Masked Perception Thresholds of Low Frequency Tones Under Background Noises and Their Estimation by Loudness Model

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This paper presents experimental measurements of masked thresholds of low frequency tones under background noises and application of loudness model to estimate the thresholds. The measurements of thresholds for tones at frequencies 20, 31.5, 40 and 50 Hz were conducted under three background noise conditions: one ambient noise and 60-100 Hz band-pass noises at two levels. The measurements were carried out in an uncontrolled environment in relatively quiet times. The perception thresholds of the same subjects were also measured for frequencies 31.5, 40 and 50 Hz inside a cabin with ambient noise levels well below the average hearing thresholds specified in ISO 389-7. Moore's loudness model has been used to estimate the masked thresholds. The estimated thresholds from the loudness model have been compared with the results obtained in the experiment. The results indicate that the noise above 50 Hz is effective in masking the low frequency tones at 50 Hz and below, and that Moore's loudness model can predict reasonably the average of the measured masked thresholds.

1. INTRODUCTION

Sources of low frequency noise in the environment are growing. Many house appliances, such as ventilation systems and refrigerators, and some civil engineering structures, such as viaducts and railway tunnels, are some of the common sources of low frequency noise. Recent field investigations [1-3] have indicated that increasing numbers of people are complaining about problems arising from low frequency noise. The low frequency noise occurs, normally, as a part of a complex sound containing energies over wide frequency range. As the response of the auditory system to sounds of different frequencies differs, the quantification of the total response from these complex sounds is complicated. It is now understood that the levels obtained from commonly used frequency weighting networks, such as the A-weighting, do not correlate well with the response to complex sounds with audible low frequency components [4-6]. The reason for this is the fact that the rapid change in the auditory sensations, such as loudness and annoyance, with respect to the change in the sound pressure levels at low frequencies is not taken into account in the weighting networks.

In order to calculate the response to complex sounds more accurately, Zwicker and co-workers developed loudness models [7]. Although the model is widely used for practical purposes, low frequency sounds below 50 Hz are not included in it. Moore et al. [8,9] developed revised loudness models based upon the original work by Zwicker, which could be used for frequencies down to 20 Hz.

These loudness models were developed basically from experiments on masking effects, which can be measured quantitatively by measuring the masked threshold of a test sound in the presence of masker sounds. The measurements of masked thresholds show that low frequency sounds below 50 Hz can also produce masking effects. Finck [10] used 100, 115 and 130 dB sound pressure levels of 10, 15, 25 and 50 Hz tones as masker sounds and measured the masked thresholds of test sounds in the frequency range of 50 to 4800 Hz. His results showed that the maskers could produce constant masking effects up to 500 Hz. Watanabe et al. [11,12] used pure tones and complex tones at frequencies of 10 and 20 Hz as masker sounds to measure the masked thresholds of tones at frequencies from 4 Hz to 50 Hz. They also used band-pass noises with different widths centered on 20 Hz as masker sounds to measure the masked thresholds of pure tone at 20 Hz. Their results varied greatly among the subjects, and in some cases the masked threshold appeared lower than the threshold in quiet. In a similar study, Fidell et al. [13] showed that sound at 40 Hz is masked by a masker with band limits of 11-400 Hz.

Although these results indicate that masking effects are present in the low frequency regions below 50 Hz, they cannot be used directly to construct a loudness model because of the limited available data and the large variations among the data. Therefore, Moore's loudness model below 100 Hz is based on the extrapolation of data above 100 Hz [9]. The application of the model to estimate the threshold of complex sounds [9] and the loudness of complex sounds [14] for high frequencies showed that the results are accurate enough within subjective variability. However, the applicability of the model for low frequencies has yet to be verified.

Furthermore, direct application of the model based on the auditory mechanism is questionable in the low frequency region below 50 Hz, as there are reports suggesting a presence of other mechanism of the perception besides auditory at these frequencies. From the experiments with components of sound below 50 Hz and noise above 50 Hz, Inukai et al. [15, 16] indicated that other factors of perception such as vibration and feelings of pressure are also associated with sounds below 50 Hz. However, results from a survey of complaints about infrasound and low frequency noise showed that 93% of the complainants perceive the sound through the ears [17].

In order to understand the mechanism of perception of low frequency sounds more accurately, the measurement of masked thresholds of low frequency sounds masked by high frequency sounds is useful. The present study, therefore, has been carried out to measure masked thresholds of low frequency tones under different levels of background noise and to investigate the applicability of Moore's loudness model to estimate the thresholds. The perception thresholds of low frequency tones at 50 Hz and below are measured under different background noise conditions in controlled and uncontrolled environments and the results are compared with the estimated results from the loudness model.

