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Twenty-two cases of low-frequency noise complaints - a detailed investigation

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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 were made of the sound in the complainants' homes. Each complainant was then invited to the laboratory where low-frequency thresholds and equal-loudness contours were measured. In a blind test it was examined if they are able to hear the sound recorded in their homes. Details from noise recordings, analysis and the experimental design are presented, however, since the experiments were finishing at the time of paper submission no results are presented at the present stage, but the final results will be presented at the conference.

1.0 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], (explained in English in [5]). The explanations could be that there simply is no external physical sound that is the cause of annoyance (low-frequency tinnitus?), 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 hearing at low frequencies. Furthermore the characteristics of the annoying sound (frequency components, levels etc) will be examined. Finally data for comparing different methods for measuring low-frequency sounds in rooms including the Danish [4], and the Swedish method [6] is obtained.

A sample of 22 complainants who all participated in the survey [1], [2] was included in the investigation. Sound recordings were made in their homes, and analyzed. The subjects had standard audiometric tests at an external clinic. In our laboratory their low-frequency hearing threshold was determined and their low-frequency equal-loudness contours were examined using a newly developed low-frequency test facility [7]. In a blind test it was investigated if they are able to hear the sound recorded in their home and this was the annoying sound. Furthermore a matching of some characteristics of the annoying sound (frequency, level and tonal or noise) was performed. The paper gives an overview of the selection of subjects, recording and analysis of noise and the experimental design. However, since the experiments were finishing at the time of paper submission no results will be reported at the present stage. The results will be presented at the conference.

2.0 METHODS

2.1 Selection of subjects

A sample of 22 subjects from the group of people who had participated in the initial survey was selected. 20 subjects were selected randomly, while two subjects were selected because of long-time contact with the department. For more detail on the selection procedure see [8].

2.2 Recording of low-frequency noise

One crucial part of this investigation is to make good recordings that represent the sound that exists in the homes of the complainants. This can be difficult since reflections from the surfaces in a room cause standing wave patterns especially at low frequencies. This means that there are peaks and dips in the sound pressure level (SPL) depending on both frequency and position. If measurements are performed in only one or a few points in the room, then there is a great risk of placing the microphone in a pressure dip of the standing wave pattern of the annoying frequency components of the sound. Standing wave patterns usually have 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 [9]. 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, this is not always the case, so alternative measurement positions are usually needed.

Considering the variations in the sound field in rooms at low frequencies it was decided to make recordings in a total of 20 positions in the room using different placement criteria. These positions were 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 to three-dimensional corners without touching any surface. Furthermore eight recordings were made in positions that comply with the “corner position” in the Danish guidelines for measuring low-frequency noise [4]. One position was chosen in accordance with the Swedish “corner method” [6]. The three others were chosen elsewhere in the room (fulfilling both the Danish and the Swedish method), avoiding the middle position. Preferably in positions where the complainant is experiencing the highest sound or most annoyance.

The recordings were performed using a four channel recording system (01 dB Harmonie connected to a laptop) with four GRAS 40 EN one-inch microphones and four GRAS 26AK preamplifiers. Using this system it was possible to record 4 channels simultaneously meaning that the sound at 4 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 laptop. The lower frequency limit for the microphones and the system is approx. 0.5 Hz while the upper frequency limit of the recording system with the selected sampling frequency was 2.5 kHz.

The room where the complainant was 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. Before recording the main power of the house was switched off in order to avoid any disturbing sound from freezers etc. Recordings were only performed if the complainant were still able to hear the low-frequency noise. Recordings were made in at least five three-minute periods each with four different microphone positions. In some cases it was necessary to make extra recording periods because of too many disturbances.

