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Differences of Basilar Membrane Responses Due to Spiral Geometry Identified from Passive Cochlea Numerical Models

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ABSTRACT

In this study, the dynamics responses of basilar membrane in an inner ear were investigated in order to identify the differences between spiral and uncoiled cochleae using passive finite element models. To compare the dynamics responses of the basilar membrane, an uncoiled cochlea model was developed considering the fluid-structure interactions and the transverse orthotropic material properties of basilar membrane. A spiral cochlea model was also constructed by transforming only the nodal coordinates of the uncoiled model into spiral geometry. Then, the dynamic characteristics of two cochlear models were compared in frequency domain. Compared vibrational components of basilar membrane in longitudinal and radial directions in the spiral cochlea model showed large differences compared to those of the uncoiled one. It was discussed whether these differences have influences on the hearing capability in very low and high frequency ranges.

Keywords: Basilar membrane, Spiral geometry, Finite element models
I-INCE Classification of Subject Number: 76

1. INTRODUCTION

Effects of spiral geometry in inner ear have been an interesting concern for many years. One of controversial issues is whether the spiral geometry of mammal cochlea enhances the hearing sensitivity and widens the low and high limits of audible frequency bands[1, 2]. Finite element models enables us to clarify this controversy due to their high flexibility in scrutinizing a phenomenon if the models are sufficiently valid. Recently, the first author investigated the spiral effects using the uncoiled and the spiral FE models[3].

In this paper, the results of the author's previous study are summarized briefly. Then, the motions of the basilar membrane are further investigated in order to identify the spiral effects by comparing the pressure distributions and the fluid flows on the basilar membranes.

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2. ANALYSIS OF DYNAMIC RESPONSES IN COCHLEA

2.1 Finite Element Models

Finite element (FE) models were developed in order to identify the spiral effects in human cochlea[3]. Figure 1 shows an FE model for the spiral cochlea. The FE models include the basilar membrane, the osseous spiral lamina, the cochlear fluid, the round window and the oval window. In the FE models, the cochlear fluid was assumed as compressible acoustic media, and has small displacements. The fluid and the membrane structures such as the basilar membrane (32mm in length), the spiral osseous lamina and the round/oval windows were fully coupled using the finite element formulation. The basilar membrane was modelled as a transverse isotropic thin shell in the FE models.

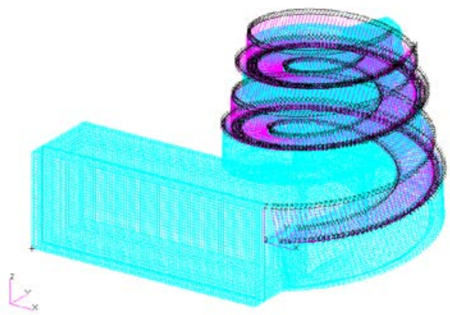


Fig. 1 – A finite element model for the spiral cochlea

The spiral FE model was generated using a geometric transformation from the uncoiled FE model[4, 5]. Figure 2 shows the concept of the geometric transformation used in this study. Here, a plane that is perpendicular to the basilar membrane in the uncoiled FE model was transformed into a plane perpendicular to the central line of the spiral basilar membrane. This geometric transformation was conducted only for the nodal coordinates of the FE model. Very fine meshes of the FE models enable us to neglect differences due to the mesh distortion between the two FE models. Thus, two FE models can be considered as being all the same except the geometry.

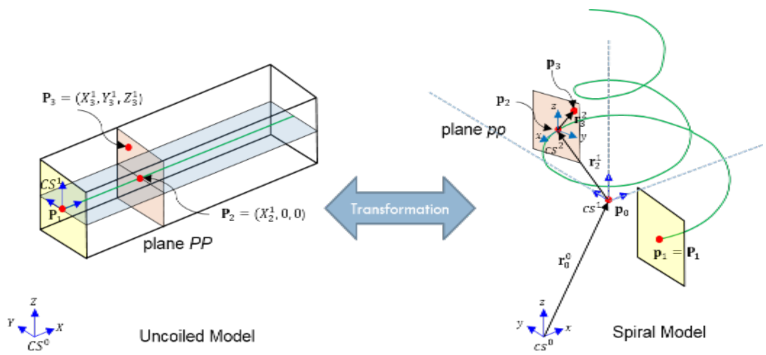


Fig. 2 – Nodal point transformation from the uncoiled FE model into the spiral one

