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EXPERIMENTAL INVESTIGATION OF A HYDROMECHANICAL SCALE MODEL OF THE GERBIL COCHLEA

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ABSTRACT

In this research, an uncoiled scale gerbil cochlea is designed and fabricated. The cochlea model is an uncoiled, 16 times scale model of the real gerbil cochlea and has only one duct. Both the basilar membrane width and the duct size vary along the length of the device, in analogy to the physiology. The cochlea duct is filled with silicone oil and driven by a modal exciter (shaker) at different frequencies. The movement of the basilar membrane is measured using laser vibrometry at different locations along the basilar membrane. The ratio of the basilar membrane velocity to drive velocity is computed and plotted. The characteristic frequency of the model varies from 7000 Hz at 2 cm from the base of the cochlea to 350 Hz at the 15 cm from the base. Two different viscosities silicone oil, 20 cSt and 500 cSt are used for the basilar membrane movement measurements. A WKB method is applied to the calculation of the basilar membrane movement of the scale cochlea model, in which the fluid motion is fully three dimensional.

INTRODUCTION

In mammals, Sound waves are collected by the outer ear and are funneled through the ear canal to the eardrum. Sound waves cause the eardrum to vibrate. The three bones in the middle ear transmit and amplify the vibrations to the oval window of the inner ear. These vibrations produce traveling waves in the cochlea duct and cause the movement of the basilar membrane (BM). As they travel, waves grow in amplitude, reaching a maximum and dying out. The location of the maximum BM displacement is a function of the stimulus frequency, with high frequency waves being localized to the base of the cochlea and low frequency waves to the apex of the cochlea. Thus each cochlea location has a characteristic frequency (CF), to which it responds with maximum displacement.

The response of the cochlea to vibratory stimulation has been described in great detail in [1]. The fluid motion in the cochlea models were investigated by [2] and many other researchers have been studying the pattern of traveling waves [3–5]. A number of researchers have reported sacled-up hydromechanical models of simplified one- or two-duct cochlear models. Helle [6] built one small model of length *200 mm* with constant duct height and varying basilar membrane plate dimensions. This model showed frequency-position mapping over *212-848 Hz* band and the maximum phase accumulation of 10π radians. Cannell [7] constructed and experimented with a number of models of varying size and taper. The author showed frequency-position mapping over *25-800 Hz* band and maximum phase accumulation of 4π radians. Chadwick and Adler [8] built a *630 mm* long cochlear model with constant dimensions. The model uses isotropic beams to represent BM. In Lechner's model [9], basilar membrane is made of rubber. The rubber membrane is istropic with varying width and includes PVDF actuators. The author demonstrated mapping over *40-400 Hz* band and phase accumulation of up to 18π radians. The model showed sharpening with active feedback.

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However, the quantified material properties were not available for the basilar membrane, which greatly affect the response of the cochlea to vibratory stimulation and mapping of the characteristic frequencies. The physical models used to investigate the cochlear vibration usually use plastics or rubbers to substitute basilar membrane. Due to the available quantified material properties of gerbil basilar membrane recently [10], it is possible to use a scale physical gerbil cochlear model to investigate the traveling wave patterns which is similitude to those of the real gerbil cochlea by means of *scaling law* and the mapping of the characteristic frequencies.

In this paper, we focus on the design and fabrication of a *16* times scale gerbil cochlea model and measurements of the cochlea response at different locations to a sweep sinusoidal stimulation. The experimental results are compared with mathematical results derived using WKB method. Two boundary conditions are investigated using WKB method to accommodate the possible boundary conditions for the physical model. The results show that the experimental results of the scale hydromechanical gerbil model agree with the WKB results and thus verify the reliability of the cochlear model. With this cochlear model, the future study will investigate the traveling wave patterns and the mapping of the characteristic frequencies of the gerbil cochlea through *scaling law* using gerbil basilar membrane material properties.

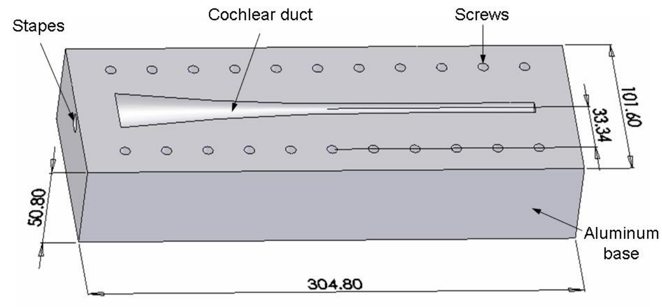

Figure 1. COCHLEAR DUCT AND IT'S BASE.