2.3 Analysis of low-frequency noise recordings and selection of stimuli

The recordings at the 22 homes gave a total of at least 22 hours of recordings. Before detailed analysis of the recordings 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 [10]. This threshold weighted spectrogram proved to be a valuable tool as it shows the normal audibility of the different frequency components over time. Unwanted elements like impulse-like sounds shows up as a spread over a larger frequency area while noise from passing cars can be seen as frequency components that change with time. An example of this can be seen in Figure 1 where horizontal lines shows steady tonal frequency components while vertical lines shows intermittent disturbances and the varying frequency components from around 50 to 100 Hz is noise from passing cars.

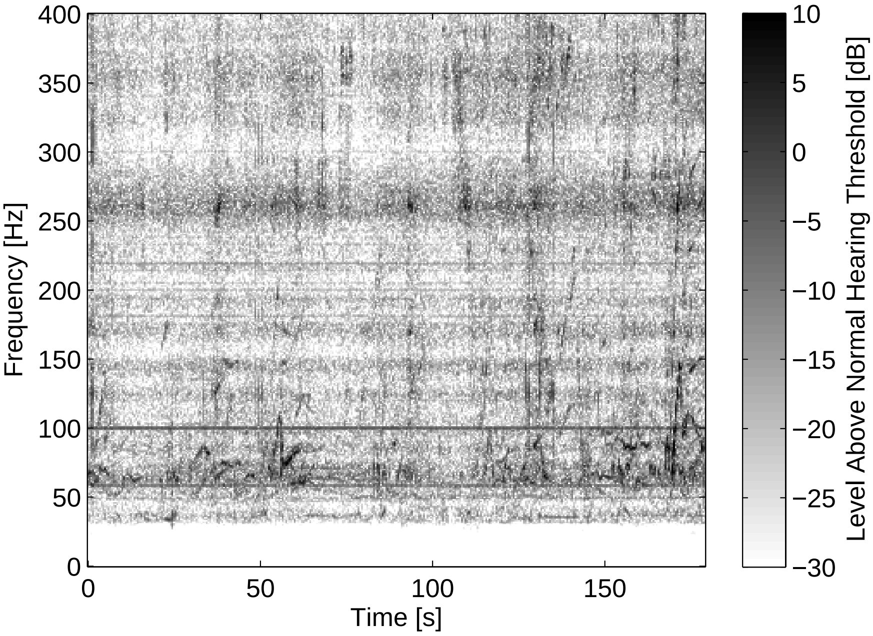

Figure 1: Example of a threshold weighted spectrogram of one recording. The frequency resolution in this spectrogram is 1 Hz.

This tool has some limitations when used to assess audibility. It assumes that the pure-tone normal hearing threshold is applicable also for noise and does not take the critical-band concept into account. This also means that the levels shown are sensitive to the chosen frequency resolution. 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 quite louder than a higher frequency component that is considerably above the hearing threshold.

A spectrogram was made for each recording making it possible to visually find suitable measurements periods without the need of listening to the full length of the recordings. These periods were carefully examined by listening to them (supported by the spectrogram) and sections of 30 seconds were chosen. These sections were then further analysed using spectrograms and 1/3-octave band analysis and parameters like linear, A-weighted and G-weighted SPLs were calculated. Figure 2 shows a 1/3-octave band analysis from a section from the noise shown in Figure 1 including calculation of relevant parameters.

