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A LIVE DEMONSTRATION OF A BIOMIMETIC COCHLEA DANCING TO MUSIC

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INTRODUCTION

The mammalian cochlea has the impressive ability to convert sound into thousands of independent frequency and amplitude coded neural signals. In this design nature draws from the mechanical interaction of fluids and tissues to generate a traveling wave within the cochlea. For a pure tone the peak amplitude of the wave occurs at a specific location in the cochlea. This traveling wave is further amplified, and the place of maximum response is further tuned, by electro-motility of outer hair cells.

We have constructed a physical model of the cochlea, based on the original work of R. Keolian[1], which demonstrates the cochlear traveling wave and real-time spectrum analysis. The model has been outfitted for visualization of the cochlear response to complex sounds including music and speech. A live demonstration of this model will be presented.

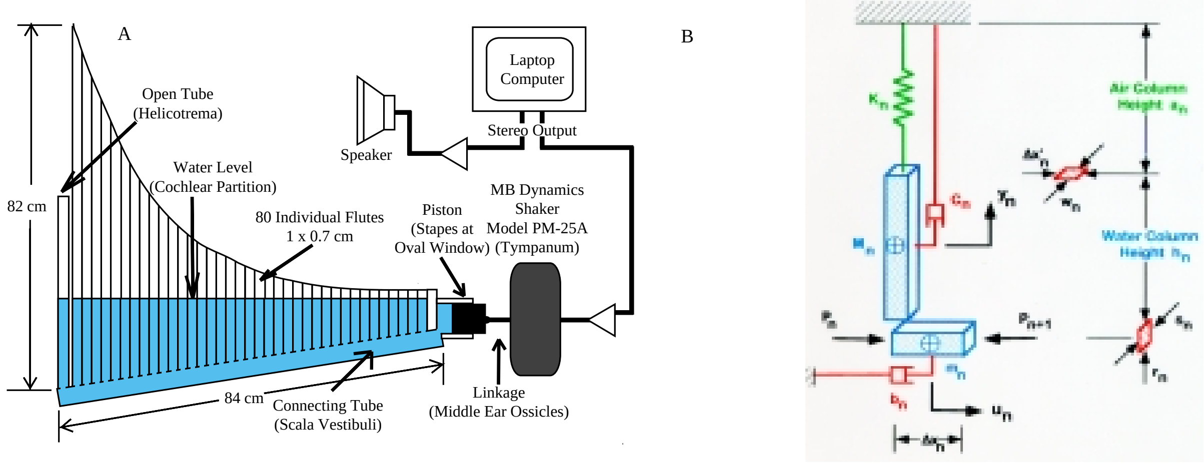

Fig. 1. Physical and Mathematical Models. The physical model is shown in A, and a mathematical model of each flute of the physical model is shown in B.

METHODS

Fig. 1 is a schematic of the physical model. The biomimetic apparatus consists of 80 slender tubes (cochlear partition) interconnected on the bottom by a water-filled tube (scala vestibuli) and individually sealed at the top. The water fills only the bottom portion of each tube -- the top portion is filled with air. This simulates the position dependent mass, stiffness and best frequency of the cochlear partition. A piston (stapes at the oval window), actuated by an electromagnetic shaker (eardrum), drives the fluid in the bottom tube (perilymph in the scala vestibuli). The water mass in each tube increases, and the air column stiffness decreases, as the distance from the piston is increased. This simulates the morphology of the mammalian cochlea.

The physical model admits traveling waves from ~5-80 Hz, which is a much lower frequency range than normal sound stimuli. In order to play music and speech into the model, we shifted the spectra of the sound down to a level appropriate for the model (~1/40). The frequency-shifted signal is played into the model in temporal synchrony with the original sound. This was done in short-time discrete segments isolated from the sound by a sliding Hanning window. We also applied a compressive nonlinearity to amplify low level sounds relative to high level sounds.

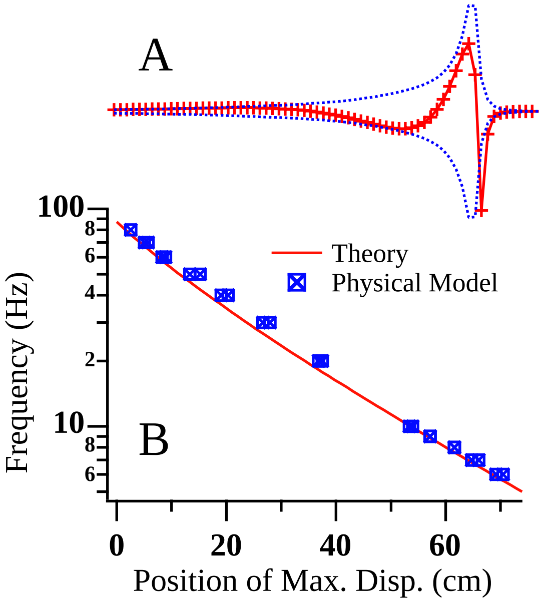

Fig. 2. Theory vs. Experiment. The traveling wave is shown in A and the best frequency as a function of position in B.

RESULTS AND DISCUSSION

Fig. 2 shows results of a mathematical model predicting the traveling wave (A) and the place of maximal response to pure tones (B) in the physical model of the cochlea. Results are for the simple lumped parameter model illustrated in Fig. 1 B. The model equations treat the water in the physical model as incompressible and Newtonian. The bulk modulus of the air located in the top part of each of the flutes was combined with the geometry to determine the effective stiffness acting on the fluid surface. The resulting second order differential equations describing the dynamics of each discrete mass were then coupled together using conservation of mass. The traveling wave and the position of best frequency predicted by the mathematical model correspond well with experimental observations in the biomimetic device.

Music played into the physical model demonstrates the complex response of the cochlear partition. The most interesting responses are obtained when music is digitally recorded in stereo, processed and replayed. One channel is frequency shifted and played into the model while the other channel is played without modification. This allows the observer to see the motion of the cochlear partition in synchrony with hearing the original sound. Shifting the spectra causes an unrecoverable loss of information; nevertheless a plethora of sound-correlated activity is clearly observed in the physical model.

It is also interesting to observe the influence of the compressive nonlinearity. Outer hair cells in the living cochlea serve to amplify low level components of the sound (<~65dB) without altering high level components. Since the physical model is a passive mechanical device it does not have this capability. In a sense, the physical model can be viewed as a hearing impaired individual that has lost the nonlinear amplification offered by the outer hair cells. To compensate for this we apply a compressive nonlinearity to the sound prior to playing it into the model. This attempts to compensate for the missing hair cells. In other words, the hearing impaired physical model has been fitted with a modern nonlinear hearing aid. This processing amplifies low-level sounds, thus making motion of the cochlear partition visible in many regions of the model that would otherwise be silent.

The physical model provides a visual demonstration of real-time signal processing carried out by the mammalian cochlea. It is particularly well suited to demonstrate the place principle, parallel processing, influence of the outer hair cells, and information content of auditory signals.

ACKNOWLEDGMENTS

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REFERENCES

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