Frequency Response Of The Human Middle Ear System With Eardrum Perforation

Hidayat Hidayat, Sudarsono Sudarsono, Darma Aviva, Rozaini Othman

Abstract: A human ear system is divided into three sections namely outer ear, middle ear and inner ear. The human middle ear system is composed of an eardrum, three tiny bones (malleus, incus, stapes) and ligaments. The eardrum is a thin membrane separates the outer and the middle ear system. A hole in the membrane (eardrum) of the middle ear also called as eardrum perforation. The purpose of this research is to show the frequency responses of the human middle ear system with eardrum perforation using the finite element method. The geometric model of human middle ear system with eardrum perforation was obtained from CT scan imaging. Then, the CT scan data was converted to DICOM File. Before exported to finite element analysis software, the data converted to STL file. Finally, the geometrical of human middle ear system was generated by CAD Software using physical properties of components of the human middle ear system with eardrum perforation reported by the previous researchers. Two types of the human eardrum were used in this study namely eardrum perforation and normal eardrum. Then, frequency response analysis had been carried out to show the response on the displacement of stapes of human middle ear system in the frequency range 100 Hz to 10 kHz. As for the frequency responses, the response of human middle ear system with eardrum perforation is lower than normal eardrum due to the decreasing of the mass of human eardrum.

Index Terms: ossicles, human middle ear, eardrum, membrane, frequency response, perforation, membrane.

1 Introduction

A human middle ear system consists of an eardrum and three ossicles. The three ossicles, namely malleus, incus and stapes have functioned as a mechanical system to transmit voice or sound through from ear canal to inner ear. An eardrum perforation such as an eardrum with a hole accompanies liquid discharge from middle ear through the ear canal. Closing the hole in an eardrum can protect water from entering in the middle ear and ear infection. There are many researchers on human middle ear system used finite element analysis to solve the dynamic problem. Finite Element Analysis (FEA) is a type of computational program that uses the finite element method to simulate the behavior of engineering structures and components under various conditions. Finite element analysis is a powerful tool to simulate the human middle ear vibrations due to the complicated shape of the human middle ear system. The main benefits of finite element analysis in this research are to determine natural frequencies, vibration mode, frequency response and time history response analysis of human middle ear with eardrum perforation which cannot be obtained by using traditional analysis method. Mehta, R.P et al. carried out a prediction of conductive hearing in eardrum perforation [1]. Saliba, I et al. calculated the differences scale of perforation sizes of the human eardrum and the effect of perforation on frequencies and the levels of the hearing. [2]. Zahnert, T et al. performed experiment using LDV to find out the characteristic of acoustic transfer of various thicknesses of cartilages [3][4]. Lee, C.F et al. constructed a cartilage plate to determine the optimal graft thickness for cartilages used in myringoplasty using the finite element analysis [5]. In this research, the geometrical model of the human middle ear system was obtained from CT scanning imaging. Firstly, the CT scan data was converted into DICOM (Digital Imaging and Communication in Medicine) file. After that, the DICOM file was converted again to STL file. The STL file was imported to the CAD software namely Solidworks to generate the geometric model of the human middle ear system. Then, the geometric model as IGES file was imported to the FEA (Finite Element Analysis) software to generate a finite element model. The FEA software was used to perform frequency responses analysis of human ear system with perforated eardrum to show the responses of the human hearing system in the frequency range between 100 to 10,000 [Hz] was performed. The value of $P = 2.0 \times 10^{-2}$ [Pa] was used as the sound pressure level subjected to the human eardrum. There are two types of human eardrum used in this research namely the normal and perforated eardrum. In the frequency response analysis, the responses of displacement of stapes of the two types of eardrum will be compared in order to show the effect of perforation on the human eardrum.

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2 Material and Methods

2.1 Finite Element Model of The Human Middle Ear System

Figure 1 shows the finite element model of the human middle ear system with eardrum perforation. The human temporal bone was scanned using CT scan machining to obtain the image of the human middle ear system as a DICOM (Digital Imaging and Communication in Medicine) file. Then, the DICOM file was converted to STL file using 3D Slicer software. The STL file was imported to the CAD software (Solidworks) to generate the 3D modeling of the human middle ear system. There are four main parts were assembled in CAD software namely human eardrum and ossicles. The ossicles are three tiny bones (malleus, incus, and stapes) connected between human eardrum and cochlea. The geometrical model on CAD software was exported to the Finite Element Analysis (FEA) software as an IGES file to create the finite element model. The finite element model is composed of the human eardrum, ossicles (malleus, incus and stapes), ligaments (superior malleal ligament, lateral malleal ligament, anterior malleal ligament, superior incudal ligament, posterior incudal ligament, stapedius annular ligament), tendons (stapedius tendon and tensor tympanic tendon), and joints (incudomalleolar and incudostapedial joint). The human eardrum perforation was divided by 1,553 pieces of six-node triangular elements. As for the ossicles, ten-node tetrahedron elements were used to mesh the malleus, incus and stapes. The malleus, incus and stapes was dicritized with 1,156, 1,970 and 454 ten-node tetrahedral elements. The ligaments and tendon were defined using truss element. The material properties (Young's modulus, mass density) of the human middle ear system and ligaments, tendons are shown in table 1 and table 2, respectively.