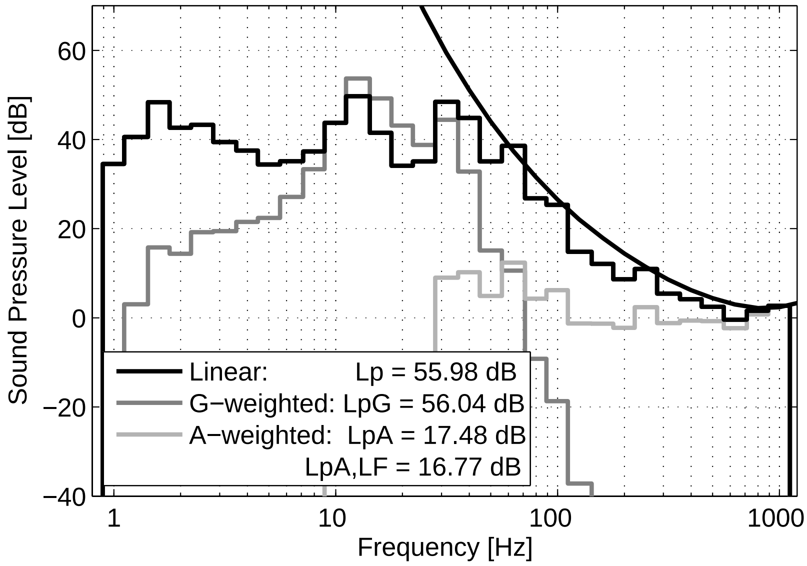

Figure 2: Example of a 1/3-octave band analysis of a selection of a recording compared to the normal hearing threshold. The black shows the linear SPL, while dark grey shows G-weighted and light grey shows the A-weighted SPL. The black curve is the normal hearing threshold

From the analysis a number of 5 second low-frequency noise stimuli from each case were found that are believed to be representative for the noise that exist in the home.

2.4 Test setup

It is not a simple task to reproduce a broad-band low-frequency noise stimulus in a controlled sound field using conventional methods because of the problems with standing waves. 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 80 Hz for the smallest chamber). If conventional equalization is used the sound is only controlled in a single point and slight head movements leads to considerable errors. Furthermore it is very difficult to equalize for the pressure dips that are usually found at low frequencies. Therefore a special low-frequency test facility that uses sound field control in order to create free-field conditions was used for this experiment [11], [7] (see Figure 3 for a diagram of the room).

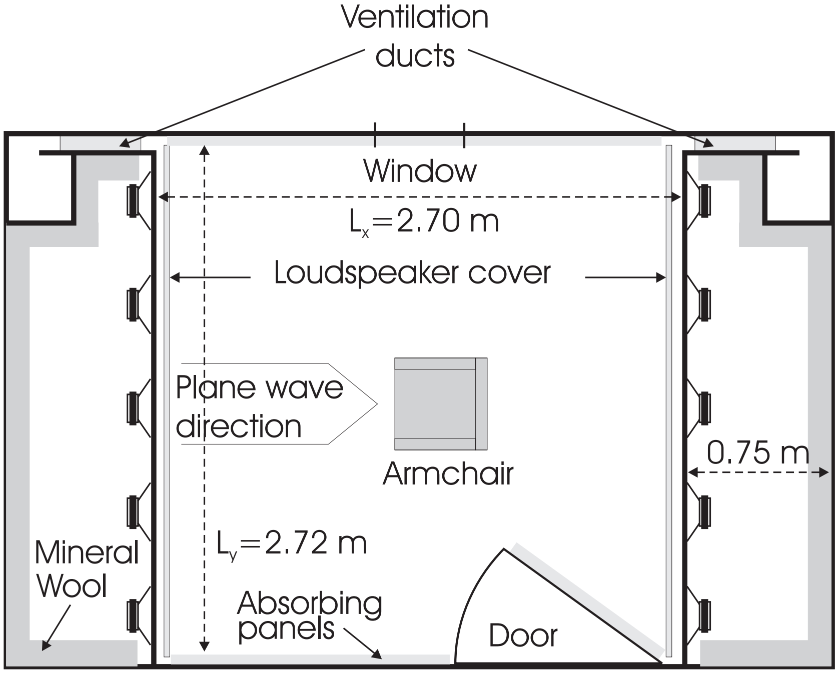

Figure 3: Diagram of the low-frequency test facility seen from above.

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 homogenous sound field for the major part of the room as seen by the pressure distribution plots in Figure 4. The signal for each of the 40 loudspeakers is filtered through it's own unique filter that not only takes care of the plane wave generation and absorption but also equalizes for the individual loudspeaker response. This means that the test facility has a flat frequency response (± 1 dB) up to approx. 300 Hz in most of the room as seen in Figure 5.

