequency floors ($f_1 > 10$ Hz).

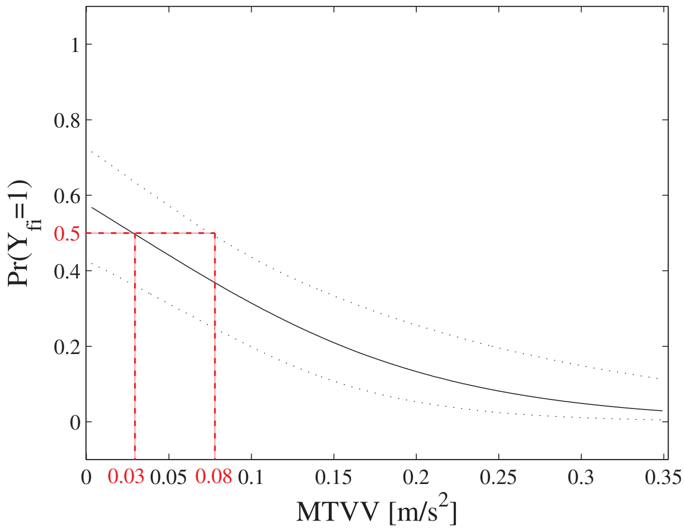


Figure 27: Vibration acceptability model involving MTVV – Overall regression line. —: median value; – –: lower and upper limits of the 95% credibility interval.

Part III
Conclusions

Psycho-vibratory tests were performed on 5 different timber floors in a laboratory environment at two different locations, merging the data stemming from both studies (that conducted at SP Växjö and that conducted at LU) for purposes of enhancing the statistical reliability of the results. A total of 60 persons participated in the tests. Acceleration measurements were carried out while the persons, tested individually, either were walking on the floor in question or were seated in a chair placed on it at the same time as the test leader was walking on the floor. After each subtest, questionnaires were handed out to the participants concerning different attributes of the floors. Non-subject-dependent measurements were also carried out in order to investigate the dynamic and static properties of each of the floors. Different measurement protocols were employed, these being put together by combining various existing methods reported in the literature. All of the data of this sort gathered were post-processed and were used for classification of the floors in accordance with different criteria.

The criteria employed, described in [21], [26] and [19], were found to describe fairly well the performance of the floors in terms of vibration acceptability (see Tables 9-11), especially in the case of measured data, certain discrepancies being found when calculated data were employed. The inconsistencies obtained may be due to the fact that the analytical formulae proposed for the different criteria described in [26] assume that semi-rigid connections are present and to [19] not taking account of composite action. Accordingly, results based on use of calculated data need to be interpreted with care.

Nevertheless, despite the timber floors basically complying with the criteria currently employed, subjective vibratory studies of modern timber framework buildings still frequently yield results showing the inhabitants involved to often be annoyed by vibrations [51]. This may be due in part to the design criteria employed being based originally on measurements and subjective ratings carried out in single-family houses. Thus, reconsideration of the questions of interest here and the development of new design criteria are needed.

Furthermore, the answers the subjects provided were confronted with both measured and calculated objective parameters in efforts to determine the best design indicators of vibration acceptability and vibration annoyance, respectively. This involved use of multilevel regression. The paper can thus also be seen as exemplifying the fact that multilevel regression, not widely used as yet, can be a valuable tool for modelling repeated measures data that involves substantial inter-individual differences in rating. Two objective parameters, made use of in work reported on in the literature, were found to be the best indicators of vibration annoyance: Hu and Chui's criterion (calculated from measured quantities), $r_{HC,m}$, and the first eigenfrequency calculated according to Eurocode 5, $f_{1,c,EC5}$. The Maximum Transient Vibration Value, MTVV, determined on the basis of the accelerations experienced by the subjects, proved to be the best indicator of vibration acceptability. These findings, obtained in what can be considered a pilot study in the sense of its involving only a small sample of wooden floors (5 different ones), though there was a sufficiently large number of subjects to provide clear statistical support for the conclusions drawn concerning these floors, should be followed up by a more comprehensive study, involving a broader sample of wooden floors.

Notes:

The work reported on here was submitted for publication in form of two articles:

- *Psycho-vibratory evaluation of timber floors – Part I: Existent criteria, measurement protocol and analysis of objective data.*
  J. Negreira, K. Jarnerö, A. Trollé, L-G. Sjökvist, D. Bard.

- *Psycho-vibratory evaluation of timber floors – Part II: Towards the determination of design indicators of vibration acceptability and vibration annoyance.*
  A. Trollé, L-G. Sjökvist, K. Jarnerö, J. Negreira, D. Bard

Both articles are being reviewed at the date of publication of this report.

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Psycho-vibratory evaluation of timber floors – Existent criteria, measurement protocols, analysis of objective data and determination of design indicators of vibration acceptability and vibration annoyance

The ultimate aim of the study was to develop indicators of human response to floor vibrations, especially regarding vibration acceptability and annoyance, based on relationships between questionnaire responses and the parameters determined based on measurements carried out. Five different floors were tested at two laboratories (SP in Växjö and Lund university). Acceleration was measured while a person either was walking on the floor or seated in a chair placed as the test leader was walking on the floor.

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