2. EXPERIMENTAL METHOD

2.1 THRESHOLD MEASUREMENT UNDER BACKGROUND NOISES

In order to investigate the masked thresholds of human subjects for low frequency tones under masker sounds, a room environment with ambient sound was selected. A room (6.5 ¥ 3.75 ¥ 5.3 m), as shown in Figure 1(a), was used for the measurement, and test sounds were produced from a low frequency speaker (YAMAHA, YST 800) placed in the middle of the room at a height of 1.0 m above the ground. An infrasound microphone (RION NA-18) was used to measure the sound. In order to keep the ambient sound at constant levels, the experiments were conducted during night hours at a relatively quiet time.

A function generator (NF

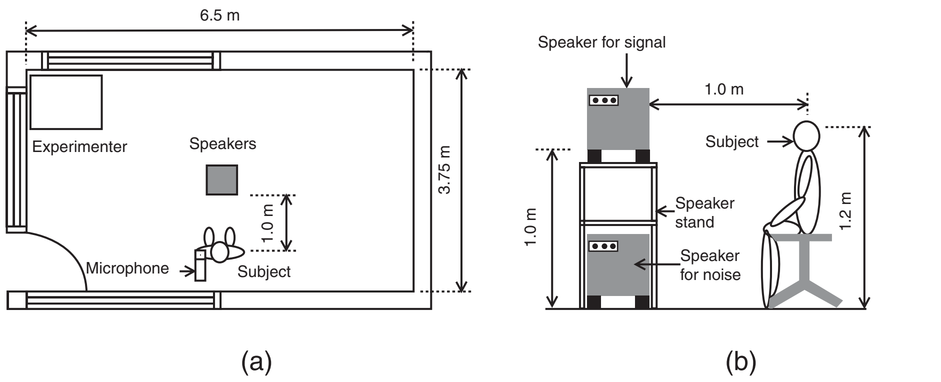

Figure 1 *Schematic diagram of the experimental setup for the uncontrolled environment. (a) Plan view of the experimental setup; (b) Elevation showing placement of speakers and subject.*

ELECTRONIC INSTRUMENTS, E-1011A) was used as the source for the pure tone test sounds, and the frequencies of the test sounds used in the experiment were 20, 31.5, 40 and 50 Hz. Masked thresholds of the test sounds were measured under three different masker sounds: one ambient noise (Ambient Noise) and two band-pass noises from frequency 60 to 100 Hz at different levels (Noise 1 and Noise 2). The band-pass noises were generated from a PC operated by the experimenter. In later discussion, the test sounds are referred as "signals" and the masker sounds in the background are referred as "background noises".

Four male and one female subjects, aged between 26 and 29 yrs, participated in the experiment. The subjects were placed in front of the speaker at a distance of one meter for all cases except for signals at 20 Hz, where the subjects were placed at 30 cm from the speaker. The change in the position was necessary to achieve sufficient level of 20 Hz signal without any significant higher harmonics. During the measurements, the subjects were seated in an upright position with the height of their ear adjusted at 1.2 m as shown in Figure 1(b). The microphone was placed at 0.2 m from center of the subjects' head. The noises were produced from another speaker of same type. The speaker was placed below the speaker for the signal, as shown in Figure 1b.

The subjects could adjust the level of the signals from the function generator, and the thresholds were measured by the method of adjustment with four repetitions - two starting below audibility and two starting above. Before starting the measurements, the subjects were given a sufficient time for practice so that they could distinguish between the signals and the background noises.

The 1/3 octave band sound pressure levels of the three background noises are shown in Figures 2(a) and 2(b) by continuous lines. As seen in the figures, the background noises exceed the ISO hearing threshold above 50 Hz. As the ambient noise was not controlled during the experiments, the reproducibility of these noise conditions during the measurement of the perception thresholds was investigated.

The average 1/3 octave band sound pressure levels in the frequency range 50-200 Hz, which were measured for signals of frequency 31.5 Hz at its masked threshold under Ambient Noise, are shown in Fig. 2(a) by filled circles. Their comparison with the 1/3 octave band sound pressure levels of Ambient Noise only showed that the difference is about 1 dB at 63 Hz, 2 dB at 100 Hz and no difference at other

