ICA 2016 Buenos Aires
Buenos Aires – 5 to 9 September 2016
Acoustics for the 21st Century…

PROCEEDINGS of the 22nd International Congress on Acoustics

Psychological and Physiological Acoustics (others): Paper ICA2016-885

More robust estimates for DPOAE level at audiometric frequencies

Dorte Hammershøi[a], **Rodrigo Ordoñez**[b], **Anders Tornvig Christensen**[c]

[a]Department of Electronic Systems, Aalborg University, Denmark, dh@es.aau.dk
[b]Department of Electronic Systems, Aalborg University, Denmark, rop@es.aau.dk
[c]independent

Abstract

Current clinical methods determine $2f_1 - f_2$ distortion product oto-acoustic emission (DPAOE) levels at discrete frequencies, and often only at the audiometric standard frequencies in order to save time. The measured result is known to be a superposition of at least two components, the generator component originating from a region around the primary f_2, and the reflection component from the $2f_1 - f_2$ site. Distinct interference patterns in high resolution DPOAE data reveal that these two components can be of similar magnitude, and periodically cancel each other entirely. When measurements are made at only few frequencies, there is a risk to find one or more low amplitude measurement, even in a healthy ear with otherwise high emissions. In the present study, data from previous studies measured with a high frequency resolution is used for simulating a better use of measurements at and around the audiometric frequency. A "local" model of the two component superposition is applied, and the trade-off between measurement time, and robustness of the measure is discussed.

Keywords: oto-acoustic emission, audiology, hearing, instrumentation, inner ear

More robust estimates for DPOAE level at audiometric frequencies

1 Introduction

Oto-acoustic emissions (OAEs) are natural bi-products of the active mechanisms in the inner ear. These were first reported by Kemp in 1978 [11], and associated with the health of the outer hair cells. One type of otoacoustic emission is produced using at two-tone stimulus, where the frequencies f_1 and f_2 and levels L_1 and L_2 of the two primaries can be varied to excite various distortion products. The $2f_1 - f_2$ distortion product is the most prevalent and best studied distortion product in humans, e. g. [12, 6, 5, 15, 7, 14, 17, 23, 24, 1, 2]. The measurement of $2f_1 - f_2$ is currently an option in clinical instrumentation for measurement at given standard audiometric frequencies.

The DP-gram (the measured $2f_1 - f_2$ sound pressure level as a function of frequency) reveals a fine structure with alternating dips and peaks, e. g. [8, 5, 25, 4, 10, 22, 21, 3, 18, 9] if measured with a sufficiently high frequency resolution. This is a result of the superposition of two underlying $2f_1 - f_2$ components; the first being excited in the vicinity of the f_2 frequency, often referred to as the generator component (here denoted dp_g), and the second stemming from the region of the basilar membrane with specific characteristics tuned to the $2f_1 - f_2$ frequency. The latter is often referred to as the secondary component or the reflection component, and here denoted dp_r.

The fine structure is inherent to the measurement of DPOAE, and when clinical measurements are made at audiometric frequencies, typically few in number and typically spaced an octave apart, it is most likely that one or more of these measurements will coincide with a dip in the DP-gram. Such measurements will typically be discarded, and the measurement possibly repeated for certainty, and time is wasted, when really the measured DP value deep in the trough of the dip was well estimated in the first place. This is intuitively clear, but measurements at other frequencies are in fact equally “polluted" by the secondary component and possible higher order reflections. At frequencies where the generator and secondary component add in phase, the measured value will be up to $6\ dB$ higher, than the amplitude of the generator component alone.

Considerable effort has been made to disentangle the generator component and reflection component, or just to get estimates for the generator component, which is not influenced by the component from the $2f_1 - f_2$ site. Some have used inverse Fourier Transform to obtain the “time" domain representation of the two components, e. g. [20, 3], or sweeps e. g. [13], or advanced models of the two component interaction and the health of the active mechanisms [22]. These efforts suggests that a DP-gram based on the generator component alone can be obtained, and that this DP-gram will probably better describe the health at a given site (for a given audiometric frequency).

The *purpose of the present investigation* is to study the trade-offs between measurement time, Δt, and reliability of the measurement in a combined approach using a minimal (local) model to disentangle the two interacting components around given audiometric frequencies (1, 1.5, 2, 3, 4, and 5 kHz). The motivation for the model is that the existing methods (as mentioned above) depend on a wide range of frequencies to be measured, which is unfavourable for clinical practice.

