Coiled Hydromechanical Scale Model of the Inner Ear

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Abstract. A new type of hydromechanical cochlear model is described. Both straight and coiled models have been produced, with the goal of examining differences in wave motion in the two geometries experimentally. The single duct system is fabricated using a novel, low cost, flexible manufacturing approach based on computer controlled laser cutting, thermal shrink films, and bonding. Steady state vibration patterns were observed using laser vibrometry. Forward traveling waves are observed for all frequencies. At high frequencies, more complex vibration patterns appear including higher order crossmodes, backward traveling waves, and standing waves. The coiled model exhibits more asymmetry in the structural vibration shape in the radial (cross-duct) direction than the straight model.

Keywords: hydromechanical cochlear model, cochlear modeling, coiling
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INTRODUCTION

The hydromechanical model described here is targeted at two goals. First, we are interested in demonstrating a high dynamic range, high sensitivity acoustic sensing system based on inner ear mechanics. Production of such an engineered system has been attempted in the past (e.g. [2-4, 8, 11, 12]), but many issues remain. The work described here is a step towards creating a flexible manufacturing process and mechanical structure which could be used in such a system. Second, we are interested in investigating open questions in inner ear wave mechanics and feedback control through the use of a physical model. The particular system described in this paper is a scale model of the inner ear with a duct length approximately three times that of the human cochlea. Both straight and coiled models have been produced, allowing comparison of the traveling wave mechanics observed in the two geometries. The choice to study coiling in a model was motivated by the recent work of Manoussaki, Chadwick, Cai and Dimitridas [1, 6, 7]. In these three papers, they suggest from mathematical models that cochlear coiling may result in an asymme-

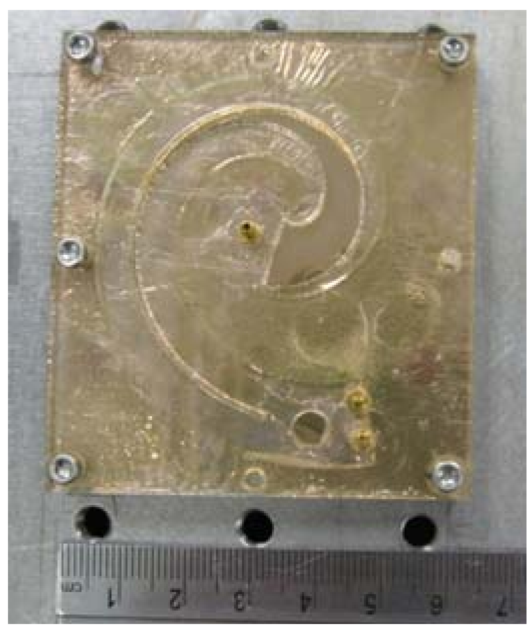

FIGURE 1. Photograph of the coiled model.

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try of the traveling wave, which could increase the sensitivity of the organ, particularly at low frequencies. This result is at odds with some previous papers which suggested that coiling did not have a major impact on the mechanics of the traveling wave on the basilar membrane [5, 9, 10].

METHODS

The single duct system, shown in 1, was fabricated using a novel, low cost, flexible manufacturing approach. In contrast to previous hydromechanical models (e.g. [2-4,8,11,12]), which were manufactured using micromachining methods or computer numerically controlled machining, the current system is fabricated from cast acrylic using high speed, precision laser cutting. This allows rapid production of complex two dimensional geometries, including coiling, at low cost. The cochlear partition was created using thermal shrink polyethylene film with a thickness of 2.5 microns. Curing time and temperature were optimized to produce the desired tension. The structure was bonded together with a spray adhesive and mechanical hardware. After assembly, the film was sputtered with 30 nm of gold to improve reflectivity. Fluidic hardware was attached mechanically and the duct was filled with silicone oil at a viscosity of 500 cSt. The viscosity may be tuned to adjust damping in the system. The fluid chamber behind the membrane is 13.8 mm wide and 2.9 mm deep.

The film tension was characterized using a MEMS force sensor as shown in Fig. 2. The small displacement linear stiffness was used to determine the as-assembled partition tension. For the results shown here, the membrane tension is 12 N/m, measured in the final assembled, fluid filled, and sealed configuration.

