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A large-diaphragm piezoelectric panel loudspeaker and its acoustic frequency response simulation method

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ABSTRACT

The authors applied the Finite Element Method (FEM) to analyze the electro-mechanical transformation and micro dynamical characteristics of a piezoelectric panel loudspeaker with triple layered piezoelectric ceramic slices in 2 × 2 rectangular arrangements. According to the simulated micro-vibration data, the authors built an acoustic analysis model combined with a linear superposition method to rapidly obtain the Sound Pressure Level (SPL) frequency response. FEM calculations of resonant modes, resonant frequencies, and the amplitude at the center of the diaphragm were in good agreement with measured values. The measured SPL frequency response agreed with the simulation, supporting the FEM model and the SPL frequency response calculation method proposed in this paper. In addition, an improved structure by addition of an elastic mat was illustrated and demonstrated to provide a smoother low-frequency SPL frequency response verified by both measurement and simulation methods.

1. Introduction

During the past few years, the Computer, Communication, and Consumer industries, or 3C, have become the fastest growing industries in the world. Today there are widespread uses of portable consumer products such as laptop computers, mobile phones, and projection screens; becoming an essential part of daily work, communication and recreation [1–3]. In these products, the loudspeaker is an important electromechanical and electroacoustic component that converts electrical signals into sound waves in the audio frequency range [4]. Nowadays, the desired characteristics of 3C products are slimness, light-weight, wide-screen, low power consumption, and high acoustic output & quality.

For loudspeakers, the most common type currently in use is the moving-coil loudspeaker, also known as a dynamic loudspeaker; which is mainly composed of a magnet, a moving coil, front/rear cavities, and the cone (also called vibration diaphragm). As the electronic current flows, the coil moves under the Lorentz force, moving back and forth in conformity with the original signal. The cone passes this movement onto a large area of air, resulting in the production of sound pressure waves. Due to the space requirements of this structure and the need for front/rear cavities in acoustic design, the minimum thickness is limited to 2–3 mm, insufficient to meet the requirement of miniaturization for a new generation of 3C products [3,5].

To achieve even thinner designs, piezoelectric panel loudspeakers provide an alternate solution [6,7]. As an important category of transducer materials, piezoelectric ceramics exhibit excellent electromechanical coupling effects and allow a rapid response to external force. This material has been extensively studied and widely used in many fields, such as communication, aviation, detection, automation, and household appliances. There have been recent rapid developments of many piezoelectric ceramic devices like piezoelectric transformers, sensors, and actuators to meet the increasing needs of electromechanical components that are thin, lightweight, and offer high performance.

The frequency response of the sound pressure level (SPL) response of a loudspeaker, described as its acoustic quality, is determined by multiple parameters of the loudspeaker. Although there have been some experimental studies [8–11] of optimized structures, the process has been limited by incomplete information and is time-consuming. To address the problem of limited information and to increase the speed of discovery and experimentation, simulation of the SPL frequency response is crucial. However, only a few works have been devoted to such analysis for loudspeakers in

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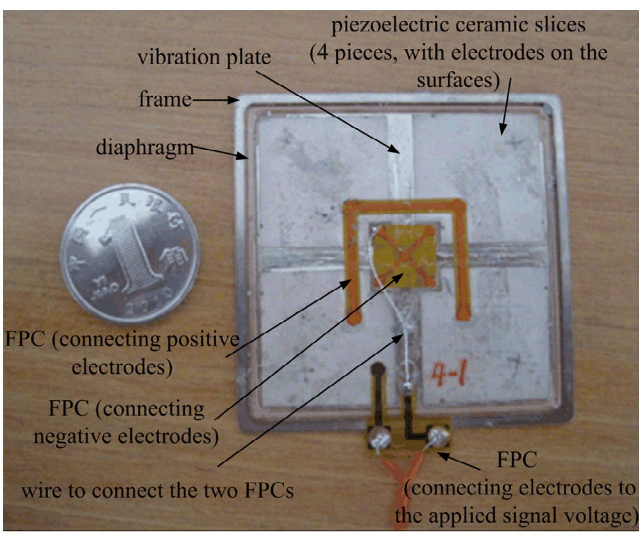
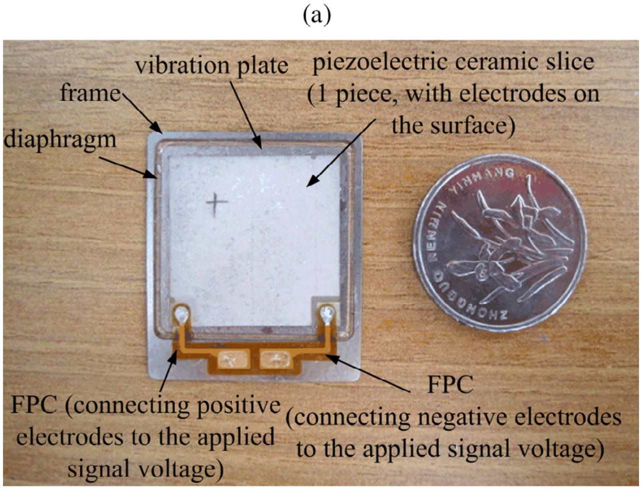
the emerging fields of electroacoustics and most of these works have been focused on traditional loudspeakers (the moving-coil loudspeaker).