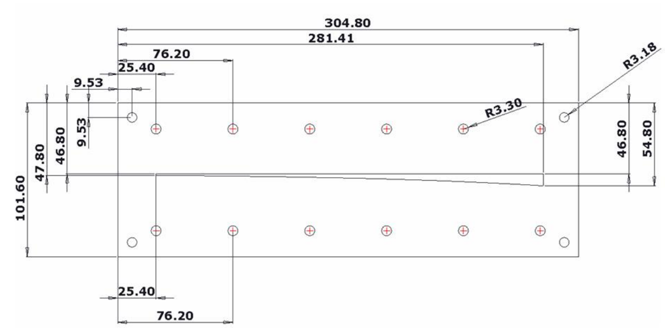

Figure 2. COCHLEAR MEMBRANE AND IT'S SUPERSTRUCTURE.

MODEL

Physical Model

This physical cochlear model is intended to represent the passive cochlear dynamics. No active elements are included in the structure. The *16* times scaled-up cochlear model has one duct. The cochlear duct is built on a aluminum base as show in Fig. 1. The duct's height and width vary with the its length. A plastic thin film made of Polyoxymethylene (Delrin, DuPont) is used to represent basilar membrane. A clear plastic plate made of cast acrylic has an open slot whose width changes exponentially along its length. The plate represents spiral lamina and spiral ligament of cochlea. The open slot is where the basilar membrane is and it allows the membrane move out of plane. The plate structure and dimensions are shown in Fig. 2. The Delrin membrane is sandwiched between two acrylic plates and they are fixed in place to an aluminum base with an aluminum cover on them using many screws. A rectangular rubber strip is placed between the aluminum base and the acrylic plate to seal the cochlear model from leaking. A piece of rubber is attached and fixed to the left plane of the aluminum base where there is small hole represents oval window of the cochlea. A screw with hemisphere head which represents Stapes of the middle ear is used as the drive mechanism. All the dimensions in the figures are millimeters. A photograph of the cochlear model and shaker set up is shown in Fig. 3.

All the physical parameters used in this analysis listed in Table. 1.

Mathematical Model

Mathematical model and results are used to compare with the experimental results. The mathematical method implemented in the cochlear model is Wentzel-Kramers-Brillouin(WKB) method. The WKB theory is a method for approximating the solution of a differential equation of the form $\frac{d^2y}{dx^2} + f(x)y = 0$, where $f(x)$ is slowly varying with respect of the solution. The WKB asymptotic method applied to the calculation of cochlear model is derived by Steele and Taber, in which the fluid motion is fully three dimensional [11]. The fundamental mechanism of the cochlea is due to the geometric and physiologic variation which occurs with the distance from the Stapes. In the typical mammalian cochlea, this variation is quite slow. Thus the WKB asymptotic method is well suited for the treatment of this problem. The basic idea behind the WKB method is that when the wavelengths are sufficiently short, the properties can be taken as constant over the space of a wavelength. The basilar membrane was treated as a plate in [11], and the plate deflection is approxi-

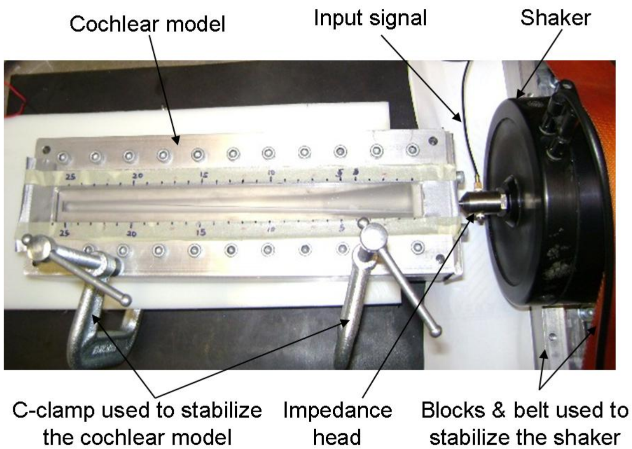

Figure 3. COCHLEAR MODEL AND SHAKER SETUP.

