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AN INVESTIGATION OF LOW-FREQUENCY NOISE COMPLAINTS

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SUMMARY

In Denmark and in other industrialized countries there are cases where people complain about annoying low-frequency or infrasonic noise in their homes. Besides noise annoyance people often report other adverse effects such as insomnia, headache, lack of concentration etc. In many cases the noise can only be heard by a single person in the household, and if measurements are performed the authorities cannot find any noise exceeding the existing limits for noise. This raises the fundamental question whether the complainants are annoyed by an external physical sound, or if other explanations must be sought. The main aim of this study is to answer this fundamental question by thoroughly investigating 22 such cases. Recordings and analyses are made of the sound in the complainants' homes. Then each complainant is invited to the laboratory where low-frequency thresholds and equal-loudness-level contours are measured. In a blind test it is examined if they are able to hear the sound from their home. The paper reports on the methodological considerations regarding selection of respondents, recording and analysis of noise and laboratory experiments. However, since the investigation is still ongoing, no results are presented at this stage.

1. INTRODUCTION

In Denmark and in other industrialized countries there are cases where people complain about annoying low-frequency or infrasonic noise in their homes. A survey of such complaints including 203 persons was carried out at the Department of Acoustics, Aalborg University [1], [2]. The complainants usually described the noise as sounding like an idling diesel engine. Besides noise annoyance they reported other adverse effects such as insomnia, headache, lack of concentration etc. In many cases the noise could only be heard by a single person in the household which suggests that the noise is below the normal hearing threshold [3]. If noise measurements had been performed, the authorities typically did not find any noise that exceeded the Danish limits for low and infrasonic noise [4], [5]. The explanations could be that there simply is no external physical sound that is the cause of annoyance, or it could be other reasons such as insufficiency of the measurement methods used.

The main aim of this study is to investigate if it really is external physical sound that disturbs the complainants in their homes, and if they have an extraordinary low-frequency hearing. If it is external physical sound then the characteristics of the sound (frequency components, levels etc) will be examined. Furthermore different methods for measuring low-frequency sound in rooms including the Danish [4], [5] and the Swedish method [6] will be examined in practice. A sample of 22 complainants who all participated in the survey [1], [2] is included in the investigation. Sound recordings are made in their homes, and by the use of psychometric tests it will be examined if they are able to hear the sound. The paper will report on methodological considerations concerning the selection of respondents, recording and analysis of noise and laboratory evaluations. However, since this is still an ongoing investigation, no results will be reported at the present stage.

2. SELECTION OF CASES OF COMPLAINTS

It was decided to select a study sample of 22 subjects from the group of people who had participated in the initial survey. Based on their answers in the initial survey 26 persons were removed from the original population before selection. This applies to 23 subjects who had reported that the problem had been solved fully or partly, one subject who had expressed his/her own doubt that noise could be the cause, one subject who had reported that he/she did not have a sensory perception of sound, and one person who was under age. From the remaining 177 persons 20 subjects were selected randomly, while two subjects were selected because of long-time contact with the department.

In the original survey an unproportionally large number of the persons were geographically located in the north part of Zealand [1], [2]. The reason for this could be a combination of many low-frequency noise sources in this area and/or the special attention on this subject in the local media. In order to ensure that the random selection of the relatively low number of subjects would not result in subjects mainly from this area (or outside this area), it was decided to adjust the random selection procedure in such a way that the proportion of subjects from North Zealand and the Copenhagen area (zip-code < 3700) was as close as possible to that of the original population. Some of the selected subjects were not interested to take part in the investigation and new subjects were randomly chosen keeping the geographical distribution constant.

All 22 subjects that were included in the study population filled beforehand in a questionnaire evaluating general health (SF-36 Health Survey). This questionnaire was also sent out to the subjects who took part in the initial survey. The aim with this questionnaire is to compare the complainants' general health and wellbeing with a large reference material obtained from Danish people.

