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Determination of vibration acceptability and annoyance design indicators for human response to wooden-floor vibrations

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ABSTRACT

The vibrational response of wooden floor systems is an issue that needs to be dealt with more adequately. Notably, studies addressing human response to vibrations are needed in order to better estimate what level of vibrations in dwellings can be seen as acceptable. In this investigation, measurements on five different floors were performed in a laboratory environment at two locations in Sweden. 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. Independently of the subjective tests, acceleration measurements were also carried out, using a shaker as excitation source, with the aim of determining the dynamic characteristics of the floors. In addition, static load tests were performed using displacement gauges so as to measure the floor deflections. The ultimate aim 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.

Keywords: Psycho-vibratory evaluation, Timber floors, Vibration annoyance, Vibration acceptability, Design indicators, Multilevel regression.
I-INCE Classification of Subjects Number(s): 51.4

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). However, this criterion has proved to not be sufficient in regard to vibration serviceability, for timber constructions in particular, complaints by inhabitants there being frequent, even when present-day building code regulations are met. 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 on five different prefabricated wooden floor structures were carried out in a laboratory environment at two different locations in Sweden, Lund University (*LU*) and the SP Technical Research Institute of Sweden (*SP*). A total of 60 persons participated in the tests conducted. The tests were divided into two parts: a "seated subtest" and a "walking subtest". 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 the 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.

The comparison of the data obtained from the questionnaires to the accelerations experienced by the subjects, as well as to the objective non-subject-dependent parameters obtained, enabled design indicators of

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different subjective attributes (vibration acceptability and vibration annoyance) to be determined. To do so, use was made of multilevel regression. Multilevel regression, not yet in wide use, is a suitable statistical method for modelling repeated measures data in which inter-individual differences in rating are substantial, just like in the present work. Therefore, the present study aims at obtaining more thorough knowledge of the relationship between perceived vibrational discomfort and certain objective engineering parameters.

2. EXPERIMENT: METHODS

2.1 The floors tested

In the present investigation, five separate floors, 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.

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 of 600 mm. These studs were stabilised by use of plywood slabs, and they were bolted to the concrete floor of the laboratory. In attaching the floor elements to the supporting beams, the floor suppliers' instructions were followed.

2.2 Psycho-vibratory measurements

2.2.1 Non-subject-dependent measurements

Prior to the subjective psycho-vibratory testing, objective measurements for each of the five floors were performed in order to determine various static and dynamic parameters. In this way and for frequencies of up to 40 Hz, dynamic measurements using a shaker as excitation were carried out to extract the eigenfrequencies, damping ratios, mode shapes and modal density, from the measured frequency response functions (FRFs). Also, the impulse velocity response was calculated from the driving point mobility. Likewise, static measurements were performed so as to extract the subfloor and topfloor deflections due to a 1 kN point load.

2.2.2 Subject-dependent measurements

Subject-dependent measurements were carried out during the subjective tests, 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 1), 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 1, 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.
- 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 1. 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.

After completion of each subtest for a given floor, subjects were asked to describe, through filling in a questionnaire, their experiences of the given floor in terms of various subjective attributes. The questionnaires used at *LU* and *SP* were not identical, the questionnaires for use in the two organisations having been developed separately, yet questions about certain matters of central interest – primarily matters of whether one is annoyed by vibrations and whether one considers the vibrations to be acceptable – were rather similar in both cases, which led to a merging of the questionnaire results.

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 are the following:

- Overall frequency-weighted RMS accelerations: for each accelerometer, the frequency-weighted RMS (Root-Mean-Square) acceleration, a_{w}, was computed in accordance with standard (2) (see its section 6.4.2). 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 (2), section 8.2.3).
- 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

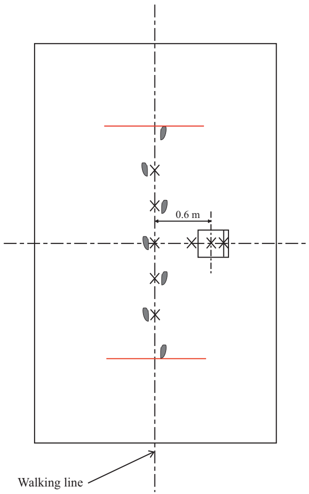


Figure 1 – Measurement setup. The accelerometers' locations are marked by crosses.

