Relating $2f_1 - f_2$ distortion product otoacoustic emission and equivalent rectangular bandwidth

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To explore the extent of distortion product otoacoustic emission (DPOAE) toward low frequencies we measured in 21 normal-hearing human subjects its dependence on the ratio between evoking stimulus frequencies, f_1 and f_2, at $2f_1 - f_2$ distortion frequencies 88, 176, and 264 Hz. The "optimal" ratio evoking the largest DPOAE level is frequency dependent but well-guided by 1.52 equivalent rectangular bandwidth (ERB).

INTRODUCTION

Distortion-product otoacoustic emission (DPOAE) is the healthy ear's active response at distortion frequencies of two simultaneously-presented tones with frequencies f_1 and f_2 ($f_1 < f_2$) (Kemp, 1979). This two-tone stimulus evokes two traveling waves on the basilar membrane. Throughout the region excited by both tones (corresponding to the f_2 wave) distortion is generated, mostly at the $2f_1 - f_2$ frequency in humans.

DPOAE is thus, like typical measures of the frequency tuning of hearing, related to the excitation of the basilar membrane as controlled by varying the two-tone stimulus parameters. The DPOAE level for example is a bell shaped function of the frequency ratio f_2/f_1 and the "optimal" ratio is traditionally defined as that which on average evokes the largest DPOAE level.

Six systematic studies of the DPOAE level-ratio dependency consistently find an optimal ratio close to 1.22 (Christensen *et al.*, 2015a). Even though a slight increase in the optimal ratio is also consistently found as the $2f_1 - f_2$ decreases, a ratio fixed at 1.22 is standard in DPOAE measurements across frequency. With this ratio the average DPOAE level-to-noise ratio is below zero below a distortion frequency of about 0.5 kHz (Gorga *et al.*, 1993).

In the present study, the DPOAE level-ratio dependence was measured in 21 normal-hearing subjects at three $2f_1 - f_2$ frequencies: 88, 176, and 264 Hz. This is about an order of magnitude lower in frequency than typically measured and should help solidify the apparent frequency dependence of the optimal ratio.

METHODS

In 21 normal-hearing human subjects, the dependence of the $2f_1 - f_2$ DPOAE level on the stimulus frequency ratio f_2/f_1 was measured at $2f_1 - f_2$ frequencies of 88, 176,

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and 264 Hz. The ratios measured are shown in Table 1. The stimulus levels were 65 and 55 dB sound pressure level (SPL) for f_1 and f_2, respectively, calibrated in a Brüel & Kjær 4157 ear simulator (IEC 60318-4:2010).

$2f_1 - f_2 = 88$ Hz	$2f_1 - f_2 = 176$ Hz	$2f_1 - f_2 = 264$ Hz
1.286 (9/7)	1.250 (5/4)	1.200 (6/5)
1.333 (4/3)	1.286 (9/7)	1.250 (5/4)
1.375 (11/8)	1.333 (4/3)	1.286 (9/7)
1.400 (7/5)	1.375 (11/8)	1.333 (4/3)
1.444 (13/9)	1.400 (7/5)	1.375 (11/8)
1.500 (3/2)	1.444 (13/9)	1.400 (7/5)
1.556 (14/9)	1.500 (3/2)	1.444 (13/9)

Table 1: Overview of tested stimulus parameters.

Low-frequency noise in the ear canal from breathing, blood circulation, etc., is usually filtered out electronically and the transducer sensitivities of commercial probe systems are generally tailored to OAE measurements above 0.5 kHz. Therefore, to condition measurements properly at low frequencies a custom probe system was built for use in the present study (Christensen *et al.*, 2015b), shown in Fig. 1.

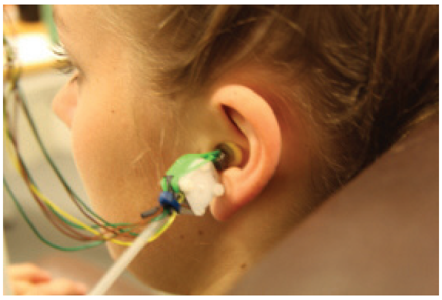

Fig. 1: Custom-made probe in a subject for DPOAE measurements at low frequencies. The $2f_1 - f_2$ frequency was held fixed at 88, 176, and 264 Hz as the stimulus ratio was varied to find the one evoking the largest DPOAE level.