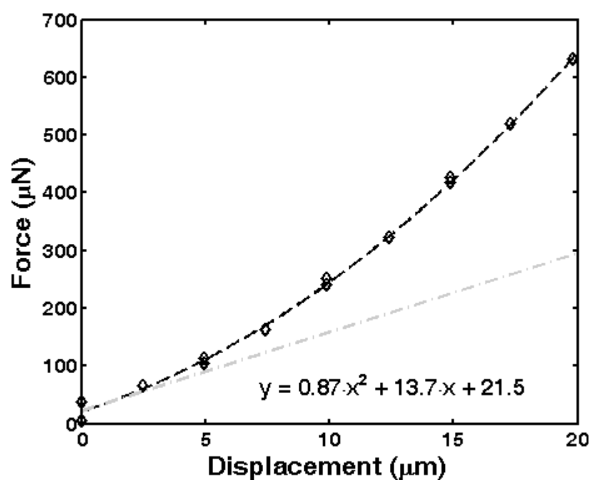

FIGURE 2. Point stiffness measurement and curve fit.

The centerline of the membrane and duct for the spiral model was a logarithmic spiral with a total angular extent of 2π radians. The radius of curvature at the apex (wide end) of the membrane was 6.54 mm. The radius of curvature at the base (narrow end) of the membrane was 31.5 mm. The total length for the centerline in both the spiral and straight model was 10 cm. For both models, the width of the membrane grows exponentially from 0.8 mm at the base to 10.4 mm at the apex.

Laser vibrometry testing was carried out with the model mounted to an optical table. A pure tone driving pressure was presented to the input port at a series of frequencies from 50 Hz to 5 kHz. The input port is a circular membrane, visible in Fig. 1, located just past the base. The pressure was delivered by a 2 inch diameter speaker mounted inside an ABS plastic box. The ABS plastic box completely enclosed the speaker, providing between 20 and 40 dB of transmission loss. Thus, the majority, although not all, of the acoustic excitation enters the system through

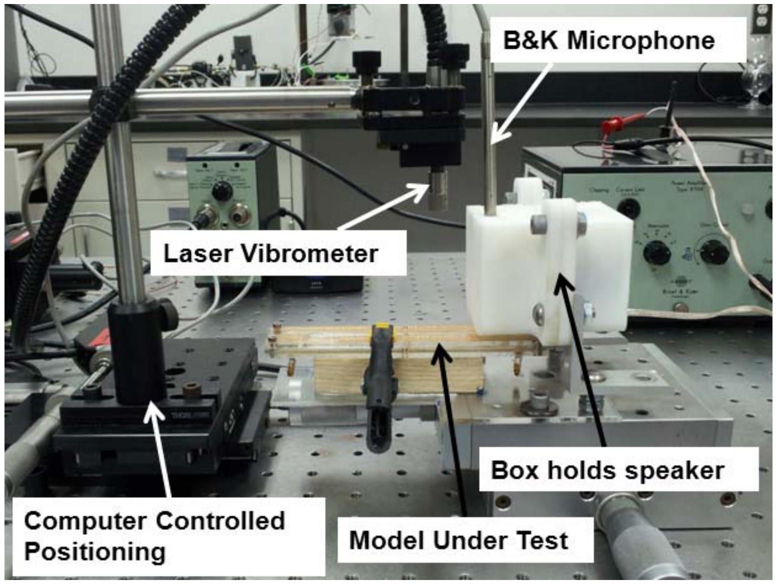

FIGURE 3. Experimental setup for laser vibrometry measurements.

the input membrane rather than impinging directly on the tapered membrane. The drive pressure was recorded inside the box using a Bruel and Kjaer ¼" microphone. A Polytec single point fiber optic vibrometer was used to capture steady state membrane magnitude and phase relative to the drive pressure. Computer control of a micropositioning stage allowed the vibrometer to scan over the membrane in a raster pattern, recording the vibration magnitude and phase over a grid of points covering the membrane. The experimental setup is shown in Fig. 3.