3. RECORDING OF LOW-FREQUENCY NOISE

3.1. Microphone positions

One crucial part of this investigation is to make good recordings that represent the sound that exists in the homes of the complainants. It is however not sufficient to place a microphone at a random position in the living room or bedroom and then record the sound. Due to reflections from the walls especially at low frequencies there will be standing wave patterns in the room. This will give frequency-dependant peaks and dips in the sound pressure level (SPL). If measurements are performed in only one or a few points in the room, then there is a risk of placing the microphone in a pressure dip of the standing wave pattern of the annoying frequency component(s) of the sound.

It is reasonable to assume that a person is annoyed by the largest SPL that exists in the region of the room where the person's ears will normally be located. If the complainant is able to pinpoint an exact position where the sound is most annoying then this point is considered to be the best recording position. However, the complainants are not always able to do this, so alternative measurement positions are usually needed. Standing wave patterns usually have their pressure peaks in corners so if measurements are performed in several three-dimensional corners (where two walls meet the floor or ceiling), then the risk of missing a frequency component is small. It was decided to make recordings in a total of 20 positions in the room using different placement criteria. These positions are chosen both with respect to getting representative noise recordings and with respect to obtaining data that will make it possible to compare different procedures for microphone placement.

Eight recordings were made with the microphones placed as close as possible (within a few centimeters) to three-dimensional corners. Furthermore eight recordings were made in positions that represent a range of positions complying with the "corner" positions in the Danish guidelines for measuring low-frequency noise [4], [5]. The positions were at a height of 1.25 m and at distances of either 0.5 m or 1.0 m from the two walls (see left Figure 1). One position was chosen in accordance with the Swedish "corner" procedure [6]. In short the procedure states that each corner is examined at a distance of 0.5 m from the walls and the height is varied between 0.5 m and 1.5 m. The corner and height with the highest C-weighted SPL is used (see right Figure 1). Three additional positions were chosen elsewhere in the room where persons would typically be (fulfilling both the Danish and the Swedish method), avoiding the middle position. These positions were preferably chosen, where the complainant experienced the highest sound or most annoyance.

