Implantable MEMS Accelerometer Microphone for Cochlear Prosthesis

Darrin J. Young, Mark A. Zurcher, Wen H. Ko
Electrical Engineering and Computer Science Department
Case Western Reserve University
Cleveland, OH 44106 USA
darrin.young@case.edu

Maroun Semaan, Cliff A. Megerian
Department of Otolaryngology-Head and Neck Surgery
University Hospital of Cleveland
Cleveland, OH 44106 USA
Cliff.Megerian@uhhs.com

***Abstract*—A MEMS accelerometer is proposed as an implantable middle ear microphone for future fully implantable cochlear prosthesis. Vibration characterization of human temporal bones by using laser Doppler vibrometer indicates that a MEMS accelerometer needs to achieve a sensing resolution of 75 $\mu g/\sqrt{Hz}$ with a bandwidth of 10 kHz to detect normal conversation. A prototype MEMS accelerometer is designed and fabricated. When interfaced with a low noise CMOS capacitance-to-voltage converter, the sensor achieves a sensing resolution of 78 $\mu g/\sqrt{Hz}$ at 500 Hz with a sensitivity of 11.5 mV/g and bandwidth of 6.4 kHz. The overall system attached on umbo demonstrates the capability of detecting normal conversation.**

I. INTRODUCTION

Over 20 million people in the United States are affected by sensorineural hearing loss. Contemporary acoustic hearing aids can achieve moderate rehabilitation in a large number of sensorineural hearing loss cases. However, inherent technological limitations, such as acoustic feedback and distortion, and perceived social stigma associated with these devices have resulted in many patients being deprived of basic hearing abilities. Although partially implantable middle ear and cochlear prosthetic systems have gained acceptance, reliability, practicality and social stigma concerns are presented by the use of external accessories such as microphones and electronics. Therefore, the development of fully implantable high-performance prosthetic systems is highly desirable.

Several research groups have made progress [1] - [3] in developing systems that rely on piezoelectric and electromagnetic effects for compensating conductive hearing loss. To date, however, no fully implantable prosthetic system is commercially available. External radio frequency coils, microphone, and speech processor are used for modern semi-implantable cochlear implants. The speech processors can be potentially integrated as a part of the existing implant unit. However, a significant challenge is presented in realizing a high-performance implantable microphone. This paper describes a MEMS accelerometer proposed as an implantable middle ear microphone for realizing future fully implantable cochlear prosthesis. Figure 1 shows the proposed conceptual prosthetic system architecture.

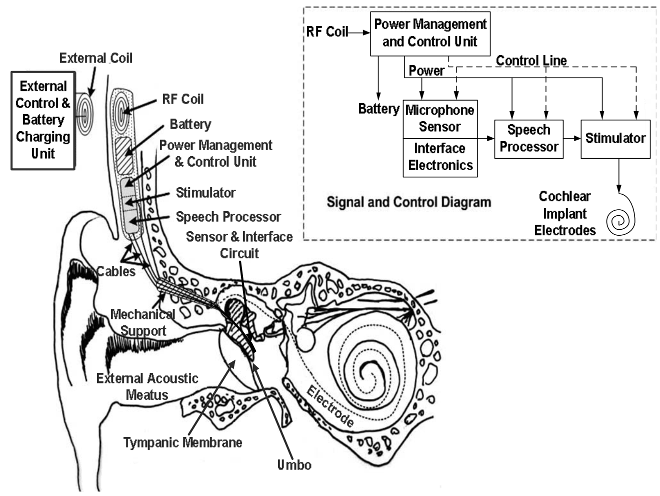

Figure 1. Proposed fully implantable cochlear prosthetic system architecture.

Based on accelerometer operating principle, the proposed middle ear microphone can be attached to the umbo to convert the bone vibration to an electrical signal representing the input acoustic information. Further processing of the electrical signal can be performed by the cochlear implant speech processor, which is followed by a stimulator to drive cochlear electrodes. The speech processor, stimulator, power management and control unit, rechargeable battery and radio-frequency (RF) coil can be housed in a biocompatible package located under the skin to form a wireless communication link with the external adaptive control and battery charging system.