Data were recorded with a frequency resolution of 1.46 Hz and the averaging duration was 95.7, 24.7, and 9.6 s at 88, 176, and 264 Hz, respectively. The duration of each measurement was usually about 10% longer because data were rejected if victim of either burst or slowly varying noise. The DPOAE level was calculated from the power in the fast Fourier transform (FFT) bin corresponding to the $2f_1 - f_2$ frequency and the noise level was calculated from power in the bins in the outer two thirds of an equivalent rectangular bandwidth (see Eq. 1) around the $2f_1 - f_2$ frequency.

RESULTS

Fig. 2 shows the DPOAE level-ratio dependence in four subjects.

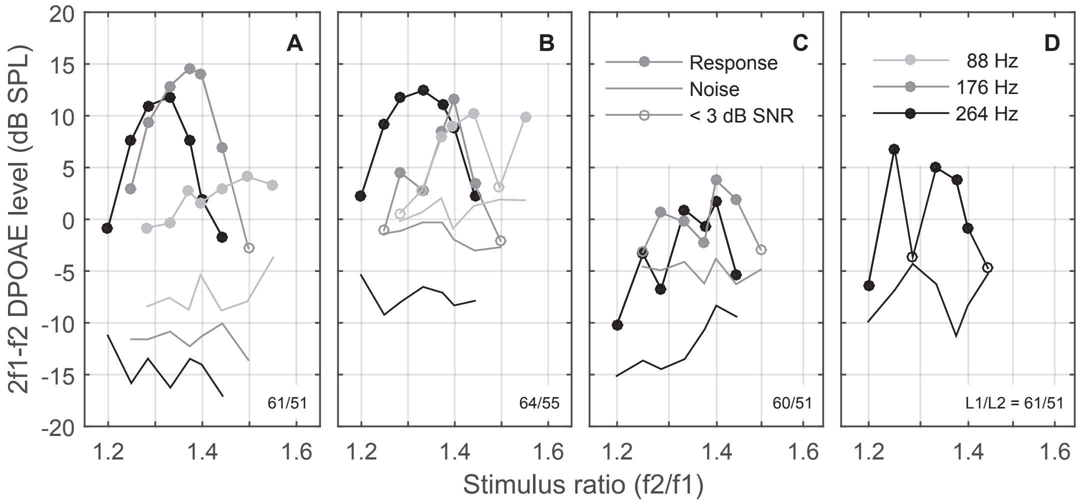

Fig. 2: Individual DPOAE levels as a function of the stimulus ratio f_2/f_1 at three different $2f_1 - f_2$ frequencies. Data points with signal-to-noise ratios less than 3 dB were rejected and the entire curve was excluded from the average if more than three points were rejected.

Aside from some irregularity, such as the dip in subject D, the bell shaped dependence known from mid and high frequencies also exists at low frequencies.

Fig. 3 shows the average DPOAE level-ratio dependence in subjects with enough measurements above the noise floor.

Eight, 15, and 20 out of 21 subjects had at least four out of 7 measured points with a signal-to-noise ratio better than 3 dB. The prevalence does not decrease toward low frequencies, as can be seen in Fig. 3, because the DPOAE level is generally lower. The prevalence decreases instead because the noise floor increases at lower frequencies, even though in this study the averaging duration was markedly increased as the $2f_1 - f_2$ frequency decreased, exemplified in Fig. 2.

The optimal ratio is not 1.22 as it is at higher frequencies. It is 1.46, 1.37, and 1.31 at 88, 176, and 264 Hz, respectively.

DISCUSSION

Equivalent rectangular bandwidth (ERB) is a measure of the bandwidth of behavioral tuning curves (Glasberg and Moore, 1990). Its empirical relation to the center frequency f [kHz] is given by

$$\mathrm{ERB}(f) = 24.7 \cdot (4.37f + 1) \quad \text{[Hz]}. \qquad \text{(Eq. 1)}$$

