Using DPOAE to explore Cochlear function

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Abstract

The goal of this presentation is to discuss our present understanding of cochlear function using DPOAEs. To understanding of how the cochlea works one needs an understanding of the experimental data on: **(1)** the tympanic membrane (TM), **(2)** middle ear (ME), **(3)** cochlear function (both basilar (BM) and tectorial membranes (TM), **(4)** inner and outer hair cells (IHC, OHC), **(5)** auditory nerve (AN), and the **(6)** cochlear amplifier (CA).

Conclusions: My summary of neural tuning curve data from 1985 used nonlinear (NL) distortion product (DPOAE) generation. *The most surprising result is that the cochlea is much more linear than previously assumed. NL behavior:* "Low-side" suppression is where a nonlinear suppressor frequency f_s is $\leq 1/2$ octave below than the characteristic ("best") frequency (f_{bf}). There is no "low-side" suppression for f_{bf} below 65 [dB-SPL]Fahey and Allen [1985]. For suppressors above 65 [dB], the suppression dominates, with a compression slope of $\approx$2 [dB/dB]. The "obvious" explanation is that the neural threshold of excitation to both the inner and outer hair cells have approximately the same threshold. *Namely, the suppression threshold of the OHC, which control the NL suppression, are close to, or even equal to, the IHC threshold.*

If the IHC and OHC thresholds are the same in the tail of the tuning curves, then how can the CA function at threshold levels? This is a highly unexpected result, because low-side suppression, as measured on the basilar membrane, has a 20-30 [dB] higher threshold [Cooper, 1996, Geisler and Nuttall, 1997]. *Is the OHC action restricted to the neighborhood of the neuron's best frequency (BF)?*

This would require that the neural low-side suppression and loudness recruitment (the reduced loudness of low-intensity sounds in the hearing-impaired ear) are closely related (i.e., must be the same phenomena). The ramifications of this observation seem important as they will impact the diagnosis of cochlear hearing loss, thus the fitting of hearing aids [Allen, 1991, 1990; See comment by Lyon, page 332],

In summary: **Low-side suppression acts like an automatic gain control, elevating the loudness threshold with no audible distortion.**

For the cited publications see: `https://auditorymodels.org/index.php?n=Main.Publications`.

Goals

- To understand the cochlea, one needs experimental data on the following:
  - $P_{ec}(f)$: sound in the ear canal at frequency f
  - ME: middle ear
  - BM: basilar membranes
  - TM: tympanic membrane,
  - IHC, OHC: inner and outer hair cells
  - DP: Distortion product
  - DPOAE: Low-side 2-tone suppression distortion product f_{dp}
  - AN: auditory nerve
  - BF: best frequency of neural tuning curve f_{bf}
  - CA: **cochlear amplifier definition**

The cochlea

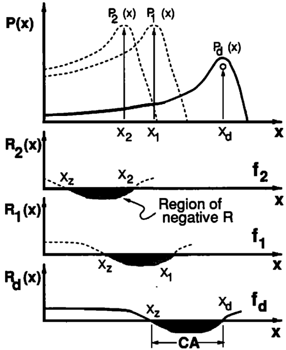
- The cochlea is a complex organ, the source of hearing

Figure: *Image of the two cochlear ducts, the Basilar membrane (BM), and the organ of Corti (OoC). The OHC and IHC are buried between the tectorial and basilar membranes.*

- Using the distortion product method we can discover how it works

Low-side suppression: Definition of DPOAEs *[Allen and Fahey, 1992]*

- Two primary frequencies $f_2 > f_1 \gg f_d$ create NL DPOAEs: $f_d \equiv f_1 - (f_2 - f_1) = 2f_1 - f_2$



- The two tones "mix" in the region between $X_2 < X_1$, mostly around X_2
- The regions of the CA is assumed to be the three shaded region $(X_z < X_2(f_2) < X_1(f_1) \ll X_d(f_d))$

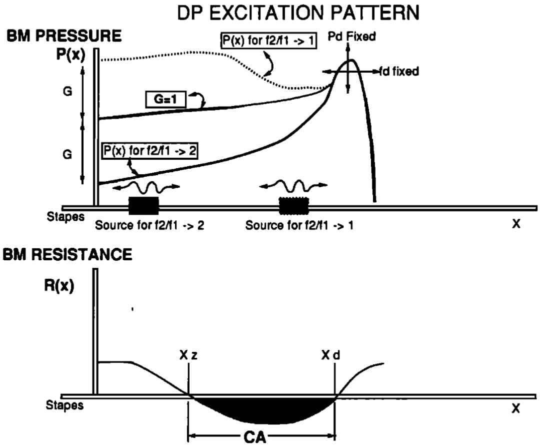
Exp-I (AF-92): Measure the gain of the Cochlear Amplifier (CA)