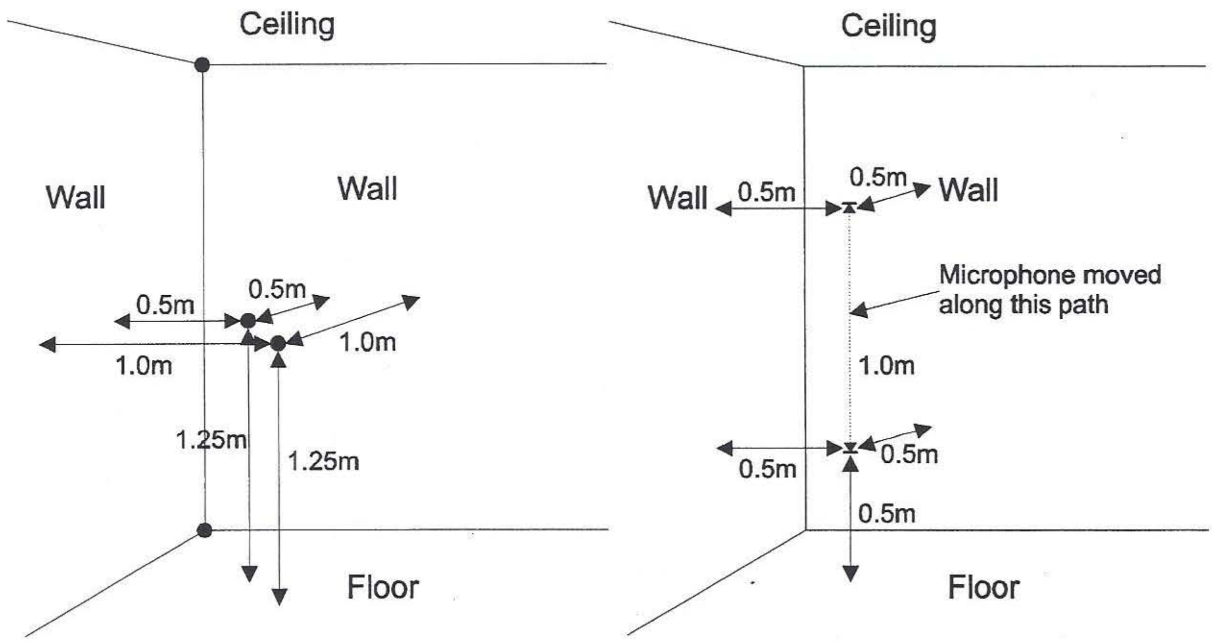

Figure 1: Left figure shows the four microphone positions (black dots) used for noise recordings in each corner in a room (Danish "corner method" and three-dimensional corners). The right figure shows the path where the microphone is moved in order to find the position with the highest C-weighted SPL (Swedish "corner method").

One criteria for choosing recording duration was efficiency since recording in 20 positions takes a considerable time. Another criteria was to get continuous sections of at least 30 seconds without disturbing sounds like passing cars etc. since this would allow for a high-resolution frequency analysis and give sufficiently long noise samples for use in a blind test.

A recording duration of three minutes was considered to be sufficient for finding undisturbed 30-second sections. If at the end of a recording period it was considered questionable that the period contained a 30-second period without disturbances, the recording was retaken.

3.2. Recording equipment

Ideally the sound in all 20 microphone positions should have been recorded simultaneously, since this would make the comparison between the different positions as good as possible. However, for practical reasons this was not possible. The recordings were performed using a four channel recording system (01 dB Harmonie connected to a notebook) with four GRAS 40EN one-inch microphones and four GRAS 26AK preamplifiers. Using this system it was possible to record four channels simultaneously meaning that the sound at four different microphone positions was recorded in each recording period. The recordings were performed at 16 bit and a sampling frequency of 6.4 kHz and stored on the hard drive of the notebook. The lower frequency limit for the microphones and the system was approx. 0.5 Hz while the upper frequency limit of the recording system with the selected sampling-frequency was 2.5 kHz.

3.3. Recording procedure

Before visiting a person the meteorological conditions were checked and if there was too much wind (usually max. 7 m/s depending on the geographical conditions) or rain the recordings were postponed. On the scheduled day, the complainant was also asked beforehand (by phone) if the annoying sound was present, and a few times it was necessary to postpone recordings due to absence of the sound. Before the recording the main power of the house was switched off to avoid any disturbing sound from freezers etc. All complainants confirmed that the noise was still present after this.

The room where the complainant is most disturbed was used for the recordings (usually the living room or bed room). If the complainant could not point out a room then the living room was chosen.

Recordings were made in at least five periods each with four different microphone positions. The first period covered all four three-dimensional corners of one wall, and the next period covered the four three-dimensional corners of the opposite wall. The third period covered the corners of one wall in distances of 0.5 and 1.0 m from both walls (Danish "corner" positions), while the fourth period covered the opposite wall in the same distances. The fifth period was used for the Swedish "corner" position and the three positions in typical living areas of the room.

