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Human vibration perception from single- and dual-frequency components

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Abstract

This paper covers three different studies with respect to human perception of vertical vibrations. Although the amplitudes and frequencies throughout the experiments are set to match those that might occur in lightweight floor constructions, the results can be seen as general. A motion simulator generates signals from 5 to 31.5 Hz and the test subjects receive the vibrations sitting on a wooden chair. In the first study, the absolute threshold values from sinusoidal signals are determined. The results agree reasonably well with those found from other similar studies. In study number two, threshold values are determined in the presence of an 8 Hz base component. The threshold values were generally found to be higher than those obtained in the first study, except in the case of 10 Hz which due to beating effect gave an even lower threshold level than when the signal was played alone. The third study is about annoyance from dual sinusoidal vibrations, always including a base signal of 8 Hz at fixed amplitude. In similarity with study two, test persons reported to be more annoyed as the second signal component gets close to the base frequency and, naturally, they also got more annoyed as the amplitude increased.

1. Introduction

A major concern for the serviceability of lightweight floors is the low-frequency vibrations induced by normal human activities, primarily walking but also running and jumping, e.g. as a result of children playing. Walking possesses a pace frequency of about 1.6–2.4 Hz, and its harmonics might well excite a floor at its fundamental frequency leading to severe response amplification. From a structural dynamic point of view, the human–floor system forms a dynamic system that can be modelled as

$$\text{VIBRATION RESPONSE} = \text{DYNAMIC PROPERTIES} \times \text{INPUT FORCE}.$$

Humans play double roles in this system; both as the source and as the sensor. The activities exert forces on the floor and at the same time, occupants receive floor vibration through their body, by visual impression and/or by sound. The dynamic properties of the floor system can be calculated theoretically or measured experimentally by modal testing.

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In most cases, the vibration in the vertical direction is, naturally, dominant. Even though floor constructions exist in which also horizontal vibrations play a crucial role they are omitted in this paper. Several studies are found in the literature regarding human perception to vertical vibrations. A pioneer study was performed by Reiher et al. [1] back in 1931. In their experiment, a scale of human tolerance defined by peak deflection and frequency was developed in relation to steady-state vibrations applied for 5 min. Wiss et al. [2] developed an equation to predict human response rate to transient vertical vibrations based on frequency, peak displacement and damping ratio. ISO 2631-2 1989 [3] provided a base curve that should be used in combination with given multipliers (the multiplier depends on the type of housing). The ISO base curve represents magnitudes of approximately equal human response. Studies from Parsons et al. [4] showed that the use of this base curve will either overestimate the effects of low-frequency vibration or underestimate the effects of high-frequency vibration. However, in the latest version of this standard, ISO 2631-2 2003 [5] the base curve as well as the design guidelines from 1989 are withdrawn. The latter with the motivation that "Guidance values above which adverse comments due to building vibration could occur are not included any more since their possible range is too widespread to be reproduced in an International Standard."

A number of researchers have come up with different suggestions for floor design criteria over the years. Ohlsson [6], Wyatt and Dier [7] and Talja et al. [8] have all suggested a deflection criterion for high-frequency floors and an acceleration limit for low-frequency floors. The definition of a high/low frequency floor depends on the fundamental frequency, where suggestions of 7, 8 or 10 Hz are commonly found for the frequency of transition.

The argument for this choice of fundamental frequency is that no higher harmonics than the fourth should be considered when it comes to walking-induced vibration. Then, making sure that the fundamental frequency of the floor is above this limit, typically 8–10 Hz, no annoying vibrations are assumed to occur. The statement that the fourth harmonic is the limit for consideration could be questioned and Ellis [9] proclaims that harmonics up to the eighth order should be taken into account. In this paper, the frequency range of interest is set to 5–25 Hz (5–31.5 Hz for one experiment) which should be sufficiently large to cover the significant vibrations related to light weight floor constructions. Light weight floors typically fall into the category of high frequency, whereas heavy floors normally relate to low frequency. The amplitude range during test range is 0–35 $\mathrm{mm/s^2}$ rms which should relate to vibration commonly found in floors.

Floor serviceability is in general indeed a challenging task; the nature of floor vibration is a multimodal topic of multiple frequencies, and the human perception is difficult to predict even though the exact vibration is known. A series of experiments with focus on human perception of vertical vibrations are reported in this paper. Having a clear understanding of the human response to this kind of well-defined and well-controlled vibrations, should result in the development of proper design criteria. The application should primarily be to light weight constructions, but since the results to a great extent are of general character, they also apply to other kinds of floors and to other vibration situations.

The experiments consist of three studies: (I) threshold values from single-frequency vibrations, (II) threshold values for a second frequency component, and (III) annoyance of dual sinusoidal vibrations. Study I will, providing the results agree with those from other similar studies, serve as a kind of assurance that the experimental set-up and methods used are reliable. Study II can be seen as an indication of the importance in perception of dual sinusoidal vs. single. Studies I and II use a reduced number of test persons while Study III—with focus on the annoyance of dual sinusoidal vibration—uses more test persons for better consistency in the results.