- Basic idea: move the acoustic source from the ear canal onto the BM, by using DPOAEs
- Record from a neuron having BF frequency f_{bf}
- Fixed the DP frequency $f_d = f_{bf} = 2f_1 - f_2 = f_1 - (f_2 - f_1)$
- Fixed the DP pressure at the neurons threshold
- Vary the source location at $X_2(f_2)$ along the BM at $X_2(f_2) < X_d(f_d)$.
- Move source through the region of negative resistance (region of CA gain)
- Measure the EC pressure $P_{ec}(f_2)$ as a function of $X_2(f_2)$

The gain of the CA is quantified based on the magnitude of $P_{ec}(X_2)$

Measuring the gain of the CA via a BM DPOAE–SOURCE

- Use a DPOAE source on BM at "place" $X_2(f_2)$, determined by f_2, and a neuron as the detector



- Please Google: "Allen-Fahey experiment"

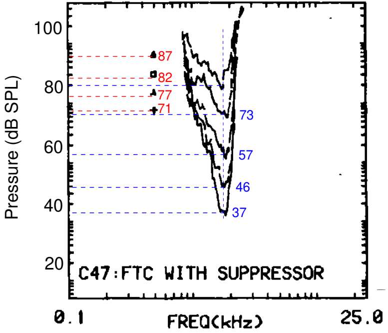
Exp-II (FA-85): Neural low-side suppression measured (2d-filter)

Experimental data:

- FA-85 measured Low-side neural suppression threshold and showed that:
  the neural detection threshold ≈ low-side suppression thresholds
- Cooper (1996) and Geisler-Nuttal (1997) measured the low-side suppression on the BM and found a threshold difference between 20 and 30 dB
- It is an unequivocal conclusion that there must be a "second-filter" action between BM neural response
- Evans and Wilson [1975] were right: Models with no second filter are incomplete!
- **The NL BM depends on a 2d filter.**

Example of Low-side suppression (FA-85)

- BF = 1.8 kHz, $f_2 = 500$ [Hz], $f_1 = (1800+500)/2 = 650$ [Hz]



- There is no low-side suppression below 65 [dB-SPL]
- Suppression Slope = 2.2 [dB/dB] above 65 dB-SPL [Delgutte, 1990]

Low-side suppression on the BM [Cooper, 1996]

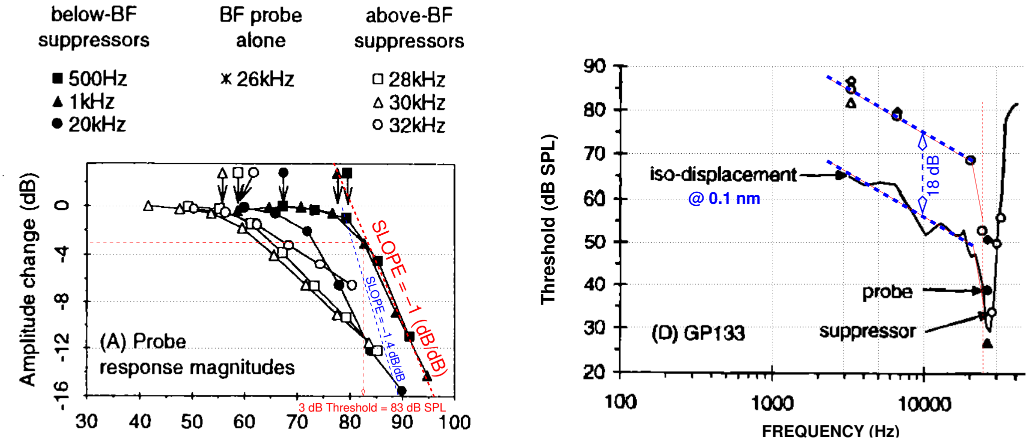


Figure: *LEFT: BM Suppression of a 26 [kHz] probe by Low-side suppressors at 0.5, 1, 20 [kHz] RIGHT: BM Suppression as a function of frequency The BM low-side suppression is very different from the neural data of AF-93: 1) The detection and suppression threshold are 18 [dB] apart, and 2) it depends on frequency [Cooper, 1996]*

Low-side suppression on the BM [Geisler and Nuttall, 1997]