II. HUMAN TEMPORAL BONE CHARACTRIZATION

The most efficient sensing performance can be achieved by attaching the accelerometer at an ossicular location exhibiting the greatest vibration amplitude responding to an external acoustic stimulus. Published data indicates that the umbo vibrates with the largest vibration amplitude in response to auditory inputs [4] - [5]. However, previously reported measurements have been performed along a direction perpendicular to the tympanic membrane. Due to the curved umbo surface, it is possible that the device may become misaligned anterior or posterior to the long process of the malleus during attachment, which could potentially degrade sensitivity. Therefore, it is necessary to investigate and characterize the umbo vibration response along different axes. In this research, the direction perpendicular to the tympanic membrane is defined as the primary axis of the umbo, and the vector parallel to the tympanic membrane plane and perpendicular to the long process of the malleus is defined as the secondary axis of the umbo, as depicted in Figure 2 for illustration purpose. Measurement data obtained on umbo along the two axes can provide better understanding of sensor performance associated with any device position misalignment and can also be used as a design guideline for the MEMS accelerometer development.

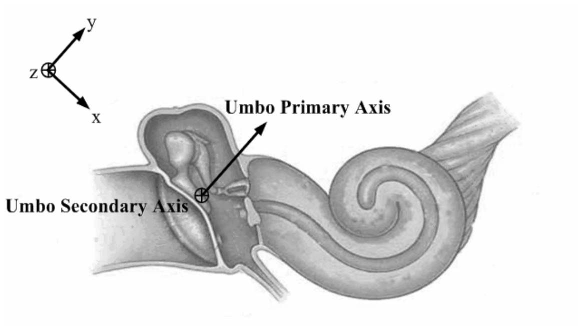

Figure 2. Illustration of axes characterized by laser Doppler vibrometer (LDV). Relative to the axes shown in the inset, the umbo primary axis is along the y – axis, and the umbo secondary axis is measured along the z – axis into the plane of the picture.

Four cadaveric temporal bones were used to study the vibration characteristics of the umbo. The bones were kept stored in 1:10,000 merthiolate in 0.9% saline solution to maintain soft tissue compliance and hydration after thawing. All temporal bones were individually inspected under a microscope to verify an intact tympanic membrane, ear canal and ossicular bone structure. Any bone with any evidence of pathology or structural damage due to middle ear cavity exposure was not used. Temporal bones were then sequentially opened in two stages. A simple mastoidectomy with a facial recess approach was performed first. After the initial opening of the middle ear cavity, the temporal bone was further opened in a second stage of drilling. In this stage, the facial recess was widened such that full access was gained into the middle ear. The drilling proceeded until the tympanic membrane could be visualized. The bone was then thoroughly rinsed in saline and two pieces of 1 mm^2 reflective material, each weighing approximately 50 micrograms, were placed as targets for the umbo primary and secondary axes characterization. A temporal bone under examination was placed in a weighted temporal bone holder. An insert earphone driven by a waveform generator presented pure tones within the audible spectrum to the tympanic membrane. A probe microphone was positioned approximately 4 mm from the tympanic membrane to monitor the input sound pressure level. A laser Doppler vibrometer (LDV) exhibiting a velocity resolution of 5 μm/s over the frequency range of DC to 50 kHz was used to measure the umbo vibrational characteristics.

Figure 3 compares the average peak-to-peak acceleration of the umbo measured along the primary axis and along the secondary axis in four cadaveric ears, stimulated by an input tone of 80 dB, 90 dB, and 100 dB sound pressure level (SPL) within the audible spectrum [6].

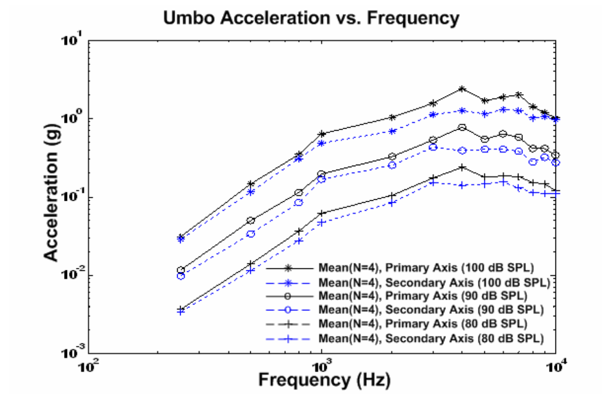

Figure 3. Acceleration frequency response at 80 dB, 90 dB, and 100 dB SPL measured along umbo primary and secondary axes.

