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Indoor Measurements of Noise at Low Frequencies - Problems and Solutions

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ABSTRACT

Due to standing waves, the sound pressure level within a room may vary as much as 20-30 dB at low frequencies. Principal properties of low-frequency sound in rooms are illustrated by simulations, and sound pressure distributions as well as the performance of Swedish and Danish measurement methods are studied by measurements in three rooms. For assessment of annoyance, mainly areas of the room with high sound pressure levels are of interest, since persons present in such areas are not helped by the existence of lower levels in other areas. The level that is exceeded in 10% of the room (L_{10}) is proposed as a rational and objective target for a measurement method. The Swedish method showed results close to the target, but, due to a doubtful use of C-weighting in the scanning, it may give results below the target in case of complex sounds. The Danish method was found to have a high risk of giving results substantially below the target, unless complainants can precisely appoint measurement positions, where the sound is loudest/most annoying. An alternative method using measurements in four three-dimensional corners of the room is proposed. This easy and straightforward method seems to give reliable results close to the proposed target.

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 attenuate the sound. The resulting pattern of high and low sound pressure levels is called a standing wave pattern. In practical situations, the 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 work, only frequencies below 200 Hz are considered.

Due to the standing waves, a measurement in a single position is not sufficient to describe the sound in a room. For technical matters, e.g. measurement of sound transmission between rooms, the power average over the room is often a relevant measure. Methods exist for estimating this, usually by taking the power average of the levels in a number of measurement positions (e.g. the ISO 140 series [1] and ISO 10052 [2]). For assessment of noise annoyance, however, the room average 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. Therefore, at low frequencies, measurement values should represent high-level areas of the room rather than the room average. This was argued e.g. by Jakobsen [3] "*The result shall express the loudest noise which inhabitants may normally expose themselves to in a dwelling (office etc.). ....The optimum would be to measure in one point, just where the sound is most intense*" (authors' translation) and Simmons [4],[5] *"To assess the* *subjective annoyance of the actual sound field in a room .... the maximum sound pressure level (SPL) in the room may be preferred"*. That it is widely accepted that, at low frequencies, measurements should represent high-level areas, is reflected in several guidelines that devise measurements to be made at positions appointed by the annoyed person and/or in corners of the room [6],[7],[8],[9],[10]. (Corners are generally assumed to hold levels above room average).

The present work studies the performance of current measurement methods in practice with focus on those of the Swedish and Danish guidelines, which are the most detailed given. Detailed measurements of sound fields are made in three different rooms for selected frequencies and frequency bands. Frequencies of 31.5 Hz and 125 Hz are chosen to illustrate effects in the lower and upper parts of the frequency ranges covered by the methods (31.5-200 Hz third-octave bands in Sweden, 10-160 Hz third-octave bands in Denmark). The signals are pure tones and third-octave-band-filtered pink noise. The sounds are generated by loudspeakers in an adjacent room in order to ensure a steady sound field and adequate signal to noise ratio. Both methods show inadequate performance in various ways, and a simple and reliable alternative is proposed.

The description of the experimental work is preceded by an introductory section on low-frequency sound in rooms (Section 1) and a section on existing measurement methods (Section 2).

1. SOUND IN ROOMS

This section presents some general issues related to low-frequency sound in rooms and its measurement. 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).

1.1 One-dimensional wave

If a plane wave is generated by one wall of a rectangular room and reflected by the opposite (rigid) wall, the reflected wave will have the same magnitude as the incident wave but propagate in the opposite direction. For a sinusoidal wave of frequency f, the pressures of the incident and reflected waves, p_i and p_r respectively, can be described by Eqs. (1) and (2):

$$p_i = A\sin\left(2\pi f\left(t - x/c\right)\right) \tag{1}$$

$$p_r = A\sin\left(2\pi f\left(t + x/c\right)\right), \tag{2}$$

where A is the pressure amplitude, c the speed of sound, t the time and x the distance of travel. By appropriate selection of zero time, x is the distance from the reflecting wall. The total sound pressure p_t is found by adding the pressures of the incident and reflected waves:

$$p_t = p_i + p_r = 2A\cos\left(2\pi f \cdot \frac{x}{c}\right)\sin\left(2\pi f \cdot t\right) = 2A\cos\left(2\pi \frac{x}{\lambda}\right)\sin\left(2\pi f \cdot t\right) \tag{3}$$

where $\lambda = c/f$ is the wavelength. The total sound can thus be identified as a sinusoid of which the amplitude varies with distance to the reflecting wall as given by the cosine term.

The pressure magnitude is seen in Figure 1. At the reflecting wall (right end), 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 wall, the two waves are added with opposite phase, and thus they extinguish each other. At half a wavelength from the reflecting wall, 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 wall depends on the length of the room in comparison with the wavelength. If the length of the room covers an integer number of 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.

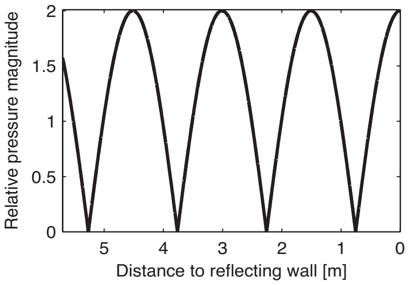

Figure 1 Relative pressure magnitude as a function of distance to reflecting wall (right). One-dimensional wave at 114 Hz emitted from left wall.

For sound propagation in three dimensions, analytical solutions become significantly more complex, in particular when the boundaries are not completely rigid. In the following, numerical solutions are therefore given from simulations using the finite-difference time-domain method (FDTD) [11]. All simulations were carried out using a 0.1 m cell size and a sampling frequency of 6 kHz. The impedances of the boundaries (walls, floor, ceiling) 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; however, this has little effect on the reflections and thus the standing wave pattern, as long as the magnitude of their impedances is much higher than that of the air. 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 sound wave is generated by one entire wall surface, thereby ensuring propagation in only one dimension. The source position is indicated by the rectangular bar next to the left wall. The sound pressure only varies along the length of the room, and there is no change along the width or height. A logarithmic grey-scale (i.e. in dB) is used, and the dips are more than 30 dB. Even when the dips are substantial, they are still finite, since the reflected wave is not of exactly the same amplitude as the incident wave, and thus they do not completely extinguish each other. Also, due to the discrete sampling in time and space, the absolute minima may not be represented by the simulations.

It is worth noting that, for 20 Hz, the high level found at the reflecting wall extends far into the room. At 114 Hz, the high level at the reflecting wall extends less 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 reflecting wall, but in large parts of the room.

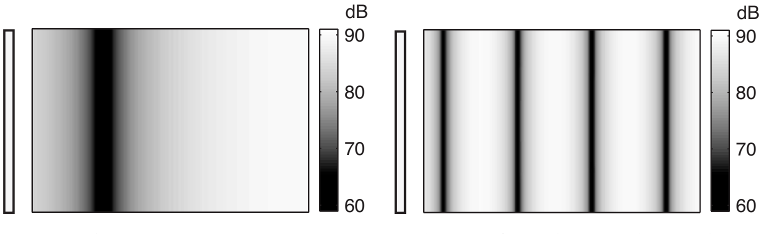

Figure 2 Sound pressure distribution in a 5.7 m by 3.8 m by 2.8 m (L x W x H) room. (Data from floor plane, but variation with height is marginal). Sinusoidal sound wave generated by left wall indicated by rectangular bar. Left: frequency = 20 Hz. Right: frequency = 114 Hz. Simulated using FDTD with 0.1 m cell size and 6 kHz sampling frequency.