mated as

$$w(x,y,t) = W(x)\eta(x,y)e^{i(\omega t - \int_0^x \lambda(x)dx)} \quad (1)$$

where the spatial variation of the solution in x has been expressed as the product of slowly varying envelope function, *W(x)*, and the oscillatory function, $e^{-i\int_0^x \lambda(x)dx}$. The plate cross-mode shape is a function of x. For simply supported edges,

$$\eta(x,y) = \sin(\pi y/b(x)) \quad (2)$$

For clamped edges,

$$\eta(x,y) = \sin^2(\pi y/b(x)) \quad (3)$$

$\lambda(x)$ is the wave number varying with x. It is solved through "eikonal" equation

$$F(\lambda,\omega) = \frac{1}{4}\omega^2(2\rho_f H_e q(\lambda) + \rho_p h) - K(1+id_E)\Gamma(\lambda) = 0 \quad (4)$$

Where ρ_f, ρ_p are the fluid and plate density respectively, h is the thickness of the basilar membrane, d_E is the hysteretic damping accounting to the viscoelastic basilar membrane property, $H_{eq}(\lambda)$ is the equivalent fluid thickness related to structure and fluid mode shapes, cochlear dimensions and material properties,

Table 1. PARAMETERS OF THE COCHLEAR MODEL.

Parameter	Value	Note
E_p	$2.5x10^9 Pa$	plate modulus
μ	$20/500cSt$	fluid viscosity
d_e	0.01	hysteretic damping
ρ_p	$1384kg/m^3$	plate density
ρ_f	$950kg/m^3$	fluid density
υ	0.35	Poisson's ratio
l	$0.256m$	plate length
h	$76x10^{-6}m$	plate height
$b(x)$	$b(0)e^{\frac{x}{l}\ln(\frac{b(0)}{b(l)})}m$	plate width
$L_1(x)$	$L_1(0) = 0.03m$	duct width
——	$L_1(\frac{4}{l}) = 0.0145m$	$L_1(x)$ linearly varying with x
——	$L_1(l) = 0.0082m$	between these three points
$L_2(x)$	$L_2(0) = 0.011m$	duct height
——	$L_2(\frac{4}{l}) = 0.0056m$	$L_2(x)$ linearly varying with x
——	$L_2(l) = 0.0082m$	between these three points
A_{st}	$5.518x10^-5m^2$	Stapes area

$$H_{eq} = (\int_0^b \eta^2(y)dy)^{-1} \\ \text{x} \sum_{j=0}^{\infty}(\frac{A_j^2}{m_j L_1(tanh(m_j L_2) - m_j\beta_j^{-1})})\text{x}\begin{cases}1 & j=0\\ 2 & j=1,2,..\end{cases} \quad (5)$$

Where A_j is the integration of structural mode shapes with fluid mode shapes,

$$A_j = \int_0^b \eta^2(y)cos(j\pi y/L_1)dy \quad (6)$$

$$m_j = \sqrt{(j\pi/L_1)^2 + \lambda^2} \quad (7)$$

$$\beta_j = \sqrt{(m_j)^2 + i\rho_f\omega/\mu} \quad (8)$$

K is the stiffness of the Basilar membrane,

$$K = \begin{cases} \frac{\pi^6 D}{8b^5} & \text{for simply supported edges} \\ \frac{8\pi^4 D}{b^5} & \text{for clamped edges} \end{cases} \quad (9)$$

Where D is the bending stiffness of the plate.

Γ is a function of the plate width,

$$\Gamma = \begin{cases} \frac{2b}{\pi^2}[1+(\frac{\lambda b}{\pi})^2]^2 & \text{for simply supported edges} \\ \frac{b}{6}[1+\frac{1}{2}(\frac{\lambda b}{\pi})^2+\frac{3}{16}(\frac{\lambda b}{\pi})^4] & \text{for clamped edges} \end{cases} \quad (10)$$

$W(x)$ is solved by "transport" equation

$$W(x) = C(\frac{\partial F(\lambda,\omega)}{\partial \lambda} b(x))^{-\frac{1}{2}} \quad (11)$$

where C is a constant.

