Mechanical Systems and Signal Processing 116 (2019) 710–724

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Harnessing the bilinear nonlinearity of a 3D printed biomimetic diaphragm for acoustic sensor applications

Jong-Yun Yoon [a], Gi-Woo Kim [b,*]

[a] Department of Mechatronics Engineering, Incheon National University, 22012, South Korea
[b] Department of Mechanical Engineering, Inha University, 22212, South Korea

ARTICLE INFO

Article history:
Received 30 May 2018
Received in revised form 4 July 2018
Accepted 14 July 2018

Keywords:
Tympanic membrane
Biomimetic diaphragm
Bilinear stiffness
3D printing
Nonlinear frequency response
Acoustic sensor

ABSTRACT

This study presents an initial assessment of a newly shaped biomimetic diaphragm aimed at mimicking the function of the tympanic membrane (TM) of the human auditory system. The TM consists of three parts, namely, the malleus, pars tensa, and pars flaccida, and its dynamic behavior is typically known to be different from other common, thin membranes. The constructed membrane has a curved conical shape with the apex pointing medially, and with an initially bucked shape. The malleus is also firmly attached to the medial surface of the membrane at its center. In addition, the TM is connected to a surrounding annulus ligament (muscle) and is concave at its deepest part (the umbo). As a result, the TM does not move as a normal flat and thin diaphragm. In this study, we investigated the bilinear nonlinearity of an elliptic and conical shaped diaphragm similar to the actual TM of the human auditory system to deliver improved vibrating characteristics. It is reported that the proposed adaptively diaphragm structure fabricated by using 3D printing technology can exhibit bilinear nonlinearity when the sound pressure level (SPL) of the incoming sound is high, thus resulting in a flat sensitivity and a broad frequency response.

1. Introduction

Typically, an acoustic sensor is an electrical device used to covert sound wave energy into electrical energy. A microphone is one of the common examples of an acoustic sensor: a ubiquitous device that is extensively used in many applications, such as smart phones, hearing aids, sound recordings, broadcasting, and voice recognition [1]. These electrical devices produce electrical energy when a moving part, such as a suspended diaphragm, is exposed to sound pressure vibrations. The electrical signal is in turn produced via Faraday induction using either a magnet and a coil, or a variable capacitance between two plates. This signal is usually sent to an amplifier, as its vibration amplitude is insufficient to directly drive a loudspeaker or a recording device. Microphones can be categorized into several different types, and each employs a different method to convert sound pressure from a sound wave to an electrical signal. Most microphones, such as the condenser and dynamic types, use the vibrating diaphragm as a moving part that responds to input sound pressure. Microphones produce their own characteristic frequency responses to sound input. Furthermore, microphones may not be uniformly sensitive to sound pressure. Frequency response functions (FRFs) can graphically represent the sensitivity in decibels over a range of frequencies on-axis sound (sound arriving at 0° to the diaphragm). FRFs may be insensitive (i.e., uneven and non-uniform) below low frequencies or above high frequencies. In general, microphones exhibiting a more uniform frequency response are generally

* Corresponding author.
E-mail address: gwkim@inha.ac.kr (G.-W. Kim).

