Dynamics Analyses of Human Middle Ear System Using Finite Element Method

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Abstract

The human ear can be divided into three main parts: the external ear, the middle ear and the inner ear. The human middle ear system consists of an eardrum, ligaments, tendons, and three ossicles, namely three tiny bones (malleus, incus and stapes) which are linked by each other, and connect with the eardrum and the inner ear. The purposes of this research are to make a three-dimensional model of human middle ear system and to simulate the dynamic behaviors using the finite element method. Firstly, the geometric models on human middle ear system were generated by the CAD software (Solidworks 2015) using the physical properties of components of human middle ear system reported by other researchers. In this study, three kinds of models were made to investigate the dynamic behaviors of the human middle ear system. A flat elliptic eardrum was defined as Model I. As for the boundary conditions of eardrum of Model I, the clamped condition was used in 6 degrees of freedom. Then, Model II was created for a concave elliptic eardrum. The complete model of the human middle ear system composed of a concave elliptic eardrum, three ossicles, some ligaments and a few tendons was created as Model III. The ligaments, the tendons and the cochlea in the inner ear were modeled with the translational springs. As for the boundary conditions of eardrum of Model II and Model III, the clamped condition was used in 5 degrees of freedom and the torsional spring was used for the rotational motion around one axis of the local coordinate frame. Then, the Optistruct of HyperMesh was used as the solver in Finite Element Analysis. Finally, the eigen-value, frequency response and time history response analyses have been carried out for each analysis model. In the frequency response analyses, the value of 2.0x10-6 [Pa] was used as the sound pressure in the frequency range from 100 [Hz] to 10,000 [Hz]. The reason why the human eardrum has the concave shape was revealed. Then the authors have succeed in the dynamics simulations on human middle ear system.

Keywords— Eardrum, Ossicle, Middle Ear, Dynamics, Finite Element Method

Introduction

Hearing loss is one of the most severe problems in usual life activity of the human being. WHO reports that over 5% of the world’s population have hearing loss. Conductive hearing loss is the most common case due to problems in the middle ear or the outer ear at times. A human middle ear which includes an eardrum and three ossicles (malleus, incus and stapes) is a mechanical system to transmit sounds from outer ear to inner ear. The conductive hearing loss occurs when sounds hardly transfer through the ear canal to the eardrum and three ossicles. The otosclerosis in which the ossicles in middle ear become stiff or the dislocation of three ossicles causes severe conductive hearing loss. Conductive hearing loss can often be treated with a surgery using artificial ossicles. If it is possible to perform the simulation of dynamic behavior of the middle ear before the surgery using artificial ossicles, it must be very helpful.

The past researches on middle ear system are introduced as follows. Wada et al. measured Young’s modulus, thickness and damping ratio of the human eardrum by using measuring apparatus developed by themselves [1]. As for dynamics analysis on the middle ear system, a cat eardrum was firstly investigated by a finite element analysis on the curved conical eardrum by W. R. I. Funnell and C. A. Laszlo [2]. D. D. Greef et al. performed dynamics analysis on a new anatomically-accurate model composed of the tympanic membrane and malleus using the finite element method [3]. Computational modeling methodology of multi-body system was examined in order to simulate and study the middle ear mechanical response to acoustic stimuli by F. Bohinke et al. [4]. Y. Liu et al. carried out a three-dimensional finite element analysis of human ear in order to analyze lesion of ossicular chain [5]. E. Skrodzka and J. Modlawksa performed modal analysis of the human tympanic membrane of middle ear using the finite element method [6]. C. F. Lee et al. proposed a practical approach that uses high-resolution computed tomography (HRCT) to derive models of the middle ear for finite element analysis [7]. R. Z. Gan et al. performed a three-dimensional finite element analysis of the human ear that included the external ear canal, eardrum, ossicular bones, middle ear.
suspensory ligaments/muscles, and middle ear cavity [8]. A practical and systematic method for reconstructing accurate computer and physical models of entire human middle ear were proposed by Q. Sun et al. [9]. T. Koike et al. performed the finite element analysis of the human middle ear and compared calculated results with measurement data [10]. The displacements of the tympanic membrane in a human ear were measured by using a Laser Doppler Vibration (LDV) and compared with those of a finite element analysis of the middle ear by T. S. Ahn et al. [11]. However, in most reports on the finite element analysis, three-node triangular and four-node tetrahedron elements that are constant strain elements have been used. Then, there is no report that clarifies why the eardrum has a concave shape.

