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Resonance mode and sound pressure produced by circular diaphragms of electrostatic and piezoelectric speakers

Hsin-Yuan Chiang, Yu-Hsi Huang *

Department of Mechanical Engineering, National Taiwan University of Science and Technology, No. 43, Sec. 4, Keelung Rd., Taipei 10607, Taiwan, ROC

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ABSTRACT

To investigate the frequency response characteristics of a push–pull electrostatic speaker (60-mm diameter) and free-edge-like piezoelectric speakers (68-mm and 73-mm diameters), this study was employed optical and acoustic measurements from 20 Hz to 20 kHz. The optical measurements of displacement amplitude and mode shape were used to predict sound pressure levels (SPLs). Comparisons with measured SPL values were used to verify the predictions. When using a mesh with acoustic flow resistance, i.e., unless damped, the electrostatic and piezoelectric speakers both produced numerous resonant frequencies. The two evaluation methods produced SPL values that were in good agreement. The piezoelectric speakers produced jagged SPL curves with peaks steeper than those of the electrostatic speaker. At the first axisymmetric mode, the electrostatic speaker was affected by acoustic resistance, which resulted in the following quality factor (Q) values: without mesh ($Q = 6.16$) and using a mesh with specific acoustic resistance of 145 rayl ($Q = 1.74$). By contrast, the piezoelectric speakers at modes (0,1)–(0,4) were unaffected by acoustic resistance, which resulted in Q values of 10–11, regardless of whether mesh was applied. Because higher Q performs larger acoustic response and lower Q presents wide broadband, this study concluded that the characteristics make electrostatic speakers suitable for headphones and piezoelectric speakers suitable for audio signaling devices.

1. Introduction

Membranes and plates are the most common structural elements used in diaphragms for the generation of sound vibrations. The membrane and plate are two-dimensional (2D) generalization of a string and beam, respectively [1]. Loudspeakers (or speakers) are acoustic actuators, which convert electrical signals into sound. Different vibrating diaphragms and driving mechanisms present different frequency response characteristics for different applications. For example, moving coil speakers, commonly referred to as dynamic drivers, are commonly used in headphones (earphones) [2] and loudspeakers. Electrostatic speakers consist of a thin (<15 μm), electrically-charged diaphragm suspended between two perforated metal plates. These provide excellent sound reproduction and low distortion [3]. Piezoelectric speakers produce sound via the inverse piezoelectric effect, and can produce considerable sound pressure in a thin, compact package [4].

Vibrating surfaces with negligible stiffness (compared with the restoring force due to tension) are referred to as membranes. Vibrating surfaces with greater stiffness are referred to as plates [5]. Vibration characteristics of circular membranes and plates have been discussed in numerous papers. Jabareen and Eisenberger [6] presented exact solutions for the axisymmetric as well as antisymmetric modes of circular and annular membranes, in which any piecewise polynomial variation in density can be represented as a power series solution. Leissa [7] presented a summary of previously published literature on vibrating circular plates up to the year 1969. The natural frequencies of thin, circular plates with clamped, simply supported, and free edge conditions have also been studied extensively. Amabili et al. [8] evaluated the natural frequencies and modes for the free vibrations of free-edge circular plates vibrating in a vacuum or in contact with liquid, and also considered the influence of Poisson's ratio.

During the 1960s and 70s, several pioneers [9–12] outlined the construction of push-pull electrostatic headphones and amplifiers, and investigated the frequency response characteristics in open air and using artificial ears. In the 1990s, Streng [13] outlined the movement of charge on the membrane of a push-pull electrostatic loudspeaker. Under steady-state operations (harmonic excitation), the movement of charge can produce harmonic distortion and a net change in the charge of the static membrane. Mellow and Kärkkäinen [14] advanced the methods for calculating the radiation characteristics of circular membranes in free space and in an

* Corresponding author.
E-mail address: yhhuang@mail.ntust.edu.tw (Y.-H. Huang).

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infinite baffle. Bai et al. [15] presented a fully experimental modeling technique and a procedure for optimizing the design of push-pull electret loudspeakers. In their design, the diaphragm is made of fluoro-polymer containing nanopores to enhance charge stability and density. Chen et al. [16] fabricated the 100-mm-by-100-mm electret loudspeaker (4-g weight and 1-mm thickness) consumes only 0.15 mW to generate a sound pressure level (SPL) of 88 dB at 1 kHz. This high efficiency device is ideal for application in electric cars.