2. Experimental set-up

A new motion simulator, designed to simulate floor vibration, has been developed at Luleå University. It consists of a forced air-cooled electromagnetic shaker (Derritron VP30) installed in a specially made steel frame. A light, but proportionately stiff wooden plate (in order to avoid resonance frequencies within the typical range of floor vibration), rests on the foundation's four corners, with cellular polyetherurethane dampers (Sylomer® R25) in between. The shaker is connected to the centre of the wooden plate by a steel rod. A wooden chair, with a sitting seat made of 6 mm plywood with an underlying stiffener, for the test person to sit on completes the arrangement which can be seen in Fig. 1. The chair's position is controlled before every experiment, to assure an exact position, but has no fixed mechanical connection to the plate.

In order to achieve reliable results, it is important that the background vibration level, i.e. the vibration magnitude of other frequency components than the actual excitation frequency, is satisfactorily low. In Fig. 2, the response from the plate and the chair as the system is excited with a sinusoidal frequency of 8 Hz is presented. It can be seen that the vibration spectra are neither contaminated by any notable general noise nor by any harmonics of significant magnitude. It was then concluded that the background vibration level should not cause interference with the exciting signal.

Since the device should be used to evaluate vibrations in the vertical direction only, it is of great importance that the arrangement does not vibrate significantly in any other directions and that no resonances occur within

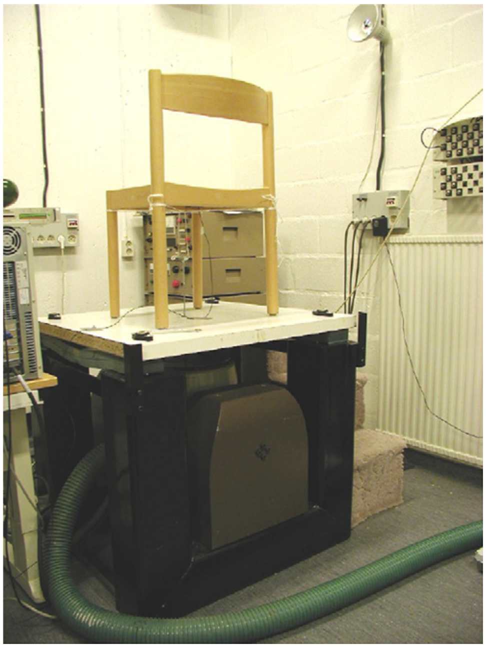

Fig. 1. The motion simulator used in the experiments.

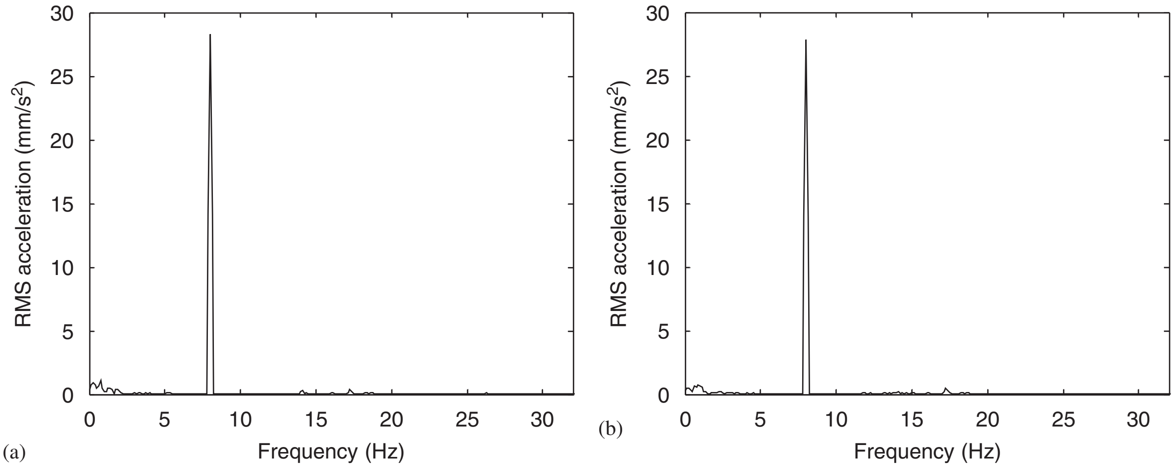

Fig. 2. Background vibration spectra measured on (a) the plate and (b) underneath the chair. The system is driven by a sinusoidal signal of 8 Hz.