The approach will consider the typical and maximum widths of the fine structures as reported by [8, 4, 10, 18], and share the measurement time Δt available across N measurement points at discrete frequencies close to the given audiometric frequency of interest. The N measured points shall be close enough in frequency to allow the local model to fairly represent a given dip, so that the generator component's contribution at the given audiometric frequency can be estimated from the model parameters. The model shall be specific for the region around a given audiometric frequency, and a model fit is made for each audiometric frequency (not for the entire frequency range). The model will also be evaluated with respect to its robustness to determine reliable data in the absence of distinct fine structures in the DP-gram.

It has been suggested that the $2f_2 - f_1$ distortion product may better describe decline from aging [16], and it is hypothesized that the $2f_2 - f_1$ component is dominated by the secondary (reflection) component, and can be interpreted accordingly. The present paper focus on the $2f_1 - f_2$ component, and the possibly better determination of the generator component, but the model approach can be combined with data for $2f_2 - f_1$ component, and thereby possibly strengthen the model estimates (without added measurement time).

2 Method

A simulation of various measuring conditions are employed, where time Δt_i, number of measurement points N_i for each audiometric frequency f_i, and frequency range Δf_i these N_i points cover are varied (the subscript i refer to the given audiometric frequency). Data from two previous investigations [18, 19], where measurements were made with a high frequency resolution are used for the present study.

2.1 Model

The proposed model is based on a signal analytical approach, identifying the periodicity in the measured DPOAE amplitudes as a function of frequency in the region of a given audiometric frequency as a key model parameter. The alternating peak and dip structure in the typical DP-gram resembles that of a comb-filter, which one would get by superposition of a wide-band signal with a delayed version of the original source signal (an “echo"). This will not hold true as a valid model for the entire frequency range, but if only the physiological parameters that controls the DPOAE variables can be considered constant within the given frequency range Δf, then the comb-filter model will provide estimates for both the amplitude of the generator component dp_g, the amplitude of the generator component dp_r, and the phase between them (corresponding to the delay ΔT between the two).

The general expression for the feed-forward comb-filter can be expressed as:

$$|H(f)| = |\,\hat{A_g} + \hat{A_r}\cdot cos(2\pi f\cdot \hat{\Delta T}) - i\cdot \hat{A_r}\cdot sin(2\pi f\cdot \hat{\Delta T})| \quad (1)$$

where $\hat{A_g}$ is the amplitude of the generator component, $\hat{A_r}$ the amplitude of the secondary component (reflection component), and $\hat{\Delta T}$ the delay between generator component and reflection component.

The estimated sound pressure level contribution from the generator component can then be computed as

$$DP_g = 20\cdot log_{10}\left(\frac{\hat{A_g}}{\sqrt{2}\cdot 20\mu Pa}\right) \quad (2)$$

and the estimated phase difference $\hat{\varphi} = \frac{\hat{\Delta T}}{2\pi}$.

2.2 Data

The data include $2f_1 - f_2$ DPOAE measurements for 50 normal hearing subjects [18] and for 12 normal-hearing symphony orchestra musicians [19]. The $2f_1 - f_2$ DPOAEs were measured using the ILO96 Research system from Otodynamics. DPOAEs were measured in the frequency range of $903\ Hz < f_2 < 6201\ Hz$ with $f_2/f_1 = 1.22$ and fixed primary levels of $L_1/L_2 = 65/45\ dB$.

2.3 Data analysis

The standard Matlab function *nlinfit* is used to obtain a least means square fit of the model (as described by Eq. 1). The *nlinfit* requires qualified best guesses for the model parameters, and then iteratively explores the parameter space to find the optimal fit.

The starting point for $\hat{A_g}$ used here is the average of the N measured values around the given audiometric frequency (in the unit $[Pa]$). The starting point for $\hat{A_r}$ is half of the starting point for $\hat{A_g}$, conservatively assuming a ripple height of $6\ dB$.

The starting point for $\hat{\Delta T}$ is based on the average spacing between ripples found in previous investigations [8, 10, 18]. The spacing between ripples across humans vary on average from $\frac{1}{8}$ to $\frac{3}{32}$ octaves for the frequency range of primary interest ($1\ kHz < f < 5\ kHz$) with a decreasing relative width as a function for frequency (from approx. $100\ Hz$ to approx. $350\ Hz$ [18]. The starting point for $\hat{\Delta T}$ is therefore determined for each audiometric frequency and based on $\frac{1}{8}$ of an octave.