Of the simulation works regarding piezoelectric loudspeakers, Bai et al. [3] employed the genetic algorithm and the Taguchi method to achieve optimal designs with low fundamental frequency and high acoustic output. Doare et al. [12] derived a dynamical model of a piezoelectric loudspeaker that was used to optimize the geometries used to minimize the vibration of the plate along its second and third modes. Fan et al. [13] presented an integrated equivalent circuit model of a thermo-acoustic resonance pipe driven by a piezoelectric loudspeaker and optimized the coupling conditions. However, another convenient and effective way to simulate the vibration and SPL frequency response are still required. Aiming to improve the acoustic performance, the design of the piezoelectric panel loudspeaker still lacks theoretical guidance, and instead relies mainly on designer experience. Current structures of piezoelectric loudspeakers show a relative decrease in acoustic quality compared to moving-coil loudspeakers, with a lower sound output, a narrower low-frequency range, and a more fluctuating SPL frequency response. To overcome these limitations, simulation can be a powerful tool to explore the variations of the many parameters used to determine an optimal design.



(a)



(b)

Fig. 1. Piezoelectric panel loudspeaker samples. (a) study sample, (b) reference sample.

In this study, implementation, simulation, experimentation and an improved structure of a piezoelectric panel loudspeaker are described. The structure and its unique features are presented in Section 2. The modeling, simulation, and calculation methods for the dynamic and SPL frequency responses and the corresponding dynamic and acoustic experiments are reported in Sections 3 and 4, and the improved structure with addition of an elastic mat is illustrated and shown to provide a flatter SPL low-frequency response. Comparing these results with the previous work of the authors [10], this study focuses more on the simulation and calculation methods for SPL frequency responses, and provides more details about the structures and features of the piezoelectric panel loudspeaker.

2. Structure and features

The study and reference samples of the piezoelectric panel loudspeaker are shown in Fig. 1 and the specifications of the sample are shown in Fig. 2 and Table 1. Samples were obtained by sticking piezoelectric ceramic slices onto a metal sheet which served as the vibration plate. A poly-ether-ether-ketone (PEEK) flexible membrane bound with the vibration plate is applied as a diaphragm to absorb the vibration of the vibration plate and to reduce the fundamental frequency, and a frame provides simple support to the diaphragm.

Compared with the reference sample that has the same thickness, the study sample is more synonymous with the wide screen trend of 3C products due to the larger diaphragm. The 2×2 rectangular arrangement of piezoelectric ceramic slices is used to enhance the vibration and acoustic output of the diaphragm.

Both the study and reference samples use the same piezoelectric ceramic slice as shown in Fig. 3. The material of the piezoelectric ceramic is a ternary system of $x\mathrm{Pb(Mg_{1/3}Nb_{2/3})O_3}$-$y\mathrm{PbZrO_3}$-$(1-x-y)\mathrm{PbTiO_3}$ with a typical composition of $x = y = 0.35$. As shown in Fig. 4a and b, a parallel triple-layered ceramic structure due to the special electrode layout is applied to enhance deformation and the corresponding acoustic output. With voltage applied

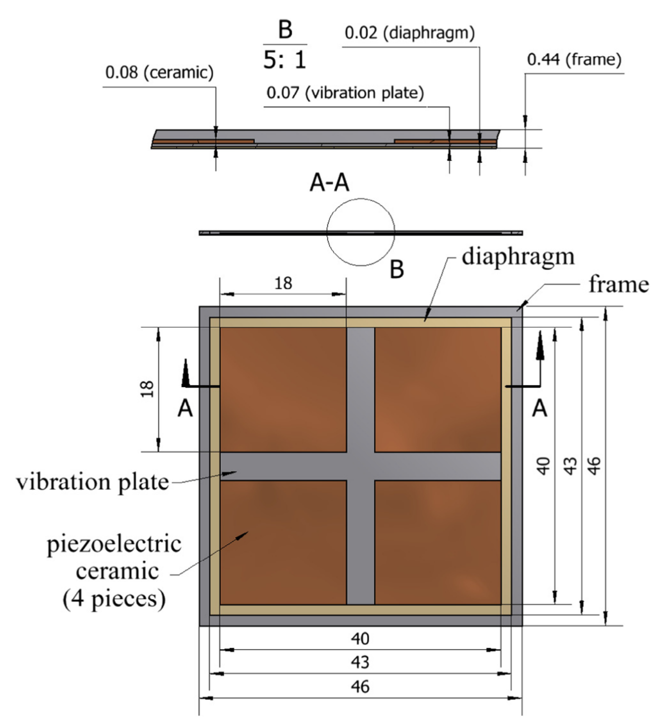


Fig. 2. Schematic diagram of the study sample (all dimensions are in mm).