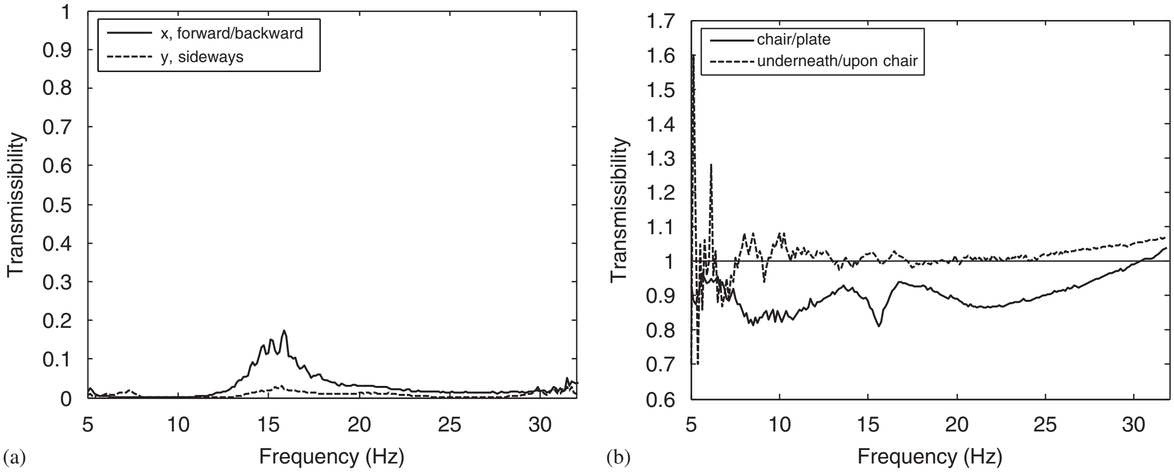

Fig. 3. (a) Transmissibility of the plate's x- and y-direction (forward/backward —— and sideways - - - - respectively). (b) Transmissibility between the chair (underneath) and the plate ——, and transmissibility of the chair: underneath sitting seat/upon sitting seat - - - -.

the used frequency range. A test was performed that measured the response from different positions and directions on the plate. The transmissibility from the main vertical direction to the horizontal directions is seen in Fig. 3a. No sharp resonance peaks were found below 32 Hz and the transmissibility was, except from a small region at 15 Hz in forward/backward direction, well below 10%. It was therefore regarded that levels from non-main directions were satisfactorily low.

Normally, the response acceleration is measured from the upper side of the seat, ISO 2631 and Griffin [10]. But since the accelerometer then must be placed on the sitting surface causing discomfort to the test person, an alternative location, underneath the seat, was used throughout the experiments. The transmissibility between these two ways of measuring–underneath/upon sitting seat—both performed with a seated person, is shown in Fig. 3b. Since the gain is more or less unity, it is verified that the alternative sensor location will work properly.

The vibration reaches the test person not only through the chair but also through the wooden plate, by his feet. Therefore the vibration level, measured with a seated subject, from the plate is compared with the level from the chair. From the transmissibility in Fig. 3b it can be seen that even though the difference is small, the vibration in the chair is often at a lower level than the plate. The reason could probably be that the relatively soft wooden chair absorbs a certain amount of energy.

Throughout the experiments, the vibration response underneath the sitting surface was measured with a Bruel & Kjær system containing a front-end 3560C–module 3032A, accelerometers 4508B002 and 4370 and software PULSE. The vibration signals were generated from two sources: (1) the built-in signal generator of the B&K system and (2) the software LabView (in conjunction with the hardware National Instrument PCU 6502 and BNC 2090) in which an PID regulator controlled the amplitude. The test subjects were always asked to sit on the chair in a comfortable upright position. The back was then in natural contact with the backrest of the chair, even though it was not given as a specific instruction. The subjects wore ear cups which were used in order not to be influenced by ambient noise. Normal indoor shoes and clothes were worn.

3. Study I: threshold values from single-frequency vibrations

3.1. Objective

The objective was to determine the human threshold values when exposed to vertical vibrations of single frequencies. The threshold value is here defined as the lowest possible vibration magnitude that can be detected from a sinusoidal signal with constant amplitude.

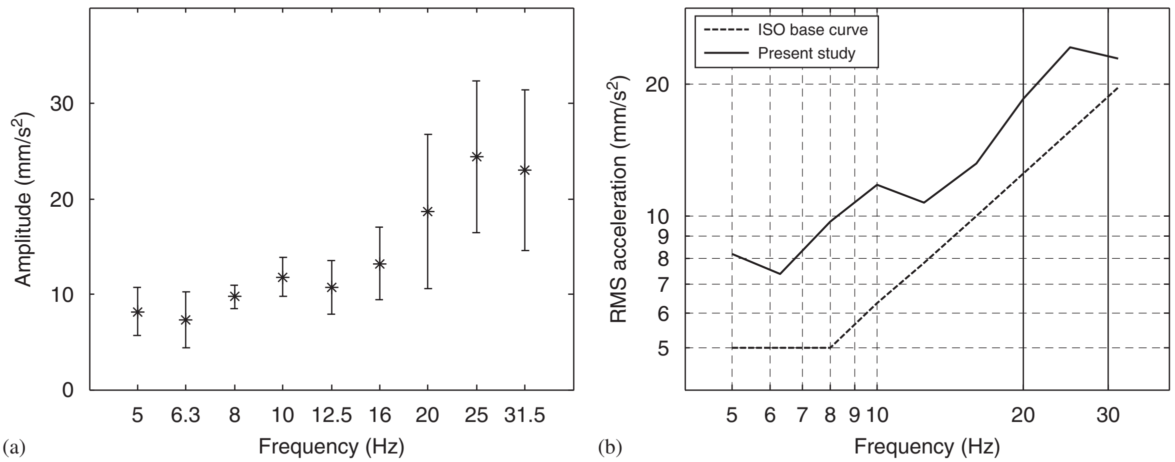

Fig. 4. (a) Means with confidence intervals of the threshold values from sinusoidal vibration. (b) Means of threshold values from the present study —— compared with ISO base curve ----.

