SIMULATING AND MEASURING OTOACOUSTIC **EMISSIONS**

Cecilia Casarini

SIMULATING AND MEASURING OTOACOUSTIC EMISSIONS

Cecilia Casarini

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OUTLINE

SIMULATING AND MEASURING OTOACOUSTIC EMISSIONS

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Outline

Physiology of the ear

Outer Ear Middle Ear

Otoacousti Emissions

Cochlear Model

Sillidiations

Measurement

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- 1 Physiology of the ear
 - Outer Ear
 - Middle Ear
 - Inner Ear
- 2 Otoacoustic Emissions
- 3 Cochlear Model
- 4 Simulations
- Measurements
- 6 Conclusions

Physiology of the ear - OUTER EAR

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 Pinna (or Auricula): receives sounds from any direction, responsible of sound localization

Outer Ear

Outer Ear Middle Ear Inner Ear

Otoacoustic Emissions

Cochlear Model

Measurement

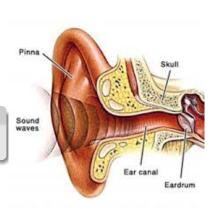
Conclusion

• Ear canal: 2.5 cm long.

Resonant frequencies

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

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



Physiology of the ear - MIDDLE EAR

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Middle Far

and fluid to avoid reflection:

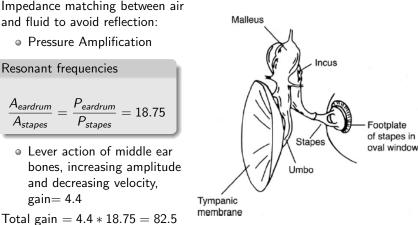
Pressure Amplification

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

Reissner's membrane

Apical Region

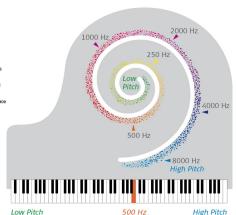
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Inner Far

vascularis Spiral limbus ligament prominence Scala tympani Modiolus Spiral lamina Two main functions:

- Tonotopy
- Active feedback: compressive, non linear



Basal Region

OTOACOUSTIC EMISSIONS

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Physiology of the

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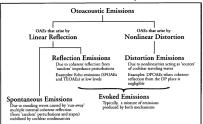
Stimulus-based classification:

- 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

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Cochlear Model

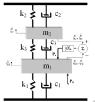
Three examples of cochlear models:

- 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:

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





COCHLEAR MODEL

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Conclusions

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:

$$FP(t) = \ddot{\Xi}(t), F$$
 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:

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

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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

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

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

The parameter α determines the nonlinearity of the system:

$$lpha(extbf{x}, extbf{t}) = lpha_0 \left[1 - anh \left(rac{1}{\sqrt{\lambda \pi}} \int_0^L e^{-(extbf{x} - extbf{x}')^2/\lambda} rac{\xi^2(extbf{x}', extbf{t})}{\xi^2_{sat}} d extbf{x}'
ight)
ight]$$

Simulations - TONOTOPY

BM displacement, f0 = 250, N = 2000

BM Length (mm)

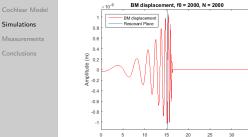
BM Length (mm)

25 30

35

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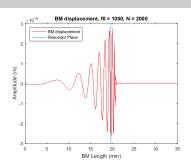
× 10⁻⁶

Amplitude (m)

BM displacement

Resonant Place

10



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



Simulations - NONLINEAR vs LINEAR

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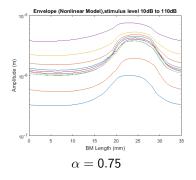
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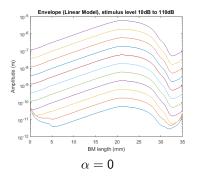
Simulations

Massuramant

Conclusion

Saturation of the nonlinear active mechanism vs linear case:





Simulations - TEOAEs

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Physiology of the

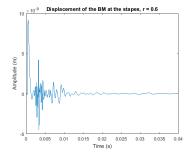
Outer Ear Middle Ear

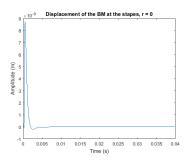
Otoacousti

Emissions

Simulations

Mascuromont





Simulations - DPOAEs

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Physiology of the ear

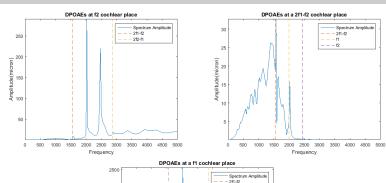
Outer Ear Middle Ear Inner Ear

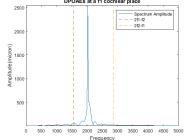
Otoacousti Emissions

Cochlear M

Simulations

Measurement





Measurements

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Physiology of the

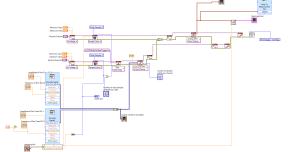
Middle Ear Inner Ear

Otoacousti Emissions

Cochlear Model

Measurements





Measurements - TEOAEs

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Outer Ear Middle Ea

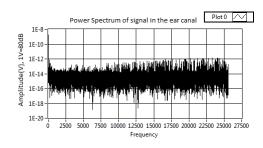
Otoacousti

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Cocilical Model

Measurements

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Measurements - DPOAEs

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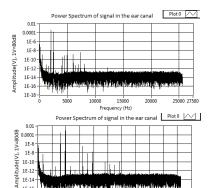
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1E-10

1E-12

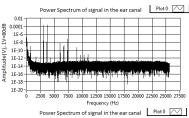
1E-18

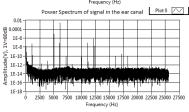
Measurements



5000 7500 10000 12500 15000 17500 20000 22500 25000 27500

Frequency (Hz)





Measurements - DPOAEs (Model vs Experimental measurements)

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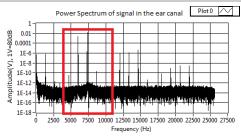
Outer Ear Middle Ear

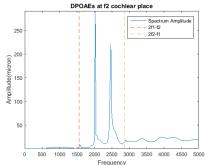
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Measurements - DPOEAEs (emissions not detected)

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Physiology of th

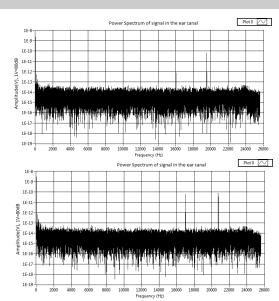
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Measurements





Conclusions

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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!

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