# Estimating auditory filter bandwidth using distortion product otoacoustic emissions

ANDREAS H. RUKJÆR[1], SIGURD VAN HAUEN[1], RODRIGO ORDOÑEZ[2,*], AND DORTE HAMMERSHØI[2]

[1] *Acoustics and Audio Technology, Aalborg University, Aalborg, Denmark*

[2] *Signal and Information Processing, Department of Electronic Systems, Aalborg University, Aalborg, Denmark*

The basic frequency selectivity in the listener's hearing is often characterized by auditory filters. These filters are determined through listening tests, which estimate the masking threshold as a function of frequency of the tone and the bandwidth of the masking sound. The auditory filters have been shown to be wider for listeners with sensorineural impairment. In a recent study (Christensen *et al.*, 2017) it was demonstrated on group basis that the distortion product stimulus ratio that provided the strongest $2f_1 - f_2$ component at low frequencies had a strong correlation to the theoretical relation between frequency and auditory filter bandwidth, described by the equivalent rectangular bandwidth (ERB, Glasberg and Moore, 1990). The purpose of the present study is to test whether a similar correlation exists on an individual basis at normal audiometric frequencies. The optimal $2f_1 - f_2$ DPOAE ratio is determined for stimulus ratios between 1.1 and 1.6, at fixed primary levels ($L_1/L_2 = 65/45$ dB SPL). The auditory filters are determined using notched-noise method in a two alternative forced choice experiment with noise levels at 40 dB SPL/Hz. Optimal ratios and auditory filters are determined at 1, 2, and 4 kHz for 10 young normal-hearing subjects.

## INTRODUCTION

Since the discovery of otoacoustic emissions (OAEs) by Kemp (1978), they have become a central element in auditory research as an objective measure of peripheral auditory function. Otoacoustic emissions can be used to describe the state of the inner ear, in particular, of the outer hair cells (OHC), responsible for the active processes in the cochlea and the low level sensitivity of the hearing. Distortion product otoacoustic emissions (DPOAE) are the cochlear response to a two-tone paradigm. DPOAEs are thought to be generated as a result of interaction between the excitation patterns created by the primary stimulus frequencies in the basilar membrane (BM). Research shows that cochlear frequency tuning can be related to DPOAE phase delay (Bowman *et al.*, 1998), to DPOAE suppression tuning curves (Gruhlke *et al.*, 2012), as well as to response delay from stimulus frequency OAEs (Bentsen *et al.*, 2011). These results show that frequency specific OAEs can be used to describe frequency tuning

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[*] Corresponding author: rop@es.aau.dk

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characteristics, yet the relation between the individual measures and the cochlear tuning characteristics are rather complex, being subject to several assumptions and undergoing complex data analysis procedures. This results in measures that may be well suited for auditory research but are not suited for clinical application.

The present work is inspired by the findings of Christensen *et al.* (2015, 2017), which at low frequencies demonstrated the relation between the optimal $2f_1 - f_2$ DPOAE stimulus ratio ($f_2/f_1$) and the equivalent rectangular bandwidth (ERB), as defined by Glasberg and Moore (1990):

$$f_1 - f_2 = \gamma ERB(f_2), \qquad \text{(Eq. 1)}$$

where the constant $\gamma$ was found experimentally to equal approximately 1.5 in Christensen *et al.* (2015, 2017) for normal hearing populations.

The auditory filter bandwidth depend on: (1) the properties of the underlying morphology, and (2) the state of health in the underlying morphology (See Ch. 1 Sec. 6B in Moore, 2012). If changes to the the optimal DPOAE stimulus ratio are correlated to changes in the auditory filters due to cochlear damage, DPOAE measurements may offer a fast alternative to the psychoacoustic test of auditory filter bandwidth. If not, it may hold individual information of the underlying morphology, and may serve as a calibration or normalisation factor for the psychoacoustic (and other) individual measurements.

The purpose of the present investigation was to further examine the individual relation between the psychoacoustic (ERB) and objective (optimal DPOAE stimulus ratio) estimates for normal hearing subjects at typical audiometric frequencies.

## METHODS

Auditory filter bandwidths and optimal DPOAE ratios were determined for 10 young (18-25 years), normal hearing (hearing level, HL $< 20$ dB, middle ear pressure, MEP $< \pm 100$ daPa) subjects around the standard audiometric frequencies of 1, 2, and 4 kHz.