3.2. Method

Seven subjects took part in the study, all male, university students or personnel with an average age of 31 years. The average height was 177 cm and the average weight was 74 kg. Nine single sinusoidal signals were tested: 5, 6.3, 8, 10, 12.5, 16, 20, 25 and 31.5 Hz. The signals correspond to the centre frequencies of one-third octave band. A low-weight control amplifier, Sentec SCA1 put in the test person's lap, was used for amplitude adjustment by a discrete turn knob without cue marks. For each test signal, the amplitude was initially set to zero after which the test person slowly increased the level until he just could feel the vibration. The threshold was measured once for each signal and subject. The signals were played to the test subjects in a fully random order and the test lasted 20–30 min for each person.

3.3. Results

The results clearly show that the sensitivity is higher, i.e. the threshold value is lower, for lower frequencies compared to higher. At 5 Hz, the mean threshold was about 8 mm/s^2 while it was 23 mm/s^2 at 31.5 Hz. The obtained results are also more consistent for the lower frequencies. This is shown by the confidence intervals (95%) of the threshold values' mean, Fig. 4a. In Fig. 4b the mean threshold values are compared with the ISO base curve [3]. Values from the present study are higher for each of the tested frequencies, approximately a factor 1.6 higher. Some other similar investigations [4,11] have also obtained greater threshold value than the ISO base curve. Since the results are in agreement with other studies, it is assumed that the experimental equipment and testing procedure are reliable and that the results from the following studies II and III can be treated with confidence.

4. Study II: threshold values for a second frequency component

4.1. Objective

The objective was now to find the perception threshold of a sinusoidal vertical vibration signal in the presence of another sinusoidal signal having fixed amplitude.

4.2. Method

In the second experiment, six persons from Study I participated. A base frequency of 8 Hz with fixed amplitude of 35, 50 or 70 mm/s^2 rms was used together with a second signal, the test frequency of 10, 12.5, 16,

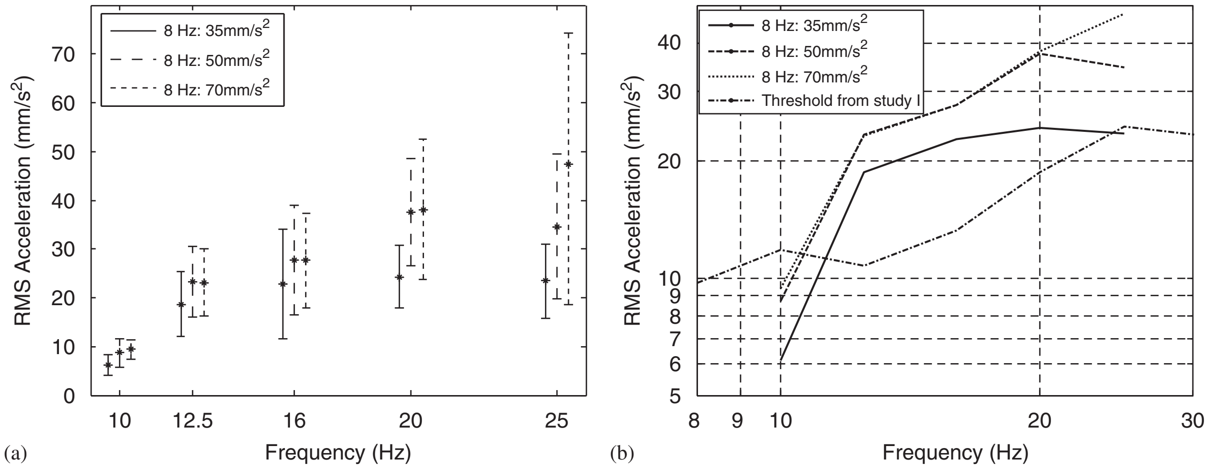

Fig. 5. Mean threshold values in the presence of a base frequency of 8 Hz at three different amplitudes, 35 mm/s^2 ——, 50 mm/s^2- - -, and 70 mm/s^2 · · · ; (a) together with confidence intervals and (b) together with threshold values · - · - · from single frequencies as comparison.

20 or 25 Hz. In total, 15 combined signals, each built up of two frequency components, were tested (three base amplitudes times five test frequencies).

During the experiment, the base frequency was first set to one of the fixed amplitude levels. Then, the test subject controlled the amplitude of one test frequency at the time by using the same control amplifier as in Study I. Starting from zero level, the amplitude of the test frequency was slowly increased until it just was felt that the signal was changed, i.e. the presence of the second frequency component could be noticed, and finally, the response level was measured.

The test was performed in three steps related to the three amplitudes of the base frequency. Within each step, the test frequencies were randomly ordered.

4.3. *Results*

Fig. 5a shows the average threshold value and corresponding confidence interval (95%) as a function of test frequency at the three different amplitudes of the base frequency. For comparison, the threshold values for single sinusoidal vibrations from Study I are incorporated in Fig. 5b.

