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Indoor measurements of sound at low frequencies

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Summary
Due to standing waves, the sound pressure level within a room may vary as much as 20-30 dB with low-frequency tonal noise, somewhat less with noise bands. For assessment of annoyance from low-frequency noise it is relevant to measure a level close to the highest level of the room, rather than a room average. As a means in this, current Swedish and Danish measurement methods include corner measurements. These positions are however still with some specified height and distance to the walls, and they may not effectively serve the purpose. Alternative measurement positions were investigated based on theoretical considerations and observations from numerical simulations. The performance of the methods in practice was studied by measurements in three rooms, while various low-frequency sounds were produced in adjacent rooms. The sound pressure level was measured in 1) the entire room by scanning, 2) corner positions specified by Swedish and Danish measurement methods, and 3) all three-dimensional corners. The level that is exceeded in 10% of the space in a room ($L_{90\%}$) was found to be a reasonable target for a measurement method rather than the absolute maximum. Good results can be expected with the Swedish method, as the Swedish corner position is obtained by scanning and yields levels close to the target; however there are serious concerns regarding the use of C-weighting in the scanning. With the Danish method, good results can only be expected, if complainants can accurately appoint measurement positions, since the corner position in this method generally fails to represent the high levels in the room. As an alternative method, it is proposed to use the power average of measurements in some or all three-dimensional corners. This method is simple and seems to offer reliable and repeatable results in all rooms and at all frequencies.

1 Introduction

When sound waves propagate inside a room they are reflected by the boundaries. In some positions, the reflected waves appear in phase with the original wave and thus amplify the sound, while in other positions the reflections appear in opposite phase and thus attenuate the sound. The resulting pattern of high and low sound pressure levels is called a standing wave pattern. In practical situations, the sound pressure level may vary as much as 20 to 30 dB for pure tones, somewhat less for noise bands. Standing waves are mainly of importance at low frequencies, and in the present article, frequencies below about 200 Hz are considered.

When standing waves are present, it is not possible to describe the sound level in a room with a single figure. For technical matters, e.g. measurement of sound transmission between rooms, the power average over the room is often adequate, and several methods exist for estimating this from measurements, usually taking the power average across a number of measurement positions. For assessment of noise annoyance, however, an average across the room is not adequate, since persons being present in a high-level area of a room are not helped by the existence of lower levels in other areas of the room. Thus, as also argued e.g. by (Jakobsen 1996) and (Simmons 1997, 1999), at low frequencies it is relevant to consider the highest sound pressure level rather than a room average. The current measurement methods in Sweden (SP 1996) and Denmark (Miljøstyrelsen 1997) are developed with an aim of estimating a sound pressure level that is representative of the highest levels that occur in relevant areas of the room. It is, however, somewhat uncertain to what extent the procedures are successful.

The present work studied the performance of the current measurement methods in practice. Detailed measurements of the sound field were made in three different rooms for selected frequencies and frequency bands. Frequencies of 31.5 Hz and 125 Hz were chosen to illustrate effects in the lower and upper parts of the frequency bands covered by the current methods (31.5-200 Hz in Sweden, 10-160 Hz in Denmark). The signals were pure tones and third-octave-band-filtered pink noise. The sounds were generated by loudspeakers in an adjacent room in order to ensure a steady sound field and adequate signal to noise ratio. Since both current methods showed inadequate performance in various ways, possible alternative methods were considered. A proposal for an alternative, simple and reliable method is given. This article contains a brief introduction on low frequency sound in rooms, in which the fundamental problems are illustrated through numerical simulations.

2 Sound in rooms

The standing wave pattern that occurs when sound propagates inside a room results in significant variation in the sound pressure within the room. The wavelength is inversely proportional to the frequency of the sound, thus the standing wave pattern will also depend on frequency. If the sound wave propagates in all three dimensions it will be reflected by all the boundaries of the enclosure and the standing wave pattern extends to all three dimensions as well. In the first subsection, a simple one-dimensional example of wave propagation between two boundaries is considered. In following subsections, propagation is extended to two and three dimensions. The examples are based on a rectangular enclosure with the dimensions 5.7 m by 3.8 m by 2.8 m (L x W x H).

2.1 One-dimensional wave

If a plane wave is generated by one end-wall of a room and reflected by the (rigid) wall at the opposite end, the reflected wave will have the same magnitude as the incident wave but propagate in the opposite direction. The pattern is described by

$$P_t = P_i + P_r = P \cdot \sin\left(\frac{2 \cdot \pi \cdot f}{c} \cdot (c \cdot t - x)\right) + P \cdot \sin\left(\frac{2 \cdot \pi \cdot f}{c} \cdot (c \cdot t + x)\right),$$

where the total pressure P_t is the sum of the pressure of the incoming wave P_i and the pressure of the reflected wave P_r. The pressure amplitude is given by *P*, and the distance to the reflecting wall is given by *x*. The speed of sound in air is given by *c* and *t* is the time, thus *c* multiplied by *t* is the distance of the wave travel. Thus the pressure magnitude in the standing wave pattern as a function of the distance to the reflecting wall can be written as a cosine function given by

$$P_t(x) = \left| 2 \cdot P \cdot \cos\left(\frac{2 \cdot \pi \cdot f}{c} \cdot x\right) \right|$$

The resulting pressure is seen in Figure 1. At the reflecting surface, the two waves are in phase, and the resulting pressure is two times the pressure of the incident wave. At one quarter of a wavelength from the reflecting boundary the two waves are added with opposite phase, and thus extinguish each other. At a half wavelength from the reflecting surface the two waves are again added in phase and the pressure is again doubled. This is all repeated with half-wavelength intervals. The sound pressure at the emitting boundary depends on the length of the room in comparison with the wavelength. If the length of the room covers an integer number of a half wavelengths, the high pressure is also seen on the emitting wall. If it covers a quarter of a wavelength plus an integer number of half wavelengths, the pressure at the source is zero.

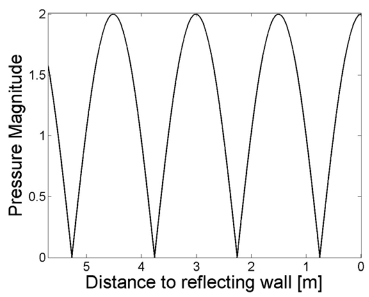

Figure 1: One-dimensional wave at 114 Hz emitted from left wall and reflected by right wall. The absolute pressure magnitude is shown as a function of distance to the reflecting wall.

For sound propagation in three dimensions, analytical solutions become significantly more complex, in particular when the source is also complex. In the following, numerical solutions are therefore given from simulations using the finite-difference time-domain method (FDTD) (Botteldooren 1995). The simulations were carried out using a 0.1 m cell size and a sampling frequency of 6 kHz. The impedances of the walls were 200 times that of the air. By choosing this factor less than infinity, account was made for loss in terms of less than total reflection and to some – less accurate – extent also damping inside the room, e.g. from furniture. In practice, boundaries may have complex impedances, and the imaginary part is not accounted for. A volume velocity source was used, and the levels were adjusted, so that the highest sound pressure is 90 dB in all the examples.

In Figure 2 the one-dimensional wave is displayed for 20 Hz (left) and 114 Hz (right), however calculated in a three-dimensional room using FDTD simulation. The source position is indicated by a black line next to the left end-wall. Since the impedances of the boundaries are finite, the reflected wave does not completely extinguish the incoming wave. A logarithmic color gray-scale (i.e. in dB) is used, and the dips are more than 30 dB. The sound pressure only varies along the length of the room, and there is no change along the width or height.

