Modelling inertial actuators and cochlear micromechanics

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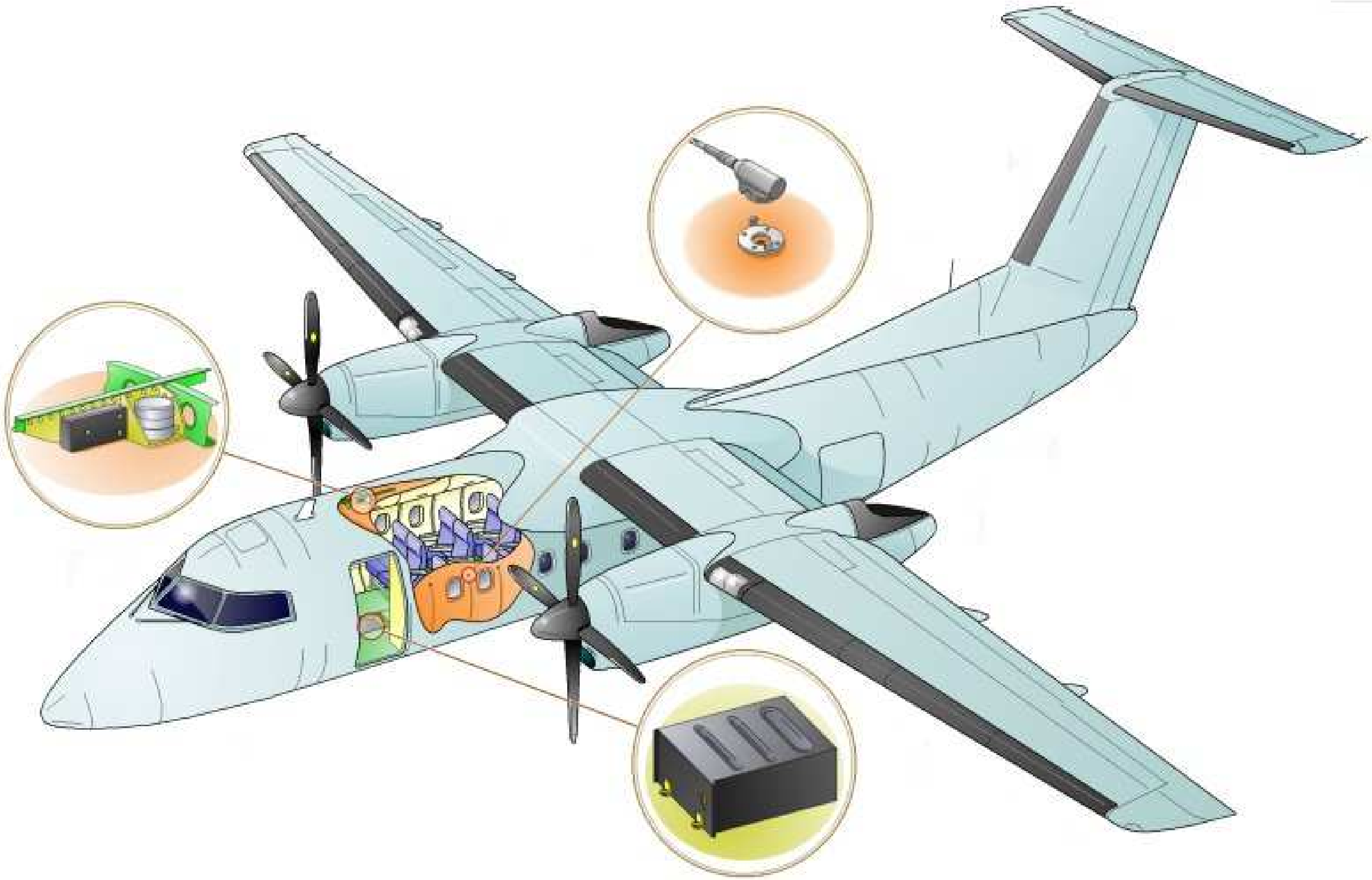
Global control through local feedback

Local feedback with inertial actuators

Active amplification in the cochlea

Active Noise Control System for Propeller Aircraft



Controller with 46 structural actuators and 72 microphones built by Ultra Electronics and now fitted to over 1,000 aircraft

Application to larger aircraft

Airbus A400M Aircraft

Potential Open Rotor Aircraft

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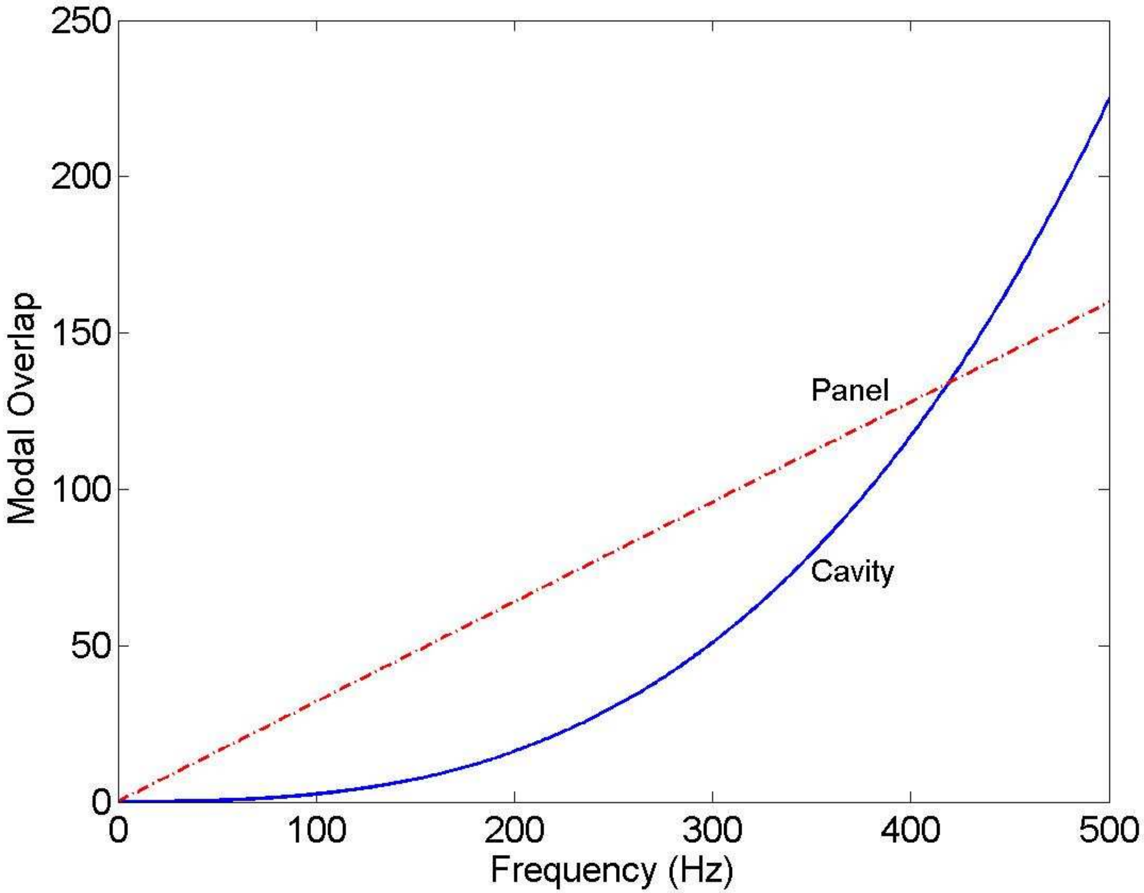
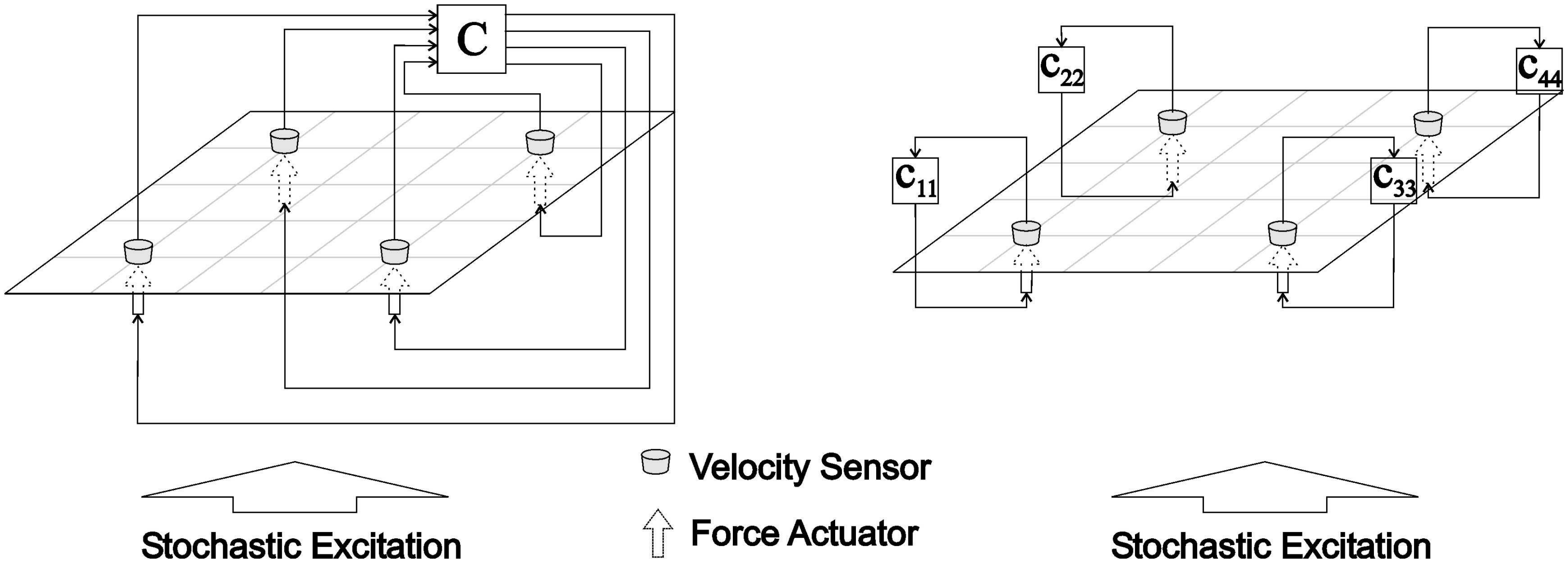
Number of actuators required

