Study on Attenuation Characteristics of Reissner's Membrane Mode in Cochlea

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ABSTRACT

Multiple propagation modes progress along the basilar membrane and Reissner's membrane, called basilar membrane mode (BM mode) and Reissner's membrane mode (RM mode), respectively. This study focuses on the effects of the RM mode on the hearing process and investigates the difference in the attenuation characteristics between the RM and BM modes in the vicinity of the cochlea base by using modal analysis. Results indicated that the RM mode has fewer effects on the hearing process, except otoacoustic emissions, due to its bigger attenuation constant than the BM mode in the vicinity of the cochlea base. The structural dependency of the attenuation constant of the RM mode is also investigated.

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Keywords

Cochlea; Organ of Corti; Basilar Membrane; Reissner's Membrane; Mode Analysis; Attenuation Constant

Introduction

The cochlea is a fluid-filled spiral-shaped duct, separated by the Reissner's membrane (RM) and the basilar membrane (BM) into three regions: the scala vestibuli, scala media, and scala tympani. When the cochlea is stimulated by an acoustic wave, a dynamic fluid-structure interaction elicits a transverse wave on the BM from the base to the apex of the cochlea. The transverse wave grows in magnitude and decreases in wavelength until peaking at a specific frequency-dependent position. The high-frequency waves culminate near the base, whereas the low-frequency waves propagate further and peak near the apex [1].

However, the BM mode was widely studied [2], few studies are conducted on the RM mode. Fuhrmann et al. investigated the effects of the RM on the wave propagation in the cochlea if the RM has neither mass nor stiffness and can be considered as a rigid boundary with the no-slip condition [3]. Reichenbach et al. indicated that the RM mode plays an important role in transmitting the signals of otoacoustic emissions [4] and the RM mode does not evoke a significant displacement of BM, although a disturbance moving in the BM mode propagates on both membranes. Moreover, they showed that in the basal region of the cochlea at frequencies above 1 kHz, the RM sustains waves with wavelengths smaller than the height of the scale without any penetration into the membrane's surrounding fluids [4].

The present study focuses on the effects of the RM mode on the hearing process except otoacoustic emissions and investigates the difference in the attenuation characteristics between the RM and BM modes in the

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vicinity of the cochlea base by using modal analysis. In the previous study [5], we considered an ideal fluid without viscosity in the analysis. In this work, the viscosity of the fluid is introduced into the analysis. The difference in the attenuation constant between the RM and BM modes was studied and the effects of these modes were investigated on the hearing process. Also, the structural dependency of the attenuation constant of the RM mode was assessed in the current study.

Material and Methods

In this study, COMSOL Multiphysics was used based on the finite element method (FEM) on a 2D cross-sectional model of the cochlea. The human cochlea has an approximately 35-mm-long spiral, modeled as an uncoiled, triple-chambered fluid-filled duct which is composed of the scala vestibuli, scala media, and scala tympani.

Figure 1 shows the cross-section of the cochlea. In this study, modal analysis was used to investigate the attenuation characteristics of the RM and BM modes, providing the cochlear duct has a circular shape with the angle θ between the RM and BM. It is also assumed that the scala vestibuli, scala media, and scala tympani were enclosed by rigid boundaries, except for the RM and BM. Furthermore, the width w, height h, and Young's modulus E of BM were used as parameters in the following equations (1-3) [6]:

$$w=0.1[mm]+\frac{0.4[mm]}{35[mm]}\times z \tag{1}$$

$$h=7.5[\mu m]-\frac{5[\mu m]}{35[mm]}\times z \tag{2}$$

$$E=50[MPa]-\frac{47[MPa]}{35[mm]}\times z \tag{3}$$

where z is the length along the cochlea duct and varies from 0 to 35 mm. Here, the structural parameters of the RM were considered independent from the location. The radius r of the cochlea and the angle θ between the RM and BM were 0.5 mm and 15 degrees, respectively. The density, bulk modulus, and viscosity of the fluid were 1.034×10^3 kg/m^3 [7], 2.2×10^9 Pa [2], and 2.8×10^{-3} Pa·s [7], respectively. Further, the density and Poisson's ratio of the RM and BM were respectively 1.2×10^3 kg/m^3 [7] and 0.49 [7]; and Young's modulus of the RM was 15 MPa [8]. FEM with 10,664 elements was applied for the analysis.

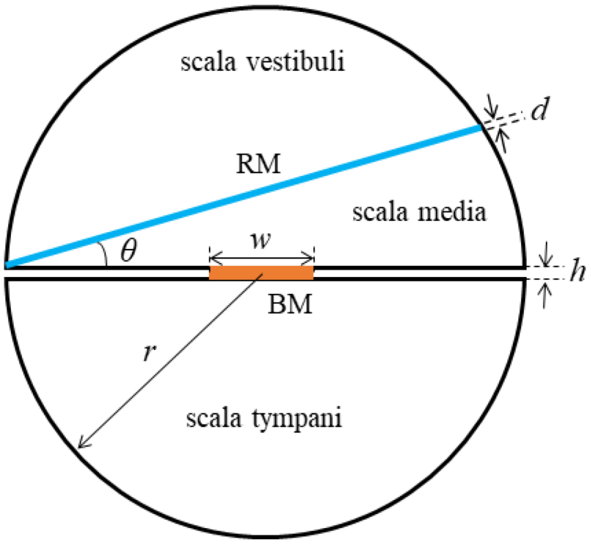

Figure 1: Analysis model

Technical Presentation

Firstly, the membrane displacement is shown in Figures 2(a) (RM mode) and (b) (BM mode) with f = 2000 [Hz] and z = 0 [mm]. The RM mode vibrates only the RM, while as seen in Figure 2(b), the BM mode vibrates both the BM and RM.