1.2 Two-dimensional wave

Two examples of two-dimensional wave propagation 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 offcentre on the left wall, as indicated by the rectangle on the left side of the figures. For 20 Hz, the pattern has some resemblance with the one-dimensional case with high levels at the right wall and a band of low levels near the left wall. 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.

For the one-dimensional wave, the walls can be considered as the "terminations" of the room. For the two-dimensional wave, the analogue "terminations" are the corners of the room, and some observations can be made in parallel to those made for the one-dimensional wave. At 20 Hz, the high level observed in two corners (right end) extends far into the room from the corners, whereas, at 114 Hz, the high level seen in two corners (lower left and upper right) only extends little into the room but re-occurs in other parts of the room. For both frequencies, a level slightly higher than in the corners is seen close to the source.

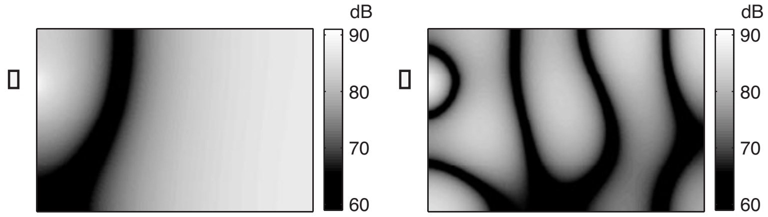

Figure 3 Sound pressure distribution in a 5.7 m by 3.8 m by 2.8 m (L x W x H) room. (Data from floor plane, but variation with height is marginal). Sinusoidal sound wave generated by vertical line source on left wall (implemented as 2.8 m by 0.3 m piston) indicated by rectangle. Left: frequency = 20 Hz. Right: frequency = 114 Hz. Simulated using FDTD with 0.1 m cell size and 6 kHz sampling frequency.

1.3 Three-dimensional wave

Two examples of three-dimensional wave propagation 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 wall at all heights. Another high-level area is seen around the left wall, close to the upper corner, 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 at the source position.

If three-dimensional corners are considered as the "terminations" of the room for a three-dimensional wave, 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 in some three-dimensional corners extends less into the room but re-occurs in other parts of the room. Again, a slightly higher level than in the three-dimensional corners is seen close to the source (here only for one of the frequencies, 20 Hz). (Note that, in the two figures, three-dimensional corners are seen as two-dimensional corners at the upper left and lower right frames).

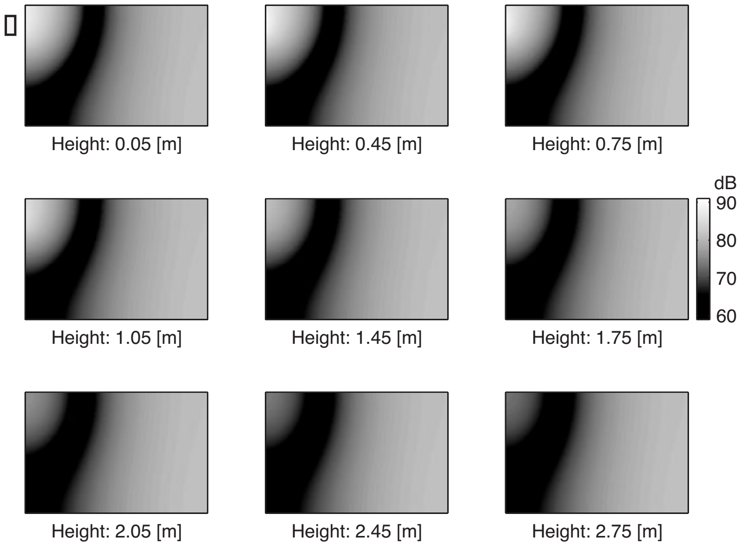

Figure 4 Sound pressure distribution in a 5.7 m by 3.8 m by 2.8 m (L x W x H) room. Sinusoidal sound wave at 20 Hz generated by a concentrated source in lower left corner (implemented as a 1 m by 1 m piston) indicated by rectangle. Simulated using FDTD with 0.1 m cell size and 6 kHz sampling frequency.

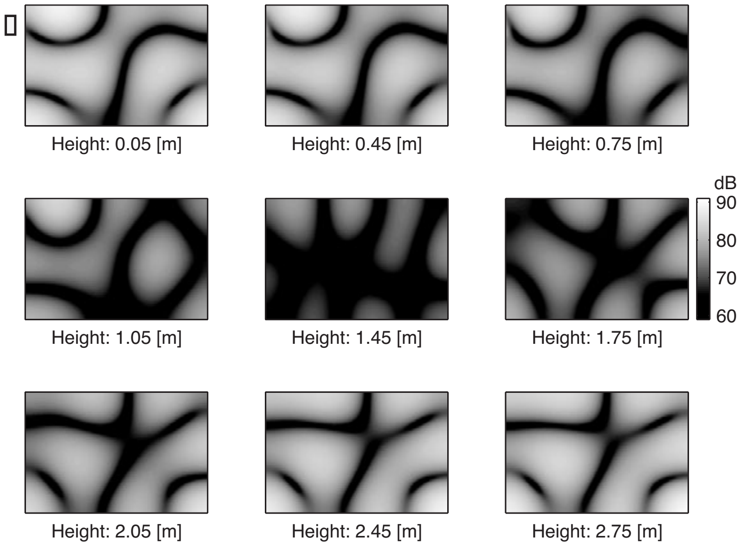

Figure 5 Sound pressure distribution in a 5.7 m by 3.8 m by 2.8 m (L x W x H) room. Sinusoidal sound wave at 114 Hz generated by a concentrated source in lower left corner (implemented as a 1 m by 1 m piston) indicated by rectangle. Simulated using FDTD with 0.1 m cell size and 6 kHz sampling frequency.

1.4 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 [12] as in equation (4):

$$f_{(p,q,r)} = \frac{c}{2} \cdot \sqrt{\frac{p^2}{L^2} + \frac{q^2}{W^2} + \frac{r^2}{H^2}} \tag{4}$$

where *L, W* and *H* are the dimensions of the room, *p*, *q* and *r* 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.

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 larger than the half wavelength (3.2 m) of a free travelling wave of the same frequency.

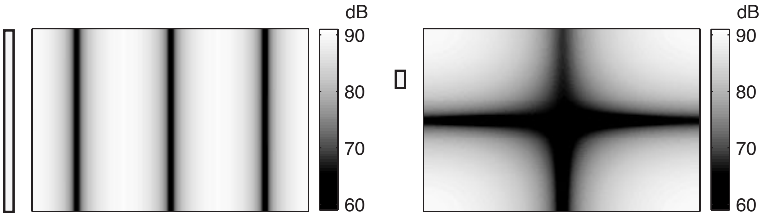

Figure 6 Sound pressure distribution in a 5.7 m by 3.8 m by 2.8 m (L x W x H) room. (Data from floor plane, but variation with height is marginal). Left: sinusoidal sound wave at 90 Hz (mode 3,0,0) generated by left end-wall indicated by rectangular bar. Right: sinusoidal sound wave at 54 Hz (mode 1,1,0) generated by vertical line source on left end-wall indicated by rectangle. 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. 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 larger than the half wavelength (1.4 m) of the free wave in the length and width directions. The asymmetry in low-level areas that is particularly visible at height 1.45 m is due to the asymmetrical position of the source and the finite sampling of the room.