The acceleration frequency response along the primary axis is nearly identical to that along the secondary axis. The acceleration amplitude increases with a slope of 40 dB per decade from 250 Hz to 1 kHz and with a slope of about 20 dB per decade from 1 kHz to 4 kHz. Above 4 kHz the acceleration signal remains relatively flat. Although the frequency trends are very similar, a 20% increase in acceleration amplitude is measured on the umbo along the primary axis compared to the secondary axis. While the difference between the two axes measurement is small, it occurs with approximately equal magnitude in all bones at all sound levels. Therefore, any potential misalignment in sensor placement will have a minimal impact on the output signal amplitude because of the similar acceleration amplitude response, and also negligible frequency distortion due to the similar frequency response.

In our proposed prosthetic system, ossicular elements such as incus and stapes are not used to couple acoustic energy into the cochlea. Therefore, incus can be removed to reduce the mechanical impedance seen by the umbo as a means to further enhance its vibration amplitude in response to an acoustic stimulation [7]. Figure 4 presents the acceleration amplitude measured along the umbo primary axis before and after incus removal, stimulated by input tones of 80 dB and 100 dB SPL within the audible spectrum. After removal of the incus, the vibration acceleration frequency response increases by 3 - 5 dB below 2 kHz. The frequency associated with maximum acceleration amplitude shifts from 4 kHz to 3 kHz. The frequency response after incus removal decreases with a slope of approximately -40 dB per decade above the frequency of maximum acceleration. Figure 5 presents the corresponding umbo acceleration as a function of input sound level at 500 Hz and 5 kHz before and after detachment of the incus, indicating a linear relationship of 20 dB per decade for both cases. As depicted in the figure, this allows for an acceleration projection for input sound level below 70 dB SPL, which is the resolution limit of the LDV measurement system.

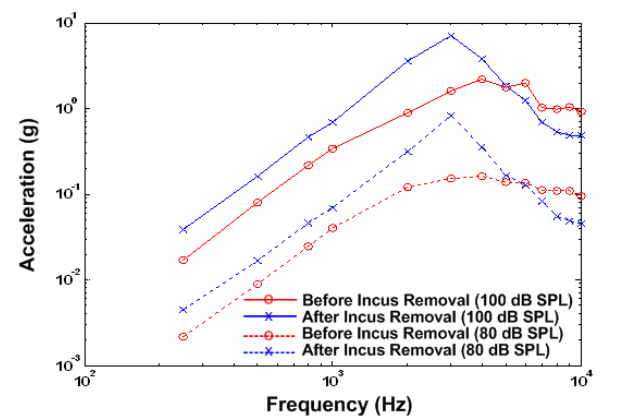

Figure 4. LDV measurements of umbo acceleration vs. frequency before and after incus detachment at 80 SPL and 100 SPL.

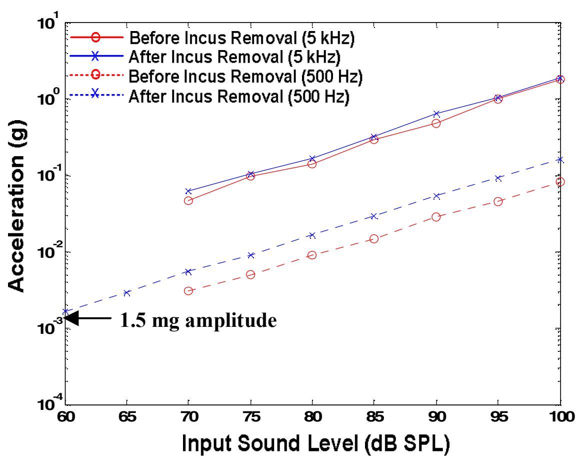

Figure 5. LDV measurements of umbo acceleration vs. input sound level before and after incus detachment at 5 kHz and 500 Hz.