It is worth noting that, for 20 Hz, the high level found at the end-wall extends far into the room. At 114 Hz, the high level found at the end-wall extends only little into the room, but it re-occurs periodically throughout the remaining part of the room. Thus, it is characteristic for both frequencies that the high level is not only found in a narrow region close to the end-wall, but in large parts of the room, where typically people might be present.

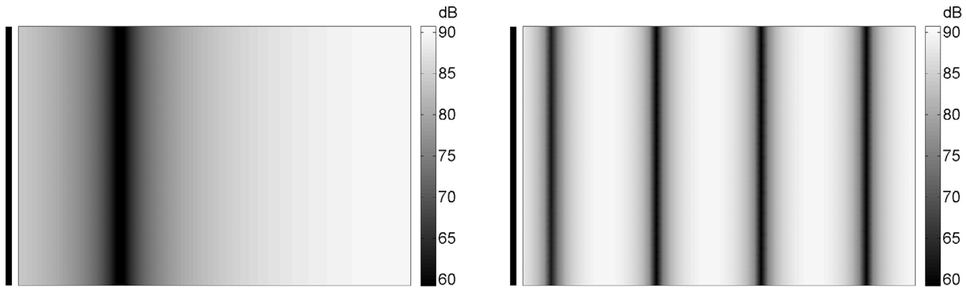

Figure 2: Sound pressure distribution in a 5.7 m by 3.8 m by 2.8 m (L x W x H) room. Sinusoidal sound wave generated by left end-wall indicated by black line. Left: frequency = 20 Hz. Right: frequency = 114 Hz. Simulated using FDTD with 0.1 m cell size and 6 kHz sampling frequency.

2.2 Two-dimensional wave

If a sound wave propagates in two dimensions of a rectangular room, it is reflected by two orthogonal sets of two parallel boundaries. Two examples are given in Figure 3, where the two-dimensional standing wave pattern is illustrated for 20 Hz (left) and 114 Hz (right). The sound source is a vertical line source positioned off-centre on the left end-wall, as indicated by the black line. For 20 Hz, the pattern has some resemblance with the one-dimensional case with high levels at the right end-wall and a band of low levels near the source end. At 114 Hz, the pattern deviates considerably from that of the one-dimensional wave with irregular areas of high levels separated by curved bands of lower levels. There are no changes along the height.

If the corners are considered as the “ends” of a two-dimensional room, some observations can be made analogue to those made for the one-dimensional wave: At 20 Hz, the high level observed in two corners extends far into the room from the corners, whereas, at 114 Hz, the high level seen in two corners only extends little into the room but re-occurs in other parts of the room. A level slightly higher than in the corners is seen close to the source.

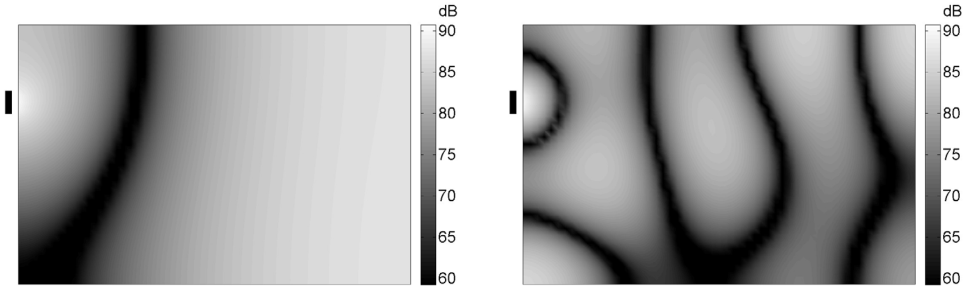

Figure 3: Sound pressure distribution in a 5.7 m by 3.8 m by 2.8 m (L x W x H) room. Sinusoidal sound wave generated by vertical line source on left wall indicated by black line. Left: frequency = 20 Hz. Right: frequency = 114 Hz. Simulated using FDTD with 0.1 m cell size and 6 kHz sampling frequency.

2.3 Three-dimensional wave

If a sound wave propagates in three dimensions of a rectangular room, it is reflected by three orthogonal sets of two parallel boundaries. Two examples are given in Figure 4 and Figure 5. Since the level now also varies vertically, the figures contain two-dimensional plots at various heights. At 20 Hz (Figure 4), a large high-level area is seen at the right end-wall at all heights. Another high-level area is seen around the left end-wall, close to one side-wall, but most prominent at low heights. A skew low-level band, much like that of the two-dimensional wave, is seen at all heights. At 114 Hz (Figure 5), a complicated pattern of high- and low-level areas is seen, and the pattern varies significantly with height. It is characteristic that around the middle of the room in the vertical direction (heights of 1.05 m, 1.45 m and 1.75 m) the level is relatively low. A horizontal plane around the middle of the room is close to a half wavelength at 114 Hz from both floor and ceiling. It is worth noting that the level is not generally high at the source position; in the 20-Hz example (Figure 4), the level is high close to the source, but in the 114-Hz example (Figure 5), there is a clear dip right at the source position.

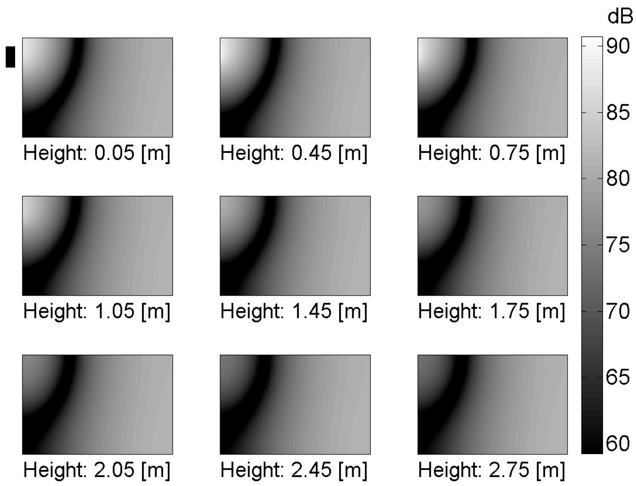

Figure 4: Simulation of sound pressure distribution in a 5.7 m by 3.8 m by 2.8 m (L x W x H) room. Sinusoidal sound wave at 20 Hz generated by piston in lower left corner indicated by black line. Simulated using FDTD with 0.1 m cell size and 6 kHz sampling frequency.

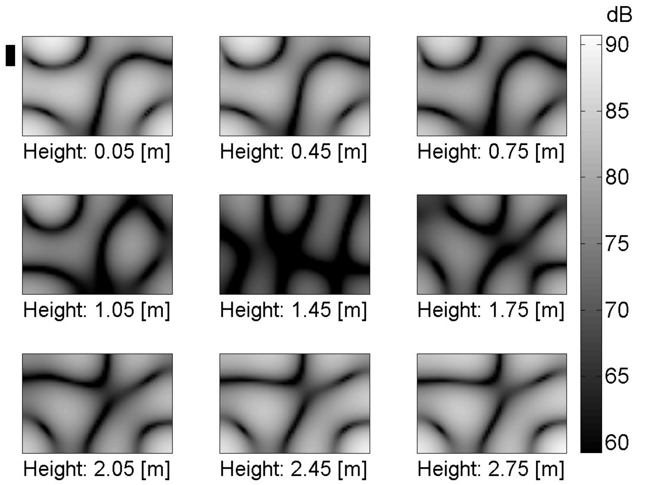

Figure 5: Sound pressure distribution in a 5.7 m by 3.8 m by 2.8 m (L x W x H) room. Sinusoidal sound wave at 114 Hz generated by piston in lower left corner indicated by black line. Simulated using FDTD with 0.1 m cell size and 6 kHz sampling frequency.