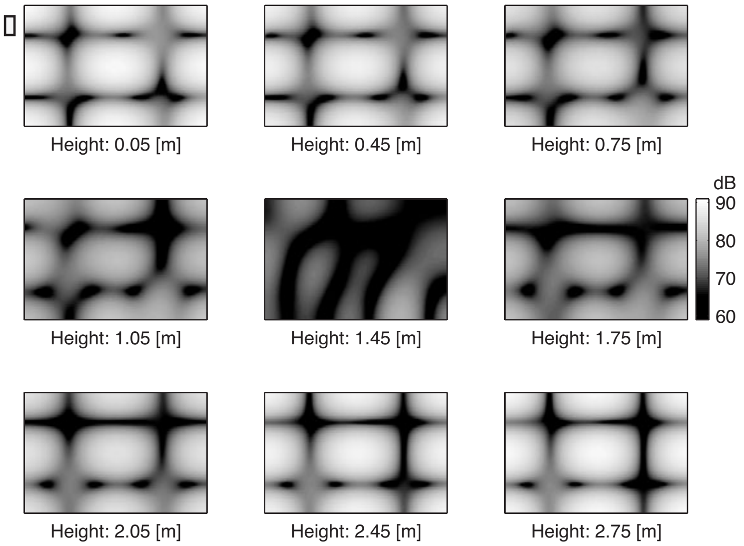

Figure 7 Sound pressure distribution in a 5.7 m by 3.8 m by 2.8 m (L x W x H) room. Sinusoidal sound wave at 124 Hz (mode 2,2,1) generated by piston in lower left corner indicated by rectangle. Simulated using FDTD with 0.1 m cell size and 6 kHz sampling frequency.

In general, the standing wave patterns at the modal frequencies are symmetrical in one, two or three dimensions. High levels are found at the "terminations" of the room in a broad sense, i.e. walls, 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.

The first 25 modal frequencies for the rectangular example room are displayed in Table 1. Note that the 114 Hz frequency used for the non-modal examples is close to the modal frequencies f(1,2,1) and f(3,1,1).

Table 1

First 25 modal resonances for the example room (excluding the first mode f(0,0,0)).

Mode number	Modal frequency
f(1,0,0)	30.09
f(0,1,0)	45.13
f(1,1,0)	54.24
f(2,0,0)	60.18
f(0,0,1)	61.25
f(1,0,1)	68.24
f(2,1,0)	75.22
f(0,1,1)	76.08
f(1,1,1)	81.81
f(2,0,1)	85.86
f(0,2,0)	90.26
f(3,0,0)	90.26
f(1,2,0)	95.15
f(2,1,1)	97.00
f(3,1,0)	100.92
f(2,2,0)	108.48
f(3,0,1)	109.08
f(0,2,1)	109.08
f(1,2,1)	113.16
f(3,1,1)	118.05
f(4,0,0)	120.35
f(0,0,2)	122.50
f(2,2,1)	124.58
f(1,0,2)	126.14
f(3,2,0)	127.65

A comparison of the standing wave patterns at modal and non-modal frequencies shows that, at modal frequencies, high levels are found at all "terminations" for the given mode (two walls, four two-dimensional corners, eight three-dimensional corners), while, at non-modal frequencies, high levels are only found at some of these.

1.5 Summarizing observations

For both modal and non-modal frequencies, and for one-, two- and three-dimensional waves, it was seen that the high level observed in some three-dimensional corners either extends far into the room or repeats in other regions of the room (within a couple of decibels). Conversely, the highest level in the room was always observed in at least one three-dimensional corner. This makes the corners unique for capturing the highest level of a room.

Some moderation applies near a concentrated source, though, where the level may be higher than in other areas, including three-dimensional corners. On the other hand, high levels are not generally seen at the source position. If a concentrated source is near a three-dimensional corner, the level observed in that corner, may not apply to other areas of the room.

The authors have made a large number of other simulations (varying the frequency, source position, room dimensions and impedances), and generally, similar observations could be made.

2. MEASUREMENT PROCEDURES

With the observations on standing wave patterns in mind, it is obvious that the result of a measurement in a room will depend much on the position. In many countries, recommended procedures for indoor measurements of sound at low frequencies for annoyance assessment have not paid attention to this problem. In other countries, the problem is recognized, and in these, measurement procedures generally aim at finding a level that represents high-level areas of the room rather than the room average. Guidelines of selected countries are briefly reported in the following.

2.1 Sweden

The Swedish procedure for measuring low-frequency noise in dwellings is described in [10]. It covers the third-octave bands ranging from 31.5 Hz to 200 Hz. The measurement procedure is based on Simmons' work [4],[5], which evaluated results of 24 different measurement methods in 10 rooms. General conclusions were that above 250 Hz all measurement methods (except a few special corner methods) performed well in estimating the room power average. However, for low-frequency noise, general-purpose methods (not intended for low frequencies) proved unsuitable, since they had unacceptable scatter and in general underestimated the room power average. For measurements at low frequencies, it was proposed to search for the corner position with the highest C-weighted level ("strongest" corner) and include measurements at that position.

The resulting Swedish procedure uses the power average of the levels measured in three positions. Two positions are selected as representative ear positions in normal 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 height must be 0.6, 1.2 or 1.6 m. The distance between positions should not be less than 1.5 m, however this is considered less important than obtaining positions that are representative of the usage of the room. The third position is a corner position selected by vertically scanning the two-dimensional corners of 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. The selected position is denoted ***SE corner*** in the following.

2.2 Denmark

The Danish guidelines for measuring low-frequency noise and infrasound in rooms are given in [9] and described by Jakobsen in [13]. The frequency range covered is 5-160 Hz. The measurement procedure is based on the work by Jakobsen [3]. Measurements were made in three rooms, and in conclusion, it was proposed to adopt a modification of the Swedish method for use in Denmark. As in the Swedish method, the power average from measurements in three positions is used, however the choice of positions deviates somewhat. Two positions of height 1-1.5 m are selected based on 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. Like in the Swedish method, the third position is a corner position, but no scanning for maximum is performed. 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 distances to the adjoining walls must be 0.5-1.0 m. In the following, a corner that fulfils these requirements is denoted a ***DK corner***. In small rooms (below 20 m^2), two DK corner positions in different floor-plane corners may be used as the only measurement positions.

2.3 Other countries

A slightly modified version of the Swedish method has been adopted in ISO 16032 [14] as an engineering method for measurement of sound from service equipment in buildings in octave bands from 31.5 Hz to 8 kHz. The method still uses the power average of levels measured in three positions, of which one is a corner similar to the SE corner, except that the scanning for maximum is done at discrete heights of 0.5 m, 1.0 m or 1.5 m. The other two positions are selected with slightly other restrictions than in the Swedish guidelines.