The number of actuators required for control depends on the number of significantly excited modes, which is given by the *Modal Overlap*



GLOBAL VIBRATION CONTROL THROUGH LOCAL FEEDBACK

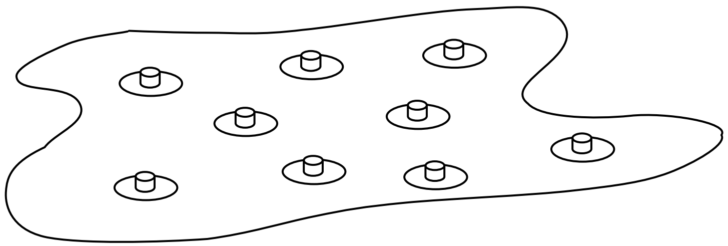


Centralised feedback *Local feedback*

Implications for modular controllers

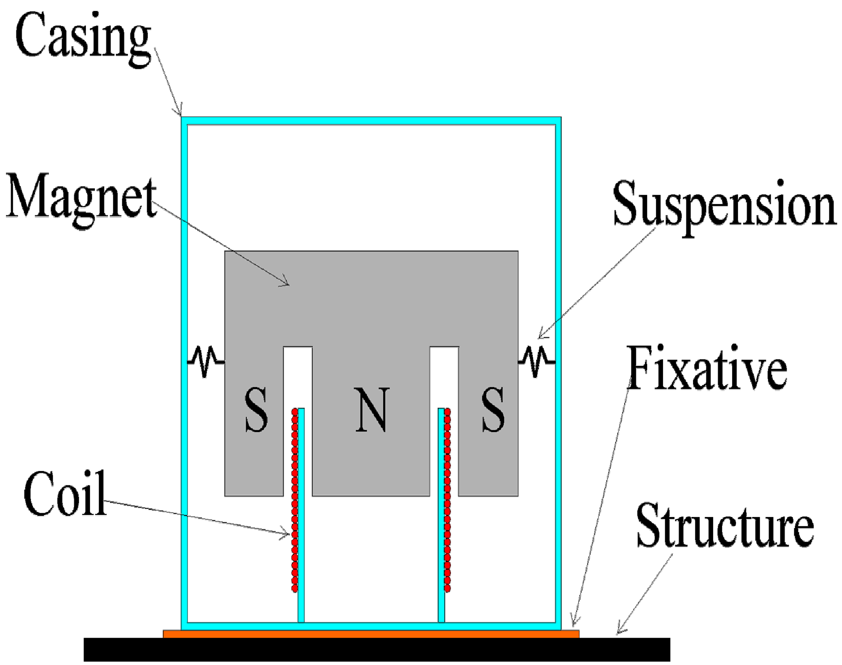
If the actuators and sensors are collocated and dual, an array of independently acting modules with *local* feedback loops are guaranteed to be ***stable*** (Balas, 1979), regardless of

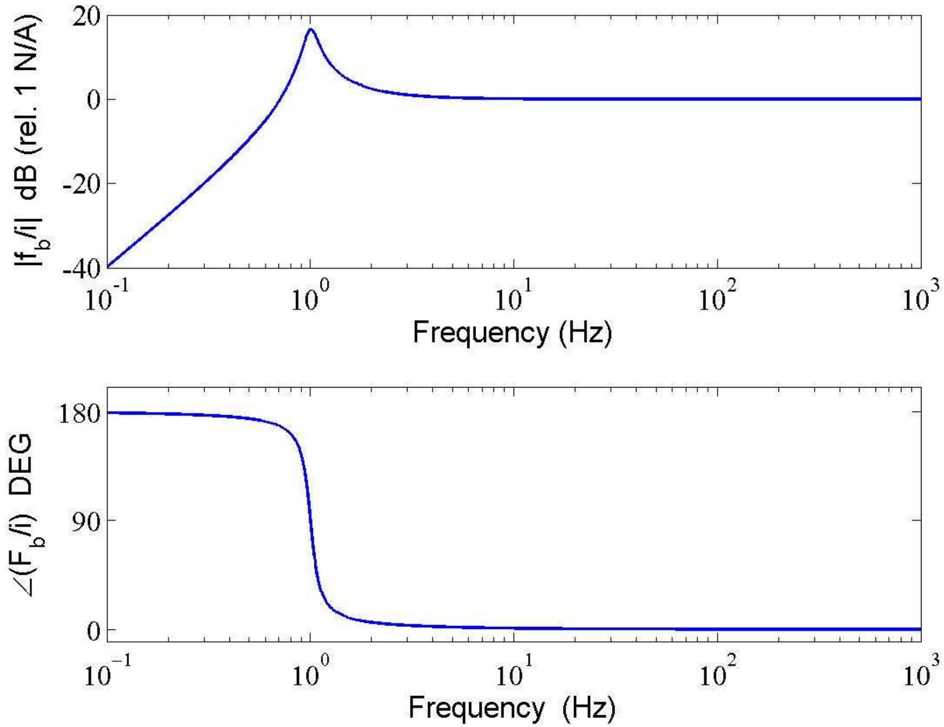
1) changes in the dynamics of the system under control
2) failures in individual modules
3) The positions of the local modules



Self-tuning of the feedback gains also allows the ***performance*** to be optimised to the environment

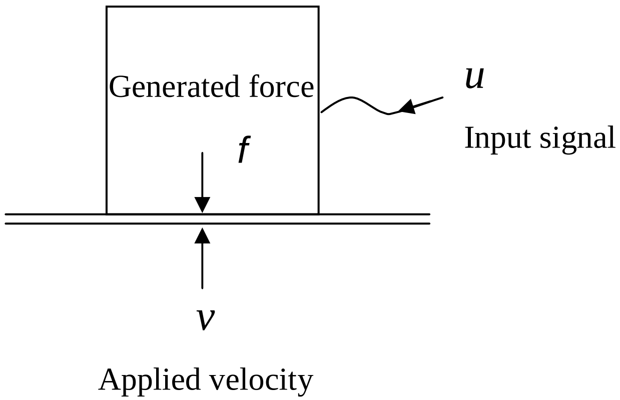
IMPLEMENTATION USING INERTIAL ACTUATORS (PROOF MASS)





The blocked response is independent of the structure

General description of the actuator



Whatever the dynamics of the actuator, provided it is linear, superposition applies so that

