LETTER

Vibration Analysis of Human Middle Ear with Differential Floating Mass Transducer Using Electrical Model

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SUMMARY In this paper, the vibration characteristics of stapes, driven by the implanted differential floating mass transducer (DFMT) in the human middle ear, are analyzed by using an electrical model. The electrical model has been simulated by using the PSpice, in which the simulated results are compared with the experimental results by using the fabricated DFMT and the human temporal bones.

key words: *electrical model, lumped model, middle ear, DFMT*

1. Introduction

Recently, implantable middle ear hearing devices (IMEHDs) have been actively studied as an alternative to conventional hearing. The IMEHDs consist of a microphone, a signal processor, and a vibration transducer. The vibration transducer, an output device of IMEHDs, is implanted with a clip on a human ossicular chain by means of middle ear surgery, and transmits a mechanical vibration to the stapes [1], [2]. As one of the vibration transducers, the differential floating mass transducer (DFMT), which consisted of two magnets, a coil, and two vibration membranes, was fabricated and noted in our previous study. In addition, as a patient's requirement, the vibration characteristic of DFMT can be tuned by adjusting the stiffness of the vibration membrane in the fabrication process [3], [4]. However, the vibration characteristic of stapes, driven by the implanted DFMT, was different from the DFMT itself because vibration transmitted from the DFMT to stapes is affected by the mechanical coupling between the DFMT and the human auditory peripherals. Therefore, it is necessary to analyze the vibration characteristics of stapes after implantation of DFMT for developing DFMT of IMEHDs, and this analysis should be conducted, considering the vibration characteristics of DFMT as well as middle ear. The vibration characteristics of stapes, driven by the implanted DFMT, were studied on the basis of simplified acoustical models of middle ear transfer function and DFMT, by Song. However, the studied vibration characteristics were different from in-vitro experimental results because the mechanical properties of human auditory peripheral, such as malleus, incus, stapes, and ligaments were not considered in the acoustical model of Song [5].

In this paper, the vibration characteristics of the human middle ear, driven by implanted the DFMT, are analyzed by using an electrical model. First, in order to extract the electrical model, the lumped mechanical model for the human middle ear and the DFMT have been adopted and combined, considering the clip for coupling DFMT and the ossicular chain. Then, the combined lumped mechanical model is transformed into equivalent electrical model. By changing the stiffness of the vibration membrane, a variation of the stapes displacement, driven by the implanted DFMT, is simulated by using PSpice. The simulated vibration characteristics have been compared with the in-vitro experimental results by using the fabricated DFMT and human temporal bones. Through the comparison, it is verified that the vibration analysis, using the electrical model, is helpful for predicting the vibration characteristics of stapes driven by DFMT after the implantation.

2. Frequency Response Vibration Analysis of Human Middle Ear Driven by Attached DFMT

For the vibration analysis of the human middle ear driven by the implanted DFMT, the lumped mechanical model for the DFMT, as well as that for the human middle ear as stated previously in other publications, are adopted and combined [6]. All the mechanical elements of the DFMT and the human middle ear are transformed into the passive elements of the equivalent electrical model. The vibration characteristics of stapes, driven by the implanted DFMT, are investigated according to the changing values of passive elements corresponding to the components of DFMT.

2.1 Lumped Mechanical Model

The structure of DFMT was modeled into the simple vibration system of two masses and two springs in the previous studies. In regards to the lumped mechanical model of the human middle ear, the properties of the tympanic membrane, malleus, incus, stapes and ligaments were used the mean value of the human auditory peripheral, and were also cited, based on the data in Feng's paper. The two lumped mechanical models were combined, as shown in

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Fig. 1, through the clip which is used to attach the DFMT to the incus.

Then, the system can be described by Newton's kinetic equations, as follows:

$$[m][\ddot{x}] + [c][\dot{x}] + [k][x] = [\mathrm{F}] \qquad (1)$$

Where [M], [C], [K], [X] and [F] represent the mass, damping coefficient, stiffness coefficient, displacement and force, respectively. Each matrix can be represented by using passive elements, such as the inductor, resistor, capacitor, current and voltage by means of the electro-mechanical equivalent relationship.