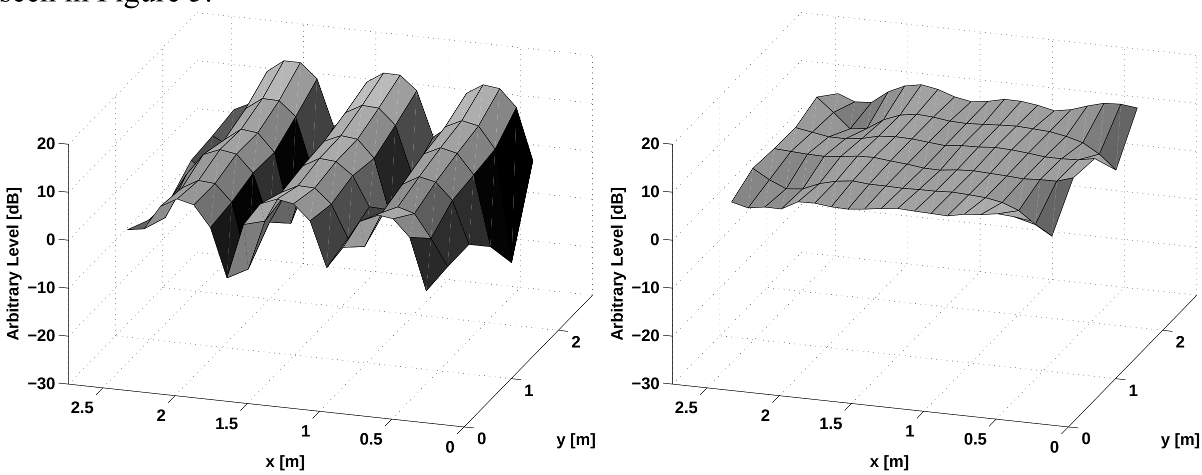

Figure 4: Sound pressure distribution at 250 Hz in a horizontal plane at a height of 1.35m without (left) and with (right) sound field control. With sound field control it is only the regions close to the loudspeakers that exhibit significant pressure variations.