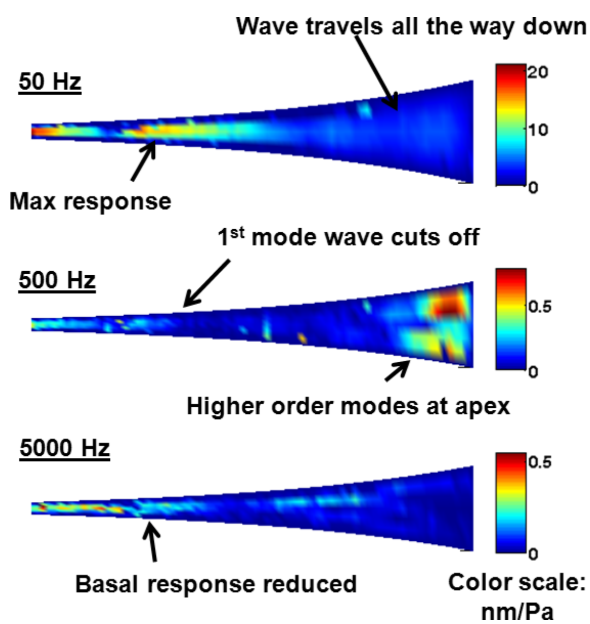

FIGURE 4. Vibration response for the straight model.

RESULTS

Figure 4 shows the vibration magnitude patterns for the straight model at 3 driving frequencies. A traveling wave is observed at all three frequencies. At 50 Hz, the wave travels all the way down to the apex (wide end) of the structure with a first crossmode. The maximum response is seen about halfway down, as noted in Fig. 4. At 500 Hz a similar type of response is seen, with the exception that a strong second duct crossmode

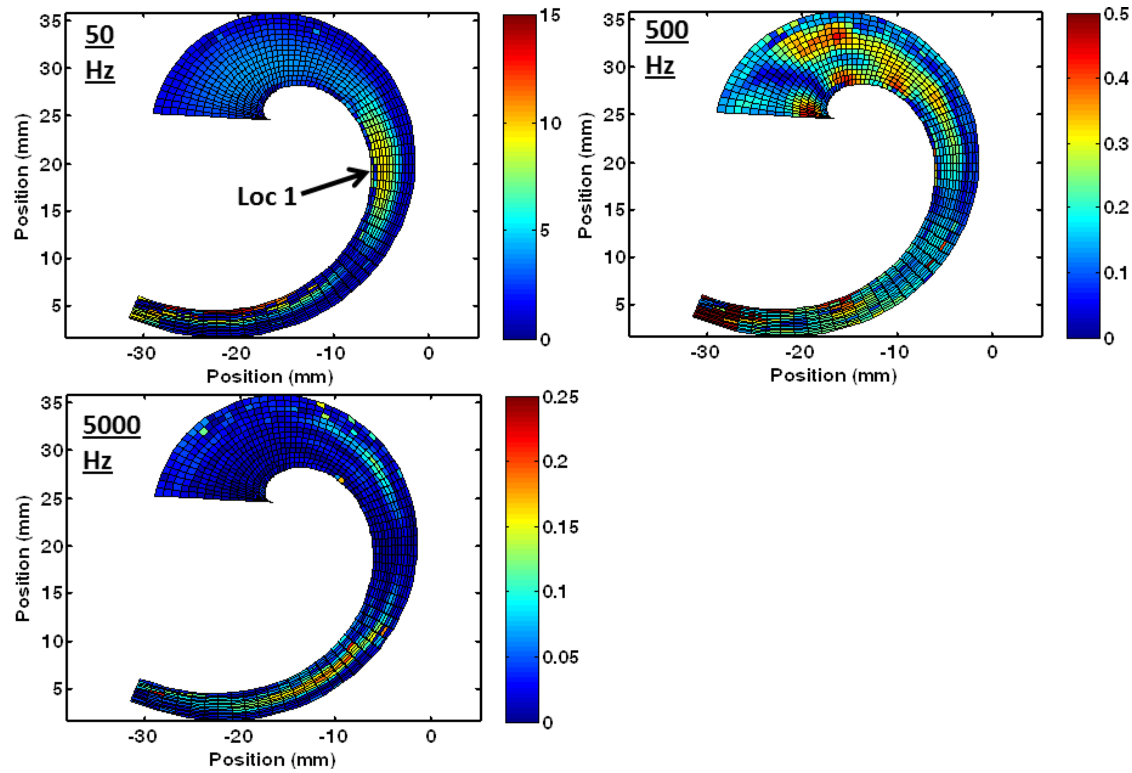

FIGURE 5. Vibration magnitude response for the coiled model. Color bar is in nm/Pa.

appears at the wide end. At 5 kHz, the wave cuts off at a more basal location (narrow end) and less vibration is seen at the apex (wide end) of the structure. Strong reflections, standing waves, or backward traveling waves are not seen at any frequency. The point of maximum response seen in the 50 Hz case is also seen at other frequencies between 50 Hz and 500 Hz (not shown) and may indicate a defect or point of low tension in the membrane.