The rules in Germany are given in [15]. The frequency range covered is 10-80 Hz. Measurements must be carried out in the room where the noise is most annoying. The problem with level variations within the room is not mentioned, and only one (arbitrary) position is used. Similar rules exist in Austria [16].

The Dutch guidelines for measurement and assessment of low-frequency noise from 20 to 100 Hz are described in [8]. These guidelines prescribe the use of a single measurement position chosen either by the complainant, or in the corner of the room with 0.2 to 0.5 m distance to the walls. No height above the floor is given.

Japanese guidelines regarding low-frequency noise from stationary sound sources were published in [6] and also described in [17] and [18]. Measurements are performed in different ways depending on whether there are complaints of rattling in buildings or of mental and physical discomfort. In the case of complaints of rattling, measurements are performed outside in a position 1 or 2 m from the complainants building, and the sound pressure is evaluated in third-octave bands in the range from 5 to 50 Hz. If the noise is claimed to cause mental and physical discomfort, measurements are performed inside the complainant's residence. Only one measurement position is used, and it must be appointed by the complainant. The measurements are evaluated in third-octave bands in the range from 10 to 80 Hz.

American rules for description and measurement of environmental sound are given in ANSI S12.9 Part 1 [7]. For measurements of noise indoors, a "space-time-averaged" level is preferred. Depending on the averaging method, this may refer to various measures, but most likely, it is meant to be a power average. Measurement positions must generally have at least 1 m distance to the walls, ceiling, floor and other major reflecting surfaces and 1.5 m distance to windows. For low frequencies, multiple microphone positions are required, and room corners are preferred locations. Whether such corner positions are exempt from the distance requirements is not specified. It is noted that, due to standing waves, indoor measurements have greater variability than equivalent free-field outdoor measurements.

2.4 On corner positions

As seen in the simulations and summarized in Subsection 1.5, three-dimensional corners are useful positions for capturing the highest level of a room. Measurements in three-dimensional corners with a minimum distance to the room boundaries (distance < 0.1 m, i.e. in the order of a small fraction of a wavelength), are therefore included in the measurement programme of the present investigation. These are denoted ***3D corners*** in the following.

As already reported, several methods use what they denote corner positions. However, these are usually understood as two-dimensional corners of the floor plane, and it is not obvious that sound in these positions should generally represent maxima of sound waves that propagate in three dimensions. The scanning technique of the Swedish method may efficiently account for the vertical dimension. Random selection of the corner as with other methods, and a height typically around the middle of room in the vertical dimension, seem less convincing. Furthermore, requirements of a distance to the walls may disqualify the positions as corner positions, even in two dimensions. In particular with the Danish method, this distance may amount to a substantial part of a wavelength at the highest frequencies concerned.

3. METHOD

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 Swedish and Danish guidelines as well as in 3D 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, three walls made of gypsum boards and one double brick wall with a large window. The living room and the bedroom had brick-walls, wooden floors and wooden ceiling. 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 an adjacent room, 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 phenomena observed did not differ qualitatively from those with the source outside, and the final measurements were only made with the source outside the rooms.

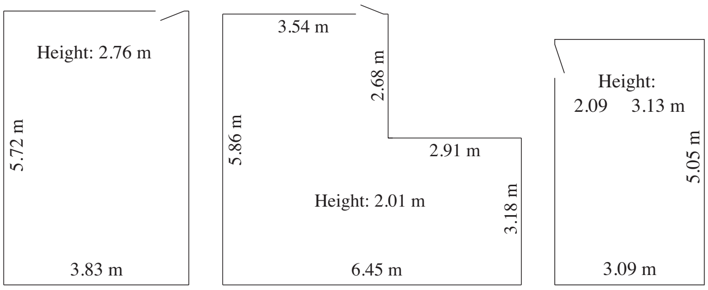

Figure 8 Floor plans of rooms used for measurements: 1) office (left), 2) living room (centre) and 3) bedroom (right).

3.2 Sound signals

The sound signals were pure tones and third-octave-band noise (the latter referred to as noise signal in the following) at 31.5 Hz and 125 Hz (a total of four signals). 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). Two signals were emitted simultaneously from each their loudspeaker, either the two tone signals or the two noise signals. During the analysis, the simultaneous signals were separated by third-octave filters.

3.3 Measurements

The sound in the room was measured by a scanning technique, where a microphone mounted on a 1.5-2 m pole was moved by hand through the entire space of the room with constant speed (utilizing string and tape as distance markers, and a stopwatch). 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 (01 dB) and subsequently analyzed in Matlab (The MathWorks).

The scanning was performed in a number of equally spaced vertical planes, parallel to the end wall. Each plane was scanned in a number of horizontal bars, equally spaced in the vertical dimension. The bars were alternately scanned left-right and right-left to avoid large jumps. The spacings (between bars in a plane and between planes) were at the most one eighth of a wavelength. Since 31.5 Hz and 125 Hz were measured at the same time, the maximum spacing was set by the higher of these frequencies, i.e. 0.34 m. Minimum distance to walls was half of this. The total scanning trajectories were approx. 480 m for the office and the living room, and approx. 350 m for the bedroom. 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, 0.8 s for the 31.5 Hz sine, and 0.2 s for the 125 Hz sine. These windows result in an r.m.s. value of the error of 0.5 dB for the noise bands (see e.g. [19]), much lower 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. This means that the microphone was moved less than one tenth of a wavelength within a time window for the two noise signals, and much less (< 0.015 times the wavelength) for the tone signals. For practical reasons, the room was split into sections (octants), and the octants were scanned one after the other by starting at a 3D corner and ending at the centre of the room. Since the scanning of a room was quite demanding and took a long time (88 minutes for the living room), scanning (and recording) was halted at appropriate stages between room sections. In some areas (mostly in the living room and bedroom), it was not possible to follow the scanning pattern strictly due to obstructing furniture etc.

Measurements in 3D 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 DK and SE corner positions were made in separate periods after the scanning. The SE corner was found by manual scanning of the C-weighted level while only one signal was generated at a time, before a separate recording was made. To obtain eight examples of DK corner positions, measurements were made in each of the two-dimensional corners at distances of 0.5 m and 1.0 from the walls, all at a height of 1.25 m. The DK corner measurements were made simultaneously four at a time, utilizing four channels of the measurement system. In the L-shaped living room, two extra DK and 3D corners exist, and measurements were also made in these.

3.4 Analyses

In addition to raw data and general statistics on these, possible outcomes of the Swedish and Danish methods were calculated by Monte Carlo analyses. In these, two positions in the room were selected randomly among those where measurements could take place according to the rules (different rules for the Swedish and Danish methods, see Sections 2.1 and 2.2). The Danish method does not have a requirement on distance between positions, but since very close positions would hardly be chosen in practice, a horizontal distance of at least 1 m was used with the Danish method. Furthermore, the Danish method states that positions near the centre of a room should not be used, but no distance is specified. A distance of 0.5 m to the centre along both the width and length of the room was used. For the selected positions, the closest point on the scanning trajectory was found, and, using information on the scanning pattern, these were converted to time within the scanning period, and the corresponding levels were observed. For the Swedish method, the two levels were power averaged with the level of the SE corner. For the Danish method, the two levels were power averaged with the level in one DK corner, selected randomly among those eight where measurements took place. For each method, room and signal, the procedure was carried out 1,000 times, thus 1,000 different outcomes of the method were obtained, and statistics of these are presented. With the procedure carried out 1,000 times, differences between repeated runs were marginal. The aspect that the two non-corner positions were chosen randomly and not - as preferred in the

Danish method - appointed by an annoyed person as positions, where the noise is particularly annoying, is discussed in Section 5.3. Since the bedroom is below 20 m^2, the Danish method was accomplished by taking the power average of two randomly selected DK corners (24 combinations when avoiding two positions in the same floor-plan corner).