These measurement results can serve as a design guideline to define the specifications for the prototype MEMS accelerometer. Audiologists report that audible speech is primarily focused between 500 Hz and 8 kHz, and that the loudness of normal conversation is approximately 60 dB SPL. From Figure 5, it can be seen that within the audible spectrum, 500 Hz has the lowest acceleration response, and thus it is the most difficult for detection. The projected acceleration amplitude at 500 Hz and 60 dB SPL in Figure 5 is approximately 1.5 mg. Today's state-of-the-art cochlear implants have multiple channels and electrodes to provide an appropriate stimulus to the correct location within the cochlea. At 500 Hz, the electrode channel bandwidth is on the order of 200 Hz. Therefore, to detect sounds at 60 dB SPL at 500 Hz, an accelerometer with a sensitivity of $75\ \mu g/\sqrt{Hz}$ and a bandwidth of 10 kHz is needed. From Figure 4 it can also be seen that within the audible spectrum the maximum peak-to-peak acceleration is about 10 g. Another important design consideration is the total device mass. The mass of the umbo and long process of the malleus is about 20 – 25 milligrams. It has been shown that adding a mass greater than 20 milligrams can potentially result in a significant damping effect on the frequency response of the middle ear ossicular chain, particularly at frequencies above 1 kHz. Therefore, the total mass of the packaged sensing system needs to be kept below 20 milligrams.

III. MEMS Accelerometer with Interface Circuit

A prototype MEMS lateral-axis differential capacitive accelerometer is designed to be used as an implantable middle ear microphone for the proposed prosthetic application. The device occupies a 1mm x 1mm area and consists of 190 sets of parallel sensing fingers exhibiting a thickness, width, minimum air gap and overlap dimension of 25μm, 2μm, 2μm and 96μm respectively, thus achieving a nominal capacitance of 2 pF. The proof-mass is suspended by mechanical springs with compliance of 54 N/m, corresponding to a mechanical resonance of 10 kHz and differential sensitivity of 5.2 fF/g. Assuming a mechanical Q of unity in ambient, the sensor is expected to exhibit a Brownian noise floor of $30\ \mu g/\sqrt{Hz}$. The device is fabricated by a commercial SOI MEMS process. Figure 6 presents an SEM of the fabricated sensor.

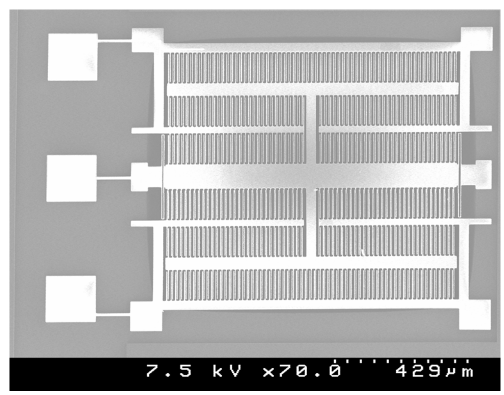

Figure 6. SEM of fabricated accelerometer.

The MEMS accelerometer, modeled as differential capacitors, are driven by a stimulation clock with an amplitude, V_s, of 1.2V and are interfaced by a differential charge amplifier, which converts the sensor capacitance change to an output voltage as shown in Figure 7.

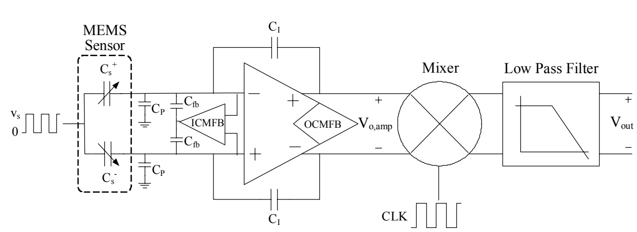

Figure 7. Electronic interfacing architecture.

A clock frequency of 675 kHz is used to modulate the sensor information away from the 1/*f* noise of the amplifier, critical for achieving a high sensitivity. An input common-mode feedback (ICMFB) circuit is designed to suppress any output offset due to the parasitic capacitance mismatch and drift over time [9]. The charge amplifier output is then mixed by the same clock and low-pass filtered to obtain the desired analog acceleration information. With a low noise charge amplifier exhibiting an input referred noise floor of $5\,nV/\sqrt{\text{Hz}}$, an acceleration sensing resolution of $25\,\mu\text{g}/\sqrt{\text{Hz}}$ is expected.