It is convenient to normalize the plate amplitude with respect to that of the Stapes. The ratio of the plate to the Stapes amplitude at the center of the basilar membrane cross section along x direction is

$$\begin{aligned} \frac{W(x,\frac{L_1}{2},t)}{\delta_s t} &= \frac{W(x)e^{i(\omega t - \int_0^x \lambda(x)dx)}}{-i(A_0 w(x)/\lambda A_{st})_{x=0} e^{i\omega t}} \\ &= A_{st}(\frac{\lambda}{A_0})_{x=0}[\frac{(b(x)\frac{\partial F(\lambda,\omega)}{\partial \lambda})_{x=0}}{(b(x)\frac{\partial F(\lambda,\omega)}{\partial \lambda})}]^{\frac{1}{2}} e^{i\phi-\zeta} \end{aligned} \quad (12)$$

where A_{st} is the Stapes area, A_0 is A_j when $j=0$, the phase is from the real part of the λ

$$\phi = \frac{\pi}{2} - \int_0^x Re(\lambda)dx \quad (13)$$

and the damping factor is from the imaginary part of λ

$$\zeta = -\int_0^x Im(\lambda)dx \quad (14)$$

From Eqn. (12), the displacement ratio of the basilar membrane to Stapes at different location under different frequency stimuli can be computed. The results can be used to compare with the experimental results.

Scaling Law

The gerbil cochlea dimensions are very small. The width of the basilar membrane close to the Stapes is about *0.1 mm* and *0.3 mm* at the apex of the cochlea and the length of the uncoiled basilar membrane is about *11 mm*. It is difficult to carry out the experiments with dimensions as small as these. A feasible way to have the experimental observation is to enlarge the dimensions of the cochlea in the prototype model without distort the motion phenomena when the cochlea model is subject to the same stimuli as those to the gerbil cochlea. The conditions necessary to obtain the similarity of the cochlea model and the gerbil cochlea are constrained by the *scaling law*, which is derived through dimensional analysis with *Buckingham Pi theorem*.

If all of the dimensions of the cochlear model are proportional to the gerbil cochlea, *i.e.*, based on one length l, for instance, the length of the basilar membrane, if all the other dimensions can be expressed as the ratio to l, and the ratios of the cochlear model are the same as those of the gerbil cochlea, then these two cochlear models will themselves be alike. Also despite the change in length by some factor, the equation of motion remails the same and their motions will be similar. The movement of the basilar membrane and the fluid in the cochlear duct is determined by some constants: the density ρ and viscosity η of the fluid, the stimuli frequency f, and the elasticity of the membrane E. The elasticity can be expressed as the volume compliance ε, which is the volume displacement of the membrane per unit of length when a unit pressure is applied to one side. The constant ε has the dimensions $\varepsilon = volume/(length * pressure) = kg^{-1}m^3s^2$, where *kg,m,s* are the units for mass, length and time respectively.

The motion equation can be expressed in the form $\phi(l,\rho,\eta,f,\varepsilon) = 0$. According to the *Buckingham Pi theorem*, given a relation among 5 parameters of the form $\phi(l,\rho,\eta,f,\varepsilon) = 0$, the 5 parameters can be grouped into 2 independent dimensionless ratios expressible in functional form by

$$\Phi(\frac{\rho f l^2}{\eta}, \frac{\eta^2 \varepsilon}{\rho l^4}) = 0 \quad (15)$$

If the 5 constant parameters are chosen in a way that as we go from gerbil cochlea to the cochlear model, $\frac{\rho f l^2}{\eta}$, $\frac{\eta^2 \varepsilon}{\rho l^4}$ remain same, then the equation of motion is the same and the movements of the both models are alike. The basilar membrane length l is chosen to be 16 times of that gerbil basilar membrane length. The fluid density ρ and viscosity η, the stimuli frequency f can be chosen to make $\frac{\rho f l^2}{\eta}$ constant. The volume compliance is a function of membrane width w and height h. Once the height of cochlear model membrane is chosen, by varying the width of the membrane, we will be able to get the cochlear model membrane volume compliance ε_m to represent the gerbil cochlear membrane volume compliance ε_g. The gerbil cochlear membrane volume compliance ε_g can be computed using finite element method by using the gerbil basilar membrane material properties derived from [10]. Once the 5 parameters are chosen to satisfy the *Buckingham Pi theorem*, then the motion of the cochlear model can

