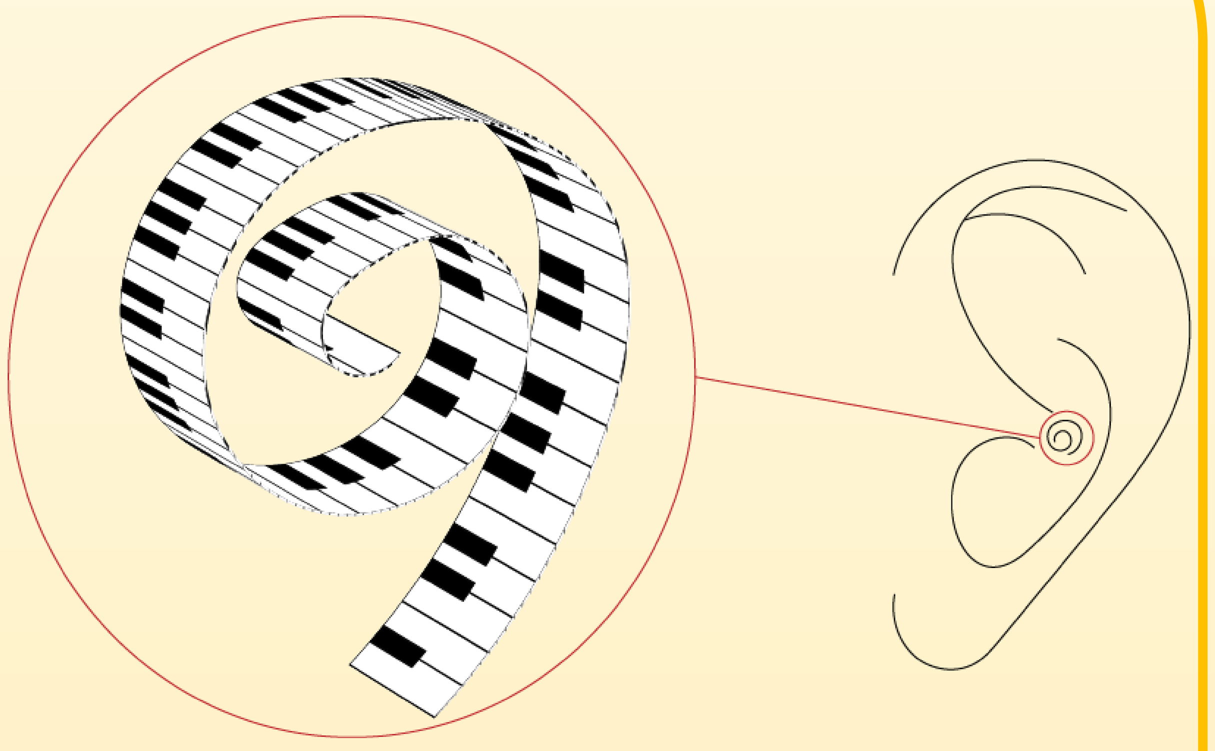
SIMULATING AND MEASURING OTOACOUSTIC EMISSIONS

OVERVIEW

1. BACKGROUND
2. METHODS & RESULTS
3. CONCLUSIONS & FURTHER WORK

PHYSIOLOGY OF THE INNER EAR



The cochlea has two main functions:

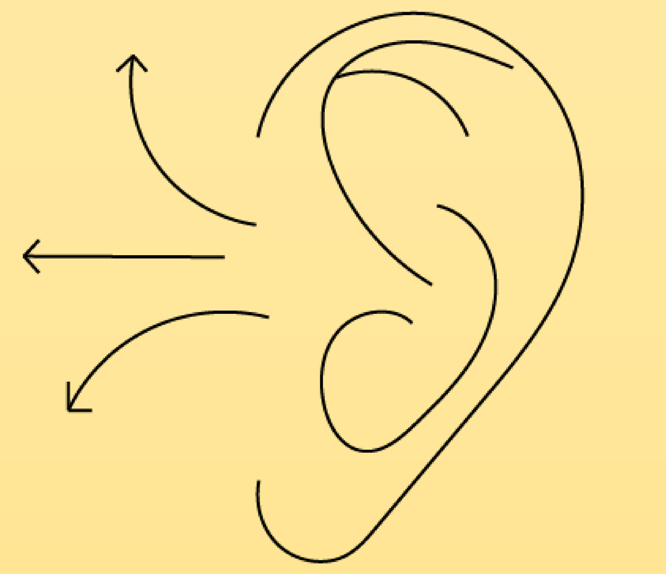
1. **TONOTOPY:**

When a sound pressure wave enters the inner ear, the basilar membrane oscillates with increasing amplitude and decreasing speed, until it reaches the resonant place corresponding to the frequency of the stimulus. The oscillation decays and then stops right after the tonotopic place. Equal distances along the basilar membrane correspond to a fixed interval, which means that the distance between the resonant peak of two octaves will always be the same (like in the piano!)