2.2 Validation of FE models

A fundamental function of the basilar membrane is to classify the transmitted vibration into frequency bands. The frequency decoding can be represented by plotting the maximum positions of vibration amplitudes of the basilar membrane with respect to excitation frequency, which is so-called the cochlear map. The cochlear maps for the uncoiled and the spiral FE models were calculated to check the validity of the developed FE models. Figure 3 shows the calculated cochlear maps. The calculated cochlear maps were compared with a reference[6]. Considering different lengths of the basilar membranes (i.e., 32 vs. 35 mm) in two studies, Fig. 3 well illustrates that the developed FE models are valid in representing the function of the cochlea.

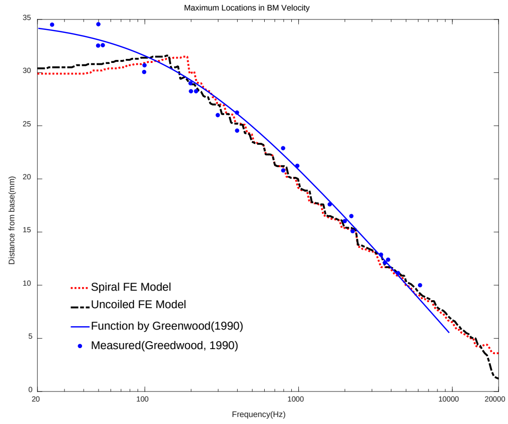


Fig. 3 – Cochlea maps calculated by the uncoiled and the spiral FE models

3. Numerical Analysis Results and Discussion

3.1 Input Impedance of Cochlea

Input impedance of cochlea is a measure to represent the resistance of transmitted vibration from middle ear. Figure 4 shows the calculated input impedance of the cochleae by using the uncoiled and the spiral FE models. In Fig. 4, the spiral cochlea has lower input impedance in almost frequency region although this tendency is controverted at a few frequencies due to resonant peaks. Especially, the amount of the impedance gain due to spiral geometry becomes larger in very low frequency region: i.e., under 100 Hz region. This result supports that the spiral geometry is more advantageous to lower the lower limit of audible frequency. In addition, the spiral cochlea has lower input impedance in very high frequency region as shown in Fig. 4, which is also an advantageous merit to extend the upper limit of audible frequency.

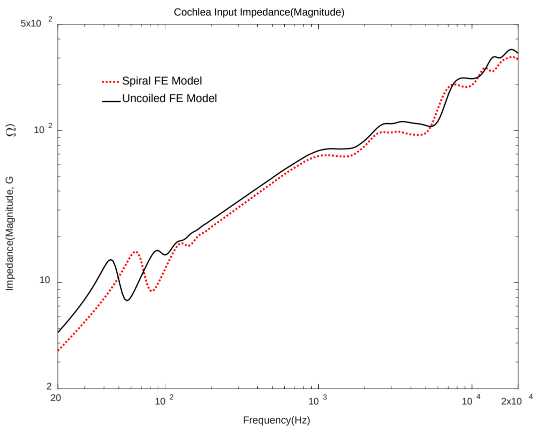
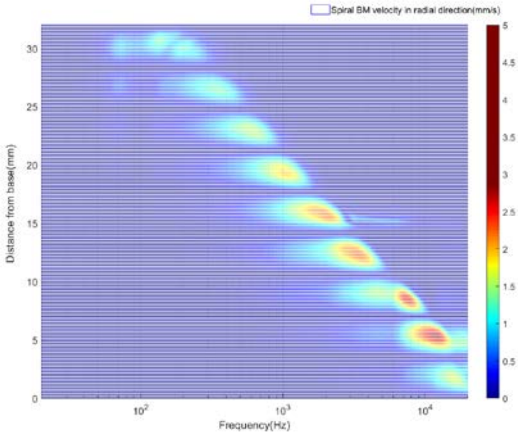