If three-dimensional corners are considered as “ends” of a three-dimensional space, observations can be made in parallel to those for the one- and two-dimensional waves. At 20 Hz, the high level found in some of the three-dimensional corners extends far into the room from the corners, whereas, at 114 Hz, the high level seen in some of the three-dimensional corners only extends little into the room but re-occur in other parts of the room. Note that, in the two figures, three-dimensional corners are seen as two-dimensional corners at the upper left and lower right frames. Again, a slightly higher level than in the corners is seen close to the source.

If several waves with different frequencies propagate in a room, all waves will produce high levels in some of the three-dimensional corners; in other positions of the room, high levels from the individual waves may coincide less often. This may result in higher levels in the corners for complex sounds.

2.4 Room modes

Frequencies for which the wavelength is related in a simple manner to the room dimensions are called modal frequencies. For a rectangular room, they have been given e.g. by (Everest 1988):

$$f_{(x,y,z)} = \frac{c}{2} \cdot \sqrt{\left(\frac{x}{L}\right)^2 + \left(\frac{y}{W}\right)^2 + \left(\frac{z}{H}\right)^2}$$

where L, W and H are the dimensions of the room, x, y and z integer mode numbers (0, 1, 2, 3....), and c the speed of sound in air.

The simplest room modes are called axial modes, and they occur, when only one mode number is non-zero. In this case, the mode number tells how many half wavelengths there are in the given direction. An example, the (3, 0, 0) mode (90 Hz), is shown in the left frame of Figure 6. It is seen that there are three half wavelengths (each 1.9 m) along the room. Axial modes interfere with only two boundaries of the room and are thus relatively strong, i.e. the level variations in the pattern are high.

If two mode numbers are non-zero, tangential modes occur. An example, the (1, 1, 0) mode (54 Hz), is shown in the right frame of Figure 6. It is seen that there is a single high–low–high level pattern in each of the directions along length and width, but the distances between the tops are not the same in the two directions, and both are higher than the half wavelength (3.2 m) of a free-traveling wave of the same frequency. Tangential modes interact with four room boundaries and are thus more damped than axial modes.

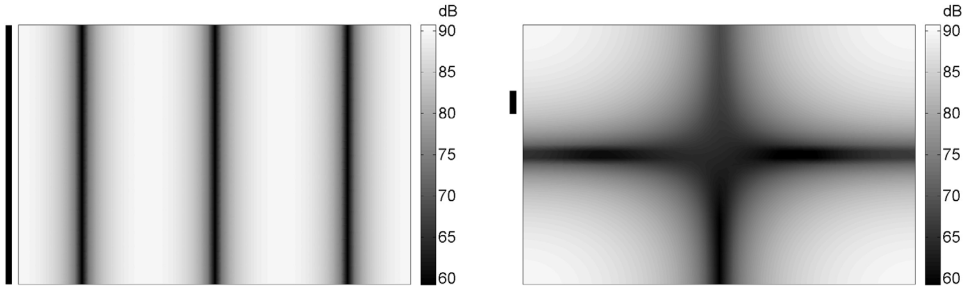

Figure 6: Sound pressure distribution in a 5.7 m by 3.8 m by 2.8 m (L x W x H) room. Left: sinusoidal sound wave at 90 Hz (mode 3,0,0) generated by left end-wall indicated by black line. Right: sinusoidal sound wave at 54 Hz (mode 1,1,0) generated by vertical line source on left end-wall indicated by black line. Simulated using FDTD with 0.1 m cell size and 6 kHz sampling frequency.

Modes where all mode numbers are non-zero are denoted oblique modes. These interact with all six surfaces and are even weaker than tangential modes. An example, the (2, 2, 1) mode, is shown in Figure 7. It is seen that two high–low–high patterns are seen in each of the length and width directions, while only one is seen in the height direction. Again, the distances between the tops vary between directions and are higher than the half wavelength (1.4 m) of the free wave in all directions.

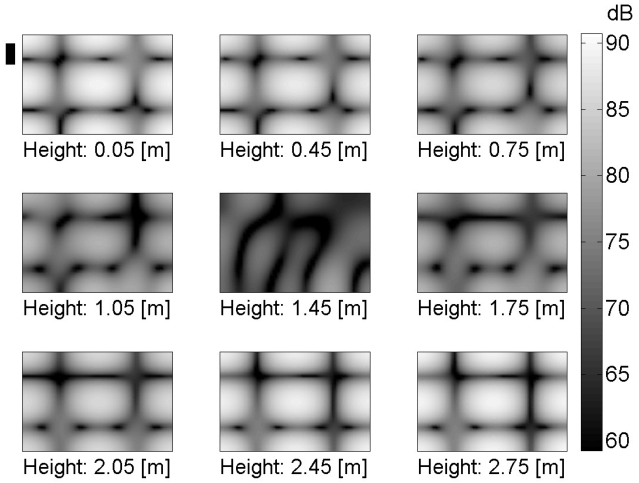

Figure 7: Sound pressure distribution in a 5.7 m by 3.8 m by 2.8 m (L x W x H) room. Sinusoidal sound wave at 124 Hz (mode 2,2,1) generated by piston in lower left corner indicated by black line. Simulated using FDTD with 0.1 m cell size and 6 kHz sampling frequency.

In general, the standing wave patterns at the modal frequencies are symmetrical in one, two or three dimensions. High levels are found at the “ends” in a broad sense, i.e. surfaces, two-dimensional corners or three-dimensional corners, respectively.

Between the maxima, a number of dips are found corresponding to the mode number in the particular direction.

A comparison of the standing wave patterns at modal and non-modal frequencies shows that, at modal frequencies, high levels are found at all ”ends” for the given mode (two surfaces, four two-dimensional corners, eight three-dimensional corners), while, at non-modal frequencies, high levels are only found at some of these. Whatever a modal or non-modal frequency, in the examples the highest levels of the room were observed in one or more three-dimensional corners, and, conversely, a level observed in a three-dimensional corner was also observed in other areas of the room. However, a region may occur in the vicinity of the source, where the level is higher than in corners. On the other hand, high levels are not generally seen at the source position. The authors have made a number of other simulations, and these observations seem to hold in general

2.5 Measurement procedures

Having the observations on standing wave patters in mind, it is obvious that it is not possible to characterize the sound in a room by a single value, and in particular, measurements in single positions will give results that differ widely between positions. In practice, it is typically not known how the sound is transmitted into a room, and often there are irregularities in the room. Also the type of sound, and thus the frequency to be measured is typically not known, and it is thus not possible to calculate suitable measurement positions. Sweden and Denmark have established rules regarding how to perform measurements in order to ensure a value that is representative of the level, to which people in the room may be exposed. The rules aim at a reproducible measurement result close to the highest level that occurs in those parts of the room, in which inhabitants may be present.

