Simulating Hearing Loss

Delft University of Technology

Leo Koop

April 9, 2015

Outline

Next Subsection

Simulating Hearing Loss

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

Simulating Hearing Loss

- An incas^3 project
- Supervisor: Peter van Hengel

Next Subsection

Motivation - Hearing Loss, Becoming more Prevalent

World Health Organization

entre | Publications | Countries | Programmes | Governance | About WHO

Media centre

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

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

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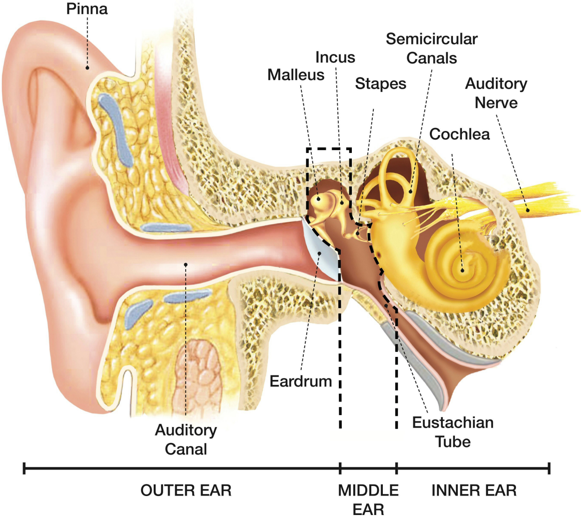
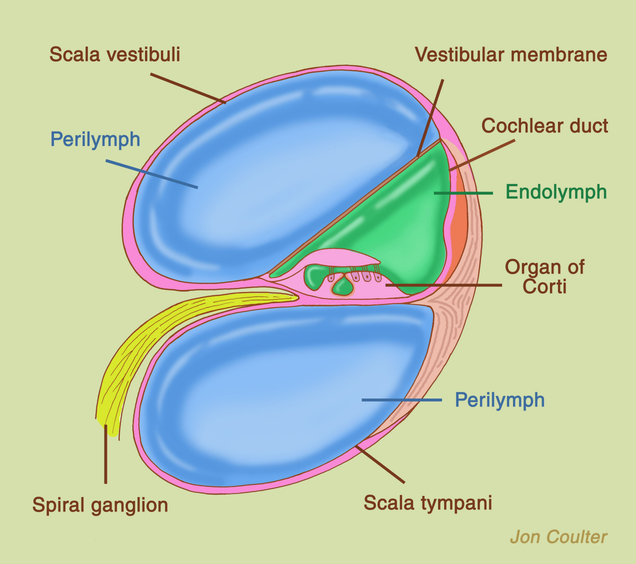
The Ear

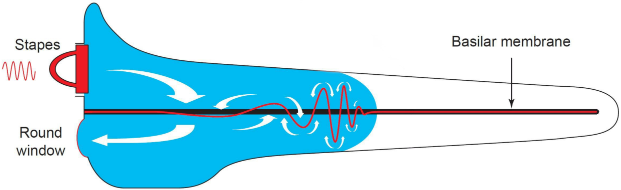


Pinna
Semicircular Canals
Incus
Malleus
Stapes
Auditory Nerve
Cochlea
Eardrum
Auditory Canal
Eustachian Tube
OUTER EAR
MIDDLE EAR
INNER EAR

The Cochlea, a Cross Section



The Cochlea



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Modeling the Cochlea

The Main Equation

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

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

Modeling the Cochlea

The pressure term

$$p(x,t) = m\ddot{y}(x,t) + d(x)\dot{y}(x,t) + s(x)y(x,t) \tag{2}$$

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$$p(x,t) = m\ddot{y}(x,t) + d(x)\dot{y}(x,t) + s(x)y(x,t) \tag{2}$$

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

Simplifying the equations

We introduce $g(x,t)$ as follows:

$$g(x,t) = d(x)\dot{y}(x,t) + s(x)y(x,t) \tag{3}$$

Then rewrite $m\ddot{y}(x,t)$ as:

$$m\ddot{y}(x,t) = p(x,t) - g(x,t) \tag{4}$$

This allows us to then rewrite Equation (1) as:

$$\frac{\partial^2 p}{\partial x^2}(x,t) - \kappa p(x,t) = -\kappa g(x,t) \tag{5}$$

Where $\kappa = \frac{2\rho}{hm}$.

Simplifying the equations

Equation 5 can be further reduced to 2 first degree ODEs by introducing v as follows:

$$\frac{\partial y}{\partial t}(x, t) = v(x, t) \tag{6}$$

$$\frac{\partial v}{\partial t}(x, t) = \frac{p(x, t) - g(x, t)}{m} \tag{7}$$

Which can then be solved with a numerical integrator, say Classical Runge Kutta 4

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Damping and Stiffness Terms

The pressure term

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Non-linear damping term

$$d(x,\dot{y}) = \Bigg\{(1-\gamma)(\delta_{sat}-\delta_{neg})\left[1-\frac{1}{1+e^{(\Lambda-\alpha)/\mu_\alpha}}\right] + \gamma(\delta_{sat}-\delta_{neg})\left[1-\frac{1}{1+e^{\Lambda-\beta/\mu_\beta}}\right]+\delta_{neg}\Bigg\}\sqrt{m\ s(x)}$$

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Linear stiffness term

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Non-linear case; an additional delayed feedback stiffness term

$$\begin{aligned} c(x,\dot{y}) = \Bigg\{ &(1-\gamma)(\sigma_{zweig}) \left[\frac{1}{1+e^{(\Lambda-\alpha)/\mu_\alpha}}\right] \\ &+ \gamma(\sigma_{zweig}) \left[\frac{1}{1+e^{\Lambda-\beta/\mu_\beta}}\right] \Bigg\} \end{aligned} \tag{8}$$