### DPOAE measurements

An Etyomotic Research ER-10C probe system with a Roland UA-25EX sound card controlled through a customised MATLAB program was used to obtain the DPOAE measurements. The fixed-$f_2$ paradigm was utilised and stimulus levels were fixed at 65/45 dB SPL. The probe was calibrated using a Brüel & Kjær Type 4157 ear simulator with a Brüel & Kjær Type 4138 microphone. Before measurements, individual levels were adjusted using the sound card's input gain to match a 500-Hz tone measured in the ear-canal to the corresponding reference level measured in the ear simulator. During the measurements the operator could monitor the measured signal, and an amplitude rejection criteria was used to avoid noisy recordings due to swallowing or movement of the probe.

Each response was recorded at 48 kHz and 24-bits resolution. The recorded signal was analysed using an average of 10 frames of 4800 samples and a discrete Fourier transform (DFT) of the same length, giving a frequency resolution of 10 Hz. Primary frequencies were chosen so all components of interest ($f_1$, $f_2$ and $2f_1 - f_2$) had an integer number of periods in the analysis frame, so no windowing was applied. The noise level of the measurement was estimated by averaging the amplitude of all DFT bins within 1 ERB centred at a given $2f_1 - f_2$ frequency (excluding the distortion component itself).

Taking into account the possible presence of fine structure in the DPOAE levels, five measurements were made within one dip-to-dip bandwidth of the expected fine structure, according to Reuter & Hammershøi (2006). For each audiometric frequency, DPOAE levels were obtained using five primary frequency pairs linearly spaced within a 100, 160 and 320 Hz bandwidth centred at 1, 2 and 4 kHz respectively. For each set of primaries eight different ratios were used between 1.1 and 1.5, as shown in Fig. 1. In order to ensure that all major signal components have an integer number of periods in the analysis window, the primary ratios changed for the five DPOAEs around each audiometric frequency. Thus, eight individual ratios were tested for each of the five sets of primaries, within a narrow frequency band around each of the three audiometric frequencies.

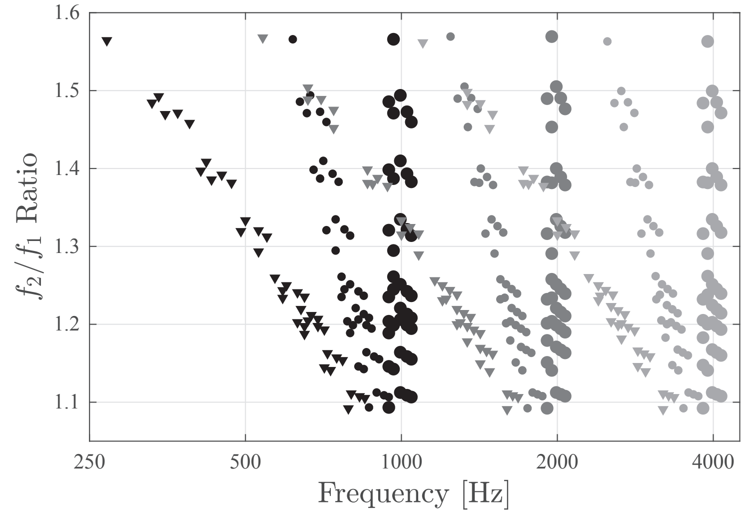

**Fig. 1:** Measured ratios as a function of primary and DPOAE frequencies, $f_2$ (large circle), $f_1$ (small circle), $2f_1$-$f_2$ (triangle)

The choice of frequencies included primary ratios that exceed 1.5 (see Fig. 1), at these high ratios the response of the $2f_1 - f_2$ component is close of $f_1/2$ and may be influenced by other distortion products. All DPOAE values obtained with primary ratios higher that 1.5 were excluded from further analysis (one case for 1 and 4 kHz and two cases for 2 kHz).

### Auditory filter determination

Auditory filters were estimated using the notched noise method as described by Glasberg and Moore (1990), with relative notch widths $\Delta f/f_c$ of 0, 0.05, 0.1, 0.2, 0.3 and 0.4. The noise masker was presented simultaneously with the stimulus tone with a 100-ms Hanning ramp applied to both start and end of the combined signal. Each noise and stimulus interval was presented with 0.5-s duration and a 0.25-s pause between intervals. The masker was presented at a level of 40 dB/Hz.

Thresholds were estimated using a 2-alternative forced-choice paradigm with a 1-up 2 down tracking rule which estimates the 70.7% point on the psychometric function (Levitt, 1971). The 8-dB initial step-size was reduced to 4 and 2 dB after each reversal and a single threshold estimate was taken as an average of 6 reversals obtained with the smallest step-size. Subjects were given approximately 10 minutes under supervision for familiarisation with the procedure.

