

# A Laboratory Study on a Capacitive Displacement Sensor as an Implant Microphone in Totally Implant Cochlear Hearing Aid Systems

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**Abstract:** A totally implant cochlear hearing aids system, integrating an implant microphone, interface electronics, a speech processor, a stimulator, and cochlear electrodes, can overcome the uncomfortable, inconvenient, and stigma problems associated with the conventional and semi-implantable hearing aids. This paper presents a laboratory feasibility study on the use of an electret condenser microphone (ECM) displacement sensor, serving as an implant microphone, and combined with a spring coupler to directly sense the umbo acoustic vibration. The umbo vibration characteristics were extracted from literature to determine the coupler and sensor requirements. A laboratory model was built to simulate the vibration source and experimentally study the transmission coefficient. Experimental data demonstrate that by using a 10 N/m stiffness spring, the umbo vibration amplitude as high as 67% can be transmitted to the sensor. Measurement of the sensor system on the temporal bone was also made. The minimum detectable sound pressure level (SPL) at 1 kHz is 41 and 67 dB for laboratory and 38 and 64 dB for temporal bone measurement for 1 and 388 Hz bandwidth, respectively. Better performance was achieved in a higher frequency. Results and analysis of this study can be used as a guideline for the future design of displacement sensors as implant microphones.

## I. INTRODUCTION

It is estimated one out of ten Americans, even more throughout the world, suffers from conductive as well as sensorineural hearing loss [1], and is supposed to wear a certain type of hearing aid device. While conventional hearing aids can offer moderate rehabilitation, inherent limitations, such as ear canal irritations, distortion and occasional ringing, and social problems with being perceived as handicapped, have deprived many patients of clear hearing. Partially implant cochlear hearing systems, have gained acceptance and enabled the persons with severe hearing loss to gain hearing and speech functions. However, the external microphone and electronics present concerns on reliability in sporting events, inconvenience, and social stigma. It is, therefore, desirable to develop totally implant cochlear hearing aid systems [2-4], which include an implant

microphone to pick up sound vibration signals, a speech processor to select and arrange the signal from the microphone, a stimulator to generate electrical impulses, and cochlear electrodes to transmit the impulse to the auditory nerve. Several approaches of using an implant microphone, with different principles, have been reported. Piezoelectric material, generating electrical signal when strain applied, can be used to sense the umbo vibration. The disadvantages are too stiff and difficult to maintain good contact with the umbo [5, 6]. Optic fiber approach is complex and it may temporarily lose signal [7]. Alternatively, a magnetic sensor on malleus head was tried and the result was encouraging [3]. However, the weight, size and the loading effect are large and the magnetic materials are objectionable for patients go through a Magnetic Resonance Imaging (MRI) examination. Using an acceleration sensor for conversion may be an approach and was studied [8]. The low frequency sensitivity, mass loading, noise, packaged weight, and the size are major challenges.

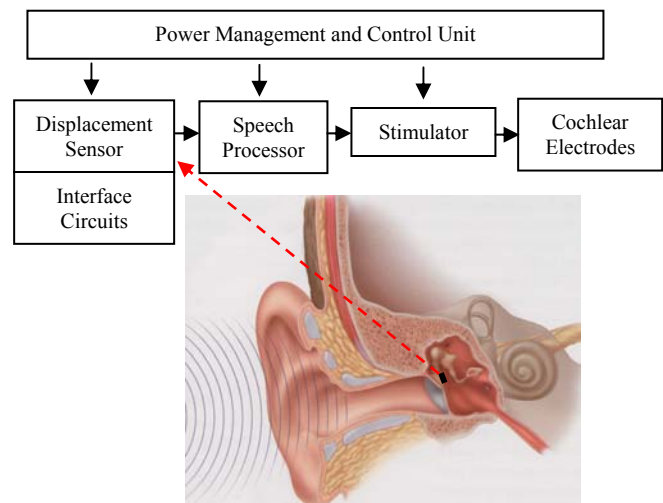


Fig.1. A totally implant cochlear hearing aids system

Our proposed approach is shown in Fig.1. The displacement sensor will be mounted inside the middle ear cavity and the spring is used to connect the umbo to the sensor. Therefore, the umbo vibration can be efficiently transferred to the displacement sensor, which can result in high sensitivity. The concept of using the displacement sensor as the implant microphone and spring coupler in totally implant cochlear hearing aid systems is shown in Fig.2.

