Development and Characterization of Piezoelectric Artificial Cochlear with micro Actuator mimicking Human Cochlear

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Abstract. This paper presents the development of piezoelectric artificial cochlear (P-AC) capable of analyzing incoming acoustic or mechanical signals without external power source. The P-AC consists of membrane part and package part. The package part provides liquid environment through which the incoming signal is transmitted to membrane part. The membrane part responds to the transmitted signal and local area of the membrane part vibrates differently depending on its local resonant frequency. Previously in our group, we have demonstrated the feasibility of the P-AC with trapezoidal membrane part as sound analyzer by using mouth simulator as a sound input. In this research, we modified the P-AC to have the membrane part of logarithmically varying width. Also by incorporating mico-actuator into the package part that mimic the function of stapes bone in middle ear, we created similar environment to cochlear where human basilar membrane vibrates. The fabricated P-AC successfully demonstrates frequency separation of incoming mechanical signal from micro-actuator into several frequency bands within human hearing range.

1. Introduction

Human ear is a miniaturized acoustic transducer of great sensitivity (20 μPa ~ 60 Pa) and wide dynamic frequency range (20 Hz ~ 20 kHz). Scientists have tried to understand the mechanosensory system in human ear and found that the phenomenon of frequency separation of acoustic signal and its energy conversion by studying the structure of basilar membrane within the cochlear – a snail shell-shaped organ in the inner ear [1]. Basilar membrane has a structure of trapezoidal shape with varying thickness, which is thick and narrow near the base (close to oval window) and becomes thinner and wider near the apex. Thus the base area in the basilar membrane has a high resonant frequency, but the apex area has a low resonant frequency. This unique structure provides a frequency separation of incoming signal. As a basilar membrane vibrates upon incoming acoustic stimulation, the stereocilia on the hair cells near the vibrating basilar membrane become mechanically affected and generate bioelectrical signal. This bioelectrical signal is transmitted to the auditory nerves. The conversion of mechanical vibration input to electrical signal output is similar to that of piezoelectric membrane or cantilever.

Several researchers have studied to develop a sound analyzer inspired by human cochlear. Xu demonstrated a frequency filter function of acoustic sensor by using an epoxy cantilever structure [2]. Chen et al. developed beam type acoustic sensor and characterized its vibration and frequency selectivity in the water [3]. An acoustic sensor with polyimide membrane with Si_3N_4 beams was developed by White and Grosh and its vibrational behaviour was measured by using capacitive sensors

[4]. Physical cochlear model made of polyimide membrane with Al beams was developed by Puria et al. and characterized with Laser vibrometer [5]. These researches have presented promising results of artificial cochlear as a sound analyzer but energy conversion of vibration to electrical signal was not possible. Recently, Ito et al. developed a biomimetic acoustic sensor with piezoelectric membrane and presented its capability of frequency separation and energy conversion of acoustic signal input from a speaker [6].

The objective of this research is to develop biomimetic piezoelectric artificial cochlear (P-AC) having functions of frequency separation and corresponding electric signal generation and to characterize the developed acoustic sensor in a similar fashion as human basilar membrane vibrates upon the mechanical stimulation by stapes bone in the middle ear.

2. Design and Fabrication

The P-AC consists of two components; membrane part and package part (figure 1). The membrane part has piezoelectric thin film as a membrane, stainless use steel (SUS) frame defining the shape of membrane and patterned electrical pads. The schematic of the membrane part is shown in figure 2. The length in y axis of opening in the SUS frame is 28 mm and the width in x axis varies logarithmically from 0.97 mm (y = 0 mm) to 8.0 mm (y = 28 mm). The thickness of piezoelectric polymer film is 25.4 μm.

