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Observed effects of HRTF measurement signal level

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ABSTRACT

The effect of varying the signal level on the magnitude response of a head-related transfer function measurement was investigated. Measurement signals with levels ranging between 56 and 86dB SPL were presented over a loudspeaker and recorded using blocked meatus microphones placed in a dummy head. Results indicate that, relative to a 74 dB reference level, for measurement signals below 62dB and above 80dB SPL (1) interaural level differences increase as a function of decreased signal level, and (2) the ipsilateral ear shows a variance in spectral notch depth and center frequency location.

INTRODUCTION

This paper describes observations regarding the magnitude response of a head-related transfer function (HRTF) measurement as a result of varying signal level. Although previous research has demonstrated the effect of varying the distance of the measurement loudspeaker in HRTF measurements, particularly for distances less than 1 m (Duda and Martens, 1998), it would be expected that, except for extreme conditions of sound pressure levels, the magnitude of the HRTF would vary linearly in relationship to the level of the measurement signal. This paper describes some non-linear effects that were observed as a function of sound pressure levels that varied between 56 dB and 86 dB, relative to measurements made at a reference level of 74 dB. Controls were made for the effect of room acoustics, measurement equipment, and other obvious aspects that may have influenced the results. A suitable explanation has not been found at this point, although there is the possibility of locally reactive intensity effects.

2. METHODS

2.1 Measurement environment

Measurements were performed in a 5 x 4 x 3.5 m room acoustically treated to attenuate early reflections. The room setup is shown in Figure 1.

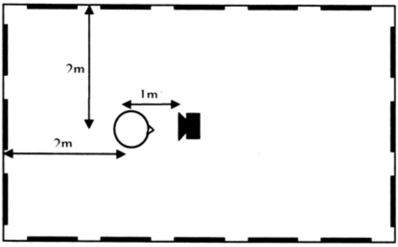

Figure 1. *Measurement setup*

2.2 Apparatus

Simulated blocked meatus measurements were made using a Neumann KU-100 dummy head and two matched Panasonic WM-60A microphones, placed at the entrances to the middle ear of the dummy (the KU-100's internal microphones were not used). Comparative measurements were taken on two human subjects using an identical setup. A small, custom-designed loudspeaker specifically designed for HRTF measurements was mounted on a boom stand, 1 m distant from the center of the measured head. The head was at least 2 m from the nearest wall. Golay code pairs of length 0.0053 seconds were used as the measurement signal. Modified HeadZap scripts from AuSIM Inc. (running under the Mathworks Matlab environment) were used to generate the test signals and record the response. The recorded outputs were digitized at 48kHz sampling rate with a 24-bit resolution. The data was windowed in order to remove room reflections. No equalization was applied to the results. Each impulse response is 128 samples in length.

2.3 System validation

Prior to making the HRTF measurements, a magnitude response linearity check of the reproduction and recording equipment was made. The loudspeaker was calibrated to an A-weighted level of 74 dB using a reference microphone (Brüel and Kjær 4191) and a dynamic signal analyzer (Agilent Technologies 35670A). The measurement microphones were then positioned at a distance of 1 meter from the loudspeaker without the dummy head. Measurement signals were played at six levels increasing from 56 to 86 dB in constant intervals of 6 dB, and then normalized to the same level by the measurement software. The differences in frequency response of the reproduction and recording equipment is < 3 dB between 1 – 20 kHz (figure 2).

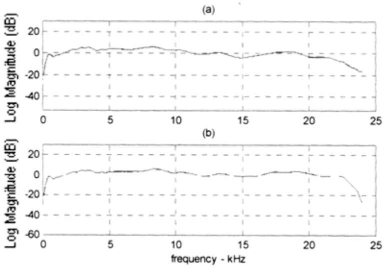

Figure 2. *Tests of linearity and repeatability of the measurement system without the dummy head. Free-field measurements taken in 6 dB increments from 56-86 dB SPL for left (a) and right (b) ear microphones. Figure displays five repeated measurements for each SPL tested, normalized to74 dB.*

HRTF measurements were then made with the same measurement signal and the same range of levels used in the linearity check, at 30° azimuth increments (from 0° to 360 °), and 15° elevation increments (from -45° to +45° elevation). The observed phenomena described below were observed for all measured positions that were not on the median plane.