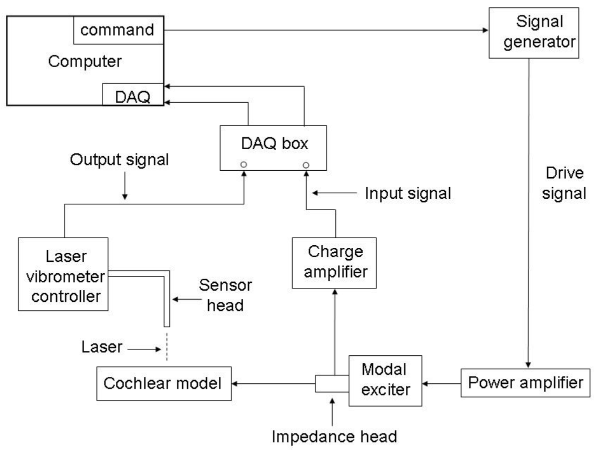

Figure 4. SETUP FOR COCHLEAR MODEL EXPERIMENT.

represent the motion of the gerbil cochlea and can be observed through the experiments.

EXPERIMENTS

The experiments are set up as shown in Fig. 4. LabVIEW is used to perform the data acquisition analysis. LabVIEW command is sent from computer to a signal generator and the drive signal generated by it is amplified by a power amplifier which excites a modal exciter (*shaker*). An impedance head is mounted on the shaker. The drive signal is sent to a charge amplifier through the acceleration sensor on the impedance head. The charge amplifier changes the acceleration signal to a velocity signal which becomes the input signal sent to the data acquisition box. The impedance head driving by the shaker excites the Stapes of the cochlear model. The vibration of the Stapes sets the fluid in the cochlear duct and the membrane in motion. The motion of the membrane is detected by the laser vibrometry. The detected signal is then sent to the data acquisition box as output signal. Both input and output signals are sent to the computer where they are analyzed by the LabVIEW program. The results from the LabVIEW are used to compare with the WKB mathematical results.

Two different viscosities silicone oil, *20 cSt* and *500 cSt* are used as the fluid in the cochlear duct to investigate the viscosity influence on the fluid motion. A sweep sinusoidal signal ranging from *100 Hz* to *20000 Hz* is used to stimulate the cochlea so that at each measuring location, we can observe the membrane responses to different frequency stimuli, thus finding the characteristic frequency for that location.

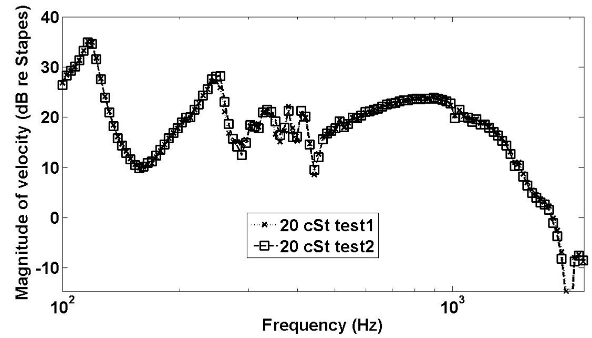

Figure 5. REPEATABILITY OF THE COCHLEAR MODEL.

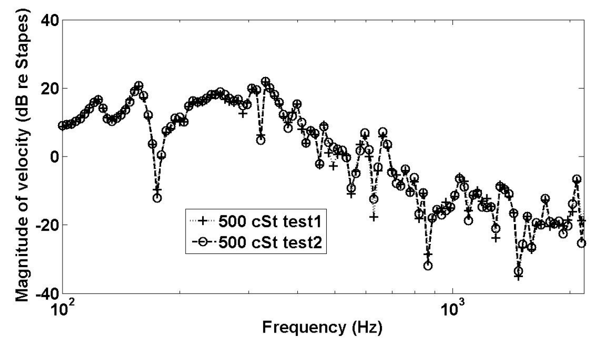

Figure 6. REPEATABILITY OF THE COCHLEAR MODEL.

RESULTS AND DISCUSSION

Experiment repeatability of the cochlear model

Repeatability of the experimental results is the closeness of the agreement between the results of successive measurements of the same experiments carried out under the same conditions. The repeatability quantifies the reliability of the cochlear model. The repeatability test is carried out using two different silicone oils and at different locations.

For *20 cSt* silicone oil, the experiment measurements are recorded at *10 cm* from the base and the comparison for two tests is shown Fig. 5. For *500 cSt* silicone oil, the experiment measurements are recorded at *18 cm* from the base and the comparison for two tests is shown Fig. 6. The plots show the experiments are very repeatable at different locations for different viscosity fluids.