2. **ACTIVE FEEDBACK:**

Active Feedback: the outer hair cells amplify the displacement of the basilar membrane in the tonotopic place in a compressive and nonlinear way. That is why humans are capable of such an impressive hearing level range from 0 dB to 120 dB.

OTOACOUSTIC EMISSIONS



Otoacoustic emissions (OAEs) are low level sounds that are generated in the cochlea and that travel backwards outside our ears. They have been used already for many years in newborns hearing screenings and it has been suggested that they could become a mean for biometric recognition.

They are classified as:

- Spontaneous (SOAEs): no stimulus is needed to evoke them. They can be recorded in the ear canal.
- Transient-evoked (TEOAEs): the stimulus is transient, they are composed of all the frequencies present in it and the lower frequencies will be delayed because of the longer round trip needed to reach their tonotopic place before travelling back to the outer ear.
- Distortion-product (DPOAEs): if the stimulus consists of two frequencies f1 and f2 with a ratio around 1.22, they will contain f1, f2 and their linear combinations, in particular 2*f1-f2 and 2*f2-f1.

PHYSICAL MODEL OF THE COCHLEA

Main assumptions:

- The cochlea is uncurled and modelled as a 1D rectangular box (macromechanics):

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

where p_d is the pressure and ξ is the displacement of the basilar membrane.

Matrix formulation using finite-difference approximation:

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

- The cochlea is divided in N partitions of independent oscillators (micromechanics):

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

State space formulation:

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

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

OVERALL STATE-SPACE EQUATION

(macromechanics + micromechanics)

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

where M is the mass matrix of the system:

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

NONLINEARITY

The mass matrix can be changed to:

$$M = I - B_E G(Z) F^{-1} C_E$$

where

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

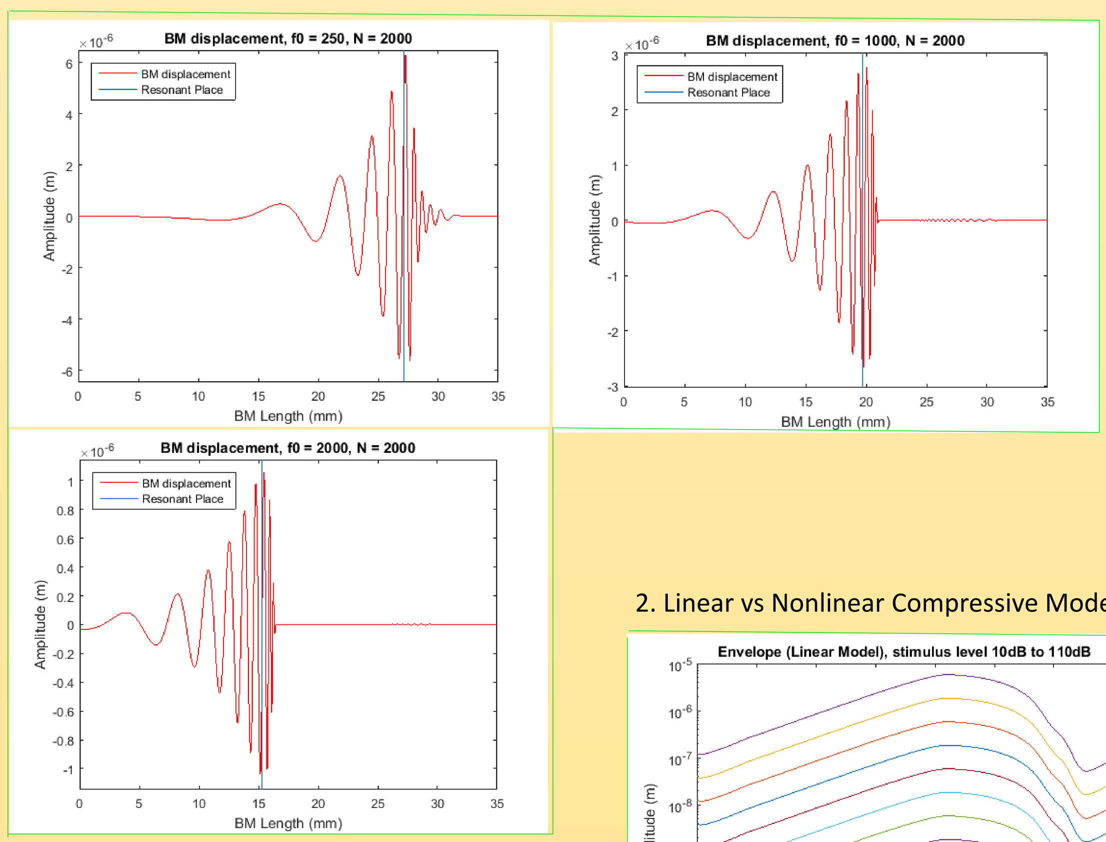
The nonlinear parameter α is:

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

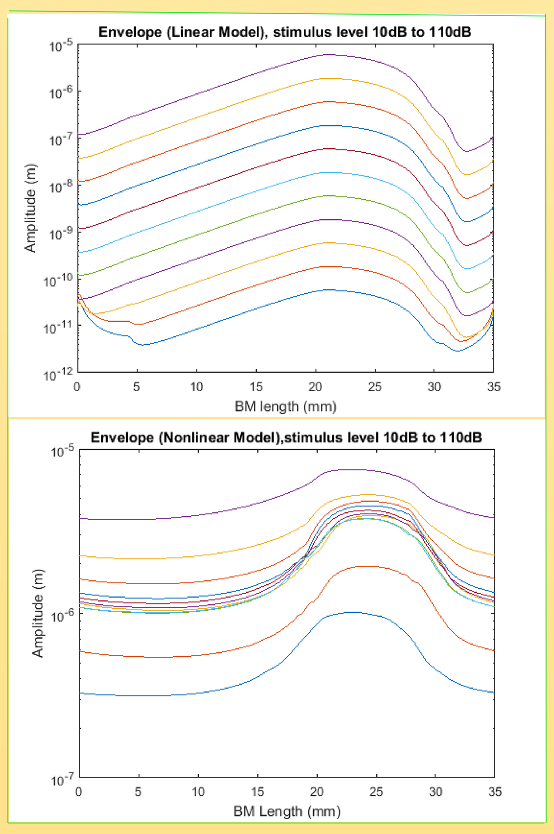
SIMULATIONS

(Matlab)