The frequency range Δf is in the current paper also equal to $\frac{1}{8}$ octave, and the number of points N_i include all those available in the given data set within that $\frac{1}{8}$ octave frequency range around a given audiometric frequency (this will be varied in further analyses).

3 Results

Figure 1 shows an example of DPOAE measurements for a single subject which has pronounced fine structures, where there is a considerable risk that one or more measurements

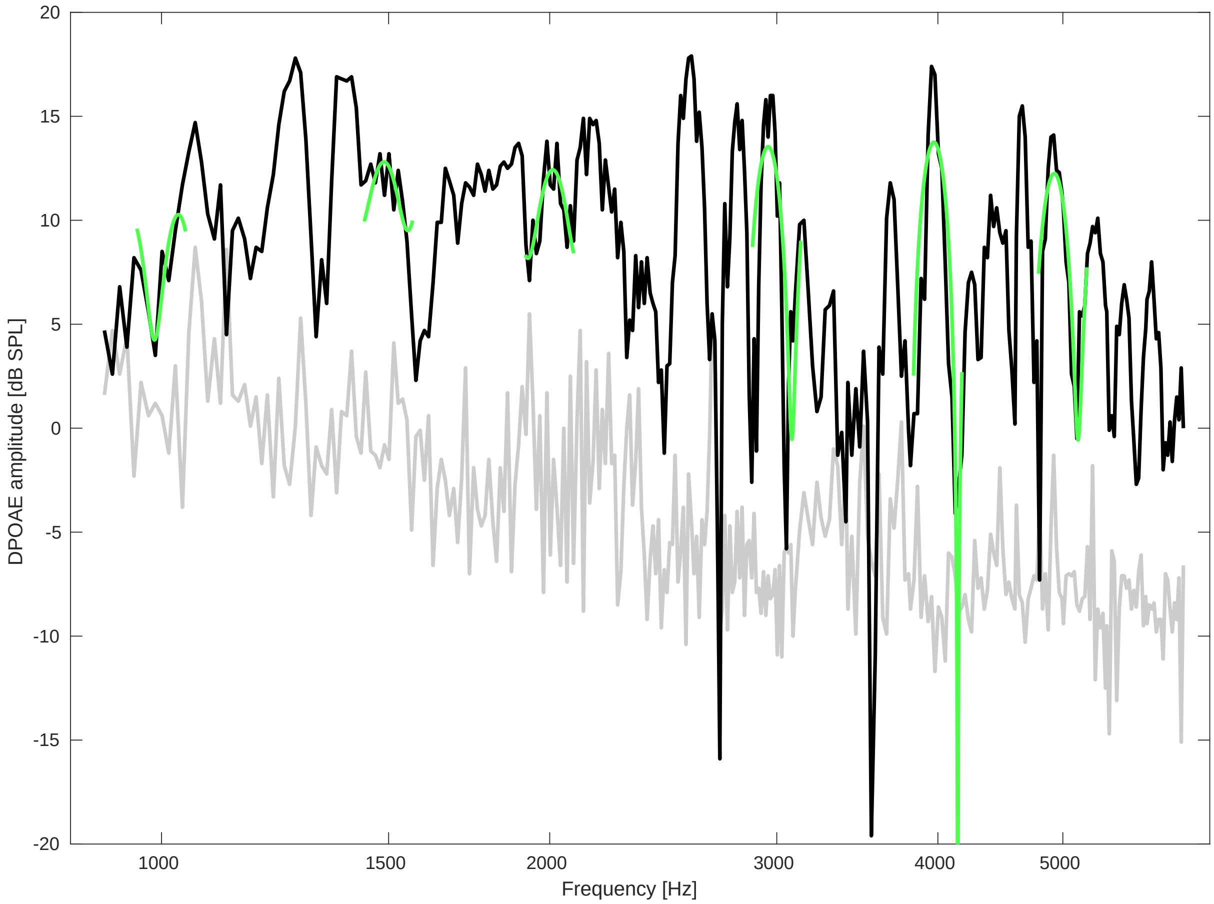

Figure 1: **DPOAE(f_2) for subject 18 from [18]. Original measured values are shown with black, and the estimated noise floor is shown with grey. The green lines overlaid around each audiometric frequency shows the result of comb-filter models fitted using the data points within the frequency ranges of the green lines.**

coincide with a peak or dip. The comb-filters estimated around each audiometric frequency give fair approximations of the general contour in the vicinity of the given audiometric frequencies.

