Sensors and Actuators A 158 (2010) 183–192

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Development of piezoelectric acoustic sensor with frequency selectivity for artificial cochlea

Hirofumi Shintaku[a,*], Takayuki Nakagawa[b], Dai Kitagawa[a], Harto Tanujaya[a], Satoyuki Kawano[a], Juichi Ito[b]

[a] Department of Mechanical Science and Bioengineering, Graduate School of Engineering Science, Osaka University, Machikaneyama-cho 1-3, Toyonaka, Osaka 560-8531, Japan
[b] Department of Otolaryngology, Head and Neck Surgery, Graduate School of Medicine, Kyoto University, Kawahara-cho 54,Shogoin, Sakyo-ku, Kyoto 606-8507, Japan

ARTICLE INFO

Article history:
Received 25 July 2009
Received in revised form
13 November 2009
Accepted 22 December 2009
Available online 4 January 2010

Keywords:
Fluid-structure interaction
Acoustic MEMS sensor
Artificial cochlea
Biomechanical engineering
Piezoelectric device

ABSTRACT

In this paper, we report a novel piezoelectric artificial cochlea which realizes both acoustic/electric conversion and frequency selectivity without an external energy supply. The device comprises an artificial basilar membrane (ABM) which is made of a 40 μm thick polyvinylidine difluoride (PVDF) membrane fixed on a substrate with a trapezoidal slit. The ABM over the slit, which mimics the biological system, is vibrated by acoustic waves and generates electric output due to the piezoelectric effect of PVDF. The width of ABM is linearly varied from 2.0 to 4.0 mm along the longitudinal direction of 30 mm to change its local resonant frequency with respect to the position. A detecting electrode array with 24-elements of 0.50 × 1.0 mm rectangles is made of an aluminum thin film on ABM, where they are located in a center line of longitudinal direction with the gaps of 0.50 mm. Since the device will be implanted into a cochlea filled with lymph fluid in future, the basic characteristics in terms of vibration and acoustic/electric conversion are investigated both in the air and in the silicone oil which is a model of lymph fluid. The in vitro optical measurements show that the local resonant frequency of vibration is varied along the longitudinal direction from 6.6 to 19.8 kHz in the air and from 1.4 to 4.9 kHz in the silicone oil, respectively. Since a resonating place vibrates with relatively large amplitude, the electric output there becomes high and that at the other electrodes remains to be low. Thus, the electric voltages from each electrode realize the frequency selectivity. Furthermore, the effect of surrounding fluid on the vibration is discussed in detail by comparing the experimental results with the theoretical predictions obtained by the Wentzel–Kramers–Brillouin asymptotic method. The theoretical prediction indicates that the surrounding fluid of the higher density induces the larger effective mass for the vibration that results in lower resonant frequency. From these findings, the feasibility of artificial cochlea is confirmed both experimentally and theoretically.

1. Introduction

The sensorineural hearing loss is a type of deafness which is often caused by the damage on hair cells of cochleae in inner ears. The hair cells convert acoustic sounds to electric signals that stimulate auditory nerves. As a clinical treatment for the hearing loss in children and adults, the artificial cochlea is recently well used. The device bypasses the damaged hair cells by generating the electric current in response to the acoustic sound [1,2]. The current artificial cochlea consists of an implantable electrode array for the stimulation and an extracorporeal device including a microphone, a sound processor and a battery. The acoustic sound is detected and is analyzed with respect to the frequency by the extracorporeal device. The processed signals are transferred through a transcutaneous system. Then, the auditory nerves are stimulated through the electrodes inserted in the cochlea. The disadvantages in the current system are the indispensability of extracorporeal devices, the small number of electrodes which closely connects to the limitation of tones, and the relatively large power consumption. This situation motivates us to develop a fully self-contained implantable artificial cochlea.

The important functions of cochlea are not only the conversion of acoustic wave to electric signals but also the frequency selectivity [3,4]. The basilar membrane which is a biological diaphragm in the cochlea plays an important role for the frequency selectivity. The local eigen frequency of membrane is changing along the place

* Corresponding author. Tel.: +81 6 6850 6179; fax: +81 6 6850 6179.
E-mail address: shintaku@me.es.osaka-u.ac.jp (H. Shintaku).

0924-4247/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.sna.2009.12.021

Nomenclature

A_j	Fourier coefficient
$b(x)$	width of ABM, m
D	bending rigidity, N m
E	Young's modulus, Pa
f	frequency, Hz
h	thickness of ABM, m
$k(x)$	wave number, m^{-1}
L_1	width of fluid channel, m
L_2	depth of fluid channel, m
L_3	length of ABM, m
p_f	pressure, Pa
w	displacement of ABM, m
$W(x)$	envelope function, m
(x, y, z)	Cartesian coordinates, m

Greek letters

$\eta(x, y)$	shape function for ABM's bending in y direction
ν	Poisson ratio
ρ_f	density of fluid, kg m^{-3}
ρ_m	density of PVDF, kg m^{-3}
$\phi_f(x, y, z, t)$	velocity potential, m^2/s
ω	angular frequency, rad/s

Subscripts

f	region of fluid channel f = l or u
j	mode number of Fourier coefficient
l	lower fluid channel
m	PVDF
u	upper fluid channel

of it, because of varying mechanical boundary conditions and the mechanical rigidity. Thus, when the eigen frequency at a local place match to that of acoustic wave, the place vibrates with relatively large amplitude due to the resonance. The vibration stimulates hair cells especially at the resonated place. As a result, the frequency of acoustic wave is recognized as the difference in tones.

