Laboratory Listening Tests

Pontus Thorsson

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Laboratory listening tests on footfall sounds

Pontus Thorsson
Chalmers University of Technology
Division of Applied Acoustics

Chalmers University of Technology
Department of Civil and Environmental Engineering
Division of Applied Acoustics
Gothenburg, Sweden

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Preface

One of the main questions in the AkuLite project is to find a more relevant measure of footstep sounds, and preferably to link this measure to an objective measurement method. The present report describes the listening tests that have been performed in the AkuLite project, its direct results and possible evaluation and measurement strategies.

Förord

En av huvudfrågorna i AkuLite-projektet är att försöka ett mer relevant mått för ljud från fotsteg på golv, och helst hitta en koppling mellan detta mått och en objektiv mät- och utvärderingsmetod. Denna rapport beskriver de lyssningsförsök som utförts inom AkuLite, slutsatser från dessa samt beskriver en möjlig mät- och utvärderingsmetodik.

Summary

This report presents a detailed description of the listening tests that have been performed in the AkuLite project. A thorough literature study has been performed on low frequency hearing, listening test methodology, annoyance in buildings and to annoyance to footstep sounds.

Based on the literature study a listening test methodology has been devised that can use measured data from field situations. No requirements of the room acoustics of the recording room are needed since it’s the acceleration in the ceiling that is recorded. The recorded acceleration signals are reproduced using ceiling-mounted loudspeakers and subwoofers. The reproduction system was designed to reproduce signals down to 16 Hz. The reproduction level was measured to be equal to footsteps on the real floor. The listening test was done using pairwise comparisons between one sound with fixed level and one sound where the subject could vary the reproduction level. Two questions were used in the tests: 1) adjust the sounds to equal annoyance, and 2) adjust the sounds to equal loudness.

To test the human hearing for footstep sounds recordings on one lightweight and one heavyweight floor were made. These signals are then filtered to remove information below 50 and 100 Hz respectively, and the signals were adjusted in strength in order to start listening test comparisons at different sound levels. Adjustment of structural reverberation time has also been tested.

The main conclusion of the listening tests is that signal information below 50 Hz is important for the subjective perception. The subjective perception seems to be determined from the sound levels, the structural reverberation time seemed not be important. When evaluated as isophon curves, the shapes were very alike the isophon curves defined in ISO 226:1985.

Different objective measures for evaluating the footstep sounds were tried using the residual between the mean subjective score and the value of the objective measure as error marker. The minimum residual sum of all listening test comparisons was the average A-weighted maximum level.

Sammanfattning

Denna rapport beskriver de lyssningsförsök som genomförts i AkuLite-projektet. En grundlig litteraturstudie har utförts som innefattar hörande av låga frekvenser, metodik för lyssningsförsök, ljudstörningar i bostäder samt störning från fotstegsljud.

Utifrån litteraturstudien har en lyssningsförsöksmetodik utarbetats som kan använda mätdata från fältsituationer. Inga restriktioner av rumsakustik i inspelningsrummet behövs eftersom det är accelerationen i taket som spelas in. De inspelade accelerationssignalerna återgivs med takmonterade högtalare tillsammans med subwoofrar. Uppspelningssystemet har konstruerats för att kunna återge signaler ned till 16 Hz. Uppspelningsnivån uppmättes i uppspelningsrummet så att den var samma som vid inspelningsrummet. Lyssningsförsöket gjordes med parvisa jämförelser mellan ett ljud med fast nivå och ett som försökspersonen kunde bestämma nivån. Två frågor användes i försöken: 1) justera ljuden så att de är lika störande, och 2) justera ljuden så att de är lika starka.

För att prova hur människans hörsel uppfattar stegljud så har inspelningar gjorts för ett lätt bjälklag och ett tungt bjälklag. Dessa signaler filtrerades sedan för att ta bort information under 50 och 100 Hz, och signalerna justerades i nivå för att inleda parvisa jämförelser vid olika. Justering av strukturefterklangstiden har också tagits med i försöken.

Huvudslutsatsen från lyssningsförsöken är att signalinformation under 50 Hz är viktigt för den subjektiva uppfattningen. Den subjektiva uppfattningen verkar bestämmas främst av ljudnivån, strukturefterklangen verkade inte viktig. En utvärdering av resultaten i form av isofonkurvor visade att formen för dessa var väldigt lika de som definieras i ISO 226:1985.

Olika objektiva utvärderingsmått testades genom att använda residualen mellan medelvärdet för den subjektiva utvärderingen och det objektiva måttet som värde för felet. Den minsta summan av residualer för alla jämförelserna erhölls för medelvärdet för den A-vägda maximalnivån.

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1. Introduction

The report begins with a thorough literature study on psychoacoustic aspects of sound and annoyance in dwellings, especially focused on footstep sounds, i.e. impulsive and low-frequency dominated sounds. The study is moreover limited to dwellings, as the main focus of the AkuLite project is dwellings in particular.

Based on the literature study and the main objectives of the project, the listening tests were designed to study the perceived subjective strength of recorded footstep sounds. Two similar tests were performed and the results from both are analysed separately and in combination.

2. Literature study

2.1 ANNOYANCE IN DWELLINGS - GENERAL ASPECTS

In multi-family dwelling houses there are many important sound sources which can lead to annoyance. The sources can be separated into exterior sources, i.e. sound sources outside of the building, and interior sources which have their origin inside the building. In the AkuLite project we have limited ourselves to interior sources since the effects of exterior sounds have been studied thoroughly elsewhere (see e.g. Miedema 2004, Gidlöf Gunnarsson 2008, Vos 2001 and therein cited references).

In a limited study of 40 complaints of poor sound insulation in the UK the complainants (and their neighbours) were asked both closed and open-ended questions about the nature and reasonability of the complaints (Grimwood 1997). It was clear that the complainants had a clear distinction between excessive noise due to their neighbours' behaviour and excessive noise due to poor sound insulation. The most commonly reported problem were activities requiring a quiet environment, e g sleeping or resting. In the majority of the cases both the complainants and their neighbours had modified their behaviour in some way because of the acoustic climate. Some 35 % reported the need of being quiet (including visitors) and a smaller group (18 %) claimed not to have visitors due to the poor sound insulation (Grimwood 1997).

An attempt to quantify weighting factors between different sound sources, both exterior and interior, has been made by Jeon *et al* (Jeon *et al* 2010). In the study both a survey of acoustic climate in existing dwellings and a laboratory experiment using synthesized acoustic climate was used to find the subjective mean weight of the A-weighted equivalent levels of respective source. Dissatisfaction was used instead of annoyance due to its simpler interpretation by the subjects, and the dissatisfactions for respective source were assumed to be independent, i.e. interaction effects were excluded. The model of total dissatisfaction was as shown in Eq (1).

$$D_{overall} = \beta_1 D_1 + \beta_2 D_2 + ... + \beta_n D_n \qquad (1)$$

An advantage of Jeon's proposed model is that the total dissatisfaction can be evaluated based on physically different metrics as opposed to a summation of acoustic energies. Each contributing dissatisfaction component has its own dependency of the important acoustic metric

$$D_n = f(L_n) = \alpha_n L_n + c_n \qquad (2)$$

where L_n is the acoustic metric and α_n and c_n are regression coefficients. Based on a survey with interviews of 512 respondents in Korea the mean subjective weights of four different source types were (ranging from most to least important using Eq. (1)):

- Floor impact noises (*b* = 0.64)
- Airborne noises (*b* = 0.19)
- Traffic noises (*b* = 0.11)
- Drainage noises (*b* = 0.09)

This shows that floor impact noises can be the most dominant noise source with respect to dissatisfaction of the acoustic climate in dwellings. This finding is in good accordance with the findings in a study by Raw and Oseland where an interview survey of 422 conversion flats in London and Birmingham was conducted (Raw and Oseland 1991). Neighbours above were in the study judged to be more disturbing than neighbours below, and impact noise was judged to be the principal component of the noise coming from above. An unexpected result in Raw and Oseland’s study was that the floor material was not significant regarding noise from above while a hard floor material increased the disturbance from below. Jeon's study was conducted in houses with concrete structures while the structure type is undefined in Raw and Oselands study.

A survey study on two-storey attached houses by Langdon et al have shown that the principal sound sources to be airborne in such a case, but in their paper they stress the importance of impact noise sources as well (Langdon et al 1981).

Many different studies note that the standard test procedure for impact noise between dwellings does not rate the annoyance of footsteps or jumping in a reasonable way (e. g. Watters 1965, Olynyk and Northwood 1968, Blazier and DuPree 1994, Grimwood 1997, Jeon et al 2006). In short description there are strong objections to the standardized measurement method that uses the ISO tapping machine. The main question seems to be if the tapping machine can give results that correlate well to actual walking persons.

Regarding interior sound sources these can be classified into airborne and structure-borne sources depending on the nature of excitation. The most common airborne sound sources found in the literature are reproduction systems for music and speech (Music systems, radio, television), voices, bathroom use, technical appliances (washing machine, vacuum cleaner etc), telephones. The most common structure-borne sound sources found are footsteps, banging doors, bathroom use, washing machine, sockets and switches, impacts on kitchen work surfaces (Grimwood 1997).

In another study by Jeon et al a social survey in 611 apartments in the Seoul area was conducted with the main focus of characterising impact noise sources in dwellings with box-type reinforced concrete structures (Jeon et al 2006). One result of this survey was that people walking, children running and jumping summed up to 80 % of the complaints. In the same study spectra of impact force and sound pressure level in the receiving room are presented for real impact sounds (adult walking, children jumping and running) and for standard impact sources (tapping machine, impact ball and bang machine). All spectra for human impacts are dominated by low frequencies (< 125 Hz). This is confirmed by another study by Shi et al (1997) where force spectra for human walking, running and jumping are shown to have strong components at very low frequencies (< 20 Hz). It is thus of great importance to study both physical and psychological hearing effects down to very low frequencies.

A low background noise level inside dwellings is often desirable, but the absence of background sounds can increase the perception, and then probably also the annoyance, of less loud sounds. In the literature there are examples of cases where a low background noise level is contributing to the poor experienced sound insulation (Grimwood 1997). In one study it is reported that it is the ability to detect the sound that triggered complaint rather than the relative loudness (Blazier and DuPree 1994).

2.1.1 The difference between perception and annoyance

From the area of product sound quality research, it has been suggested that sound quality not only depends on the form of the sound (that is, the sound as described by physical measures such as A-weighted sound pressure level, loudness, sharpness etc.) but also on the interpreter (the listener and his/her previous memories, experience and emotional state) and the content (the information which can be derived from the sound – i.e. the sound's meaning) (Genell 2008). This relationship can be described by the semiotic triangle (see Figure 2.1). In the case of footfall noise, the different corners of the semiotic triangle can be interpreted as follows:

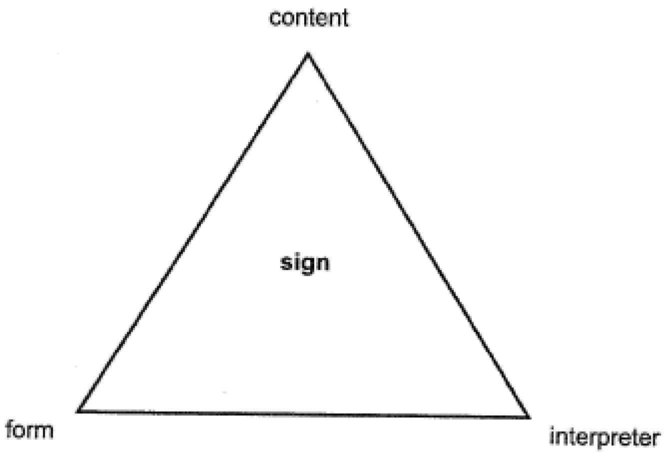

Figure 2.1: The semiotic triangle

- **Interpreter:** Is in our case the resident in the underlying flat. The total annoyance of the footfall noise will be influenced by his/her expectations, previous exposure to similar situations related to noise disturbances by neighbours, to his/her mood, general sensitivity to noise etc. As there are large inter-individual differences in the hearing threshold in the low frequency range (Yamada 1980), this is obviously something, which needs to be considered. Cultural factors can also influence the interpreter (Jeon et al 2004).
- **Form:** Here we have the basic metrics found in standards and regulations, which quantifies basically the level of the sound (with certain weights to adjust for spectral content). Also other more aurally adequate metrics have been proposed, such as loudness, sharpness, fluctuation strength and interaural cross correlation. Some of these have been shown to correlate well with perceived annoyance, but the challenge here remains to define a set of metrics which are sufficient for describing the sensation of footfall noise regardless of construction type (wood, concrete, etc) and which can give a more detailed objective (that is, not only loudness but also "dullness", "thumpiness", rattle, and other).
- **Content:** In general it can be quite difficult to quantify what information the listener can derive from the sound. This task seems however easier in case of footfall disturbances since we have a defined target source – "someone is walking / running / jumping on the floor above me" – which can be either identified or not by the listener. To develop an objective measure which indicates if a certain type of noise can be identified as a footfall noise or not, or other perceptual identifications such as gait, type of footwear etc may be trickier however.

Many studies on annoyance due to community noise and similar attempts to relate annoyance to form only – i.e. suggesting that a certain level metric (in dB) should be enough to determine whether people will be annoyed or not by a certain type of noise. In other words, one rather tries to directly establish if any of the existing metrics (be them sound level or sound quality related) can predict annoyance. The semiotic triangle approach suggests that measuring only the form dimension of sound explains one component of annoyance, and that the situation must be much more carefully elaborated to fully understand the problem. For example, a person who has had bad experiences of being exposed to noise from neighbours, or maybe paid a great deal of money to live in a flat with supposedly high degree of acoustical comfort will most likely rate footfall noise independent of level or other form-related factors but will be annoyed as long as he/she can hear the noise at all (cf. Blazier and DuPree 1994).

We suggest using a different approach, starting from understanding the relation between the basic physical parameters of the sound and the perceptual experience of those and then going to understanding of what perceptual experiences (in combination with the listener's interpretation and information extraction) leads to annoyance. From this information one could then derive suitable measures, which could predict the perceptual (and listener-related) attributes, which lead to annoyance. It seems as if it is better to start from identifying what type of perceptual characteristics a certain sound has, identify which of those characteristics creates annoyance in a certain situation (and for a certain individual) and then develop or select suitable measures which quantifies those characteristics, rather than doing the opposite (starting from selection of measures which may quantify annoyance without knowing what perceptual and contextual attributes which create annoyance). The overall proposed workflow is presented in Figure 2 below.