Viscosity influence on the cochlear model

20 cSt and *500 cSt* silicone oil is used to investigate the viscosity influence on the cochlear motion when subjected to the same stimuli. The experiments show that for these two particular silicone oil, the cochlear model does not demonstrate significant difference for the membrane vibration. The comparison is shown in Fig. 7.

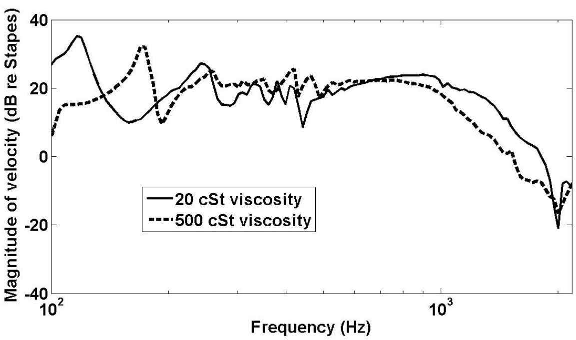

Figure 7. VISCOSITY INFLUENCE ON THE COCHLEAR MODEL.

Scaling parameters of the cochlear model

The human being cochlea fluid density is $1034\ kg/m^3$ and viscosity is *0.00197 Pas* [1]. We take gerbil cochlear fluid has same density and viscosity as that of human being. The volume compliance ε_g for the gerbil is calculated using finite element commercial package COMSOL at several locations along the basilar membrane and listed in Table. 2. According to the *scaling law* and *Buckingham Pi theorem*, the two independent dimensionless ratios for the gerbil cochlea are equal to those of the cochlear model,

$$\frac{\rho_g f_g l_g^2}{\eta_g} = \frac{\rho_m f_m l_m^2}{\eta_m} \tag{16}$$

$$\frac{\eta_g^2 \varepsilon_g}{\rho_g l_g^4} = \frac{\eta_m^2 \varepsilon_m}{\rho_m l_m^4} \tag{17}$$

The fluid used in the cochlear model has density $950\ kg/m^3$ and kinematic viscosity *500 cSt*, which is *0.475 Pas* dynamic viscosity. According Eqn. (16), when the gerbil cochlea responds to the frequency f_g, to have same motion response, cochlear model has to operate at frequency f_m,

$$f_m = \frac{\rho_g l_g^2 \eta_m}{\rho_m l_m^2 \eta_g} f_g = 0.9712 f_g \tag{18}$$

According Eqn. (17), the volume compliance of the cochlear model to satisfy the According to the *scaling law* and *Buckingham Pi theorem*,

$$\varepsilon_m = \frac{\rho_m l_m^4 \eta_g^2}{\rho_g l_g^4 \eta_m^2} \varepsilon_g = 1.154 \varepsilon_g \tag{19}$$

Table 2. PARAMETERS CALCULATED FROM SCALING LAW.

Volume compliance	Gerbil	Model
ε *(1.14 mm)*	$1.22\text{x}10^{-13}$	$1.41\text{x}10^{-13}$
ε *(3.99 mm)*	$8.37\text{x}10^{-13}$	$9.66\text{x}10^{-13}$
ε *(6.612 mm)*	$3.79\text{x}10^{-12}$	$4.37\text{x}10^{-12}$
ε *(7.3 mm)*	$5.47\text{x}10^{-12}$	$6.31\text{x}10^{-12}$

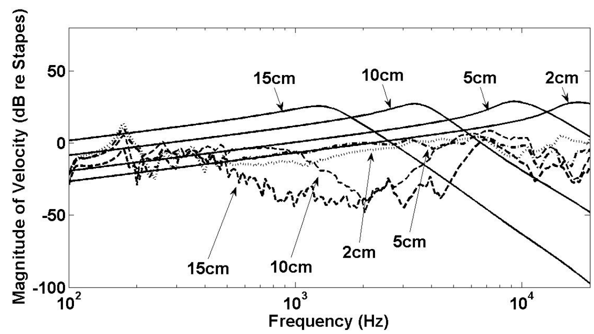

Figure 8. MAGNITUDE COMPARISON OF WKB AND EXPERIMENTAL RESULTS FOR CLAMPED BOUNDARY CONDITION.

The calculated volume compliance of the cochlear model is list in Table. 2. Volume compliance has unit $kg^{-1}m^3s^2$ The location indicated in the table is the distance from the base of the cochlear model.