4. ANALYSIS OF LOW-FREQUENCY NOISE RECORDINGS

The recordings at 22 homes gave a total of at least 22 hours of recordings. Before analysis it was first necessary to find suitable passages without disturbing elements like passing cars etc. In order to improve and speed up the laborious process of finding suitable passages a joint time frequency analysis tool was developed. It consists of a short-time Fourier spectrogram with a threshold-weighted color scale. The threshold used for the weighting is the normal hearing threshold [3] combined with a 2nd order regression of infrasonic threshold data [7]. This threshold-weighted spectrogram proved to be a valuable tool as it shows the normal audibility of the different frequency components over time. Unwanted impulse-like sounds (e.g. creaks in wooden constructions) show up as a spread over the entire frequency spectrum, while passing cars can be seen as frequency components that change with time. In a normal spectrogram it is difficult to assess the audibility of the different frequency components of the simple reason that it usually is the low-frequency components that have the highest SPL. But the steep slope of the normal hearing threshold means that high SPLs are needed for low-frequency components to be audible. Therefore strong low-frequency components might not even be audible although they have larger SPLs than the higher frequency components. This is illustrated in Figure 2 where the left spectrogram shows a normal spectrogram of a ventilation noise recording where it is obvious that the low-frequency components have the highest SPLs. However, by weighting the spectrogram with the normal hearing threshold it is revealed that most of the low-frequency components below 50 Hz are not even above the normal hearing threshold.

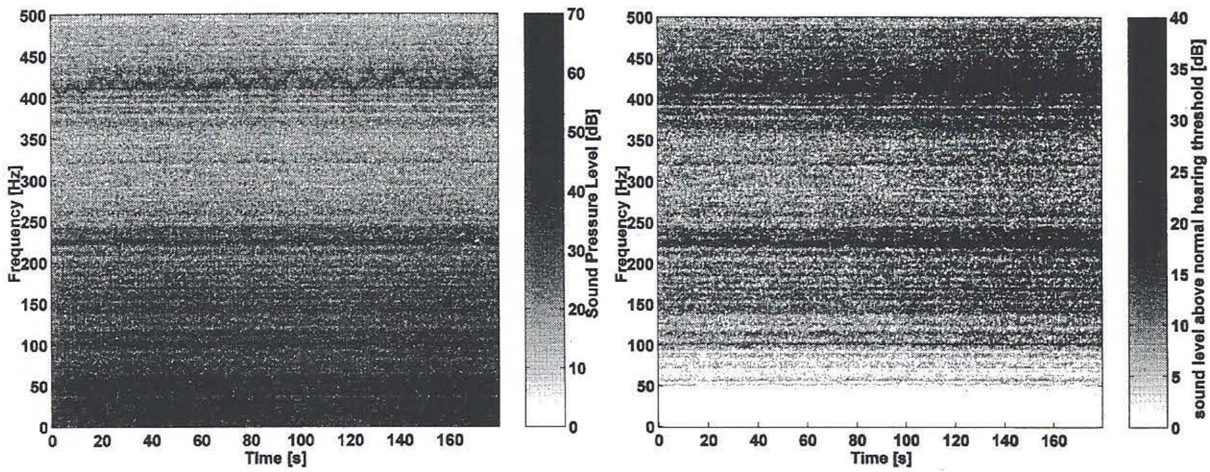

Figure 2: An example of a normal spectrogram (left) and a threshold weighted spectrogram (right) of ventilation recording.

This tool has some limitations though. It assumes that the pure-tone normal hearing threshold is applicable also for noise and does not take the critical-band concept into account. Furthermore it is important to bear in mind that it only shows the amount of dB above the hearing threshold which is not equal to how loud the different frequency components are perceived. The compression of the equal-loudness-level contours means that if a low-frequency component is just a few dB above the hearing threshold then it might be perceived louder than a higher frequency component that is considerably above the hearing threshold.

A spectrum is made for each recording making it possible to find visually suitable measurements periods without the need of listening to the full length of the recordings. These periods are then carefully examined by listening to them (supported by the spectrogram) and sections of 30 seconds are chosen. These sections are then frequency analysed using FFT and 1/3 octave band analysis, and parameters like linear, A-weighted and G-weighted SPLs are calculated. After the analysis a set of low-frequency noise recordings are found from each case which are representative for the noise that exists in the home. Furthermore, by comparing the data from different microphone positions it is investigated how the results can vary depending on which placement criteria is used (Danish, Swedish or three-dimensional corner) and how the results can vary within each criteria.