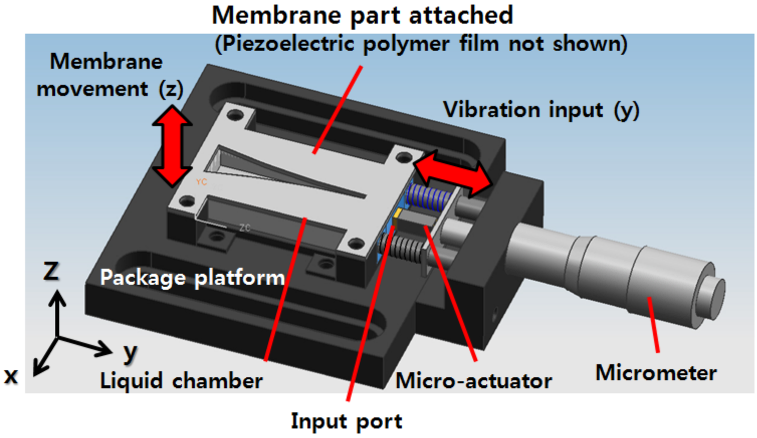

Figure 1. 3D drawing of package part of P-AC

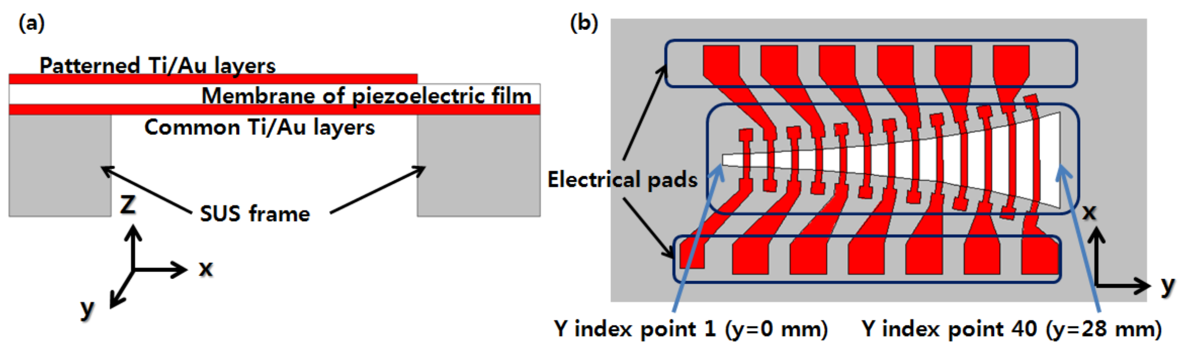

Figure 2. 2D schematic of membrane part design of P-AC (a) from side view and (b) from top view.

A common electrical pad is on the bottom side of piezoelectric polymer film and 13 patterned electrical pads are designed on the top side. The package part consists of liquid chamber, platform and micro actuator. The membrane part is attached to liquid chamber and liquid chamber is fixed on package platform. A micrometer assembled with package platform can adjust the position of micro actuator such that the input port of liquid chamber is in precise contact with the tip of micro actuator (figure 1).

The fabrication process involves microfabrication process to make a patterned electrical pads and assembly process of membrane part and package part. The piezoelectric polymer film used was polyvinylidene difluoride (PVDF) film of thickness 25.4 μm (Kynar® Film, Professional Plastics, Singapore). 20 nm / 200 nm thick titanium (Ti) / gold (Au) layers were sputtered with a shadow mask on the top side of PVDF film. The shadow mask has openings for patterned electrical pads. Additionally Ti/Au layers were sputtered on the bottom side without shadow mask for common electrical pad for harvesting piezoelectric signal. The SUS frame was prepared with precision machining with a line saw process and attached with processed PVDF film. For improving piezoelectricity of PVDF film, corona poling process was introduced before bonding process. The package platform and liquid chamber was prepared with conventional machining process. The micro actuator used was PICMA® Stack Multilayer Piezoactuaotr (P-883.11, PI-Korea, Korea) and assembled on the platform with micrometer. Finally, the membrane part was assembled over the liquid chamber and fixed together with the platform. The Fabricated P-AC is shown in figure 3.