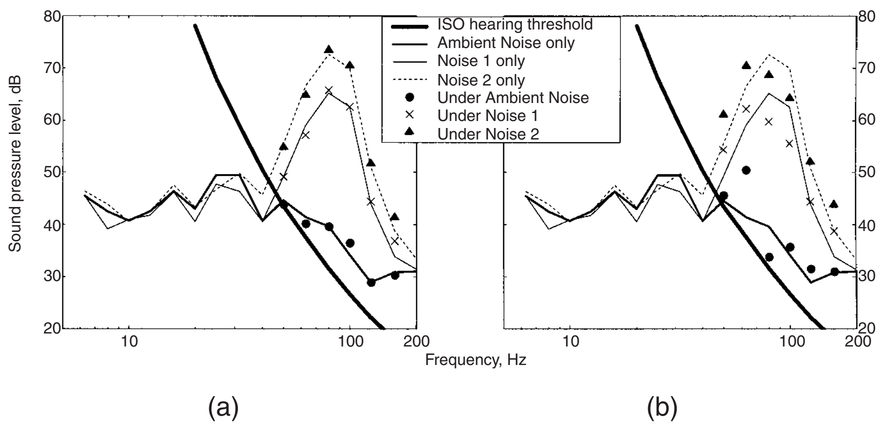

Figure 2 *Three levels of background noises used in the experiment for the signals at frequencies (a) 31.5 Hz; and (b) 20 Hz. Measurement of noises only conditions (continuous lines) and the average of measured 1/3 octave band sound pressure levels of five subjects measured at frequencies from 50 to 200 Hz for both the noise and the signals (symbols) are shown. The reference hearing threshold curve specified in ISO 389-7 is also shown.*

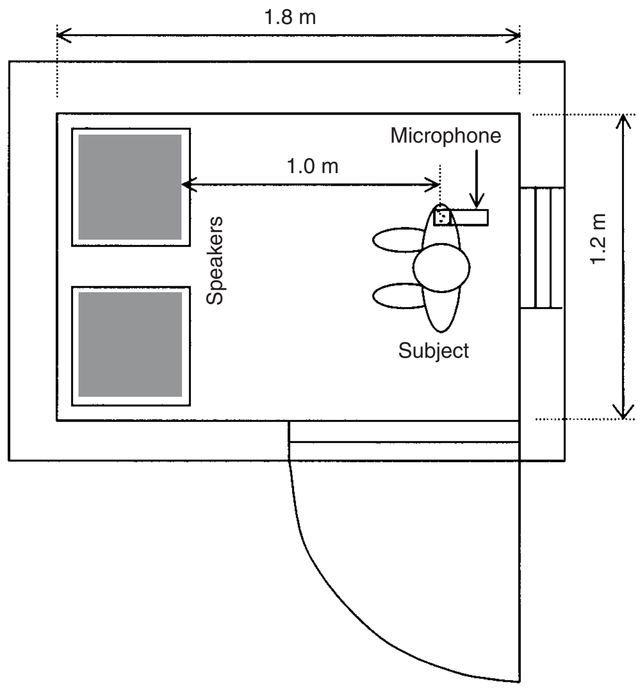

Figure 3 *Schematic diagram of the plan view of the experimental facilities inside the cabin.*

frequencies. Similar comparison for measurements under Noise 1 (shown by crosses in the figure) with Noise 1 only and Noise 2 (shown by filled triangles in the figure) with Noise 2 only showed that the differences are within a similar range. The results were similar for measurements of perception threshold at frequencies 40 and 50 Hz. Therefore, the background noises were considered reproducible for the measurement of perception thresholds at frequencies 31.5, 40 and 50 Hz and they are represented by the measured 1/3 octave band sound pressure levels of the noise only conditions in further discussion.

However, as seen in Fig. 2(b), the

average 1/3 octave band sound pressure levels of signal at 20 Hz under background noises, shown by symbols in the figure, differ significantly from the measurements for noise only cases. The measurements showed that higher harmonics at 60 Hz exceeded the ISO threshold by about 5 dB when the sound pressure level of 20 Hz signal was at 80 dB. Although the levels of background noises were at sufficiently high to mask these 60 Hz harmonics, there was an effect of varying the sound pressure levels of the background noises in some sets of measurements. Therefore, the three background noise conditions (Ambient Noise, Noise 1 and Noise 2) for the signal at 20 Hz are represented by the average 1/3 octave band sound pressure levels measured for all the subjects.

2.2 THRESHOLD MEASUREMENT IN QUIET

The measurements of the thresholds in quiet for the same subjects were conducted in a cabin of size 1.8 ¥ 1.2 ¥ 2.3 m (Fig. 3) designed for experiments on low frequency noise. Four speakers (YST 800) placed in two horizontal lines were used, and the subjects were placed in front of the speakers at a distance of 1.0 m. The microphone (RION NA-18) was placed 0.2 m from center of the subjects' head position near their right ear. The measured background noise in the cabin at the location of the microphone is shown in Fig. 4 along with the average hearing threshold level specified in ISO 389:7 [18]. The sound pressure level of the background noise crosses the ISO hearing threshold curve above 160 Hz. The noise conditions above 100 Hz in the cabin were similar to another experiment room for low frequency noise [19].