RMS velocity, v_w, was computed in accordance to standard (3). An overall frequency-weighted RMS velocity was also determined (see standard (2), 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 line" (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.

- Maximum Transient Vibration Value (MTVV): for each accelerometer, the maximum transient vibration value was computed in accordance with standard (2) (see its section 6.3.1). An overall MTVV was also determined (see standard (2), section 8.2.3).

2.3 Conjoint analysis of subjective data and objective parameters

2.3.1 Merging the subjective data

As previously mentioned, the questionnaires handed out at both locations were different. Of the rather many questions posed to the subjects either at SP or at LU, 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, both posed for the seated subtest, concerned vibration annoyance and vibration acceptability, respectively. At *LU*, regarding vibration annoyance, the subjects were asked to express a judgment on a 11-point numerical scale ranging from "0" ("not at all annoyed") to "10" ("extremely annoyed"); regarding vibration acceptability, they were requested to express a dichotomic judgment: "acceptable" or "not acceptable". At *SP*, the subjects' answers to both questions were to be given on a six-point categorical scale, for instance, regarding vibration acceptability: "definitely not acceptable", "not acceptable", "barely acceptable", "acceptable", "fully acceptable", "acceptable with any reservations whatever". The vibration annoyance answers at both locations were transformed into scores on a 0-100 scale. The vibration acceptability answers at SP were transformed into dichotomic judgments before merging (see (4) for the merging strategy).

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.

The large amount of non-subject-dependent objective parameters available (see (4) for a list of the non-subject-dependent objective parameters computed) 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. This preliminary analysis is not presented here, see (4).

2.3.2 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 analysing the repeated measures data that were collected, use was made of multilevel regression models, within a Bayesian framework. This regression method has been used for meta-analysis of *in situ* noise annoyance studies earlier (see e.g. (5)); its being sparsely used for modelling subjective data collected under laboratory conditions (see e.g. (6)). The reader is referred to (4) for a presentation of the advantages of multilevel regression over classical regression regarding the modelling of repeated measures data.

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.

Only the statistical analysis performed for vibration annoyance will be presented hereafter. The reader can refer to (4) for details about the statistical analysis regarding vibration acceptability.

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

$$\begin{aligned} Y_{\mathrm{fi}} &= (\beta_{00} + u_{0\mathrm{i}}) + e_{\mathrm{fi}} \\ u_{0\mathrm{i}} &\sim N(0, \sigma^2_{\mathrm{u}_0}) \text{ , for } i = 1, ..., I \\ e_{\mathrm{fi}} &\sim N(0, \sigma^2_{\mathrm{e}}) \text{ , for } i = 1, ..., I \text{ and } f = 1, ..., F \end{aligned} \quad (1)$$

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 $u_{0\mathrm{i}}$ 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 $u_{0\mathrm{i}}$ are assumed to have a mean of zero, and a variance $\sigma^2_{\mathrm{u}_0}$ 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.

Two-level models with a fixed regression slope were then tested. These models can be written as follows:

$$\begin{aligned} Y_{\mathrm{fi}} &= (\beta_{00} + u_{0\mathrm{i}}) + \beta_{10} X_{\mathrm{fi}} + e_{\mathrm{fi}} \\ u_{0\mathrm{i}} &\sim N(0, \sigma^2_{\mathrm{u}_0}) \text{ , for } i = 1, ..., I \\ e_{\mathrm{fi}} &\sim N(0, \sigma^2_{\mathrm{e}}) \text{ , for } i = 1, ..., I \text{ and } f = 1, ..., F \end{aligned} \quad (2)$$

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.