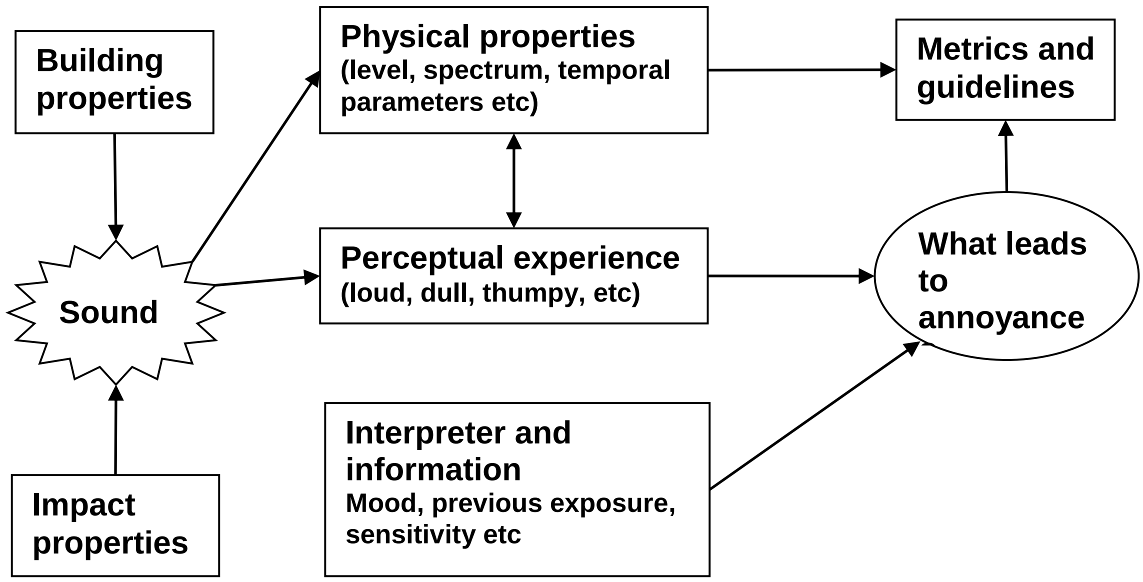

Figure 2.2: Proposed workflow for evaluation of footfall noise

2.1.2 Perception and annoyance of low-frequency sounds

Classically it is claimed that human hearing has a low frequency limit around 20 Hz. In spite of this there are numerous papers that have studied the hearing threshold at lower frequencies (Yeowart et al 1967 and 1969, Whittle et al 1972 and Yeowart and Evans 1974). In the present author's opinion the "classical" 20 Hz limit comes from where the concept of pitch has its lower limit (Zwicker and Fastl 2006), which is supported by another author (Leventhall 2003) who has made a thorough literature review of low frequency hearing and its effects.

The hearing thresholds for low-frequency tones presented in the respective references are in reasonable agreement with each other, and the main characteristics are shown in Figure 3. It is evident in the figure that the hearing threshold cannot be modelled by extrapolating a straight line from data in the 20-30 Hz region. The broken line around 16 Hz can be found in all references and must be understood as an important characteristic of low-frequency hearing. This conclusion is further emphasized by comments by the experiment subjects on the hearing sensation. For frequencies higher than the 16 Hz octave band an octave band-limited noise was experienced as a fairly steady-state exposure while it was experienced as a rough and peaky experience for lower frequencies (Yeowart et al 1969).

One specific feature of low-frequency hearing is that the hearing threshold appear to be different for band-limited noise and for pure tones in the sense that the threshold for noise is lower, i e human hearing is more sensitive, than for pure tones. The difference is reported to be around 4 dB at 4 Hz and decreasing to no significant difference at 125 Hz, except at 16 Hz, where a peak of 5-6 dB is found (Yeowart et al 1969). This last effect is believed to be related to the difference in subjective impression described earlier.

The nature of perception of low-frequency sounds is also discussed in the literature. The question is if low frequencies are perceived through hearing or any other physiological response, e g vestibular response. One paper (Yeowart and Evans 1974) has reported very similar hearing thresholds for tones through headphones and full-body exposure in the frequency range between 5 and 20 Hz. No references have been found which report differences in hearing threshold or perceived loudness depending on stimulus excitation. Thus low-frequency hearing seems to be perceived predominantly through the ears.

The standard ISO isophon contours which are defined ISO 226 only include frequencies down to 20 Hz. However, according to the literature the 20 Hz value in ISO 226:1987 seems to be a linear extrapolation of the 25 and 31.5 Hz values and not an individual data point (Whittle et al 1972). An attempt to extend some isophon curves down to 3.15 Hz is made by Whittle et al (1972) where they made a best estimate of the binaural hearing threshold and the 33.5, 53.0 and 70.5 phon curves respectively (see figure 2.3). The estimations were made from listening tests with subjects in a sealed box exposed to tone bursts between 3.15 and 50 Hz. In these curves it is clear that to simply extrapolate linearly below 20 Hz would greatly underestimate the perception of frequencies below 20 Hz.

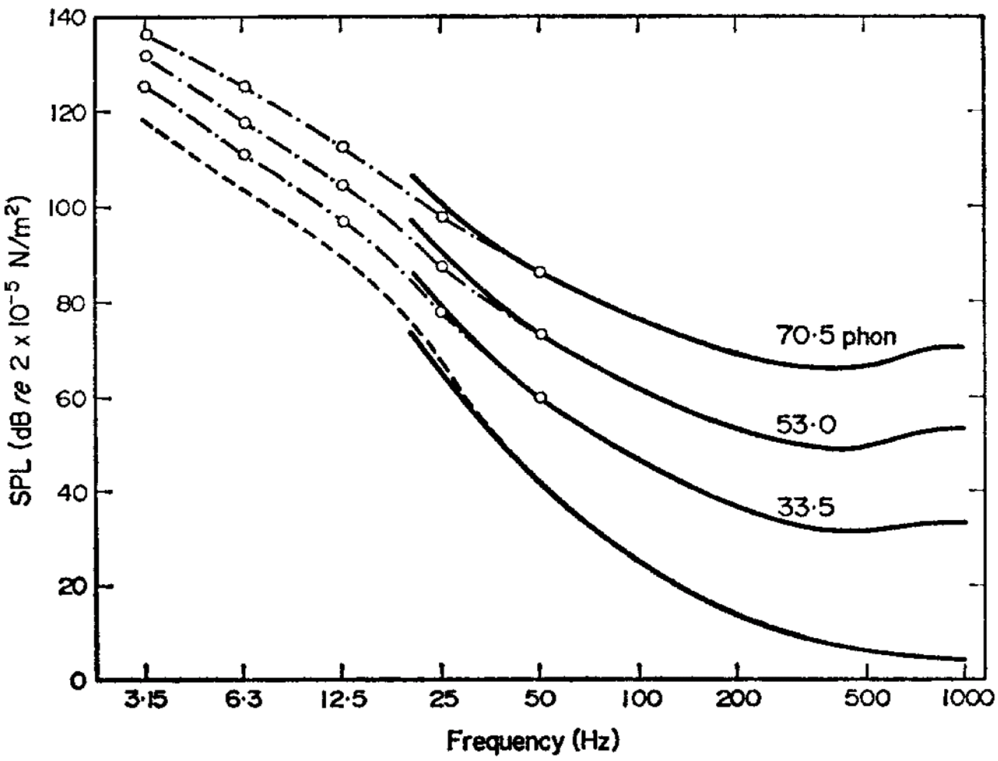

Figure 2.3: Binaural hearing threshold and three example isophon curves extended to 3.15 Hz (from Whittle et al 1972)

2.2 PERCEPTUAL ASPECTS OF FOOTFALL SOUNDS

2.1 Spectral aspects

It is clear that the spectra of the footfall generated noise in heavyweight constructions (such as concrete floors) and lightweight construction (such as wood-joist floors) are different – with the lightweight constructions having a more pronounced low frequency range (Mortensen, 1999). However, this does not mean that low frequencies are of no importance in heavyweight constructions (cf measured spectra in Jeon et al 2006). Examples of linear sound pressure levels measured in a new dwelling fulfilling the requirements for Sound class C according to SS 25267 when a 90 kg male is walking and jumping can be seen in the top pane in figure 2.4. In the lower pane of figure 4 the relative importance of respective octave band when weighted with the 33.5 phon contours from Whittle et al (1972), also presented in Figure 2.3. In this figure it is clear that frequencies down to 16 Hz can be important. This is in good accordance with measurements made at VTT, Finland (Parmanen et al 1999).

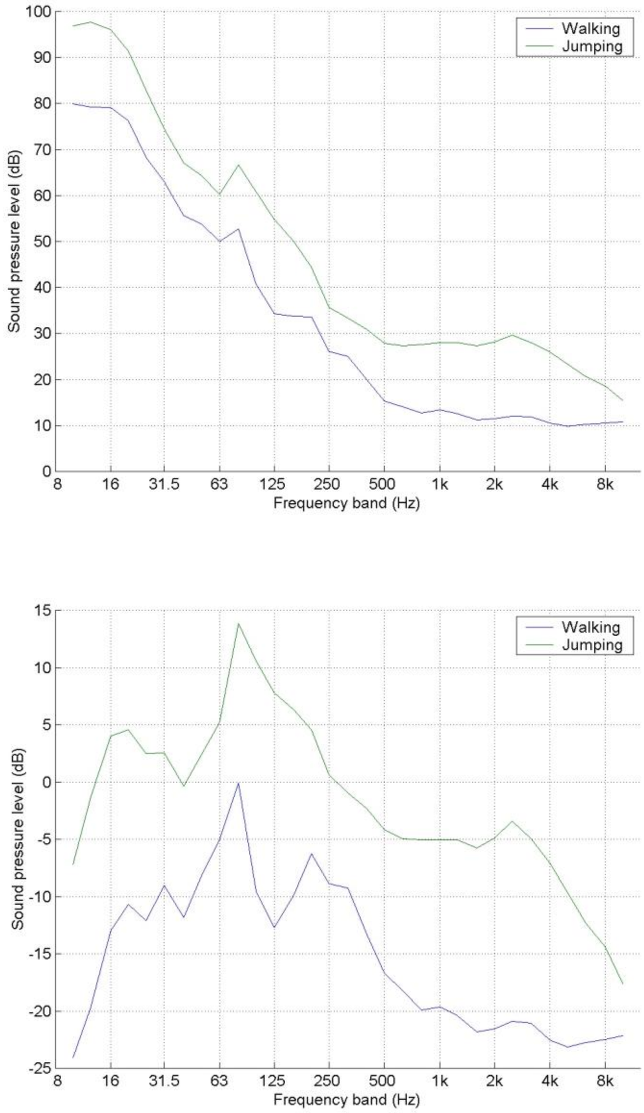

Figure 2.4: Measured sound pressure level in an example dwelling in a lightweight construction for an adult walking and jumping, linear (above) and weighted with 33.5 phon frequency weights (below).

An investigation by Bodlund (1985) questioned the appropriateness of the ISO reference curve. Figure 2.5 from this investigation shows two floor constructions, one concrete (dashed line) and one wood-joist floor. These two floors had almost the same impact indices but the subjective ratings for the wood were much lower compared to the concrete floor (3.4 vs 4.9 on a 7-grade scale from “quite unsatisfactory” to “quite satisfactory”).

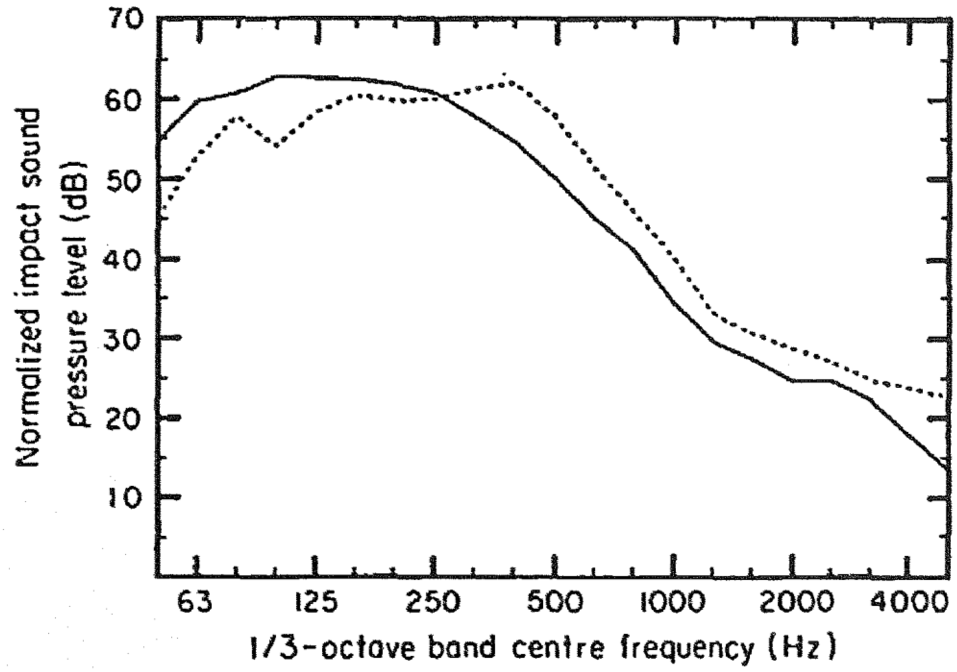

Figure 2.5: Measurement (1/3-octave band) of two floors in the study by Bodlund (1985). Dashed line = concrete floor, solid line = wood joist floor

In a similar vein, Blazier and DuPree (1994) studied a case where the owners of luxurious wood-frame residential buildings had raised severe complaints against the lack of acoustical quality in their apartments. Standardised measurements (ASTM E-492 IIC) in the buildings did however not show poor sound insulation properties. Interviews with occupants revealed that "thuds", "thumps" and "booming" sounds were the main cause of the annoyance. Blazier & DuPree drew the conclusion that the impact sound's energy in the low frequency region, which obviously cannot be detected by the IIC method, was one of the main reasons for the annoyance. Furthermore, it was noted that it seemed to be the ability to detect the event which led to annoyance rather than the unwanted signal's relative loudness whenever it occurred. As lightweight constructions may give rise to high impact sound levels in the low frequency range (in Blazer & Dupree's case, up to 80 dB around 20 Hz), the impact sounds are not naturally masked by environmental noise in the as more high frequency transmitted sounds, speech, plumbing etc, may be. This makes signal detectability more cumbersome in lightweight constructions.

Also other investigations have shown that low frequency sound insulation is important for the acoustical comfort (Rasmussen and Rindel 2005). In a study performed by Rindel (2003), music as well as footfall noise from walking and running were used as noise sources in the evaluation procedure. An improved correlation between subjective and objective evaluation was found if the spectrum down to 50 Hz was taken into account.

This suggests that measures should obviously take into account the overall shape of the footfall spectrum, but also that people are more sensitive to disturbances with more pronounced low frequency content, which may be a result of the fact that such disturbances are not easily masked by other sounds. Both Bodlund and Rindel (2003) (and others) suggest extending the measurement frequency range down to 50 Hz; It might be even advisable to consider also lower frequencies given the frequency content of e.g. Blazier & Dupree's case and the other measurements that will be presented further on in this discussion. Research from automotive domain may further guide the direction of research, e.g. investigations on the perception of "booming" – which seems to be related to loudness in the <200 Hz region (Lee and Chae 2004).

In a similar vein, Lee (2010) investigated the correlation between different types of sound pressure level spectra due to footstep noise and annoyance. Various recordings from apartments in concrete buildings were used which were classified into three groups, A, B and C; spectra are shown in Figure 2.6 below. All stimuli were presented at a fixed level of 50 dB ($L_{i,Fmax,AW}$). A paired-comparison test was used to determine the difference in terms of annoyance for the sounds. It was found that Group C sounds, which had a dominant sound pressure level at 250 Hz, were more annoying than Group A sounds, with the lowest spectral peak, and Group B sounds, with the maximum sound pressure level at 125 Hz. Additionally, interviews were conducted after the experiments, which showed that Group C sounds were most annoying due to the high frequency content, while Group A sounds were more annoying than Group B sounds because of their low frequency content. A few subjects answered however that Group A sounds were less annoying than Group B because of the warm impression of the low frequency components. No obvious conclusions can be drawn from this, but it is clear that the overall shape of the spectrum plays a role in persons' judgment of annoyance.