3. RESULTS

The analysis of the data shows most noticeable effects in the back hemisphere, at azimuth locations between 120° and 150°. For clarity, we focus on results at these locations.

Two main observations regarding the effect of measurement signal level can be made from the resulting HRTF magnitude responses. First, at a given measurement location, the interaural level difference (ILD) changes as a function of signal level. Second, the frequency magnitude spectrum changes in a non-linear manner as a function of signal level. These changes include variable notch and peak depths as well as movement of the center frequency of spectral peaks and notches in the 8 – 17 kHz region.

3.1 Interaural Level Difference (ILD)

The ILD changes as a function of signal level consistently across all azimuth and elevation locations tested. Results on the 0° elevation plane present the most visible effect. Figure 3 shows ILDs for measurements taken with the dummy head at 90° azimuth, 0° elevation, with signal levels between 56dB and 86dB. The ILD decreases rather linearly with increasing signal level.

The ILD can be approximated by a one-pole one-zero transfer function defined by:

$$H(s,\theta) = \frac{\alpha(\theta)\, s + \beta}{s + \beta}$$

where $\alpha(\theta) = 1 + \cos\theta$ and $\beta = 2\frac{c}{a}$

The predicted ILD for a location at 90° azimuth is shown in figure 3 as a dotted line.

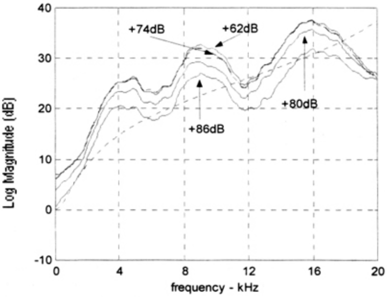

Figure 3. *Interaural level difference between ipsilateral and contralateral ears for the dummy head at 90° azimuth, 0° elevation. Plot shows normalized measurements taken every 6dB from 62 to 86 dB SPL. Dashed line represents the predicted ILD according to Duda & Martens (1999).*

Measurements made at 120° azimuth, 0° elevation demonstrate a non-linearity in the ILD at frequencies above 13 kHz (see figure 4). At the higher levels (80-86 dB) the ILD continuously increases as a function of frequency. A similar phenomenon, although not as striking, was observed with the human subject at the same location (see figure 5). The ILD of high level test signals are, in general, up to 7 dB lower than the ILD for low level test signals. However, figures 4 and 5 show that the ILD for high level test signals tends to "cross over" around 13 kHz and become greater than test signals with a low amplitude. Other locations exhibit similar phenomena. The frequency at which the crossover occurs changes varies between 11 - 15 kHz.

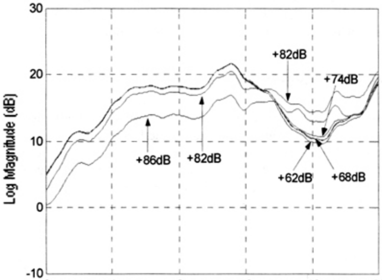

Figure 4. *Interaural level difference for the dummy head at 120° azimuth, 0° elevation. Plot shows normalized measurements taken every 6 dB from 62 to 86 dB SPL.*

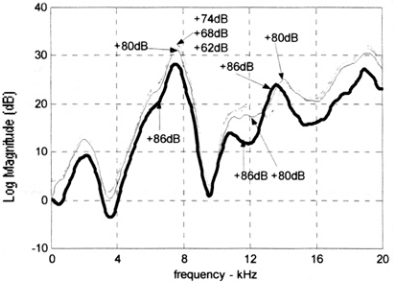

Figure 5. *Interaural level difference for human subject at 120° azimuth, 0° elevation. Plot shows normalized measurements taken every 6dB from 62 to 86dB SPL. Bold line represents measurements at 86dB SPL.*

The observed differences for the contralateral ear level between the lowest and highest signal levels changes as a function of the test sound source elevation for any given azimuth. As the elevation moves away from the horizontal plane, the difference at the contralateral ear between measurements taken at the 56 and 86 dB levels becomes smaller at a rate of about 1.5 dB per 15° elevation. Figure 6 illustrates the variance for the impulse responses of the contralateral ear for elevations ranging from +45° to -45°. These results were obtained by taking the difference between the responses measured with a test signal at +86 dB, and at 56 dB. The plots show the biggest variance at elevation 0°.

