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Published in:
Proceedings of Internoise 2000

Publication date:
2000

MEASUREMENTS OF EQUAL-LOUDNESS CONTOURS
BETWEEN 20 HZ AND 1 KHZ

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ABSTRACT

The equal-loudness relation for pure tones in free-field is investigated for the frequency range below 1 kHz with a resolution of 1/3-octave. Levels ranging from the absolute threshold of hearing to 100 phon are examined. The psychoacoustical measurements are based on an adaptive sequential maximum likelihood method implemented with the 2-AFC response paradigm. The number of trials used by the method is relatively low. However, the experiments show that even a smaller number of trials produces reliable and nearly similar data. The results are, as expected, deviating from the standardized equal-loudness contours in ISO 226. A much better agreement is seen between the results of the present investigation and the more recent investigations on equal-loudness contours at low frequencies.

1 - INTRODUCTION

As a contribution to the revision of ISO 226:1987 [1] researchers at Aalborg University has made an investigation of the threshold of hearing and equal-loudness contours in the frequency range 20 Hz to 1 kHz. In the past, several investigations have been made at our laboratory of the hearing abilities in the infrasonic and low frequency range: Kirk [2], Møller and Andresen [3], Watanabe and Møller [4, 5]. The aim of the present investigation is, however, to determine the equal-loudness level contours and the threshold of hearing strictly according to the preferred test conditions (ISO/TC 43/WG 1 [6]) which have been published in the meantime. Preliminary results of the present work was published by Lydolf & Møller [7] and was finally published in a dissertation by Lydolf [8].

The low frequency range may be considered to be the most interesting part of the loudness contours because the ISO 226 standard has the most severe deviation from other equal-loudness data in this particular range. Moreover data from equal-loudness experiments is often lacking at low frequencies and high levels because of the natural limitations of the physical sound reproduction system used.

2 – METHOD

Experimental setup. It is notoriously difficult to produce a free propagating wave at low frequencies and high levels. In the present experiment this problem was solved by using two different test environments. An anechoic room was used for measurements with frequencies above 50 Hz and a small pressure field chamber with an inner volume of 1.1 m³ was used for frequencies below 100 Hz. Sound pressure levels up to 138 dB could be produced in the pressure field chamber and this provided sufficiently intense stimuli for determination of the 100 phon curve. The maximum sound pressure level obtained in the anechoic room was less than in the pressure field but was at least 109 dB. A reference tone of 1 kHz could not be presented in the pressure field chamber in a well defined way so the equal-loudness investigations in the chamber was based on the use of an individually adjusted anchor point at 100 Hz which was determined in the experiment in the anechoic room.

The pressure field chamber was equipped with 8 loudspeakers of 13" diameter and the same type and number of speakers were used in the anechoic room for stimuli presentation in the 50-400 Hz range. The stimuli between 500 Hz and 1 kHz were presented by a midrange horn loudspeaker placed in the frontal direction of the test subject. The low-frequency speakers in the free-field setup were placed symmetrically on each side of the horn.

Stimuli and test subjects. The experiments included 27 test subjects in the free-field part and 17 in the pressure field part, all with otologically normal hearing according to the specifications in the preferred test conditions [6]. All 1/3-octave center frequencies from 20 Hz to 1 kHz were used for a threshold measurement and determinations of the equal-loudness levels at: 20, 40, 60, 80, 90 and 100 phon. The 90 phon level was included because the 100 phon level was expected to be close to the upper limitation of the experimental setup and thus might not be possible to determine for all subjects. Stimuli were pure tones with a duration of 1 s and the pause between the test tone and the reference tone for loudness comparison was 0.5 s. The order of the test tone and the reference tone was randomized in order to minimize the order effect.

Psychophysical methods. The psychophysical method for threshold measurements was chosen as the ascending method implemented nearly as described in ISO 8253-1 [9]. It starts with a descent from 30 dB HL with a step size of 10 dB and makes 3-5 ascents with a step size of 5 dB. The modification consists of an interlacing of the presentation levels of two successive ascents in order to achieve a resolution of 2.5 dB which is equal to a half step size. The threshold estimate is carefully calculated as the 50 % detection level by a maximum likelihood estimation technique and does not rely on averaging the lowest detectable level as described in ISO 8253-1.