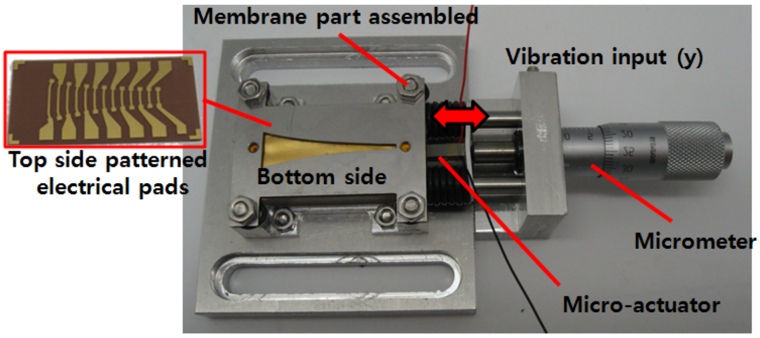

Figure 3. Photograph of fabricated and assembled P-AC

3. Experimental Results

The fabricated P-AC was characterized mechanically by measuring its vibrational property upon external mechanical stimulation from micro actuator. The micro actuator was operated by electrical signal from function generator which can control the magnitude and frequency of mechanical stimulation. The membrane vibration or displacement in z axis was measured with scanning laser Doppler vibrometer system (PSV-I-400 LR and OFV-505, Polytec, Germany) (figure 4). Artificial body fluid was introduced into the liquid chamber until the fluid becomes fully contacted with the piezoelectric polymer film. Along the central part of membrane in y axis, the vibration data were collected on 40 different points (Y index point 1 (y = 0 mm) ~ Y index point 40 (y = 28 mm)). The frequencies of applied signals were 100 Hz ~ 4,000 Hz in 100 Hz step. The upper limit of experimental frequency was decided based on the preliminary test results of frequency response of micro actuator which has a 3-dB cut-off frequency near 4,000 Hz.

The measured vibrational data of the P-AC membrane showed the clear frequency separation into four different frequency bands. First frequency band was 100 Hz ~ 400 Hz and has a displacement peak near Y index point 35. Second frequency band 700 Hz ~ 1400 Hz (z-displacement peak near Y index point 22). Third and fourth frequency bands were 2200 Hz ~ 2700 Hz and 3200 Hz ~ 3700 Hz (figure 5). The displacement peak was above 1 μm in all frequency bands. The vibration envelope at the frequencies between two neighbouring frequency bands showed mixed shape of multiple peaks. The piezoelectric signal output from membrane vibration was measured as a preliminary in air environment with sound pressure input of 94 dBSPL (= 1.0 Pa) and the maximum piezoelectric signal was 6.3 mV_{PP} at 1,200 Hz while the displacement is below 0.1 μm.

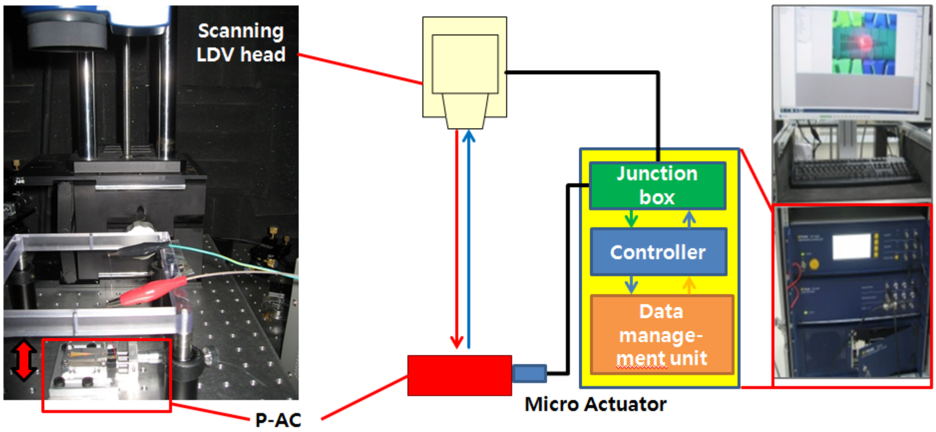

Figure 4. Schematic and photograph of experimental setup for measurement of vibration properties of P-AC