In the present study, the CAD software (Solidworks 2015) was used to create the three-dimensional model of the human middle ear. Then, the HyperWorks (finite element analysis code) was used to carried out the dynamics analyses of the human middle ear. In the finite element analyses, three types of models, namely Model I (flat elliptic eardrum), Model II (concave elliptic eardrum) and Model III (complete model of the human middle ear) was used. The Model I and the Model II were used to clarify why an eardrum has a concave shape. Then the Model III was used to carried out dynamics analyses of the human middle ear system. Firstly, the computational precisions of the finite element analyses in uses of a three-node triangular element (low order element) and a six-node triangular one (high-order element) have been examined because it is well known that the three-node triangular element is constant strain one and its computational precision is poor. Then the eigen-value and frequency response analyses were carried out for all models. The eigen-value analysis were carried out to obtain the natural frequencies and the vibration modes. Then, the frequency response analysis was performed to show the response of each model in the frequency range 100 to 10,000 Hz under the sound pressure level, P = 2.0 × 10^-6 Pa. Finally, time history response analyses on Model III were carried out using Formant frequencies as external forces.

Flat Elliptic Eardrum Using Clamped Boundary Conditions

**Dimensions of Model I (flat elliptic eardrum)**

Figure 1 shows the dimensions of Model I that is the finite element model of a flat elliptic eardrum. As for the dimensions of Model I, the values of 10.0mm, 9.0mm and 0.1mm were used as the major axis, the minor one and the thickness, respectively by considering those reported by other researchers [3].

![Dimensions of Model I](image)

**Figure 1:** Dimensions of Model I that is the finite element model of flat elliptic eardrum

**Examination of proper type and partition number of finite elements on Model I (flat elliptic eardrum)**

A proper type and partition number of finite elements on Model I were examined. Three-node triangular elements that are high-order elements and six-node triangular elements that are low-order ones were used as finite elements. As for the material properties of an eardrum, the values of 33.4 MPa, 1.2 kg/m^3 and 0.3 were used as the Young’s modulus, the mass density and the Poisson’s ratio, respectively by considering those reported by other researcher [10]. Then, eigenvalue analysis was carried out for Model I with the clamped boundary conditions using the HyperMesh (Finite Element Analysis (FEA) code).

Figure 2 shows the partition number of finite elements affecting natural frequencies of Model I (flat elliptic eardrum) with the clamped boundary conditions. As for Model I, there are six natural frequencies less than 1,500Hz. The
FEA solutions, namely numerical solutions of natural frequencies are approaching to the analytical ones, namely exact ones as the number of finite elements becomes larger. The FEA solutions on natural frequencies hardly vary over 1,000 elements. It is also well known that the computational precision is not good for a two-dimensional three-node triangular element and a three-dimensional four-node tetrahedron one because their strains become constant inside their elements. Therefore, it was decided to divide the flat elliptic eardrum (Model I) into 1,274 elements using the six-node triangular one in this research.

\[ f_i (i = 1 \sim 6) \] : i-th natural frequency

**Figure 2:** Partition number of finite elements affecting natural frequencies on Model I (flat elliptic eardrum) with the clamped boundary conditions.

**Concave Elliptic Eardrum Using Torsional Springs as Boundary Conditions**

**Finite element model of Model II (concave elliptic eardrum using torsional springs as boundary conditions)**

Figure 3 shows the finite element model of the Model II (concave elliptic eardrum) using torsional springs as boundary conditions that is divided by 1,220 pieces of six-node triangular elements. As for the major and the minor axes of the Model II, the same values as the Model I were used. For the height of concave shape of the Model II, the value of 1.5mm was used considering by the other researcher [10]. The material properties of the Model II are the same ones as those of the Model I. Each node at the boundary of Model II has its own local coordinate frame, \( oxyz \). In the local coordinate frame, three translational motions in the \( x \)-, \( y \)-, and \( z \)- directions and two rotational ones around the \( x \)- and \( z \)- axes were fixed. Then the torsional springs were applied to rotational motions around the \( y \)-axes at the nodes on boundary of Model II. The torsional springs were used to control the stiffness of the boundary of Model II in order to make the boundary conditions of Model II similar to those of a human eardrum.
Figure: 3 Finite element model of the Model II (concave elliptic eardrum) using torsional springs as boundary conditions that is divided by 1,220 pieces of six-node triangular elements

Validation of torsional springs used as boundary conditions of Model II

The eigenvalue analyses were carried out for Model II with torsional springs as boundary conditions using the HyperMesh. Figure 4 shows the torsional spring constants affecting the natural frequencies of Model II (concave elliptic eardrum using torsional springs on the boundary). The various torsional spring constants were used in the range from $K_{\theta} = 0$ to $K_{\theta} = 100 \text{ Nmm/rad}$ for the first six natural frequencies of Model II. The least square method was used to make approximate curves. It can be seen that the first six natural frequencies become constant in $K_{\theta} = 0.1 \text{ Nmm/rad}$ and more.