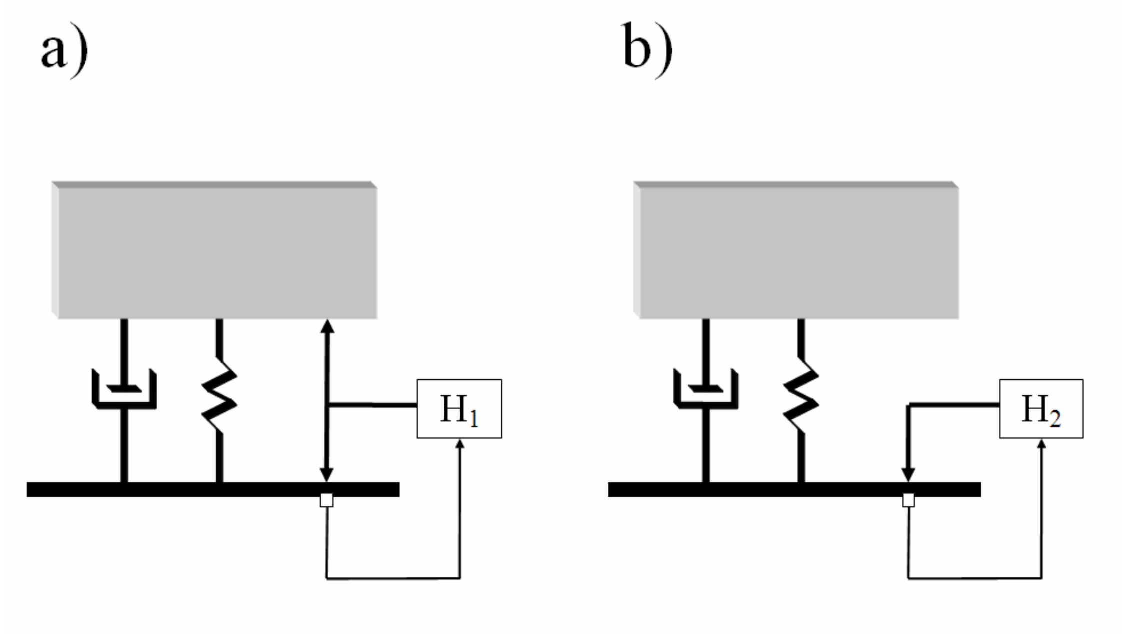
$$f = T_a u + Z_a v$$

Blocked actuator response

Undriven actuator impedance

General analysis of a reactive actuator

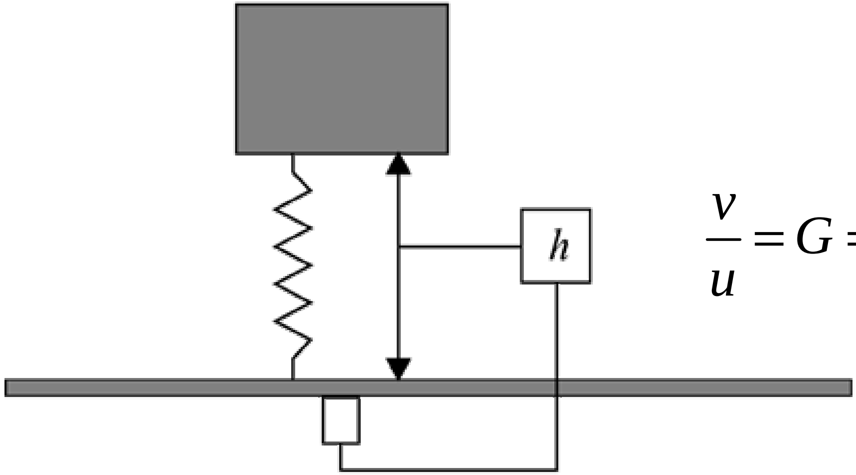
The feedback loop with the reactive actuator can be shown via superposition (see appendix to ACTIVE 2009 paper) to be equivalent to a passive attachment and a **collocated** feedback controller, with a modified controller and perfect force actuation



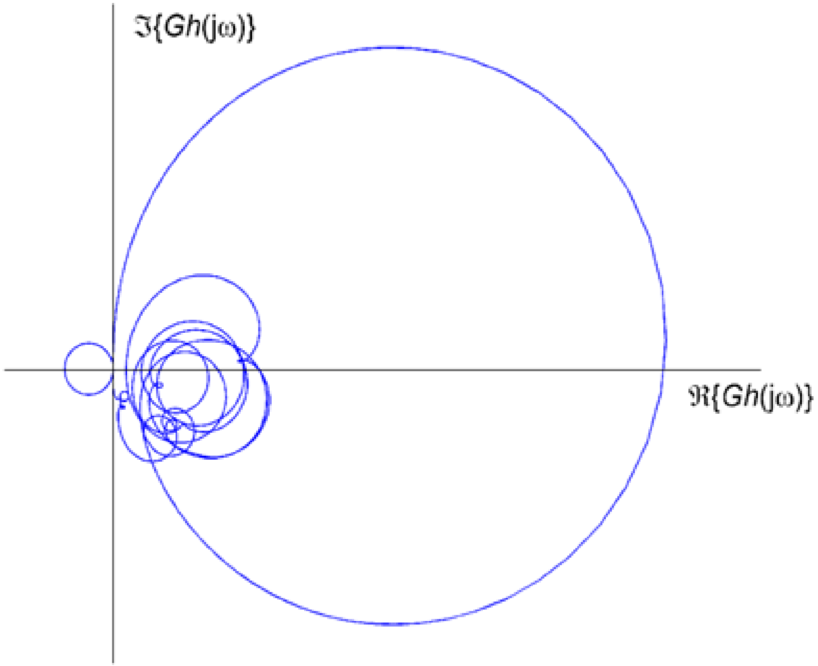
$$H_2 = T_a H_1$$

This reformulation helps in the design of compensators and the study of interaction between multiple modules

Nyquist Plot for a Single Velocity Feedback Loop with an Inertial Actuator on a Plate

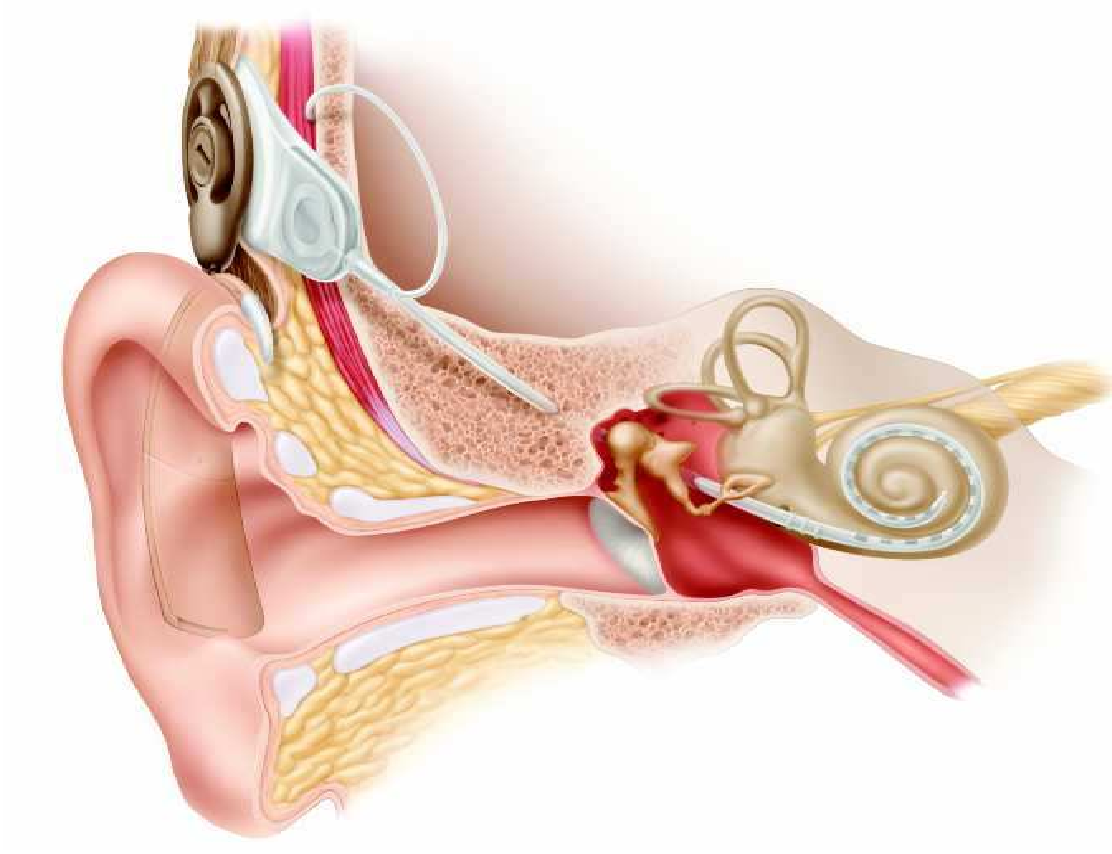


$$\frac{v}{u} = G = YT_a$$



The plate resonances generate loops on the right, corresponding to negative feedback and creating attenuation. The actuator resonance causes a loop on the left, corresponding to positive feedback, causing enhancement and threatening stability