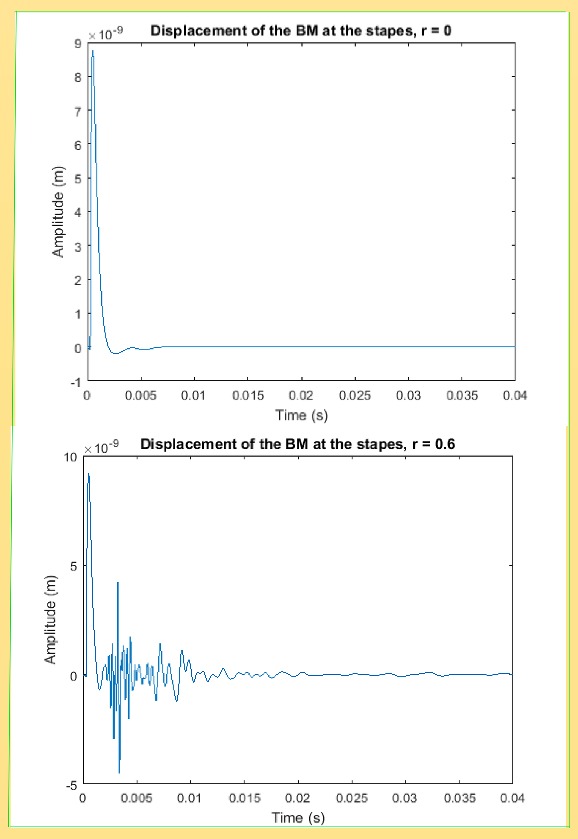
1. Tonotopy at 250 Hz, 1000 Hz, 2000 Hz



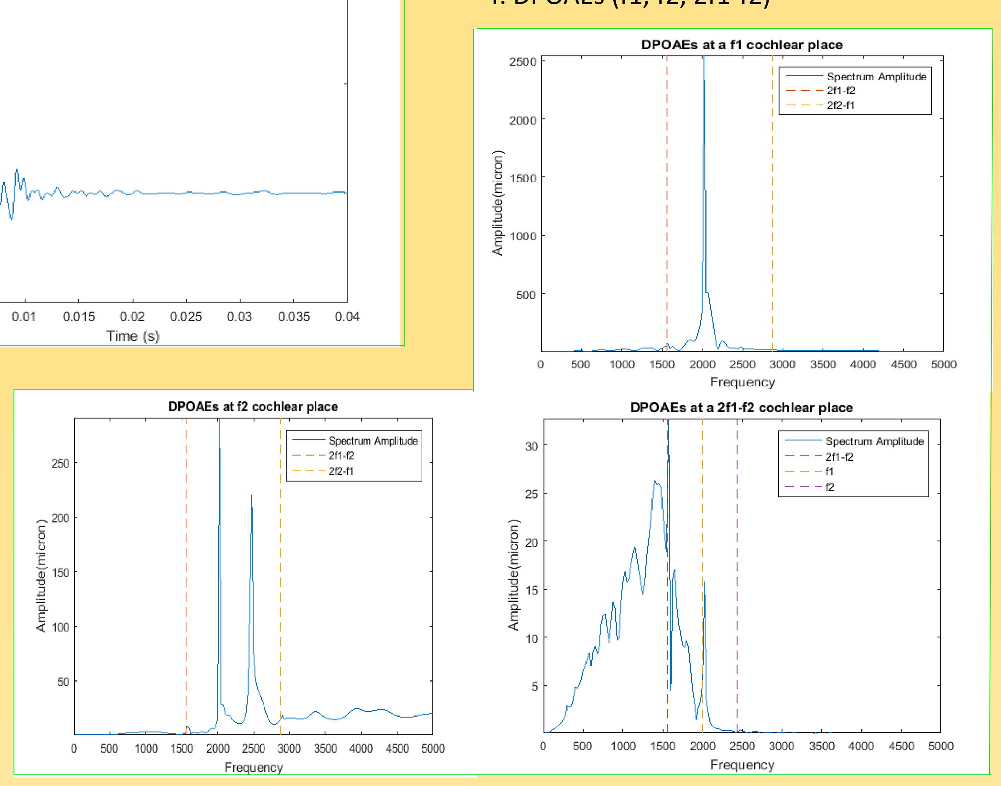
2. Linear vs Nonlinear Compressive Model



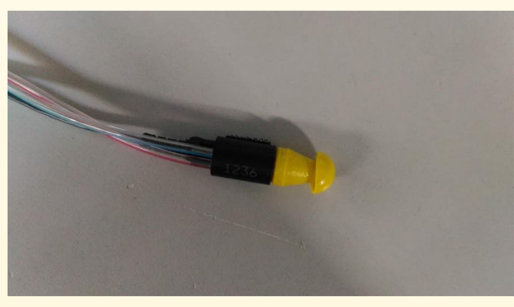
3. No TEOAEs (Linear) vs TEOAEs (roughness added)



