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Short communication

A novel opto-electromagnetic actuator coupled to the tympanic membrane

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ABSTRACT

A new type of electromagnetic vibration transducer designed to be placed onto the tympanic membrane was developed. The actuator consisted of two photodiodes, two permanent magnets, an aluminum ring, two opposing wound coils, a latex membrane and a Provil NovoTM membrane. An optic probe was designed to allow sound and light signals to enter the ear canal, thereby preventing the acoustic occlusion effect of traditional ear molds. Two light-emitting diodes were used for carrying the input signals. The corresponding photodiodes were used for receiving the light signals and generating currents in the actuator. The opto-electromagnetic vibration actuator was fabricated and tested using a Laser Doppler vibrometer. The actuator showed displacements of vibration between 30 and 1 nm from 300 to 6500 Hz and reduced in amplitude at higher frequencies. The average gain of the actuator with 140 μ A on the umbo displacement was about 20 dB relative to 87 dBA at the distance of 6 cm from the tympanic membrane and 0 μ A in actuator.

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1. Introduction

Hearing impairment affects more than 30% of the population older than 65 years in age worldwide. Currently, the best treatment or alleviation for these hearing-impaired patients available is to provide a hearing aid followed by aural rehabilitation. Conventional acoustic hearing aids have some inherent problems. For instance, distortion happens when the electronic signals are converted back into acoustic signals through the output receivers (Plomp, 1978). Moreover, acoustic feedback and occlusion effects are another two commonly encountered conditions (Plomp, 1978; Perkins, 1996). In order to solve the aforementioned problems of conventional hearing aids, Perkins in 1996 developed an Earlens system with a magnetic actuator on the ear drum. Unfortunately, the functional gains of his system were variable and the magnetic forces were quickly decreased with increased distance.

This work developed and tested a new type of “opto-electromagnetic” vibration actuator which can be attached onto the tympanic membrane (TM). The idea was adapted from the Earlens system of Dr. Perkins (1996). However, the electric wires were wound surrounding the magnet on the actuator. This minimizes the required current to drive the magnet and provide stable vibration (Hüttenbrink, 1999). Furthermore, in order to leave the canal open, the input sound signals are carried and transmitted remotely from the signal processor to the actuator via visible light. The light strikes on two photodiodes, which generate currents to drive the electromagnetic actuator. Through this opto-electromagnetic actuator, sounds can be amplified and converted to induce the vibration of auditory ossicles directly.

2. Materials and methods

2.1. Design of the actuator and signal processing

The newly designed opto-electromagnetic actuator was shown in Fig. 1. The actuator consisted of two photodiodes, two permanent magnets, an aluminum ring, wound coil, latex membrane and a Provil NovoTM membrane (Heraeus Kulzer, New York, USA). The thickness of the latex membrane was about 0.1 mm. The Provil NovoTM membrane was used to fit the conical concavity of the TM. The actuator was placed on the umbo area of the TM and mineral oil was used to

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maintain its position. The adhesive forces between the TM and Provil membrane were provided by the mineral oil (Perkins, 1996).

An optic probe about 40 cm in length and 0.76 mm^2 in cross section area was designed to be inserted to pass the cartilaginous portion and reach the second portion of external ear canal. That leaves the working distance between the probe tip and the actuator around 10–15 mm. The probe will be shaped with package materials so that orientation of the probe is adjustable and can provide direct incidence of light on the PD, thus will minimize the effect of misalignment. Two light-emitting diodes (LED) were used (ED-014BL-B1 and ED-014BL-G; OPTO TEC, Taiwan) for carrying the input signals. The corresponding photodiodes (PD) were used (PD-0120C-B and PD-0120C-G; OPTO TEC, Taiwan) to receive the light signals and to generate the currents in the actuator, as shown in Fig. 2. The maximum output current of the PD was about $290 \mu\text{A}$. We used two half-wave rectifiers to process the input signals. In Fig. 2, the diode A and B are two half-wave rectifiers. The actual voltage of the electrical signals was carefully controlled below 3 V. By

meticulously controlling the pre-amplifier, we can adjust the excitation voltage of the LED and make the PD to generate enough currents ($106\text{--}140 \mu\text{A}$) to drive the actuator. In addition, these diodes were used to avoid reaching the inverse breakdown point of LED and to protect the LEDs. The positive cycles of sound signals passed through the blue LED, which were then received by the corresponding blue PD. Likewise, the negative cycles of signals passed through the green LED, and then were received by the corresponding green PD. In this way, the output signals could generate currents in the coils of the actuator. Since the actuator was composed of two bi-directionally wound coils, the magnetic fields created by the cycling currents were transformed into mechanical vibrations of the actuator.

2.2. Fabrication and testing of the actuator on the human temporal bone

The actuator was fabricated based on the results calculated by a three-dimensional (3D) middle ear finite element (FE) model (Lee et al., 2006) and adaptations of its original design. The vibration transducer was created by a computer-aid design. Then, the new-coupled TM-transducer complex was loaded to the 3D FE model. The air gap between the magnet and the coil, the input current, and vibration force could be estimated by FE simulation as reported in our previous work (Lee et al., 2007). The winding of coils and other fabrication process was performed by a skillful technician in our laboratory.