The filter shapes were derived from the notched-noise experiment data using the polynomial fitting method described by Patterson (1976). A 3rd order polynomial was fitted to the data and the ERB estimate was obtained from the integral of the fitted curve multiplied by $2f_c$, assuming symmetric filters.

## RESULTS

### DPOAE

Figure 2 shows the individual DPOAE levels for three subjects as a function of the $f_2/f_1$ ratio, as well as average values across subjects. The figure shows that both the individual and group results display a bell-shaped dependency to the stimulus ratio. To determine the optimal ratio, a 2nd order polynomial was fitted to the individual and group data obtained with primary frequency ratios below 1.35. For higher ratios, DPOAE values either decrease close to the noise floor, or show a steady increase in level. The latter seems to be related to an increasing noise floor (especially at 1 kHz), or to other artefacts as the ratio approaches 1.5. The maximum value of the fitted curves is defined as the optimal ratio. Inspection of the individual results shows that for 2 and 4 kHz all subjects, with the exception of subject 4 at 2 kHz, show the expected bell-shaped curve, for these cases the maximum DPOAE value was always found with ratios in the range of the fitted curve. In the case of 1 kHz, the results are more dependant on the levels of the emissions. Subjects with high emission levels (Subjects 1, 6, 7 and 8) have a clear bell-shaped curve and maximum DPOAEs are found with ratios in the range of the fitted curve. For subjects with low emission levels (Subjects 2, 3, 4, 5, 9 and 10), maximum DPOAE values were sometimes found at ratios above 1.35. For these subjects emission levels are in some cases within a few dB of the noise floor.