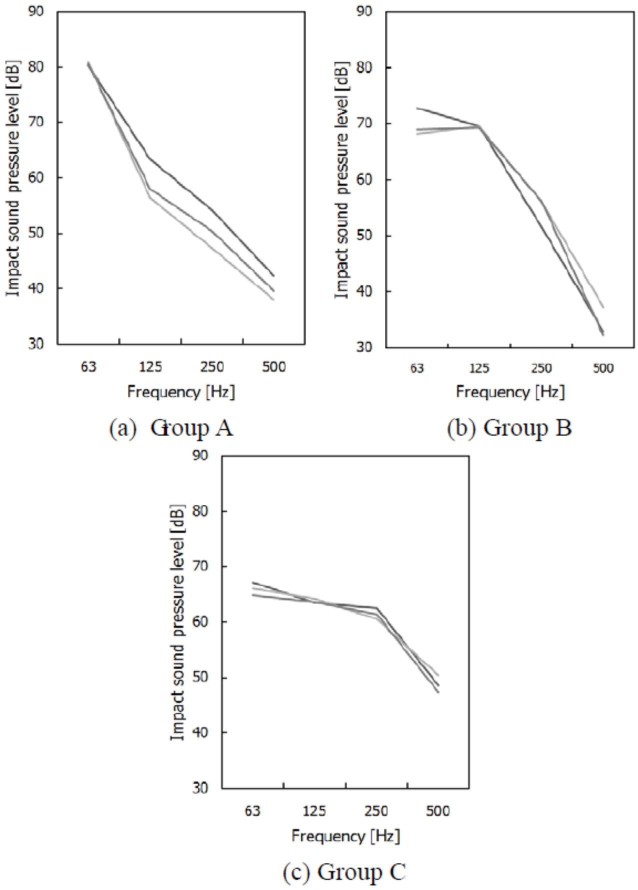

Figure 2.6: Spectra of the different stimuli used in the experiment by Lee (2010).

It should however be mentioned in this context that there are pronounced individual differences in the hearing threshold in the low frequency range. Experiments have shown that the threshold may differ as much as 15 dB between individuals in the frequency range 8 Hz-63 Hz (Yamada, 1980). Moreover, although audibility remains below 20 Hz, tonality is lost below 16-18 Hz (Leventhall, 2003), which indicates that these low frequencies may have to be treated separately in an analysis of the correlation between subjective and objective measurements.

Sources that are dominantly low frequent are, besides footstep sounds in lightweight constructions, traffic noise indoor, some forms of industrial noise, ventilation noise, aircraft noise and shooting noise from large-calibre weapons (Berglund et al 1996). Vos (2001) have studied the annoyance from shooting noises of weapons with calibres between 7.62 mm and 155 mm, ranging from pistols to hand grenades and Howitzer guns. Some of these impulses included high sound pressure levels at frequencies below 63 Hz (Vos, 2001). Listening tests were made simulating both an outdoor and an indoor situation. The annoyance in the outdoor situation was almost entirely determined by the A-weighted sound exposure level (SEL) for all weapon types. In the indoor situation the A-weighted sound exposure level was not as successful as descriptor, and after some trials the rating level with the best fit to the subjective data was found to be

$$L_r = L_{AE} + 12 + b(L_{CE} - L_{AE})(L_{AE} - a) \qquad (3)$$

with a = 45 dB and b = 0.015 dB^{-1} (Vos 2001). Thus the difference between C-weighted and A-weighted level is possible to use to rate annoyance from predominantly low-frequent sounds. Meloni and Rosenheck (1995) also found that the A-weighted SEL was a good descriptor for annoyance outdoors. Weapon's blasts are good reference to footstep sounds (or other impact sounds) since they both are impulsive in nature.

In a study aiming at finding a good descriptor for perceived noisiness of vehicles it was however found that the C-weighted level alone was inferior to A-weighted and loudness levels, both in an outdoor and an indoor situation (Watts and Nelson, 1993). It was further found that sound exposure levels were more closely related to the subject's perceptions than maximum levels. The annoyance for different frequency weighted noise levels in workplaces has been studied by Kjellberg et al (1997) in order to study the importance of the low frequencies. The noise exposure in this study was “business as usual” noise at respective subject's workplace, thus covering environments in offices, laboratories and industry. They found a small but significant increase in the annoyance model when the difference between C-weighted and A-weighted levels was included in their analysis as a independent variable (Kjellberg et al 1997).

The difference between C- and A-weighted levels has also been used by Nilsson (2007) for assessing perceived loudness and annoyance for road traffic. It was found that sounds with a high difference L_C-L_A was perceived louder and more annoying than sounds with a low difference. However, it was found that the Zwicker loudness levels were approximately similar in annoyance and perceived loudness irrespective of the L_C-L_A difference.

The findings for other noise sources are in good accordance with the study by Mortensen (1999) who found best correlation between A-weighted sound pressure levels and subjective loudness of footfall sounds, as compared to C-weighted or linear levels. In his study field measurements according to ISO 140 (both airborne sound insulation and impact sound insulation) between sample dwellings with both heavy and light constructions was made. The differences found between the construction types were used to filter recordings of music, male walking and children playing. These filtered signals were used in listening tests. A similar method was also used in a previous pilot project with similar conclusions (Nielsen et al 1998).

One difference between the pilot study and the main study was that strong differences in annoyance and subjective loudness were found regarding the subjects' sex and age (Mortensen, 1999). This shows that non-acoustic parameters can be important factors. In two papers it has also been shown that culture can give differences in subjective judgements on loudness and annoyance. Jeon et al (2004) showed that significant differences were found between a Korean and a German subject group when using footfall sounds as stimuli. Kuwano et al (1988) showed that cultural factors could go deeper than just difference in subjectively perceived levels; they can influence the subconscious analysis of the stimuli. This can be understood as a similar mechanism as the difference in meaning of particular words in different languages, as shown by Botteldooren et al (2002).

There is an on-going discussion on how low frequencies that need to be included in field measurements and listening tests in order to describe the subjective sound airborne and impact noise insulation in a correct way. A study made by Jakobsson (2010) showed that there are numerous sound sources that can excite frequencies down to 20 Hz in lightweight buildings, but no differences in subjective judgements was found in general if frequencies below 50 Hz were removed in listening tests. The results show however that there is a significant difference for footfall sounds, see figure 7.

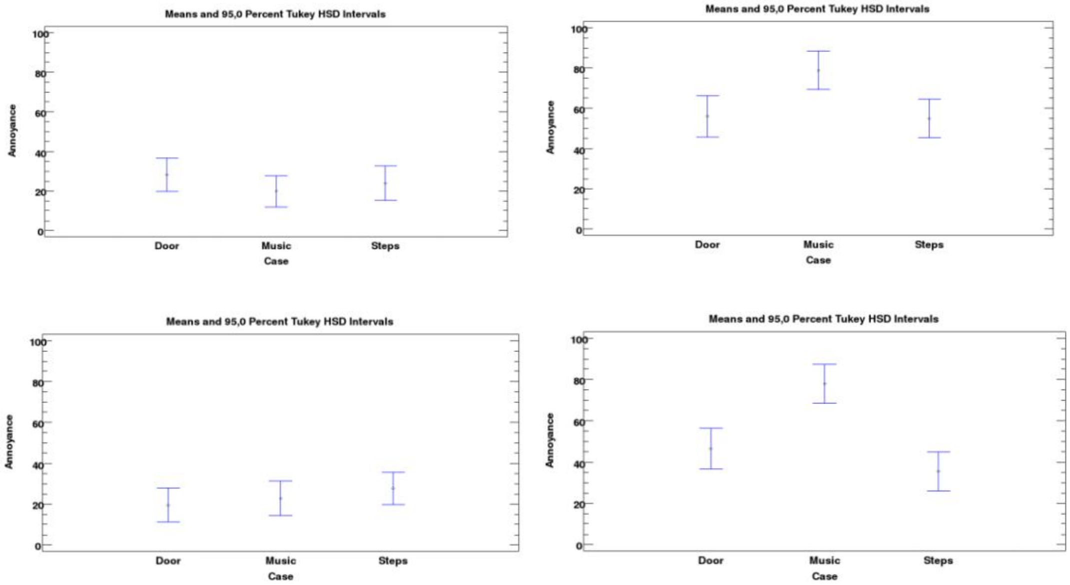

Figure 2.7: Subjective evaluation of linear (above) and 50 Hz high-pass filtered sounds (below). Diagrams from (Jakobsson 2010).

Subjective evaluation of footfall sounds from a male and a female walker on both lightweight and heavyweight floors has been studied by Hammer and Nilsson (1999). They showed that Loudness measures gives the closer correlation to the subjective loudness level than either weighted measure using the tapping machine or A- and C-weighted equivalent levels respectively.

2.2 Temporal aspects

Footfall noise carries distinct signatures not only in its spectral pattern but also in its temporal characteristics. Naturally, the speed of walking and will create a temporal variability in the sound which is clearly perceivable by the receiver. But type of floor construction, gait, footwear etc will affect how the individual footfalls evolve temporally and this may have significance for the perceived quality of the sound. Being typical impulse signals, footfall noise may be objectively characterized by measures such as crest factor (peak-to-average), rise time and kurtosis (peakedness or impulsiveness). Within the domain of automotive sound quality research it has been e.g. suggested that a combination of loudness and kurtosis can be used to quantify rattle (Cerrato et al., 2001) but the understanding of how these types of metrics are related to perception is relatively limited. However, it appears as if the initial part of the impulse is of specific interest for sound quality, as our hearing systems seems to be more sensitive at the onset of the sound compared to other portions.

Along these lines, an investigation by Kuwano et al. (1999), showed that the temporal pattern of Sharpness in the initial 60 ms of the impulse affected the perceived quality of the sound (in this case, the stimuli used were sounds of hitting a golf ball with a golf club). More specifically, it was found that the difference between Sharpness at 60 ms and Sharpness at 0 ms was positively correlated with the sensation of "refreshing". That is, if Sharpness onsets gradually this is perceived as better as compared to if Sharpness onsets rapidly. The context and overall preference for these types of sound is naturally not comparable to disturbing noises such as footfall impulses, but this study indicates the relevance of taking into account the temporal envelope of impulse sounds. A hypothesis relevant for footfall impulses could e.g. be that if the rise time is increased by lowering e.g. the stiffness in the floor or by having a surface that promotes a different type of gait, this may improve subjective ratings although the overall level may actually increase.

Conversely, it is also reasonable to assume that the characteristics of impulse decay may influence the perception. From room acoustics research it is known that the decay of sound (the reverberation) inside a room should have a high modal density, i.e. have no perceivable tonal components, to be perceived as natural and "uncoloured".

In a recent experiment, Mohlin (submitted) investigated the audibility of tonality in sinusoids damped by either exponential or Gaussian functions. It was found that tonality can be detected in >3.4 kHz tones as short as 2.6 ms and that this Just Audible Tonality (JAT) depends on frequency in the way that longer durations are needed for lower tones (about 20-25 ms for frequencies 150 Hz and 250 Hz). Moreover, analysis also show that Gaussian and exponential tones differ in Q-values with Gaussian having more focused energy around the frequency peak which may explain why it is easier to detect tonality in these types of decays. Considering that a footstep impulse may be significantly longer than 25 ms, it is clear that tonality can be detected in such sounds as long as the energy is not spread over too many critical bands. These results may provide important input to improving metrics that describe perceived tonality in decaying impulses (such as the Spectral Flatness measure).

The footfall noise in the receiver's position it is naturally a result of the excitation properties (the person walking above you), the transmitting surface (the floor) and the properties of the receiving room. It may thus be difficult to tell whether the decay of the impulses stem from resonances in the floor structure or from the room, especially if the decay times are of similar magnitude. Nonetheless, a relevant hypothesis for footfall impulses would be that if the decay contains audible tonal components (regardless of where these tonal components come from), this is perceived as worse as if the decay is more broadband.

It has been suggested that, apart from loudness, other traditional sound quality measures may be used to quantify also footfall noise (Lee, 2010). As temporally related measures such as fluctuation strength and roughness were developed for continuous signals, this suggestion is somewhat surprising. However, impact sources produced on the floor induce vibration and resonance in the floor and ceiling structures so that a fluctuation in loudness occurs. Measurements have also shown that fluctuation strengths may vary among various sound insulation treatments (Jeon and Sato, 2008).

In a study by Lee (2010), a paired-comparison experiment was carried out to determine the overall correlation between subjectively perceived annoyance of impact sounds and various sound quality metrics. The stimuli were nine different recordings of impact balls presented at same level (50 dB ($L_{i,Fmax,AW}$) which could be grouped into three categories A,B, and C where A sounds were obtained from slightly smaller rooms than B/C sounds. “A” sounds consequently had a more pronounced low frequency content than B/C. Subjects were for each stimulus pair asked to assess “Which stimulus would be more annoying if you were exposed to it in the living room?” (Lee, 2010, p. 89). In the calculation of correlation coefficients, overall values for loudness, roughness, fluctuation strength and sharpness were used. The analysis showed that annoyance was significantly and positively correlated with fluctuation strength, indicating that increased modulation (greater temporal variation) resulted in more annoyance. Moreover, also loudness was positively correlated with annoyance and found to contribute more to annoyance than fluctuation strength. Similar results were found in a previous study using different measurement techniques (Jeon and Sato, 2008). While it is reasonable to assume that there should be metrics which are better suited to capturing the temporal quality of impact sounds than fluctuation strength, the results presented by Lee (2010) and Jeon and Sato (2008) clearly indicates that the temporal variation of the decay of footfall-like impact sounds has significant influence on annoyance.

In another study, Lee (2010) used semantic differential scales to further investigate the perceptual response to the A/B/C impact sounds discussed above. Subjects were asked to rate the stimuli on a 75 different adjective scales. Out of these 75 adjectives, 12 which seemed most reliable were chosen (see section.. below for a list of these scales). By means of factor analysis, these 12 adjectives were grouped into three main categories that were named “reverberance and spaciousness”, “dullness” and “loudness” respectively. Hence, one can conclude that for these stimuli, the spatial impression, the spectral or tonal quality, and the perception of loudness seem to define the underlying perceptual dimension. The stimuli used were recorded in concrete box frame type reinforced concrete apartments with a concrete slab thickness between 150 mm to 180 mm and it is possible that wooden joist floors with more pronounced low frequency content and resonances will elicit other perceptual responses. Still, the study by Lee may serve as a good starting point for explorations in lightweight constructions.