Table 1. *Material Properties of the human middle ear system*

Human Ear Components	Young's Modulus [N/m^2]	Mass density [$\times 10^3$ kg/m^3]
Eardrum	3.2×10^7	1.2×10^3
Malleus	1.41×10^{10}	2.55×10^3
Incus	1.41×10^{10}	2.36×10^3
Stapes	1.41×10^{10}	2.20×10^3
Incudomallear joint	1.41×10^{10}	3.20×10^3
Incudostapedia joint	6.1×10^5	1.20×10^3

Table 2. *Material Properties of Ligaments and Tendons*

Ligaments and Tendons	Young's Modulus [N/m^2]	Mass density [kg/m^3]
Superior malleal ligament	4.8×10^4	2.5×10^3
Lateral malleal ligament	6.7×10^4	2.5×10^3
Anterior malleal ligament	2.1×10^4	2.5×10^3
Superior incudal ligament	4.9×10^4	2.5×10^3
Posterior incudal ligament	6.5×10^5	2.5×10^3
Tensor tympanic tendon	2.6×10^6	2.5×10^3
Stapedius tendon	5.2×10^3	2.5×10^3
Tympanic annulus	6.0×10^4	1.2×10^3
Stapedius annular ligament	2.0×10^4	2.5×10^3

The finite element model consists of eardrum perforation, ossicles, ligaments and tendon. The ossicles are three tiny bones namely malleus, incus and stapes linking each other connected to the eardrum perforations. The geometrical shapes of the human middle ear system were defined considering by the other researchers [7].

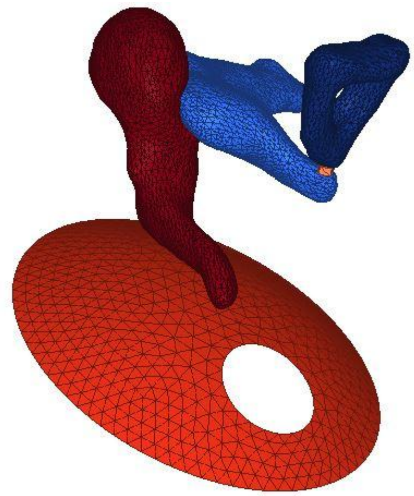

Fig. 1 *Finite Element Model of Human Middle Ear System with Eardrum Perforation*

4. Frequency Response Analysis

It is well known that there are two methods to perform frequency response analysis namely direct method and modal method. In this research, frequency response analysis of the finite element model was carried out by using the modal method. In the modal method, the eigenvector or vibration mode of the finite element model was used to uncouple the equation of motions and then the frequency response was obtained by summation of each modal responses. As for the external force, the harmonic excitation was assumed as follows.

$$\boldsymbol{f} = \boldsymbol{f_o}\, e^{j\omega_o t} \quad (1)$$

Where $\boldsymbol{f_o}$ and ω_o are the amplitude and the angular frequency of the harmonic excitation. In this study, the value of $P = 2.0 \times 10^{-6}$ Pa was used as the external forces. Then, the equation of motion of the finite element model can be written as follows.

$$\boldsymbol{M}\ddot{\boldsymbol{z}} + (1 + jG)\boldsymbol{Kz} = \boldsymbol{f}_o e^{j\omega_o t} \quad (2)$$

Where $\boldsymbol{z}$ and G are the displacement and damping, respectively. The structural damping was used as the damping in equation of motion. Then the value of $G = 1.5$ was used in frequency range 10 Hz to 10 kHz. In Eq. (3), the displacement will be transformed into the modal displacement. The transformation equation is given by

$$\boldsymbol{z} = \boldsymbol{\phi}\, \boldsymbol{z}(\boldsymbol{\omega}_o) e^{j\omega_o t} \quad (3)$$

where $\boldsymbol{z}(\boldsymbol{\omega}_o)$ is the modal displacement. Then, the velocity and the acceleration can be obtained as follows.

$$\dot{\boldsymbol{z}} = j\omega_o \boldsymbol{\phi}\, \boldsymbol{z}(\boldsymbol{\omega}_o) e^{j\omega_o t} \quad (4)$$

$$\ddot{\boldsymbol{z}} = -\omega_o^2 \boldsymbol{\phi}\, \boldsymbol{z}(\boldsymbol{\omega}_o) e^{j\omega_o t} \quad (5)$$