5. PLAYBACK OF LOW-FREQUENCY NOISE RECORDINGS

The noise recordings selected in the analysis are going to be played back in the laboratory. It is however not possible to play back a broadband low-frequency noise recording in a controlled sound field using conventional methods. An anechoic room is only anechoic down to a certain frequency (typically 60-70 Hz for the best anechoic rooms) and a pressure field chamber is only containing a pressure field up to a certain frequency (usually around 80 Hz for the smallest chamber that can accommodate a person). Therefore a special low-frequency test facility that uses sound field control is used for this experiment [8] (see Figure 3 for a diagram of the room).

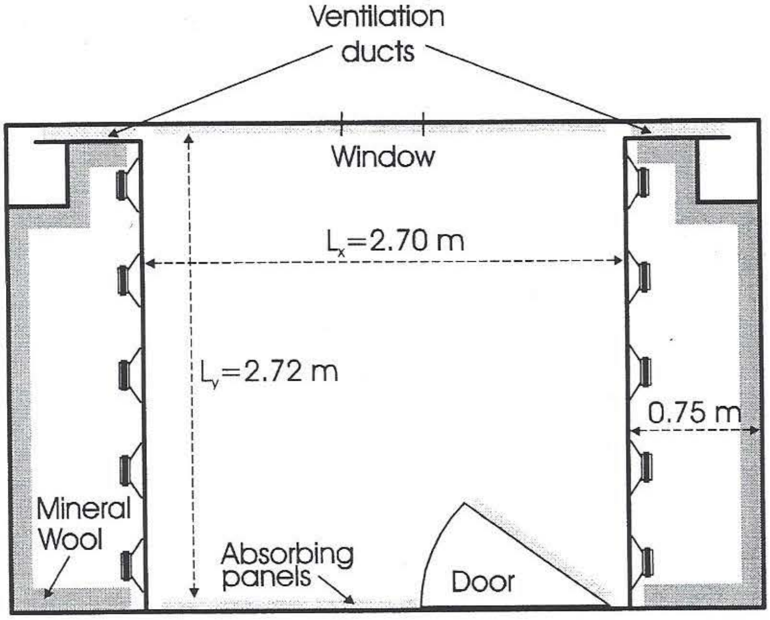

Figure 3: Diagram of the low-frequency test facility seen from above.

It uses digital signal processing in order to generate a plane traveling wave at one wall covered with 20 loudspeakers. The plane wave propagates through the room and is actively absorbed when it reaches the opposite wall also covered with 20 loudspeakers. This approach of sound field control is advantageous as it minimizes reflections from the boundaries of the room thereby giving a flat frequency response (± 1 dB) up to approx. 300 Hz in most of the room (approx. 390 Hz in the optimal listening position). Figure 4 shows a frequency response of the playback system in the centre of the room before and after the use of sound field control while Figure 5 shows the sound pressure distribution in the room at 250 Hz before and after the use of sound field control.

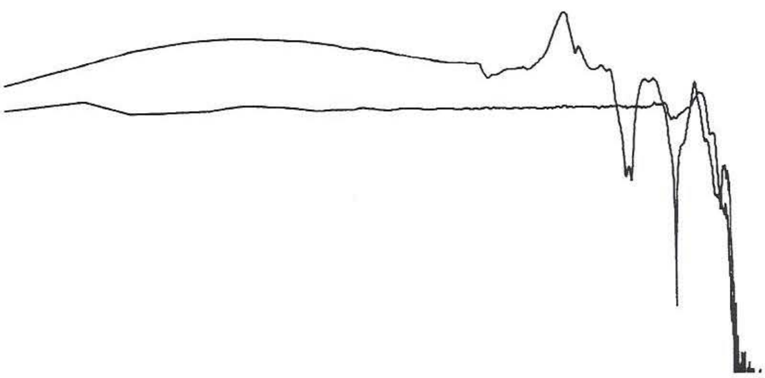

Figure 4: Frequency response of the playback system in the centre of the room before (dotted) and after (solid) sound field control.

