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Pedersen, Steffen; Møller, Henrik; Persson-Waye, Kerstin

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INDOOR MEASUREMENTS OF LOW-FREQUENCY NOISE FOR ANNOYANCE ASSESMENT

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Pedersen, Steffen[1]; Møller, Henrik[1]; Persson Waye, Kerstin[2]
[1]Acoustics, Dept. of Electronic Systems, Aalborg University; Fredrik Bajersvej 7 B5, DK-9220 Aalborg Ø, Denmark; [stp] [hm]@acoustics.aau.dk
[2]Occupational and Enviromnental Medicine, Göteborg University; Medicinaregatan 16, 40530 Göteborg, Sweden; kersin.persson-waye@amm.gu.se

ABSTRACT

The sound pressure level within a room may vary as much as 20-30 dB at low frequencies. Mainly the highest levels are of concern with regards to annoyance assessment, rather than a room average. The highest levels can however be very difficult to find. Sound fields in rooms were investigated using numerical simulations and scanning measurements of the entire sound pressure distributions in three different rooms. Measurements were also performed in three-dimensional corners as well as according to Swedish and Danish guidelines, which include positions close to corners in the floor plane (0.5 to 1 m) in an attempt to ensure high levels. The sound pressure level that is exceeded in only 10% of the space of a room (L_{10}) is proposed as a reasonable target for a measurement method. The Swedish method showed good results, however its inclusion of C-weighting can potentially be problematic. The Danish method was found to have a high risk of significantly underestimating the noise present in a room, unless complainants can precisely appoint the measurement positions. It was found that a very good estimate of the L_{10} target level can be obtained by measuring only in four three-dimensional corners.

INTRODUCTION

When sound waves propagate inside a room, they are reflected by the boundaries, resulting in standing wave patterns. 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 adequate. 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, as argued e.g. by Jakobsen [1] and Simmons [2],[3].

The present work studies the performance of current Swedish and Danish measurement methods in practice. Detailed measurements of sound fields are made in three different rooms for selected frequencies and frequency bands. The description of the experimental work is preceded by an introductory section on low-frequency sound in rooms and description of Swedish and Danish measurment procedures.

Sound in rooms

If a plane wave is generated by one end-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. At the reflecting wall, 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.

For sound propagation in three dimensions, analytical solutions become quite complex, in particular when the boundaries are not completely rigid. Thus, sound pressure distributions in rooms were investigated using the finite-difference time-domain method (FDTD) [4]. 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. A volume-velocity source was used, and the levels were adjusted, so that the highest sound pressure is 90 dB in all the examples. 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).

A series of simulations were performed to investigate the sound pressure distribution in rooms. Three different sound sources were used, all positioned on one end-wall of the room; a piston source, a line source and an entire end-wall. Several frequencies were used, with emphasis on both modal and non-modal frequencies. Two examples of three-dimensional wave propagation are given in Figure 1. Since the level varies vertically, the figure contains two-dimensional plots at various heights.

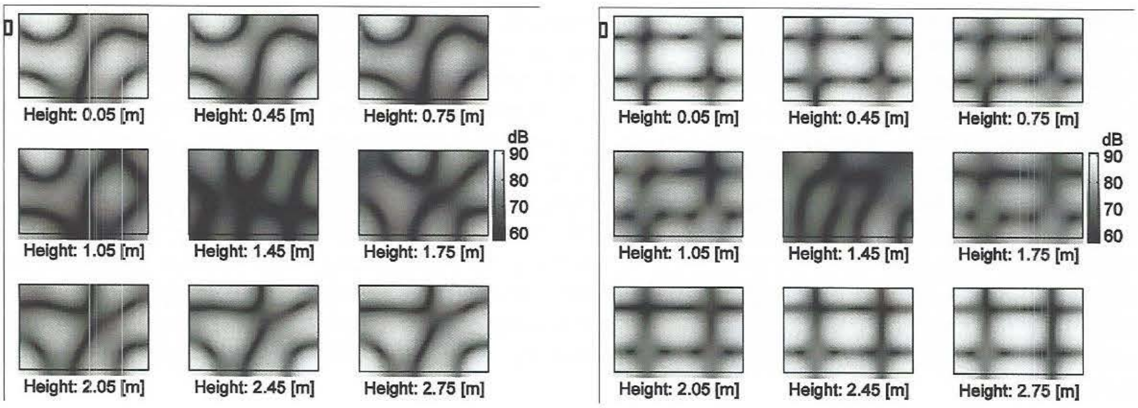

Figure 1: Sound pressure distribution in a 5.7 m by 3.8 m by 2.8 m (L x W x H) room. Left: Sinusoidal sound wave at 114 Hz. Right: Sinusoidal sound wave at 124 Hz (mode 2,2,1). Sound generated by piston in lower left corner indicated by rectangle. Simulated using FDTD with 0.1 m cell size and 6 kHz sampling frequency.