Even though the confidence intervals, probably due to the limited number of test persons, sometimes are large, especially at higher frequencies, some tendencies are clear regarding the test frequency. Subjects are more sensitive, i.e. lower threshold level, as the test frequency gets closer to the base frequency. The result at 10 Hz is significantly different from the other test frequencies. For example, when the base frequency level is set to 35 mm/s^2, the threshold value is 6 mm/s^2 at 10 Hz while it is 22 mm/s^2 at 25 Hz. The 10 Hz test frequency was actually even more easy to detect in the presence of the base signal compared to the case when it was played alone (Study I).

Threshold values at all test frequencies tended to be lower when the base frequency amplitude was set at 35 mm/s^2 as compared with the higher settings of 50 and 70 mm/s^2 though this difference was not statistically significant.

5. Study III: annoyance of dual sinusoidal vibrations

5.1. *Objective*

The objective was to subjectively evaluate the annoyance of vibration signals consisting of dual frequencies. The signals were composed to be representative of those that might occur in a floor structure.

5.2. Method

Fifteen subjects took part in this study, 13 male and two female. They were all university students or personnel with an average age of 35 years. The average height was 178 cm and the average weight was 76 kg.

A base component, with constant frequency and amplitude throughout the experiment, was set to 8 Hz, 35 mm/s^2 rms. In addition, a second frequency component was added to the base one. The added component consisted of one of the five frequencies: 10, 12.5, 17, 20 or 25 Hz. The reason to choose 17 Hz instead of 16 Hz as in previous experiments, is that severe phase dependence would occur using a 16 Hz component since it is a harmonic of 8 Hz. By using 17 Hz, the phase relation to the base component is by far less sensitive. Five different amplitudes were used for the added component: 7, 14, 21, 28 and 35 mm/s^2 rms that correspond to 20%, 40%, 60%, 80% and 100%, respectively of the base component's amplitude. Thus the test subjects were in total exposed to 26 signal combinations according to Table 1.

The choice of the base component is motivated by the fact that 8 Hz is a typical fundamental floor frequency. It also constitutes the borderline between low- and high-frequency floors and should consequently be the most annoying frequency that is allowed to occur in a high-frequency floor (typical lightweight constructions). The amplitude of 35 mm/s^2 rms is the upper acceptance limit in home and office environments according to AISC [12]. This level should be high enough to let the test person concentrate on the characteristic in the vibration without being questioned whether there is a signal present or not. The level is also low enough not to cause any major discomfort during the short exposure time.

The experiment started by letting the test subject become familiar with the actual kind of vibration by playing five, randomly chosen, of the 26 available signals. After this introduction, the subject was exposed to the 26 test signals in a random order. After a short settle time when starting up each signal, typically a few seconds, the subject was informed that the correct amplitude was achieved and the signal then lasted for 10 s. Then the test person was asked to rate the experienced annoyance due to the vibration on a 11-point (0–10) numeric scale where "0" is defined as "not at all annoying" and "10" as "extremely annoying". When judging, they were instructed to think of them selves as being at home or in office environment. The whole test lasted about 20–25 min for each subject.

Table 1
The test subjects were exposed to 26 signals, each of them comprising two frequency components (except signal No. 1)

Signal no.	Frequency (Hz)	Amplitude (mm/s^2)	Signal no.	Frequency (Hz)	Amplitude (mm/s^2)	Signal no.	Frequency (Hz)	Amplitude (mm/s^2)
1	8	35	10	8	35	19	8	35
	–	–		12.5	28		20	21
2	8	35	11	8	35	20	8	35
	10	7		12.5	35		20	28
3	8	35	12	8	35	21	8	35
	10	14		17	7		20	35
4	8	35	13	8	35	22	8	35
	10	21		17	14		25	7
5	8	35	14	8	35	23	8	35
	10	28		17	21		25	14
6	8	35	15	8	35	24	8	35
	10	35		17	28		25	21
7	8	35	16	8	35	25	8	35
	12.5	7		17	35		25	28
8	8	35	17	8	35	26	8	35
	12.5	14		20	7		25	35
9	8	35	18	8	35			
	12.5	21		20	14			

5.3. Results

Fig. 6 shows the mean annoyance of the 26 test signals in which it can be seen that the perceived annoyance is frequency and magnitude dependent. The general tendency is that the annoyance increases as the amplitude of the second frequency component increases while the annoyance decreases as the frequency of the second component increases. As an example of the former; when the second frequency component is 10 Hz, the average annoyance is 5.2 at 7 mm/s^2 but 6.8 at 35 mm/s^2 and as an example of the latter; when the amplitude of second frequency component is 21 mm/s^2 the average annoyance is 6.8 at 10 Hz but 5.4 at 25 Hz. It was also found that the lowest annoyance, 4.4 in average, occurred in the case where the second frequency component was omitted.