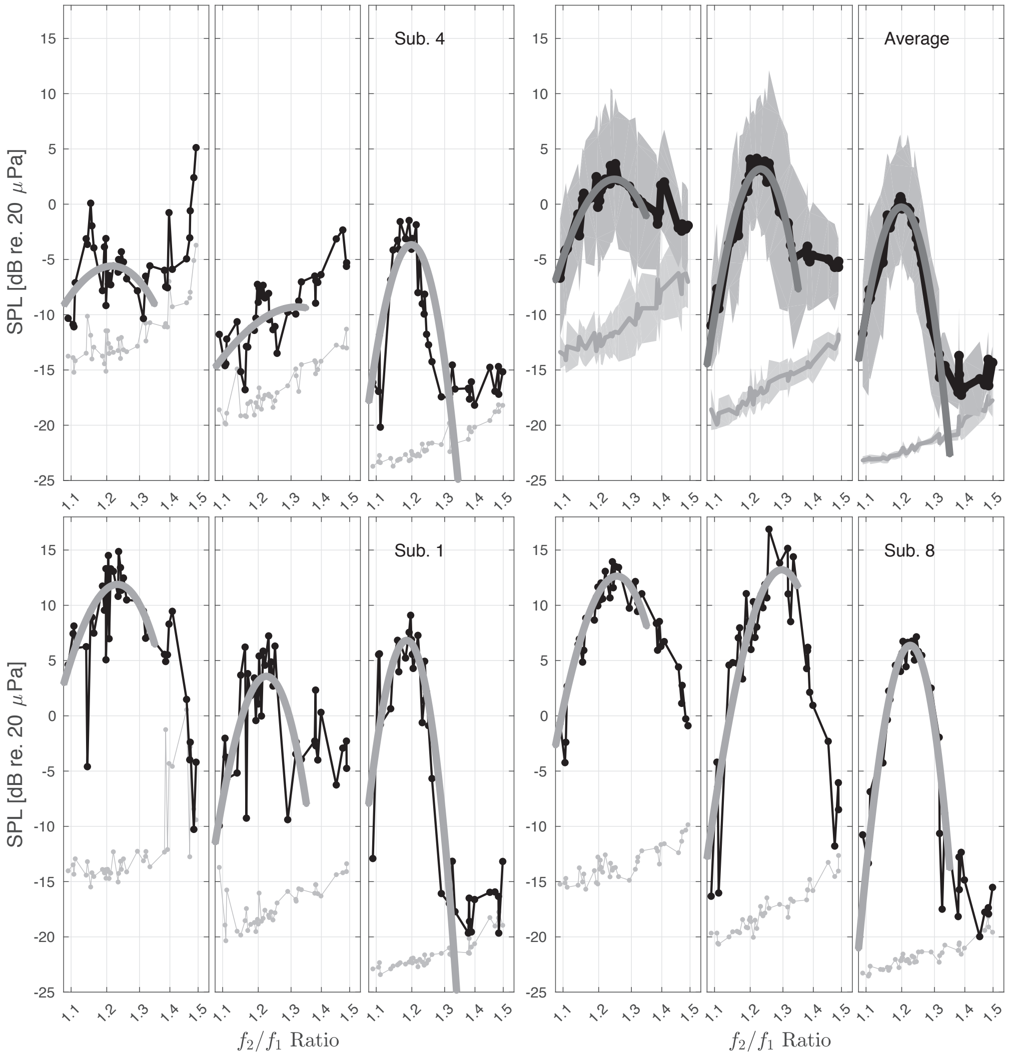

**Fig. 2:** Individual DPOAE levels for three subjects as a function of primary frequency ratios. Thick lines represents a 2$^{nd}$ order polynomial fit for data points with primary ratios between 1.1 and 1.35. Thin lines represent the measured values and the noise floor of the measurement. Top right panel, the group average in black with ±standard deviation (shaded area) and the grey line shows the 2$^{nd}$ order polynomial fitted to the averaged data.

## Auditory filter results

The estimated notched-noise thresholds are shown in Fig. 3 for three subjects and for the group average. The figure shows that the wider the masking notch, the lower the masking effect on the stimulus tone, and that the slopes are steep, as is expected for normal-hearing individuals. There are however a few exceptions like subjects 3 and 7 at 4 kHz or subject 4 at 2 kHz.