2.2.3 Spatial aspects

From traditional room acoustics research it is known that the spaciousness or perceived diffuseness of the sound field is important for the perceived quality of the room. In general, in rooms for music (concert halls, opera houses etc.) it is desirable to have a certain amount of spaciousness, envelopment or source widening to achieve a good quality impression. Given that the spatial human auditory system is well developed in terms of source localization and used for survival mechanisms, it is reasonable to assume that spatial qualities of the sound would affect the way we perceive more everyday sounds, such as footsteps, as well. When it comes to everyday sound sources, as opposed to music, it seems however reasonable to assume that people prefer to be able to localize the source as the location of the source is important if we want to be able to approach or avoid it. If a car is approaching you when walking in the street for example, you would certainly like to be able to localize where it comes from to be able to take evasive action. A more spacious sound field also gives the impression of the source being wider and bigger which for some sounds would make them more threatening (Tajadura et al., 2010).

In this vein, Jeon et al. (2009) studied the influence of Interaural Cross Correlation (IACC) and SPL on annoyance for transmitted impact sounds created by dropping an impact ball in an overhead apartment. It was found that high IACC (i.e. less diffuse, and more localizable sound) resulted in lower annoyance ratings. The contribution of IACC to annoyance was found to be less than that of SPL - about 20.4% of the scale rating was contributed by IACC. Jeon et al. investigated also the temporal variation of IACC vs annoyance but found that the influence of this was negligible in comparison to running IACC. Considering that IACC may be easier to adjust than SPL this is a very interesting finding. Jeon et al. also made measurements of different constructions and found that sound insulation treatments, especially in sidewalls, are effective in obtaining higher IACC values. Similarly, one could increase IACC and reduce annoyance of footfall noise by distributing the receiving room's sound absorption on the walls instead of in the ceiling.

2.2.4 Auditory-Vibrotactile cross-modal aspects

When studying the perceptual aspects of noise, it is important to keep in mind that humans perceive the surrounding world through all their senses. One has shown that the sensory modalities interact in several different ways and already on a low level of processing in the brain (i.e. at the pre-cognitive stages). Hence, visual impressions, vibrations, smell etc may affect annoyance, acceptance and similar ratings even if the question explicitly relates only to noise/sound.

Auditory-visual effects have for example been studied quite extensively for basic stimuli such as noise bursts, light flashes etc. In some cases it may be that the visual sense dominates perception, typically when you have some spatial discordance between sound and visual impression. For example, sound may be perceived as coming from the direction of a simultaneous visual event even if the sound source is located somewhere else (the ventriloquist effect, Bertelson & de Gelder, 2004). In other cases, sound may dominate the perception, which especially holds true for temporal aspects. An example of this is when presenting a sequence of light flashes together with a sequence of tone beeps. If the number of beeps is different from the number of light flashes, it appears as if one saw as many light flashes as there were beeps. These effects occur, as mentioned, on a low level and cannot be overridden by actively focusing on not perceiving them.

Studying the combined perception of sound and vibrations are interesting from the viewpoint of perception of footfall noise in dwellings, since the occupants will indeed be exposed to both sound and vibrations in the building and that their relative balance will differ depending on how the building construction is constituted. The vibration amplitude generated by footsteps can in lightweight buildings be clearly noticeable, as shown by Bard and Jarnerö (2010) comparing acceleration measurements with the base curves given in the out-dated version of ISO 2631-2. The measured accelerations were well above the base curves and a standing person would most probably perceive the vibrations. They moreover show that the acceleration spectra are almost like fingerprints, i.e. they are individual. This conclusion has also been made by Li et al (1991) who recorded walking sounds that were used for listening tests on identification of the walker's gender.

Auditory-vibrational cross-modal effects are likely to be significant both since the physical mechanisms for sound and vibration generation are similar and since the auditory and somatosensory perceptual systems have certain commonalities. For example, an established finding is that low frequency sound can be detected by both somatosensory and auditory systems. Recent evidence also shows that vibrations of higher frequency (200 Hz was used in this investigation) can elicit responses in the auditory cortex and hence also a sensation of hearing something when only being exposed to vibrations (Caetano & Jousmaki, 2006). There are however scholars are sceptical about the claim that there is a causal connection between such brain activation and actual auditory percepts (Yarrow et al., 2008). It is believed that the “synaesthetic” auditory sensation that is generated is in fact a result of response bias or at least some process that is not purely perceptual, which is also indicated by the experiment performed by Yarrow et al. (2008).

Nonetheless, studies on community noise have shown that concurrent sound and vibrations could increase the annoyance of the noise as compared to when there are no or very subtle vibrations present (Öhrström & Skånberg, 2006, Öhrström & Skånberg 1995).

In a controlled lab experiment, Howart & Griffins (1991) studied the annoyance of train noise and vibrations in combination. It was found that high levels of noise combined with low-level vibrations diminished the annoyance of the vibration. That is, there seems to be some sort of partial masking of the vibration perception when combined with high noise levels. On the other hand, for high vibration levels, the annoyance from vibrations was increased when noise was added. It is unclear to the authors however whether these effects represent some true cross-modal effects or if they are merely a result of response bias. In general it seems more fruitful to let subjects assess the response of the total stimuli combination when several sensory modalities are involved rather than rating them independently – which is also pointed out by Howart & Griffins (1991). It is nonetheless clear that abatement methods need to address both noise and vibration to similar extent. For example, if noise is reduced to great extent while vibrations remain, people will more clearly notice the vibrations and still get annoyed (Paulsen & Kastka, 1995, Västfjäll, 2008).

Besides the auditory-vibrational level balance, it is reasonable to assume that there is also a relationship between difference in the arrival time of the auditory and vibrotactile stimuli and the perceived annoyance, loudness or similar attributes. Structure borne and airborne noise may indeed have different arrival due to different propagation speeds. An investigation by Martens & Woszczyk (2005) on multimodal displays revealed that the perceived powerfulness increased, when the structure-borne component of the displayed impact event arrived 10 to 20 ms later than the airborne component. Moreover, there is also evidence that the auditory localization process may be altered by adding vibrations (in a similar way as in the auditory-visual ventriloquist effect, see above). For example, Tajadura et al. (2009) conducted an experiment where participants were exposed to sound beeps coming from the front or from the rear that were combined with either synchronous or asynchronous whole-body vibrations. It was concluded from this study that when the synchronous vibrations were present, sound was to greater extent perceived as coming from the centre of the participants head or from the rear – i.e. a shift in auditory localization towards the origin of the vibrations. Similar effects have been found for lateral stimuli as well (Caclin et al., 2002) and it was noted here that the effect occurs predominately when sound localization cues are ambiguous. In the case of footfall noise this might mean that since low IACC (poor localizability) has been shown to increase annoyance (Jeon et al., 2009) when the footsteps are less localizable due to low IACC, concurrent vibrations may aid localization and thus reduce annoyance. It seems reasonable to assume however, that it is not localizability per se which reduces annoyance, but also to where the sound is localized (cf e.g. Tajadura et al., 2010). As whole-body vibrations may result in that the sound is localized as being closer to the listener, it may be that it is perceived more threatening and hence also more annoying.

From this discussion one may conclude that earlier studies of joint auditory-vibrotactile annoyance indicate that both noise and vibrations may be a cause of annoyance. There also seems to be a cross-modal link between audition and the tactile sense which may cause either synergistic, dominance or antagonistic effects. Whether these effects are a result of a bona fide perceptual cross-modal integration, a higher-level cognitive process or simply a response bias is not entirely clear, and it can be noted that this has been a matter of discussion also in investigations of cross-modal effects between other modalities (Bertelson & de Gelder, 2004). The methodologies employed when investigating auditory-vibrotactile effects of footfall should naturally also take required measures to avoid potential response biases. In case of high-level low frequency sound and vibrations, which is typical for lightweight building constructions, the effect is however most likely a “truly” perceptual effect since low frequency vibrations are proven to excite both the auditory and tactile sensory systems. There might also be an indirect effect of vibrations; in that the vibrations induced in the underlying room cause audible rattling in furniture and other objects inside the dwelling (Öhrström & Skånberg 2006, Findreis & Peters, 2004)). According to Findreis & Peters (2004), such effects occur only for vibration frequencies below 20 Hz – which however indicates that the effect should be significant in lightweight floor structures since these may have resonant properties around and even below 20 Hz.

2.3 SUGGESTED METHOD FOR LISTENING TESTS

2.3.1 Survey methodics

There are a number of different techniques to consider when designing listening test. Within classic psychophysics research the aim is usually to obtain a psychometric function such as the one presented in Figure 3.1 (Poulsen, 1987), showing at what magnitude a certain stimulus parameter becomes perceivable or possible to discriminate from a reference stimulus. In this example, level versus audibility is shown, but other dose-response combinations could be the topic of investigation as well. A level of 50% is in this example set as the threshold for detection, meaning that it is equally possible to get a positive as a negative response at this level.

Different methods may be employed to measure the psychometric function but in general it involves varying the stimulus parameter up/down in a number of steps and asking the subject to respond whether or not he/she can detect or discriminate the stimulus. One of the classical methods is the staircase procedure, which was introduced in 1960 by Bekesy. If we consider the example of measuring the hearing threshold (which was Bekesy's application), the sound starts at an audible level and gets quieter after each of the subject's responses, until the subject does not report hearing it. The amplitude of the sound is then increased stepwise, until the subject reports hearing it, at which point it is made quieter in steps again. In this way the method "zeroes in" on the threshold.

Instead of being presented in ascending or descending order, the stimulus variations can be presented in a random order, which is usually referred to as the method of constant stimuli. Since the levels of a certain property of the stimulus are not related from one trial to the next, this prevents the subject from being able to predict the level of the next stimulus, which reduces errors of habituation and expectation. Although this method allows for full measurement of the psychometric function, it can result in a lot of trials when several conditions are interleaved.

Yet another method is the method of adjustment where subject is asked to adjust the level of the stimulus property, until it is just barely detectable or is the same as the level of a reference stimulus. The difference between the variable stimulus and the reference stimulus is recorded after each adjustment. The advantage of this method is that it is fast and simple but may suffer from the overadjustment effect – that subjects tend to set the variable level to high in a balance test (Poulsen 1987).

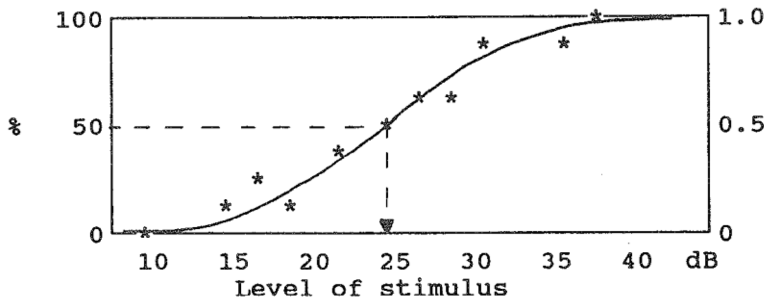

Figure 2.8: Example of a psychometric function obtained from a up/down experiment on level vs audibility. (from Poulsen, 1987)

More refined “up/down” methods have also been developed, such as the Parameter Estimation by Sequential Testing (PEST), which aims at improving the statistical power and reducing the number of unnecessary trials. Although these methods are essential for detecting thresholds and in general measuring psychometric functions of various stimulus aspects, they are not appropriate when exploring the perceptual dimensions underlying a group of stimuli.

The semantic differential technique is a commonly used method where subjects give their ratings on a number of adjective scales that are believed to cover the various perceptual dimensions. Example adjectives that have been used in evaluation of audio equipment are Clarity (unclear – clear), Spaciousness (closed – spacious) and Brightness (dull-bright) (Gabrielsson, 1987). The twelve semantic differential scales used by Lee (2010) to characterize the subjective perception of footfall-like impulse noise are presented below:

- Dry- Reverberant
- Vacant- Full
- Dwarfish – Grand
- Narrow – Wide
- Sharp – Dull
- Light – Heavy
- Thin – Thick
- Shallow – Deep
- Weak – Strong
- Quiet – Loud
- Calm – Roaring
- Tenuous – Full-toned

By means of e.g. factor analysis, principal components analysis or cluster analysis, the subjects’ response data may be grouped so that the underlying main dimensions or categories of perception can be derived. In the example scales from Lee (2010) above, the first four scales were categorized as describing spaciousness, the middle four described “dullness” and the last four as describing “loudness”.

The drawback of this method is that since it is the experiment designer who selects the adjectives, which are the basis for the test, there is a risk that the subjects in the test overlook some adjectives while others are not even perceivable. Moreover, there is a risk that the experiment designer uses overly technical jargon in the adjective selection and definition that is not clearly understandable to subjects. Also, in cases where there is a need for scales in different languages, special attention must be paid to ensuring that the selected adjectives and their translations have the same meaning.

Another common method is the paired comparison. In this case, all possible stimulus combinations are presented to the participant who rates the difference or similarity between the stimuli pairs. In comparison to the semantic differential method, the advantage of the paired-comparison method is that it avoids the problem of imposing a set of predefined attributes on the judgment. The drawback of this method (when used alone) is that while the results show how the different stimuli group / map onto different dimensions, it is up to the experiment designer to interpret what the dimensions mean. Another drawback is that the number of trials may become very large if there are a large number of stimuli.

The multidimensional unfolding approach (MDU) is not a method in its own but rather a collection of experiment and analysis methods (including the ones presented above) aiming at providing a better understanding of the perceptual space for a set of sounds and showing how perceptual character and preference relate to each other. Within product sound quality it has been used to connect the physical properties of sound with the sensory ratings as well as the preference of these (Sköld, 2008). The course of the MDU method is subdivided into four steps as follows:

1. Semantic scale evaluation. This step is performed in a similar manner as described above. Special attention needs to be directed to ensuring that the scales used are appropriate for the sound set.

2. Multi-Dimensional Scaling (MDS). In this step, an expert panel evaluates the difference between the stimuli in a paired-comparison design (again, as described above). The analysis will show how the different sounds map on to the perceptual space.

3. Preference mapping. Here a group of target customers rates their preference for the different sounds by means of, for example, a two alternative forced choice test (2AFC).

4. Synthesis of results. The results from step 1 and 3 are here connected to the results of step two by means of regression analysis. Traditional (or new) psychoacoustics metrics can also be included in this step if they provide relevant information. The step 1 results will help identifying the perceptual dimensions underlying the sound set (i.e. what they mean) and the results from step 3 show which of the dimensions are important for preference.

While the MDU may be helpful in providing a complete understanding of a group of sounds, it may still be difficult to carry out step 1 above without performing a series of pre-tests to assess the validity of the adjective scales. The repertory grid technique (Rumsey & Berg, 2006) may be a solution to this issue however. In this technique, stimuli are presented in pairs or triads and subjects are asked to freely describe, using their own words, how the sounds differ from each other, or how two stimuli are similar and different from the third. A grid is then constructed upon which subjects rate each of the stimuli according to each of the adjectives identified in the previous phase.

An important distinction to make, which is clearly dealt with in the MDU, is whether the experiment deals with evaluation of sound or the reaction to sound (Västfjäll, 2004). By evaluation is meant the case when the sound itself is the object of the rating, for example by asking participants if they think that the sound is sharp or dull, loud or quiet. Reaction on the other hand assesses the listener's response to and preference for the sound, that is, if they think the sound is annoying, makes them feel pleasant and so forth. Traditional sound quality research often fails to make this distinction even if evaluation and reaction may be completely different both in terms of determinants and effects. In our case, both evaluation and reaction should be considered, but it is important to distinguish between them in an experimental situation since reaction is to great extent connected to the interpreter and his/her expectations, mood and prior exposure to similar stimuli.