4. DPOAEs (f1, f2, 2f1-f2)



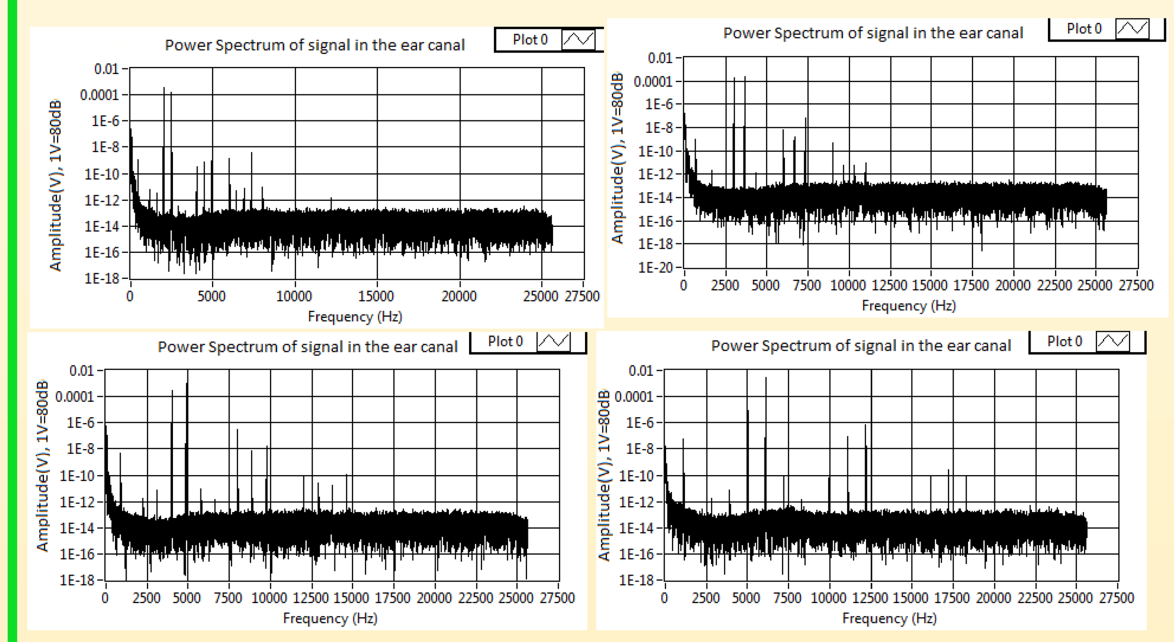
EXPERIMENTAL MEASUREMENTS OF OAEs



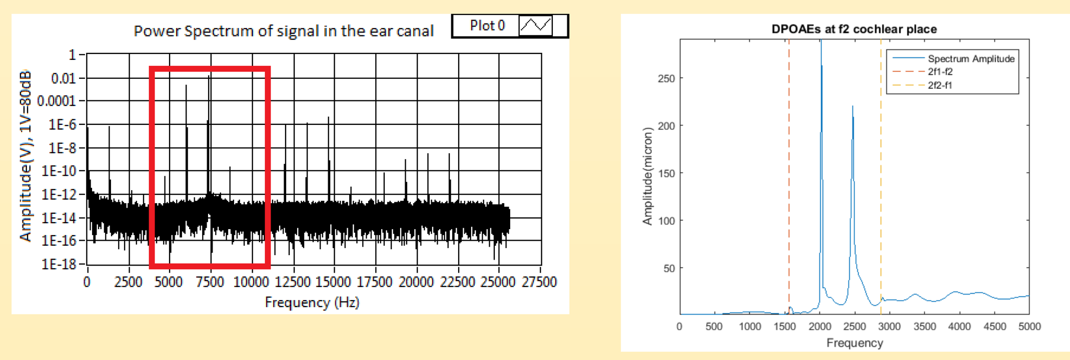
Probe used to record OAEs in the ear canal

NI hardware used to connect the probe to a LabVIEW code.

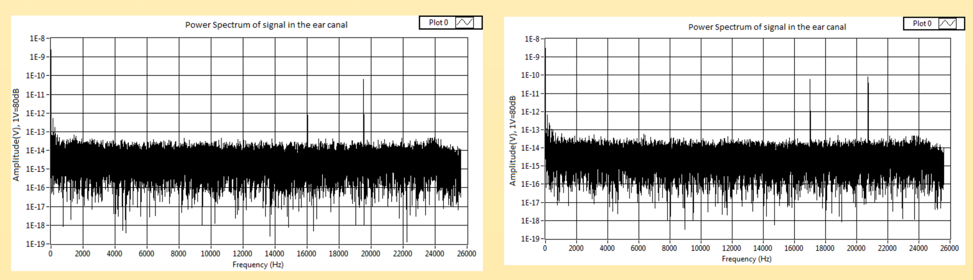
1. Measurement of DPOAEs in the left ear of a subject with different evoking stimuli



2. Comparison between measured DPOAEs (left) and simulations (right)



3. No DPOAEs detected at 16 kHz and 17 kHz. The subject (26 years old) can still hear the stimulus, but the emissions are not recorded. This is possibly what happens when a person's hearing in a certain frequency range is still functioning but will be eventually damaged in a near future (this is why OAEs could potentially substitute audiograms).



CONCLUSIONS AND FURTHER WORK

- The experimental measurements confirmed the validity of the cochlear model.
- However, we need a faster computational method to be able to simulate more complex and nonlinear models.
- A new research question has been formulated: will otoacoustic emissions measurements substitute audiograms in the future?
- A potential further work would consist in building a more affordable equipment for research, composed of an in ear headphone with a mini-speaker included. An app could be build to be able to measure the emissions from a smartphone in a cheap and reliable way.

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