Figure 4: Torsional spring constants affecting the natural frequencies of Model II (concave elliptic eardrum using torsional springs on the boundary)

Natural frequencies and vibration modes of Model II using torsional spring constants

Calculational method

Firstly, the eigenvalue analysis was carried out for Model II using the torsional springs, $K_{\theta} = 0.1 \text{ Nmm/rad}$ so that the results can be the same ones as those with the clamped boundary conditions. Secondary, the eigenvalue analysis was carried out for Model II using the torsional springs, $K_{\theta} = 3.0 \times 10^{-5} \text{ Nmm/rad}$ proposed by the other researcher [10] that can imitate the boundary conditions of a human eardrum.

Results

Figure 5 shows the vibration modes of Model II using the torsional spring constant, $K_{\theta} = 0.1 \text{ Nmm/rad}$ on the boundary. The first vibration mode of Model II has four loops in $f_1 = 2,918 \text{ Hz}$. Then, the second vibration mode has five loops in $f_2 = 3,028 \text{ Hz}$. There are six loops for the third vibration mode and four loops for the fourth one in $f_3 = 3,060 \text{ Hz}$ and $f_4 = 3,063 \text{ Hz}$, respectively. The fifth vibration mode has six loops in $f_5 = 3,378 \text{ Hz}$. Finally, the sixth vibration mode has eight loops in $f_6 = 3,422 \text{ Hz}$.

(a) Vibration mode of 1st natural frequency, $f_1 = 2,918 \text{ [Hz]}$  
(b) Vibration mode of 2nd natural frequency, $f_2 = 3,028 \text{ [Hz]}$
Figure 5: Vibration modes of Model II using the torsional spring constant, $K_\theta = 0.1$ Nmm/rad on the boundary.

Figure 6 shows the vibration modes of Model II using the torsional spring constant, $K_\theta = 3.0 \times 10^{-5}$ [Nmm/rad] on the boundary. The first, second and third vibration modes have similar modes. Their vibration modes have two large loops and two small ones in $f_1 = 2,599$ Hz, $f_2 = 2,616$ Hz and $f_3 = 2,621$ Hz, respectively. The fourth vibration mode has one large loop and two small ones in $f_4 = 2,661$ Hz. The fifth vibration mode has four loops in $f_5 = 3,012$ Hz. Then, the sixth vibration mode has eight loops in $f_6 = 3,116$ Hz.
Frequency response analyses

Calculation method
The Optistruct of HyperMesh was used as the solver to perform the frequency response analyses of Model I (flat elliptic eardrum) using clamped boundary conditions and Model II (concave elliptic eardrum) using the torsional springs on the boundary under the sound pressure level, $P = 2.0 \times 10^{-6}$ Pa in the frequency range from 100 Hz to 10,000 Hz. As for the structural damping coefficient, $G$, the value of $G = 0.4$ proposed by the other researchers [1] was used. Two kinds of values on the torsional spring constants were used on the boundary of Model II. The torsional spring constant, $K_\theta = 0.1$ Nmm/rad was used so that the result can be similar to that with the clamped boundary conditions. Then the torsional spring constants, $K_\theta = 3.0 \times 10^{-5}$ Nmm/rad proposed by the other researchers [10] was used so that the results can be similar to those of a human ear.

Result
Figure 7 shows the frequency responses on displacement of umbo of Model I (flat elliptic eardrum) using clamped boundary conditions and Model II (concave elliptic eardrum) using torsional spring on the boundary under the sound pressure level, $P = 2.0 \times 10^{-6}$ Pa. The results show that the first natural frequency of Model I is quite lower than them of Model II. A frequency response of a human ear is desired to be constant in a broad frequency range. A human being can easily hear sounds well if the frequency response of an eardrum has the above characteristics. Then, it means that a concave shape like Model II is better than a flat one like Model I as a shape of an eardrum. It is assumed that a shape of a human eardrum may be a concave one in the process of evolution.
Figure 7: Frequency responses on displacement of umbo of Model I (flat elliptic eardrum) using clamped boundary conditions and Model II (concave elliptic eardrum) using torsional spring on the boundary under the sound pressure level, $P = 2.0 \times 10^{-6}$ Pa