2.3.2 Annoyance or emotional reactions

We have up until now presumed that annoyance is the main metric to assess reaction. An alternative to this would be to instead measure subjects' affective (emotional) reactions to sound. This approach has proven to be successful in a number of recent studies using acoustic stimuli (Västfjäll, 2004, Sköld, 2008, Tajadura et al., 2010). One fundamental reason why emotions should be considered is that they are central in our everyday life and inform us about our relationship to the surrounding environment. Moreover, within emotion psychology there is a large number of instruments for measuring emotion which can give a more nuanced understanding of human reaction than simple annoyance measures. An example of a self-report measure that have been developed within emotion psychology and proven useful also for auditory stimuli is the Self Assessment Manikin scale (Bradley & Lang, 1994, shown in Figure 2.9 below). Interesting to note however, is that also physiological measures (such as galvanic skin response and facial muscle activity) and behaviourally related measures (such as reaction time) can be used to assess emotional reactions which avoids the problems with self-assessment its possible cognitive influence.

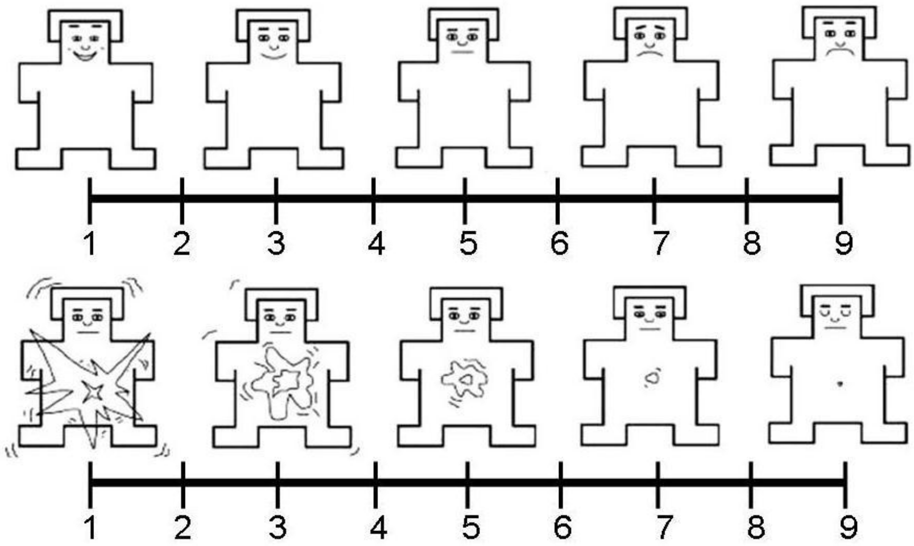

Figure 2.9: The self assessment manikin (SAM) scales (Bradley & Lang, 1994). The top scale measures the "Valence" dimension (positive-negative) while the bottom scale measures activation or arousal (high activation – low activation)

2.3.3 Presentation of stimuli to subjects

In most psychoacoustic studies headphones are used to present the stimuli. The stimuli could be either monaural, stereophonic or binaural. Binaural stimuli are often used to make the stimuli more enveloping and life-like, and it can also be used for localizing acoustic sources. Binaural hearing relies on high-quality recordings made in correct situations, since the recordings always will include the room acoustics of the recording (= receiving) room. This presents a problem to find different recording rooms that will have sufficiently equal room acoustics so that the room acoustics itself does not influence the listening test.

3. Design of listening tests

The listening tests found in the literature have been performed using headphones or loudspeakers. Tests relying on the binaural hearing system have predominantly used headphones. Even though no direct studies on localization of low-frequency sounds have been found in the literature it is reasonable to assume that the directional cues are weaker for low frequencies due to smaller inter-aural amplitude and phase differences. A limited listening test performed by the author on a small group of trained listeners showed that footstep sounds with a spectrum as in Figure 2.2 are easily localized. In the test, sounds were played from different directions.

1. Directly in front of the listener
2. One speaker from the left and one from the right
3. Directly above the subjects' head

The sounds played directly above were judged as most annoying. This indicates that the perceived localization is important with respect to annoyance.

To use headphones in the forthcoming listening tests, which focus on low-frequency sounds, may not give accurate results. In anechoic conditions in the test room cross filters can be used to allow for binaural loudspeaker stimuli, but that method is also sensitive due to the same reasons.

A more robust design would be to use stimuli that are physically radiated from above the subject. Using this design the sensitivity towards the test room's inherent room acoustics should be smaller. Either the radiation could be realized by inserting vibrations in the ceiling, but it can be cumbersome to accurately control the radiated sound power. A simpler method would be to use hidden loudspeakers mounted in the ceiling. A moving walker could then be realized by using an array of loudspeakers mounted along the walker's path. The signal fed to the loudspeaker array would then be based on vibration signals instead of pressure signals, i.e. it should be recorded using accelerometers instead of microphones. Accelerometer recordings are preferable in this context since they avoid room acoustics effects in the recording room, which reduces the acoustic requirements of the recording room.

We therefore propose to record the vibrations of the ceiling due to a live walker on the floor above. Multiple accelerometers are mounted in a line directly below the walker. The sound pressure level is simultaneously recorded in the receiving room to ensure that the stimuli are replayed at a realistic level and with a correct spectrum. The recorded vibrations will then be presented to the subject by hidden loudspeakers hanging in the ceiling in the same positions as the accelerometers were mounted.

3.1. RECORDING METHOD

The largest common rectangle (without hindering furniture) in the sending and the receiving room is marked on the floor and in the ceiling respectively. All walking takes place along this rectangle's diagonal. Four accelerometers are mounted in the receiving room's ceiling along the diagonal, with 600 mm distance in between (see Figure 3.1 for the setup). The signals from all accelerometers are recorded simultaneously, both when a person is walking without shoes and for a reproducible source (impact ball or tapping machine). The airborne sound is recorded binaurally to estimate the common sound quality metrics.

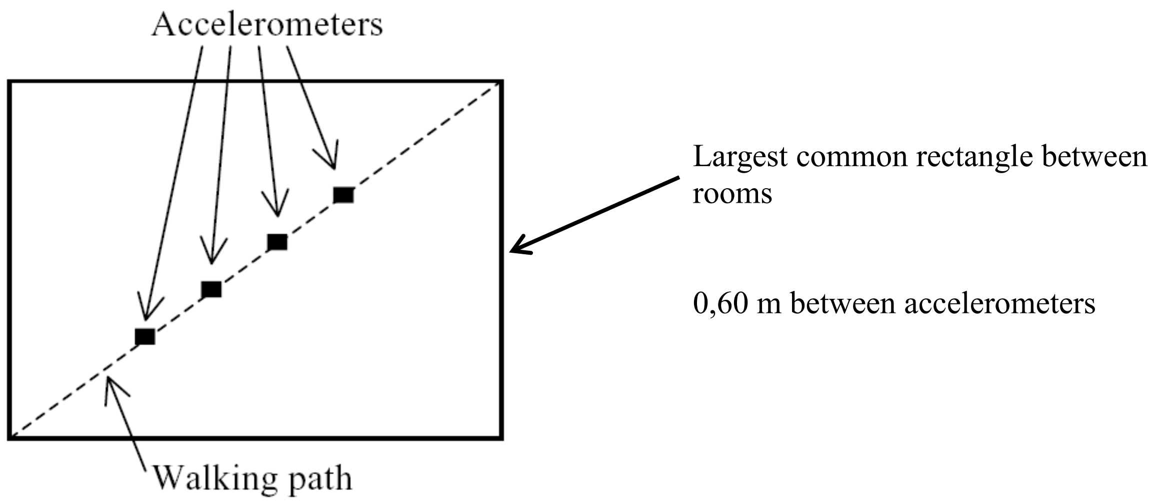

Figure 3.1: Recording positions and walking path.

An important aspect considering the chosen recording method is if the recordings really can be used together with loudspeakers as described in the next section. Theoretically it should work if the ceiling vibrations are dominated by its normal direction, but this has been tested for the chosen measurement locations (see section 3.3).

3.2. REPRODUCTION METHOD

According to Figure 2 it seems sufficient to reproduce frequencies from 16 Hz, but this hypothesis has been tested on several other lightweight floor constructions as well (see Figure 3.2). From the results in that figure it is clear that using a low frequency limit of 16 Hz would not limit the listening test results.

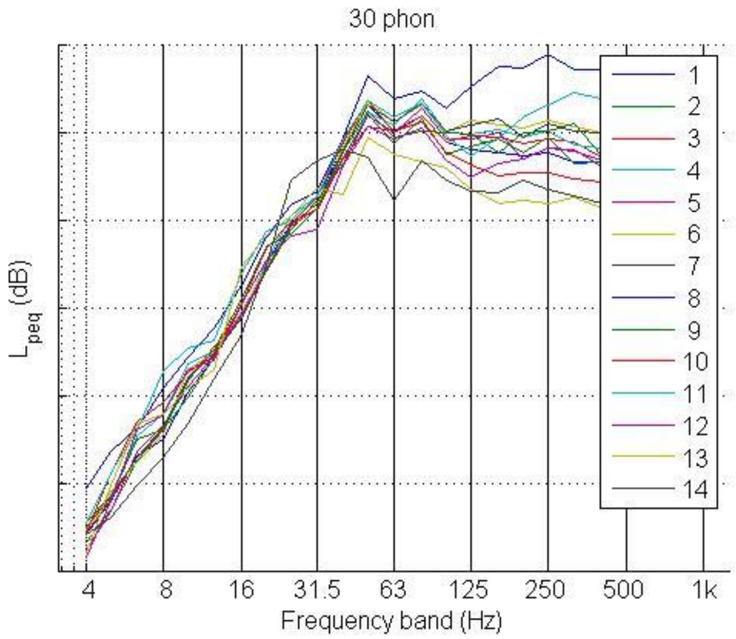

Figure 3.2: Spectrum shapes for recordings of a walking male (the author) on 14 different lightweight floors. The spectras are weighted with the 33.5 phon curve in Figure 2.3. The level difference between two horizontal dotted lines is 20 dB.

The reproduction system consists of four full-range speakers (Genelec 8030A), which are mounted in the listening room's ceiling in the same configuration as the accelerometers. These speakers are hidden behind a suspended ceiling made of 15 mm mineral wool of relatively low density, which means that the sound reduction index of the ceiling is very small at the frequencies of interest in these listening tests (f < 1 kHz). The full-range speakers have a low frequency limit around 60 Hz; so two subwoofers reproduce the low frequency range, 16 - 80 Hz. Two Sunfire True Subwoofer EQ12 Signature, which according to the producer have their low frequency limit (-3 dB) at 16 Hz. The low frequency limit was not explicitly tested, but level calibration of the reproduction system was made in the listening rooms down to 20 Hz. The reproduction setup is shown in Figure 3.3.

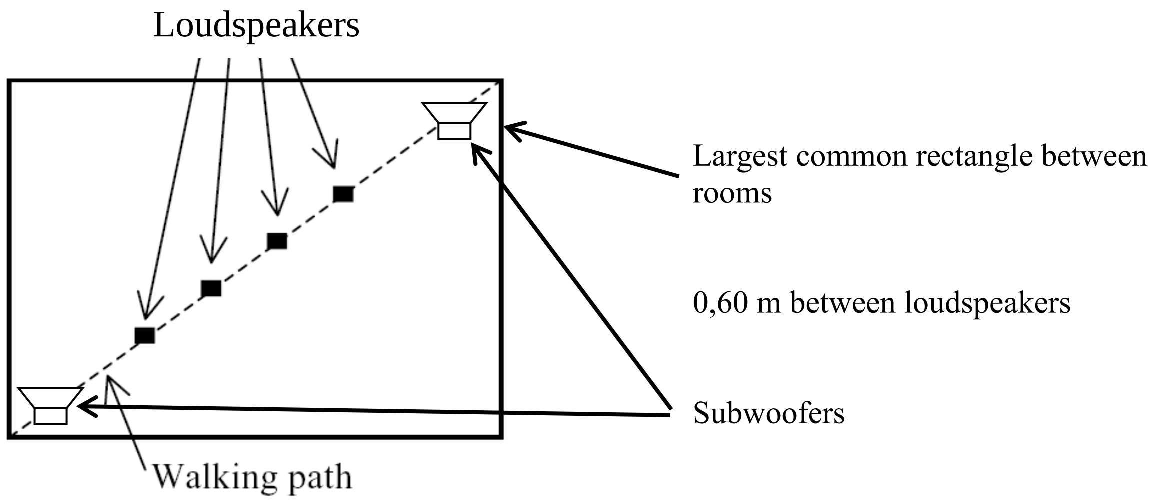

Figure 3.3: Setup of system in the listening room.

The listening room can be any normal room that has "regular" room acoustics, i.e. no strong resonances in the low-frequency region and a reverberation time close to the reference case (T_{60} = 0.5 s) in ISO 140-7. The subwoofers can compensate for the room strength and the level balance between ceiling loudspeakers and subwoofers is adjusted using the sound pressure recordings as reference. It is moreover important to use listening rooms with no strong room modes.

3.3 CHOICE OF RECORDING LOCATIONS

Test recordings using the method described in section 3.1 has been made prior to recording the actual data used in the listening tests. The recording locations used for the listening test was the following:

- Lightweight floor: Separating floor between bedrooms in BoKlok houses in Alingsås. This particular house was included in the AkuLite precision measurements; see (Ljunggren, 2013). The floor was measured to have a good airborne sound reduction but an impact sound insulation which was just outside the national requirements ($L'_{n,w} + C_{I,50\text{-}2500}$ = 57 dB). See the above reference for more information.
- Heavyweight floor: Solid concrete floor in the library at the Division of Applied Acoustics, Chalmers. According to the construction drawings this floor is made of 200 mm solid concrete. To simulate a separating floor between dwellings it was retrofitted

with a 15 mm parquet floor on 3 mm elastic underlay. The floor was then measured according to SS-EN ISO 140-7 to $L'_{n,w} + C_{I,50\text{-}2500}$ = 56 dB, which is within 1 dB from the result for the lightweight floor.

From a practical standpoint considering the Swedish national requirements on impact sound insulation, these two floors would be almost identical.

As was mentioned in section 3.1 it is necessary that the accelerations in the ceiling's normal direction is dominating in order for the listening test setup to work. Measurements of the normal and in-plane vibrations have been performed for both floors and the results are shown in Figure 3.4. In that figure it is evident that the acceleration in both floors are dominated by the normal direction. The difference between the acceleration in the normal direction and the in-plane directions match the used accelerometers transverse sensitivity. This means that the actual in-plane accelerations may be even lower. Note also in the figure the level difference between the lightweight and the heavyweight floor.

Similar measurements were also done for other vibration sources such as a tapping machine, dropping small wooden blocks and pulling chairs. The conclusion from all measurements was the same; the acceleration in the ceiling was dominated by the ceiling's normal direction irrespective of excitation source.

The recorded accelerations and sound pressure levels from these two locations are used as base recordings in the listening tests. Only recordings from the male walker (the author) were used in the listening tests. These base recordings are then filtered to test aspects of low frequency hearing as is described in section 3.6.