The mechanical and acoustic characteristics of the actuator were measured with a Laser Doppler vibrometer (Polytec OFV-2802 and OFV-508, Karlsruhe, Germany). The sound source was a commercially available high-quality speaker (Pioneer TS-D1602R, USA). The speaker is capable of handling power of 60 W, 260 W maximum, with a wide frequency response of 35–32 kHz at 88 dB. A sound level meter (Rion NA-24, Japan) in its "A" weighted scale was used to measure and control the sound pressure relative to the TM. The speaker was 13 cm away from the TM, while the sound level meter was at a distance of 6 cm from the TM. Human formalin-fixed cadaver temporal bone was obtained because it is impossible to use fresh temporal bone to do experiment in this country. The pinna was removed and the ear canal was trimmed a little wider to assist the insertion and fixation of the actuator. Then the actuator was placed on the TM. The temporal bone was placed in a bone holder attached to a heavy metal plate and a retro tap (Polytec, Karlsruhe, Germany) was glued to the umbo. All experiments were carried out in the dark so that the equivalent input sound level of ambient light is negligible.

3. Results

3.1. The physical characteristics of the actuator

The mass of the actuator was about 115 mg. The components of the actuator have been shown in Fig. 1. The diameter and the thickness of the small permanent magnet were 2.5 and 0.4 mm, respectively. The diameter and the thickness of the large

Fig. 1. The components of opto-electromagnetic vibration actuator including two photodiodes (1a), a small permanent magnet (1b), latex membrane (1c), a large permanent magnet (1d), aluminum ring (1e), two opposite direction wound coils (1f) and a provil novo membrane (1g).

Fig. 2. The diagram of two half-wave rectifiers: The positive cycles of signals passed through the blue light-emitting diode (LED BLUE). Then they were received by corresponding blue photodiode (PD BLUE). Likewise, the negative cycles of signals passed through the green light-emitting diode (LED GREEN). Then they were received by the corresponding green photodiode (PD GREEN).

Fig. 3. A: The actuator (1) was put onto the TM (2) of human temporal bone (3). B: The bone was placed in a temporal bone holder attached to a heavy metal plate and a retro tape glued to the umbo (arrow).

permanent magnet were 2.5 and 0.8 mm, respectively. The permanent magnets were a neodymium iron boron (NdFeB) metal alloy. The maximum magnetic flux density on the surface of the magnet was 3000 G. The air gap between the magnet and the coil was 200 μm . The wire diameter of the wound coil was 15 μm . To get the maximum magnetic force of the actuator, we added an aluminum ring with an inner diameter of 3.5 mm, an outer diameter 4.7 mm and a height of 0.7 mm. The fabricated prototype of the opto-electromagnetic actuator coupled to the ear drum was shown in Fig. 3.

3.2. Vibration amplitude measurements

Fig. 4 shows the in vitro experimental frequency response of the umbo and malleus driven with 87 dBA about 6 cm from the eardrum, as our reference and the frequency response of the fabricated actuator driven with currents of 106, 120 and 140 μA . A first resonant frequency (RF) appeared near 900 Hz, whereas the second RF occurred at 2000 Hz and the third RF occurred near 5500 Hz. The frequency response of the fabricated transducer indicated that the displacement of vibration is from 10–1 nm (at 300–6500 Hz) and reduces with higher frequencies. Over 6500 Hz, the vibration amplitude of the actuator with different input currents was smaller than that without an input current. The average gain of the actuator on umbo displacement was about 20 dB relative to 87 dBA at the distance of 6 cm from the TM and 0 μA in actuator.

The vibration amplitude of the ear drum without the actuator was also shown in Fig. 4. It appears that the curve has a resonance peak at around 5500 Hz, which disappeared after loading the actuator. There were 6–20 dB attenuation (depending on frequency) of umbo displacement after the actuator was loaded primarily due to the mass effect of the actuator.

Fig. 4. Frequency response of the fabricated vibration transducer driven with 87 dBA in the eardrum and driven with 106, 120 and 140 μA . The displacement curve of the umbo without the actuator was also shown.

4. Discussion

In this study, a novel electromagnetic vibration actuator which can leave the ear canal open was created and measured with a Laser Doppler vibrometer. The configuration of this actuator offers several advantages over conventional hearing aids. The potential benefits include elimination of feedback and occlusion, and direct drive of the ossicles (the amplified signals do not need to be converted back into sound like the conventional hearing aids do, hence reducing distortion and increasing clarity). In addition, the open ear canal provides a pathway for the retention of normal resonances. Most importantly, the actuator placement does not require an operation. Preliminary studies suggest that remote transmission and some amplification can be achieved by this actuator. The RF of the rigid TM was found to be around 5500 Hz without attaching the actuator. The displacement–frequency response of unloaded TM is different from those reported in the literature and predicted by our FE model. The major reason of this discrepancy may result from the rigidity of the formalin-immersed TM, calibration using an “A” weighted scale and frequency response of the speaker may also be contributing factors. Loading the actuator but not driving it will inevitably cause hearing reduction compared to the unaided condition. This reduction has to be compensated by the gain provided by the actuator and the amplifier that connects the optic probe.

The frequency responses of the actuator reveal multiple peaks in the response curve, and these peaks may be a consequence of the different vibration modes of the actuator systems in the middle ear. However, these peaks can be resolved and addressed with psychoacoustic tuning curves or by reshaping with the signal processor. Additionally, the ideal mass of the vibration actuator needs to be much less than 110 mg in order to avoid a mechanical bias force. Gan et al. (2001) reported masses as little as 25 mg can cause attenuation of displacement. The fabricated actuator is the prototype now. The mass and size of the actuator can be miniaturized by using more powerful permanent magnets and more efficient PD in the future so that the hearing reduction by loading this actuator can be minimized.

Conflicts of interest

None.

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