Complete Model of Human Middle Ear

Finite element model of Model III (complete model of human middle ear)

Figure 8 shows the finite element model of Model III (complete model of the human middle ear) using the torsional springs on the boundary of an eardrum and the translational springs as four ligaments, a tendon and a tensor tympanic membrane and a cochlea. The complete finite-element model of the human middle ear in this research includes the concave elliptic eardrum and the three ossicles, namely three tiny bones; malleus, incus and stapes. The three ossicles linking each other connect with the eardrum and the cochlea. The shapes and dimensions of the three ossicles were decided by considering the references [4], [7]. Then the three ossicles were meshed by using the ten-node tetrahedron elements that are the high-order elements. The material properties of ossicles were considered by the other research [5]. Then, the values of 14.1 GPa and 0.3 were used as the Young’s modulus and the Poisson’s ratio, respectively. The values of $2.55 \times 10^{-9}$ kg/m$^3$, $2.36 \times 10^{-9}$ kg/m$^3$ and $2.20 \times 10^{-9}$ kg/m$^3$ were used as the mass densities of malleus, incus and stapes, respectively. The ligaments, the tendon, the tensor tympanic membrane and the cochlea were defined as the translational springs. Each one of them has its own local coordinate frame. The $x$-direction of each local coordinate frame was defined as the normal direction to the surface of ossicle. Three translational springs were attached to positions of the ligaments, the tensor tympanic membrane and the tendon except the cochlea in the $x$-direction of local coordinate frame. The values of translational spring constant, $K_i$ ($i = x, y, z$) for the ligaments, the tensor tympanic membrane, the tendon and the cochlea were decided by trial and error so that the stapes can perform a piston motion in the $x$-direction of local coordinate frame. The values of $K_x = 1.2$ N/m in the $x$-direction, $K_y = 0.3$ [N/m] in the $y$-direction and $K_z = 0.3$ N/m in the $z$-direction were used as the translational spring constants for the ligaments, the tensor tympanic membrane and the tendon. The part contacting with the stapes and the cochlea moves like a piston in the $x$-direction. Then, the translational spring constant in the $x$-direction of the cochlea was decided as $K_x = 0.2$ N/m by trial and error so that the stapes can perform piston motion in the $x$-direction of the local coordinate frame.

Figure 8: Finite element model of Model III (complete model of the human middle ear) using the torsional springs on the boundary of an eardrum and the translational springs as four ligaments, a tendon and a tensor tympanic membrane and a cochlea.
**Eigenvalue analysis**

**Calculational method**

The eigenvalue analysis of the Model III (complete model of human middle ear) was carried out to obtain the natural frequencies and the vibration modes in the frequency range from 100 Hz to 10,000 Hz. The torsional spring constant, $K_\theta = 3.0 \times 10^{-5}$ Nmm/rad was used for the rotational motion around the y-axis on the boundary of the eardrum.

**Result**

Figure 9 shows the vibration modes of the Model III (complete model of the human middle ear). The first, second and third vibration modes have similar modes, but the directions of motions of the three ossicles are different. Then the first vibration mode has one small loop. The three ossicles move in the normal direction to the surface of the eardrum in $f_1 = 1,033$ Hz. The second vibration mode in $f_2 = 1,728$ Hz has two small loops. The directions of motions of the three ossicles in $f_2 = 1,728$ Hz are different from the first one in $f_1 = 1,033$ Hz. Furthermore, the third vibration mode in $f_3 = 1,846$ Hz has two small loops, and the directions of motions of the three ossicles are different. The fourth, fifth and sixth vibration modes have similar modes in which the displacements at loops of the three ossicles are very small. The fourth vibration mode in $f_4 = 2,659$ Hz has two loops in which the both loops have the same direction on displacements. The fifth vibration mode in $f_5 = 2,697$ Hz also has two loops, but one loop moves in the opposite direction to the other one. Then, the sixth vibration mode has four large loops and one small loop in $f_6 = 3,013$ Hz.