Comparison of WKB with experimental results

The WKB method is implemented to verify the validity of the model by the comparison with some experimental results. Four locations are measured along the membrane, *2 cm, 5 cm, 10 cm and 15 cm* from the base respectively. Two boundary conditions are investigated using WKB method accommodate to the possibility of the boundary conditions for the cochlear model. One possible boundary condition is both edges of the membrane clamped because the membrane is sandwiched between two acrylic plates. The magnitude comparison of the experimental results with clamp edged boundary conditions is shown in Fig. 8 and phase comparison is shown in Fig. 9.

The experimental results used here for the comparison are from *500 cSt* silicone oil. The cochlear model exhibit a systematic resonance around *200 Hz* which can be seen from the plot for all four locations. The plot demonstrates the model system is unreliable above *7000 Hz*. In Fig. 8 for the clamp edged boundary condition, at location *2 cm* from the base, the WKB method calculated a characteristic frequency about *16000 Hz* while the experiment shows the characteristic frequency is around *7000*

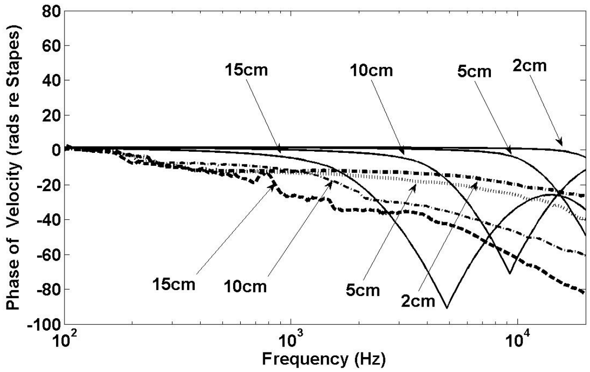

Figure 9. PHASE COMPARISON OF WKB AND EXPERIMENTAL RESULTS FOR CLAMPED BOUNDARY CONDITION.

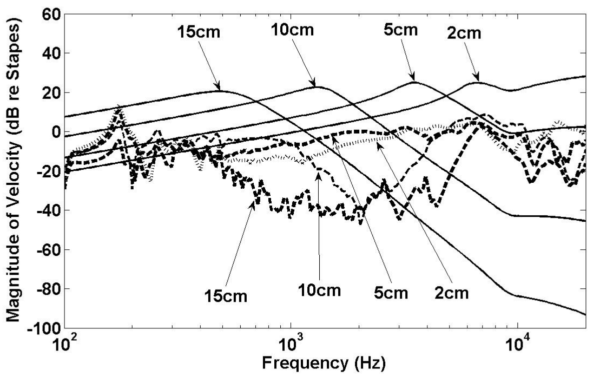

Figure 10. MAGNITUDE COMPARISON OF WKB AND EXPERIMENTAL RESULTS FOR SIMPLY SUPPORTED BOUNDARY CONDITION.

Hz. At *5 cm* from the base, WKB has characteristic frequency *9000 Hz* and experimental characteristic frequency is *3000 Hz*. At *10 cm* from the base, WKB has characteristic frequency *3300 Hz* and experimental characteristic frequency is *1000 Hz*. At *15 cm* from the base, WKB has characteristic frequency *1300 Hz* and experimental characteristic frequency is *500 Hz*. The plot indicates large difference between characteristic frequencies calculated from WKB method and experimental results. The magnitude of the ratio of membrane to Stapes velocity calculated from WKB method is about *10-20 dB* higher than that from experiments. For both WKB and experimental results, the phase decreases drastically as the frequency band passes its characteristic frequency.

Another possibility for the boundary is simply supported. It is possible that the fluid in the cochlear duct get into between the membrane and the acrylic plate which is immersed in the fluid. In Fig. 10 for the simply supported boundary condition, at the location *2 cm* from the base, the WKB method calculated a characteristic frequency about *7000 Hz* same as that of the experimental characteristic frequency. At *5 cm* from the base, WKB has characteristic frequency *3300 Hz* which is very close to experimental characteristic frequency *3000 Hz*. At *10 cm* from the base, WKB has characteristic frequency *1300 Hz* and experimental characteristic frequency is *1000 Hz*. At *15 cm* from the base, WKB has characteristic frequency *500 Hz* and experimental characteristic frequency is *400 Hz*. For the simply supported boundary condition, the experimental results are very close to the WKB results. There are about *100-300 Hz* difference in terms of characteristic frequencies at different locations. The magnitude of the ratio of membrane to Stapes velocity calculated from WKB method is about *15-25 dB* higher than that from experiments, similar to that from clamp edged boundary condition. The phases for WKB and experimental results are very close.