The psychophysical method for the equal-loudness level measurements
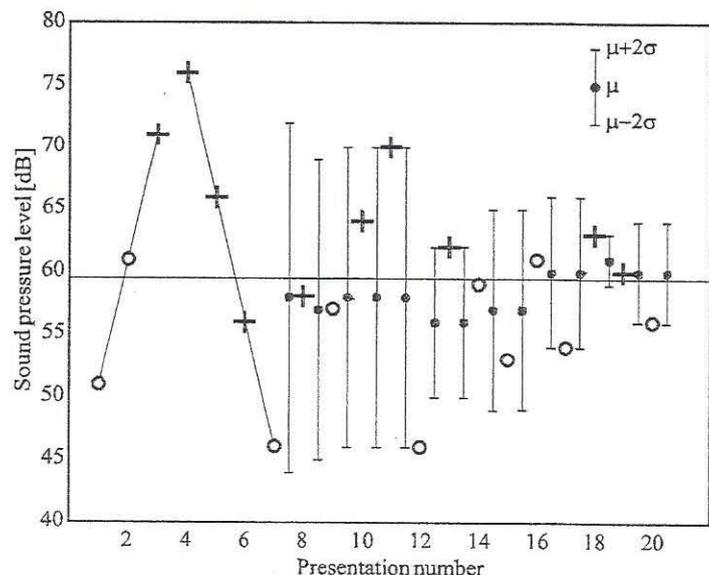
was the sequential maximum likelihood method. This method was introduced by Hall [10] and a previous investigation at our laboratory [3] has provided good experiences with a modified version of this method.

An illustration of the level presentation strategy of the sequential maximum likelihood method is seen in figure 1. The fundamental idea is to present test tone levels close to the point of subjective equality. However, in order not to stress the subjects more than necessary with only difficult trials other levels were included too.

The initial test tone level was identical to the reference loudness level according to ISO 226. Before the method itself was started an ascent and a descent with a step size of 10 dB were made, and the order of the ascent and descent was determined by the initial response. These few presentations were used to produce a rough estimate of the point of subjective equality and ensured that the test tone had been evaluated both as louder and softer than the reference tone before the sequential maximum likelihood method took over.

A model of the psychometric function for the test subject was updated during the course of the measurement for the sequential maximum likelihood method. The psychometric function was modeled as a cumulative normal distributed function described by the mean, μ, and standard deviation, σ. The presentation levels chosen by the method were randomly chosen between five different levels on the current psychometric function: μ, $\mu\pm\sigma$ and $\mu\pm2\sigma$. The estimated values of the mean and two times the standard deviation are plotted as the vertical error bars in figure 1. The method terminated when all the five different levels on the psychometric function was presented.

Schedule of the measurements. The threshold and equal-loudness level measurements in the two experimental setups were made over 3 days for each test subject. Two days were spend using the anechoic room and one day was used in the pressure field chamber. Each of the test subjects was paid on hourly basis and their participation comprised of approximately 6 hours work. On every day a training session was made prior to the real experiments. Each session had a duration of 10-13 minutes and it was followed by a brake of approximately the same duration. A session included about 7-10 measuring points at the same phon level and they were neighboring frequencies. After each determination of a point of subjective equality a pause of 30 s was given in order to reduce the bias of the context effect (see Gabriel [11]). None of the test subjects participated in a threshold experiment less than two days after a loudness experiment. In order to avoid the effect of a temporary threshold shift, TTS, the loudness levels were tested in ascending order.
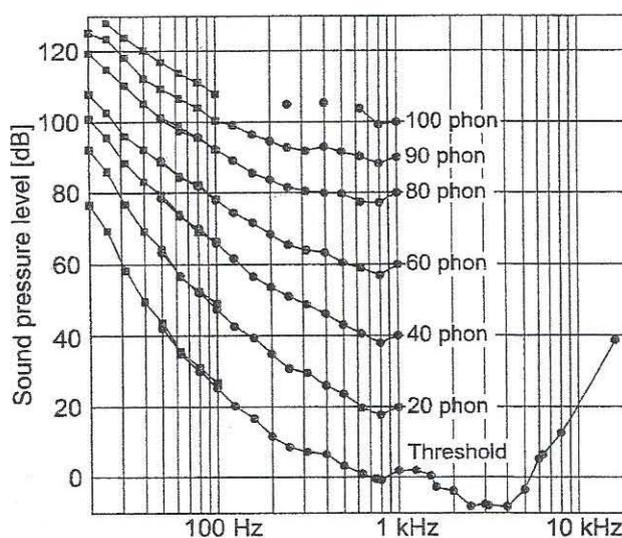
3 - RESULTS