Finally, two-level models with a random regression slope were tested. These models can be written as follows:

$$\begin{aligned} Y_{\mathrm{fi}} &= (\beta_{00} + u_{0\mathrm{i}}) + (\beta_{10} + u_{1\mathrm{i}}) X_{\mathrm{fi}} + e_{\mathrm{fi}} \\ \begin{bmatrix} u_{0\mathrm{i}} \\ u_{1\mathrm{i}} \end{bmatrix} &\sim N\left(\mathbf{0}, \begin{bmatrix} \sigma^2_{\mathrm{u}_0} & \sigma_{\mathrm{u}_{01}} \\ \sigma_{\mathrm{u}_{01}} & \sigma^2_{\mathrm{u}_1} \end{bmatrix}\right) \text{, for } i = 1, ..., I \\ e_{\mathrm{fi}} &\sim N(0, \sigma^2_{\mathrm{e}}) \text{ , for } i = 1, ..., I \text{ and } f = 1, ..., F \end{aligned} \quad (3)$$

where the terms $u_{1\mathrm{i}}$ are (random) residual error terms (for the slope) at the individual level. The residual errors $u_{1\mathrm{i}}$ are assumed to have a mean of zero, and a variance $\sigma^2_{\mathrm{u}_1}$, which is to be estimated. The term $\sigma_{\mathrm{u}_{01}}$ is the covariance between the residual error terms $u_{0\mathrm{i}}$ and $u_{1\mathrm{i}}$.

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© (7). 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 (8). 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 (9). For differences in DIC of less than 5, it can be misleading to simply report the model having the lower DIC value (9).
- 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 (8):

$$R_1^2 = 1 - \frac{E(V(e_{\text{fi}}))}{V(Y_{\text{fi}})} \tag{4}$$

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.

A given model will only be considered to clearly outperform another model if it performs better in terms of both criteria.

3. RESULTS AND DISCUSSION

3.1 Determination of an indicator of vibration annoyance

All the objective parameters tested are presented in Table 1. Again, note that the non subject-dependent indices tested were selected on the basis of the results of the preliminary analysis (PCA).

Table 1 – Objective parameters tested.

Non subject-dependent indices	Calculated first eigenfrequency, obtained in accordance with Eurocode 5 ($f_{1,\text{c,EC5}}$)
	Hu and Chui's criterion ($r_{\text{HC,m}}$)
	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)

The null model M0 is shown in Table 2.

Table 2 – 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; $\sigma_{\text{u}_0}^2$: 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.

	Coefficient (95% CI)
Fixed part	
β_{00}	61.33 (56.73; 65.94)
Random part	
σ_{e}^2	387.2 (324.6; 466.2)
$\sigma_{\text{u}_0}^2$	234.3 (141.4; 383.8)
DIC	2641.2
$\boldsymbol{R_1^2}$	0.475

Figures 2 and 3 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.

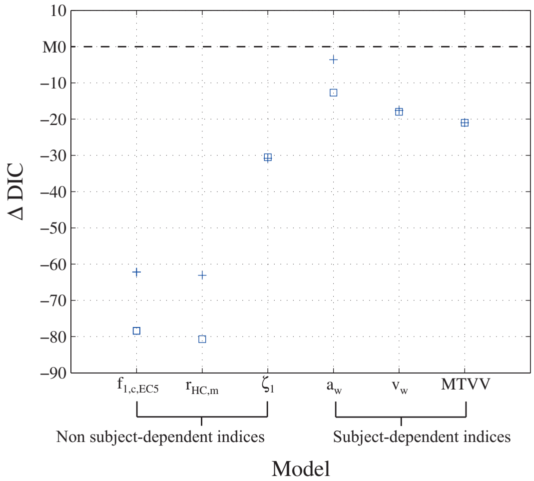


Figure 2 – Vibration annoyance - Differences in DIC (ΔDIC) between null model M0, and the models involving occasion-level predictors. +: fixed-slope model; □: random-slope model.