The tendencies appear clearer if the results are grouped with respect to frequency or amplitude of the second component as in Fig. 7 where 95% LSD-intervals have been used. The wider confidence interval for the single 8 Hz frequency condition arises because data for this condition are derived from only one exposure per subject as against five exposures per subject for the remaining data points. A LSD polynomial fit of second order (regression analysis) gives the following results when the annoyance is expressed as functions of frequency and amplitude respectively:

$$\text{Annoyance}\,(f) = 8.1 - 0.22f + 0.0045f^2, \quad 10 \leqslant f \leqslant 25, \tag{1}$$

$$\text{Annoyance}\,(a) = 4.4 + 0.093a - 0.0010a^2, \quad 7 \leqslant a \leqslant 35, \tag{2}$$

where f is the frequency (Hz) and a is the amplitude (mm/s^2 rms). The degree of explanation, in statistics known as *R-squared adjusted*, are $R^2_{\text{adj}} = 73\%$ and $R^2_{\text{adj}} = 95\%$ for model (1) and (2), respectively.

The annoyance as a function of both parameters, frequency and amplitude, can be found from multiple regression analysis where a general model containing both parameters of first and second order as well as the interaction effect (amplitude · frequency) are included, Eq. (3). The result from the multiple regression analysis is given in Table 2.

$$\text{Annoyance}\,(f, a) = \alpha + \beta f + \gamma f^2 + \delta a + \varepsilon a^2 + \zeta af. \tag{3}$$

Since the highest P-value of the parameters, 0.7150 related to the interaction effect, is higher than 0.10, it indicate that the parameter on 90% confidence level should not be included in the model. As a result, the squared amplitude might be excluded from the model without any significant loss of accuracy. By successively creating new models,

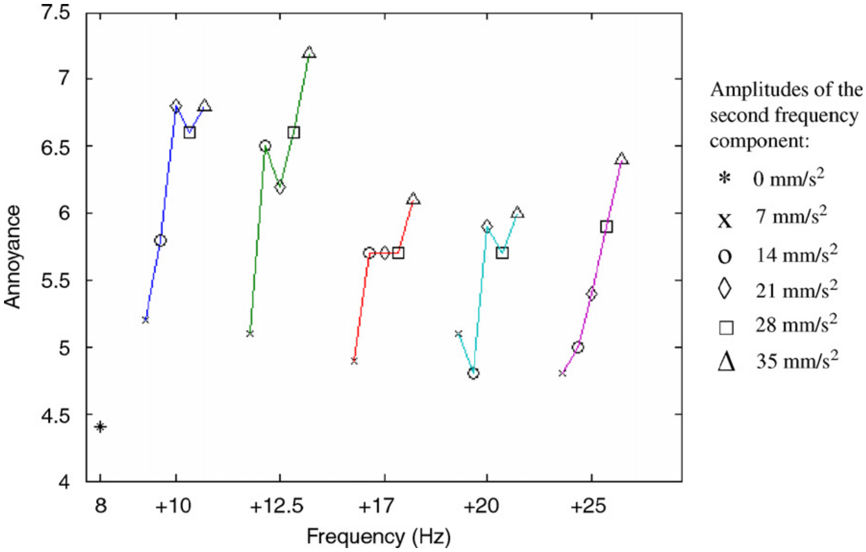

Fig. 6. Averaged annoyance rating. The single point to the left is the base frequency only, 8 Hz (signal No. 1). The next group consists of the signals 8 + 10 Hz (signal No. 2–6) and after that follows 8 + 12.5 Hz (signal No. 7–11), 8 + 17 Hz, etc. The amplitudes of the second frequency component are 0 (*), 7(x), 14(○), 21(◇), 28(□) and 35(Δ) mm/s^2.

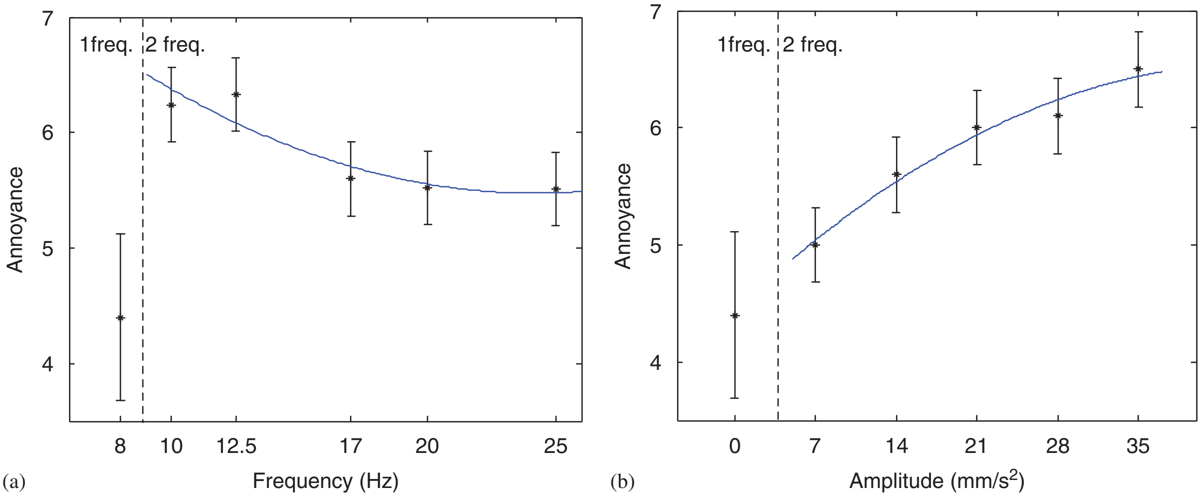

Fig. 7. The averaged annoyance and its LSD-intervals grouped in terms of (a) frequency (Hz) and (b) amplitude (mm/s^2 rms). A polynomial is in each case fitted to the two frequency components' data.