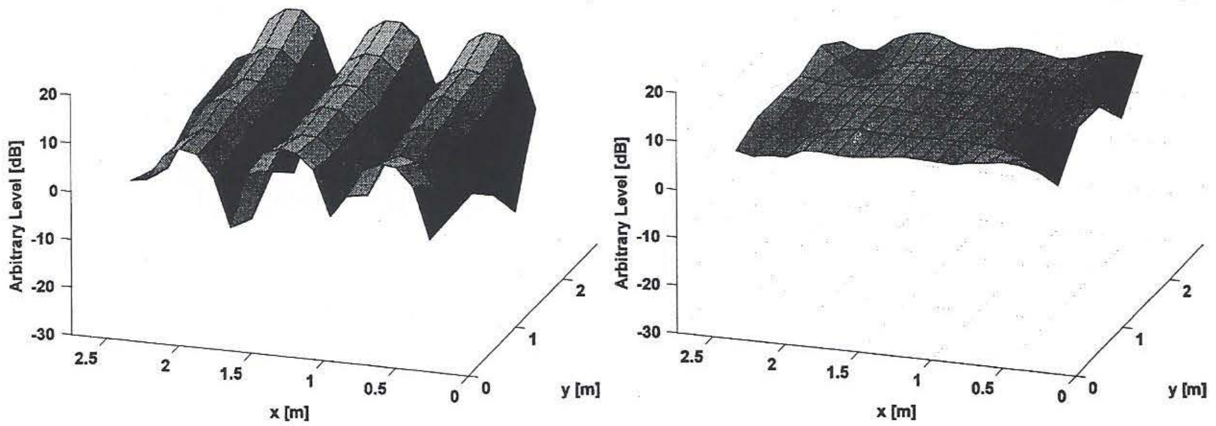

Figure 5: Sound pressure distribution at 250 Hz in a horizontal plane at a height of 1.35m before (left) and after (right) sound field control.

Using this test facility it is possible to play back broadband low-frequency noise signals in a controlled sound field with low harmonic distortion and low background noise. Furthermore the facility is well suited for low-frequency threshold and equal-loudness-level contour measurements.

6. EXPERIMENTAL DESIGN

Since the experiments are not finished yet it is not possible to report on details in the experimental design. But the general idea is presented in the following.

6.1. Screening by audiologist

Prior to the experiment the subject will undergo a series of audiologic tests (performed at an audiology clinic) including: pure-tone audiometry, tympanometry and caloric vestibular test.

6.2. Low-frequency hearing threshold measurements

The standard audiometry only covers frequencies down to 250 Hz (or 125 Hz). But for this experiment it is interesting to measure the low-frequency hearing threshold of the subjects, since extraordinary low-frequency sensitivity could be one possible explanation for the annoyance. The hearing threshold is measured for the frequency range from 5 Hz to 250 Hz using the low-frequency test facility.

6.3. Low-frequency equal-loudness-level contour measurements

It is quite interesting to see if the shapes of the equal-loudness-level contours for the subjects differ from the normal equal-loudness-level contours [9] since these data will indicate how loud they perceive low-frequency sounds. It is however, a cumbersome task to measure the equal-loudness-level contours so only a few low frequencies at 20 and 40 phon will be measured using the low-frequency test facility.

6.4. Blind test using recorded noise

In order to investigate if the complainants really hear an external physical sound a selection of low-frequency noise recordings (including the one from their own home) are presented to them in the low-frequency test facility during a blind test experiment.

7. CONCLUDING COMMENT

The methods of selecting the study sample and the methods chosen for recording the sounds have worked well. The selected subjects have been very helpful and with a few exceptions interested to participate. The completion of the study is expected to take another 12 months.

8. ACKNOWLEDGEMENT

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