SIMULATING AND MEASURING OTOACOUSTIC EMISSIONS

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OUTLINE

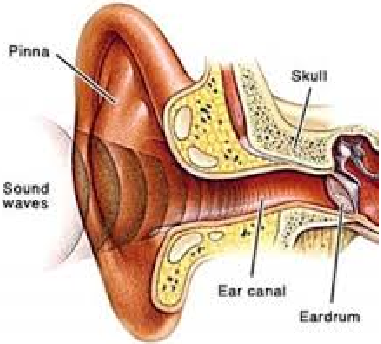
Physiology of the ear - OUTER EAR

- Pinna (or Auricula): receives sounds from any direction, responsible of sound localization.
- Ear canal: 2.5 cm long.

Resonant frequencies

$$f(n) = (2n-1)\frac{c_s}{4l}$$

- Eardrum (or tympanic membrane): vibrates when pressure wave enters the ear canal



Physiology of the ear - MIDDLE EAR

Impedance matching between air and fluid to avoid reflection:

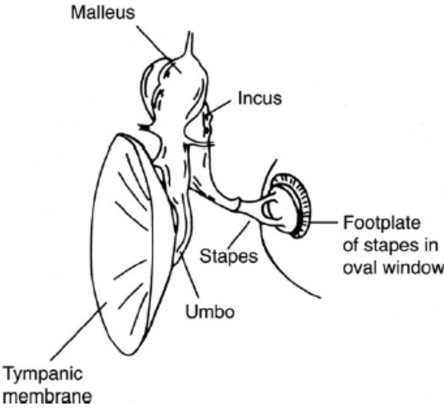
- Pressure Amplification

Resonant frequencies

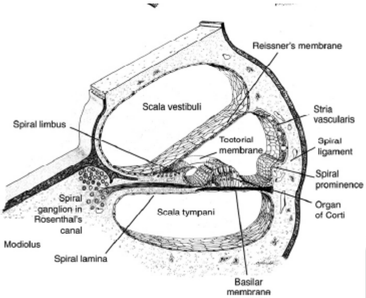
$$\frac{A_{eardrum}}{A_{stapes}} = \frac{P_{eardrum}}{P_{stapes}} = 18.75$$

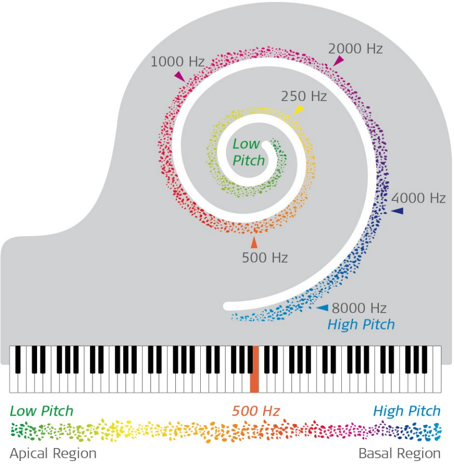
- Lever action of middle ear bones, increasing amplitude and decreasing velocity, gain$= 4.4$

Total gain $= 4.4 * 18.75 = 82.5$



Physiology of the ear: INNER EAR





Two main functions:

- Tonotopy
- Active feedback: compressive, non linear

OTOACOUSTIC EMISSIONS

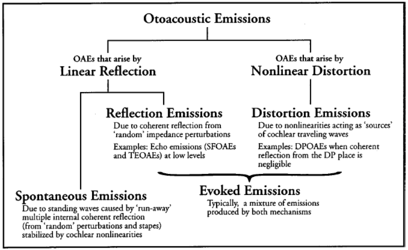
Stimulus-based classification:

- SOAEs (spontaneous)
- SFOAEs (stimuls-frequency)
- TEOAEs (transient-evoked)
- DPOAEs (distortion-product)

Generation-based classification:

- Linear reflection
- Nonlinear distortion

Mechanism-Based Taxonomy for OAEs



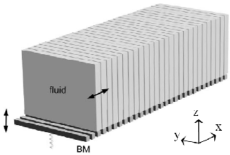
COCHLEAR MODEL

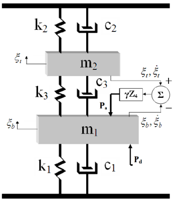
Three examples of cochlear models:

- Neely and Kim (1986): Cochlear Model in the Frequency domain
- Elliott (2007): State-space formulation in time domain
- Moleti (2009): 1DOF state-space model that also simulates otoacoustic emissions

Main assumptions:

1. The cochlea is uncurled and modelled as 1D rectangular box (macromechanics)
2. The cochlea is divided in N partitions of independent oscillators (micromechanics)





COCHLEAR MODEL

1) 1D transmission line equation for the differential pressure p

$$\frac{\partial^2 p_d(x,\omega)}{\partial^2 x} = \frac{2\rho}{H}\ddot{\xi}(x,t)$$

Using finite-difference approximation:

$$FP(t) = \ddot{\Xi}(t), F \text{ is invertible} \Longrightarrow P(t) = F^{-1}\ddot{\Xi}(t)$$

2) Micromechanical elements

$$\ddot{\xi}(x,t) + \gamma_{bm}(x,\xi,\dot{\xi})\dot{\xi}(x,t) + \omega_{bm}^2(x,\xi,\dot{\xi})\xi(x,t) = \frac{p_d(x,0,t)}{\sigma_{bm}}$$

State-space formulation:

$$\dot{Z}(t) = A_E Z(t) + B_E(P(t) + S(t))$$

$$\dot{\Xi}(t) = C_E Z(t) \Longrightarrow P(t) = F^{-1}\ddot{\Xi}(t) = F^{-1}C_E\dot{Z}(t)$$

COCHLEAR MODEL

Overall state-space equation

$$M\dot{Z}(t) = A_E Z(t) + B_E S(t),$$

where M is the mass matrix of the system:

$$M = I - B_E F^{-1} C_E$$

The mass matrix can be changed in:

Nonlinearity

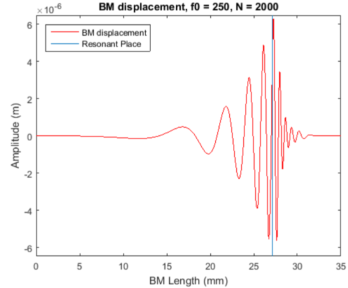
$$M = I - B_E G(Z) F^{-1} C_E, \text{where:}$$

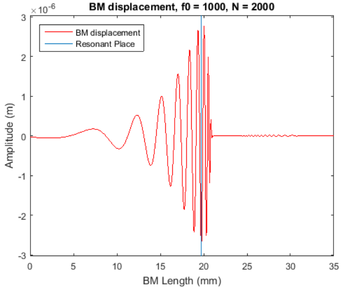
$$G(Z) = B^{-1} C + I$$

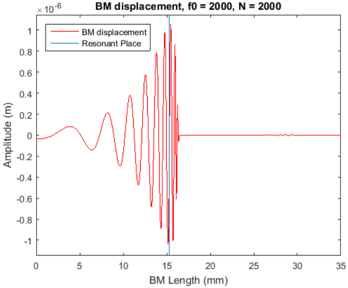
The parameter α determines the nonlinearity of the system:

$$\alpha(x, \xi, t) = \alpha_0 \left[1 - tanh \left(\frac{1}{\sqrt{\lambda \pi}} \int_0^L e^{-(x-x')^2/\lambda} \frac{\xi^2(x', t)}{\xi_{sat}^2} dx' \right) \right]$$

