The dynamic characteristic of in-vivo human ossicles

Jen-Fang Yu
Graduate Institute of Medical Mechatronics
Chang Gung University
Taoyuan, Taiwan

Ching-I Chen
Department of Mechanical Engineering
Chung Hwa University
Hsinchu, Taiwan

Abstract—The study was to analyze the dynamic characteristics of ossicles under the stimulus frequencies, 125 Hz, 250 Hz, 500 Hz, 750 Hz, 1 kHz, 2 kHz, 3 kHz, 4 kHz, 5 kHz, 6 kHz, 7 kHz and 8 kHz, by finite element method. The finite element model of the ossicles chain of patients could be built by 3D image model of the ossicles based on the high resolution computed tomography. The displacement at the footplate would hardly occur when the ossicles was excited by the sound stimuli at frequency above 2 kHz. The presented result shows that the ossicles only could transmit the stimuli under 2000 Hz by the vibration of ossicles.

Keywords- Ossicles; Finite element method; Vibration analysis; High resolution computed tomography formatting

INTRODUCTION

Otorrhea and tympanic membrane perforation are common symptoms of chronic suppurative otitis media (CSOM). The ossicles might be infected because of CSOM. To recover from hearing loss, the ossicular disruptions that resulted from the congenital anomalies of middle ear or other diseases could be improved by ossiculoplasty [1].

However, the performance of ossicles conduction would be reduced due to ossiculoplasty. The vibration of ossicles would be affected due to the positive and negative pressure of the atmospheric pressure [2-3] and resulted in conductive hearing loss. In order to solve the problem, the generalized circuit model was utilized to simulate the vibration of ossicles [4]. The malleus vibration audiometer (MVA) was also used for evaluation [5]. Nevertheless, the heavier parts of ossicles could not be described effectively, such as the malleus head and the incus body. Additionally, the vibration mode of ossicles was analyzed by the finite element method [6-7]. The finite element model of ossicles was constructed by histological section images [6] and by the CT images of ossicles obtained from anatomicizing [7].

Therefore, this study is to reconstruct the 3D model of in-vivo ossicles based on the CT image of in-vivo ossicles obtained in clinical. Then the geometry of ossicles could be obtained and the finite element model could be constructed. Besides, the harmonic vibration characteristics of in-vivo ossicles could be analyzed by finite element method.

MATERIALS AND METHODS

The geometry of ossicles was acquired by the CT image of patients in this study. The 3D model of ossicles was reconstructed by the medical imaging software, Amira®. The file format of 3D model was transformed from STL into SAT by CAD and then the SAT file was imported into the finite element analysis software, ANSYS®. The finite element model of ossicles was built by adopting the SOLID185 and by the free meshing method. The repeated nodes between ossicles were combined as one single node. The finite element model of ossicles was then built up. To reconstruct the finite element model, the joint between the incus and stapes would be considered due to the large value of Young's modulus. The COMBIN14 Spring-Damper was utilized for the vertical and horizontal direction on the stapes footplate. The vertical and horizontal spring elements were shown in figures 1(a) and 1(b), respectively.

The material parameters for each part of ossicles were different. Only the Poisson's ratio for overall structure was assumed 0.3 because the parameter used in mostly studies was quite close to this value. Based on previous study, the analysis of the dynamic characteristics of ossicles was not affected by the Poisson's ratio significantly [8]. The damping matrix was shown as follows:

\[ [c] = \alpha [M] + \beta [K] \tag{1} \]

where \([M]\) and \([K]\) indicated the mass matrix and stiffness matrix, respectively; \(\alpha\) and \(\beta\) indicated the damping parameters. The overall structure consisted of the three ossicles, the joints between incus and stapes, and the springs on the stapes.

The Young's modulus of ossicles was 14.1GPa, which was assumed to be the linear elastic, equal quality and equal direction material. The density of each part of ossicles was different shown in table 1.

The incudomalleolar joint (I-M joint) was adopted based on previous study which mentioned that there was no relative motion between the malleus and incus at low frequency (< 3 kHz) [9]. Therefore, the Young's modulus was assumed 14.1GPa. The nodes that connected the malleus and incus were combined to one node in this study. The joints between the incus and stapes were adopted according to previous study which mentioned that there was no stiffness displacement on the joints under the circumstance of the serious variety of noise and pressure [10]. Besides, there was some relative motion between the incus and stapes. The inner ear was protected and would not be damaged by the large displacement of stapes footplate. Additionally, the joints between the incus and stapes were assumed as the homogeneous materials and equivalent, and the Young's modulus was 0.6MPa [11, 12].
As for the harmonic analysis, there were 6 x-y plane springs on the vertical side of stapes footplate. The total constant of springs (K) was 60 N/m. The total damping was 0.054 N*s/m. The constant of springs of the nine 3D vertical springs on the horizontal side was assumed 9 N/m. The vertical and horizontal springs of the stapes footplate were fixed to the UX, UY and UZ direction movement of the nodes of ossicles, respectively. To simulate the response of sound transmitted to the cochlear fluid by ossicles, the vertical direction was constrained to be the 2-D spring-damper which could be merely pulled vertically. The horizontal direction was utilized to simulate the actual motion on the stapes footplate. Therefore, the 3-D spring-damper was assumed.