Figure 2 shows the same set of data as Figure 1 with a closer look around the audiometric frequencies. It can be seen that the fine structures are most pronounced around 3, 4 and $5\ kHz$. The measured value at $3\ kHz$ is approx. $5\ dB$ below the closest maximum, and approx. $15\ dB$ above the closest minimum. This represents the case, where the measurement avoids coincidence with the extreme DP values. There is only little difference between the measured value and the proposed alternative, because the measured value is in this case a fair estimate already.

The measured value at $4\ kHz$ is close to a peak in the fine structure, although not at the maximum. The model suggests that DP_g that is approx. $6\ dB$ lower than the measured value, which is probably somewhat lower than the best guess for DP_g. The model overestimates the closest dip slightly, and a more reliable estimate would probably be obtained, if data for a wider frequency range Δf was used.

The measured value at $5\ kHz$ is close to a peak in the fine structure, although not at the maximum. The model suggests that DP_g is approx. $2-3\ dB$ lower than the measured value, which is probably fairly close to the best guess for DP_g.

It can be seen that the fine structures are less pronounced at 1, 1.5, and $2\ kHz$. The model estimates are conservative, and the measured and estimated values differ only very little, as desired. This suggest that the model is also robust to situations with less pronounced fine structures.

4 Conclusions

The comb-filter model approximates the fine structure in the DP-gram well, when based on a few points around the audiometric frequency of interest.

Further analyses are required to make any further conclusions.

Acknowledgements

The project was inspired by discussions in the project on “Better Hearing Rehabilitation (BEAR)" funded by Innovation Foundation Denmark and partners, which include the Danish Technical University, the University of Southern Denmark, Aalborg and Odense University Hospitals, DELTA, Oticon, GN Resound, and Widex. These discussions are much appreciated.

The data included (first published in [18, 19]) were kindly made available by Karen Reuter Andersen.

References

[1] C. Abdala. Distortion product otoacoustic emission (2f(1)-f(2)) amplitude as a function of f(2)/f(1) frequency ratio and primary tone level separation in human adults and neonates. *J. Acoust. Soc. Am.*, 100(6):3726–3740, DEC 1996.

[2] S. Dhar, G. R. Long, and B. Culpepper. The dependence of the distortion product 2f1-f2 on primary levels in non-impaired human ears. *J. Speech Hear. Res.*, 41(6):1307–1318, 1998.

[3] S. Dhar, C. L. Talmadge, G. R. Long, and A. Tubis. Multiple internal reflections in the cochlea and their effect on dpoae fine structure. *J. Acoust. Soc. Am.*, 112(6):2882–2897, 2002.

[4] B. Engdahl and D. T. Kemp. The effect of noise exposure on the details of distortion product otoacoustic emissions in humans. *J. Acoust. Soc. Am.*, 99(3):1573–1587, MAR

1996.

[5] S. A. Gaskill and A. M. Brown. The behavior of the acoustic distortion product, 2f1-f2, from the human ear and its relation to auditory-sensitivity. *J. Acoust. Soc. Am.*, 88(2):821–839, AUG 1990.

[6] F. P. Harris, B. L. Lonsbury-Martin, B. B. Stagner, A. C. Coats, and G. K. Martin. Acoustic distortion products in humans - systematic changes in amplitude as a function of f2/f1 ratio. *J. Acoust. Soc. Am.*, 85(1):220–229, JAN 1989.

[7] R. Hauser and R. Probst. The influence of systematic primary-tone level variation l2-l1 on the acoustic distortion product emission 2f1-f2 in normal human ears. *J. Acoust. Soc. Am.*, 89(1):280–286, JAN 1991.

[8] N. J. He and R. A. Schmiedt. Fine-structure of the 2f(1)-f(2) acoustic distortion-product - changes with primary level. *J. Acoust. Soc. Am.*, 94(5):2659–2669, NOV 1993.