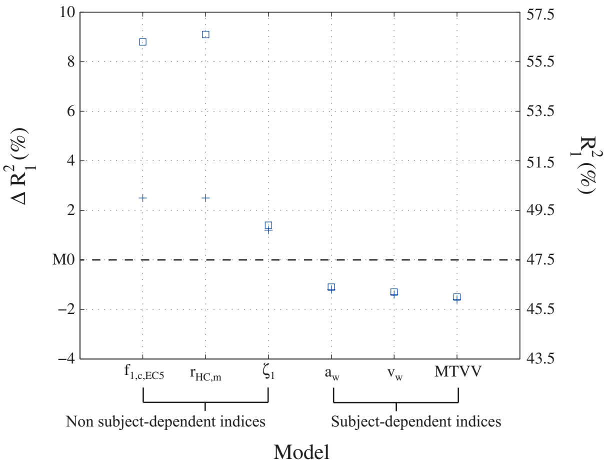


Figure 3 – Vibration annoyance - Differences in R_1^2 (ΔR_1^2) between null model M0, and the models involving occasion-level predictors. +: fixed-slope model; □: random-slope model.

3.1.1 Models involving non-subject-dependent indices

Including $f_{1,\mathrm{c,EC5}}$ or $r_{\mathrm{HC,m}}$ 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 (in both cases, $\Delta R_1^2 = 2.5\%$ and ΔDIC ≪-10 as compared with the null model M0). Employing a fixed-slope model involving $f_{1,\mathrm{c,EC5}}$ or $r_{\mathrm{HC,m}}$ 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 ($\Delta R_1^2 = 6.3\%$ and $\Delta R_1^2 = 6.6\%$, respectively for $f_{1,\mathrm{c,EC5}}$ and $r_{\mathrm{HC,m}}$, and ΔDIC<-10 in both cases, as compared with the fixed-slope model). In regard to both criteria, therefore, the random-slope model involving $f_{1,\mathrm{c,EC5}}$ or $r_{\mathrm{HC,m}}$ is the one to select. It should also be emphasised that, for both indices, 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 $f_{1,\mathrm{c,EC5}}$ and $r_{\mathrm{HC,m}}$, so that the lower $f_{1,\mathrm{c,EC5}}$ and $r_{\mathrm{HC,m}}$ are, the greater the vibration annoyance is. Hence, there is rather close consensus among the subjects in terms of the effect of $f_{1,\mathrm{c,EC5}}$ or $r_{\mathrm{HC,m}}$ on vibration annoyance. Accordingly, the model just described appears to definitely be the one to select. Moreover, one can note that a random-slope model involving $r_{\mathrm{HC,m}}$ appears to perform as well as a random-slope model involving $f_{1,\mathrm{c,EC5}}$ does ($\Delta R_1^2 = 0.3\%$ and ΔDIC>-5). It appears, therefore, that $r_{\mathrm{HC,m}}$ and $f_{1,\mathrm{c,EC5}}$ are about equally good indicators 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≪-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 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.

3.1.2 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). Hence, 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 or MTVV in a model as an occasion-level predictor with a fixed slope enables the model's out-of-sample predictive power to be improved (in both cases ΔDIC<-10, as compared with the null model M0), but it does not serve to improve its goodness-of-fit ($\Delta R_1^2 = -1.4\%$ and $\Delta R_1^2 = -1.6\%$, respectively for v_w and MTVV, in comparison with the null model M0). Thus, the fixed-slope model involving v_w or MTVV appears to not clearly outperform the null model. Also, although including v_w or MTVV in a model as an occasion-level predictor with a random slope enables the model's out-of-sample predictive power to be improved (in both cases ΔDIC<-10, as compared with the null model M0), it does not serve to improve its goodness-of-fit ($\Delta R_1^2 = -1.3\%$ and $\Delta R_1^2 = -1.5\%$, respectively for v_w and MTVV, in comparison with the null model M0). Therefore, a random-slope model involving v_w or MTVV does not clearly outperform the null model. The models involving v_w or MTVV appear to not clearly outperform the null model, v_w and MTVV thus not being indicators of vibration annoyance.