The threshold measurement method was the indirect method of adjustment with UP and DOWN sequence, where the subjects did not have direct control over the sound pressure level. During the measurements, the subjects and the experimenter could not see each other and specially designed buttons and indicators were used for communication. In the UP sequence, the subjects were presented continuous signals well below their hearing threshold and they were asked to press the 'UP' button until the sound was just noticeable to them. The experimenter would increase the level until the subject responded by pressing the

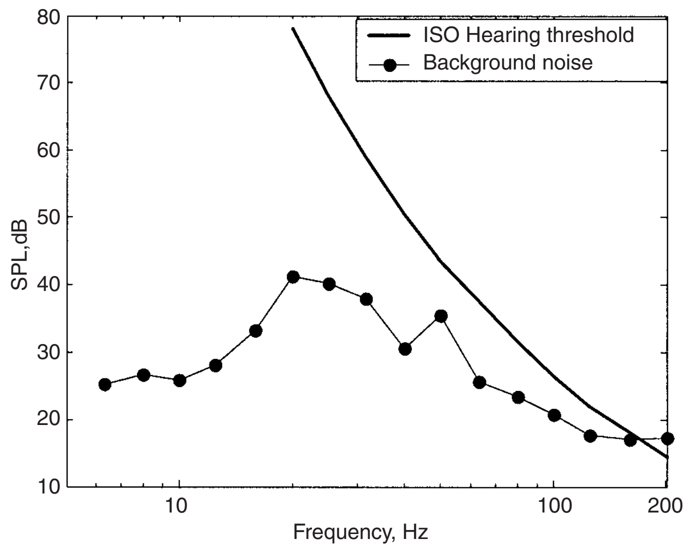

Figure 4 *Background noise measured inside the cabin at the position of the microphone shown in Figure 3.*

'DECISION' button. In case the signal became sufficiently high and the subjects asked to decrease the level, the signal was decreased to the level below audibility and the process started again. The process was similar for the 'DOWN' sequence, but the starting sound pressure level was well above the audible level of the subjects. The subjects were then asked to press DOWN button to decrease the level of the sound. The higher harmonics produced during the measurement of perception threshold at 20 Hz in quiet were significant in the absence of the background noises. Because of this limitation, the measurement of thresholds for 20 Hz tone was not carried out. Two repetitions at each frequency were made for four subjects, and four repetitions were made for one subject. The summary of all the experimental conditions is given in Table I.

3. EXPERIMENTALLY MEASURED THRESHOLDS

3.1 THRESHOLDS FOR PURE TONES IN QUIET

Results of threshold measurements for the five subjects in the quiet are shown by the filled symbols in Fig. 5(a). As can be seen in the figure, the average threshold in quiet is 6.6, 8.9 and 8.0 dB above the average threshold of hearing defined in ISO 389-7 [18] for frequencies 31.5, 40 and 50 Hz, respectively. The large difference in the two thresholds could not be due to the presence of the noise in Fig. 4, because the sound pressure level of the noise higher than ISO hearing threshold only above 160 Hz should not affect the results at 50 Hz and below adversely. Although the recommended age limit of the subjects for ISO hearing threshold is from 18 to 25 years inclusive, all of the subjects of this study were of age above 26 years. Hence, it is possible that the subjects' thresholds were higher than average thresholds specified in the ISO. As separate audiometric tests were not conducted for the subjects, this could not be verified, while the average thresholds obtained in this study are similar to the average thresholds obtained by Inukai et al. [20] for subjects aged between 19 and 62 years. For further discussion in this study, the perception thresholds measured inside the cabin are considered as the threshold in quiet for the subjects.

3.2 MASKED THRESHOLD

The average masked thresholds with different levels of background noises are also shown in Fig. 5(a). The standard deviations of the thresholds among five subjects for all the cases are shown in Fig. 5(b). The detailed experimental results for individual subjects are given in Subedi et al. [21]. It can be seen in the figure that increases in the level of background noise cause an increase in the perception threshold level. As the sound pressure levels of background noises vary among the subjects for the case of test sound at 20 Hz and average sound pressure levels of the noises are different from those at other frequencies, the results cannot be compared directly with results from other frequencies. However, it can be seen from the results that the increase in the perception threshold with increase in the level of background noise is observed at 20 Hz also. The results suggest that masker sounds at frequencies 50 Hz and above can produce masking effects to sounds down to 20 Hz. However, the increase in the perception threshold decreased with decreases in the frequency for all background noises. This tendency suggests that the masking effect decreased with increases in the frequency separation between the noise and the signal.