3.4 CHOICE OF LISTENING ROOMS

An important aspect in these listening tests is the interpreter, the listener, and his/her expectations (cf Figure 2.1 and its corresponding text). Since the AkuLite project has limited itself to dwellings it is important that the listener sits in a familiar situation during the listening test. The listening room should therefore not be a specialized laboratory room but instead a more familiar room. Moreover, since the hearing system's sensitivity is dynamic the background noise level should fulfil the national requirements for living rooms in dwellings (L_{eq} = 30 dBA and 50 dBC), but should not have lower levels.

From these assumptions the choice of listening room have been a normal office room of roughly the same size as a small bedroom. Due to practical reasons the listening tests were run in two sets, and different listening rooms were used in the sets. Both listening rooms were evaluated concerning reverberation time, diffusivity, room modes and background noise level. Both rooms were office rooms that were in use, and not particularly well isolated regarding sounds from outside of the office. This may however not a drawback, a hypothesis is here made that this could be an advantage, because then the "artificial" sounds that are included in the listening tests were blended in the surrounding acoustic environment which actually increased the perceived realism. The background to this hypothesis is the hearing system's dynamic gain, which can bias the listening test results in a very silent background.

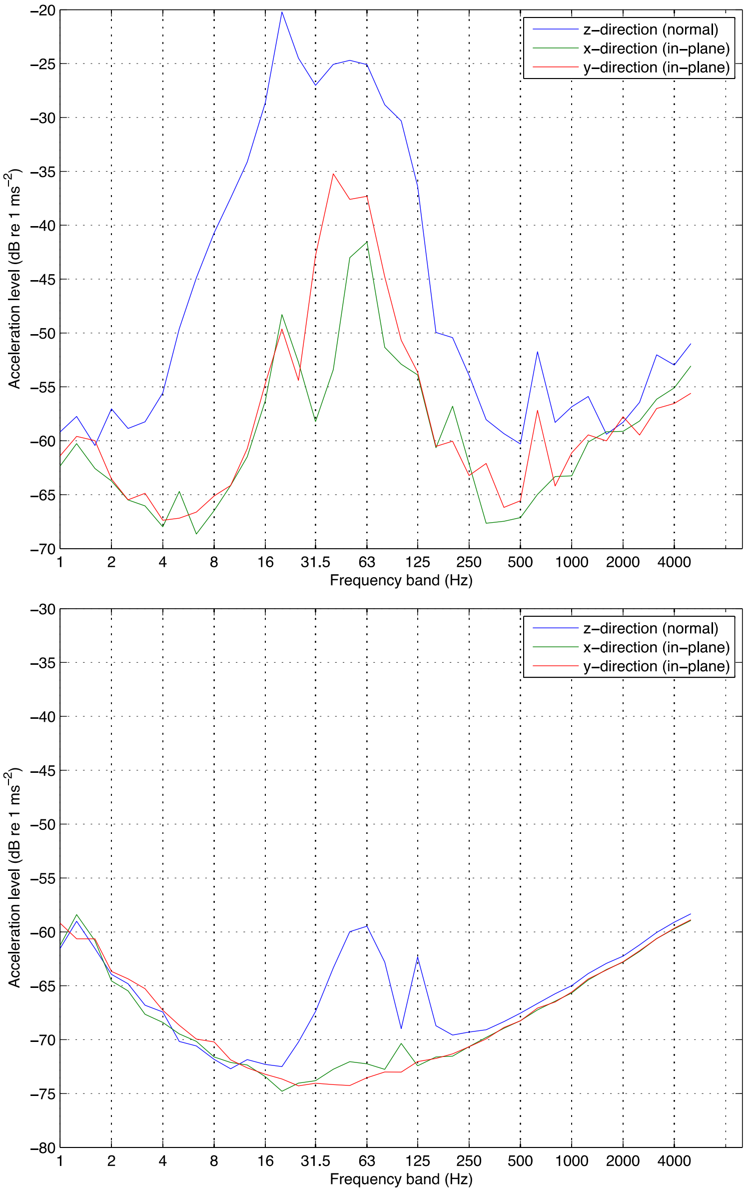

Figure 3.4: Accelerations in the normal and in-plane directions for the same female walker on the test floors. Top figure: lightweight floor, bottom figure: heavyweight floor.

3.4.1 Listening room 1: Akustikverkstan, Lidköping

This room is 4.20 x 3.00 x 2.50 m in size, all walls made of lightweight construction (2 layers of normal 12.5 mm gypsum board with sound absorbing material behind) and some glass walls. Base constructions in floor and ceiling are solid concrete; the floor was covered with 14 mm parquet on elastic interlayer. The ceiling was covered with 15 mm sound absorbing tiles made of mineral wool and with 400 mm air gap behind. The reverberation time was measured to around 0.9 s at low frequencies (20 - 63 Hz), and then decreasing to 0.2 s at high frequencies (3-5 kHz). The background noise level was dominated by ventilation noise with an equivalent level of 31 dB(A) and 48 dB(C).

3.4.2 Listening room 2: Applied Acoustics, Chalmers, Göteborg

This room is 3.80 x 2.90 x 2.50 m in size, all walls made of lightweight construction (single layer of normal 12.5 mm gypsum board with sound absorbing material behind) and large windows in one wall. Base construction in floor is solid concrete; the floor was covered with linoleum carpet. The ceiling was covered with 15 mm sound absorbing tiles made of mineral wool and with between 200 and 700 mm air gap behind. The base construction of the ceiling was corrugated steel sheets. The reverberation time was measured to around 0.7 s at low frequencies (20 - 63 Hz), and then decreasing to 0.2 s at high frequencies (3-5 kHz). The background noise level was dominated by ventilation noise with an equivalent level of 32 dB(A) and 47 dB(C).

3.5 LISTENING TEST SETUP

The choice of listening test setup is a direct A/B active comparison scheme, i.e. the listener can listen to sound stimuli A and B as many times as he/she wishes. The listener can change the strength of stimulus B with the objective to make stimuli A and B equal. In listening test set 1 the objective was to make stimuli A and B equally annoying and in set 2 the objective was to make stimuli A and B equally loud. This distinction was made in order to study if the listener's perception of the question resulted in different subjective results.

The listening test was run from a standard laptop computer running Matlab. The 4-channel sound files were played from within Matlab through a multichannel soundcard (M-Audio Fast Track Ultra 8R), which was connected to the loudspeaker system. The listener interface is shown in Figure 3.5. Pressing buttons A or B plays sound file A or B respectively. The horizontal slider sets the amplification of sound file B, with -20 dB at its left limit and +20 dB at its right.

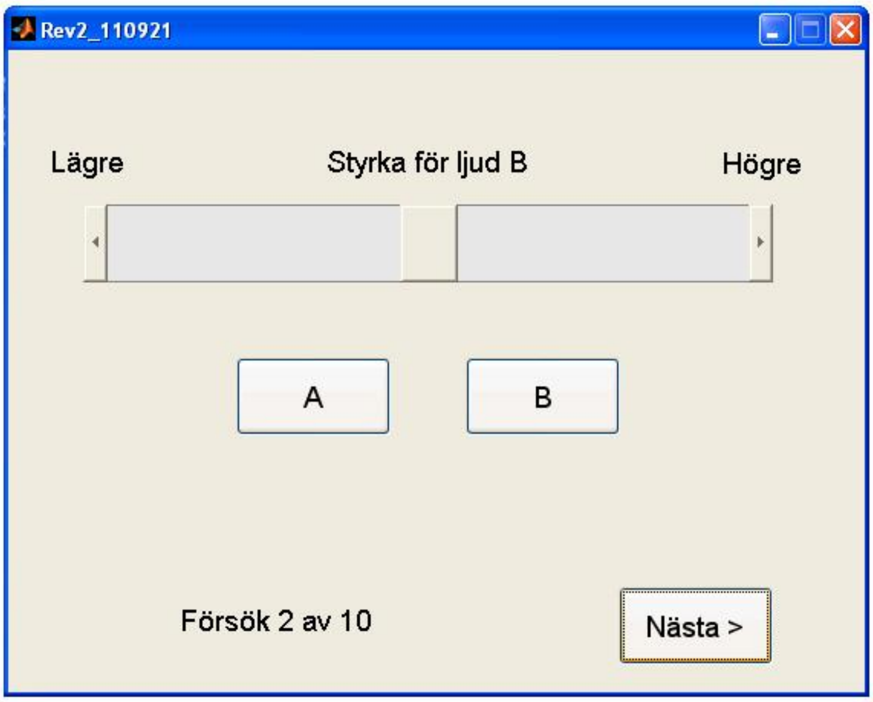

Figure 3.5: Listener user interface in the listening tests.

Both listening test sets used the same sound files and included 30 comparisons. The order of the comparisons was fully randomized. The data that is saved from each comparison is the amplification. The time to make the full test with 30 comparisons was between 5 and 45 minutes with a mean value of around 20 minutes.

3.6 DESCRIPTION OF SOUND FILES

The main aspects of low frequency hearing that is studied here is

- Frequency content
- Absolute level
- Structural reverberation time

To test this the recorded vibration files have been adjusted according to Table 3.1. No combinations of individual filters have been made, i.e. no files that have been modified in level and frequency content have been used. All filtering have been made in Matlab using Butterworth filters of second order.

The choice of 50 and 100 Hz high pass filters is made based on the frequency limits in the evaluation measures defined by ISO 717-2, i.e. $L_{n,w}$ and $L_{n,w} + C_{I,50\text{-}2500}$, and based on that the maximum values for the footstep on the lightweight floor is clearly below 50 Hz and the maximum values for the heavyweight floor is clearly below 100 Hz.

The adjustment of structural reverberation time has been made manually by inserting a exponentially decreasing window right after the initial impulse of the step. An exponentially increasing window was introduced after the decreasing windows end to avoid perceived “clicks”.

Floor	Level adjustment	High pass filter	Structural RT
Lightweight	-5, 0, +5 dB	None, 50 Hz, 100 Hz	As is, halved RT
Heavyweight	-5, 0, +5, +10 dB	None, 50 Hz, 100 Hz	As is, halved RT

Table 3.1: Signal modifications used in the listening tests.

The original signals for both the lightweight and the heavyweight floor were reproduced at twice the speed to get a wider parameter variation. This was done to simulate hypothetic floor constructions that have the same spectrum shape, but translated one octave higher. Silent portions were manually introduced between the individual steps to maintain the same footstep rate.

The differences in acceleration levels between footsteps on the lightweight and the heavyweight floors were also used to test to what extent it is possible to modify a recorded signal into another floor. The sound file for the lightweight floor was thus filtered using these level differences into an estimate of the heavyweight floor and vice versa. This filtering was made using second-order Butterworth band pass filters.

Figure 3.6 shows equivalent frequency spectra for all individual signals that were used in the tests.

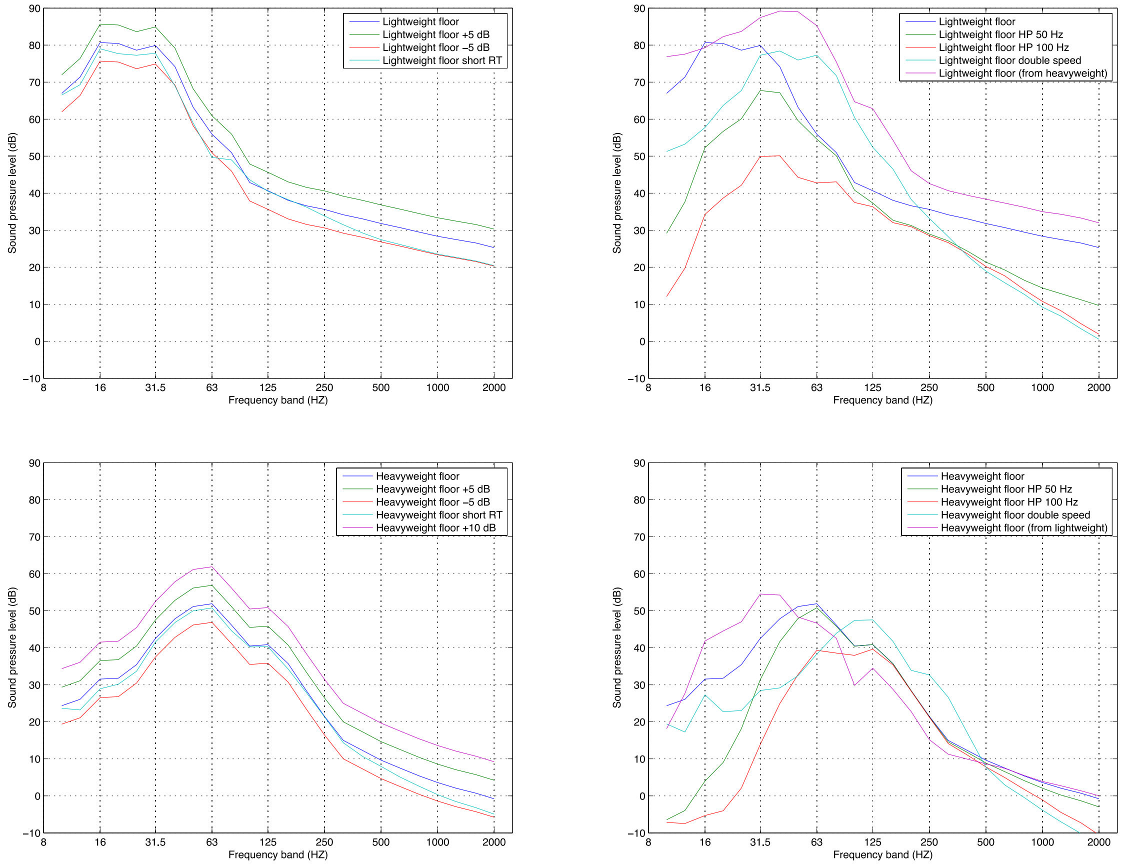

Figure 3.6: Equivalent level spectra for all signals used in the listening tests.

4. Listening test results

In total 60 listening tests were performed, 26 in the first set and 34 in the second. The difference between the sets was, as explained in section 3.5, that the assignment was ”equally annoying” in the first set and ”equally loud” in the second. However, only very small differences were found between the sets, and the differences were not statistically significant. Thus all 60 answers have in the following evaluation been treated as one group. No significant differences for the first or for the last comparisons were seen during the evaluation, i.e. no effects due to training or tiredness could be seen. Thus all comparisons for all subjects is used in the evaluations. Single mistakes by a few subjects are suspected but no special effort has been made to remove these.

4.1 STATISTIC EVALUATION OF COMPARISONS

In this section each comparison is evaluated statistically regarding the subjects' chosen amplifications. Figure 4.1 shows an overview of the statistical results for all comparisons. The first sound given in each row is the A-sound (constant level) and the second is the B-sound (amplifiable by the subject). In the figure, the vertical line is the median value, the edges of the box shows the 25th and 75th percentiles and the whiskers extend to the outmost data points not considered as outliers (outliers are marked with ”+”). Data points that are outside the 99.3 % confidence interval for a normal distribution are identified as outliers.