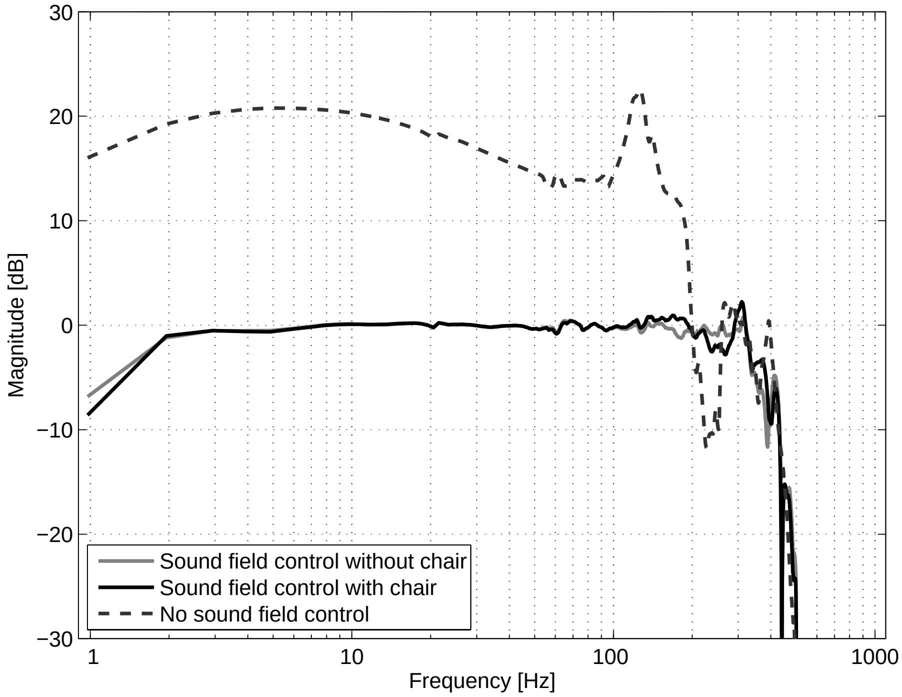

Figure 5: Frequency response of the playback system in the listening position with sound field control and chair (solid black), with sound field control and no chair (solid grey) and without sound field control and with chair (dashed black). The deviations below 2 Hz is caused by low signal-to-noise ratio for this frequency area.

Using this test facility it is possible to reproduce broad-band low-frequency noise stimuli in a controlled sound field with low harmonic distortion. Furthermore the facility is well suited for low-frequency threshold and equal-loudness-level contour measurements.

The subject was seated in an armchair in the centre of the room facing the sound-transmitting loudspeaker wall. The presence of the chair in the sound field degraded the sound-field control slightly above 100 Hz however for frequencies from approx. 2 Hz to 200 Hz the deviations were within ±1 dB and to 300 Hz within ±2.5 dB (see Figure 5). The levels of the stimuli were calibrated for the centre of the subjects head in the absence of the subject, but with the chair in position. Acoustical transparent fabric was placed in front of the loudspeakers in order to hide the loudspeakers from the subject.

The ventilation system for the test facility was designed to deliver fresh air and keep the room cool without making audible noise. When the cooling compressor is running (only for short periods depending on the outside temperature) there is more background noise in the room at 50 Hz, but the noise level is always more than 10 dB below the normal hearing threshold as seen in Figure 6.

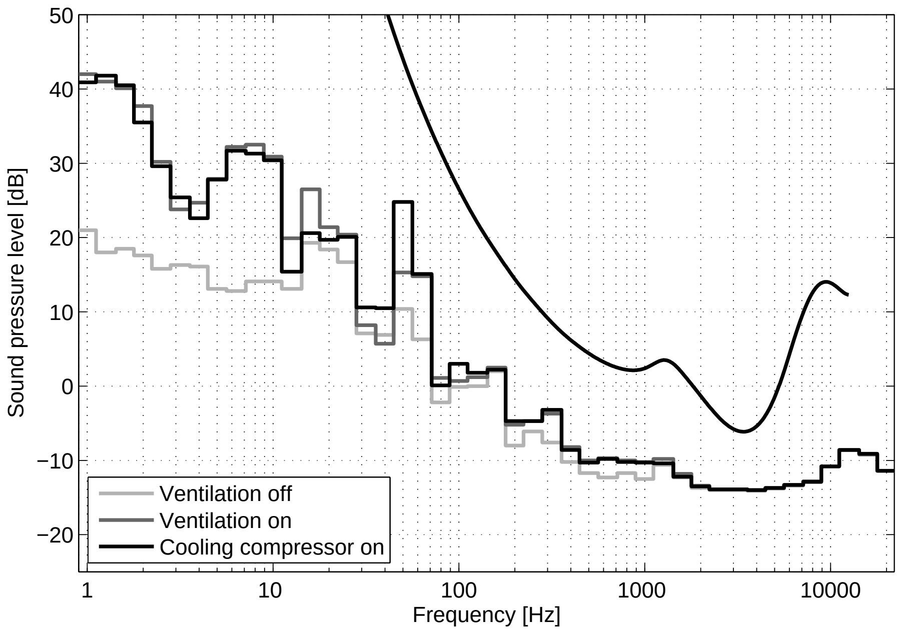

Figure 6: Background noise measured in 1/3-octave bands in the listening position with ventilation off (light grey), ventilation on (dark grey) and ventilation and cooling compressor on (black). The black curve is the normal hearing threshold. The measured 1/3-octave bands from approx. 2 kHz and upwards is the noise floor of the measurement system.

