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Vibrational mode and sound radiation of electrostatic speakers using circular and annular diaphragms

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ABSTRACT

This study modeled two diaphragms comprising a pair of indium tin oxide (ITO) transparent plates sandwiching a vibrating diaphragm to create circular (30 mm radius) and annular (30 mm outer and 3 mm inner radius) push–pull electrostatic speakers. We then measured the displacement amplitudes and mode shapes produced by the devices. Vibration characteristics were used to predict sound pressure levels (SPLs) using the lumped parameter method (LPM) and distributed parameter method (DPM). The two measurement results obtained using a laser system were compared to the SPLs obtained using traditional acoustic measurement (AM) from 20 Hz to 20 kHz in order to verify our predictions. When using LPM and DPM, the SPL prediction results in the first three symmetric modes were in good agreement with the AM results. Under the assumption of linear operations, the DPM and amplitude-fluctuation electronic speckle pattern interferometry (ESPI) techniques proved effective in determining the visualization of mode shape (0,1)–(0,3). The use of ITO plates is a practical technique for the prediction of SPL, as well as measurement of mode shapes. The four evaluation methods, i.e. LPM, DPM, ESPI and AM, present a high degree of consistency with regard to vibrational mode and sound radiation characteristics.

1. Introduction

Membranes have many applications in acoustics. Membrane surfaces (i.e., vibrating diaphragms) are a fundamental component of speakers, microphones, and musical instruments (e.g., drums). Speakers and microphones are the most common sound actuators and sensors and are, in fact, closely related. Different drive mechanisms, such as dynamic moving-coil, electrostatic, and piezoelectric types, result in different vibration and sound characteristics. Electrostatic headphones and loudspeakers produce sound of very high fidelity with low distortion [1,2]. Push–pull electrostatic speakers comprise a sandwich of two conductive plates fashioned with a two-dimensional (2D) array of holes. A thin diaphragm (membrane) is suspended between the two conductive plates. The diaphragm material must be able to hold a charge of direct current (DC) bias voltage, such that the subsequent application of alternating current (AC) to the conductive plates produces a uniform electrostatic field proportional to the source audio signal. This creates a push–pull force acting on the diaphragm, the movement of which acts on the surrounding air to produce an audible signal.

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The construction of electrostatic earphones and loudspeakers was described by Selsted [1] and Sanders [3], respectively. Compared to single-ended speakers, push–pull electrostatic speakers provide a diaphragm with greater stability, which reduces second-order distortion. In the 1960s and 1970s, several researchers [4–6] designed electrostatic headphones and amplifiers. They determined that the conductive plates of electrostatic speakers must be rigid and provide an opening of least 20%. To achieve maximum acoustic output, the thickness of the spacer should be as small as possible (0.37–0.8 mm) without restricting the movement of the diaphragm at low frequencies. Diaphragms are generally thin and flexible (thickness of less than 15×10^{-3} mm) and made from polymer films capable of holding a charge generated from a DC bias voltage. These pioneers also outlined the fundamentals of electrostatic speaker constructions as, well as the characteristic responses in the open air and with artificial ears.

The vibration characteristics of circular membranes have been discussed in numerous papers. Membranes have far more freedom with regard to vibration than do strings. The careful selection of polar coordinates for the circular boundary can help to overcome many of the problems associated with circular membranes [7]. Sharp [8] presented a finite transform solution for annular membranes with symmetrical vibration characteristics using completely arbitrary initial and boundary conditions. Jabareen and Eisenberger [9] provided exact solutions for axisymmetric as well as antisymmetric modes of circular and annular membranes wherein, any piecewise polynomial variation in density can be obtained using a power series solution. They solved dynamic problems using the dynamic stiffness method for circular and annular membrane elements. Streng [10,11] calculated the membrane deflection and sound-field characteristics of electrostatic push–pull loudspeakers based on circular stretched-membranes in free space. Mellow and Kärkkäinen [12] presented an enhanced method for calculating the radiation characteristics of circular membranes in free space and in an infinite baffle.

There have been several recent reports on new materials and manufacturing methods used in the fabrication of electrostatic speakers. Bai et al. [13] conducted electroacoustic analysis of a single-ended electret loudspeaker combining finite-element and lumped-parameter models. Experimental results revealed that the single-ended electret loudspeaker suffered from a high degree of nonlinear distortion. They later [14] presented a full experimental modeling technique and design optimization procedures applicable to push–pull electret loudspeakers. The diaphragm they employed was made of fluoropolymer with nanopores to enhance charge density and stability. The push–pull configuration effectively overcomes the problem of nonlinearity found in the single-ended configuration. Zhou and Zettl [15] used a graphene diaphragm, 7 mm in diameter with a DC bias voltage of 100 V, as an audio transducer (earphone) based on the push–pull electrostatic principle. They also described sound pressure levels (SPLs) over the relevant audio frequency range using graphene speakers and high-quality commercial earphones. Chiang and Huang [16] employed the lumped parameter method (LPM) and distributed parameter method (DPM) in the measurement of vibration and the prediction of sound pressure in push–pull electrostatic speakers. The electrostatic speaker was fabricated by suspending a circular diaphragm (60 mm diameter) between two indium tin oxide (ITO) plates. The SPL values predicted using LPM and DPM were identical to those obtained via acoustic measurement. Huang et al. [17] illustrated transverse and planar vibration characteristics in two-layered piezoceramic disks in order to determine the traction-free boundary conditions using theoretical and finite element analysis as well as experimental measurements. Amplitude-fluctuation electronic speckle pattern interferometry (ESPI), laser Doppler vibrometer (LDV), and impedance analysis were used to take measurements and verify the theoretical solutions to transverse and extensional vibrations.

In this study, we employed metal sputtering on a polymer film (low mass) in the fabrication of a push–pull electrostatic speaker. This is a relatively inexpensive, facile, and, yet, a reliable process. We employed semi-analytical as well as experimental methods to predict SPL values in order to avoid the inaccuracies that inevitably occur when using the approach of finite element analysis for modeling based on uncertain properties (e.g., uniform pressure difference, specific acoustic impedance, and tension in the diaphragm). This study had three objectives. First, we sought to develop push–pull electrostatic speakers using transparent ITO plates to overcome the vibrational measurement. Second, we developed a rapid yet accurate technique for the experimental measurement of vibrations and the prediction of sound pressure without resorting to a sound field (e.g., in an anechoic chamber). Third, on the basis of the circular diaphragm, we developed [16], aiming at modeling the annular diaphragm to measure the displacement amplitudes and mode shapes, and to predict the SPLs.

The experimental used methods in this study are as follows: (1) LPM for the measurement of displacement amplitudes and prediction of modes and SPLs; (2) DPM for the measurement of mode shapes and the prediction of SPLs; (3) amplitude-fluctuation ESPI for the measurement of mode shapes (fringe patterns); and (4) acoustic measurement (AM) for the measurement of SPLs in a sound field. The experimental results demonstrate that the predicted modes and SPLs are in good agreement with the measured mode shapes and SPLs in ITO electrostatic speakers based on circular and annular diaphragms. The use of ITO plates is a practical technique for measuring mode shapes and predicting SPLs. This approach could be applied to a variety of thin-film speakers and microphones that employ perforated sheets.

2. Experiments: materials and methods

Without additional damping provided by a woven mesh with acoustic airflow resistance, the thin, light diaphragm found in electrostatic speakers vibrates in many resonant modes with many peaks in the displacement amplitude. To investigate the frequency–response characteristics associated with vibrational modes and sound pressure, we employed LPM, DPM and