The threshold and equal-loudness contours determined in this experiment are shown in figure 2 in terms of mean values averaged across subjects. The equal-loudness curves in the figure are based on the sequential maximum likelihood method. The average number of trials in the measurements was 13.3 which lasted 58 s on average. A good agreement is seen between the experiments in the two different acoustical environments for both the threshold and higher levels. A few of the equal-loudness points at the highest levels are missing because the experimental setup was not able to produce sufficiently high levels for all subjects. Only complete measurements are shown.
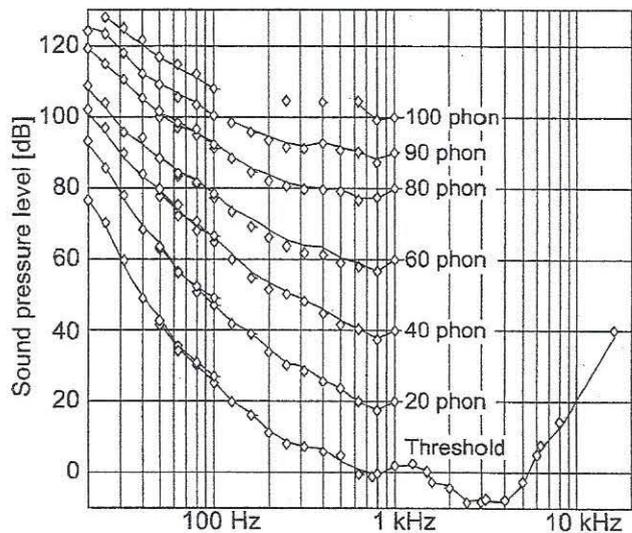
A surprising result from the experiments appeared when the quality of the rough estimate of the point of subjective equality made by the initial presentations was investigated. The rough estimate is typically determined after only 4-5 trials made by an ascent and a descent with 10 dB steps. With respect to the threshold data, the rough estimates are based on the tone familiarization in the beginning of the measurement also made by a descent and an ascent with a step size of 10 dB. The rough estimates are represented by the diamonds in figure 3. The continuos lines in the figure represents the measurements based on the full method. It is seen that the agreement between the two data sets is very good and the sparse data material does not give rise to considerably more fluctuations of the curves. However, the final estimates are systematically 1-2 dB above the initial estimates in the frequency range 80-800 Hz. This is most likely bias from the context effect. Since the starting point for the test tone level was typically placed below the point of subjective equality, PSE, there were initially more presentations below the PSE, which gives a downwards bias in the beginning of the measurement. However, when the sequential maximum likelihood method has taken over there becomes an equal amount of stimuli above and below PSE. According to Gabriel [11], levels above the PSE gives more bias upwards than levels below the PSE gives bias downwards, thus resulting in a net upward bias in the end of the measurement.
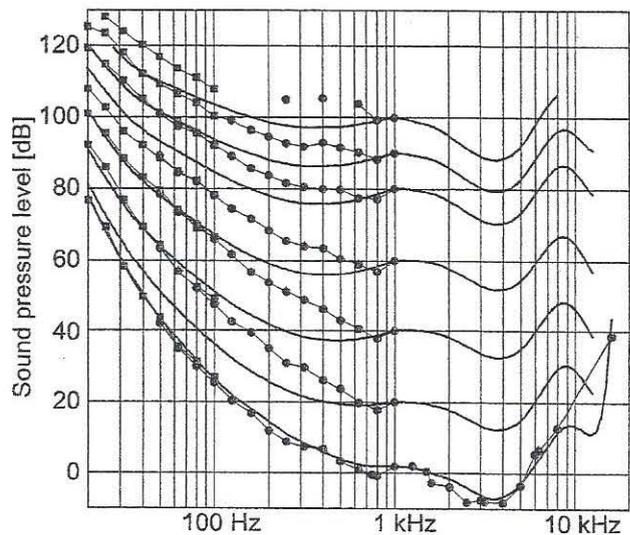
4 - DISCUSSION