The left of Figure 1 illustrates the sound pressure distrubution for a 114 Hz (non-modal) pure tone generated by a piston near a three-dimensional corner. (Note that, in the two figures, three-dimensional corners are seen as two-dimensional corners at the upper left and lower right frames). A complicated pattern of high- and low-level areas is seen, and the pattern varies significantly with height. It is observed that high levels only exist on some three-dimensional corners, and there is significant level variation between corners. The right of Figure 1 illustrates the sound pressure distribution for a 124 Hz (mode 2,2,1) pure tone generated by a piston near a three-dimensional corner. It is seen that the standing wave pattern at this modal frequency is symmetrical in three dimensions. High levels are found in all the three-dimensional corners of the room. 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 three-dimensional corners while, at non-modal frequencies, high levels are only found at some of these. For both modal and non-modal frequencies, and for one-, two- and three-dimensional waves, it was found that the high level observed in some three-dimensional corners either extends far into the room or repeat 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.

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.

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 from Sweden and Denmark are briefly reported in the following.

The Swedish procedure for measuring low-frequency noise in dwellings is described in [5]. It covers the third-octave bands ranging from 31.5 Hz to 200 Hz. The 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, within certain resctrictions. The third position is a corner position selected by scanning 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. The selected position is denoted ***SE corner*** in the following. A slightly modified version of the Swedish method has been adopted in a ISO 16032 [6] as an engineering method for measurement of sound from service equipment in buildings.

The Danish guidelines for measuring low-frequency noise and infrasound in rooms are given in [7] and described by Jakobsen in [8]. The frequency range covered is 5-160 Hz. As in the Swedish method, the power average from measurements in three positions is used. Two positions of height 1-1.5 m are selected based on the general usage of the room, however within certain restrictions. If possible, these positions should be pointed out by the annoyed person as positions, where the noise is particularly annoying. The third position is a corner 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.

As seen in the sound field simulations, 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.

METHOD

The sound field was investigated in three rooms while sound was generated in adjacent 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. All rooms were naturally furnished. 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 woofer, either the two tone signals or the two noise signals. During the analysis, the simultaneous signals were separated by third-octave filters.

Measurements

The sound in the room was measured by a scanning technique, where a microphone mounted on a 1.5-2 m boom was moved manually 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 divided 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 maximum 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 resulting in an r.m.s. value of the error of 0.5 dB for the noise bands [9], 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. Measurements were performed in 3D corners and in DK and SE corners. The SE corner was found by manual scanning of the C-weighted level while only one signal was generated at a time. 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.

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). For the selected positions, the closest point on the scanning trajectory was found, and the corresponding levels were observed. 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. 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-plane corner).

RESULTS

The measurement results showed similar characteristics between the three rooms, and the raw measurement results are only shown for the office in Figure 2. Histograms of the levels observed in the scannings are shown for each of the signals in the upper frames of

Figure 2. The lower frames of Figure 2 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.