This feasibility study of employing an electret condenser microphone as a capacitive displacement sensor with a spring

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coupler is a key step toward a totally implant cochlear hearing aids system. The results can be a guideline for future displacement sensor designs used in this system.

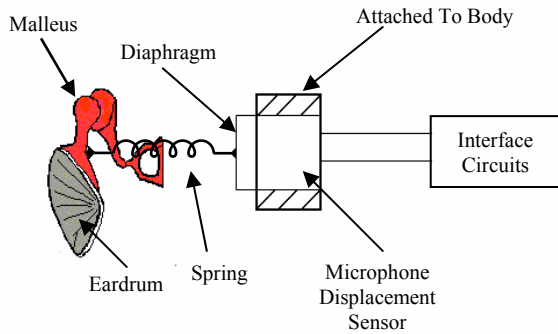


Fig. 2 Concept of a displacement sensor with a coupler

## II. CHARACTERIZATION OF THE UMBO VIBRATION

As shown in Fig.2, the displacement sensor will be connected to the umbo that has the largest displacement amplitude compared with incus and stapes [9] and is easier for surgical operations. The umbo vibrational characteristics has been studied to extract parameters, such as sensitivity, dynamic range, and loading capability, which provide a base for properly selecting the displacement sensor and designing the spring. It is known that umbo has 3 dimensional vibrations. Mark *et al.* [10] observed that the umbo vibration displacement along primary (perpendicular to eardrum) and secondary (parallel to eardrum) axes only have 20% difference, which gives us more flexibility to place the displacement sensor. The average displacement amplitudes from 250 Hz to 8 kHz, at different SPL input to the ear canal, were reported [10-13]. In order to detect 40 to 100 dB SPL sound, the sensor needs to sense displacement from 0.1 to 120 nm, in the 250 Hz to 2 kHz range, and even smaller displacement in the 2 to 8 kHz range, which presents significant engineering challenges. Besides the high sensitivity and wide dynamic range, the force and mass loading effects on the umbo are important considerations in order to fulfill the requirements of an implantable microphone sensor. Nishihara *et al.* [14] reported that with 20 mg mass loading, the umbo displacement will decrease about 6 dB. Therefore, 20 mg is considered as the maximum loading that can be applied to the umbo in our approach.

## III. LABORATORY MODEL STUDY

The purpose of this study is to build a vibration source to simulate the umbo vibration, prepare the implant sensor model, and carry out the measurement in laboratory environment. Testing results will be compared with temporal bone tests discussed later.

### A. Laboratory Model

A lab simulation model was built with Laser Doppler Vibrometer (LDV) calibrated PZT (P-810.10 from PI Company) as the vibration source to generate vibrations

equivalent to 40 to 100 dB SPL. The PZT selected meets the requirements of high conversion sensitivity (120 nm /V), large dynamic range (0.1 nm to 120 nm), linear dependence of displacement vs. driving voltage, flat frequency response at 250 to 8 kHz and large driving capability. A coupling device is required to transmit the vibration from the vibration source to the sensor, to accommodate 100  $\mu$ m DC offset due to the sensor attachment uncertainty and outside pressure fluctuation, and to reduce the umbo loading effect. Different coupling devices were studied to compare the transmission coefficient (the percentages of vibration amplitude transferred to the microphone from the PZT source). A coupling device using coiled spring, with 15 mg mass, 80 Hz resonance frequency, 10 N/m stiffness, was developed to meet the requirements. Various commercial microphones, used as displacement sensors, were tested in the laboratory to compare the sensitivity, noise and vibration transmission coefficient. The electret capacitive microphone (WM-65A103) with sensitivity of -50 dB and S/N ratio 55 dB was selected as the sensor for the feasibility study. Fig.3 shows two sets of laboratory measurements. Fig.3 (a) is transmission testing setup. The PZT is driven by a signal generator. The vibration displacement, measured by LDV, is transmitted through coupling spring to the 25  $\mu$ m thick Aluminum foil detector. Fig.3 (b) is the sensor measurement. The sensor outputs, corresponding to the vibration of various SPL, are amplified by a low-noise amplifier.