A comparison of the new data and the standardized data for the free-field threshold according to ISO 389-7 [12] and the equal-loudness contours in ISO 226 [1] is seen in figure 4. On one hand a substantial difference is seen for the equal-loudness levels where the new data suggests a 10-

15 dB elevation of the equal-loudness contours between 50 and 200 Hz for low and medium levels. On the other hand a good agreement is seen between the two set of threshold data in the full frequency range.

If the new data is going to be compared to results of other equal-loudness investigations, attention must be paid to the experimental conditions in each of the investigations. Most of the early researchers produced stimuli by the use of headphones and the reported levels may not be expressed in terms of a free-field sound pressure level. Kingsbury [13] used monaurally earphone exposure and the calibration was made in a unspecified coupler, thus for the following comparison his data is re-calibrated so the threshold fits to ISO 389-7 [12] and the loudness growth function is retained. Zwicker and Feldtkeller [14] used an earphone too and made an equalization to free-field levels in terms of an electronic filter. The response of the filter was based on a very sparse investigation of the relation between earphone and free-field listening so the loudness data is treated like Kingsbury's. Unfortunately the re-calibrations has the effect that the data seem artificially good since the curvature is strongly influenced by the reference threshold. Fletcher & Munson calibrated their headphone measurements to free-field but the data is interpolated to the nearest loudness level in 10 phon steps. Any other data at the two equal-loudness level 40 and 70 phon shown in figure 5 and 6 respectively is represented as the original data. A comparison between the results of the present investigation and all the available data show a much better agreement than if they are compared to ISO 226 alone.
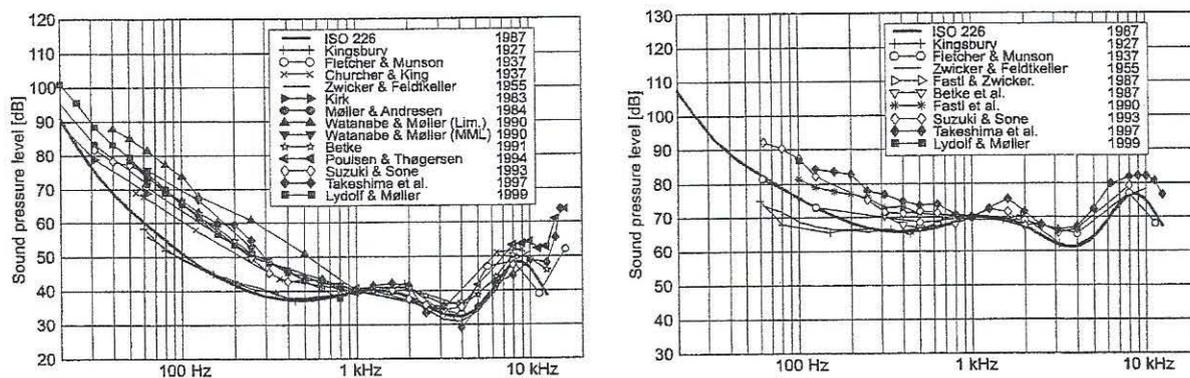
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