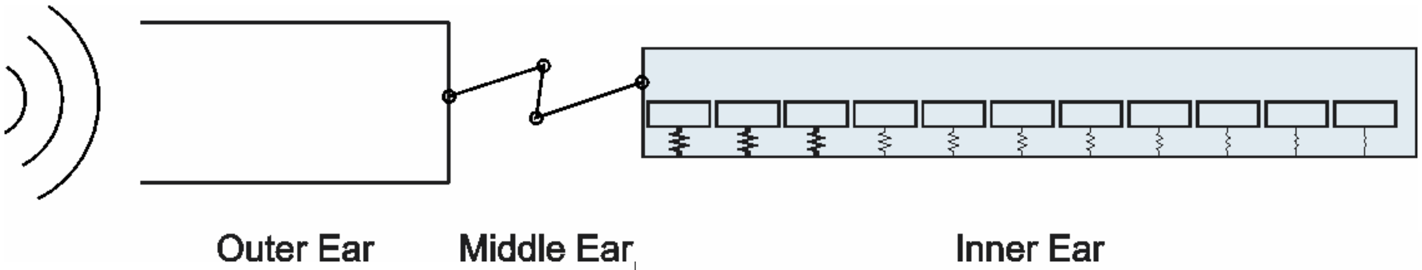
Motivation for Cochlear Modelling

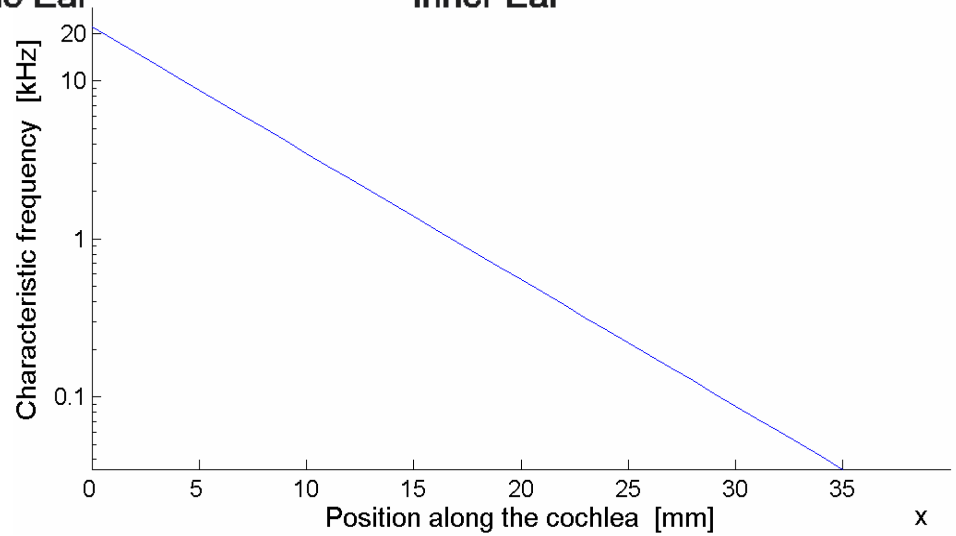


Develop signal processing systems that mimic the healthy cochlea for aids and implants

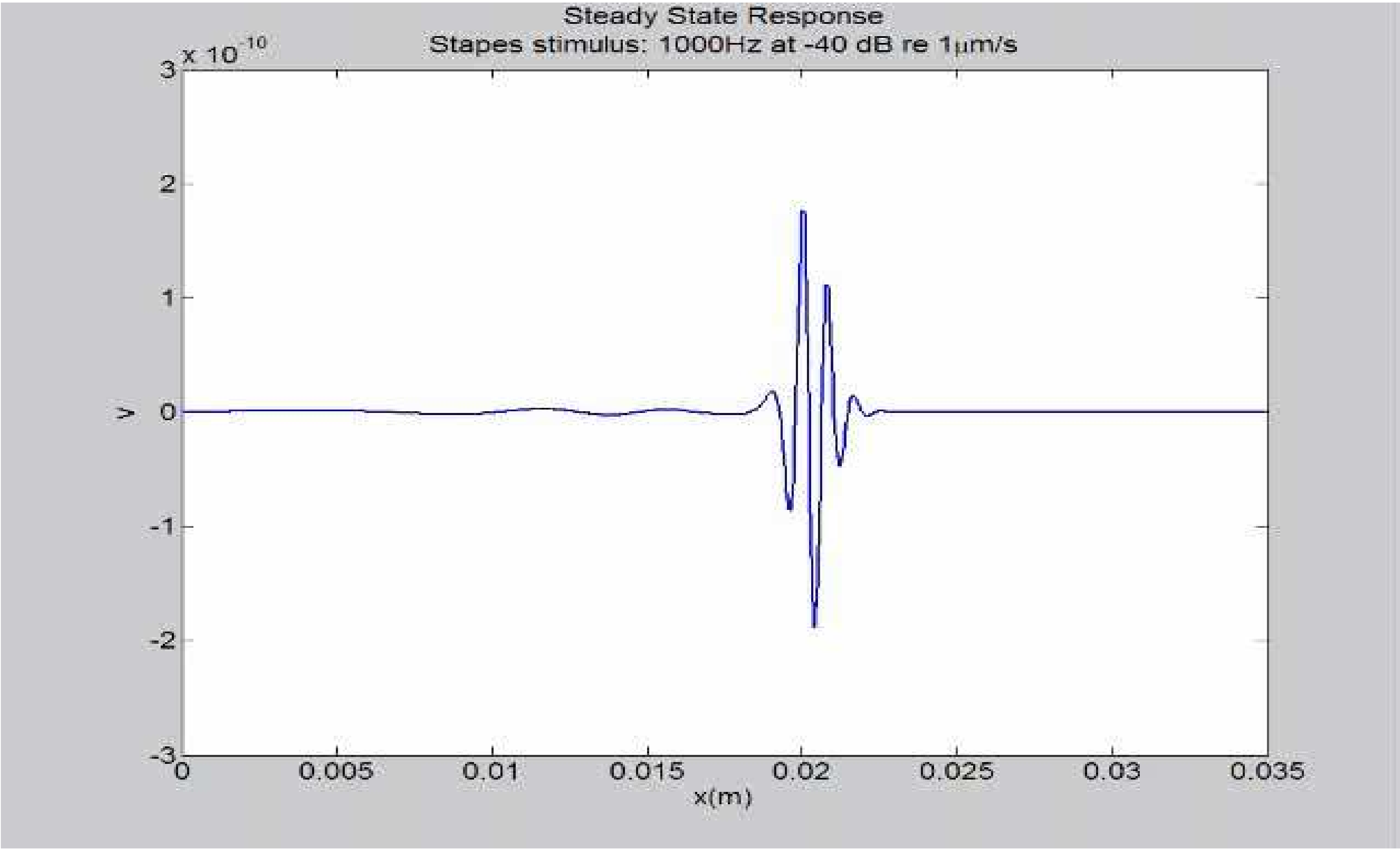
A simple model of the ear

The dynamics of the basilar membrane separating the fluid chambers within the cochlea are modelled as an array of **1DOF** systems, each tuned to its own characteristic frequency (Helmholtz 1863, von Békésy 1947).