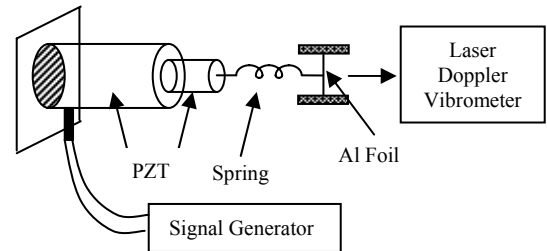


Fig.3 (a) Transmission Measurement

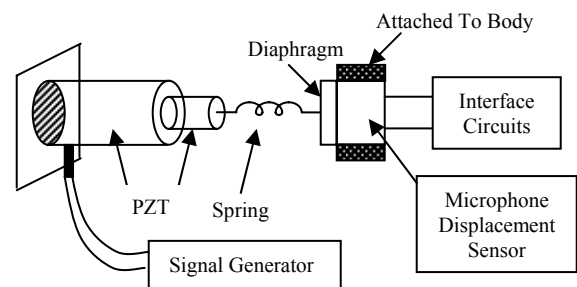


Fig. 3 (b) Sensor Measurement

The overall test fixture was housed inside an electrically shield acoustic isolation box to eliminate the electrical and sound interference. A dynamic signal analyzer was used for output signal analysis.

### B. Transmission Coefficient Study

Coiled spring is used as the coupler between the umbo and the microphone sensor. The vibration signal received by the microphone consists of three major components coupled through three different paths. They are: (1) direct acoustic

coupling through air; (2) spring wire propagation coupling, and (3) spring vibration coupling due to spring movement. Laboratory experiments were developed to identify these components as shown in Fig.4. The overall setup includes a PZT vibration source, a coupling spring and a 25  $\mu\text{m}$  thick Al foil detector. LDV is used to measure the transmitted vibration of the Al foil. In Fig.4 (a), the spring is, intentionally, not touching the Al diaphragm. Therefore, the vibration of the Al diaphragm could be coupled only acoustically through air. In Fig.4 (b), a combined effect of wire propagation and acoustic coupling were measured, since the middle of the spring is firmly clamped (no movement was observed by LDV). In Fig.4 (c), acoustic coupling, wire propagation, and spring vibration are all included. In Fig.4 (a), the gap between the spring and the Al foil is very small compared with the spring length. Therefore, the acoustic coupling in all 3 cases can be considered equal. From these measurements, the effect of each mechanism was extracted.