Sweden

The Swedish method for measuring low-frequency noise in dwellings in third-octave bands ranging from 31.5 Hz to 200 Hz is described in (SP 1996). The method uses the power average of the noise measured in three positions. Two positions are selected with regard to ear positions in the general usage of the room, however avoiding positions closer than 0.5 m to the walls and positions around 1/4-, 2/4- and 3/4-fractions along the length and width of the room. The third position is a corner position selected by scanning each of the two-dimensional corners in the floor plane for the highest C-weighted level. The scanning must take place at a distance of 0.5 m from the walls, and at heights ranging from 0.5 to 1.5 m above the floor. This corner position is denoted “SS corner” in the following.

Denmark

The Danish guidelines for measuring low-frequency noise and infrasound in rooms in the frequency range 10-160 Hz are described in (Miljøstyrelsen 1997). Like in the Swedish method, the power average of the noise measured in three positions is used, however the choice of positions deviates somewhat. Two positions of height 1-1.5 m are selected with regard to the general usage of the room, however avoiding positions closer to the walls than 0.5 m and positions in the middle of the room. If possible, these positions should be pointed out by the annoyed person as positions, where the noise is particularly annoying. The third point in the Danish method is a corner position, but, unlike in the Swedish method, the corner and height are not found by scanning. The corner is chosen arbitrarily from the two-dimensional corners in the floor-plane, and the height must be 1.0-1.5 m. The distance to the adjoining walls must be 0.5-1.0 m. In the following, a corner fulfilling these requirements, is denoted an "MS corner". In small rooms (below 20 m^2) only two MS corner positions are used.

Other countries
Also other countries have rules that use indoor measurements of low-frequency noise. The rules in Germany for the frequency range 10-80 Hz are given by (DIN45680 1997). Measurements must be carried out in the room, in which the noise is most annoying. However, the problem with level variations within the room are not mentioned, and only one arbitrary position is used. Similar rules exist in Austria (ÖNORM S 5007).

2.6 Three-dimensional corners

Both the Swedish and the Danish methods use a corner position as part of the strategy to achieve a result representative of the highest levels of the room. However, the demand of a certain height above the floor in the Danish method means that the position cannot be regarded as a real corner position to waves that propagate in three dimensions. Furthermore, the Danish rules give rather large degrees of freedom for choosing the corner position, as it can be chosen in any of the two-dimensional corners of the floor-plane, and the distance to walls can be chosen in a wide range. The option of a distance to the walls of as much as 1 m further disqualifies the position in being a corner. The Swedish method also prescribes some distance to the walls, however it is smaller, and the scanning is likely to be efficient in reaching a representative, high level. As there is a large uncertainty connected to especially the corners of the Danish method, it was decided to also investigate the levels found in real three-dimensional corners. These will be denoted "3D corners" in the following.

3 Method

As mentioned in the introduction, the sound field was investigated in three rooms while sound was generated in adjacent rooms. The sound in the entire room was measured by scanning, and separate measurements were made at corner positions as specified in the Danish and Swedish guidelines as well as in three-dimensional corners.

3.1 Rooms

The measurements were carried out in 1) a rectangular 22-m^2 office, 2) an L-shaped 33-m^2 living room, and 3) a rectangular 16-m^2 bedroom, the latter with a 19°-slope ceiling. Floor plans are illustrated in Figure 8. The office had a linoleum-on-concrete floor, concrete ceiling, and walls made of gypsum boards. The living room and the bedroom had brick-walls, wooden floors and wooden ceilings. One wall of the bedroom was made of gypsum boards, though. All rooms were naturally furnished, the office with desk, bookshelf, meeting table and light chairs, the living room and bedroom with heavier and more absorbing items such as sofas and beds. For all rooms, the sound was produced in a room next to, a corridor, a kitchen, and a children's room, respectively. For the office, preliminary measurements were also made with the source inside the room, but the effects seen did not differ qualitatively from those with the source outside, and it was decided to carry out the final measurements only with the source outside the rooms.

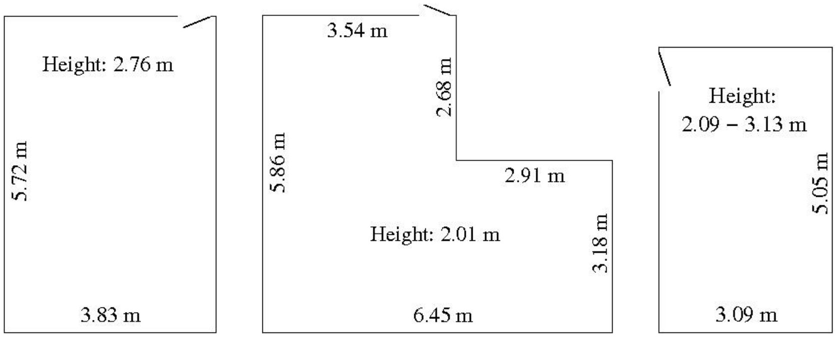

Figure 8: Sketch of floor plan of rooms used for measurements:1) office (left), 2) living room (center) and 3) bedroom (right).

3.2 Sound signals

The sound signals were pure tones and third-octave noise bands at 31.5 Hz and 125 Hz. For the office, the 31.5 Hz tone was replaced by a 33 Hz tone in order to separate it from the lowest axial room mode (30 Hz). The two noise signals or the two tones were emitted simultaneously from each their woofer. The two signals were separated by third-octave filters in the analysis.

3.3 Measurements

The sound in the room was measured by a scanning technique, where a microphone was moved through the entire space of the room with constant speed. A Type 40EN microphone was used with a Type 26AK preamplifier (G.R.A.S. Sound & Vibration), and the signal was recorded and stored on disk with a Harmonie system (01dB) and subsequently analyzed in Matlab (The MathWorks).

A room was split into smaller sections of equal volume, and each section was successively scanned in a specific pattern. The scanning pattern consisted of bars, equally spaced by at the most one eighth of a wavelength. Since 31.5 Hz and 125 Hz were measured at the same time, the spacing was set by the higher of these frequencies, i.e. 0.34 m. The r.m.s. time average of the signal was calculated for rectangular, sliding time windows of 10 s for the 31.5 Hz noise band, 2.5 s for the 125 Hz noise band, 2 s for the 31.5 Hz sine, and 1 s for the 125 Hz sine. These windows result in a statistical accuracy of 0.5 dB for the noise bands, much better for the sinusoids. The speed, with which the microphone was moved, was 0.1 m/s for the noise signals and 0.2 m/s for the tones. For both noise signals, this means that the microphone was moved less than one tenth of a wavelength within a time window. Since the scanning of a room was quite demanding and took long time (88 minutes for the living room), scanning (and recording) was halted at appropriate stages between room sections.

Measurements in three-dimensional corners were obtained by inserting an extra 10-s period with steady microphone, whenever a scanning was at such a corner. In the data processing, these periods were cut away for separate analysis. Measurements in corner positions according to the Swedish and Danish guidelines were made in separate periods after the scanning. The corner position of the Swedish guidelines was found by manual scanning of the C-weighted level, before a separate recording was made. Measurements were made in each of the corners at distances of 0.5 m and 1.0 to the walls, all at a height of 1.25 m. These eight positions are all examples of corner positions in accordance with the Danish guidelines. (In the L-shaped living room, an extra corner exists, and ten positions were used). These measurements were made simultaneously four at a time, utilizing four channels of the measurement system.