[9] S. J. Heise, J. L. Verhey, and M. Mauermann. Automatic screening and detection of threshold fine structure. *Int. J. Audiol.*, 47(8):520–532, 2008. 28th International Congress of Audiology, Innsbruck, AUSTRIA, SEP 03-07, 2006.

[10] J. Heitmann, B. Waldmann, and P. Plinkert. Limitations in the use of distortion product otoacoustic emissions in objective audiometry as the result of fine structure. *European Archives of Oto-Rhino-Laryngology*, 253(3):167–171, MAR 1996.

[11] D. T. Kemp. Stimulated acoustic emissions from within human auditory-system. *J. Acoust. Soc. Am.*, 64(5):1386–1391, 1978.

[12] D. T. Kemp and A. M. Brown. A comparison of mechanical nonlinearities in the cochleae of man and gerbil from ear canal measurements. In R. Klinke and R. Hartmann, editors, *Hearing: Physiological Bases and Pscychophysics*, pages 82–88. Springer, 1983.

[13] G. R. Long, C. L. Talmadge, and J. Lee. Measuring distortion product otoacoustic emissions using continuously sweeping primaries. *J. Acouts. Soc. Am.*, 124(3, 1):1613–1626, SEP 2008. 27th Midwinter Research Meeting of the Association-for-Research-in-Otolaryngology, Daytona Beach, FL, FEB 21-26, 2004.

[14] L. H. Nielsen, G. R. Popelka, A. N. Rasmussen, and P. A. Osterhammel. Clinical-significance of probe-tone frequency ratio on distortion-product otoacoustic emissions. *Scand. Audiol.*, 22(3):159–164, 1993.

[15] R. Probst and R. Hauser. Distortion product otoacoustic emissions in normal and hearing-impaired ears. *Am. J. Otolaryngol.*, 11(4):236–243, JUL-AUG 1990.

[16] A. Rao, E. M. Tusler, and A. Formo. Comparison of 2f1-f2 DPOAE and 2f2-f1 DPOAE fine structure in young and middle-aged adults. *Int. J. Audiol.*, 53(3):165–173, MAR 2014.

[17] A. N. Rasmussen, G. R. Popelka, P. A. Osterhammel, and L. H. Nielsen. Clinical-significance of relative probe-tone levels on distortion-product otoacoustic emissions. *Scand. Audiol.*, 22(4):223–229, 1993.

[18] K. Reuter and D. Hammershøi. Distortion product otoacoustic emission fine structure analysis of 50 normal-hearing humans. *J. Acoust. Soc. Am.*, 120(1):270–279, JUL 2006.

[19] K. Reuter and D. Hammershoi. Distortion product otoacoustic emission of symphony orchestra musicians before and after rehearsal. *J. Acoust. Soc. Am.*, 121(1):327–336, JAN 2007.

[20] L. Stover, S. Neely, and M. Gorga. Latency and multiple sources of distortion product otoacoustic emissions. *J. Acoust. Soc. Am.*, 99(2):1016–1024, FEB 1996.

[21] C. Talmadge, G. Long, A. Tubis, and S. Dhar. Experimental confirmation of the two-source interference model for the fine structure of distortion product otoacoustic emissions. *J. Acoust. Soc. Am.*, 105(1):275–292, JAN 1999.

[22] C. L. Talmadge, A. Tubis, G. R. Long, and P. Piskorski. Modeling otoacoustic emission and hearing threshold fine structures. *J. Acoust. Soc. Am.*, 104(3, Part 1):1517–1543, SEP 1998.

[23] M. L. Whitehead, M. J. McCoy, B. L. Lonsbury-Martin, and G. K. Martin. Dependence of distortion-product otoacoustic emissions on primary levels in normal and impaired ears .1. effects of decreasing L(2) below L(1). *J. Acoust. Soc. Am.*, 97(4):2346–2358, APR 1995.

[24] M. L. Whitehead, B. B. Stagner, M. J. McCoy, B. L. Lonsbury-Martin, and G. K. Martin. Dependence of distortion-product otoacoustic emissions on primary levels in normal and impaired ears .2. asymmetry in L(1),L(2) Space. *J. Acoust. Soc. Am.*, 97(4):2359–2377, APR 1995.

[25] G. Zweig and C. Shera. The origin of periodicity in the spectrum of evoked otoacoustic emissions. *J. Acoust. Soc. Am.*, 98(4):2018–2047, OCT 1995.