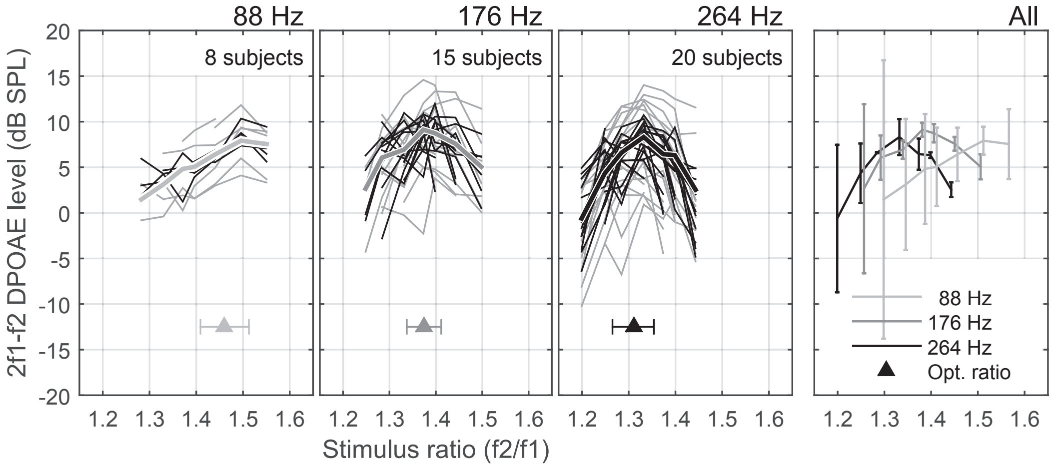

Fig. 3: Average DPOAE levels as a function of the stimulus ratio f_2/f_1 at three different $2f_1 - f_2$ frequencies. Individual data are plotted with thin lines behind the averages. The rightmost subfigure shows only the averages with error bars signifying one standard deviation. The optimal ratios shown as triangles are calculated as the average of the maximum in each individual curve.

The ERB can be related to the stimulus frequency separation in a DPOAE measurement by a scaling parameter λ (Christensen *et al.*, 2015a):

$$f_2 - f_1 = \lambda \cdot \mathrm{ERB}(f_2) \quad \text{[Hz], or} \qquad \text{(Eq. 2)}$$

$$f_1 - (2f_1 - f_2) = \frac{\lambda}{1 - 2 \cdot 24.7 \cdot 4.37} \cdot \mathrm{ERB}(2f_1 - f_2) \quad \text{[Hz].} \qquad \text{(Eq. 3)}$$

λ may then be fit by minimizing the squared difference to the data.

As summarized in Fig. 4, our results combined with the results of previous studies yield an optimal frequency separation well guided by 1.52 ERB. This shows that the optimal ratio is systematically dependent on frequency. It also suggests that the distinct places on the basilar membrane (Greenwood, 1990), excited maximally by the two stimulus tones, are secondary to the spread of excitation around those places in the generation of DPOAE. ERB is just one measure of that spread.

ENDNOTES

This is a preliminary report of an article submitted for publication in JARO.

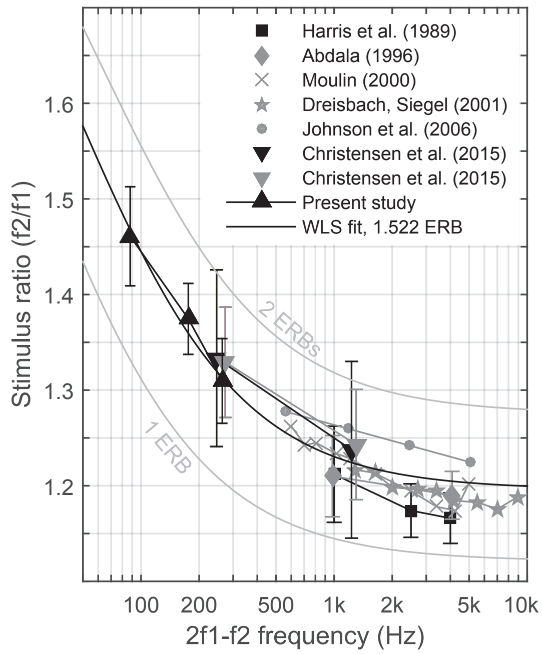

Fig. 4: Optimal ratios for DPOAE measurements as found by seven independent studies, including the present one (full references given in Christensen *et al.* (2015a)). The results comprise measurements in 98 individual subjects. Shown also is the least-squares fit of the ERB model to the data sets, weighted by the number of subjects they each represent.

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