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 indicates the distance of the microphone travel. The division of the room into eight sections is clearly seen with the 31.5 Hz noise and 33 Hz sine signals (Figure 9). The frequency is close to the lowest axial mode of the room, and as the scanning of each of the eight sections was started near a corner, a very distinctive pattern emerges. The sound pressure is high at the beginning of each octant and decreases as the microphone approaches the centre of the room. The abrupt shifts in the level are the result of the scanning process being halted between sections and the microphone being moved to its starting position in the next section to be scanned. The scannings of all octants end near the centre of the room, thus all octants end at approximately the same level. For the actual room, this is near the minimum of the room, but not exactly at the minimum, in particular not for the 33 Hz tone, where much lower values are seen before the abrupt shift in some of the octants. 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.

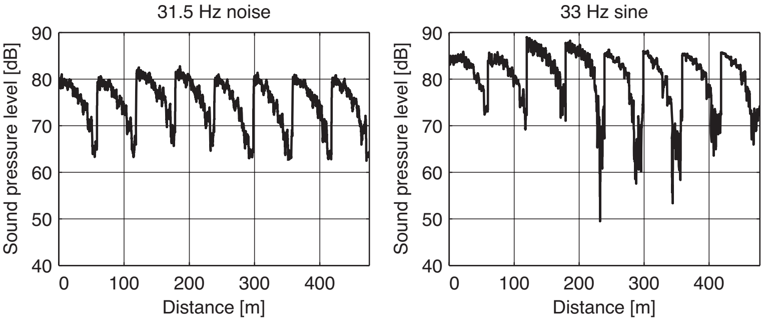

Figure 9 Scanning measurement in the office. Left: 31.5 Hz third-octave-band filtered pink-noise signal. Right: 33 Hz sinusoidal signal.

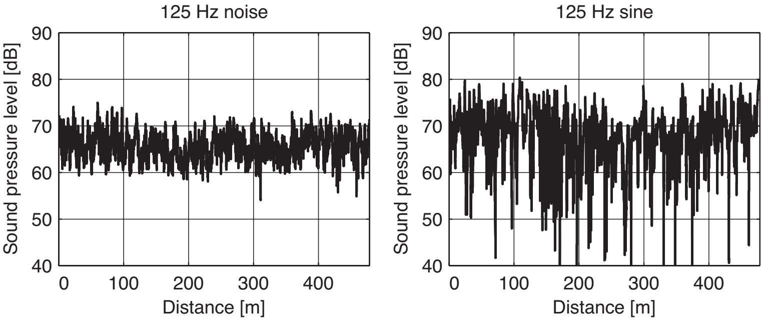

Figure 10 Scanning measurement in the office. Left: 125 Hz third-octave-band filtered pink-noise signal. Right: 125 Hz sinusoidal signal.

In the scanning measurements with the two 125 Hz signals (Figure 10), the pressure dips appear much closer throughout the room and do not show a simple pattern. By looking at a shorter time-interval from these scannings (Figure 11), it is revealed that the level varies much more in a narrow region than with the two lower frequency signals. 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.

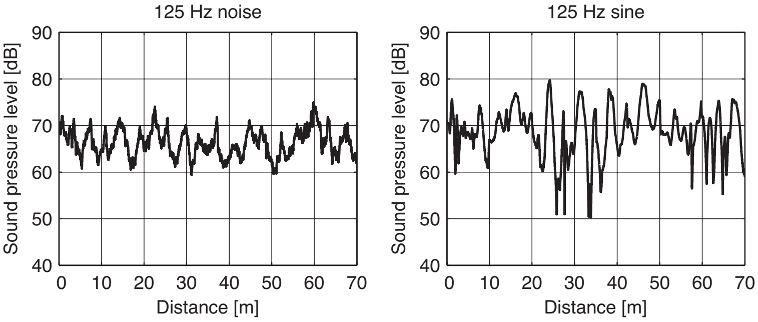

Figure 11 Zoom on first 70 m trajectory of scanning measurements in the office. Left: 125 Hz third-octave-band filtered pink-noise signal. Right: 125 Hz sine signal.

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. 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.

The lower frames of Figure 12 and Figure 13 show the room power average, results from the individual SE, DK and 3D corners, and results for the complete Swedish and Danish methods. The latter are given in terms of ranges, lower and upper quartiles and medians from the Monte Carlo analyses. The room power average was calculated as the r.m.s. level for the entire scanning period.

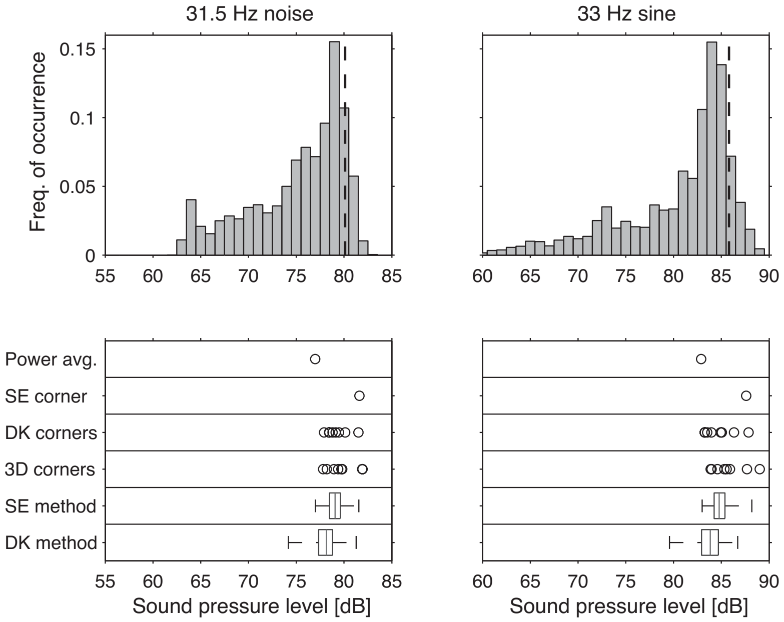

Figure 12 Measurements in office with 31.5 Hz third-octave-band noise (left) and 33 Hz tone (right). Upper frames: Histograms of scannings (dashed line indicates L_{10}, see Discussion); Lower frames: Room power average levels, levels of SE, DK and 3D corners, results of complete Swedish and Danish methods (ranges, lower and upper quartiles, medians from Monte Carlo analyses).