2.5 Screening by external audiologist

In the morning of the experiment day the subject had a series of audiologic tests performed at an audiology clinic before coming to the university. The tests included otomicroscopy, pure-tone audiometry, tympanometry and stapedius reflex, caloric vestibular test and otoneurologic test

2.6 Low-frequency hearing threshold measurements

The standard audiometry only covers frequencies down to 250Hz. But for this experiment the low-frequency hearing threshold of the subjects is of special interest since extraordinary low-frequency sensitivity could be one possible explanation for the annoyance. The low-frequency hearing threshold of the subject was measured at octave-band frequencies from 8 Hz to 250 Hz (8, 16, 31.5, 63, 125 and 250 Hz).

The low-frequency hearing threshold was measured using a modified version of the standardized ascending method according to [12]. This modified method was used by [13] in a study of different psychometric methods for threshold determination and was found to be accurate and efficient. The advantage of this method over the standardized method is that it gives a higher resolution of the psychometric function of the subjects hearing threshold.

2.7 Low-frequency equal-loudness contour measurements

It is quite interesting to see if the shape of the equal-loudness contours for the subject differs from the normal equal-loudness-level contours [14] since these data will indicate how loud the subject perceives low-frequency sounds. It is however, a cumbersome task to measure the equal-loudness contours so only octave frequencies from 8 Hz to 125 Hz with a reference tone at 250 Hz at a level of 20 dB above the hearing threshold was measured.

A two alternative forced choice (2-AFC) sequential maximum likelihood method as used by [15] which is a modified version of the procedure proposed by [16] was chosen for the equal-loudness contour measurements.

2.8 Blind test using recorded noise

In order to investigate if the complainant is annoyed by an external physical sound a selection of 5 second low-frequency noise recordings (including at least two from their home) was presented to them in a blind test experiment.

A three-interval four-alternative forced choice method was chosen for the blind test. The subject is presented to three intervals indicated by different lights. One of the intervals contains the noise stimulus while the two other intervals are silent. The subject must answers which of the intervals that contained the noise stimulus. If the subject is not able to detect the stimulus there is a possibility to answer “did not hear the sound”.

The procedure starts with the noise stimulus reproduced at the recorded level (denoted 0 dB) and next presentation level depends on the answers given by the subject. The subject must detect the sound three times in a row, before the sound is regarded as heard with some confidence. If that happens the sound is retested at the same level in order to increase the confidence. If the sound is not detected two times it is regarded as not heard and the level is increased.

After the blind test the subject was presented to all the sounds that they were able to hear at 0 or +5 dB relative to the recorded level. The subject was asked which of the sound if any resembles the annoying sound in the home. Furthermore the subject was asked if the sound was louder or softer than the annoying sound in the home and asked which of the sounds that were the most annoying.

2.9 Blind test using filtered noise recordings

The purpose of this test was to determine the audible and annoying “parts” of the broad band noise stimuli. This test was only performed if the subject was able to hear the broad band noise recording at the recorded level in the blind test.

The broad band noise recording was band-pass filtered in order to obtain stimuli with different frequency content in the ranges 0-20 Hz, 20-60Hz, 60-180 Hz and 180-400 Hz. This gave four filtered stimuli that were tested using the same procedure as the blind-test.

2.10 Matching of annoying sound

The aim of this test is to determine some characteristics of the noise that annoys the subject. The frequency content of the annoying noise was found by presenting pure tones to the subject and then change the frequency until the subject found the pitch to be the similar to the annoying noise. When the frequency area was found then a 1/3-octave band filtered noise at that frequency was presented in order to find out if the annoying sound is tonal or more like noise in character. Finally the level of the sound was matched.

3.0 RESULTS AND CONCLUSION

The experiments were finishing at the time of paper submission so no results are presented at this stage. The results will be presented at the conference.

4.0 ACKNOWLEDGEMENT

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