Response along cochlea at 1kHz



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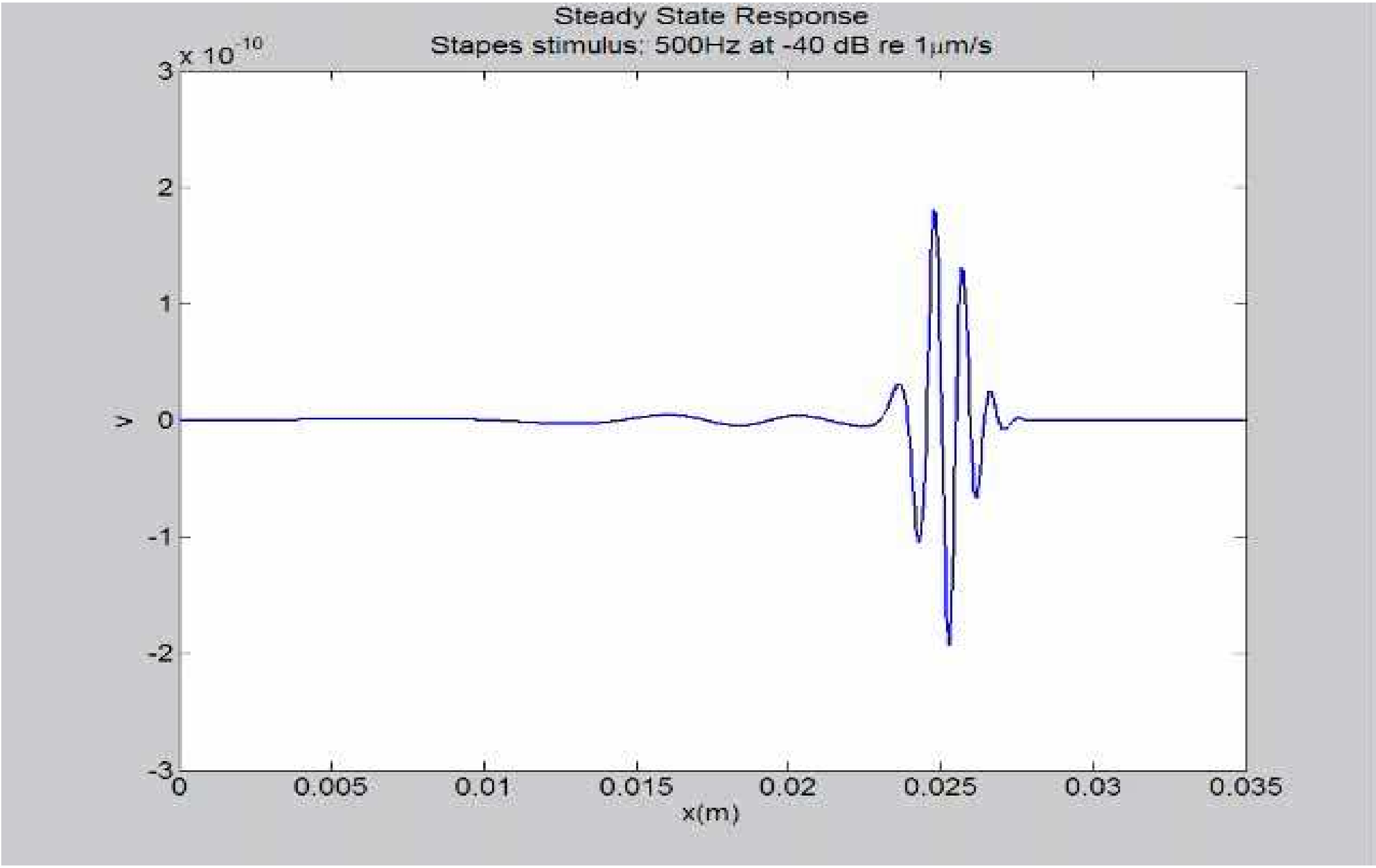
Response along cochlea at 500Hz



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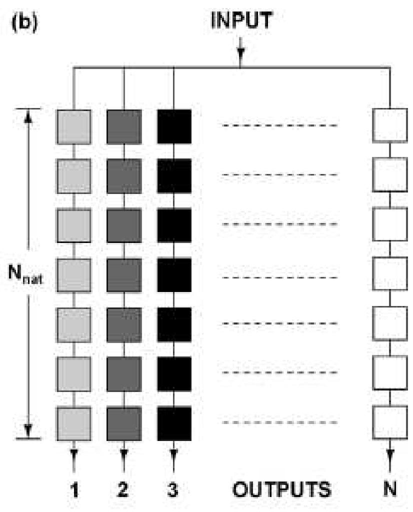
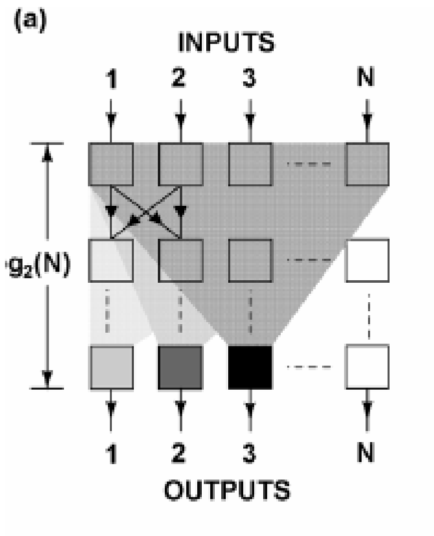
Efficiency of spectral analysis