To artificially realize the frequency selectivity, some microscaled devices have been reported. Tanaka et al. [5] and Xu et al. [6] developed acoustic sensors with the function of frequency selectivity by the use of resonance of cantilever arrays. Those sensors were evaluated in the atmospheric environment. Chen et al. [7] developed a beam array fixed on a trapezoidal channel and investigated the vibrating characteristics in the water. Despite the frequency selectivity of cantilevers or beams, their mechanical strength may not be enough for the implantation as the artificial cochleae for the long period. On the other hand, White and Grosh [8] developed a device made of polyimide membrane with Si_3N_4 beams. The demonstration for the frequency selectivity was conducted at the higher frequency range compared with the audible one. Wittbrodt et al. [9] also developed a device made of polyimide membrane with Al beams. They reported that the device possessed some similarities with the biological cochlea in terms of traveling waves, the frequency to place tonotopic organization, and the roll off beyond the characteristic place.

The acoustic sensor which is developed in this paper realizes both the frequency selectivity and the conversion of acoustic wave to the electric signal in the liquid environment without an external energy supply. The device is designed as a prototype model to test the basic concept of the acoustic sensor for the development of the self-contained implantable artificial cochlea. The device consists of a piezoelectric membrane fixed on a trapezoidal slit, where the membrane over the slit works as a detector. We name this trapezoidal membrane as an artificial basilar membrane (ABM). Discrete electrodes are fabricated on ABM by technologies of micro electromechanical systems (MEMS) to measure the electric signals generated in response to the externally applied acoustic waves. To model the liquid environment, the fluid channel which locates under ABM is filled with a silicone oil as a model of lymph fluid in the cochlea. The ABM's vibration is measured using a laser Doppler vibrometer (LDV) at the various frequencies in the range of 1.0–20 kHz. The electric output is measured through the electrodes using a preamplifier. To predict the performance of the present device, the oscillatory dynamics of ABM is theoretically analyzed based on the vibrating equation of a thin plate bending and equations for the fluid dynamics. The phenomenon of fluid-structure interaction is treated by coupling those basic equations. To treat the wave motion on trapezoidal ABM, the Wentzel–Kramers–Brillouin (WKB) asymptotic solution [10] is used under the assumption of the gradually varying wavelength. The comparison between the experimental and theoretical results makes clear the detailed mechanism underlying the frequency selectivity. In addition, discussions for the further development as an implantable artificial cochlea are described from the viewpoint of magnitude of electric signal and the device size.

2. Principles and experimental methods

2.1. Basic mechanism of frequency selectivity and electric signal generation

A schematic and a photograph of piezoelectric acoustic sensor developed here are shown in Fig. 1. The device comprises a polyvinylidine difluoride (PVDF) membrane (KUREHA, Japan) bonded on a stainless plate with a trapezoidal slit and discrete electrodes distributed along x axis. PVDF is a piezoelectric material which can convert mechanical stresses to electric signals. The trapezoidal slit is designed so that the membrane over it, i.e. ABM, can be easily vibrated by the acoustic wave. The width $b(x)$ of ABM is linearly varied in the ranges of 2.0–4.0 mm along x of 30 mm long. This shape is intended to mimic the passive basilar membrane, that is, the local resonant frequency (LRF) of ABM gradually changes due to the varying mechanical boundary conditions along x. LRF is expected to be decreased as x increases. Applying acoustic wave with a certain frequency to ABM, a local place vibrates with relatively large amplitude due to the resonance. Electric signals are generated by the piezoelectric effect with respect to the local stress in ABM. Thus, the electrode on the resonating place gives a relatively large electric output. This is the basic mechanism of frequency selectivity realized by the association of resonance of vibration and the discrete electrode array. The device is mounted on a substrate with a fluid channel, where the channel dimensions are 47 × 17 mm rectangle and 4 mm deep. To model an in vivo environment, the fluid channel is filled with silicone oil (Shin-Etsu Chemical, Japan). The density and the viscosity of silicone oil are 873 kg/m^3 and 1.75×10^{-3} Pa s, respectively, where those of lymph fluid in cochleae are typically reported as 1.0×10^3 kg/m^3 [11] and from 1.0×10^{-3} to 1.97×10^{-3} Pa s [12,13], respectively. Although the both sides of basilar membrane in vivo face to the lymph fluid, in this experiment, only the bottom side of ABM faces to the silicone oil for the stable optical measurement from the upper side. The effect of this simplification is discussed by the theoretical analysis in the later section. Furthermore, the size of this ABM is relatively large to be implanted into the human cochlea. However, the main purpose of this paper is to test the basic mechanism of proposed system in terms of acoustic/electric conversion and the frequency selectivity. The optimization and the miniaturization will be remained as a future work. The advantages of miniaturized ABM are again discussed in later section.