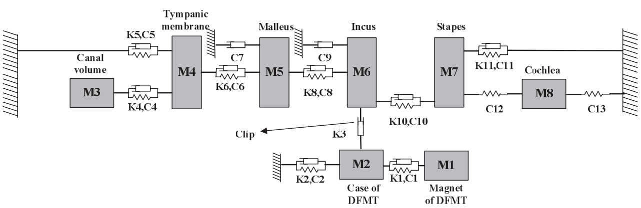

Fig. 1 Lumped mechanical models of the human middle ear coupled with the DFMT.

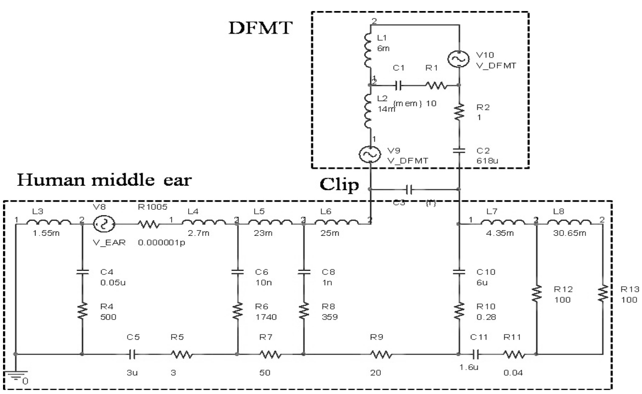

Fig. 2 The equivalent electrical model regarding the lumped mechanical models of the human middle ear, coupled with the DFMT.

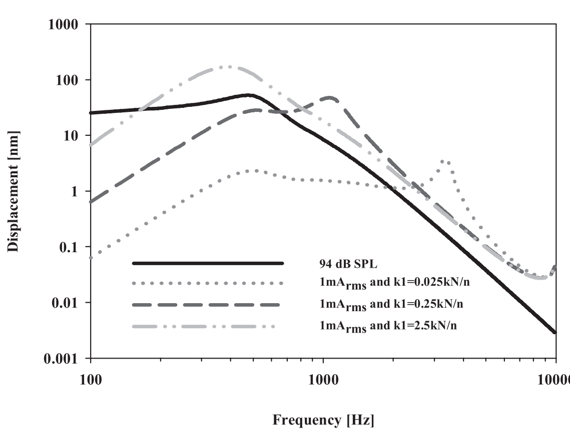

Fig. 3 The simulated stapes displacement in both cases of the DFMT unloaded and the loaded states under different conditions.

2.2 Electrical Model

Figure 2 shows the converted equivalent electrical model. The electrical model assumes that the electrical variable, L6, is connected to L2 through C3 corresponding to the incus, DFMT case and the clip. At Fig. 2, V_EAR and V_DFMT represent the sound pressure applied to the tympanic membrane and the force generated by DFMT, respectively.

2.3 Simulation of the Electrical Model

In order to predict the vibration characteristics of stapes after the implantation of DFMT, the simulation, using the electrical models in Fig. 2, is conducted through PSpice as the values of passive elements, corresponding to stiffness of the vibration membrane, have been changed. As shown in Fig. 3, the stiffness of the vibration membrane has an effect on the frequency response of stapes. Normally, hearing impaired persons who suffer from sensory-neural hearing loss require more amplification of high frequencies rather than low frequencies. Therefore, the stiffness of the vibration membrane could be selected according to the audiogram of specified hearing impaired persons.

3. Experimental Results and Disccusion

Three pairs of temporal bones and the fabricated DFMT are used in the experiment, such as that demonstrated in Fig. 4, while the experimental setup is illustrated in Fig. 5. The function generator (Tektronics Inc. AFG320) is used to generate the sinusoidal signal for purposes of driving the DFMT and earphone (Etymotic, ER2) in the region of the audio frequency by using the Labview program. The acoustic signals

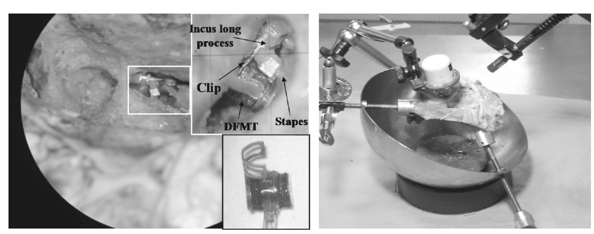

Fig. 4 Photograph of vibration measurement setup and DFMT attached to the incus long process.