Filter bank



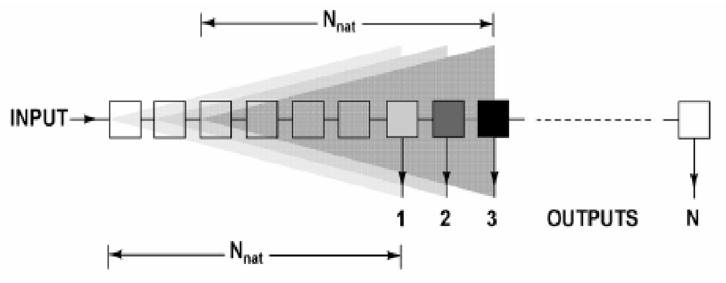
N^2

FFT



$N \log N$

Wave approach

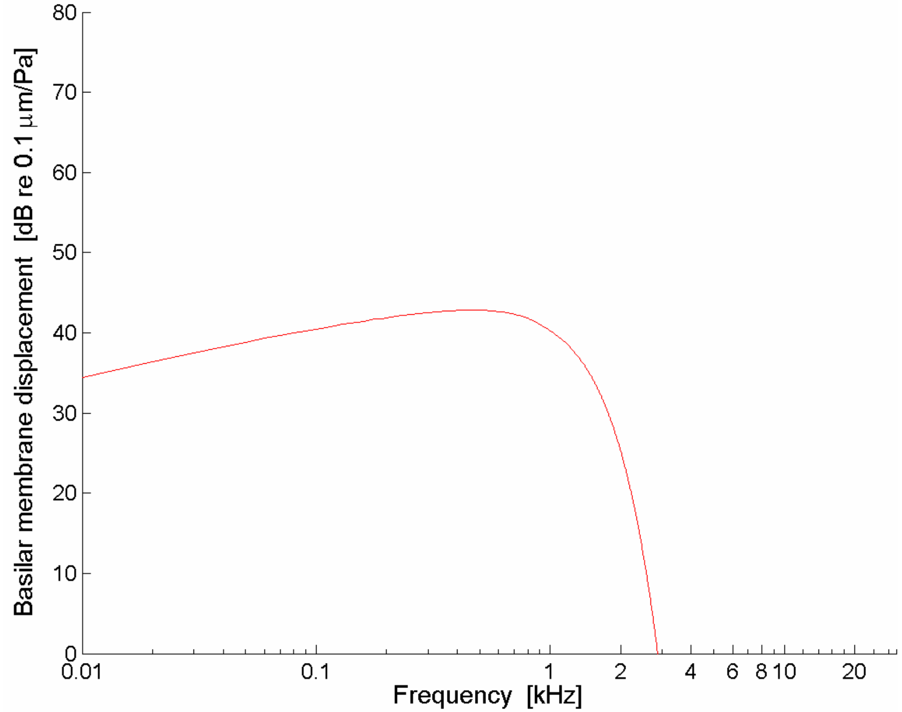


N

After Mandal et al IEEE Joun. Solid State Circuits 2009

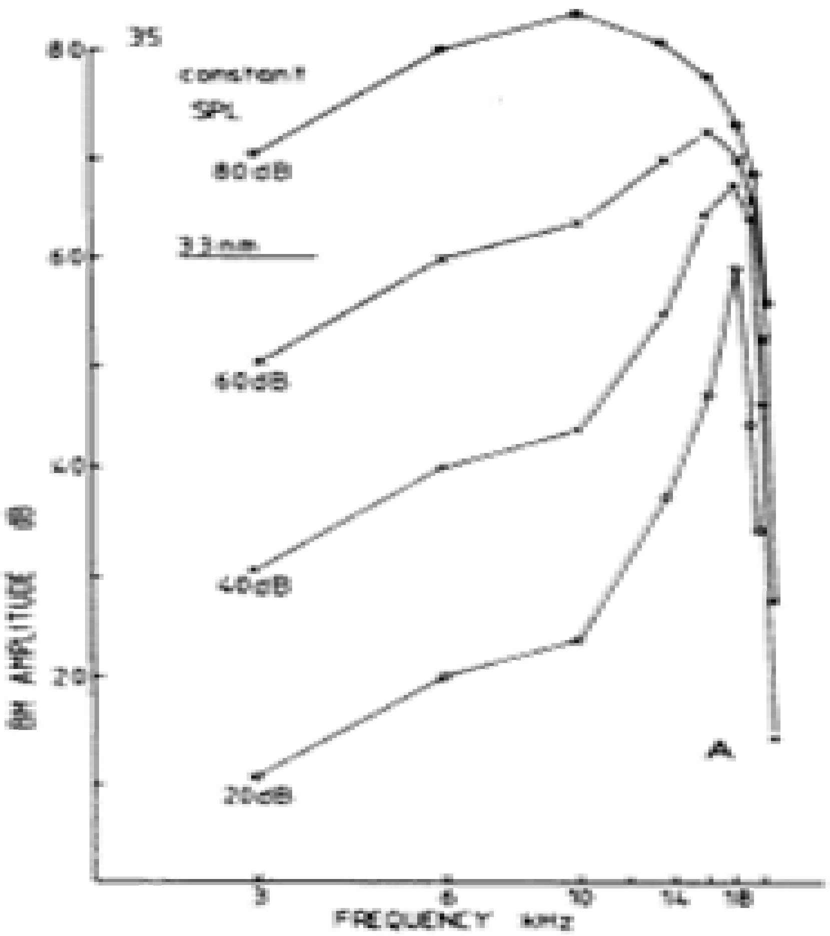
Predicted cochlear frequency response

The displacement at one place on the basilar membrane varies with excitation frequency to give a frequency response.



The frequency response of the passive model is nowhere near as sharp as that observed at low levels in a living cochlea.

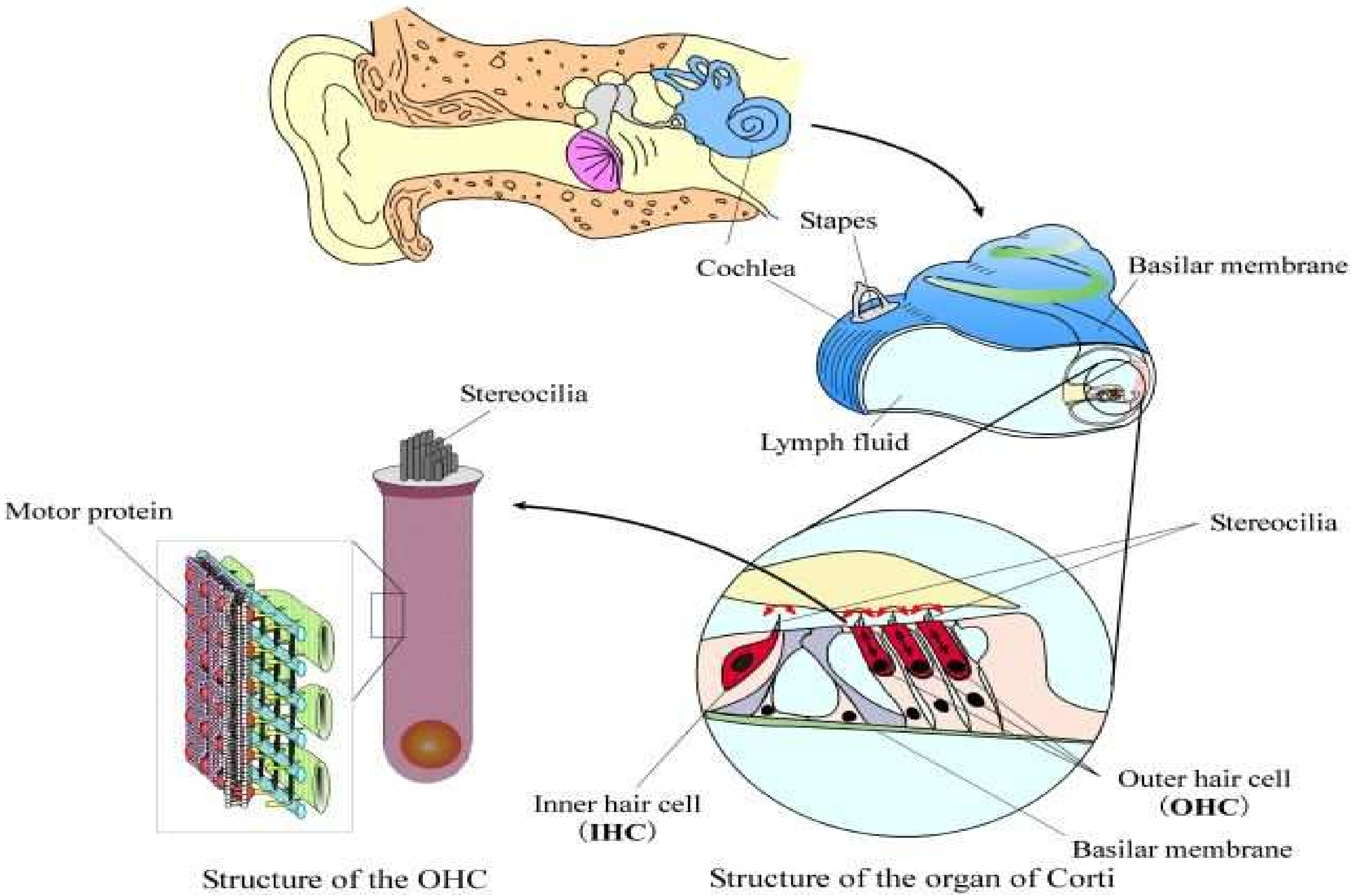
Measured cochlear motion



Level of basilar membrane motion as a function of frequency in response to pure tone pressures at different levels, as measured using the Mossbauer technique by Sellick *et al* (1982)

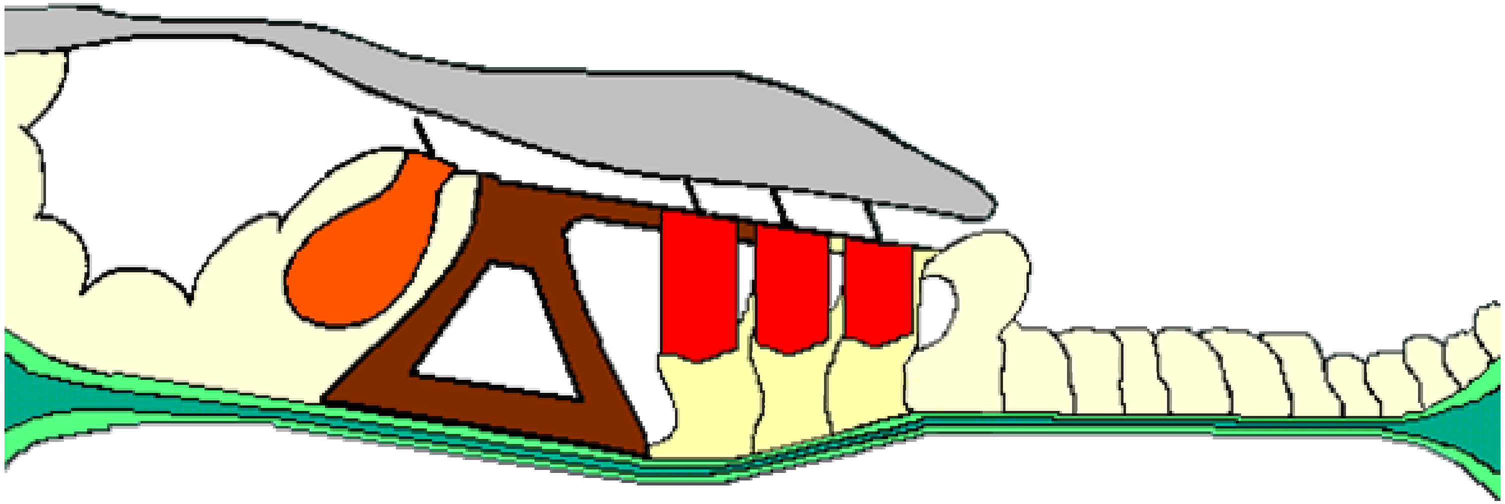
Source of the cochlear amplifier

Note that piezoelectric constant of the motor protein (prestin) is about the same as PVDF