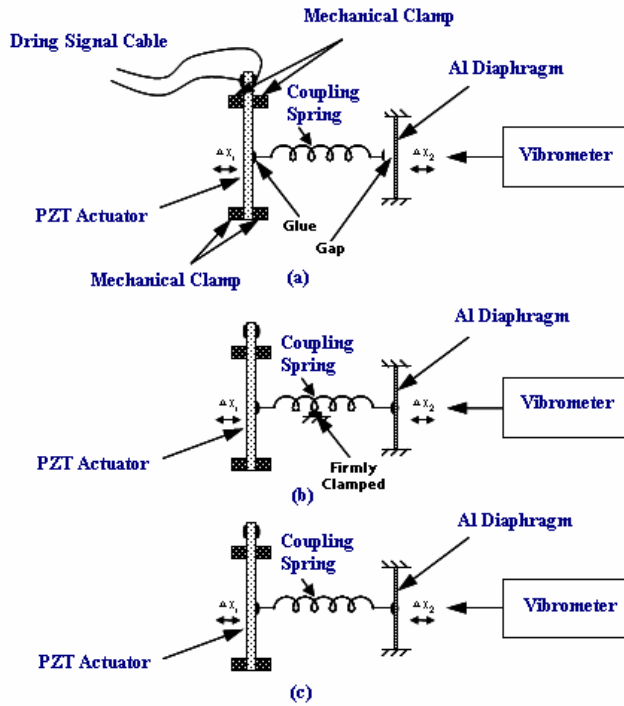


Fig.4. Laboratory setup to identify the coupling mechanisms

Fig.5 shows measured results of the transmission coefficients through different coupling mechanisms, at 800 Hz, averaged from 4 springs. They were all made with the same tungsten material, same diameter and length, but with different stiffness, 5, 45, 105 and 205 N/m. It is observed that the stiffer the spring, the higher the transmission coefficient will be. But the stiffness has limitation ( $< 300$  N/m) when the source loading effect is considered. For a spring with 5 N/m stiffness, the overall transmission coefficient at 800 Hz is 67% with majority (50%) contributed by the spring vibration, and 17% contributed by the propagation through the wire. The acoustic coupling is less than 1% and can be neglected.

Another set of experiments is designed to examine the spring End-Shapes effect on transmission coefficient. Two

End-Shapes were studied. Fig.6 (a) shows the Standard-End spring with a 0.2 mm diameter contact area, and Fig.6 (b) shows the Exponential-End spring with a 1.2 mm diameter flat round contact area. The test results shows that the Exponential-End-Shape has 5-8% more transmission coefficient. It is believed that this is due to better mechanical impedance match with the Exponential-End-Shape spring.

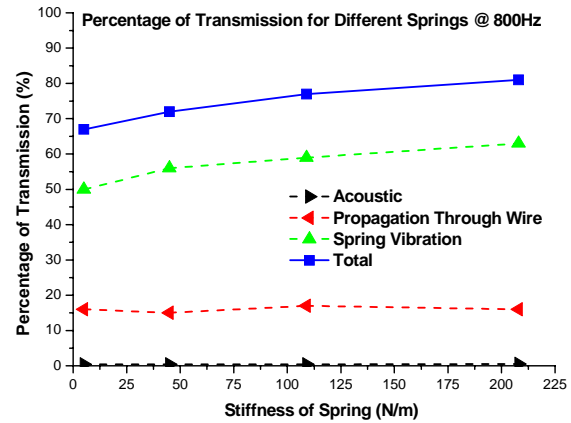


Fig.5. Coupling coefficients through different paths

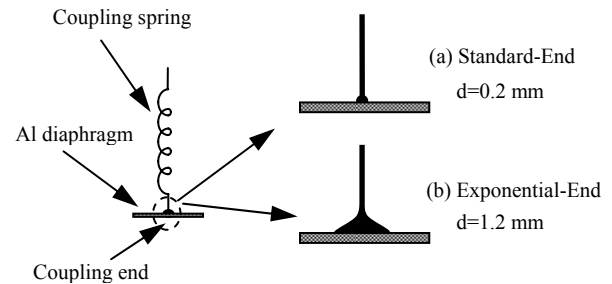


Fig.6. Transmission coefficient study on two different coupling ends shape

### C. Overall System Response

The test results show that S/N ratio at 95 dB SPL sound input is 54 and 28 dB, equivalent to minimum detectable SPL of 41 and 67 dB, for 1 and 388 Hz (20 Bands) bandwidth respectively.