The possible indication of these results would be that the main mechanism of perception of sounds at 50 Hz and below

Table I. Summary of the experimental conditions

Background condition	Noise type	Distance (m) from speaker to the subjects for test frequencies 20 Hz	31.5 Hz	40 Hz	50 Hz	Environment	Method	Number of repetitions
Quiet	-	-	1	1	1	Controlled environment inside cabin	Indirect method of adjustment	2*
Ambient Noise	Ambient noise in relatively quiet time	0.3	1	1	1	Uncontrolled environment	Method of adjustment	4
Noise 1	60-100 Hz band-pass noise	0.3	1	1	1			
Noise 2	60-100 Hz band-pass noise	0.3	1	1	1			

*4 repetitions were made for one subject

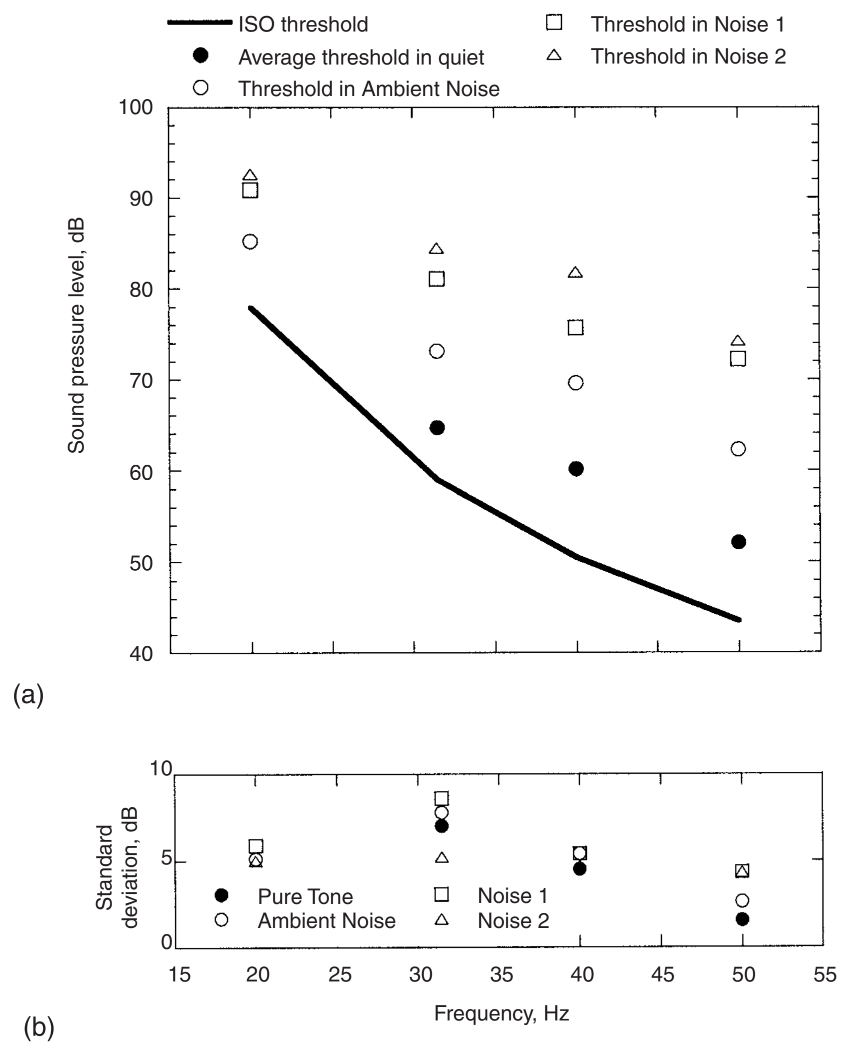

Figure 5 *Perception thresholds in quiet and under background noises. (a) Average thresholds (The reference hearing threshold curve specified in ISO 389-7 is also shown.); and (b) Standard deviation.*

is an auditory mechanism. If the masker sounds in the frequencies above 50 Hz are perceived only by auditory mechanism, these sounds should be able to produce masking effects mainly on the auditory mechanism, and perception by other mechanisms, such as vibration, pressure feeling and vibro-tactile perception, would not be masked by these masker sounds. As the masker sounds caused increase in the perception thresholds of the test sounds at 50 Hz and below by more than 20 dB, it could be possible that the main mechanism of perception of these test sounds is an auditory mechanism. However, other mechanisms of perceptions, such as vibro-tactile perception, are also involved at sufficiently higher sound pressure levels as suggested by Landstrom et al. [22].

4. APPLICATION OF MOORE'S LOUDNESS MODEL

4.1 AUDITORY SYSTEM IN THE MODEL

Moore's loudness model [9] is an empirical approach to estimate the loudness from the sound stimulus. The model takes into account the processing of the sound stimulus in different parts of the auditory system at different stages to calculate the loudness. The sub-systems of the model are shown schematically in Fig. 6. The sound stimulus 6(a) passes through outer and middle ear, and the processing in the outer and middle ear is achieved in the model by fixed transfer functions 6(b). The stimulus after the processing in the outer and middle ear reaches the inner ear and excites the inner ear where the impedance increases with decrease in the frequency. The increase in the impedance suggests that the auditory system has less efficiency at lower frequencies. This impedance in the inner ear is represented in the model by the "excitation at the threshold" 6(c), which is a threshold expressed as the sound pressure level reaching the inner ear. The inner ear is modeled as bank of overlapping auditory filters, and the "excitation pattern" 6(d) is calculated as an output of the filters for the corrected stimulus reaching the inner ear. The excitation pattern corresponds directly to the specific loudness 6(e), and the summation of the specific loudness across the ERB scale gives the loudness 6(f) for that sound. The ERB stands for the "equivalent rectangular bandwidth" of the auditory filter at certain frequency and is a function of frequency [23]. Besides the loudness of pure tones and complex sounds, the model can also be used to estimate their thresholds.