IV. Measurement Results

The MEMS accelerometer is wire bonded to the custom-designed CMOS capacitance-to-voltage converter over a thin flexible substrate, as shown in Figure 8, excluding the cover.

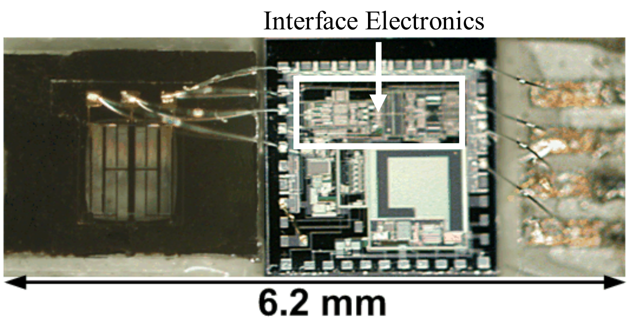

Figure 8. Packaged prototype sensing system.

The overall system weights about 25milligrams and achieves a sensitivity of 11.5mV/g (equivalent to 5 fF/g) and Brownian noise floor of $900\,nV/\sqrt{\text{Hz}}$ in ambient at 500 Hz (equivalent to 78 $\mu\text{g}/\sqrt{\text{Hz}}$) with a mechanical bandwidth of 6.44 kHz. The higher Brownian noise floor is due to the over-estimated *Q* value and reduced proof mass. The lateral over-etch also reduces the structural compliance, thus a lowered bandwidth. The sensing system is then surgically attached to an umbo for implant performance evaluation. Audio input stimuli with various amplitudes are applied for characterization. Figure 9 shows the output spectrum when stimulated by a 95 dB SPL tone at 500 Hz, achieving a 40 dB SNR for a measurement bandwidth of 62 Hz.

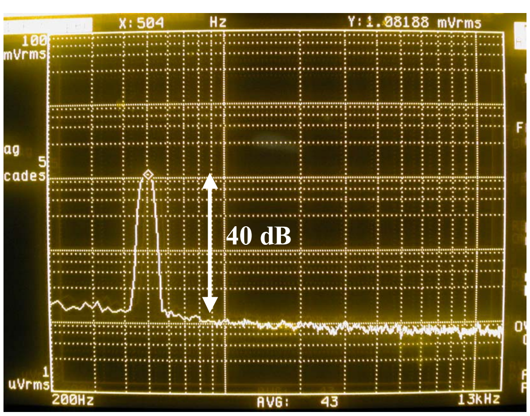

Figure 9. Accelerometer output spectrum on umbo when stimulated by 95 dB SPL at 500 Hz.

This is equivalent to a 35 dB SNR for a 200 Hz bandwidth. Therefore, the microsystem is capable of sensing 60 dB SPL tone at 500 Hz. Figure 10 shows the measured sound detection threshold over the audio spectrum, indicating that the device is adequate for detecting normal conversation.

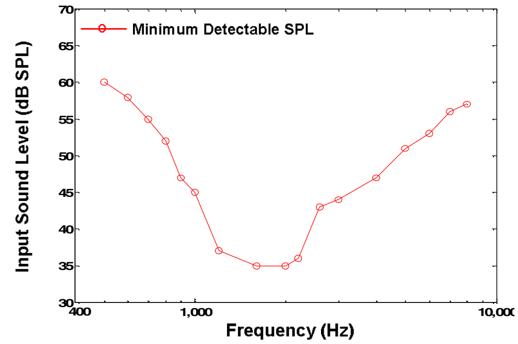

Figure 10. Minimum detectable sound level of middle ear microphone.

V. Conclusion

MEMS accelerometer with low noise interface circuits can detect and convert middle ear bone natural vibration in response to normal speech to electrical signal, which can be used to reconstruct the original sound. The proposed sensor as an implantable microphone can enable the realization of future fully implantable cochlear prosthesis.

Acknowledgement

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