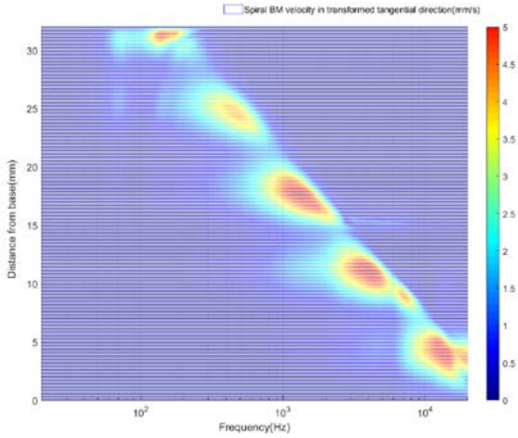
Fig. 4 – Cochlea input impedance calculated by the uncoiled and the spiral FE models

3.2 Behaviour of Basilar Membrane

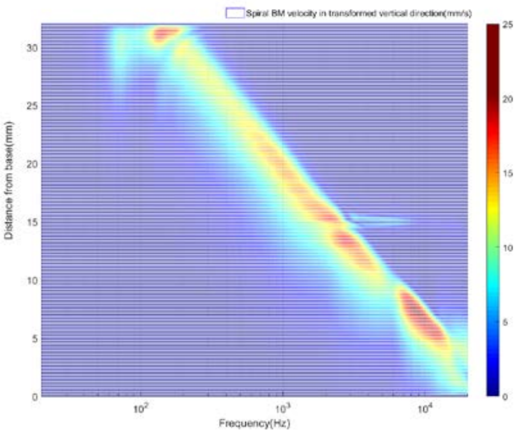
Dynamic responses of the basilar membrane were compared using the uncoiled and the spiral FE models. Figure 5 shows the velocity magnitudes of the spiral cochlea on the centreline in each direction according to excitation frequency. In the spiral cochlea, the radial and tangential components in velocity appear periodically as shown in Fig. 5, and their magnitudes are about 20% to the vertical component. The uncoiled cochlea has negligible these components although not shown here. It is noted that the radial motion of basilar membrane can enhance hearing sensitivity by increasing the bending efficiency of outer hair cell stereocilia[7]. Therefore, the radial components in the velocity magnitudes generated by the spiral geometry provide a fundamental difference of the dynamic motions between two cochleae in the viewpoint of hearing sensitivity.



(a) Radial direction



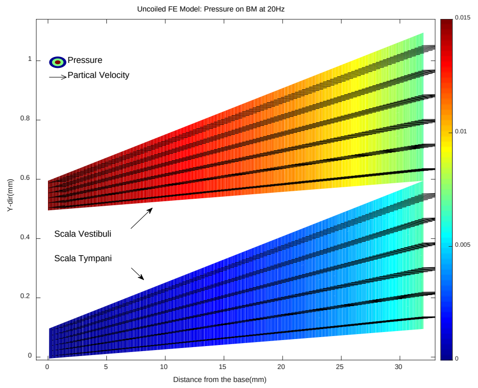
(b) Tangential direction



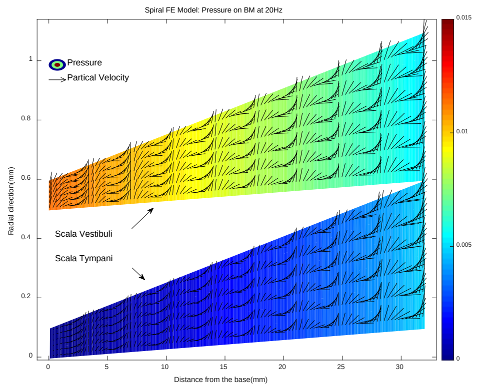
(c) Vertical direction

Fig. 5 – Velocities of the basilar membrane in the spiral FE model

Next, the dynamic responses on the basilar membrane calculated by the FE models were compared. Figures 6~8 show the pressure distributions and the particle velocities represented in magnitude on the basilar membranes at a few frequencies for the uncoiled and the spiral cochleae. The dynamic responses of the spiral cochlea were plotted on the uncoiled geometry for clear comparison. It should be also noted that the vertical dimension was magnified greatly compared to the horizontal one, and the corresponding velocity vectors were adjusted according to the magnification.