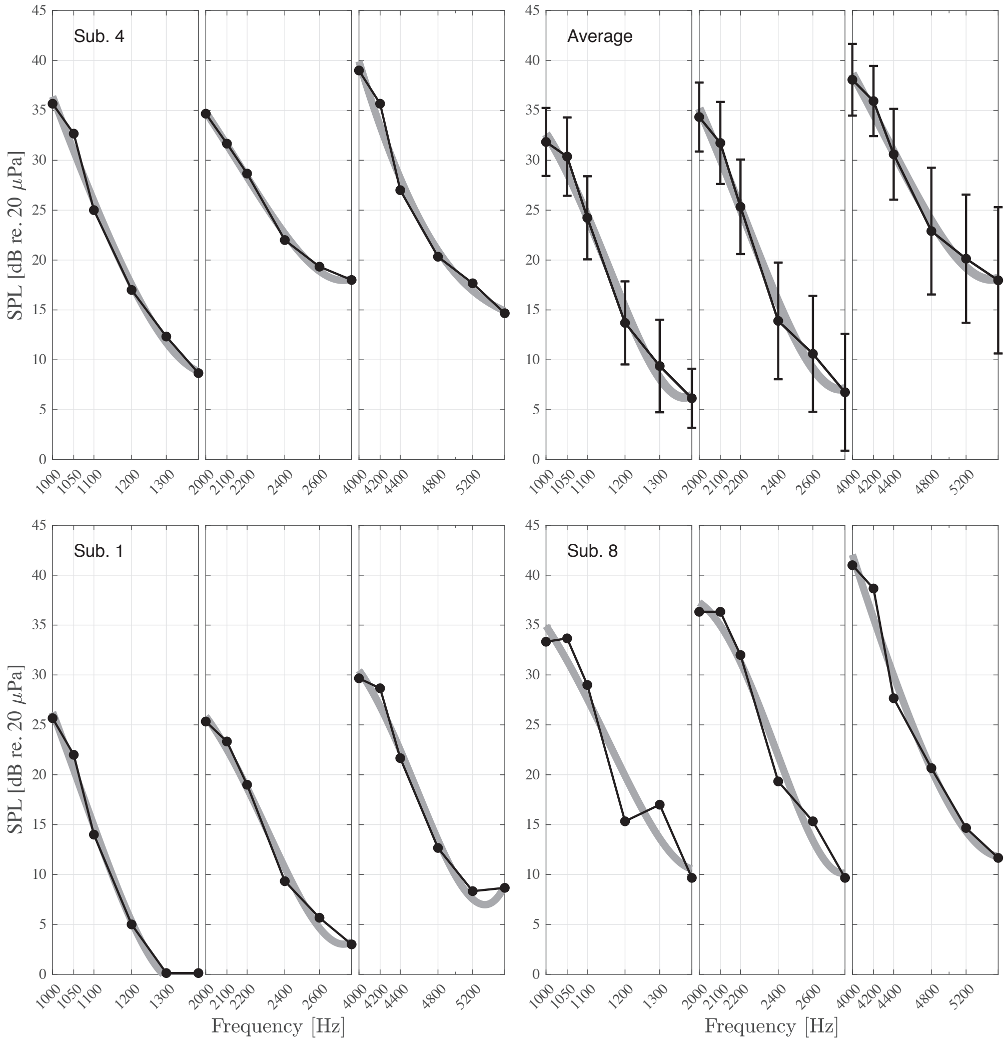

**Fig. 3:** Level of tone at threshold as a function of masker bandwidth (masker level 40 dB/Hz) in black (same three subjects as in Fig. 2), and the estimated auditory filter shapes using a $3^{\text{rd}}$ order polynomial in grey. Top right panel, group average with ±standard deviation as the error bars, in black and the grey lines shows the estimated average auditory filter using a $3^{\text{rd}}$ order polynomial.

## Optimal ratio vs. ERB

Estimates of optimal ratio and equivalent rectangular bandwidths are compared for for each subject in the scatter plots of Fig. 4, with the circles. Pearson's correlation coefficient shows that there is a non-significant positive correlation at 1 kHz ($r = 0.3805$, $p = 0.2781$) and 2 kHz ($r = 0.4815$,$p = 0.1588$), and a non-significant negative correlation at 4 kHz ($r = -0.3111$,$p = 0.3817$). This result suggests that narrower ERB estimates show lower optimal ratios, with clear exceptions, as the case of the lowest optional ratio obtained at 4 kHz that shows the widest ERB estimate for that frequency band.

In order further explore the relation between frequency selectivity and DPOAE optimal ratios, optimal ratios were expressed in terms of the width DPOAE vs. ratio curve finding the point in which the fitted 2$^{nd}$ polynomial function drops 6 dB from its maximum value, according to the following expression:

$$OR_{span} = \left(OR_{max} - OR_{-6dB}\right), \qquad \text{(Eq. 2)}$$

where $OR_{span}$ is the optimal ratio span representing the span of ratios that cover in main portion of the DPOAE vs. ratio estimate; $OR_{max}$ is the optimal ratio, and $OR_{-6dB}$ is the ratio corresponding to the $-6$ dB point. Pearson's correlation coefficient between $OR_{span}$ and ERB estimates show a weak positive correlation at 1 kHz ($r = 0.6120$, $p = 0.0601$) and 4 kHz ($r = 0.5642$, $p = 0.0893$) and a non-significant positive correlation at 2 kHz ($r = 0.1409$, $p = 0.6979$). These results are shown in Fig. 4 with the diamond symbols.

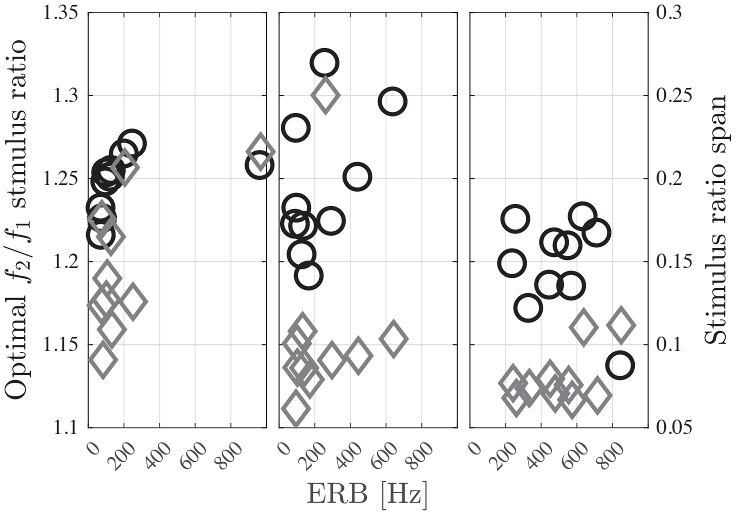

**Fig. 4:** Optimal DPOAE stimulus ratio estimated for each subject versus ERB (circles, left axis). Stimulus ratio span versus ERB (diamonds, right axis).

## CONCLUSIONS

The present data confirms the optimal ratio relation to auditory filter bandwidth on group basis, and the relation can also be recognised to a lesser degree for individual data. The data suggests that subjects with a broad auditory filter (high ERB estimate) also have larger optimal ratios. In the same manner, subjects with low ERB estimates will have lower optimal ratios. Other estimates of frequency tuning derived from the DPOAE vs. primary ratio relationships show equal or better correlation with individual ERB estimates.

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