## IV. TEMPORAL BONES TESTS

Preserved temporal bones measurements were carried out after the laboratory model was built. The experimental set up is shown in Fig.7. Calibrated sound signals, at 60 and 95 dB SPL, were applied to the ear canal. The output of the microphone sensor, coupled with the umbo through a spring coupling device, was amplified by the low noise amplifier and were measured and recorded by a dynamic signal analyzer. Fig.8 shows the noise spectral density and background interferences at the amplifier output for 3 various conditions. The results show that the microphone sensor noise is dominating. The noise spectral density of the sensor and coupling device (measured in the acoustic isolation box) can be used to estimate the Signal to Noise ratio when the desired frequency bandwidth is known. Fig. 9 shows the

measured sensor signals, from 250 Hz to 8 kHz, with 95 and 60 dB SPL sound applied to the ear canal. The measured system noise is also included. In the cochlear implant system, the total sound bandwidth is divided into channels. Some channels have several 100 Hz bandwidth and others have several kHz. The S/N ratio can be calculated for each channel according to bandwidth assignment in the specific system. The Minimum detectable SPL at 1 kHz is 38 dB and 64 dB for 1 Hz and 388 Hz Bandwidth, respectively. The results are similar to the laboratory study.



Fig.7. Measurement set-ups for temporal bone experiment

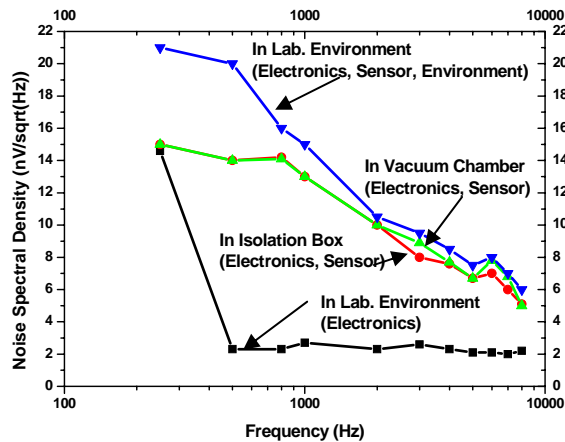


Fig.8. Noise spectrum densities (NSD) measured

## V. CONCLUSIONS

Test results from the laboratory model and temporal bone measurements indicate that the displacement sensor can be used to sense the vibration of the umbo with good fidelity for the microphone sensor used. Three mechanisms of vibration transmission are presented. Spring coupling is dominating. Propagation coupling has a smaller effect, while the acoustic coupling is negligible. The larger the spring stiffness, the higher the transmission coefficient will be, but it should be limited by the DC offset and loading effect considerations. Exponential-End-Shape can increase transmission coefficient by 5-8%. By using a 10 N/m stiffness spring, 67% of the umbo vibration amplitude can be transmitted to the sensor. From laboratory data, minimum detectable SPL at 1 kHz is 41, 67 dB, and from temporal bone measurements, it is 38, 64 dB for 1 and 388 Hz bandwidth, respectively. It has better

performance in high frequency. From these simulated results, the implant MEMS displacement sensor and coupler can be specified. Sensors with higher sensitivity (-26 dB at 1 kHz) need to be designed to sense 40 dB SPL for 1 kHz or higher bandwidth. The high performance capacitive strain sensors with 0.1 nm sensitivity at 10 kHz bandwidth [15] are being modified for this purpose.

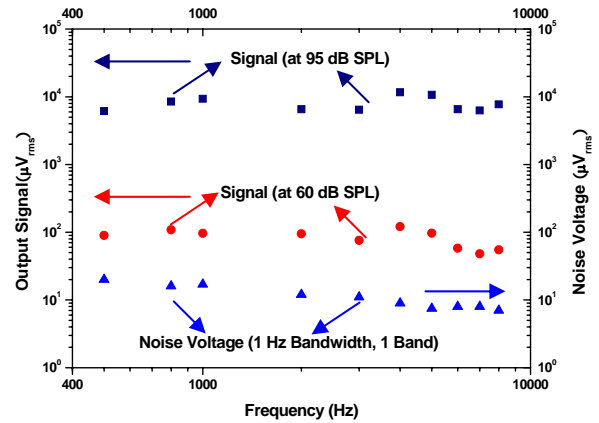


Fig.9 Temporal bone experiments results

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