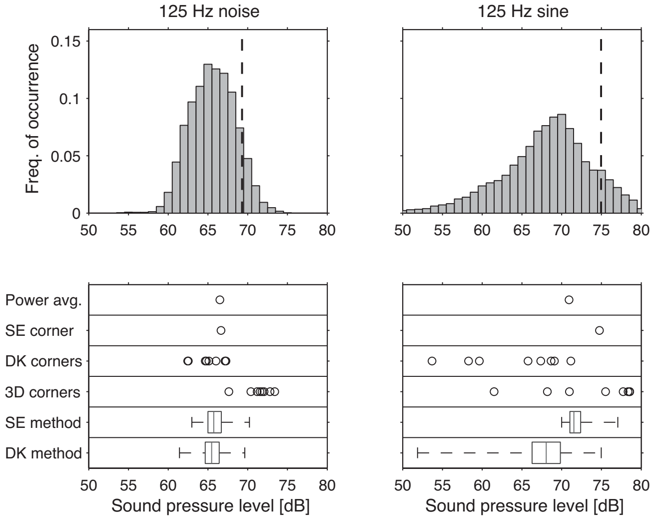

Figure 13 Measurements in office with 125 Hz third-octave-band noise (left) and 125 Hz tone (right). Upper frames: Histograms of scannings (dashed line indicates L_{10}, see Discussion); Lower frames: Room power average levels, levels of SE, DK and 3D corners, results of complete Swedish and Danish methods (ranges, lower and upper quartiles, medians from Monte Carlo analyses).

For all sounds, due to the power averaging process, the room averages lie in the upper part of the ranges, however still some decibels from the highest levels. The complete Swedish method gives results centred in the upper part of the ranges, for the 125 Hz noise though, somewhat closer to the middle of the range than for the other signals. For the Danish method, results rather tend to be around the peaks of the histograms, and the ranges are larger. The latter is particularly striking for the 125 Hz sine.

4.2 Living room

The scannings from the living room and the bedroom show the same characteristics as for the office, and they are not shown in this presentation. Histograms, room power average, corner results and results of the two methods from the living room are displayed in Figure 14 and Figure 15. Also here, wide ranges of levels are found in the room. Like for the office, the Danish method gives lower values and much higher variability than the Swedish method.

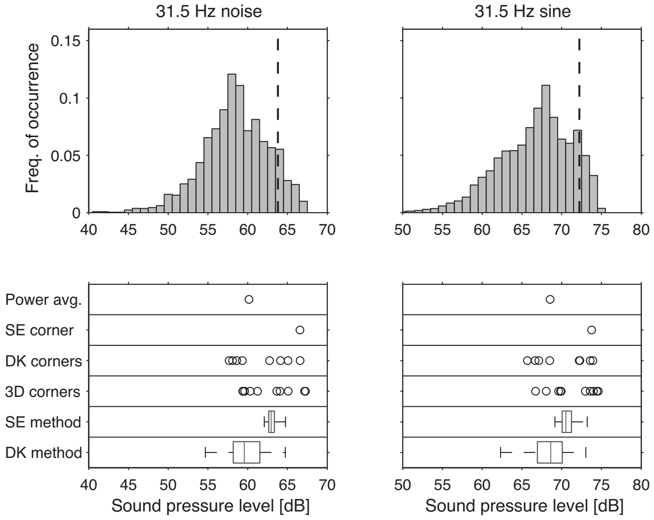

Figure 14 Measurements in living room with 31.5 Hz third-octave-band noise (left) and 31.5 Hz tone (right). Upper frames: Histograms of scannings (dashed line indicates L_{10}, see Discussion); Lower frames: Room power average levels, levels of SE, DK and 3D corners, results of complete Swedish and Danish methods (ranges, lower and upper quartiles, medians from Monte Carlo analyses).

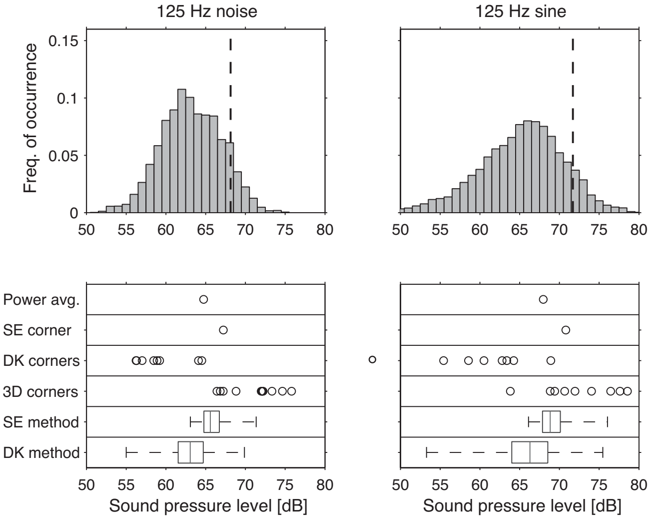

Figure 15 Measurements in living room with 125 Hz third-octave-band noise (left) and 125 Hz tone (right). Upper frames: Histograms of scannings (dashed line indicates L_{10}, see Discussion); Lower frames: Room power average levels, levels of SE, DK and 3D corners, results of complete Swedish and Danish methods (ranges, lower and upper quartiles, medians from Monte Carlo analyses).

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. For the bedroom, it was noted, though, 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. This is seen in the upper ends of the histograms as a flat range with low probability that reflects the small volume near the door. Since the door was in a corner, unusually high levels were found in some of the corner positions. Consequently, the results of the Swedish method are more towards the upper ends of the ranges than for the other rooms (and for the 31.5 Hz signals in the bedroom), and the upper quartile of the Danish method is further away from the median than in most other cases.

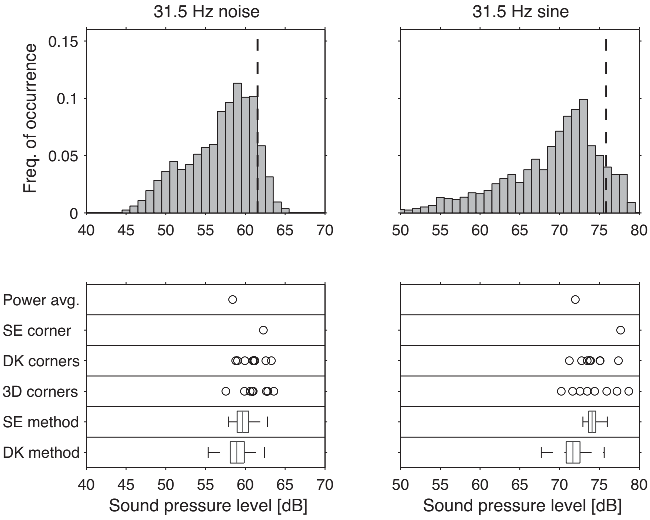

Figure 16 Measurements in bedroom with 31.5 Hz third-octave-band noise (left) and 31.5 Hz tone (right). Upper frames: Histograms of scannings (dashed line indicates L_{10}, see Discussion); Lower frames: Room power average levels, levels of SE, DK and 3D corners, results of complete Swedish and Danish methods (ranges, lower and upper quartiles, medians from Monte Carlo analyses).