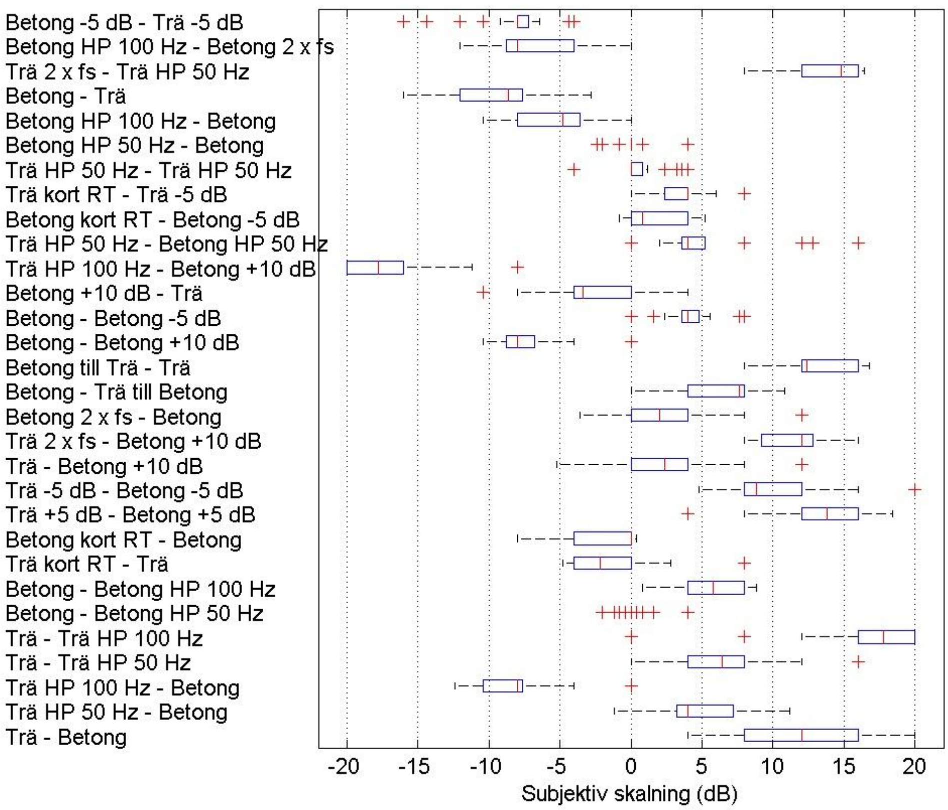

Figure 4.1: Statistical evaluation for all comparisons.

From the results in figure 4.1 it is clear that many subjects used the full amplification scale during the listening tests. A need for a larger dynamic range was only visible for comparisons including the Lightweight HP 100 Hz sounds. This sound was however the subjectively most silent sound in the tests.

From the results in Figure 4.1 it is clear that the Lightweight sound is subjectively perceived as louder (or more annoying) than if it is high pass filtered at 50 Hz, see e.g. comparison four from the bottom, where the Lightweight HP 50 Hz sound should be amplified by 7 dB to be perceived as equally loud for the median subject. For the heavyweight floor there is no similar difference, see comparison six from the bottom. Thus, the content below 50 Hz is important for the subjectively perceived loudness of footstep sounds. The qualitatively reason behind the different behaviour of the Lightweight and Heavyweight sounds is the different frequency content, which can be seem in Figure 3.6, where the Lightweight HP 50 Hz sound is considerably different than the unfiltered Lightweight sound while the difference between the Heavyweight sounds are small. In other words, The Heavyweight sound has no significant content below 50 Hz from a subjective point of view. When the Heavyweight sound is compared with the Heavyweight HP 100 Hz sound (comparison seven from the bottom), a similar difference can be seen.

Moreover, the influence of the structural reverberation time seems to be small. The median value for the lightweight floor is 2.5 dB while it is 0 dB for the heavyweight floor. This difference is almost fully accounted for the difference in level, which are 2 dB for the lightweight floor and 1 dB for the heavyweight. Thus the subjective perception of footstep sounds seems dependent on the sound's level and not its reverberation. The effect of an increased level due to long reverberation times does however still remain.

As can be seen in Figure 4.1, some comparisons are made first forward and then backward. This is intentional to create different starting levels, i.e. to use A-sounds with different levels. Since the loudness contours, i.e. from ISO 226, are compressed for low frequencies comparisons using A-B and then B-A should not give equal median values. This is clearly visible in Figure 4.1, comparisons 1 and 27 (fourth from the top) (Lightweight-Heavyweight) that use the same files cross-wise. The median value for comparison 1 (Lightweight-Heavyweight) is 12 dB, while the median value for comparison 27 (Heavyweight-Lightweight) is -8 dB. This difference is qualitatively explained by the sound level for the Heavyweight sound is considerably lower than Lightweight sound, together with that the Lightweight sound has its strongest frequency content at lower frequencies than the Heavyweight sound. All other comparisons that are made cross-wise, or which uses an amplified or damped A-sound, give the same conclusion.

4.2 LOUDNESS CONTOURS

There have been many tests with the aim of defining loudness contours, or isophon lines, due to single frequencies. In the latest version of ISO 226, dated 2003, a number of such tests are compared as a basis for the standard's chosen contours (ISO 226, 2003). These contours are shown on the left-hand side in Figure 4.2. The previous version of the standard (1985) shows different loudness contours, and these are shown in the right-hand side. The main difference is a different slope at lower frequencies where the 2005 version gives higher sound pressure levels at the same phon level.

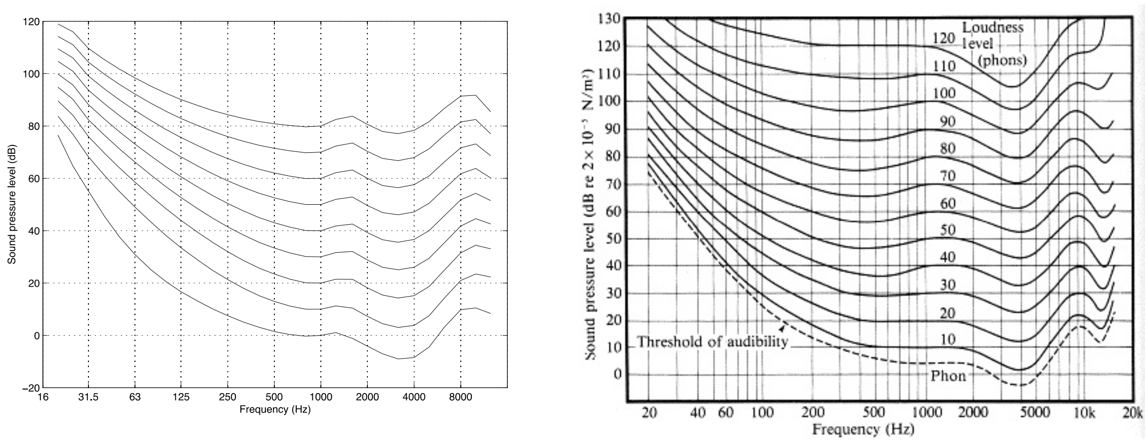

Figure 4.2: Loudness contours according to ISO 226:2003 (left) and ISO 226:1985 (right)

From the spectra in Figure 3.6 it is clear that more or less all sounds used in the listening tests show a clear peak at a particular frequency with a roll-off at both higher and lower frequencies. This is probably caused by the sound generation itself, i.e. it is an acoustic characteristic for the interaction between the striking foot and the floor, and thus it probably can be generalized to footsteps on most existing floor types. It is hardly a coincidence since the two floors used here are very dissimilar in construction.

Using this spectral characteristic it is possible to evaluate which third-octave band that includes the subjectively loudest part. Here this is done by comparing the recorded sound with a -6 dB/octave straight line, a line which has a similar shape to the isophon contours at low frequencies, though with a more shallow slope. Using this hypothesis, the third-octave band with maximum subjective level together with its corresponding level is shown for all sounds in table 4.1.

Sound	f_{max} (Hz)	L_{max} (dB)
Lightweight	31,5	80,0
Heavyweight	63	52,0
Lightweight HP 50 Hz	40	67,2
Lightweight HP 100 Hz	40	50,2
Heavyweight HP 50 Hz	63	50,9
Heavyweight HP 100 Hz	125	39,7
Lightweight short RT	31,5	77,9
Heavyweight short RT	63	50,9
Lightweight + 5 dB	31,5	85,0
Heavyweight + 5 dB	63	57,0
Lightweight - 5 dB	31,5	75,0
Heavyweight - 5dB	63	47,0
Heavyweight + 10 dB	63	62,0
Lightweight double speed	63	77,4
Heavyweight double speed	125	47,7
Heavyweight from Lightweight	40	54,3
Lightweight from heavyweight	50	89,1

Table 4.1: Evaluated maximum subjective levels and corresponding third-octave bands.

Using the values in table 4.1 and the slider values from the listening tests it is now possible to draw lines between the A and B sounds in each comparison in the listening test. In figure 4.3 this is done for the median values. Each circle marks either an A or a B sound, and the line in between shows which sounds are compared in the listening tests. The level of the B-sound is modified with the median value of the slider level at that particular comparison. The loudness curves defined by ISO 226:2003 is plotted in the figure for reference. The comparisons thus show the sensitivity to footstep sounds, as perceived in these listening tests.

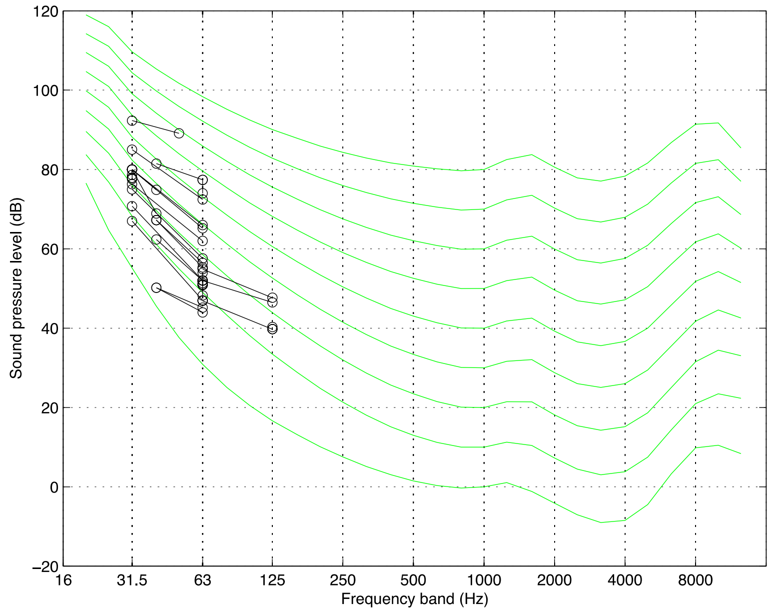

Figure 4.3: Median values for the listening test comparisons (see text for explanation).

Looking closely on Figure 4.3 this listening test has a shallower slope than the ISO 226:2003 isophon curves. When plotted on the 1985 version of the isophon curves the match is better. Thus, the ISO 226:1985 isophon curves matches this listening test better.

Using this method it is also possible to plot individual sensitivity curves, and this has been done in the evaluation process. Large individual differences have been seen and the question arises if some people are more sensitive than others towards low-frequency impulsive noise? To study this, the individual slopes for comparisons of sounds with maximum frequencies at 31.5 and 63 Hz, and 63 and 125 Hz were calculated. This choice was made on the number of comparisons that were included in the listening test. For the other slopes, only one comparison was included.

The individual slopes in these frequency ranges were plotted against each other to study if they are correlated, which can be used as an indicator on the individual sensitivity. The resulting poor correlation is shown in Figure 4.4 Thus the sensitivity in the two frequency regions 31.5 – 63 Hz and 63-125 Hz can be handled independently, at least in the context of this listening test.

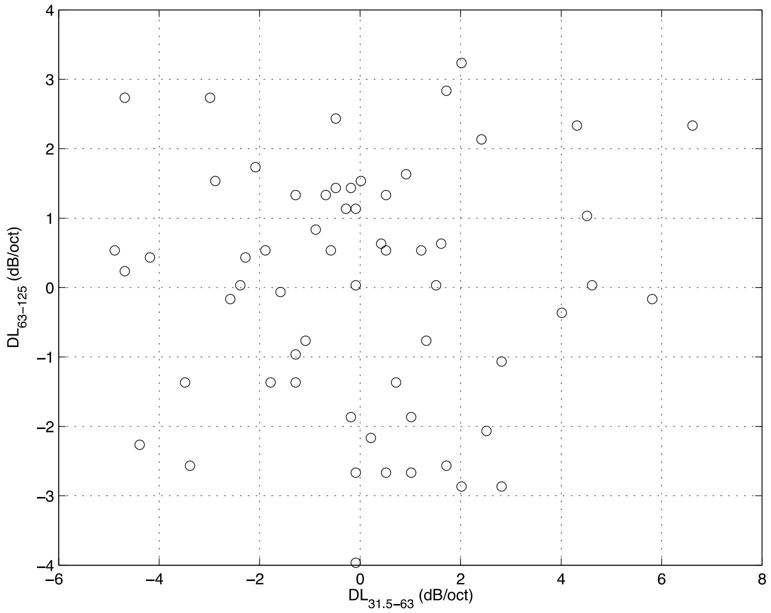

Figure 4.4: Correlation between individual slopes 31.5-63 Hz and 63-125 Hz.

Using the individual slopes it is now possible to estimate the distribution of the personal sensitivity levels at 31.5 Hz using a fixed sound level at 63 Hz. From the distribution it is possible to calculate percentiles, which could be used as additional information for interpreting the listening test results. Such distributions have been made for five starting levels at 63 Hz; 48, 53, 58, 63 and 68 dB. This corresponds the range that was covered by the listening test. For each level for the 63 Hz sound, the corresponding personal levels at 31.5 Hz was calculated and from the distribution the 10th, the 30th, the 50th (the median), the 70th and the 90th percentile was calculated. These values are shown in Table 4.2.

	48	53	58	63	68
10th	63,5	67,9	69,0	73,5	77,4
30th	65,1	69,0	71,1	76,1	80,6
50th	67,2	70,2	73,3	77,3	82,0
70th	68,1	72,0	74,7	78,9	83,7
90th	71,1	74,8	77,3	81,8	86,0

Table 4.2 Percentile levels at 31.5 Hz due to a fixed level at 63 Hz. All levels are in dB.

From the values in Table 4.2 the 10th percentile level is between 2.3 and 4.6 dB lower than the median level (the 50th percentile). This can be used to argue that measures that use a wide frequency band and that aim at restrict annoyance may need to be set some dB's on the safe side. For footstep sounds it seems as 3-4 dB lower than the isophon curve would be reasonable at 31.5 Hz. A similar distribution calculation was also made for the levels at 63 Hz due to a fixed level at 125 Hz. Alas, the range of starting levels was much smaller (41 – 47 dB), which results in less usability of the results. The 10th percentile level is in that case between 2.4 and 3.0 dB below the median level.

The conclusion from this calculation is that it seems as the difference between the 10^{th} percentile and the median level increases when the frequency gets lower. Additionally, the isophon curves are more compressed at lower frequencies, which further amplifies the differences. In the range of this listening test, the difference between two isophon curves spaced 10 phon apart varies from 5.5 dB between the 40 and 50 phon lines to 7.8 dB between the 10 and 20 phon line. At 31.5 Hz, a sound level difference of 4 dB corresponds to 7 phon around the 40 phon line, and around 5 phon around the 10 phon line. It must however be emphasized that this conclusion is based on a very limited material.