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(a) Vibration mode of 1st natural frequency, $f_1 = 1,033$ Hz

(b) Vibration mode of 2nd natural frequency, $f_2 = 1,728$ Hz

(c) Vibration mode of 3rd natural frequency, $f_3 = 1,846$ Hz

(d) Vibration mode of 4th natural frequency, $f_4 = 2,659$ Hz
Vibration mode of 5th natural frequency,
\[ f_5 = 2,697 \text{ Hz} \]

Vibration mode of 6th natural frequency,
\[ f_6 = 3,013 \text{ Hz} \]

Figure 9: Vibration modes of the Model III (complete model of the human middle ear)

**Frequency response analysis**

**Calculational method**

Figure 10 shows the structural dampings used for the Model III (completed model of the human middle ear) using the structural damping coefficient of \( G = 0.4 \) in 1,500 Hz and less, and five kinds of values on \( G \) in 1,500 Hz and more. The Optistruct of Hypermesh was used to carry out the frequency response analyses of the Model III using the torsional spring constant, \( K_\theta = 3.0 \times 10^{-5} \text{ Nmm/rad} \) on the boundary under the sound pressure level, \( P = 2.0 \times 10^{-6} \text{ Pa} \) in the frequency range from 100 Hz to 10,000 Hz. Then five structural damping coefficients were used for the frequency response analyses to examine the effect of structural damping coefficients on the displacements of stapes in 1,500 [Hz] and more.

**Result**

Figure 11 shows the frequency responses of displacements of the stapes of Model III (complete model of the human middle ear). The use of structural damping coefficient of \( G = 0.4 \) can make the displacement constant at the frequency less than 1,000 Hz. However, The value of \( G = 0.4 \) makes the displacement very large in 1,500 Hz and
Therefore, the frequency response analyses using five kinds of structural damping coefficients were carried out to decrease the large displacements in 1,500 Hz and more. Then, the value of $G = 2.5$ was selected as the structural damping coefficient in 1,500 Hz and more. Furthermore, it can be seen that the first natural frequency of the Model III became around 1,000 Hz. It is well known that the first natural frequency of a human middle ear becomes around 1,000 Hz [7], [10]. Then, the frequency responses calculated in this study show the similar results reported by the other researchers [7], [9].

![Figure 11: Frequency responses of displacements of the stapes displacement of the Model III (complete model of the human middle ear)](image1)

**Figure 11:** Frequency responses of displacements of the stapes displacement of the Model III (complete model of the human middle ear)

**Time history response analysis**

**Calculational method**

The Optistruct of HyperMesh was used to carry out time history responses analyses of Model III. The value of $P = 2.0 \times 10^{-6}$ Pa was used as the external pressure subjected to the eardrum. As for the frequencies of the external pressure, the Formant frequencies were used. The frequencies, $F_1 = 750$ Hz, $F_2 = 1,250$ Hz and $F_3 = 2,500$ Hz are the first Formant frequencies of “o”, “a” and “i” in human simple vowels, respectively. Then as for the structural damping coefficients, $G$, the values of $G = 0.4$ and $G = 2.5$ were used in 1,500 Hz and less, and in 1,500 Hz and more, respectively. As for the incremental time, $\Delta t$ and the number of time, $N$, $\Delta t = 1.0 \times 10^{-5}$ s and $N = 800$ were used, respectively.

**Result**

Figure 12 shows the time history responses of displacements in the stapes of for Model III (completed model of the human middle ear) when the eardrum was subjected to the external pressure, $P = 2.0 \times 10^{-6}$ Pa consisting of the Formant frequencies of human voice. It can be seen that the time history responses using the Formant frequencies, $F_1 = 750$ Hz and $F_2 = 1,250$ Hz have almost the same displacements. Otherwise, the time history response using the Formant frequency, $F_3 = 2,500$ Hz has smaller displacements than the others. It must be due to that the large structural damping coefficient, $G = 2.5$ was used in 1,500 Hz and more.

![Figure 12: Time history responses of displacements in the stapes of for Model III (completed model of the human middle ear)](image2)

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Figure 12: Time history responses of displacements in the stapes of Model III (completed model of the human middle ear) when the eardrum was subjected to the external pressure, $P = 2.0 \times 10^6$ Pa consisting of the Formant frequencies of human voice

Conclusion

Dynamics analysis of the human middle ear system had been performed using the finite element method for three types of models, namely Model I (flat elliptic eardrum), Model II (concave elliptic eardrum) and Model III (complete model of the human middle ear).

The summary of the results is shown below.

- It was examined that the computational precision in use of the six-node triangular element that is a high-order element is better than that of the three-node triangular element that is a low-order element because the three-node triangular element is the constant strain triangle element.
- It is assumed that the human eardrum has a concave shape because the response becomes constant in broad frequency range if a shape of the eardrum is a concave shape in the frequency response.
- It was confirmed that the calculation method proposed by the authors can perform dynamics analysis of a human middle ear system consisting of an eardrum and three ossicles and a stapes.

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References