Dynamic Behavior of Human Tympanic Membrane Perforation Using Finite Element Method

Hidayat¹, Sudarsono², Rozaini Othman³
¹Mechanical Engineering Department, Politeknik Negeri Samarinda, INDONESIA
²Mechanical Engineering Department, Universitas Haluoleo, 93232 Kendari, Sulawesi Tenggara, INDONESIA
³Faculty of Mechanical Engineering, Universiti Teknologi MARA Pulau Pinang, MALAYSIA

*Corresponding author’s e-mail: hidayat@polnes.ac.id

Abstract. Human tympanic membrane also known as an eardrum is a thin membrane that separates the outer ear and middle ear. The tympanic membrane perforation can cause longer lasting hearing loss. The purpose of this research is to simulate the dynamic behavior of tympanic membrane perforation using finite element method. In this paper, two types analysis model, namely normal tympanic membrane and tympanic membrane perforation were developed. Firstly, the geometrics model of human tympanic membrane was generated by CAD Software (Solidworks) using physical properties reported by other researchers. Then, eigenvalue analysis was carried out to simulate the dynamic behavior of two types of human tympanic membrane. As for the boundary conditions of human tympanic membrane, torsional springs were used for the rotational motion around one axis of the local coordinate frame on the boundary of tympanic membrane. Finally, the simulation of dynamic behavior of two types of tympanic membrane were compared.

1. Introduction
The human ear system is divided into three parts, namely outer ear, middle and inner ear. The middle ear system consists of a tympanic membrane, ossicles and some ligaments. As for the ossicles, these parts are three tiny bones linked each other connecting the tympanic membrane and cochlea (inner ear). The three tiny bones are malleus, incus and stapes but collectively called ossicles. The ossicles have functioned as a mechanical system to transmit the sound through from outer ear to the inner ear. A person unable to hear sound in one or both ears called hearing loss. There are three types of hearing loss, namely conductive, sensorineural, and congenital hearing loss. Many cases of conductive hearing loss happened due to problems in the tympanic membrane or ossicles — a hole in the thin membrane which separates the outer ear and middle ear called tympanic membrane perforation. The size of the hole and where is the hole in the eardrum can cause many problems. A tympanic membrane perforation or perforated eardrum such as a tympanic membrane having a hole accompanies liquid discharge from middle ear through the ear canal.

Many researchers on human middle ear system used finite element analysis to simulate the dynamic behavior of the human tympanic membrane. Finite element analysis is a powerful tool to simulate the tympanic membrane vibrations. The main benefits of finite element analysis in this research are to determine natural frequencies and vibration mode of tympanic membrane perforation which cannot be obtained by using traditional analysis method.

Wada et al. measured Young’s modulus, thickness and damping ratio of the human tympanic
membrane [1]. Ear canal was firstly investigated by using the finite element analysis on the curved conical ear canal by W. R. I. Funnell and C. A. Laszlo [2]. D. D. Greef et al. performed the dynamics analysis on a new anatomically-accurate model consists of the tympanic membrane and malleus using the finite element analysis [3]. Mehta, R.P et al. predicted the possibility of conductive hearing loss in tympanic membrane perforations [4]. Voss, S.E et al. developed a quantitative model of the human middle ear with ear drum perforation [5]. Saliba, I et al. carried out the differences of perforation sizes of the human ear drum and evaluated the effect of perforation on hearing levels and frequencies [6]. The previous research was carried out the eigenvalue analysis of tympanic membrane perforation with size of hole is 2.5 cm [7].

In this research, the dynamic behavior of the human tympanic membrane perforation was carried out. The finite element analysis software was used to carry out dynamics analyses of the human middle ear system with ear drum perforation.

Firstly, the geometric mode of the human tympanic membrane was generated by using CAD software. Then, geometric model as an IGS file was imported to the finite element analysis software. Furthermore, the eigen-value analysis of human ear drum perforations was carried out to obtain the natural frequencies and the vibration modes.