3.1.3 Synthesis

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.

Table 3 summarises the results of the multilevel regression analyses. The "–" symbol indicates the objective parameter in question to not be a good indicator of vibration annoyance. The greater the number of "+" symbols is, the more the objective parameter is regarded as being relevant as an indicator of vibration annoyance.

The multilevel models that pertain to the best indicators – $f_{1,c,EC5}$ and $r_{HC,m}$ – are shown in Table 4.

Table 3 – Summary of the results of the multilevel regression analyses. –, +, ++, +++: comparative degrees of relevance of the objective parameters as indicators of vibration annoyance.

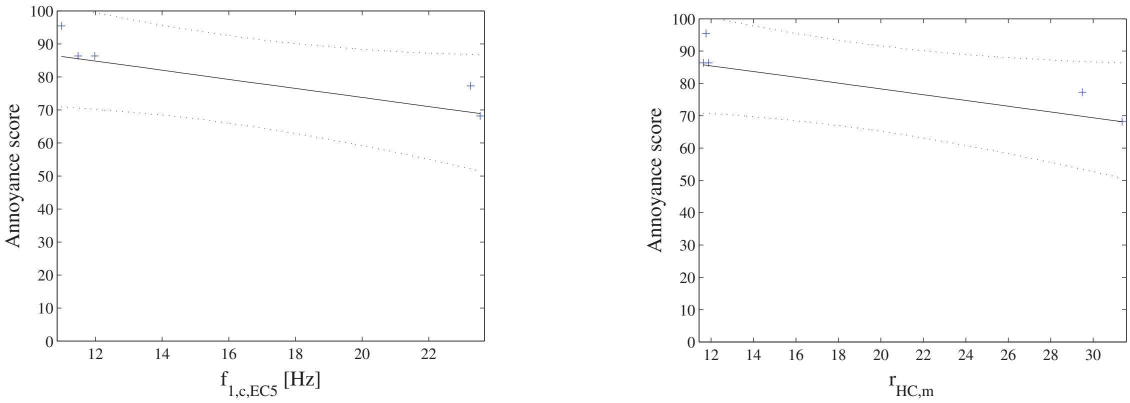
Non subject-dependent indices	$f_{1,c,EC5}$	+++
	$r_{HC,m}$	+++
	η_1	+
Subject-dependent indices	a_w	–
	v_w	–
	MTVV	–

3.2 Discussion

Different potential indicators of vibration annoyance 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. Note that the damping ratio for the first eigenmode also turned out to be an important parameter in connection with vibration annoyance. As Onysko (10) 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, vibration annoyance was not found to be correlated with floor deflection. This result contradicts both traditions and current regulations. Notably, Onysko (10) reported that already in 1840 Thomas Tredgold recommended making use of deflection limits. Toratti and Talja (11) also suggested that floor deflection is related to vibrational discomfort. In the present study, certain dynamic parameters, specifically $f_{1,c,EC5}$ and $r_{HC,m}$, were shown to be more closely correlated with vibration

Table 4 – Vibration annoyance – Random-slope models involving $f_{1,\mathrm{c,EC5}}$ and $r_{\mathrm{HC,m}}$ as occasion-level explanatory variables. 95% CI: 95% Bayesian credibility interval; β_{00}: fixed intercept; β_{10}: fixed slope; σ^2_{e}: variance of the residual errors at the occasion level; $\sigma^2_{\mathrm{u_0}}$: variance of the residual errors u_0 (for the intercept) at the individual level; $\sigma^2_{\mathrm{u_1}}$: variance of the residual errors u_1 (for the slope) at the individual level; DIC: Deviance Information Criterion; R^2_1: 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.

