

# The Dynamics of Language

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## Abstract

The human cochlea can be modeled as a coupled series of damped mass-spring oscillators, where each oscillator corresponds to a mechanical segment of the basilar membrane. This basic implementation, which simulates only the passive signal processing capabilities of the cochlea, can be complemented with a model of active nonlinear amplification, which is responsible for the ear's remarkable sensitivity and tuning. This active process has been observed to have key characteristics of a Hopf bifurcation (an oscillatory instability that occurs as parameters are adjusted continuously). This paper presents an active amplification simulation coupled with a fluid flow model of the human cochlea. The model is then tested with inputs from natural language.

## 1 Introduction

The cochlea is a small, spiral-shaped, fluid-filled cavity in the human inner ear. It is responsible for the tonotopic separation of acoustic frequencies, and for the transduction of mechanical/acoustic signals into electrical impulses subsequently carried by afferent auditory nerves to the brain. Computational simulations of the cochlea are motivated by a desire to understand the basis of our remarkable auditory sense, and by extension, how we are able to process spoken language.

However, due to its geometric complexity and small size, the cochlea is difficult to model. A simple fluid model, by itself, fails to capture the majority of its nonlinear behavior. Nonlinear behavior is characterized by the fact that nonlinear effects become more marked, the smaller the forcing. This ever-presence of the nonlinearity suggests it is neither a property of

the stiffness of the membrane nor of the fluid. Rather, the cochlea seems to be adding external energy to low-energy input signals and dampening high energy signals, in order to achieve its unique flexibility and range. And indeed, recent research has shown that the structure of outer hair cells on the basilar membrane is a linear array of coupled cells, each hovering near a Hopf bifurcation point. That is, it is a critical oscillation around a Hopf bifurcation critical value, that induces an active amplification, and transitively nonlinear behavior.

**Outline** The remainder of this article is organized as follows. Section 2 gives account of previous work. Section 3 provides the mathematical equations behind the modeling of the cochlea. The computational framework of our simulation, coded in C, will be outlined and explained in Section 4. Our results, mostly about effects of changing the parameter space, are described in Section 5. Finally, Section 6 gives the conclusions.

## 2 Previous work

The cochlea has been studied extensively. In addition to fluid model that we are adopting, that of coupled mass oscillators, there are two others:

## 3 Mathematical Basis for Modeling

It's not entirely clear what the  $P_n$  term should be, but the rest of the system looks something like this:

$$\ddot{x}_i = -\frac{1}{m_i} (k_i x_i + c_i(x_i - x_{i-1}) + b_i \dot{x}_i)$$

With  $v_i = \dot{x}_i$ , this translates into two equations for a dynamical system:

$$\begin{aligned} \dot{v}_i &= -\frac{1}{m_i} (k_i x_i + c_i(x_i - x_{i-1}) + b_i v_i) \\ \dot{x}_i &= v_i \end{aligned}$$

Of course, the actual dynamical system would have  $2n$  equations, depending on the number of oscillators included.

## **4 Computer Simulation**

## **5 Results**

In this section we describe the results.

## **6 Conclusions**

We worked hard, and achieved very little.