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A Sample Model Output

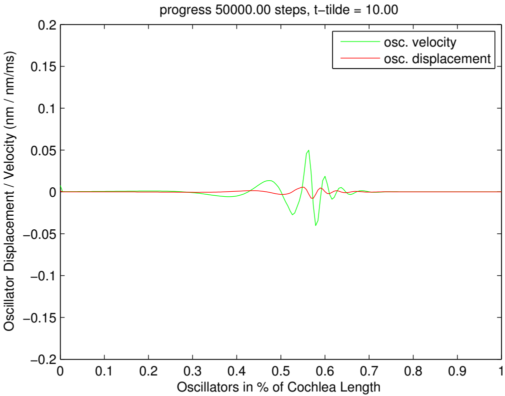

Figure: Modeling the response of the basilar membrane to a tone sound

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Simulation Approach

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

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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

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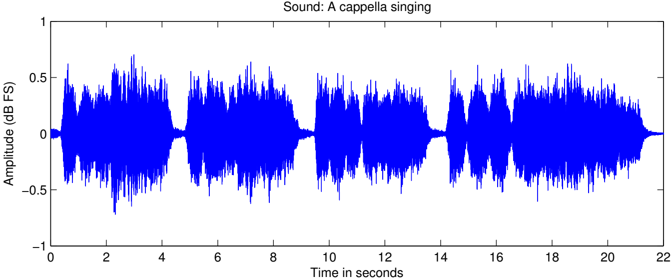
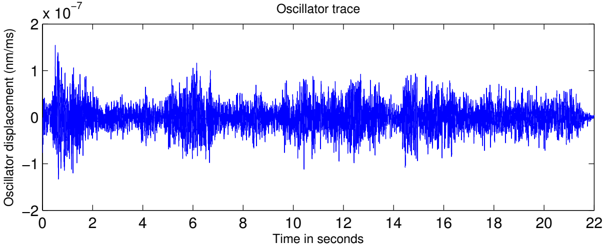
The Model Viewed as a Convolution





Finding the Inverse Filter

If the original sound is x and the result from the model is y then the model is h

$$y(t) = x(t) * h(t)$$

Performing a Fourier Transformation results in:

$$Y(f) = X(f) \cdot H(f)$$

A change in basic operation from convolution to multiplication

Finding the Inverse Filter

Then H and H^{-1} are:

$$H(f) = \frac{Y(f)}{X(f)}$$

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

$X(f)$ Can then easily be found

$$X(f) = \frac{Y(f)}{H(f)}$$

And then:

$$x(t) = Inverse\ Fourier\ Transform\ of(X(f))$$

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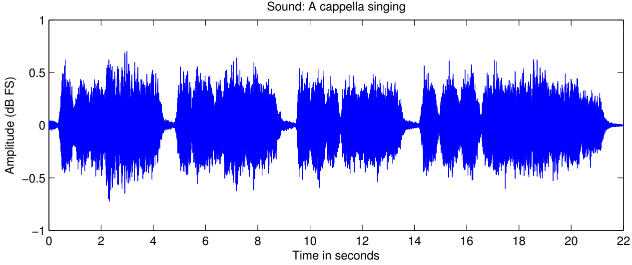
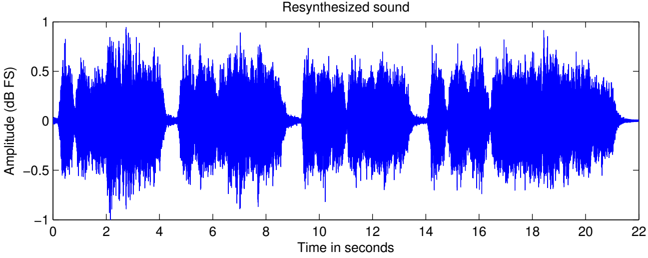
Some Results





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- Number of oscillators in the Model

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Testing

- Objective testing may be limited
- Subjective testing
    - Comparing two sounds on Right and Left channel does not work
    - Consecutive listening tends to work better
    - System limitations should be considered

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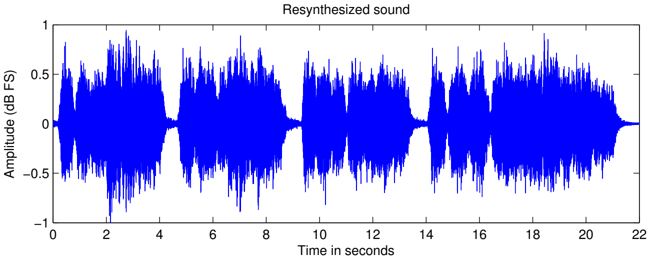
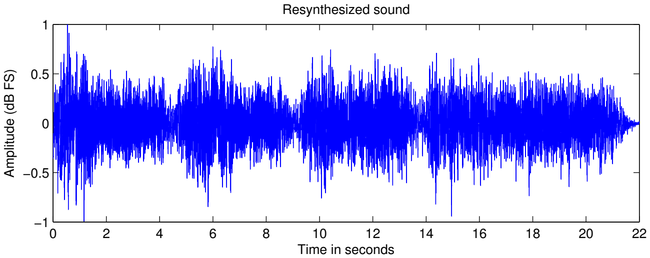
Testing and Optimization, a Possibility





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- Resynthesizing sound from the non-linear model