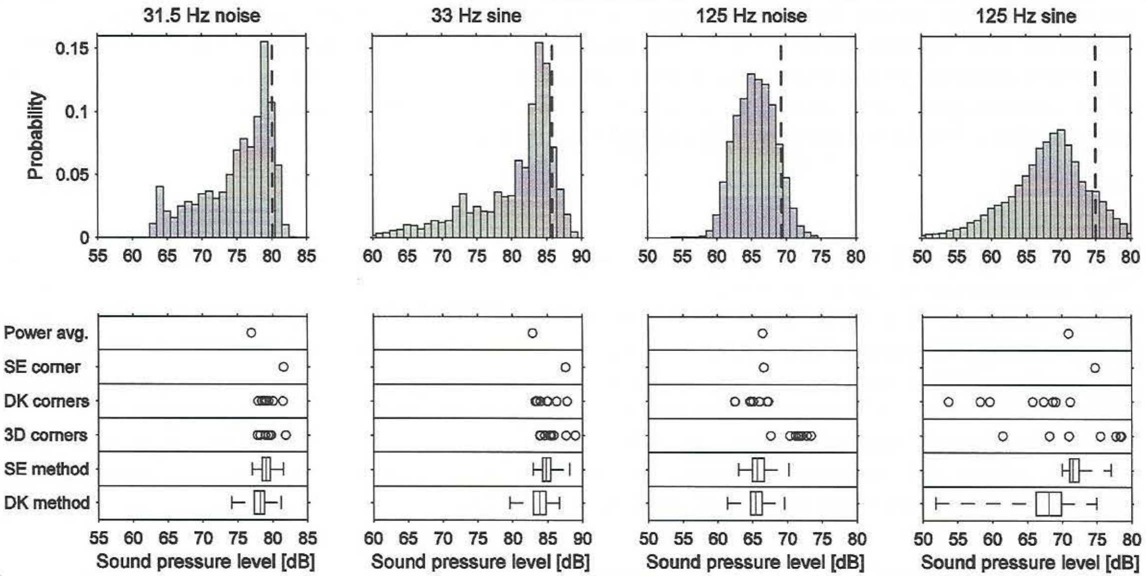

Figure 2: Measurements in office. Upper frames: Histograms of scannings (dashed line indicates L_{10}, see Discussion); Lower frames: Room power average levels, levels of SE, DK and 3D corners, results of complete Swedish and Danish methods (ranges, lower and upper quartiles, medians from Monte Carlo analyses).

DISCUSSION

It seems widely agreed that indoor measurements of low-frequency sound for annoyance assessment should reflect high-level areas of a room rather than a room average. It is proposed to use a certain point on the cumulative level distribution function, 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 denoted L_{10}, and is indicated with a dashed line on the histograms in Figure 2. It is seen that especially the Danish method may significantly underestimate the proposed target level, and thus an alternative method is proposed.

As a method for indoor measurement of low-frequency noise for annoyance assessment it is proposed to measure the level in four 3D corners. The four 3D corners are selected arbitrarily, but all surfaces (walls, floor, ceiling) must be represented. 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. The result is the power average of measurements made the four 3D corners.

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 relative to the L_{10} target are displayed in Figure 3, together with the room power average and the results for the Swedish and Danish methods for all four signals in the three different rooms.

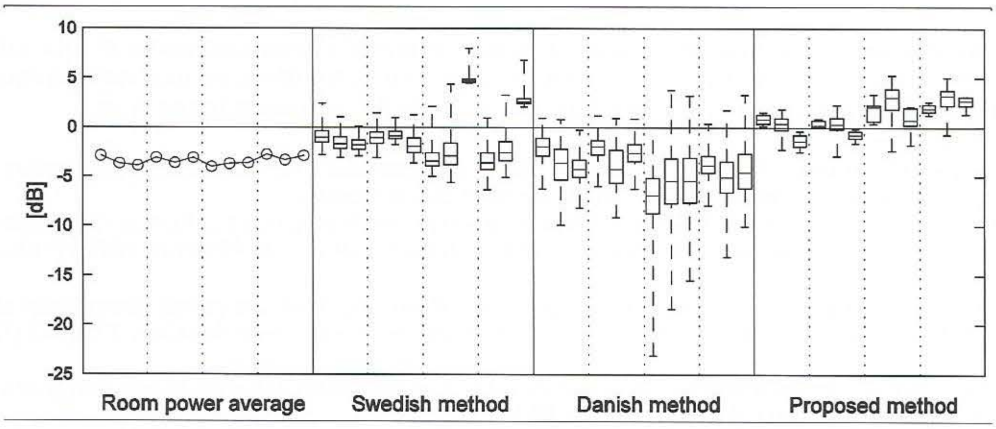

Figure 3: Summary of results given relative to the L_{10} target for each room and signal: Room power average, SE method (range, quartiles, median), DK method (range, quartiles, median) and the proposed method (range, quartiles, median). For each method, results are ordered by signal (31.5/33 Hz tone, 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).

It is seen, that the room power average proves to be consistently 3-4 dB lower than the target in all the rooms, independent of frequency and signal, and could thus by adding 3-4 dB be a good estimator of the L_{10} target. However, it is not feasible to measure in practice. The Swedish method seems to give good results, although slightly below the target level. However, there is some concern regarding its inclusion of C-weighting for the corner scanning. The results of the Danish method gives results significantly 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, there is a very large spread in the results. 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 better. The proposed method hits the target at least as well as the Swedish method and substantially better than the Danish method, and the spread is very low.

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.

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. 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 level. However, it is not feasible to measure. The national methods used in Sweden and Denmark use measurements near corners of the floor plan in their attempts to capture high-level areas of the room. Unfortunately, for different reasons, the methods may fail. The Swedish method comprises an unpractical scanning procedure, which – in order to work properly – requires that the C-weighted level is dominated by the annoying frequency component(s). The Danish method requires that the complainant can appoint precise measurement positions, where the sound is loudest/most annoying. If the preconditions are not fulfilled, both methods have a significant risk of giving values substantially below the target.

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

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