https://doi.org/10.1016/j.ymssp.2018.07.020
0888-3270/

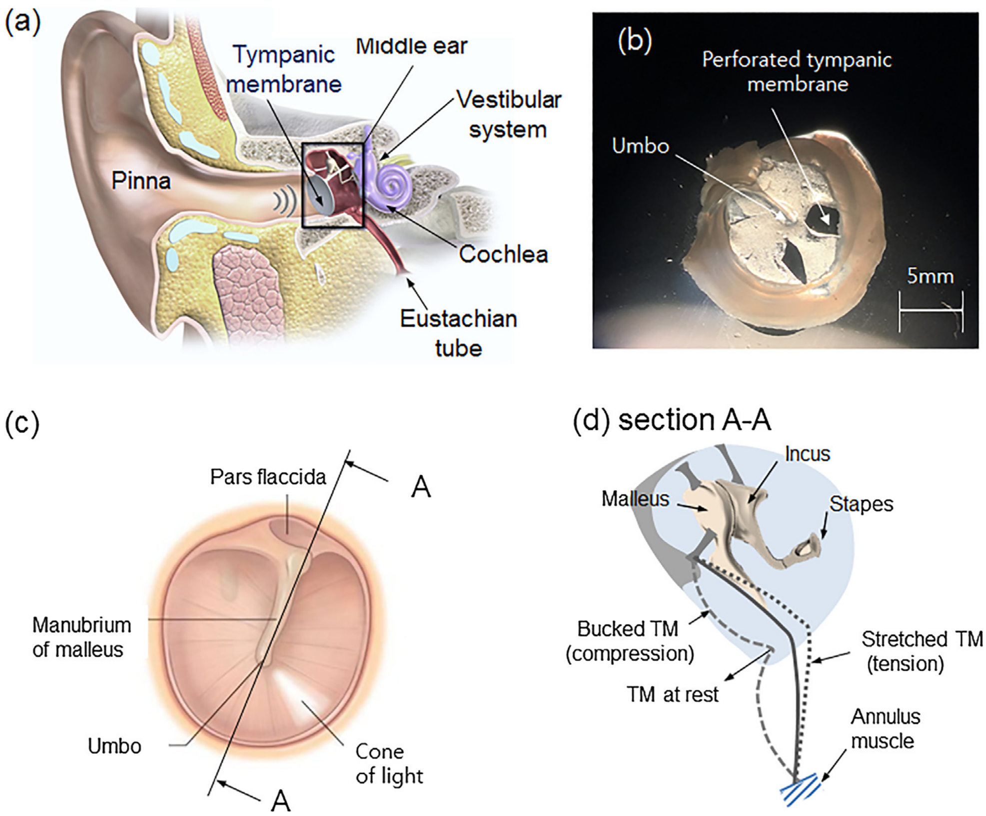

Fig. 1. Peripheral view of the human auditory system (a) overall [16], (b) microphotography of TM (young rat, provided by Inha University Hospital) (c) detailed view of human TM, and (d) detailed view of section A–A.

desirable for scientific applications. However, the flat and broad sensitivity (i.e., FRF) associated with the complex modal characteristics of in-plane vibrations in a circular thin membrane (or plate) clamped on its outer edge is challenging to the engineer. Recent attempts expended to resolve this technical limitation have included the use of new functional materials, such as graphene [2–4], in addition to other biomimetic approaches. Many researchers have explored new types of acoustic sensors, such as microphones inspired by the auditory systems of human [5–7], Ormia ochracea [8–13], bat [14] and cricket [15].

The dynamic behavior of the tympanic membrane (TM) within human auditory systems is known to be different from other common, thin membranes. It has a curved conical shape, with the apex pointing medially, and an initially bucked shape. The malleus is also firmly attached to the medial surface of the membrane at its center. The TM is connected to a surrounding annulus ligament (muscle) and is concave at the deepest part (the umbo), as shown in Fig. 1. The TM does not move as a typical diaphragm because the pressure force is transmitted only from the center of the TM (i.e., from the umbo at the apex) when the TM moves in response to the sound pressure.

Therefore, the main objective of this study is to develop a new biomimetic diaphragm similar to the actual TM of the human auditory system for the improved vibrating characteristics (e.g., flat and broad frequency response) of current diaphragms used in acoustic sensors such as microphones. An oval and conical shaped biomimetic diaphragm (50 mm $\times$ 45 mm $\times$ 0.4 mm (t)) for acoustic sensor applications is designed, and its static axial stiffness is analyzed based on a static force analysis in Section 2. Next, the dynamic behavior of 1-DOF vibrating system employing biomimetic diaphragm is investigated through the nonlinear frequency response analysis in Section 3. Finally, we experimentally validated that the flexible thin diaphragm made by thermo plastic elastomer (TPE) with 3D printing technology can exhibit bilinear behavior when the sound pressure level (SPL) of the incoming sound is high.

2. Design and static force analysis of biomimetic diaphragm

To identify the elastic characteristics of the TM, the Young's modulus of young guinea pig's TM (provided by Inha University Hospital) is evaluated by measuring its tensile properties in a micro tensile tester (model: Daeyeong), as shown in Fig. 2(a). The TM strip specimen of a young guinea pig is clamped firmly via two fixture plates, as shown in Fig. 2(b). The tensile force is measured by a load cell under a loading rate of 0.4 mm/min. The elongated displacement (deformation) of the TM strip specimen is also measured simultaneously through a high-resolution built-in rotary encoder within a ball screw