http://www.wadalab.mech.tohoku.ac.jp/contents-e.html

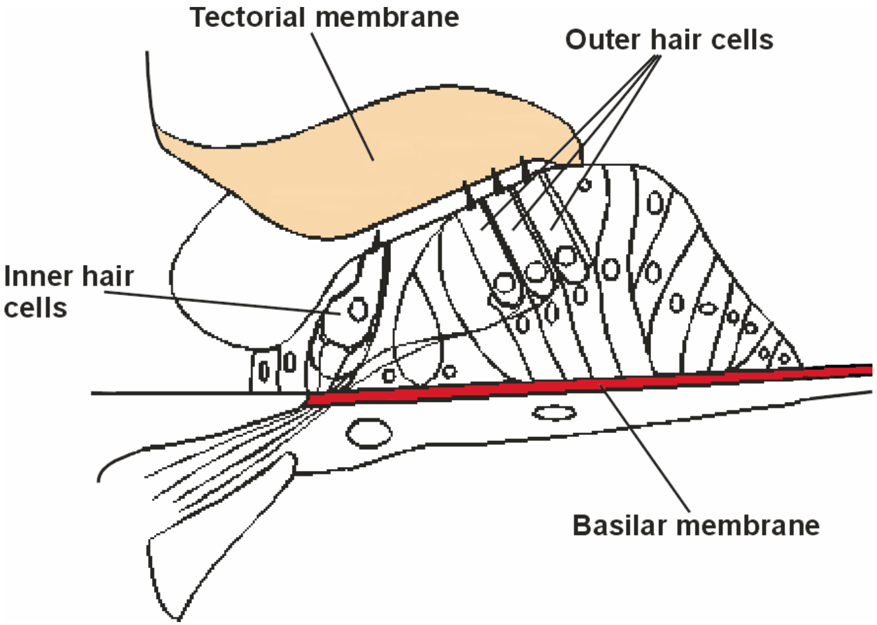
Action of the cochlear amplifier

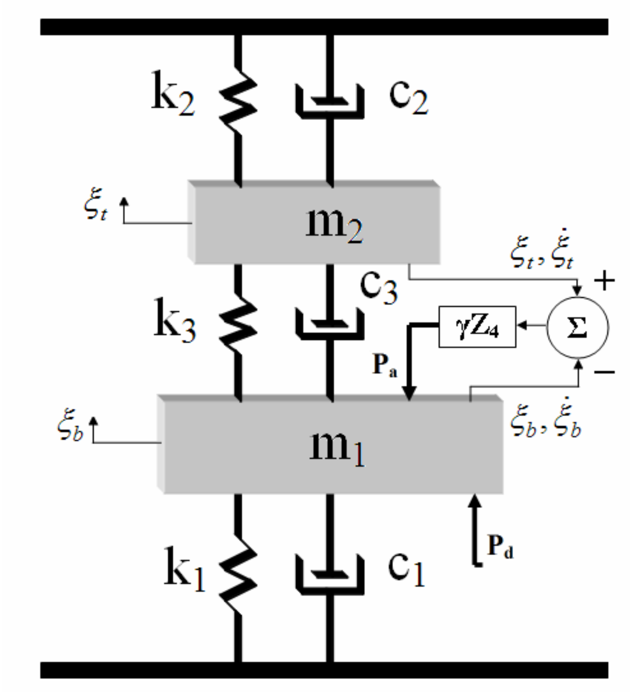


The outer hair cells responding to the shearing of their stereocillia, acting as **local control loops** providing positive feedback to amplify the motion.

Renato Nobili and Fabio Mammano; http://www.vimm.it/cochlea

Widely-used lumped model of the cochlea amplifier





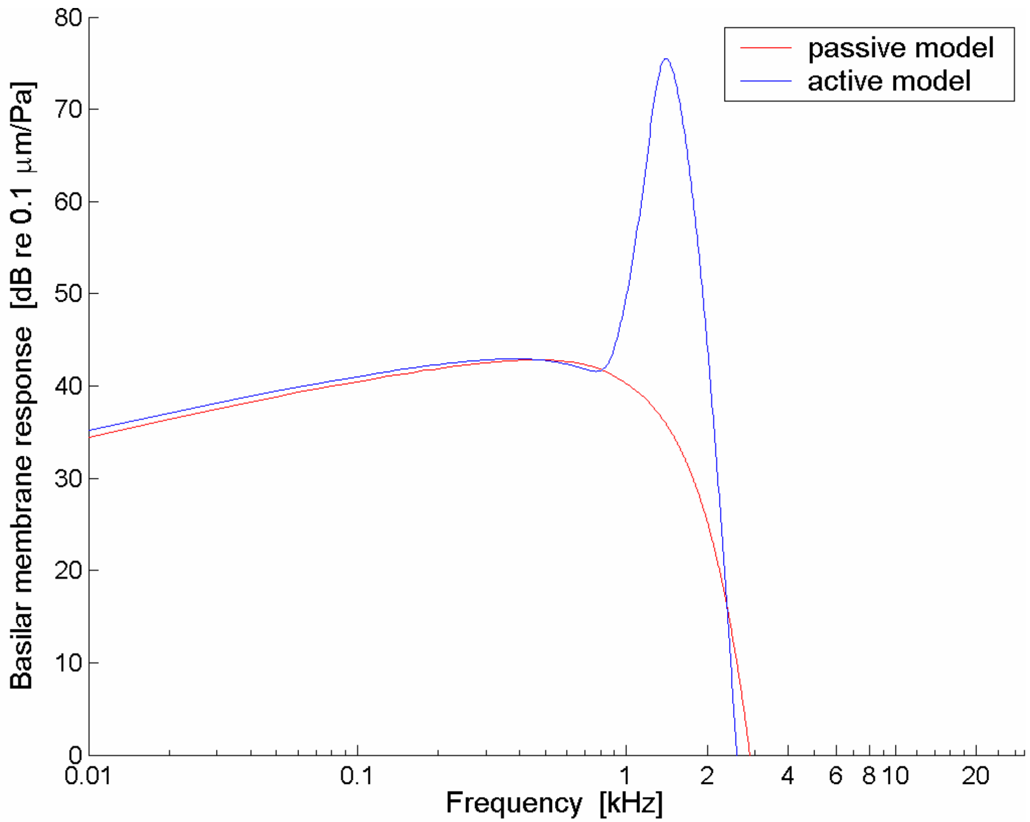
Neely and Kim 2DOF model

Inner hair cells behave as sensors.

Each outer hair cells behaves as sensor, actuators and a local feedback loop.

But, the active force has nothing to react off….