Table 2
Regression analysis of the stipulated model of Eq. (3)

Parameter	Estimate	*P*-value
α	6.54	0.0000
f	−0.203	0.0629
f^2	0.00435	0.1397
a	0.0959	0.0310
a^2	−0.000904	0.2843
$a \cdot f$	0.000472	0.7150

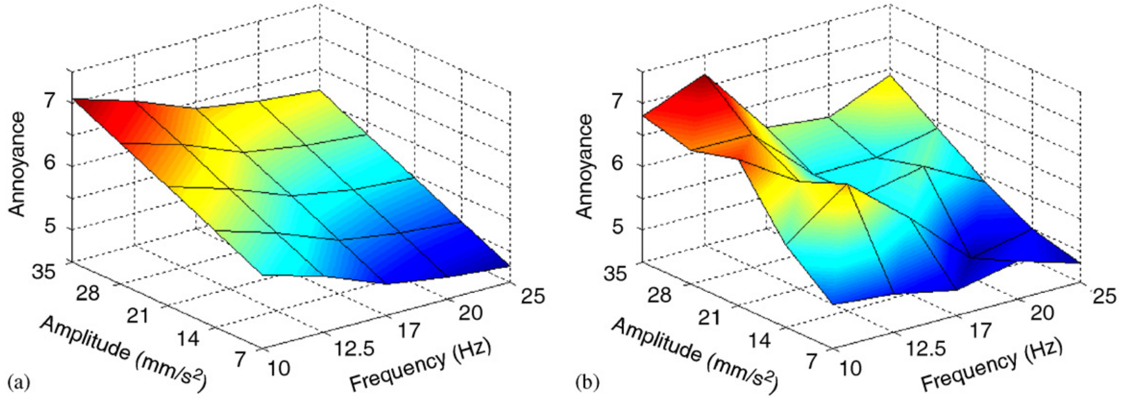

Fig. 8. Annoyance as a function of frequency and amplitude; (a) calculated by multiple regression analysis and (b) experimental results.

every time omitting the parameter that shows the highest *P*-value above 0.10 in previous model, the interaction effect *af* and squared amplitude a^2 are withdrawn on 90% confidence level. The squared frequency f^2 is just on the limit to be a part of the model or not but was finally included. With the final model according to Eq. (4), $R^2_{\mathrm{adj}} = 77\%$.

$$\mathrm{Annoyance}\,(f, a) = 7.01 - 0.213f + 0.00435f^2 + 0.0500\,a. \tag{4}$$

The result of calculated annoyance according to Eq. (4) is shown in Fig. 8 together with the experimental results.

6. Discussion and conclusions

The threshold value from Study I regarding vertical sinusoidal vibrations showed a similar pattern to the ISO base curve although it was found to be at a higher level. A possible reason is that the method of increased intensity used for the experiment tends to over-estimate the threshold value whereas a descending intensity method may under-estimate the threshold. Therefore, if a combination of these methods had been used, it is likely that the averaged result might have been somewhat lower. The base curve is however not a true threshold curve but it represents magnitudes of approximately equal human response and must be used together with a certain multiplier factor in order to make sense in terms of absolute figures. It is therefore not contradictory that the amplitude of the present study does not match the ISO curve exactly.

It is highly interesting to compare the threshold value from Study I with those obtained by other researchers. Fig. 9 contains results from Parsons et al. [4], Reiher et al. [1] and McKay [11]. The latter use results from both sitting and standing subjects while the others use sitting test persons. At a first glance, they all might look quite similar within this relatively small frequency range of 5–31.5 Hz but differences exist, particularly for the higher frequencies. From about 16 Hz and above, Parsons and McKay indicate that the threshold value remains at an approximately constant, or even decreasing, level. In contradiction, the present study as well as the Reiher work and the ISO base curve show increasing threshold value with increasing frequency. Note that the Reiher curve is just a straight line.

A restriction of the present study must be made due to the limited number of participants. Only 7 subjects were used while Parsons used 36, McKay 48 and Reiher 40. In statistics, a large number of subjects are preferable as the quantities give more power and more reliable results.

When threshold values were investigated in the presence of a second signal, test persons could easily detect a signal close in frequency to the 8 Hz base component. In fact the 10 Hz signal was detected at an ever lower level than when it was played alone. The explanation is probably to find by the beating phenomenon illustrated in Fig. 10. The summed signal of the 8 and 10 Hz components repeats every 0.5 s, i.e. with a frequency of 2 Hz. The sensitivity for the 2 Hz contribution combined with the increased peak amplitude makes it easy to detect the vibration. If we instead switch the focus from threshold values to annoyance of dual sinusoidal vibration, the findings reiterate. Test subjects are significantly more annoyed when a second component is added to the 8 Hz base component, especially if the added component is close to the base one in frequency.