Figure 5 shows the vibration magnitude for the spiral shaped model at the same three driving frequencies. For this model, traveling waves are again seen at all frequencies. At 50 Hz the traveling wave shows a peak magnitude about halfway down the spiral on the inner wall (labeled "Loc 1"). At 500 Hz, a very complicated pattern of mixed traveling and standing waves is seen, including backward traveling waves and higher order crossmodes, particularly at the apex (wide end). At 5 kHz, the wave motion is seen to cut off closer to the base (narrow end) and less vibration is seen at the apex of the device.

Both the straight and coiled models exhibit traveling waves, locations with larger vibrational amplitude, and higher order cross modes at high frequencies. However, the coiled model shows more asymmetry in the cross-mode shape, even at low frequencies. In addition, the coiled model shows significantly more complexity in the mid frequency range with combinations of asymmetric backward traveling waves, stranding waves, and forward traveling waves.

CONCLUSIONS

This paper presents the first coiled physical model of the cochlea. A low cost rapid manufacturing process for single duct physical cochlear models was presented. Vibration patterns can be complex. Traveling waves are present, but they have a very long wavelength (on the order of the length of the device). High frequency traveling waves are observed to cut off, but no strong tonotopic organization is observed. Greater asymmetry of the traveling waves and greater complexity was observed in the coiled model. It is difficult to know whether these observations are due to the coiled geometry or to variability in the membrane tension. Membrane tension was only measured at a single point in one model. Additional work needs to be done to map the membrane tension over the entire structure in both models. In addition, a two duct, rather than single duct system, would be a better model of the inner ear. Additional work needs to be done to investigate scaling laws, as well as numerical or analytical models of this structure. It would also be interesting to consider adding a middle ear, distributed active structures, or additional structures which could be analogous to the tectorial membrane or other cochlear microstructures, although this is not trivial.

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COMMENTS AND DISCUSSION

Christopher Shera: Are the measurements in Fig. 2 at a particular location along the spiral? Does the stiffness of the membrane vary with location? What is the significance of the fact that the force-displacement curve has a non-zero intercept (21.5 μN at $x = 0$)? Are the uncertainties large at small x?

Should the curve be constrained to pass through the origin?

Reply: The stiffness measurement shown in the figure is for a single location close to the basal end of the device. It seems likely that tension in the membrane could be nonuniform; this is a major concern as it will have significant impacts on vibration patterns. Additional measurements of the map of membrane tension at different locations are needed. In addition, I think it would be very valuable to be able to modify the tension at different locations in order to "tune" the device—much like one would tune a musical instrument.

The non-zero force at zero deflection is due either to hysterisis in the deflection curve or DC drift in the measurement electronics. Note that the initial measurement point is at zero (diamond symbol) but that after traveling to large deflections and then coming back to zero deflection, the force does not reduce all the way to zero (it appears to be about 40 μN).

Johannes Baumgart: It is nice to see a traveling wave in your model. I am a little bit concerned that fluid motion normal to the elastic membrane might be significantly lower than in longitudinal direction. This might explain your additional motion well behind the best frequency location and the higher amplitude towards the inner radius. The latter might be physical if the fluid flow is dominated by inertia and not viscosity. For such a potential flow the fluid motion is indeed higher at the inner radius if the membrane motion is negligible.

Reply: The motions were complex and nonuniform. At high frequencies, the traveling wave was observed to cut off and not travel all the way to the apex. At intermediate frequencies multiple cross-modes, reflected waves, traveling and standing waves were all observed.

The suggestion to use a potential flow model is a good one. Additional modeling needs to be performed. Options include thin film fluid models as well as more three dimensional models. Previous work by our group describes numerical approaches we have used in the past [12, also Cheng et al. 2008 Comput Methods Appl Mech Eng 197:4160-4172].