4 Results

4.1 Office

The time courses of the scannings are given in Figure 9 and Figure 10. As the microphone was moved at a constant speed, the abscissa also indicates the distance of the microphone travel. The scanning was performed in a pattern, where the room was split into eight parts (octants), where each octant was scanned by starting at a 3D corner and progressively moving towards the center of the room. The division into eight sections is clearly seen with the 31.5 Hz noise and 33 Hz sine stimuli (Figure 9). The sound pressure is high at the beginning of each octant and decreases as the microphone approaches the center of the room. The level is not equally high in all corners. It is evident that there is a larger variation in level for the pure tone than for the noise band. It is also noted that, like in the simulations, the high levels are not only present in a narrow range in the corner but extend widely into the room.

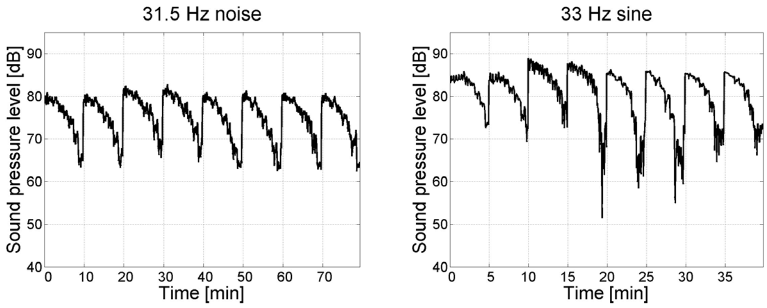

Figure 9: Scanning measurement in the office. Left: 31.5 Hz third octave band filtered pink noise signal. Right: 33 Hz sinusoidal signal.

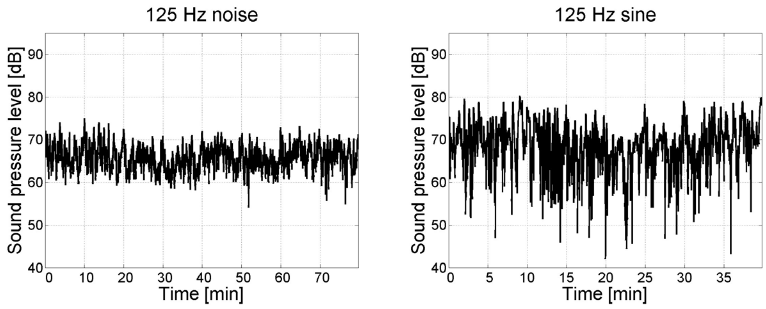

Figure 10: Scanning measurement in the office. Left: 125 Hz third octave band filtered pink noise signal. Right: 125 Hz sinusoidal signal.

In the scanning measurements at the two 125 Hz stimuli (Figure 10) the pressure dips appear much closer throughout the room and do not show a simple pattern. Zooming in on these scannings (Figure 11), reveals that the level varies much more in a narrow region than with the two lower frequency stimuli. Again, like in the simulations, the high levels are not limited to narrow regions in the three-dimensional corners but occur in many parts of the room.

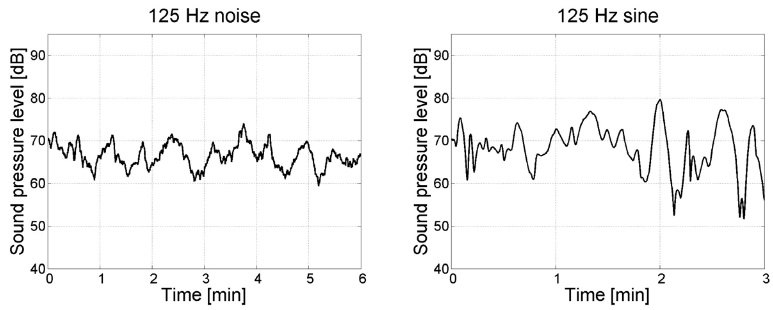

Figure 11: Zoom on the scanning measurements in the office. Left: 125 Hz noise stimulus, 6 minutes. Right: 125 Hz sine stimulus, 3 minutes. Left and right frames represent the same 36 m trajectory.

Histograms of the levels observed in the scannings are shown for each of the signals in the upper frames of Figure 12 and Figure 13. The lower frames of the figures show the results from the SS corner and the MS corners as well as from the 3D corners. The lower frames also show the room power average, calculated as the r.m.s level for the entire scanning period (identical to the equivalent level for this period).

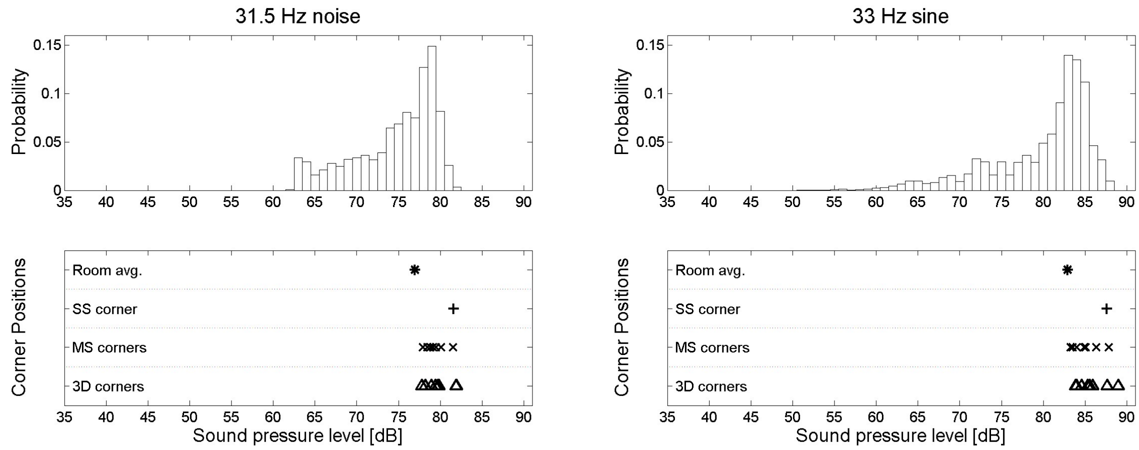

Figure 12: Histogram of scanning measurement, and sound pressure level in corner positions as well as room energy average level with 31.5 Hz noise (left) and 33 Hz sine (right) signal.

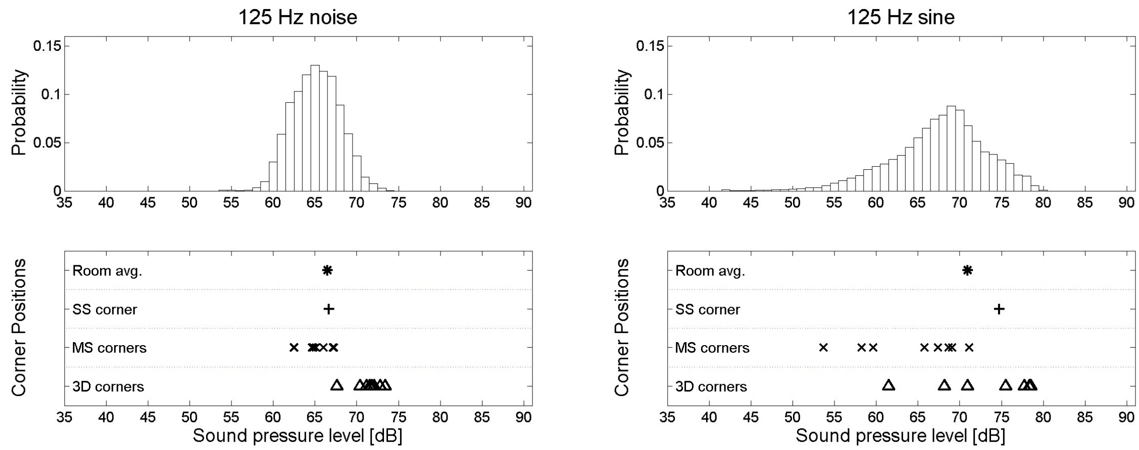

Figure 13: Histogram of scanning measurement, and sound pressure level in corner positions as well as room energy average level with 125 Hz noise (left) and 125 Hz sine (right) signal.