Simulations - TONOTOPY



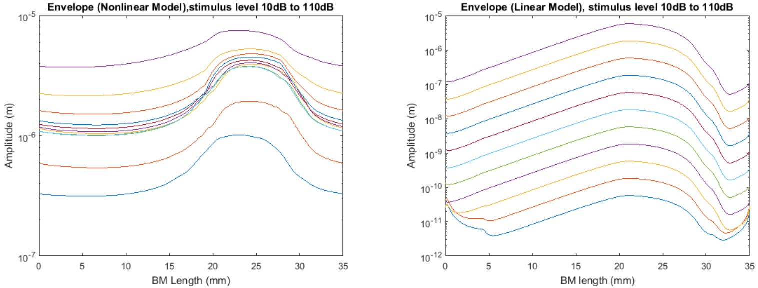




- The basilar membrane has a peak in the cochlear place corresponding to each input frequency
- Video Animation of BM motion

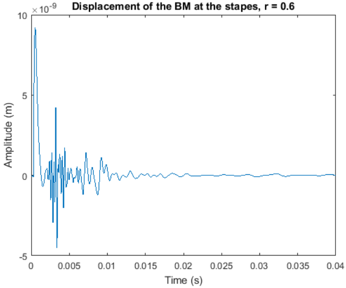
Simulations - NONLINEAR vs LINEAR

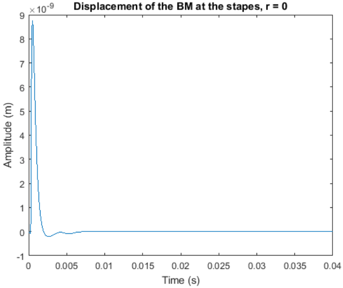
Saturation of the nonlinear active mechanism vs linear case:



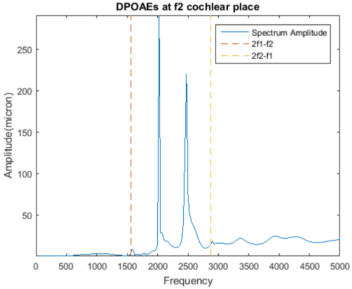
$\alpha = 0.75$ $\alpha = 0$

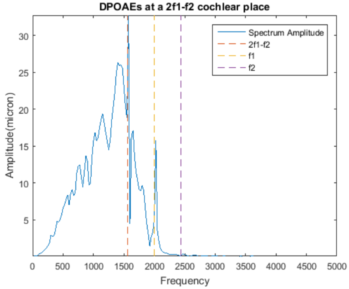
Simulations - TEOAEs

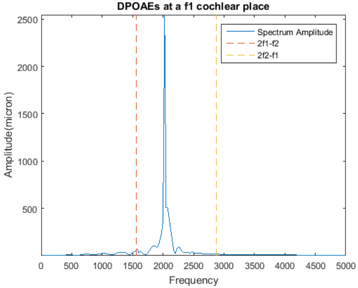




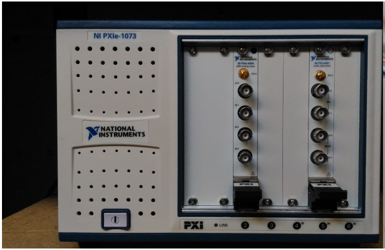
Simulations - DPOAEs

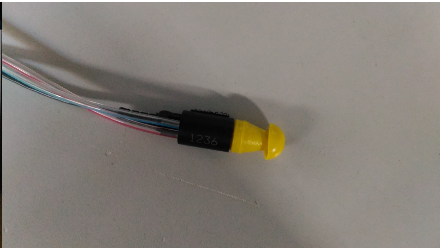


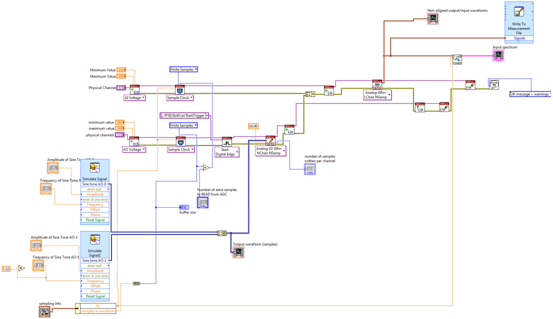




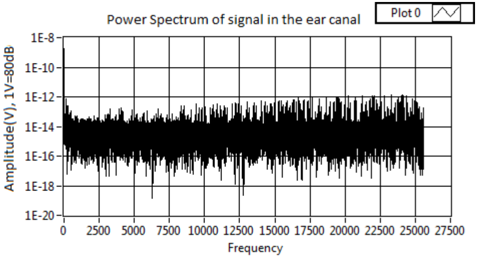
Measurements



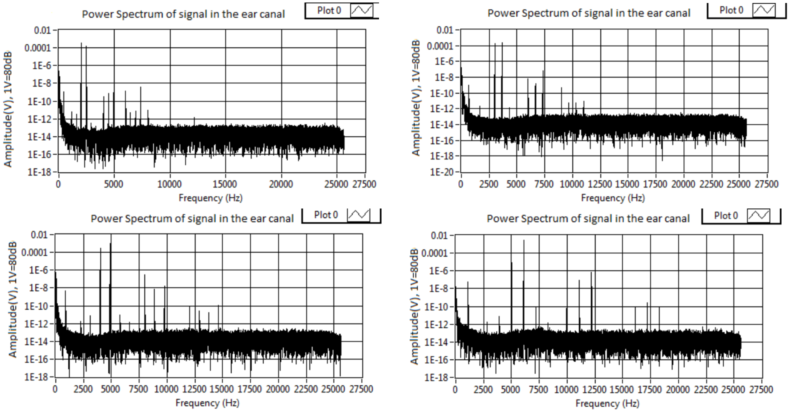




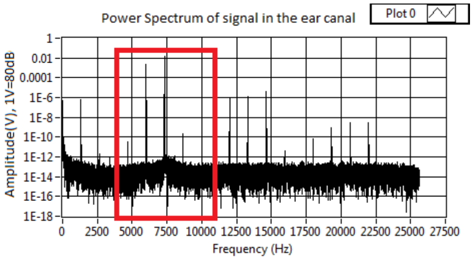
Measurements - TEOAEs

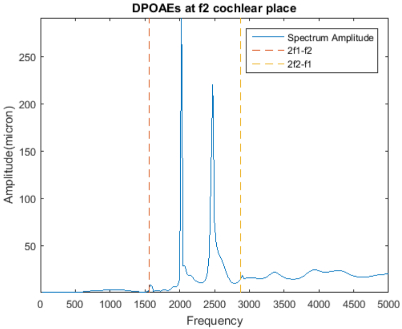


Measurements - DPOAEs

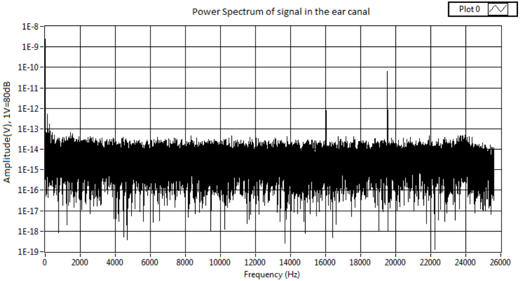


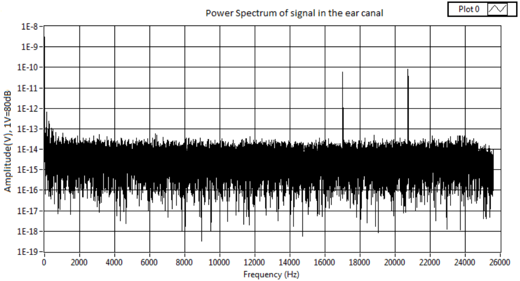
Measurements - DPOAEs (Model vs Experimental measurements)





Measurements - DPOEAEs (emissions not detected)





Conclusions

Physical Model of the Cochlea:

- Strong Linear and Nonlinear Models
- Can simulate TEOAEs and DPOAEs

However:

- We need a faster model
- We should simulate also SOAEs
- Work on Latency

Measurements:

- Successfully measured DPOAEs

However:

- We need a stronger analysis method for TEOAEs and SOAEs
- Do more experiments in order to have reliable results and in the future substitute audiograms with OAEs screening tests.

THANK YOU!