4.3 EVALUATION MEASURES FOR FOOTSTEP SOUNDS

It is very important to find a proper measure of the footstep sound level. Many suggestions have been made in the literature, but none has so far received international acceptance. Therefore the following measures have been tested towards the listening test:

- Sound Exposure Level (*SEL*)
- Equivalent level without frequency weighting (L_{eq})
- Equivalent level with A-weighting (L_{Aeq})
- Equivalent level with C-weighting (L_{Ceq})
- Maximum level with time weighting Fast (L_{Fmax})
- Maximum A-weighted level with time weighting Fast (L_{AFmax})
- Maximum C-weighted level with time weighting Fast (L_{CFmax})
- Average maximum level with time weighting Fast (L_{FMmax})
- Average maximum A-weighted level with time weighting Fast (L_{AFMmax})
- Average maximum C-weighted level with time weighting Fast (L_{CFMmax})
- ISO 532B loudness level (L_N)
- Vos suggestion (Vos, see eq. 3)
- Loudness level for single tone according to ISO 226:2003 ($L_{N,2003}$)

The average maximum levels were calculated through evaluating the maximum level for each individual footstep in the sound file and then taking the arithmetic average.

All sounds have been evaluated for all measures suggested above. Then the difference between the respective measure has been calculated according to the comparison order. For a perfect measure this difference is exactly equal to the subjective scaling, and the difference between the measure difference and the subjective difference (the amplification scaling chosen by the subjects) is zero. None of the measures above is perfect, and the corresponding difference for all comparisons, using the average value for the amplification scale, is shown in Figure 4.5.

The measure that fits the subjective scaling best as a total is the measure where the RMS sum of all individual comparisons has the minimum value. The RMS sums for all measures are shown in Table 4.3. There it is very clear that all measures that use the A-weighting give lower RMS sum than the other. The only other measure that comes close is the suggestion by Vos, and this is not surprising since he included Howitzer gun sounds in his listening test, a sound that seems, by spectrum shape, similar to footsteps on lightweight floors. The lowest residual of all measures, i.e. the measure that fits the subjective data best is the A-weighted average maximum level. From a practical point of view it is also attractive to use the A-weighting since it is the most common measure used by standard sound level meters, i.e. it is a very common measure.

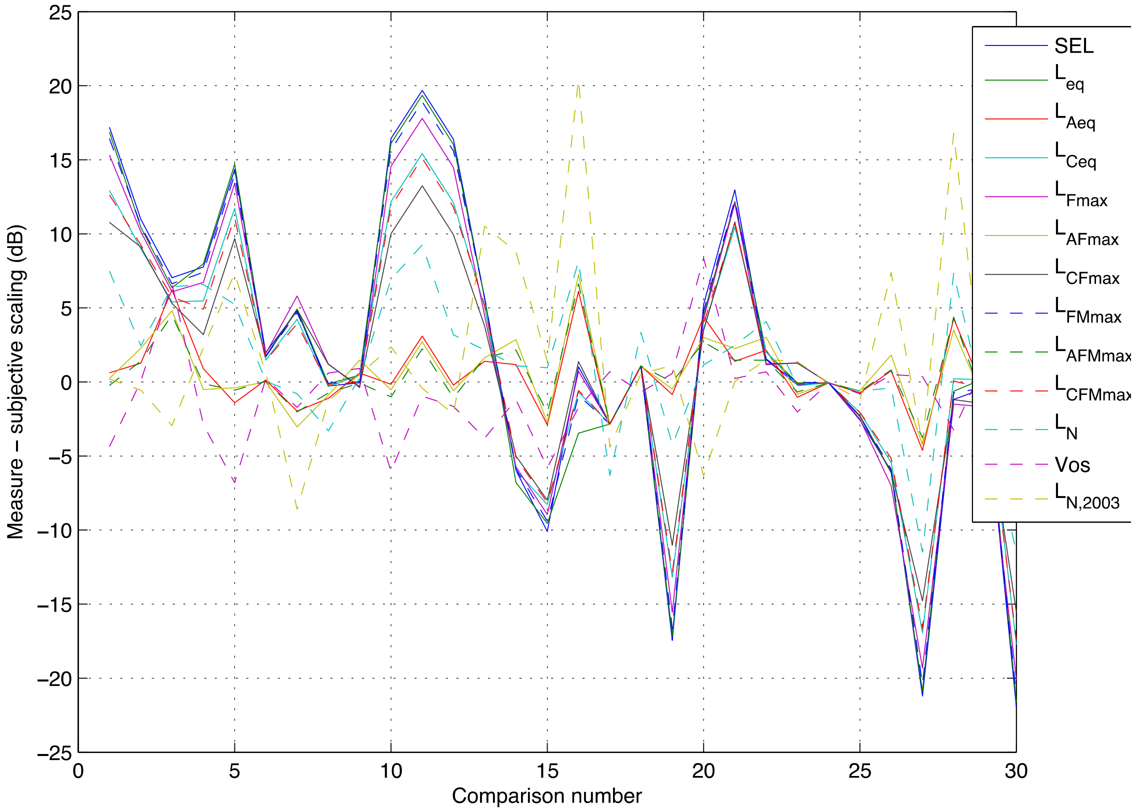

Figure 4.5: Residual plot of suggested evaluation measures.

Measure	RMS sum (dB)
SEL	335
L_{eq}	324
L_{Aeq}	21.5
L_{Ceq}	207
L_{Fmax}	277
L_{AFmax}	21.4
L_{CFmax}	161
L_{FMmax}	308
L_{AFMmax}	16.9
L_{CFMmax}	199
L_{N}	81.9
Vos	30.5
$L_{\mathrm{N,2003}}$	119

Table 4.3: RMS sum of all residual values for the suggested measures.

4.4 DESIGNING A NEW EVALUATION PROCEDURE FOR FOOTSTEP SOUNDS

From the conclusions in the previous sections it is now possible to construct a suggestion for a new measure for footstep sounds on floors. The missing link here is how to obtain a repetitive measure for footsteps. Here it is possible to use the acceleration recordings again to see if the tapping machine can be used, e.g. with some form of spectrum modification. Figure 4.6 shows the difference in acceleration level between a male walker and the tapping machine (top), between a female walker and the tapping machine (middle) and between dropping small wooden blocks from 0.5 m and the tapping machine (bottom).

As can be seen in the figure, the differences between these vibration sources and the tapping machine is in each case almost constant. But there are large differences between the different sources regarding spectra and levels. The male walker is e.g. 5 – 15 dB stronger in the frequency range 16 – 63 Hz than the female walker. This is not only caused by the walker's weight but also caused by each individual walking habits, as has been shown by previous authors (see section 2.1 in this report).

Figure 4.7 shows suggested third-octave band corrections that should be applied to the sound pressure levels that are measured with a tapping machine. These correction curves give rating levels for footsteps, pulling chairs and dropping small wooden blocks. The top figure gives the level difference without frequency weighting, and the bottom figure gives the level differences including A-weighting. The A-weighting is used, as it was the measure that gave the best fit to the listening test, according to the previous section.

As was shown in section 4.2, it may be necessary to add some dB's for the lower frequencies in the correction curves. This since the 10^{th} percentile level showed this trend, and since the maximum levels is what gave the best fit. Individual strong sounds seem to annoy people the most, i.e. the maximum level is a better descriptor than the equivalent level.

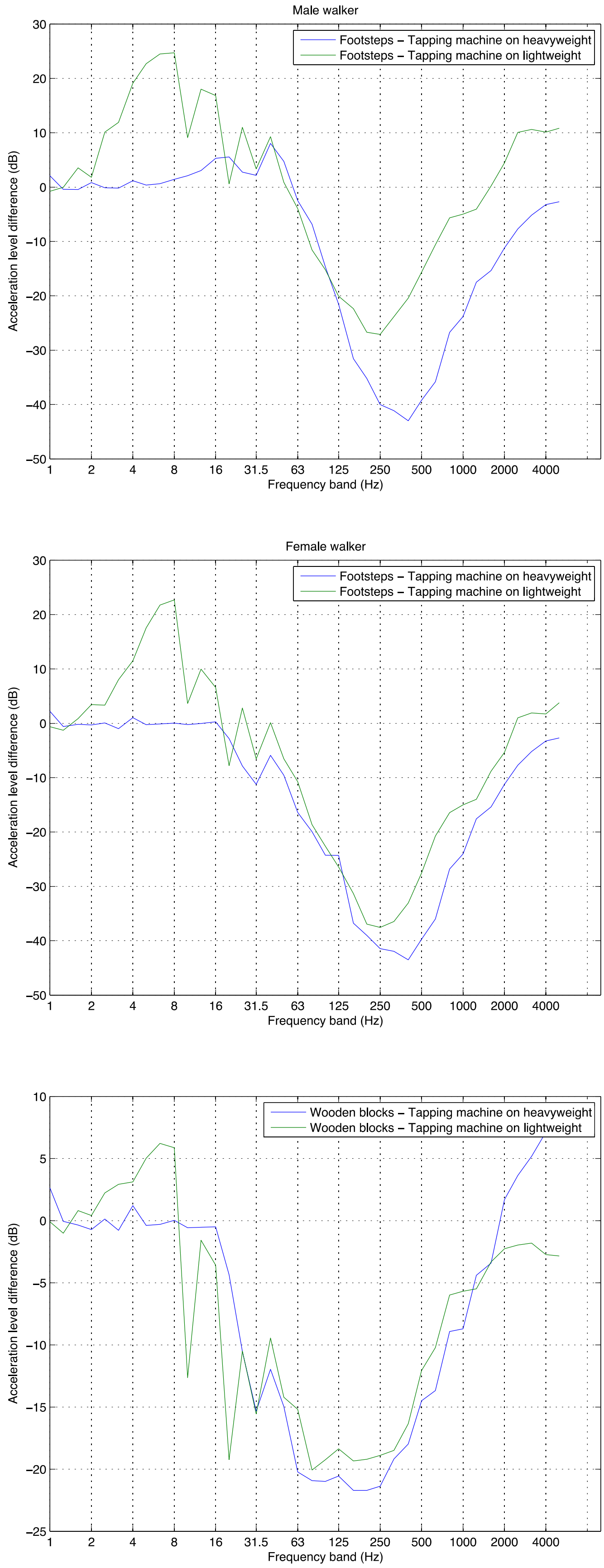

Figure 4.6 Acceleration level differences between a male walker, a female walker and small wooden blocks, and the tapping machine respectively.

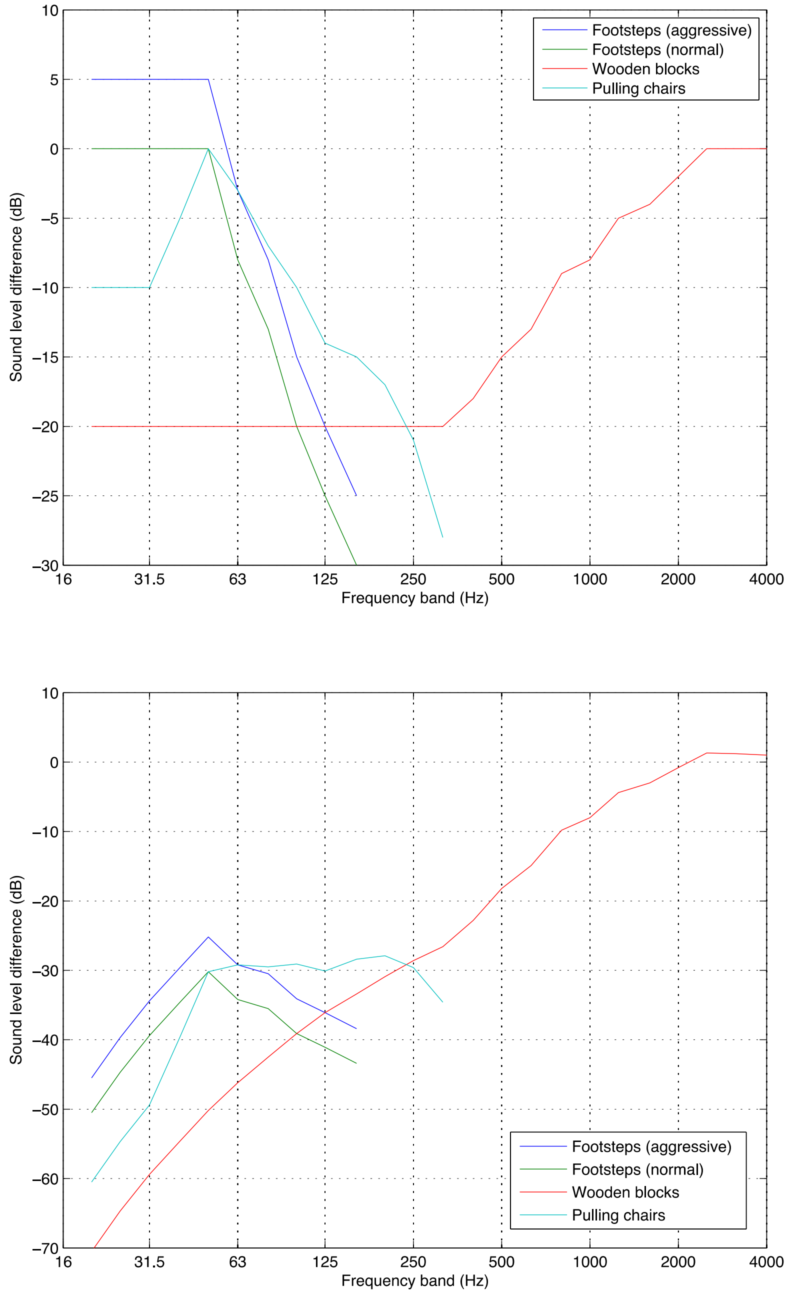

Figure 4.7: Suggested correction curves for footsteps, pulling chairs and dropping of small wooden blocks (top: linear levels, bottom: A-weighted levels).

5. Conclusions

Based on a literature survey and a listening test it is found in this report that footstep sounds include important information below 50 Hz. Recordings of footsteps on one lightweight floor and one heavyweight floor was performed and evaluated. The recordings were made using acceleration instead of sound pressure in order to avoid the room acoustics of the recording room. The acceleration signals were then filtered and replayed through 4 loudspeakers mounted in the ceiling and hidden behind a lightweight suspended ceiling. The lowest frequencies were reproduced through two subwoofers.

A suggestion of a new evaluation measure for footstep sounds is shown in this report. The measure was found through the listening test that focused on finding footstep sounds that are equally annoying or equally loud. Both questions gave the same answers from the test groups. From an evaluation of the listening tests it was found that the average A-weighted maximum sound pressure level was the best measure found, clearly better than using linear or C-weighting, and better than the loudness level. A combination of A- and C-weighted levels, which was suggested in the literature, was also tested but with higher errors.

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Laboratory Listening Tests

Listening tests have been performed in the Aku-Lite project which have been specifically aimed at understandning the important aspects of footstep sounds. As it is shown in this report, frequencies down to 20 Hz are important for the subjective rating. The listening test is fully described in this report and conclusions on objective measurement evaluations are made.

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