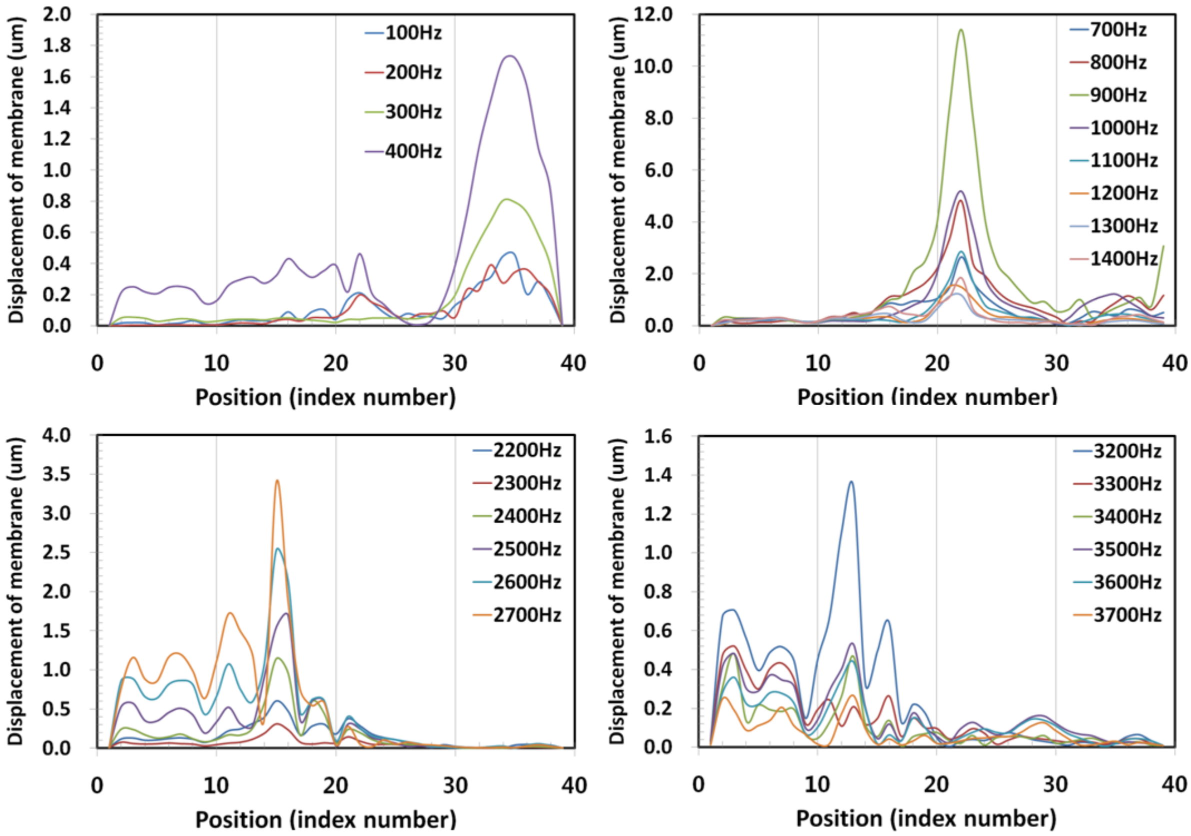

Figure 5. Vibration envelope of P-AC upon mechanical input from artificial stapes (micro actuator) within four different frequency bands of 100 Hz ~ 400 Hz, 700 ~ 1,400 Hz, 2,200 Hz ~ 2,700 Hz and 3,200 Hz ~ 3,700 Hz.

4. Discussion and Conclusion

In this study, we presented the fabrication and characterization of a piezoelectric artificial cochlear made of piezoelectric polymer film as a membrane. The piezoelectric signal output from each electrical pad was measured successfully in preliminary test condition, but measurement of piezoelectric signal output in liquid condition turn out to require further package design and experimental setup change. Additional tests will be followed. The characterization results of vibration show clear frequency separation of incoming signal from micro actuator – artificial stapes into four different frequency bands within 100 Hz ~ 4,000 Hz range. With further size reduction and enhanced frequency separation with piezoelectric signal output, the P-AC is expected to play an important role in the development of a total implantable cochlear system that operates with much less power and maintenance compared to conventional cochlear implant.

Acknowledgement

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