It is obvious from the histograms that, for all signals, a wide range of levels are seen. For the pure tones, ranges of more than 30 dB are observed, while the ranges are in the order of 15-20 dB for the noise bands. At the ends of the histograms, levels are seen that exist only in a very small part of the room; this is especially pronounced at the lower ends and for the pure tones.

For all sounds, due to the power averaging process, the room average lies in the upper part of the range, however still some decibels from the upper limit. For the 31.5/33 Hz noise and tone stimuli, the MS corners and the 3D corners give values not far from the upper ends of the range; however there is some variation between corners. For the 125 Hz sounds, the variation between corners is pronounced, in particular for the pure tone. Some, but not all, 3D corners show values around the upper limits, whereas the MS corners tend to be in the middle or lower parts of the ranges.

After the measurements, when the sound source was still emitting the 125 Hz tone, vibrations were observed in a metal sheet cover of a radiator near the 3D corner with the lowest level. Damping the cover by leaning against it increased the sound pressure level in that corner considerably. However, such conditions may occur in practical measurements, and the data recorded were accepted as representative of a real-life situation.

4.2 Living room

The scannings from the two other rooms show the same characteristics as for the office, and they are omitted in this presentation. As for the office, the scanning results are summarized in histograms and shown together with room average and corner results. The results from the living room are displayed in Figure 14 and Figure 15. Also here, wide ranges of levels are found in the room. Again, the corner measurements show large variation between corners, with values in the same range for MS corners and 3D corners for the 31.5 Hz signals, but with much lower values for MS corners for the 125 Hz signals.

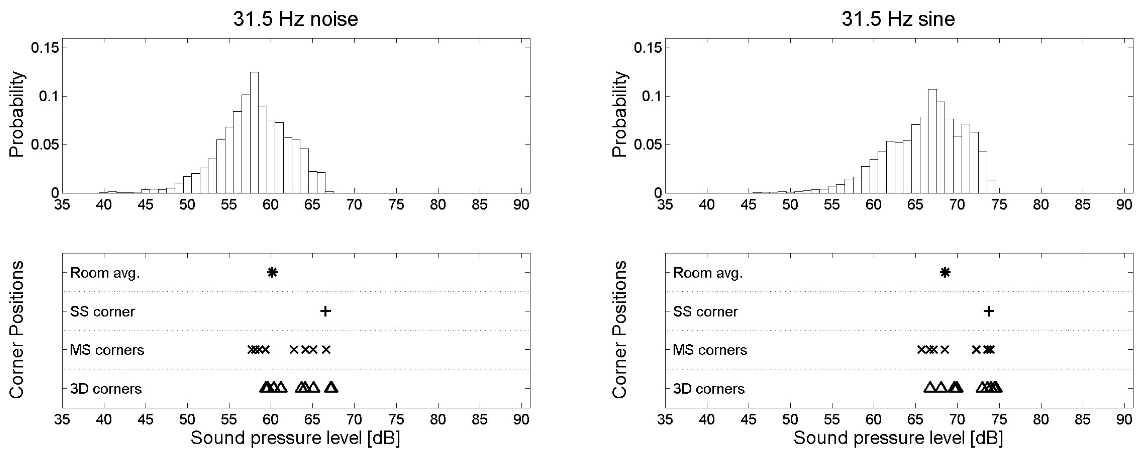

Figure 14: Histogram of scanning measurement, and sound pressure level in corner positions as well as room energy average level with 31.5 Hz noise (left) and 31.5 Hz sine (right) signal.

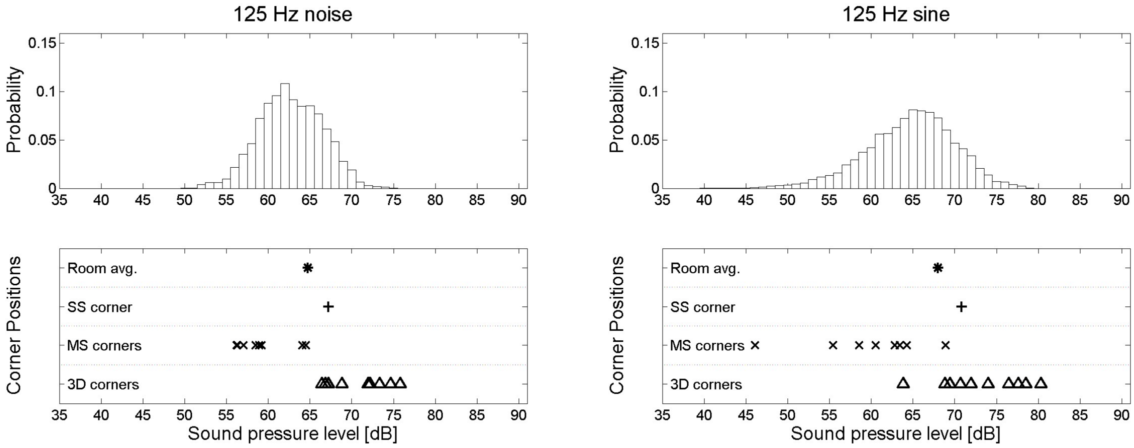

Figure 15: Histogram of scanning measurement, and sound pressure level in corner positions as well as room energy average level with 125 Hz noise (left) and 125 Hz sine (right) signal.

4.3 Bedroom

The results from the bedroom are given in Figure 16 and Figure 17. In general, similar observations can be made as for the other rooms.

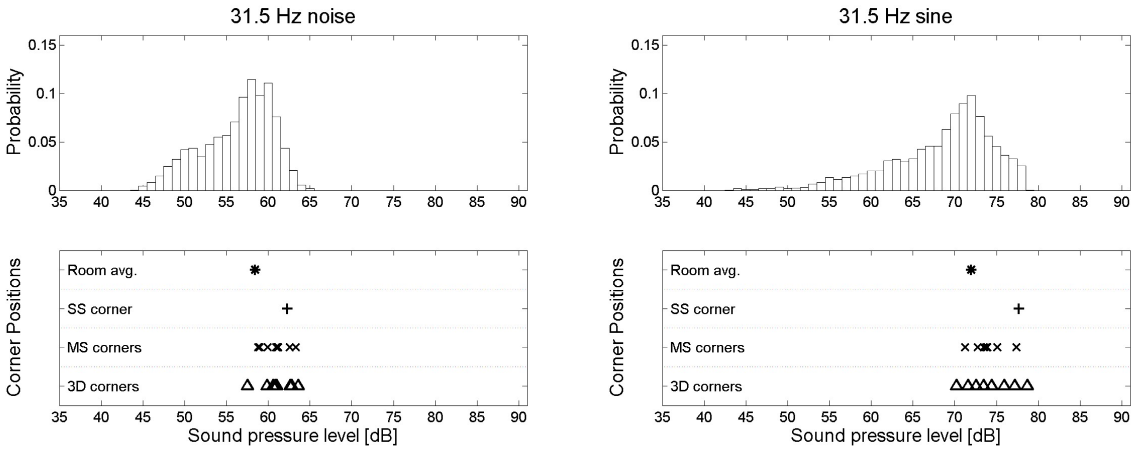

Figure 16: Histogram of scanning measurement, and sound pressure level in corner positions as well as room energy average level with 31.5 Hz noise (left) and 31.5 Hz sine (right) signal.

