Grand Challenge Research – Nonlinear and adaptive mechanical detection

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Sensory systems present some of the most fascinating phenomena in the world around us, for they are examples of nature evolving such exquisite detectors, that they operate at the very limits imposed by the laws of physics. The visual system can detect single photons, the olfactory system individual molecules. Hearing has remained one of the least understood of the senses, particularly at the very first level of processing, that of detection. At the lowest perceptible levels, sound induces movements in the inner ear that are as small as 3Å, comparable to diameters of atoms. Meanwhile, the applied pressures that the ear can withstand cover over a million-fold in the dynamic range. This feat of engineering furthermore operates in a soft, water-immersed, warm medium, namely a living system.

Nonlinear effects have been shown to explain some of the mechanisms behind this spectacular sensitivity and robustness. The inner ear contains hair cells - specialized cells which contain mechanically sensitive ion channels. When these ciliated cells are deflected by sound waves, their ion channels that open and close in response to mechanical forces. Nonlinearities have been demonstrated both in the inner ears of live animals and in the responses of individual hair cells. These nonlinearities compress the dynamic range, thus protecting the cells from damage, and ensure that the lowest levels of incoming sound receive the highest degree of sensitivity.

As with other senses, the auditory system is highly adaptive in response to the environment. If exposed to loud sound for a significant amount of time, one will have noticed the acuity of hearing to have decreased; it then returns to normal levels over time, from a few minutes to half an hour. Adjusting the sensitivity of the inner ear in response to the surroundings is highly important in preventing damage and can occur on several timescales. In individual hair cells, adaptation mechanisms have been identified that operate at timescales of one hundredth to one tenth of a second. Meanwhile, the single-cell counterparts to the longer-term effects experienced behaviorally have not been identified.

The auditory system presents us with a remarkable adaptive nonlinear system. Understanding the details of its mechanism naturally lends itself to an interdisciplinary approach, that requires the use theoretical modeling and quantitative measurement techniques of physics to be combined with biologically functional preparations. The next technological goal is to mimic the biological nano-mechanical detector with an artificial device. As the system is highly complex and not yet fully understood, we believe that the initial bio-mimetic devices should begin with a natural and fully functional biological preparation, and replace one element at a time with artificial components. In this fashion, we will be reverse-engineering the cochlea, but in a manner that varies only one parameter at a time.

The next aim would be to isolate the minimal number of elements that are crucial in the reconstruction of a functional organ, and the main parameters that determine its properties as a detector. Further directions would include construction of individual nonlinear and bistable elements to mimic the mechanics of hair cells. And finally, incorporation of feedback loop into the device would be needed to reproduce adaptive biological behavior.

Current artificial cochleas on the market bypass hair cells entirely and provide electrical stimulation to the auditory nerve fibers. We aim at the construction of an artificial system that would more closely reproduce the behavior of the original biological endorgan. The potential applications of such a device would not be limited to artificial cochlea, but would provide a more general paradigm for highly sensitive and robust mechanical detectors.