4.2 INPUT OF MASKER SOUNDS TO THE MODEL

The sound pressure levels of the 1/3 octave band spectrum up to 200 Hz, which were measured under the noise only conditions, were taken as inputs representing the masker sounds in the model to estimate masked thresholds of pure tones at frequencies 31.5, 40 and 50 Hz. As the sound pressure levels measured under the noise only conditions differed from the average sound pressure levels measured in the presence of the noise and signal of 20 Hz, the model was not applied to estimate the masked thresholds of 20 Hz.

Because the input for the masker sounds, i.e. the background noises, was limited for frequencies up to 200 Hz, it was assumed that the sounds above 200 Hz did not have any masking effects for signals below 50 Hz. In order to verify this assumption, the specific loudness for a 50 Hz signal under Noise 2 at its masked threshold is shown in Fig. 7. As seen in the figure, the specific loudness for the 50 Hz signal approaches an insignificant level above 80 Hz. Hence, the contribution to the masked threshold is only from the frequency below 80 Hz. Although the maximum contributing frequency changes with

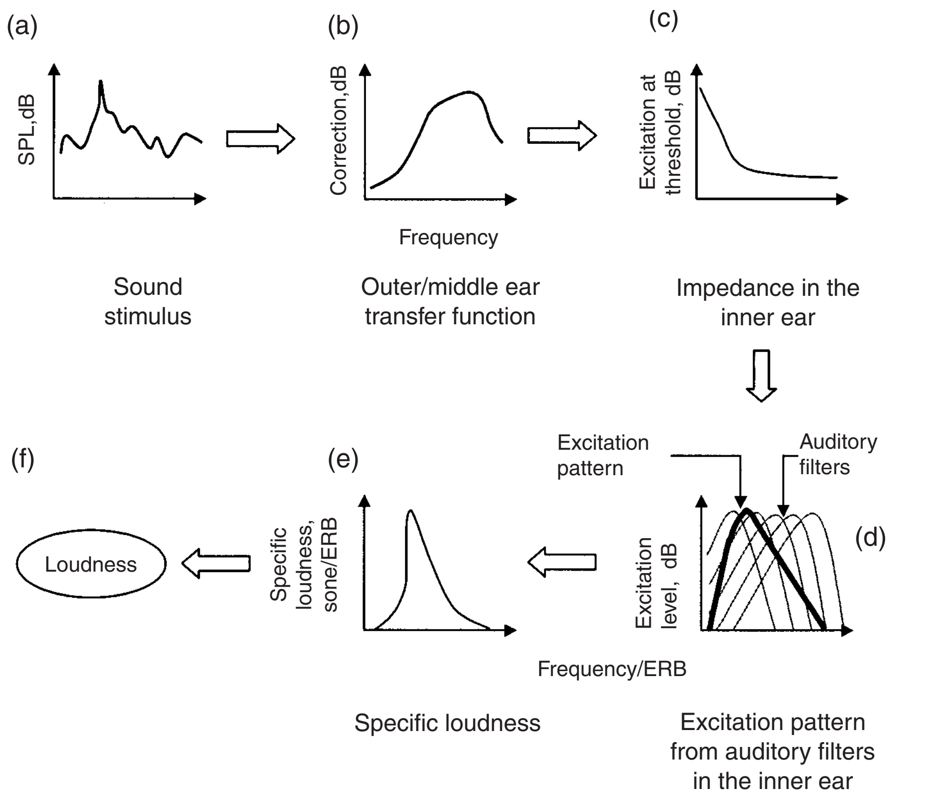

Figure 6 *Schematic diagram showing different stages in the Moore's loudness model (based upon Moore et al. [9]).*

the level of masker sound, the choice to limit the frequency up to 200 Hz for all three levels of background noises might seem appropriate.

The unit of specific loudness in Fig. 7 is sone/ERB and loudness is obtained by summing specific loudness across the ERB scale. The ERB scale is also shown on the upper axis in the figure. The obtained loudness in sones can be converted to loudness level in phons from the relation given by Moore et al. [9]. The total estimated loudnesses from Moore's model for Ambient Noise, Noise 1 and Noise 2 are 25.4, 46.5 and 55.0 phon, respectively.