	$f_{1,\mathrm{c,EC5}}$	$r_{\mathrm{HC,m}}$
	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^2_{e}	270.4 (220.6; 333.8)	267.8 (218.3; 330.3)
$\sigma^2_{\mathrm{u_0}}$	517.7 (249.5; 964.0)	415.9 (219.8; 742.8)
$\sigma^2_{\mathrm{u_1}}$	0.945 (0.333; 2.09)	0.400 (0.144; 0.870)
DIC	2562.8	2560.5
$\boldsymbol{R^2_1}$	0.563	0.566



(a) Model involving $f_{1,\mathrm{c,EC5}}$. (b) Model involving $r_{\mathrm{HC,m}}$.

Figure 4 – Vibration annoyance models – Individual regression lines for one subject (e.g. subject n°8). —: median value; – –: lower and upper limits of the 95% credibility interval;+: actual scores.

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 its mass inertia.

Figure 4 shows, for the two vibration annoyance models (involving $f_{1,\mathrm{c,EC5}}$ and $r_{\mathrm{HC,m}}$, respectively), the individual regression lines[1] for one subject (e.g. subject n°8), together with their 95% credibility interval.

It can be seen that, even though $f_{1,\mathrm{c,EC5}}$ and $r_{\mathrm{HC,m}}$ turned out to be the best indicators of vibration annoyance, 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 ($R^2_1 = 0.563$ and $R^2_1 = 0.566$, see Table 4). 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 5 shows the overall regression line[2] ($\beta_{00} + \beta_{10} f_{1,\mathrm{c,EC5}}$) and its 95% credibility interval, for the vibration annoyance model involving $f_{1,\mathrm{c,EC5}}$. It can be noted that, on the average, the floor vibrations are not experienced as annoying (with scores < 58.3[3]) for an $f_{1,\mathrm{c,EC5}}$ value (median value) 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 Dolan *et al.* (12), that of 15 Hz, for preventing

[1] For the vibration annoyance models, the individual regression lines were computed as follows: $(\beta_{00} + u_{0\mathrm{i}}) + (\beta_{10} + u_{1\mathrm{i}}) f_{1,\mathrm{c,EC5}_f}$ and $(\beta_{00} + u_{0\mathrm{i}}) + (\beta_{10} + u_{1\mathrm{i}}) r_{\mathrm{HC,m}_f}$.

[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.

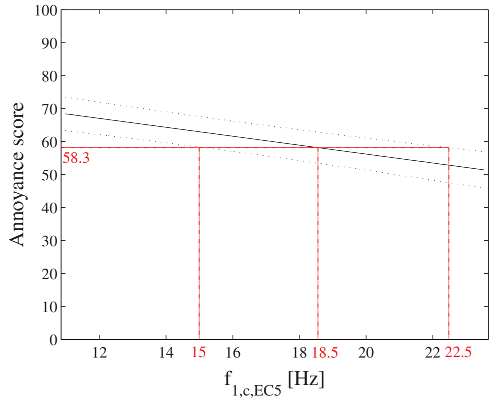


Figure 5 – Vibration annoyance model involving $f_{1,c,EC5}$ – Overall regression line. —: median value; – –: lower and upper limits of the 95% credibility interval.

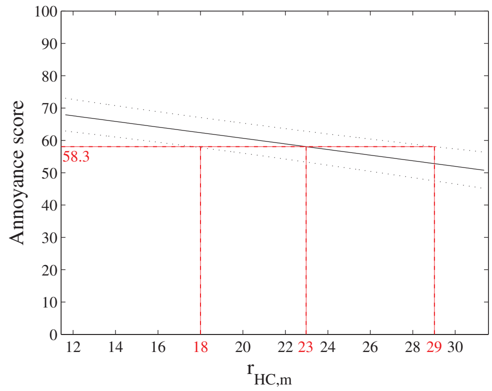


Figure 6 – Vibration annoyance model involving $r_{HC,m}$ – Overall regression line. —: median value; – –: lower and upper limits of the 95% credibility interval.

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 6 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 lie somewhere between 18 and 29. This interval includes the threshold value advanced by Hu and Chui (13), that of 18.7, above which floors can be considered to most likely be regarded by occupants as being satisfactory.

4. 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 (at SP Växjö and 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.

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 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, $f_{1,c,EC5}$. 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.

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