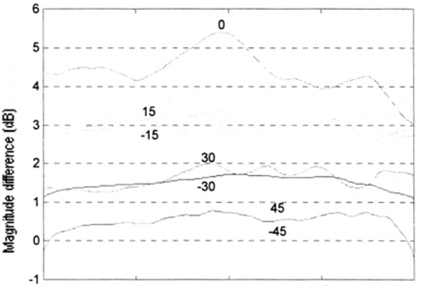

Figure 6. *Difference between the contralateral ear response at 86 and 56 dB. Measured for azimuth 120°, elevations -45° to +45°, every 15°. Elevations are indicated on plot.*

3.2 Spectral characteristics

Figure 7 shows the magnitude spectrum measured on the dummy head for the ipsilateral and contralateral ears at the 120° azimuth, 0° elevation location. The plots include measurements of test signal levels from +56 dB to +86 dB. Two spectral areas are particularly significant: (1) changes in the depth of the spectral notch centered at 8.5kHz, and (2) changes in the height of the spectral peaks in the region from 14kHz to 18kHz. These areas are enlarged in figure 8.

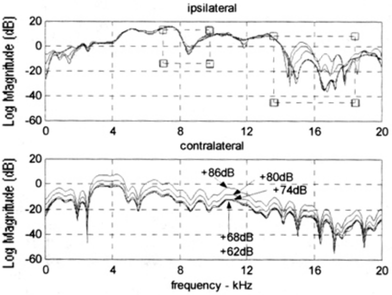

Figure 7. *Magnitude of ipsilateral and contralateral ears measured on the dummy head at 120° azimuth, 0° elevation. Areas in boxes are enlarged in figure 9.*

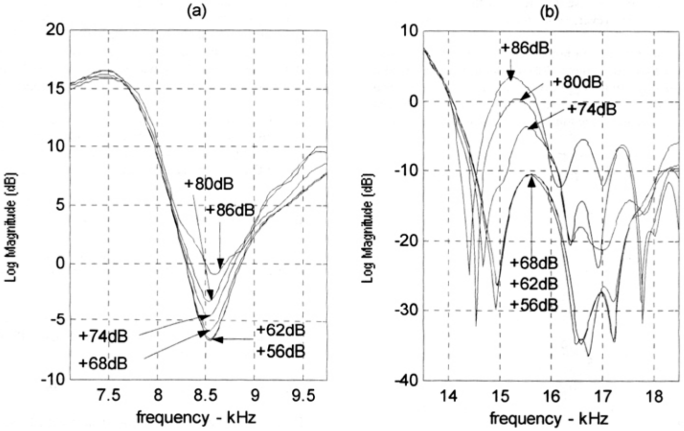

Figure 8. *Enlargements of areas in boxes of figure 7. (a) illustrates the deepening of notch at 8.5kHz as sound pressure level decreases. (b) shows peak in crease with level increase as well as a movement of the center frequency of the peak.*

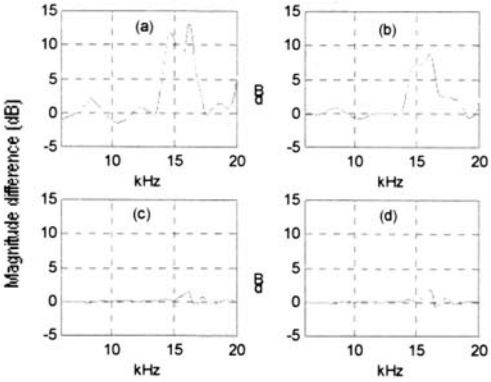

Figure 9. *Differences in spectral characteristics between a reference excitation signal of 74 dB SPL and signals at (a) 86 dB; (b) 80 dB; (c) 68 dB; and (d) 56 dB SPL. Measurements of ipsilateral ear taken at 120° azimuth, 0° elevation.*