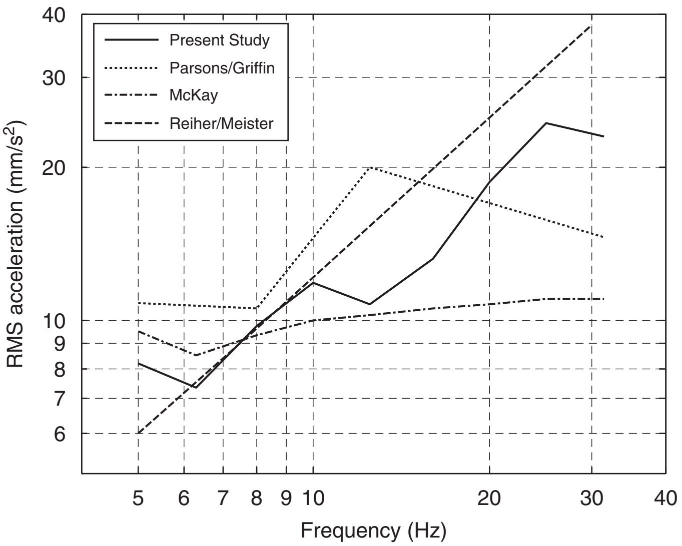

Fig. 9. Threshold values of sinusoidal vibration in comparison with three other studies, present ——, Parsons/Griffin · · · ·, McKay · - · - · and Reiher/Meister - - - -.

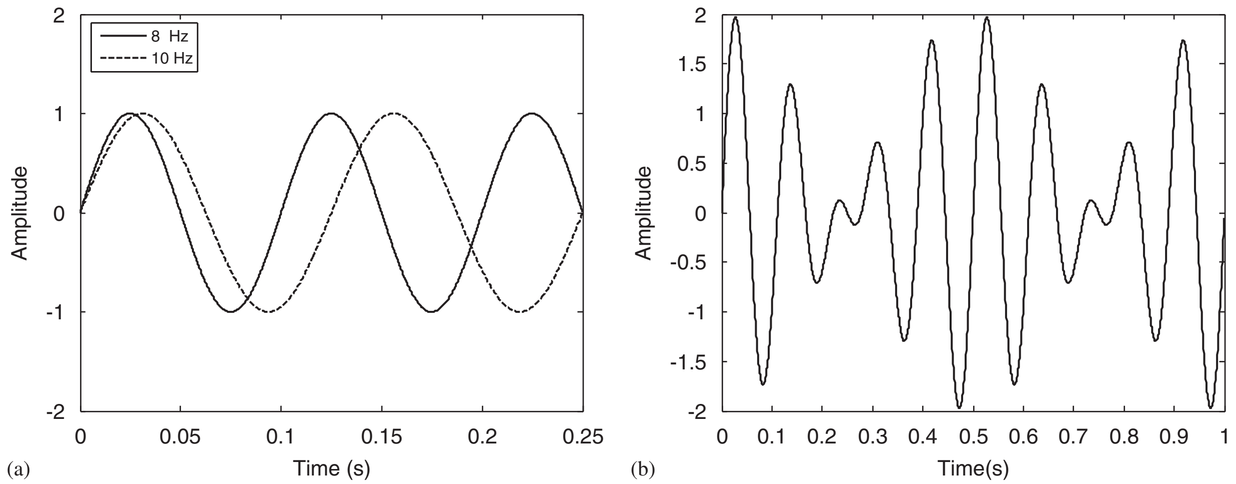

Fig. 10. (a) Two separate sinusoidal components of 8 Hz —— and 10 Hz - - - -. (b) Summation of the 8 and 10 Hz signals.

As for the application to floor serviceability, the present study provides argument for the need to consider the effect of natural frequencies other than the fundamental. Depending on how the frequency and amplitude of these natural frequencies relate to the fundamental, they could have a significant effect of the perceived vibration of the floor. However, the characteristics of the inducing force must also be considered. If the natural frequency of a floor is found to be "high enough", it is not likely to be excited by normal human activity even though it can cause trouble regarding other possible input forces.

Annoyance from floor vibration in real buildings is more complex than annoyance ratings in a motion simulator and at present ISO does not give any guidelines at all regarding floor vibrations but states in 2631-2:2003 that "it is not possible to give guidance on acceptable magnitudes of vibration until more information has been collected". Due to the complexity of perceived vibration from real floors the reported results should be interpreted as informative and showing tendencies in the development of new design criteria.

7. Future research

Further research is planned with the objective to further study the effect on humans when exposed to vibrations of multi-frequency nature. This will focus on floor vibration and will consider typical floor responses when walking serves as the input force. Signals containing a variety of single, dual and triple sinusoidal components will be subjectively evaluated in terms of annoyance and acceptance. Also response spectra from real floors, containing up to five discrete frequency components will be evaluated.

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