# Simulating Hearing Loss Using a Transmission Line Cochlea Model Delft University of Technology

Leo Koop October 28, 2015

Outline Introductions and Motivation 2 Modeling the Cochlea The General Model Model Output 3 Inverse Model The Idea Inverse Filtering Method 4 Energy Reflection The Problem **5** Sound Resynthesis Tuning Curves and Inverse Filters Filter Contribution Regions 6 Simulating Hearing Loss Modeling a Damaged Cochlea The Resulting Sound Comparison of Sound

# Simulating Hearing Loss

- Applied Mathematics Department at TU Delft
- Supervisor: Kees Vuik





# Simulating Hearing Loss

• An incas<sup>3</sup> project

• Supervisor: Peter van Hengel





# Motivation - Hearing Loss, Becoming more Prevalent





#### 1.1 billion people at risk of hearing loss

WHO highlights serious threat posed by exposure to recreational noise

Press release

27 FEBRUARY 2015 [GENEVA - Some 1.1 billion teenagers and young adults are at risk of hearing loss due to the unsafe use of personal audio devices, including smartphones, and exposure to damaging levels of sound at noisy entertainment venues such as nightclubs, bars and sporting events, according to WHO. Hearing loss has potentially devastating consequences for physical and mental health, education and employment.



# Motivation - Uses of a Hearing Loss Simulator

Education



# Motivation - Uses of a Hearing Loss Simulator

- Education
- Hearing loss prevention



# Motivation - Uses of a Hearing Loss Simulator

- Education
- Hearing loss prevention
- Simplifying hearing aid development and testing



### The Ear



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### The Cochlea, a Cross Section



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### The Cochlea





Next Subsection 2 Modeling the Cochlea The General Model

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$$\frac{\partial^2 p}{\partial x^2}(x,t) - \frac{2\rho \partial^2 y}{h \partial t^2}(x,t) = 0, \quad 0 \le x \le L, \quad t \ge 0$$
(1)



#### The Main Equation

$$\frac{\partial^2 p}{\partial x^2}(x,t) - \frac{2\rho \partial^2 y}{h \partial t^2}(x,t) = 0, \quad 0 \le x \le L, \quad t \ge 0$$
(1)

• y(x, t): The excitation of the oscillator



$$\frac{\partial^2 p}{\partial x^2}(x,t) - \frac{2\rho \partial^2 y}{h \partial t^2}(x,t) = 0, \quad 0 \le x \le L, \quad t \ge 0$$
(1)

- y(x, t): The excitation of the oscillator
- p(x, t): Pressure on the cochlear partition



$$\frac{\partial^2 p}{\partial x^2}(x,t) - \frac{2\rho \partial^2 y}{h \partial t^2}(x,t) = 0, \quad 0 \le x \le L, \quad t \ge 0$$
(1)

- y(x, t): The excitation of the oscillator
- p(x, t): Pressure on the cochlear partition
- $\rho$ : Density of the cochlear fluid



$$\frac{\partial^2 p}{\partial x^2}(x,t) - \frac{2\rho \partial^2 y}{h \partial t^2}(x,t) = 0, \quad 0 \le x \le L, \quad t \ge 0$$
(1)

- y(x, t): The excitation of the oscillator
- p(x, t): Pressure on the cochlear partition
- $\rho$ : Density of the cochlear fluid
- h: Height of the scala
- L: Length of the cochlea
- t: Time



The pressure term

$$p(x,t) = m\ddot{y}(x,t) + d(x)\dot{y}(x,t) + s(x)y(x,t)$$

(2)



The pressure term

$$p(x,t) = m\ddot{y}(x,t) + d(x)\dot{y}(x,t) + s(x)y(x,t)$$

(2)

- *m*: Mass of the membrane
- d(x): Position dependent damping
- s(x): Position dependent stiffness



### The Stiffness Term

### Linear stiffness term (theoretical)

$$s(x) = s_0 e^{-\lambda x}$$



### The Stiffness Term

#### Linear stiffness term (theoretical)

$$s(x) = s_0 e^{-\lambda x}$$



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# The Damping Term

### Linear damping term (theoretical)

$$d(x) = \epsilon \sqrt{m \ s(x)}$$



# The Damping Term

#### Linear damping term (theoretical)

$$d(x) = \epsilon \sqrt{m \ s(x)}$$



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Next Subsection 2 Modeling the Cochlea Model Output

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### **Model Output**

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### **Model Output**

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### **Model Output**

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# Model Input and Output



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Next Subsection B Inverse Model The Idea

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# Simulation Approach

- We have a model of the normal cochlea
- Can we find the Cause given the Effect?