5. COMPARISON OF ESTIMATED AND MEASURED MASKED THRESHOLDS

Moore's loudness model was applied to estimate the masked thresholds for the low frequency tones at frequencies 31.5, 40 and 50 Hz under the background noises. Comparison of the average of the measured masked thresholds for the five subjects under the three background noises with the estimated results from the model is shown in Fig. 8.

As shown in the figure, the estimated results in Ambient Noise are lower than the measured masked thresholds, while the estimated results are higher than the measured masked thresholds for Noise 1 and Noise 2. The differences in the estimated and average of measured results are within 6 dB for these frequencies. The differences are larger for the frequencies 40 and 50 Hz in the case of Ambient Noise, while they are larger for 31.5 Hz in the case of Noise 1 and Noise 2.

In order to further investigate the estimated results of the model, the estimated loudness levels from the model were compared with the loudness levels specified in ISO 226 [24]. The comparison of the equal loudness level contours calculated from the model and the ISO is shown in Fig. 9. It can be observed in the figure that at lower

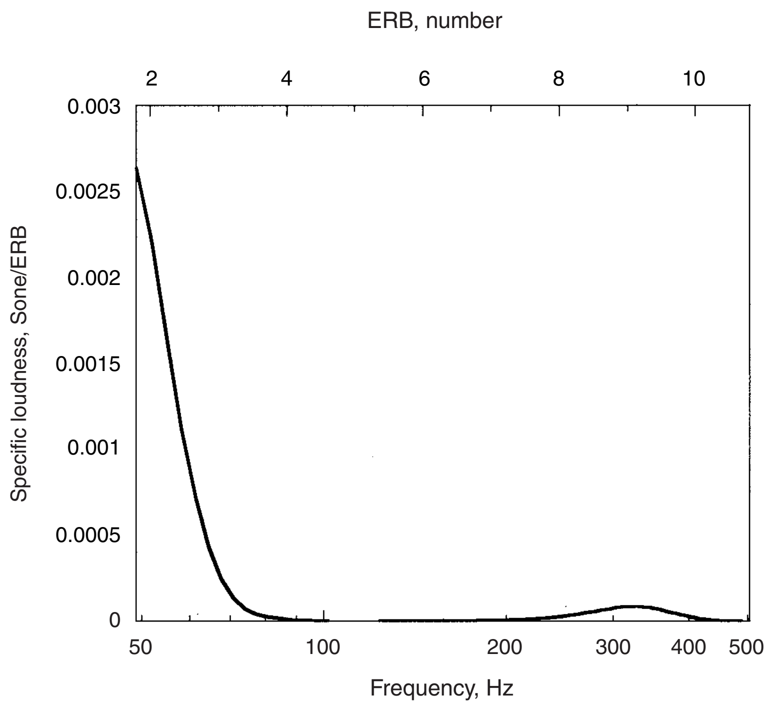

Figure 7 *Specific loudness calculated for 50 Hz signal at its masked threshold under Noise 2. Upper scale is equivalent rectangular bandwidth (ERB).*

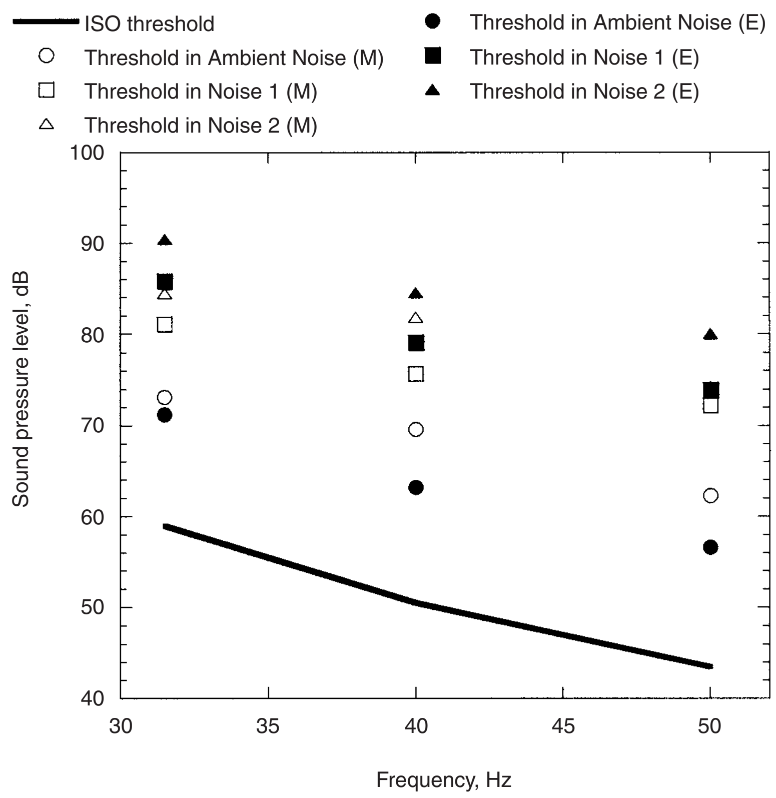

Figure 8 *Average measured thresholds under three different background noises and estimated results from Moore's loudness model (E – Estimated values, M – Measured values). The reference hearing threshold curve specified in ISO 389-7 is also shown.*