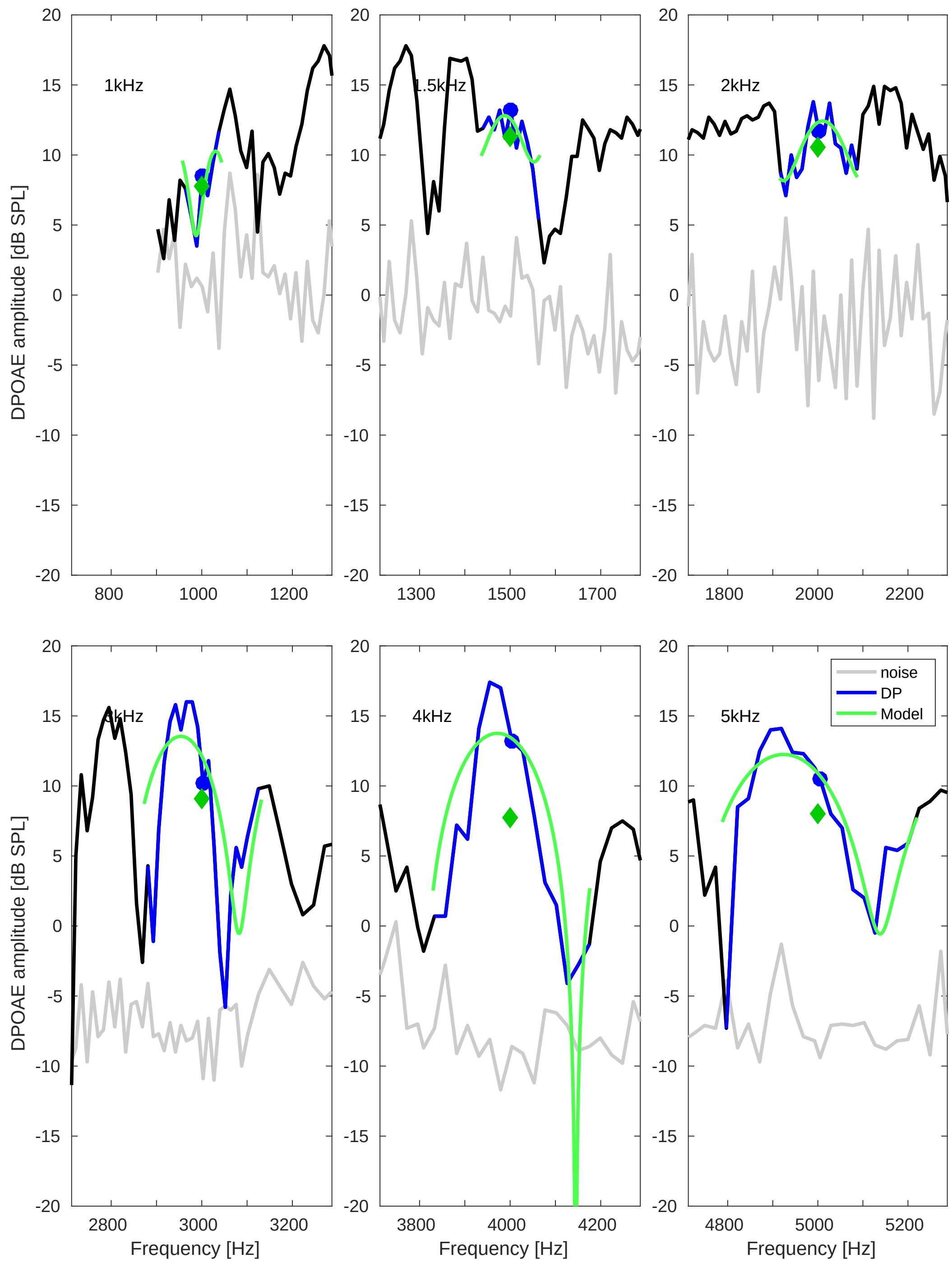

Figure 2: **DPOAE(f_2) for subject 18 from [18]. Original measured values are shown with black, and the estimated noise floor is shown with grey. The blue lines emphasize the data included in the analysis, and the blue dot shows the value measured at the audiometric frequency. The green lines show the results of the model fits, and the dark green diamond represents the estimate for the generator component DP_g, and thus the proposed alternative value at the given audiometric frequency.**