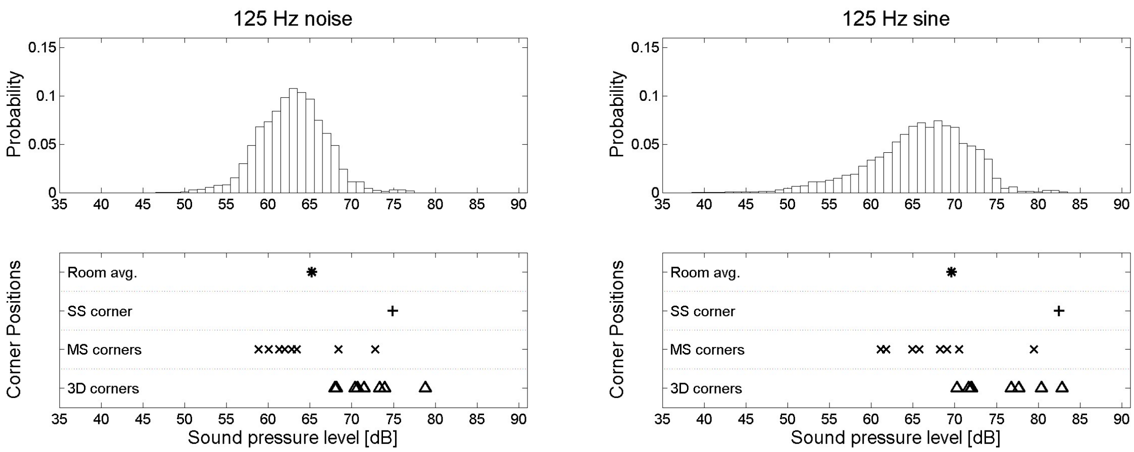

Figure 17: Histogram of scanning measurement, and sound pressure level in corner positions as well as room energy average level with 125 Hz noise (left) and 125 Hz sine (right) signal.

For the bedroom, it was noted that a large proportion of the sound was transmitted through the door. For the 125 Hz sounds, this resulted in high levels in a small region close to the door, in particular for the tone signal. This is seen in the upper end of the histograms as a flat range with low probability that reflects the small volume that the door region occupies. The highest level in the vicinity of the door was as much as 6 dB higher than the highest sound pressure level found in the remaining space of the room. Since the door was in a corner, high levels were also found in the two 3D corner positions and one of the MS corner positions near the door, and the scanning procedure in the Swedish method resulted in the SS-corner measurement being performed in the door corner.

5 Discussion

As mentioned in the introduction, it is widely agreed that indoor measurements of low-frequency sound for use in assessment of noise-induced annoyance should reflect the highest levels in a room. On the other hand, it would not be reasonable to use a level, if it only exists in a very small part of the room, and in particular not, if persons are not normally present in that part. As a target for a measurement method, it is therefore proposed to use a certain point on the cumulative level distribution function, i.e. a level, which is exceeded in a certain fraction of the room, e.g. 5-15%. Since the cumulated distribution function still has a fair slope around these values, it makes only a minor difference, exactly which percentage is used, and a value of 10% is used in the following. This level is denoted the 90th percentile or $L_{90\%}$.

Results from all rooms and all signals are summarized in Figure 18. Room power average, SS-corner levels and means and standard deviations of MS-corner levels and 3D-corner levels are given relative to the target (the 90th percentile).

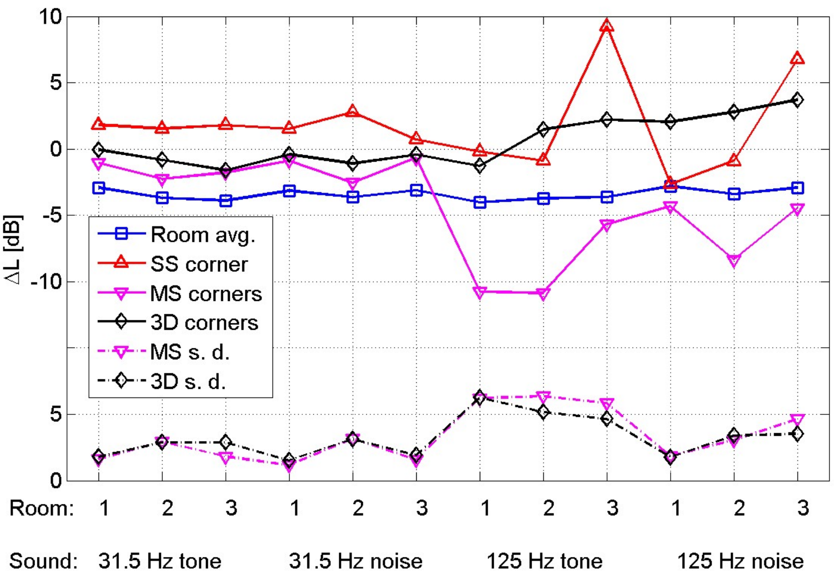

Figure 18: Summary of results: Room power average, SS corner, average of MS corners, average of 3D corners, all given relative to 90th percentile. Standard deviations of MS corners and 3D corners given at bottom of figure.

5.1 Room power average

The room power average proves to be consistently 3-4 dB lower than the target in all the rooms, independent of frequency, signal type and room. The fact that it underestimates the target could easily be compensated for by adding 3-4 dB before the noise is evaluated according to relevant limits. Unfortunately it is an extremely tedious task to perform this measurement, and thus it is not applicable in practice.

5.2 Swedish method

The SS corner yields rather good results not too far from the target. However, there is a situation in the bedroom, where too high levels are encountered. This is recalled as the situation, where a large part of the transmission into the room took place through the door resulting in unrepresentatively high levels in the vicinity of the door. Since the door was in the corner, the scanning resulted in the SS corner position being in this region.

The power averaging of levels found in three positions used in the Swedish method will guarantee a resulting level not much below the highest level. Thus, provided that the scanning is successful in the sense that the level in the SS corner is really representative of the high levels of the room, the Swedish method will work well. Even if the levels in the two remaining positions are very low, the power average will still be within 5 dB of the level in the SS corner.

The selection of the SS corner by scanning is not without problems, though. With a constant noise source, it is rather simple to perform the scanning with pure tones; however with noise bands, the level fluctuation inherent in the signal makes the scanning rather difficult. Furthermore, if the noise source is not constant, the selection of the SS corner position becomes very difficult, and a significant degree of uncertainty is inevitable. However, the biggest concern regarding the Swedish method is that the SS corner is based on scanning using the C-weighted level. The noise or part of the noise that is the cause of annoyance is not necessarily the part that contributes most to the C-weighted level. Therefore, the selection of corner and vertical position may be decided from a completely wrong part of the noise. As an example, an annoying 150 Hz tone may be present together with a 31.5 Hz tone that is not annoying, even when it generally has a much higher level. The C-weighted scanning will find the maximum point for the 31.5 Hz tone, but at this point nothing is known about the 150 Hz tone, in fact, it may even have a minimum.