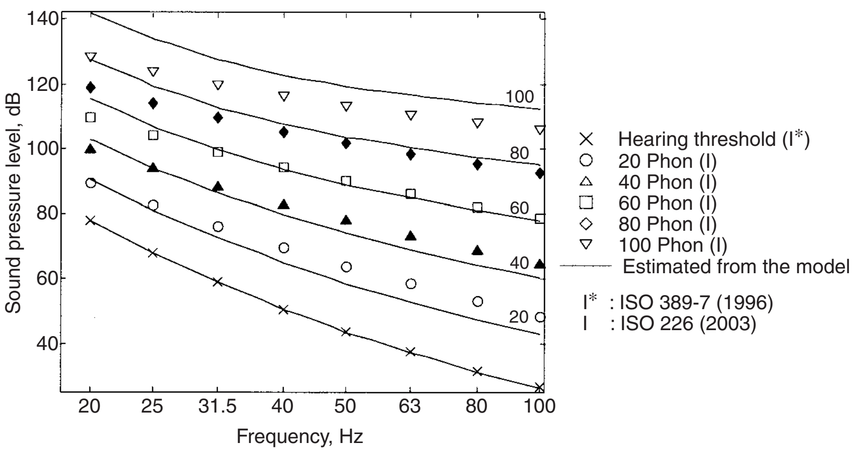

Figure 9 *Equal loudness contours from ISO 226 and estimated from Moore's loudness model. Loudness levels in phon are shown for each estimated contours. The lowest solid line is hearing threshold estimated from the model.*

loudness levels the estimated contours are lower than the contours specified in ISO 226, and with increase in the loudness levels the estimated contours gradually become higher than the contours specified in the ISO. As shown in Fig. 8, a similar change in the trend is observed also in the case of the measurements of masked thresholds, where the estimated thresholds are lower than the measured thresholds in Ambient Noise and higher in Noise 1 and Noise 2. However, the change in the trend occurred at lower sound pressure level in case of the thresholds compared to the case of loudness contours.

Furthermore, it can be pointed out that the two contours from estimated results and ISO 226 are not parallel to each other. At 20 phons loudness level the two contours cross each other roughly at 25 Hz. Although this trend is observed at all levels, the crossing point is shifting towards higher frequencies with increase in the loudness level. The possible reason for this is that the assumed efficiency of the auditory system in the loudness model at lower frequencies is lower with respect to the assumed efficiency at higher frequencies in comparison to the real behavior, and this tendency increases with increase in the loudness level. The comparatively large differences in estimated and measured thresholds at 31.5 Hz for Noise 1 and Noise 2 can also be explained by this phenomenon.

The possible reason for the relatively lower efficiency in the low frequencies is because of the assumption in the model that the assumed auditory filters in the inner ear are limited only down to 50 Hz [9]. It is considered in the model that the frequencies below 50 Hz are detected because they produce outputs from the auditory filters tuned above 50 Hz. This contradicts the experimental study on low frequencies, which suggest that tonal behavior of the sound is present down to 20 Hz [25]. Furthermore, it has been observed that the change in the slope of hearing threshold from approximately 20 dB/octave at higher frequencies to 12 dB/octave at lower frequencies occurs at about 15-20 Hz [26]. These studies suggest that the change in the hearing mechanism occurs at 20 Hz not at 50 Hz. Hence, it is recommended that the lower limit of the assumed auditory filters should be extended at least to 20 Hz.

6. CONCLUSIONS

The perception thresholds of low

frequency pure tones at 50 Hz and below were measured under four background conditions in controlled and uncontrolled environments. Moore's loudness model was applied to estimate the thresholds and its performance in the low frequency region was investigated. The findings of this study are summarized as follows:

1. The masked perception thresholds of low frequency tonal sounds at 50 Hz and below increased with increases in the level of the background noises above 50 Hz. The thresholds increased by more than 20 dB by adding higher levels of background noises. The increase in the threshold indicates that sounds below 50 Hz can be masked by masker sounds above 50 Hz.
2. The estimated thresholds from Moore's model and the average of measured masked thresholds match reasonably well within the subjective variability. However, it can be pointed out that the gradients of the equal loudness-level contours for frequencies below 50 Hz specified in ISO 226 are steeper than the contours obtained from the loudness model.

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