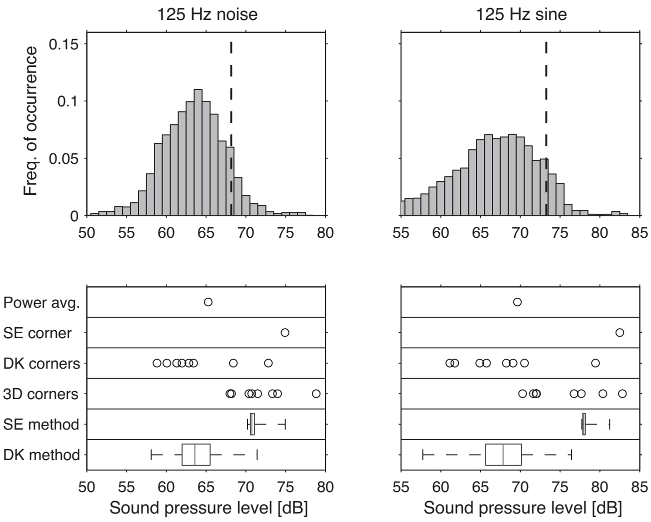

Figure 17 Measurements in bedroom with 125 Hz third-octave-band noise (left) and 125 Hz tone (right). Upper frames: Histograms of scannings (dashed line indicates L_{10}, see Discussion); Lower frames: Room power average levels, levels of SE, DK and 3D corners, results of complete Swedish and Danish methods (ranges, lower and upper quartiles, medians from Monte Carlo analyses).

5. DISCUSSION

It seems widely agreed that indoor measurements of low-frequency sound for use in assessment of noise-induced annoyance should reflect high-level areas of a room rather than a room average. 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' ears are not normally present in that part. As a rational and objective 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 small fraction of the room. A 10% exceedance level is suggested, and used in the following. This level is the 90th percentile of the cumulated distribution function and is denoted L_{10}. The level is indicated with dashed line on the histograms in Figure 12 to Figure 17.

Results from all rooms and all signals are summarized in Figure 18. Room power average, and results of the Swedish and Danish methods are given relative to the target L_{10}. For each method, the results from each of the three rooms are grouped by signal. Thus, the signals (31.5/33 Hz tone, 31.5 Hz noise, 125 Hz tone and 125 Hz noise) are separated by dashed lines, and in each of these groups, three results are shown for the office, living room and bedroom respectively.

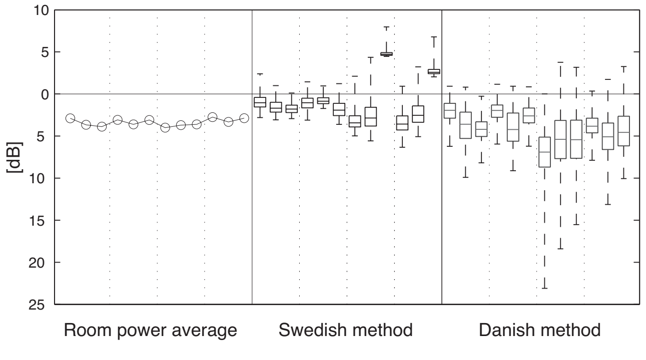

Figure 18 Summary of results given relative to the L_{10} target for each room and signal: Room power average, Swedish method (range, quartiles, median), Danish method (range, quartiles, median). For each method, results are ordered by signal (31.5/33 Hz tone, 31.5 Hz third-octave noise, 125 Hz tone, 125 Hz third-octave noise - separated by dashed lines) and for each signal by room (office, living room, bedroom).

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 and signal.

If a full scanning of the room is needed to obtain the room power average, there is no advantage in using this connection, since, from the scanning, L_{10} can be found directly. For any practical situation in the field, though, such scanning is not feasible. On the other hand, if a less demanding method exists for finding the room power average, adding 3-4 dB to the result of such method would provide a very good estimate of the L_{10} target. A method that seems promising for obtaining the room power average also at low frequencies, is power averaging along a three-dimensional diagonal (Moorhouse and Ramadoray [20]).

5.2 Swedish method

The Swedish method gives results that are concentrated around, or a few dB below, the target in most cases. An exception is the bedroom with the two 125 Hz signals, where the method shows too high levels. This is recalled as the situation, where significant transmission into the room took place through a door near a corner (Section 4.3), and where an unrepresentatively high value was seen for some corner measurements, including the SE corner.

The variability of the method is moderate, which is explained by the fact that the high corner level is always included, and the power averaging then guarantees a resulting level not far from that. Even if the two other levels are very low, the power average will still be within 5 dB of the SE corner level.

The selection of the SE corner by scanning is not without problems, though. With a constant noise source, it is easy to perform the scanning with pure tones; however, with noise bands, the level fluctuation inherent in the signal makes the scanning difficult. Furthermore, if the noise source is not constant, the selection of the SE corner position becomes very difficult, and a significant degree of uncertainty is inevitable. In the case of narrow-band or pure-tone noise, small frequency changes may even cause the maxima to move during the scanning and/or between the scanning and the measurement.

However, the biggest concern regarding the Swedish method is that the scanning uses the C-weighted level. The annoying noise component is not necessarily the component that contributes most to the C-weighted level. Therefore, the selection of corner and vertical position may be decided from a wrong component 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 has a much higher level and dominates the C-weighted level. The scanning will thus find the maximum for the 31.5 Hz tone, but at this position, nothing is known about the 150 Hz tone. Also background noise, e.g. from wind, is liable to dominate the C-weighted level and impede the scanning. If the scanning fails to catch the highest level of the annoying frequency component, the SE corner position is just an arbitrary corner position, and the result will tend to resemble those of the Danish method. Thus, the Swedish method relies heavily on, that the C-weighted level truly represents the noise component that is the cause of annoyance.

5.3 Danish method

The results of the Danish method show levels below the target in all rooms and for all signals, however worst for the 125 Hz signals and in particular for the pure tone. Furthermore, the method shows large variability in the results, also most prominent for the 125 Hz signals.

In the Danish method, it is preferred that the complainant appoints the two non-corner measurement positions, thus they are not selected randomly as in the Monte Carlo analyses. If the appointed positions really represent high-level areas of the room, results will be much better. The power averaging will guarantee a final result close to the level observed in these positions, regardless of the level measured in the DK corner (within 5 dB, if the level in only one position is high, within 2 dB, if the two levels are equally high).

Since the appointment by the complainant of high-level measurement positions is pivotal in the Danish method, it deserves some comments. Source fluctuations, changes in pure-tone frequencies that move the maxima and other matters can make this appointment difficult. It is also the author's experience that complainants are often unable to point at relevant measurement positions with sufficient accuracy. This was also noted as a general experience by the Danish Environmental Protection Agency [21]. It is difficult for the measurement technician to help, since he/she may not know what the annoying sound is, and it may not be clearly audible to him/her. Even when a complainant can point to suitable areas, 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 5).

Presumably, the corner position was included in the Danish method in order to prevent it from getting an unrepresentatively low result in cases where the two non-corner positions fail to capture the highest level. This may work for the lowest frequencies, but for frequencies in the upper end of the low-frequency range - here represented by the 125 Hz signals - this intention will fail. In the Danish method, no scanning is involved, and only a single arbitrarily selected DK corner is used. At 125 Hz, differences between DK corner positions are large, and the levels are generally low, worst for the tone. Thus, rather than assisting in capturing the high levels of the room, many DK corners will thus tend to lower the result. Examples of pressure dips in DK corner positions could also be observed in the simulations (e.g. Figure 5, central frame, upper right and both lower corners).