Several recent papers have reported on the methods used to measure the resonance modes and sound pressure of electrostatic and piezoelectric speakers. Huang and Ma [17] investigated transverse (out-of-plane) and planar (in-plane) vibrations in triple-layered piezoceramic bimorphs running in parallel and in series connection, using amplitude-fluctuation electronic speckle pattern interferometry (AF-ESPI) and laser Doppler vibrometry (LDV). Kim et al. [18] improved the frequency response characteristics of ultra-thin piezoelectric speakers based on acoustic diaphragms by analyzing vibrational modes obtained from LDV measurement. Huang and Chiang [19] employed push-pull electrostatic speakers comprising a pair of transparent conductive plates (used by indium tin oxide, ITO) sandwiching a vibrating diaphragm to measure mode shapes and sound pressure using the lumped parameter method, distributed parameter method, ESPI, and acoustic measurement. These four evaluation methods present a high degree of consistency with regard to the measurement results of vibrational mode and sound radiation characteristics.

In this study, the push-pull electrostatic and free-edge-like piezoelectric speakers with circular diaphragms were introduced on their characteristics of vibration and acoustics. These relatively thin speakers are fabricated using a facile reliable construction process. This paper aims at modeling the circular membrane of the electrostatic speaker and circular plate of the piezoelectric speaker to investigate the frequency response characteristics. The displacement amplitudes and mode shapes, and predicted the SPLs were measured by using optical measurement. Then, the SPL results obtained from optical measurement were compared to acoustic measurement in order to verify the predictions. Experiment results demonstrate that the predicted SPL values are in good agreement with the measured SPLs from the electrostatic and piezoelectric speakers with circular diaphragms. Finally, for damping effects on the electrostatic and piezoelectric speakers, each speaker unit was attached to a pair of acoustic meshes, and measured the SPLs using acoustic measurement. The results demonstrate in this study that the membrane and plate differ in their vibration mechanisms and sound characteristics. These results provide a valuable reference for the practical application of such drivers.

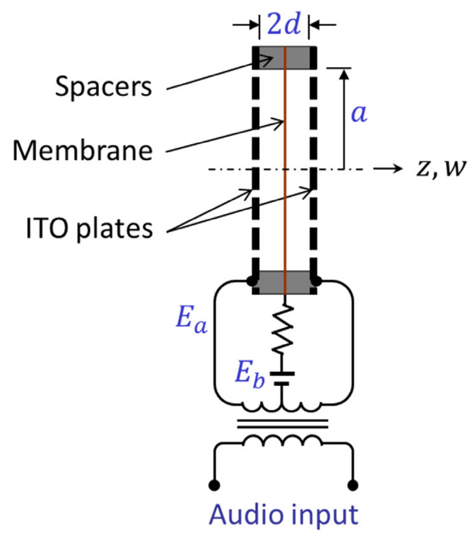
2. Materials and methods

Without additional acoustic mesh damping (air flow through a fine mesh produces dissipative losses), the thin diaphragms used in electrostatic and piezoelectric speakers produce numerous resonances in vibration and sound radiation. To analyze the frequency response characteristics, this study fabricated the prototypes (one electrostatic speaker, two piezoelectric speakers and two types of acoustic meshes), and then employed the measurements.

2.1. Fabrication of speakers and acoustic meshes

Fig. 1 shows the proposed electrostatic speaker using a circular diaphragm with diameter of 60 mm (ES-60), comprising two transparent conductive plates, two spacers, and one membrane. In a push-pull configuration, the two transparent conductive plates with a 33.2% perforation ratio are driven by an alternating current (AC) audio signal, E_a = 100 V (RMS). The 0.5-mm-thick polycarbonate spacers act as excellent insulators in gap (i.e., d = 0.5 mm) between the plate and membrane. The membrane is made of polymer film (thickness, h = 0.002 mm) coated with nickel on one side and then uniformly stretched before being attached to a supporting frame. A constant charge from direct current (DC) bias voltage, E_b = 500 V, is applied to the sound-emitting surface of the circular membrane. Under linear operations, the uniform electrostatic field is proportional to the AC signal between the two transparent conductive plates. Table 1 lists the mechanical and electrical properties of the ES-60 speaker used in this paper.

(a)



(b)

Fig. 1. (a) Photo, and (b) schematic diagram (side view) showing ITO electrostatic speaker (ES-60).

Table 1
Mechanical and electrical properties of electrostatic speaker (ES-60).

Parameter	Value
Radius of membrane, a (mm)	30
Thickness of membrane, h (mm)	0.002
Mass density of membrane, ρ_v (kg/m^3)	1340
Tension in membrane, T (N/m)	40
Perforation ratio of ITO plate (%)	33.2
Thickness of ITO plate (mm)	0.7
Distance from ITO plate to membrane, d (mm)	0.5
AC audio signal (RMS), E_a (V)	100
DC bias voltage, E_b (V)	500