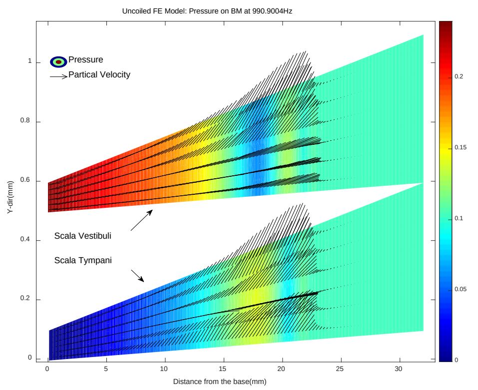


(a) Uncoiled

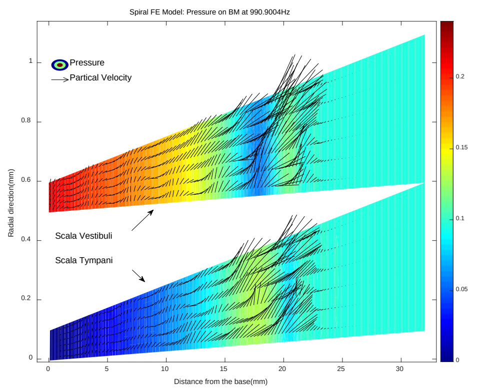


(b) Spiral

Fig. 6 – Pressure distribution and particle velocity on the basilar membrane at 20 Hz.

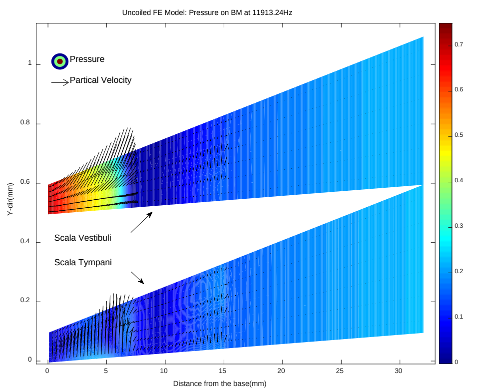


(a) Uncoiled

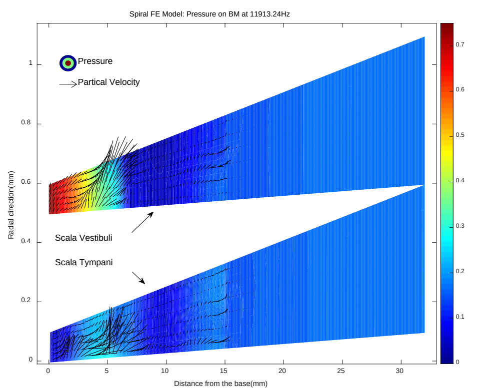


(b) Spiral

Fig. 7 – Pressure distribution and particle velocity on the basilar membrane at 991 Hz.



(a) Uncoiled



(b) Spiral

Fig. 8 – Pressure distribution and particle velocity on the basilar membrane at 12 kHz.

In very low frequency as shown in Fig. 6, the radial components of the particle velocity are dominant in the spiral cochlea whereas the pressure distributions are very similar each other. At the middle and the high frequencies as shown in Figs. 7~8, the spiral cochlea showed more complex directions of the particle velocities on the basilar membrane including bigger radial components.

4. CONCLUSIONS

In this study, the effects of the spiral geometry in a human cochlea were investigated using the FE models considering the fluid-structure interactions. To isolate the parameters associated with the spiral geometry, two FE models of which differences are only the geometry of the cochlea were developed. The isolation was conducted by introducing the geometric transformation that converts only the nodal coordinates of the uncoiled FE model into the spiral FE model.

Comparing the dynamic responses using the develop FE models for the uncoiled and the spiral cochleae, the spiral cochlea has low input impedance in almost frequency region. The fundamental difference appeared from the comparison was that the spiral cochlea has the radial and the longitudinal movements that are not found in the uncoiled cochlea. Since it is known that the radial movement enhances the hearing sensitivity in the organ of Corti, these results support that the spiral form of cochlea has advantageous in hearing capability. The amount of the differences were large in low frequency region. However, those effects were not limited in the low frequency region but influenced in almost all frequency range.

5. ACKNOWLEDGEMENTS

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