The ossicles and the ligament and spring-damper of the stapes footplate were analyzed in this study. The degrees of freedom of the three directions of the nodes that connected the spring-damper and the stapes footplate were fixed shown in figure 2. The nodes on the base area of manubrium were excited at -X direction by 90 dBSPL shown in figure 3. Based on the modal superposition (MSUP) theorem, the results of modal superposition was obtained by transforming to the original coordinates system. The results of modal superposition was expended to the overall structure to understand the response of sound transmitted to the inner ear thru ossicles after the ossicles was excited by the sound pressure (90 dBSPL) under the stimulus frequencies of 125 Hz, 250 Hz, 500 Hz, 750 Hz, 1 kHz, 2 kHz, 3 kHz, 4 kHz, 5 kHz, 6 kHz, 7 kHz, 8 kHz. Hence, the dynamic characteristic of the in-vivo human ossicles could be analyzed.

RESULTS AND DISCUSSION

The harmonic analysis focused on the joints of the malleus head and the tympanic membrane. The based area of the malleus head, 3.081 mm³, was excited by 90 dBSPL (0.623Pa). The frequency and the amplitude response of the specific nodes (figure 4) on the stapes footplate at 250 Hz to 8 kHz were observed shown in figure 5. The results were also observed by X, Y and Z directions shown in figures 6 to 14.

Based on figures 6 to 14, there was an apparent turning point on the 9 nodes of the stapes footplate at 1 kHz to 2 kHz. Therefore, the ossicles excited by the sound stimuli at frequency below 1 kHz would vibrate. The displacement was the amplitude of the sound stimuli transmitted to the stapes footplate. In contrast, the displacement would hardly occur when the ossicles was excited by the sound stimuli at frequency above 2 kHz, and the transmission power of ossicles was adopted directly.

CONCLUSION

To meet the needs in clinic, the image of in-vivo human ossicles was reconstructed successfully by computed tomography scan in this study, which could help the clinician know the distribution of ossicles for patients instantly. Therefore, the 3D image of ossicles could be successfully imported to the ANSYS® of CAE software by the SolidWorks® of CAD software. Additionally, after understanding the dynamic characteristic by finite element method, the evaluation of the substitute implant at pre-op could be offered. When the ossicles was excited by the sound stimuli at frequency below 1 kHz, the amplitude of sound stimuli was shown by the vibration of ossicles. The displacement would hardly occur when the ossicles were excited by the sound stimuli at frequency above 2 kHz, and the sound was transmitted by ossicles directly.
Figure 5  The displacement at node 1 on the footplate under stimulus frequencies including 125 Hz, 250 Hz, 500 Hz, 750 Hz, 1 kHz, 2 kHz, 3 kHz, 4 kHz, 5 kHz, 6 kHz, 7 kHz and 8 kHz.

Figure 6  The displacement at node 2 on the footplate under stimulus frequencies including 125 Hz, 250 Hz, 500 Hz, 750 Hz, 1 kHz, 2 kHz, 3 kHz, 4 kHz, 5 kHz, 6 kHz, 7 kHz and 8 kHz.

Figure 7  The displacement at node 3 on the footplate under stimulus frequencies including 125 Hz, 250 Hz, 500 Hz, 750 Hz, 1 kHz, 2 kHz, 3 kHz, 4 kHz, 5 kHz, 6 kHz, 7 kHz and 8 kHz.

Figure 8  The displacement at node 4 on the footplate under stimulus frequencies including 125 Hz, 250 Hz, 500 Hz, 750 Hz, 1 kHz, 2 kHz, 3 kHz, 4 kHz, 5 kHz, 6 kHz, 7 kHz and 8 kHz.

Figure 9  The displacement at node 5 on the footplate under stimulus frequencies including 125 Hz, 250 Hz, 500 Hz, 750 Hz, 1 kHz, 2 kHz, 3 kHz, 4 kHz, 5 kHz, 6 kHz, 7 kHz and 8 kHz.

Figure 10 The displacement at node 6 on the footplate under stimulus frequencies including 125 Hz, 250 Hz, 500 Hz, 750 Hz, 1 kHz, 2 kHz, 3 kHz, 4 kHz, 5 kHz, 6 kHz, 7 kHz and 8 kHz.

Figure 11 The displacement at node 7 on the footplate under stimulus frequencies including 125 Hz, 250 Hz, 500 Hz, 750 Hz, 1 kHz, 2 kHz, 3 kHz, 4 kHz, 5 kHz, 6 kHz, 7 kHz and 8 kHz.

Figure 12 The displacement at node 8 on the footplate under stimulus frequencies including 125 Hz, 250 Hz, 500 Hz, 750 Hz, 1 kHz, 2 kHz, 3 kHz, 4 kHz, 5 kHz, 6 kHz, 7 kHz and 8 kHz.
Figure 13  The displacement at node 9 on the footplate under stimulus frequencies including 125 Hz, 250 Hz, 500 Hz, 750 Hz, 1 kHz, 2 kHz, 3 kHz, 4 kHz, 5 kHz, 6 kHz, 7 kHz and 8 kHz.

REFERENCES