Secondly, the dispersion characteristics of each mode are shown in Figures 2(c) and (d) with the frequency characteristics of the phase constant β and attenuation constant α.

Here, β and α are the real and imaginary parts of the angular wavenumber, respectively. In Figures 2(c) and (d), the solid line shows the results of the RM mode, and the dashed, and dash-dotted lines show those of the BM mode when z = 0 and 5 mm.

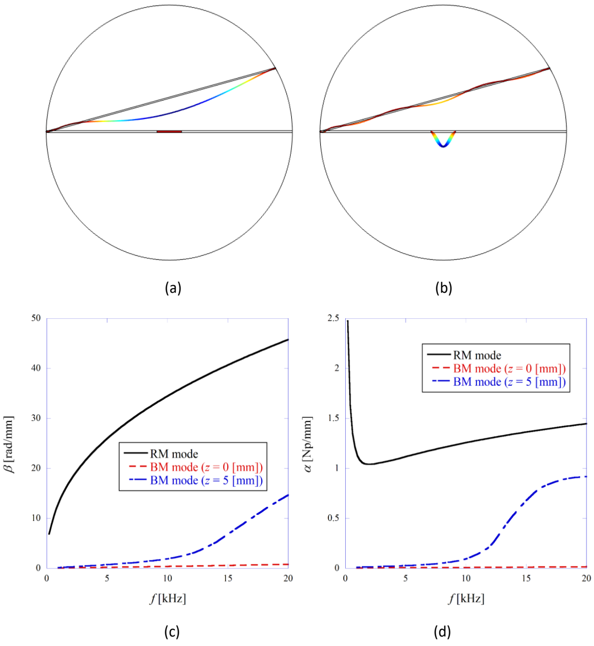

Figure 2: Displacement of membranes of (**a**) Reissner's membrane (RM) mode and (**b**) basilar membrane (BM) mode when f = 2000 [Hz] and z = 0 [mm], and frequency characteristics of (**c**) phase constant and (**d**) attenuation constant

Finally, the structural dependency of α in the RM mode is investigated. Figure 3 illustrates α as a function of the angle θ between the RM and BM, the radius r of the cochlea, and Young's modulus E of the RM.

Discussion

First, we focused on the difference in the propagation constants between the RM and BM modes and evaluated the β and α of the RM and BM modes at the locations near the base of the cochlea. Figure 2(c) shows that the RM mode has a bigger phase constant than the BM mode over the whole frequency range, i.e. the RM mode wave propagates slower than the BM mode wave in the vicinity of the cochlea base. As shown in Figure 2(d), α of the RM mode has a minimum value of around 2 kHz and increases exponentially as the frequency becomes lower. In the higher frequency range above 2 kHz, α increases linearly with an increase in frequency. Therefore, the RM mode decreases exponentially with propagating direction and vanishes near the base of the cochlea. On the other hand, α in the BM mode has a small value, and the waves with lower frequencies can propagate further toward the apex of the cochlea.

Next, the structural dependency of α in the RM mode indicates that α decreases as the angle θ between the RM and BM become larger, as seen in Figure 3(a), due to the increase of the cross-sectional area in which the fluid propagates with the larger scale of the θ, which is consistent with the dependency of the radius r of the cochlea as shown in Figure 3 (b). The cochlea becomes smaller from the base to the apex of the cochlea [2]. Therefore, α also becomes bigger as the waves move further toward the apex. Figure 3 (c) also

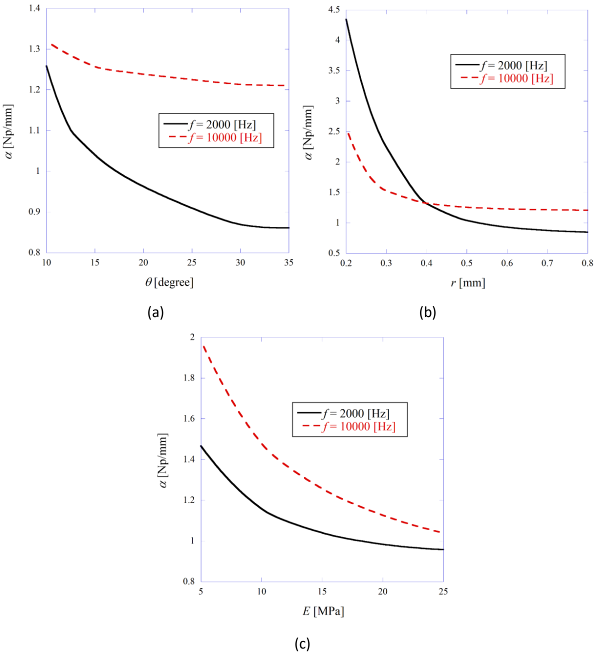

Figure 3: Structural dependency of attenuation constant of Reissner's membrane (RM) mode on (**a**) angle θ between RM and basilar membrane (BM), (**b**) radius r of the cochlea, and (**c**) Young's modulus E of RM.

shows that α decreases as Young's modulus E of the RM become larger and the viscosity effect decreased with the stiffer RM.

Conclusion

RM mode has a bigger constant of attenuation than the BM mode in the vicinity of the cochlea base, i.e. the BM mode plays the main role and the RM mode has fewer effects on the hearing process except otoacoustic emissions. The dependency of the attenuation constant of the RM mode on the angle between the RM and BM, the radius of the cochlea, and Young's modulus of the RM were investigated and their increase results in decreasing of the attenuation constant.

Conflict of Interest

None

References

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