The ipsilateral ear shows the greatest amount of spectral change as a function of signal level. Two observations can be made on the influence of the test signal level on spectral characteristics of measured responses. First, spectral notches vary in depth. In figure 8(a) the steadily decreasing depth of the notch appearing at 8.5 kHz can be seen. In this case, the depth of the notch varies by approximately 6 dB. However, other locations experience notch depth variations of up to 20 dB. Similarly to the variance in notch depth, a varying magnitude of peaks can be observed. Figure 8(b) shows a peak centered at 15.5 kHz. At low-level signals (56 dB, 62 dB, and 68 dB) the peak is constant at –11dB. As the test signal SPL increases, the peak increases in magnitude up to the maximum of 4dB, at 86dB SPL.

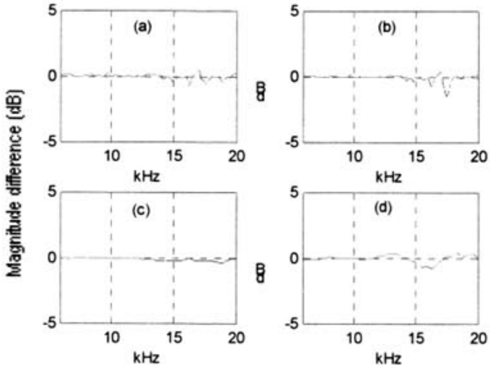

Figure 10. *Differences in spectral characteristics between a reference excitation signal of 74 dB SPL and signals at (a) +86 dB; (b) +80 dB; (c) +68 dB; and (d) 56 dB SPL. Measurements of contralateral ear taken at 120° azimuth, 0° elevation. Plots were adjusted around 0dB in order to compensate for resulting signal level decrease at high test signal levels.*

To illustrate the amount of spectral variation occurring at the different sound pressure levels, difference plots are presented in figures 9 and 10. The two figures are representations of the magnitude of the ipsilateral and contralateral ears as a function of increased or decreased measurement levels relative to the median level of 74 dB.

The second interesting phenomenon occurring in the ipsilateral ear's magnitude response is the movement of spectral notches and peaks as the signal level changes. The peak shown in figure 8(b) originates at 15.6 kHz for levels of 56, 82, and 68 dB. As the signal level increases, we see a migration of the spectral peak: 15.5 kHz at 74 dB; 15.3 kHz at 80 dB; and 15.2 kHz at 86dB SPL. Likewise, a left shift of the notches can be seen as the SPL increases. The same phenomenon has been observed in the human subject.

The movement of the center frequency of spectral peaks and notches occurs at different rates between signal level increase. However, it is consistently between 100 Hz and 600 Hz for all frequency areas.

4. DISCUSSION

The results of the investigation described in this paper suggest that the sound pressure level of the excitation signal in HRTF measurements causes fluctuations in the measured responses. Significant changes in responses have been observed including variances of spectral peak and notch depths and movements of their center frequencies, as well as a distinct difference of the ILD, particularly on the horizontal plane.

These changes are important if an HRTF measurement system is to capture information relevant to auditory localization, and may infer that a measurement system should be calibrated to a reference sound pressure level. The question remains as to what the sound pressure level should be used for HRTF measurements. The effect may possibly be due to local reactivity at the pinnae of the dummy head. The same effect was not observed in similar tests using a mannequin head without pinnae, using flush-microphones.

It has not yet been assessed whether these fluctuations will alter the ability of subjects to localize sounds in the 3D space. Listening tests need to be conducted in future work in order to determine the extent that these alterations are relevant to localization.

5. REFERENCES

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