By substituting the Eqs. (3) and (5) into the Eq (2), the equation of motion becomes

$$-\omega_o^2 \boldsymbol{M}\boldsymbol{\phi}\, \boldsymbol{z}(\boldsymbol{\omega}_o)\, e^{j\omega_o t} + (1 + jG)\boldsymbol{K}\boldsymbol{\phi}\, \boldsymbol{z}(\boldsymbol{\omega}_o) e^{j\omega_o t} = \boldsymbol{f_o} e^{j\omega_o t} \quad (6)$$

After simplifying the Eq (6), it becomes

$$\left[-\omega_o^2 \boldsymbol{M}\boldsymbol{\phi}\,\boldsymbol{z}(\boldsymbol{\omega}_o)+(1+jG)\boldsymbol{K}\boldsymbol{\phi}\,\boldsymbol{z}(\boldsymbol{\omega}_o)-\boldsymbol{f_o}\right]e^{j\omega_o t}=0 \quad (7)$$

Multiply the Eq. (7) by $\boldsymbol{\phi}^T$ to uncouple the equation. Then, the following equation can be obtained.

$$-\omega_o^2\boldsymbol{\phi}^T\boldsymbol{M}\boldsymbol{\phi}\,\boldsymbol{z}(\boldsymbol{\omega}_o)+(1+jG)\boldsymbol{\phi}^T\boldsymbol{K}\boldsymbol{\phi}\,\boldsymbol{z}(\boldsymbol{\omega}_o)=\boldsymbol{\phi}^T\boldsymbol{f_o} \quad (8)$$

where $\boldsymbol{\phi}^T\boldsymbol{M}\boldsymbol{\phi}$, $\boldsymbol{\phi}^T\boldsymbol{K}\boldsymbol{\phi}$ and $\boldsymbol{\phi}^T\boldsymbol{f_o}$ are the generalized mass matrix, the generalized stiffness matrix and the modal external force, respectively. The generalized mass matrix and the generalized stiffness matrix are diagonal matrices. As for these diagonal matrices, the equation of motion is uncoupled. In the uncoupled form, the Eq. (8) can be written as a set of uncoupled single degree of freedom as follows.

$$-\omega_o^2 m_i z_i(\omega_o)+(1+jG_i)k_i z_i(\omega_o)=\boldsymbol{\phi}_i^T\boldsymbol{f_o},\ (i=1,2,3,\ldots,n) \quad (9)$$

Where m_i and k_i are i-th modal mass and i-th modal stiffness, respectively. Each of the modal responses can be obtained using

$$z_i(\omega_o)=\frac{\boldsymbol{\phi}_i^T\boldsymbol{f_o}}{(1+jG_i)k_i-\omega_o^2 m_i} \quad (10)$$

or

$$z_i(\omega)=\frac{\boldsymbol{\phi}_i^T\boldsymbol{f_o}/m_i}{\Omega_i^2+jG_i\Omega_i^2-\omega_o^2} \quad (11)$$

The displacement can be obtained by summation of the modal responses shown as follows.

$$\boldsymbol{z}=\sum_{i=1}^{n}\boldsymbol{\phi}_i z_i(\omega_o)e^{j\omega_o t} \quad (12)$$

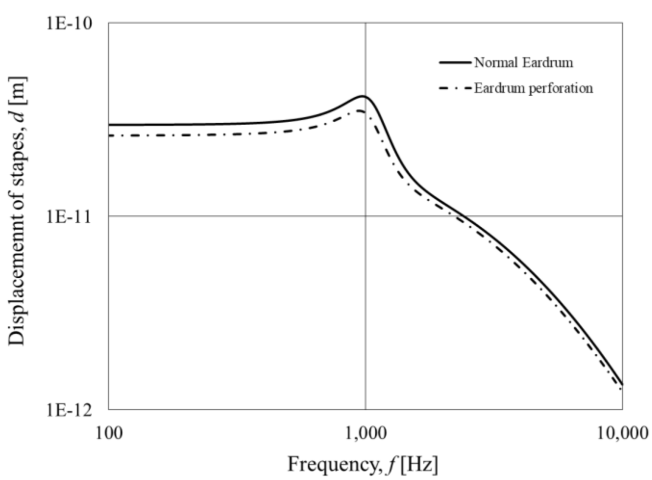

***Fig. 2** Frequency responses on the displacement of stapes of the human middle ear with eardrum perforation*

Figure 2 shows the frequency response of the human middle ear with eardrum perforation. It can be seen that the response of the human middle ear system with eardrum perforation is lower than normal eardrum. This is caused by loss of mass in the eardrum so that the response becomes decrease. Then, the first natural frequency of two types of the eardrum around 1,000 Hz.

5. Conclusion

The summary of the result is shown below.

1. The finite element model of human middle ear system with eardrum perforation had been developed.
2. The frequency response analysis had been carried out to show the response in the frequency range of 100 to 10 kHz.
3. The response of human middle ear system with eardrum perforation is lower than normal eardrum due to loss of mass.

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