# Simulation Approach

- We have a model of the normal cochlea
- Can we find the Cause given the Effect?

#### Idea

Find a method to get back the original sound from the model of a healthy ear. Use this method on a model of a damaged ear to simulate hearing loss



Next Subsection B Inverse Model Inverse Filtering Method

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### Inverse Filter Approach for a Single Oscillator

If the original sound is a and a result from the model is c then an oscillator in the model is b

$$c(t) = a(t) * b(t)$$

This in the frequency domain is:

$$C(f) = A(f) \cdot B(f)$$

A change in basic operation from convolution to multiplication



## Finding the Inverse Filter

- b(t) is the impulse response of an oscillator
- B(f) is the frequency response of an oscillator

In the frequency domain  $B^{-1}(f)$  is easily found:

$$B^{-1}(f) = \frac{1}{B(f)}$$

Given C(f) and B(f), A(f) is:

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$$A(f) = C(f) \cdot B^{-1}(f)$$

An inverse Fourier transform yields a(t)

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### The Idea



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Next Subsection **4** Energy Reflection The Problem

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### The Cochlea



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# A Good Impulse Response

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### Non-Finite Impulse Response

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### Energy Build-up in the Model

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### The Solution



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### A Better Impulse Response

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### A Better Impulse Response

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Next Subsection **5** Sound Resynthesis Tuning Curves and Inverse Filters

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### **Tuning Curves**



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### The Inverse Filters



 $B^{-1}(f)$  - filter functions

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# **Error Amplification**



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Next Subsection **5** Sound Resynthesis Filter Contribution Regions **T**UDelft

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# Choosing Contribution Bounds per Inverse Filter



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Next Subsection 6 Simulating Hearing Loss Modeling a Damaged Cochlea **tu**Delft

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# Modifying the Damping Term

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Next Subsection 6 Simulating Hearing Loss The Resulting Sound **T**UDelft

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# The Resulting Sound



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### The Resulting Sound



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Next Subsection 6 Simulating Hearing Loss Comparison of Sound **T**UDelft

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# A Normal Cochleogram



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# Simulating Damage



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# Cochleogram in Response to Damaged Sound



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### Comparing the Cochleograms



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# Sound Samples



- "1, 2, 3" From the TIDigits database
- "1, 2, 3 w/ noise" With background noise
- "1, 2, 3 w/ noise" Resynthesized without simulating damage
- "1, 2, 3 w/ noise" Approximate hearing loss of a 40 year old
- "1, 2, 3 w/ noise" Approximate hearing loss of a 60 year old
- "1, 2, 3 w/ noise" Approximate hearing loss of a 90 year old

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## Accomplishments

• Fixed an energy reflection problem in the model



# Accomplishments

- Fixed an energy reflection problem in the model
- Found a way to combine contributions from different oscillators



# Accomplishments

- Fixed an energy reflection problem in the model
- Found a way to combine contributions from different oscillators
- A transmission line cochlea model can now be used to simulate hearing loss



# Recommendations

• Sound resynthesis from a nonlinear transmission line cochlea model



# Recommendations

- Sound resynthesis from a nonlinear transmission line cochlea model
- The best method to solve the energy reflection problem



# Recommendations

- Sound resynthesis from a nonlinear transmission line cochlea model
- The best method to solve the energy reflection problem
- How to best modify the cochlea model to simulate various kinds of hearing loss



### The End

"He who has an ear, let him hear ... "

- Revelation 2:17