2. Finite Element Model of Human Tympanic Membrane

Figure 1 shows the finite element model of human tympanic membrane perforation. In this research, the human tympanic membrane perforation with the Young’s modulus and Poisson’s ratio were 33 MPa and 0.3, respectively. As for the mass density, the value of $1.3 \times 10^3$ kg/m$^3$ was used. The human tympanic membrane was generated by using CAD Software. One of the case human being have conductive hearing loss caused by the tympanic membrane perforation. The hole in tympanic membrane is around 50% of the membrane surface. As for the boundary condition of the tympanic membrane, the rotational springs elements were used around the tympanic membrane. The values $3 \times 10^{-5}$ Nmm/rad was used as the rotational spring constant in order to the finite element model in this research become similar to the real human tympanic membrane.[8]

![Figure 1. Finite Element Model of Human Tympanic Membrane Perforation](image)

3. Eigenvalue Analysis

In the dynamic analysis by using finite element method, the eigenvalue analysis was carried out to obtain the natural frequencies and the vibration modes of the finite element model without the damping. The equation of motion of the finite element model in the matrix-vector form is written by

$$M\ddot{x} + Kx = f$$  \hspace{1cm} (1)

Where $M$, $K$, $x$ and $f$ are the mass matrix, the stiffness matrix, the displacement and the external force, respectively. Then $M$ and $K$ are symetric matrices of order $n$. The $x$ and $f$ are the vectors of $n$ elements.
The natural frequencies and vibration modes can be obtained from the equation of motion by using a homogeneous equation. If there is no damping force, the homogeneous equation becomes

\[ M\ddot{x} + Kx = 0 \]  
(2)

In Eq. (2), \( x \) is assumed by using the fundamental solution, \( e^{j\omega t} \) as follows.

\[ x = x_o e^{j\omega t} \]  
(3)

Where \( x_o \) and \( \omega \) are the amplitude and the angular frequency of the finite element model, respectively.

The velocity and acceleration vectors in Eq. (2) can be given by the first and second derivatives of the Eq. (3) shown as follows.

\[ \dot{x} = j\omega x_o e^{j\omega t} \]  
(4)

\[ \ddot{x} = -\omega^2 x_o e^{j\omega t} \]  
(5)

Then, by substituting Eqs. (3) and (5) into the Eq. (2), the following equation can be obtained.

\[ -\omega^2 M x_o e^{j\omega t} + K x_o e^{j\omega t} = 0 \]  
(6)

After simplifying Eq. (6), it becomes

\[ \left[ -\omega^2 M + K \right] x_o e^{j\omega t} = 0 \]  
(7)

In Eq. (7), the angular frequency is not equal to zero (\( \omega \neq 0 \)), then Eq. (7) should become

\[ \left[ -\omega^2 M + K \right] x_o = 0 \]  
(8)

or

\[ \omega^2 M x_o = K x_o \]  
(9)

The Eq. (9) can be solved as generalized eigenvalue problem given by

\[ \Omega^2 M \phi_i = K \phi_i \]  
(10)

where \( \Omega^2 \), \( \Omega \) and \( \phi_i \) denote the \( i \)-th eigenvalue, natural angular frequency and eigenvector or vibration mode, respectively.

The \( i \)-th natural frequency can be written as follows.

\[ f_i = \frac{\Omega_i}{2\pi}, \quad (i = 1, 2, 3\ldots, n) \]  
(11)

Figure 2 shows the vibration modes of the normal and perforated eardrum. The natural frequency of tympanic membrane perforation is lower than normal eardrum. The effect of mass on tympanic membrane perforation reduce the natural frequency. The vibration modes of the perforated eardrum appeared around the hole of the eardrum.
### Vibration modes of the normal and perforated eardrum

| Vibration mode | Frequency |
|----------------|-----------|
| 1st natural frequency of normal eardrum, $f_1 = 3,062$ [Hz] |  
| 1st natural frequency of eardrum perforation, $f_1 = 339$ [Hz] |  
| 2nd natural frequency of normal eardrum, $f_2 = 3,183$ [Hz] |  
| 2nd natural frequency of eardrum perforation, $f_2 = 659$ [Hz] |  
| 3rd natural frequency of normal eardrum, $f_3 = 3,308$ [Hz] |  
| 3rd natural frequency of eardrum perforation, $f_3 = 1,377$ [Hz] |  

![Fig. 2 Vibration modes of the normal and perforated eardrum](image)

### 4. Conclusion

The summary of the results is shown below.

1. The finite element model of human tympanic membrane perforation had been developed by using CAD software.
2. The eigenvalue analysis of human tympanic membrane perforation had been performed to obtain natural frequencies and vibration modes.
3. The vibration modes of first, second and third natural frequency of human tympanic membrane perforation appear around the hole.

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