Predicted frequency response of the active basilar membrane



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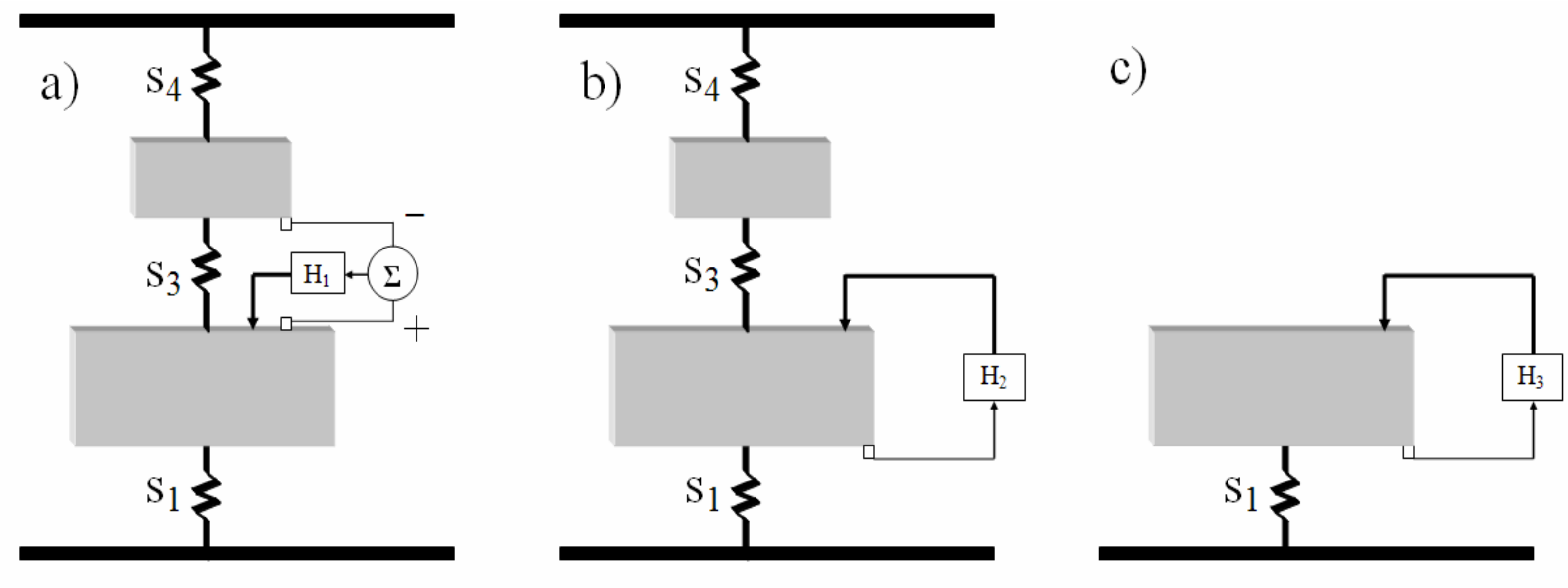
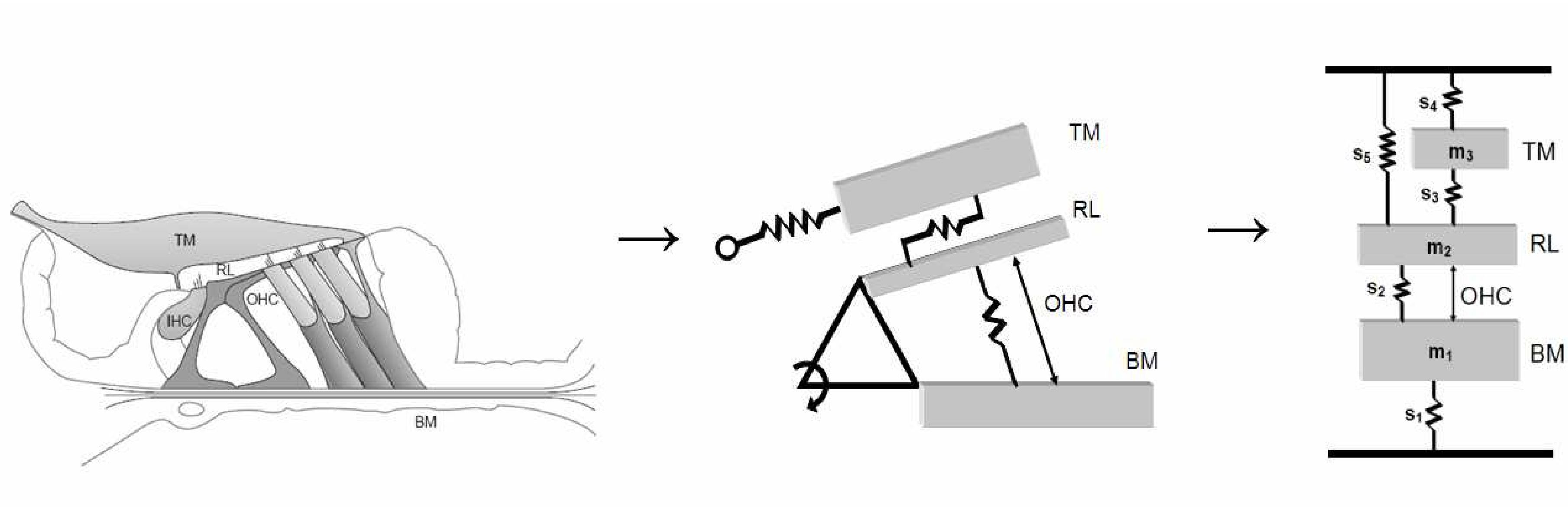
Simplification of the Neely and Kim micromechanical model



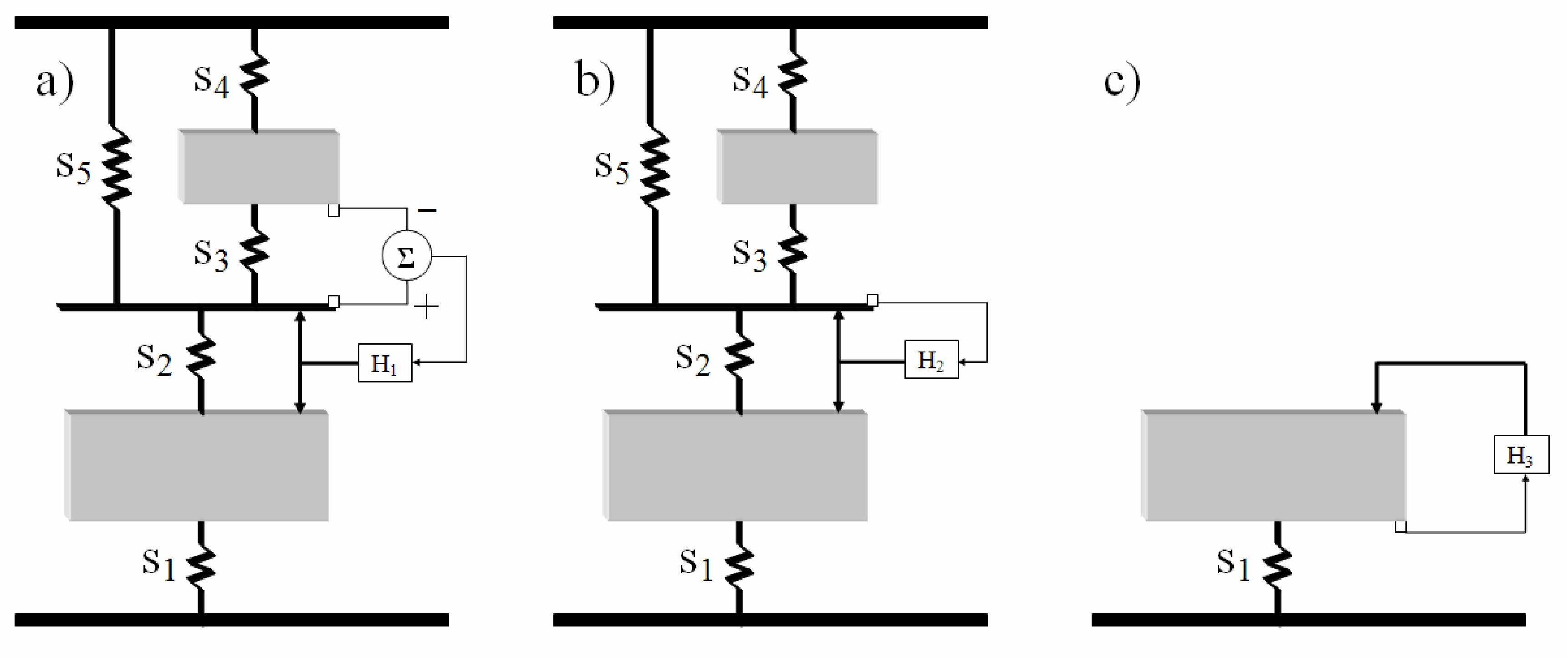
The relative velocity is only driven by the BM velocity, so the feedback loop can again be reduced to a **collocated** system

Derivation of the Reactive Micromechanical model



A 3 DOF lumped parameter model can be used to model the physical action of the cochlear partition. This reduces to a **2DOF** model if the RL mass is assumed to be small.

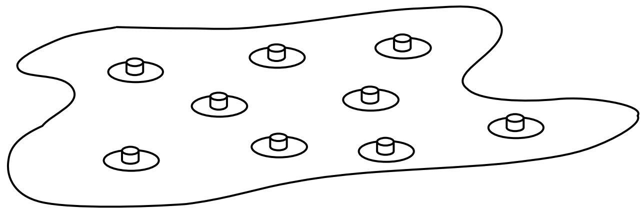
Simplification of the Reactive Model



The feedback loop with the reactive actuation can <u>again</u> be represented by an equivalent **collocated** 1DOF system

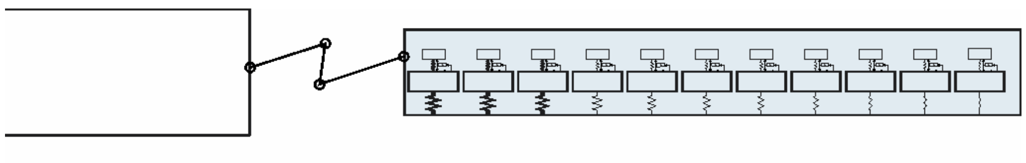
SUMMARY

Local controllers could be implemented for **reducing** the vibration in engineering structures using mass-produced *modules* containing:



An integrated actuator
An integrated collocated sensor
A local negative feedback controller
A local tuning mechanism

Nature appears to use a local control mechanism in the inner ear to ***enhance*** the vibration, thus increasing the ears sensitivity. These feedback mechanisms are distributed, active and nonlinear, but *how they are tuned is not well understood.*



General actuator theory can help understand both problems