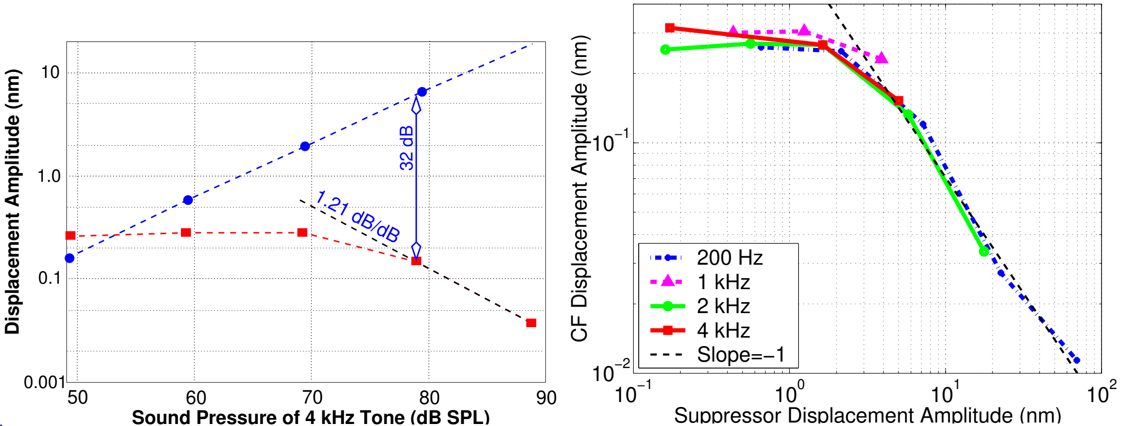
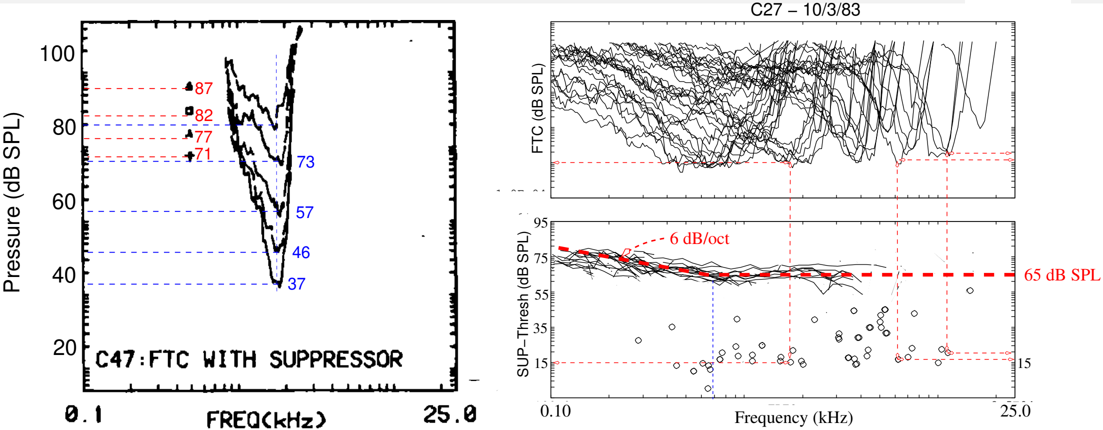


Figure: *LEFT: Data similar to that of [Cooper, 1996] showing low-side suppression on the BM. The suppressed tone frequency is 17[kHz]. There is no suppression at 69 dB and 6 [dB] for the 4 [kHz] tone is increased from by 10 dB from 69 to 79 [dB-SPL] compared to 0 [dB/dB] as seen neurally in AF-85. In this case the low-side suppression threshold difference at 0.1 [nm] is 32 [dB]. RIGHT: The BM low-side suppression is very different from the neural data of AF-93: 1) The detection and suppression threshold are 18 [dB] apart, and 2) it depends on frequency [Geisler and Nuttall, 1997].*

There is no low-side suppression below 65 [dB-SPL]



- The bold-red dashed line is the locus of Low-side suppression thresholds (at 65 [dB-SPL])
- 65 [dB-SPL] is also the excitation threshold in the low-frequency Tuning curve "tail"
- Excitation and suppression thresholds are similar (or identical?) (Amazing, or obvious?)

Block model of Cochlear function

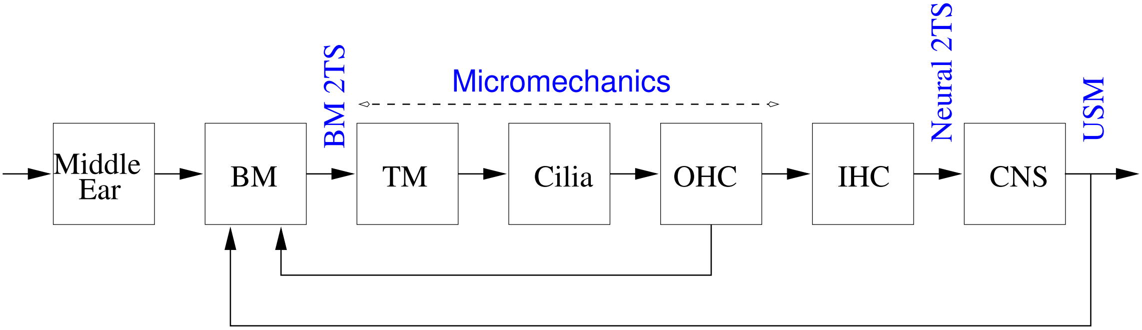
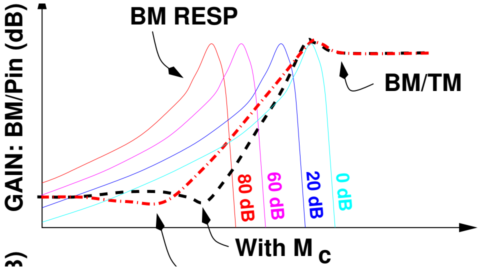