In the case of small rooms (below 20 m^2), no positions are selected by the complainant, and the Danish method relies solely on DK corner measurement. As seen for the bedroom, results show levels below the target, in particular for the 125 Hz sounds.

5.4 3D corners

On the background of the disadvantages of these methods - that the Danish method often gives levels significantly below the target, and that the Swedish method relies on an impractical and doubtful C-weighted scanning - it is obvious that alternatives are very much called for.

As seen in the simulations and summarized in Section 1.5, three-dimensional corners may be useful for capturing the highest levels of the room, and it is logical to examine the possibility of a method based exclusively on these. As predictable from the simulations and evident in the measurements (Figure 12-Figure 17), there is significant variation between 3D corners, and use of single 3D corners is not adequate. The logical choice would be the power average of all 3D corners. However, as observed in the simulations, unrepresentatively high levels may exist near the source, and it would be reasonable to exclude 3D corners close to an obvious and concentrated sound transmission path. For the rooms of the present investigation, this would result in the exclusion of two 3D corner positions in each room, all near a door.

Figure 19 shows the power average of 3D corners including and excluding the door corners. It is seen that values are close to the target. An overestimation of up to 5 dB is seen with the 125 Hz signals, however, this is reduced to a maximum of 3 dB, when the door-corner positions are removed.

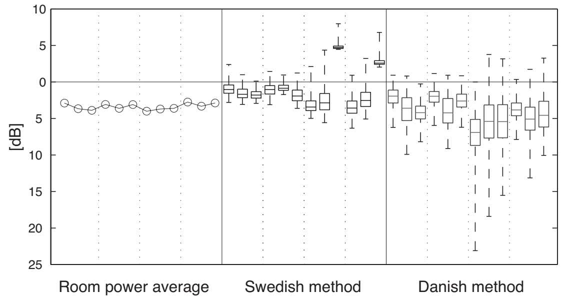

Figure 19 Results of power average of all 3D corners, and with corners near the door removed.

Also, the results from applying the (more unusual) pressure average of the levels have been investigated. This resulted only in a marginal reduction in the overestimation with the 125 Hz signals, and the standard deviation increased marginally. Thus power averaging was kept as the preferred averaging procedure.

A previous Austrian method [22] for measurement of sound of domestic technical facilities used, in cases where the noise was generated by electric transformers, the power average of the level measured in three 3D corners (0.1 m from boundaries). There are restrictions to the absorption of the boundaries, and with the use of these positions, the penalty for the presence of tonal components should be ignored. The method was included in the investigations by Simmons [4],[5], and averaged over several rooms. It was found to overestimate the room power average (measured by a grid of microphones) by approximately 4-6 dB below 200 Hz. Recalling that, in the present study, the L_{10} target was 3-4 dB above room average, the results of the Austrian method correspond to 0-3 dB above the target, which is consistent with the findings about the power average of 3D corners in the present study.

5.5 Proposal for a new measurement method

Even when a method using all 3D corners (except source-near corners) would have a number of advantages, the number of measurement positions may be on the high side for many practical situations. As a practical alternative, a method based on four 3D corners is therefore proposed in the following. Some restrictions on the selection of corners are proposed, but of course, later studies may show that other restrictions are more adequate.

The proposed method is characterized by the following:

- The result is the power average of measurements made in four 3D corners
- 3D corners are positions in three-dimensional room corners with a maximum distance to the room boundaries of 0.1 m
- If an obvious and concentrated source or transmission path is near a 3D corner, and the area is not part of the normally occupied space of the room, that 3D corner should not be selected. Large surfaces, e.g. large window areas, should not be considered as a concentrated source or transmission path
- The 3D corners are selected randomly, but all surfaces (all walls, floor, ceiling) must be represented

Applying the proposed method on the measurement data obtained in the present study gives 13 possible combinations for choosing the measurement positions in the office and the bedroom and 65 combinations in the L-shaped living room. Statistics of the results are displayed in Figure 20 together with the results for the Swedish and Danish methods. It is seen that the method hits the target at least as well as the Swedish method and substantially better than the Danish method.

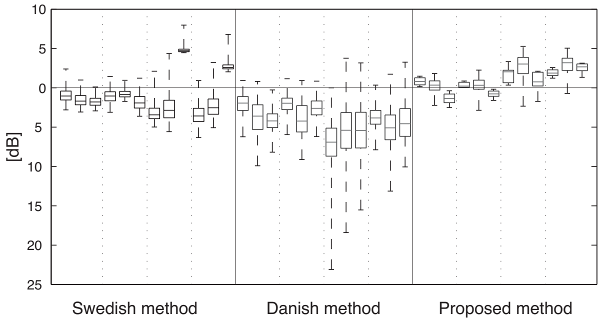

Figure 20 Statistcs (range, quartiles and median) of applying the proposed measurement method in the three rooms. Results are relative to the L_{10} target. For each method, results are ordered by signal (31.5/33 Hz tone, 31.5 Hz third-octave noise, 125 Hz tone, 125 Hz third-octave noise - separated by dashed lines) and for each signal by room (ofFice, living room, bedroom).

The proposed method has the significant advantage that the measurements will capture the low-frequency noise that is present, whatever the frequency. It should be noted that the 3D corner positions serve as the only measurement positions, thus no scanning is needed. 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, different technicians will end up with similar results within the small variation resulting from the arbitrary selection of corners. One more microphone position is used than in the Swedish and Danish methods, however a more reliable and repeatable result is obtained. Modern measurement systems often have multi-channel options, and it is probably within the capacity of most consultants to make parallel measurements in four positions. This is very convenient, since then only one undisturbed time period is needed, and all measurements represent the same period.

6. CONCLUSIONS

It is evident from simulations and from practical measurements in three rooms that the sound pressure level in rooms varies considerably at low frequencies. For low frequencies, it is thus not adequate to describe sound in a room from measurements in a single position. There seems to be agreement that, for assessment of annoyance, the measurement result should mainly reflect high-level areas of the room, since persons present in such areas are not helped by the existence of lower levels in other areas. The level that is exceeded in 10% of the space of a room, L_{10}, is proposed as a rational and objective target.

The room power average plus 3-4 dB seems to be an almost perfect estimator of the target. However, in practical situations, it is not feasible to perform a true measurement of the room power average. The national methods used in Sweden and Denmark for low-frequency noise measurements use measurements near corners of the floor plan in their attempts to capture high-level areas of the room. With the Swedish method and its vertical scanning of corners, the corner measurement serves its purpose, and the method gives good results, provided that the annoying sound dominates the C-weighted level used during the scanning. If this precondition is not fulfilled, the Swedish method as a whole has a risk of giving results below the target. With the Danish method, the corner measurement completely fails to serve its purpose. However, the method as a whole can still work well, provided that the complainant can appoint precise measurement positions, where the sound is loudest/most annoying. If this precondition is not fulfilled, which is often the case, the Danish method has significant uncertainty and risk of giving results substantially below the target.

As an alternative, it is proposed to use the power average of measurements in four three-dimensional corners of a room. This is an easy and straightforward method, which seems to give reliable results close to the proposed target.

7. ACKNOWLEDGEMENTS

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