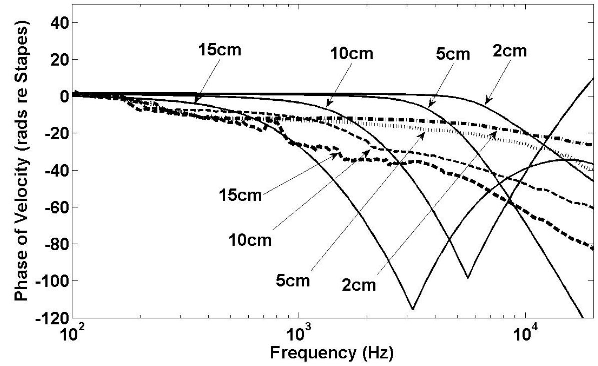

Figure 11. PHASE COMPARISON OF WKB AND EXPERIMENTAL RESULTS for SIMPLY SUPPORTED BOUNDARY CONDITION.

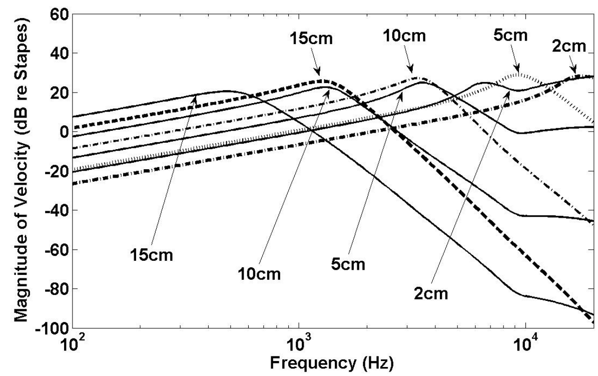

Figure 12. COMPARISON OF RESULTS FOR SIMPLY SUPPORTED AND CLAMPED BOUNDARY CONDITIONS.

The comparison of the results from two different boundary conditions is shown in Fig. 12. The magnitude of velocity ratio for simply supported boundary is *5 dB* higher than that of clamped boundary. The boundary conditions affect the characteristic frequencies greatly. The simply supported boundary shifts the characteristic frequencies to the basal direction of the cochlear model significantly.

From the comparison of the WKB results with the experimental results, it indicates that the WKB method with simply supported boundary condition resemble the experimental results. The relative magnitude of membrane to the Stapes is different by *15-25 dB* and the characteristic frequencies are very close. The similitude between the WKB method and experimental results validates the reliability of the cochlear model.

CONCLUSION

A *16* times scale hydromechanical cochlear model is designed and fabricated. The cochlear model has only one duct. The cochlear duct's height and width linearly varying with its length analogizing the physiology of the gerbil cochlea. The gerbil basilar membrane is represented by a Delrin thin film and it is fixed in place by two acrylic plates. The drive force is applied by a screw head on a rubber piece which represents the oval window membrane of the cochlea. A sweep sinusoidal program is used to generate sinusoidal signals to drive the screw head to stimulate the cochlear model system. The membrane motion is detected by a laser vibrometry and the relative magnitude and phase of the velocity between the membrane motion and the drive signal are recorded and plotted.

Repeatability is tested using different silicone oils at different locations. The results affirm the experiments are very repeatable for different viscosity fluids at varying locations.

Two boundary conditions are investigated using WKB method and the simply supported boundary condition results closely represent the experimental results. The relative magnitudes between the output signal and the input signal calculated from WKB method is about *15-25 dB* higher than those of experiments. The characteristic frequencies and the phase lagging are very close for both WKB and experiments.

A scaling law allows a scale-up cochlear model to have similar motion responses as those of gerbil cochlea if the independent parameters are chosen in a way which satisfies *Buckingham Pi theorem*. The operating frequency for the cochlear model and volume compliance of the basilar membrane to satisfy the *Buckingham Pi theorem* are calculated. Our future study will focus on characteristic frequency mapping for passive gerbil cochlea and traveling wave pattern analysis using the model and results described and experimented in this paper.

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