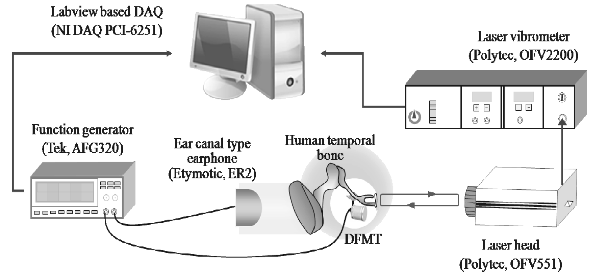

Fig. 5 Block-diagram of experimental setup.

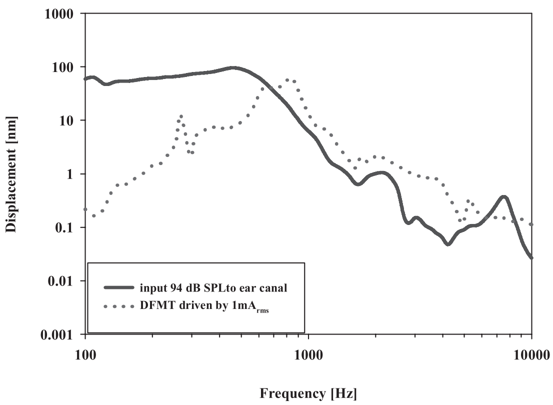

Fig. 6 The measured stapes displacements in regards to the in-vitro experiment by using the human temporal bones and the DFMT.

from the earphone are applied to the eardrum for purposes of measuring the audiogram. The peak-to-peak displacement of the stapes measured by the laser doppler vibrometer (Polytec, OFV-551) was obtained by the system (NI Co., PCI-6251) which was interfaced to the PC with the GPIB. The DFMT, with the membrane's stiffness of 0.25 kN/m, is fabricated to obtain sufficient gain at the high frequency range over 2 kHz, on the basis of the simulated results as shown in Fig. 3. The fabricated DFMT is 1.8 mm long and 2.0 mm in diameter. The clip, for the coupling the incus long process (ILP) with DFMT, is 2 mg in weight and 100 μm in thickness.

Figure 6 shows the results of the in-vitro experiment by using the fabricated DFMT and the human temporal bones. The frequency responses of stapes after implantation are similar to the simulated results, in that it has a resonance frequency of approximately 1 kHz. In addition, the vibration displacement of stapes, driven by the implanted DFMT, has in excess of 5 dB displacement, compared with that before implantation in the region above the resonance frequency.

4. Conclusion

In this paper, the vibration characteristics of human middle ear, driven by the implanted DFMT, are analyzed by using the electrical model. The electrical model is transformed on the basis of the lumped mechanical models of the DFMT and the human middle ear. The variation of stapes displacement, driven by the DFMT implanted in the human middle ear, is simulated as the vibration characteristics of DFMT have been changed. The simulated results are compared with the experimental results using the fabricated DFMT as well as the human temporal bones. Through the comparison, it is verified that the vibration analysis, using electrical model, is helpful in order to predict the vibration characteristics of stapes driven by the DFMT after implantation.

Acknowledgments

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References

[1] H.H. Kim and D.M. Barrs, "Hearing aids: A review of what's new," Otolaryngology-Head and Neck Surgery, vol.134, no.6, pp.1043–1050, 2006.

[2] A.J. Needham, D. Jiang, A. Bibas, G. Jeronimidis, and A. Fitzgerald O_Connor, "The effects of mass loading the ossicles with a floating mass transducer on middle ear transfer function," Otology & Neurotology, vol.26, pp.218–224, 2005.

[3] B.S. Song, M.K. Kim, Y.H. Yoon, S.H. Lee, and J.H. Cho, "Design of a differential electromagnetic transducer for use in IME system," IEICE Trans. Inf. & Syst., vol.E87-D, no.5, pp.1231–1237, May 2004.

[4] M.W. Kim and K.W. Seong, "Design of differential floating mass transducer for fully-implantable middle ear hearing devices using electrical model," ITC-CSCC, 2006.

[5] B.S. Song, Design of Environmental Magnetic Field Interference Free Differential Electromagnetic Transducer for Implantable Middle Ear System, Dissertation of Kyungpook National University, 2002.

[6] B. Feng and R.Z. Gan, "Lumped parametric model of the human ear for sound transmission," Biomechanics and Modeling in Mechanobiology, vol.1, pp.33–47, Springer-Verlag, Berlin, 2004.