In summary, the Swedish method is tedious because of the scanning process, but the method will work well, provided that noise is sufficiently stationary to perform the scanning, and that the annoying sound is also the sound that contributes most to the C-weighted level. If the scanning fails its objective, the three positions will be arbitrary points, of which the power average will usually be below the target. As a consequence, in such cases there is a high risk of underestimation.

5.3 Danish method

At 31.5 Hz, the MS corners yield levels close to the target and with little spread. However, at 125 Hz, the standard deviation between positions is large, and the level is in general much too low, worst for the tone. Since no scanning is involved in the Danish method, and only a single, arbitrarily selected, corner position is used, it does at 125 Hz not assist in reaching the high levels of the room. On the contrary, at

125 Hz, most MS corners are below the room power average and will thus tend to lower the final result.

In the Danish method, the complainant may appoint the two other measurement positions (within certain limitations). If the selection of these positions is successful in the sense that they are really representative of high-level areas of the room, the Danish method will work well. The power averaging will guarantee a final result close to the level observed in these positions, regardless of the level measured in the MS corner (within 5 dB, if only one level is high, within 2 dB, if the two levels are equally high). On the other hand, if a complainant is unable to point at suitable positions, it is pivotal that the MS corner position is representative of a high-level area. And as seen, this is not to be expected. It is the author's experience that complainants are often unable to point at relevant measurement positions, even when an obvious standing wave pattern is present. Also when a complainant can point to suitable areas, it should be taken into account that, if the annoying sound is in the upper end of the low frequency range, a small inaccuracy in position may compromise the result, since large variations in level can be seen within small distances (fractions of a meter, see e.g. Figure 11). In case of pure tones that vary slightly with frequency, a further complication exists, since the high-level positions will vary. In the case of small rooms, no positions are selected by the complainant, and the Danish method relies solely on MS corner measurements.

In summary, the Danish method will work well, provided that the complainant can appoint positions with sufficient accuracy. In other cases, including in general rooms below 20 m^2, two arbitrary positions and an MS corner position, or two MS corner positions, are used, of which the power average is most likely below the target. As a consequence, in such cases there is a high risk of underestimation.

5.4 3D corners

The average level of the 3D corners of all rooms is very close to the target, however with a slight overestimation at 125 Hz, especially for the noise bands, which is not unexpected. The 3D corners are thus better than the MS corners at 125 Hz, however the spread is almost as large, and thus it will not be feasible to simply replace the MS corner with a 3D corner in the Danish method. Use of single 3D corners is also not relevant.

In the introductory section on standing wave patterns, it was suggested that the highest levels of a room would exist in one or more three-dimensional corners, and, conversely, a level observed in a three-dimensional corner would also exist in other areas of the room. In the vicinity of the source, though, a slightly higher level than in other areas and the corners might exist. This was all confirmed by the measurements.

The fact that all sounds in a room are represented in some or more 3D corners, makes it logical to propose an alternative method based exclusively on 3D corners. The logical choice would be the power average of all 3D corners. However, in the measurements, it was seen that unrepresentatively high levels were sometimes seen close to a door that obviously transmitted much of the sound. It would thus be reasonable to exclude corners close to an obvious and concentrated sound transmission path. Since all rooms of the investigation happened to have the door in a corner, this would result in the exclusion of two 3D corner positions in each room. Figure 19 shows the power average of 3D corners including and excluding the door corner. It is seen that values are achieved close to the target. An overestimation of a few decibels is seen with the 125 Hz signals; however, this is reduced to a maximum of 3 dB, if door-corner positions are removed.

It should be noted that the 3D corner positions serve as the only measurement positions, thus no scanning is needed and the method is completely objective and does not rely on the capability of the complainant in appointing positions. The 3D corner positions are unambiguous, and if the noise source is constant, all technicians will end up with the same result. More microphone positions were used than in the Swedish and Danish methods – six in the rectangular rooms, eight in the L-shaped room – however a much more reliable and repeatable result is obtained. Modern measurement systems often have multi-channel options, and it is very convenient to have parallel measurements in the various positions. A preliminary look at the data suggests that rules can be set up so that measurements can be made in only three to four 3D corner positions at the expense of only slightly reduced accuracy.

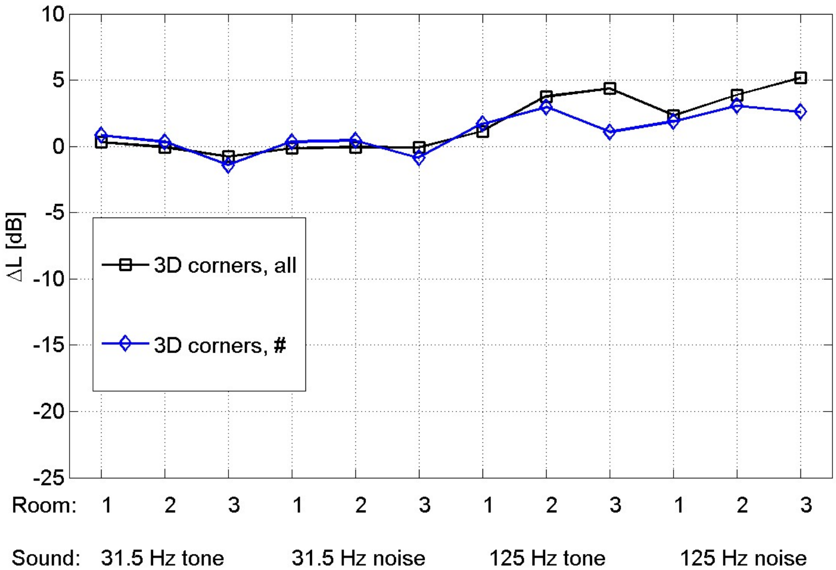

Figure 19: Results of applying the proposed measurement method in the three rooms, relative to the 90th percentile of the cumulated distribution function. # indicates that the 3D corners close to doors are removed.

6 Conclusions

It is evident from simulations and from practical measurements in three rooms, that there is a large variation in the sound level at low frequencies. It is thus not easy to describe sound in rooms from only a single or few measurements. There seems to be agreement that, for assessment of annoyance, the measurement result should in principle reflect the highest level that occurs in the part of a room, in which people may be present. However, it would not be reasonable to use a level that only occurs in a very limited part of the room, and the 90th percentile, $L_{90\%}$, the level that is exceeded in 10% of the room, is introduced as a target.

The room power average plus 3-4 dB seems to be an almost perfect estimator of the target level, in all rooms and with all tested signals. However, it is unfortunately not feasible to perform a true measurement of the room power average in practical situations.

The national methods in Sweden and Denmark use measurements in corners of the two-dimensional floor plan in their attempts to obtain levels that are representative for high-level areas of the room. The Swedish method uses a scanning technique to find the corner position with maximum level, and in principle this technique serves the purpose; however the scanning may be difficult and time consuming, and the use of C-weighting in the scanning is doubtful. The Danish method uses an arbitrarily selected corner position within certain restrictions, and the Danish corner position generally fails to represent high levels of the room.

Both the Swedish and the Danish methods use the power average of three positions, and, for the methods as a whole, reliable results can be expected from the Swedish method, provided that the scanning proves successful, and from the Danish method, provided that the complainant is able to accurately appoint high-level measurement positions. In other cases, there is a high risk with both methods of obtaining a result that is too low.

As an alternative, it is proposed to use the power average of measurements in some or all three-dimensional corners of the room. This seems to offer a straightforward method that gives reliable and repeatable results in an easy way in all rooms and at all frequencies.

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