Figure: *Sound enters via the middle ear, travels down the BM and TM, excites the cilia of the OHC, IHC → AN*

If the two thresholds differ, that difference must be due to the TM

Nonlinear BM "migration" model

- Model tuning curves as a function of input level: 0, 20, 60, 80 *[dB-SPL]*
  LEFT: BM response with TM 2d-filter model.
  RIGHT: NL model as a function of level



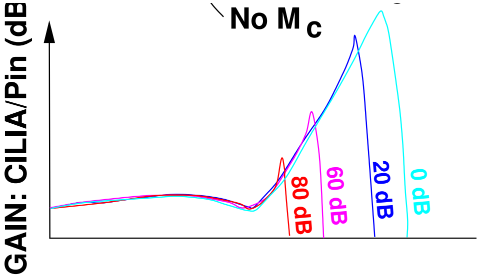


Figure: *"Second filter" on TM at 2d cochlear map frequency.*

Nonlinear time-domain model Sen and Allen [2006]

- Input signal is a pure tone from 14-124 [dB-SPL]

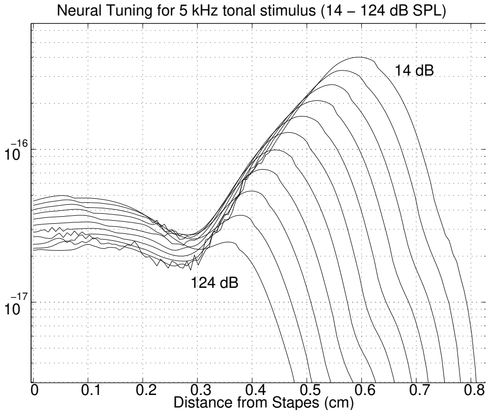


Figure: *Results of the Sen-Allen time-domain model for a single input tone with varying level.*

Conclusions

- Present view of cochlear tuning (BM vs Neural are very different $\rightarrow$ Second filter)
- The use of DPOAEs is key to our understanding of the cochlea
- The cochlea is much more linear in its filtering properties than we previously assumed
- Low-side suppression opens the door to an improved understanding of Cochlear function
- There is NO (i.e., zero) Suppression below 65 dB-SPL
- Above 65 dB-SPL, the suppression ≈ 2 [dB/dB]
- IHC (Linear) & OHC (NL) have nearly identical (equal) thresholds
- Neural and BM low-side suppression differ by 20 [dB]

Bibliography

J. B. Allen and P. F. Fahey. Using acoustic distortion products to measure the cochlear amplifier gain on the basilar membrane. *Journal of the Acoustical Society of America*, 92(1):178–188, 1992.

Jont B. Allen. Modeling the noise damaged cochlea. In P. Dallos, C. D. Geisler, J. W. Matthews, M. A. Ruggero, and C. R. Steele, editors, *The Mechanics and Biophysics of Hearing*, pages 324–332, New York, 1991. Springer-Verlag.

N.P. Cooper. Two-tone suppression in cochlear mechanics. *Journal of the Acoustical Society of America*, 99(5):3087–3098, 1996.

B. Delgutte. Two-tone suppression in auditory-nerve fibres: Dependence on suppressor frequency and level. *Hearing Research*, 49:225–246, 1990.

E. F. Evans and J. P. Wilson. Cochlear tuning properties: Concurrent basilar membrane and single nerve fiber measurements. *Science*, 190, 1975.

P. F. Fahey and J. B. Allen. Nonlinear phenomena as observed in the ear canal, and at the auditory nerve. *Journal of the Acoustical Society of America*, 77(2):599–612, 1985.

C. D. Geisler and A. L. Nuttall. Two-tone suppression of basilar membrane vibrations in the base of the guinea pig cochlea using "low-side" suppressors. *Journal of the Acoustical Society of America*, 102(1):430–440, 1997.

D. Sen and Jont B. Allen. Functionality of cochlear micromechanics–as elucidated by the upward spread ofmasking and two tone suppression. *Acoustics Australia*, 34(1):43–51, 2006.

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