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Transparent piezoelectric film speakers for windows with active noise mitigation function

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ABSTRACT

Noise pollution has a significant negative effect on psychological health and quality of life. The building envelop, particularly windows often constitute to the primary path for external noise sources to travel into the buildings. Here we have designed and fabricated transparent piezoelectric film speakers as secondary area sound source for active noise mitigation for window application with ventilation function. The performance properties of the obtained transparent speaker and its effectiveness for active noise mitigation are evaluated through numerical simulations as well as experimental measurements. The produced transparent piezoelectric film speaker exhibited enhanced overall sound pressure level (SPL) and broader frequency response range with a significantly improved SPL at frequencies below 300 Hz. Furthermore, compared to an electromagnetic speaker as a point secondary sound source, using the transparent piezoelectric film speaker as an area source resulted in more uniform noise mitigation with substantially larger averaged SPL reduction. The results presented here show the potentials and advantages of transparent piezoelectric film speakers for active noise mitigation.

1. Introduction

Prolonged exposure to high noise level can cause hearing loss. Even at a low noise level, long term noise disturbance has a significant negative effect on psychological health, quality of life and working and learning efficiency. Noise-induced deafness is the leading occupational disease in Singapore reported by the Department of Industrial Health. With increase in urban living density, the number of residential homes exposed to highway or airport traffic noise has significantly increased. Windows are often the primary path through which airborne noise enters a room.

Effective reduction of noise across all window area is the major challenge for noise mitigation through windows when transparency and acceptable aesthetics are required. Passive noise mitigation methods like double-glazed technology are mainly effective at high frequencies and lack natural ventilation. The loss of ventilation results in poor indoor air quality. As a result, heavy use of air-conditioning system is required, significantly increasing electrical power consumption.

In contrast to passive method, active noise control is more effective at low frequencies [1,2]. In literature, improving low frequency noise mitigation performance has been reported by embedding active noise mitigation elements in windows [3,4]. Uses of electromagnetic loudspeakers embedded within air gap of the double-glazed windows [5–7] or discretely installed on single layer window glass, are examples of demonstrated methods for active noise control (ANC), particularly at low frequencies. However such windows have not been widely commercialized because they are bulky, costly, and not aesthetically acceptable. Further, windows with the discrete electromagnetic loudspeakers are not able to achieve uniform noise mitigation over a large area and noise reduction varies significantly at different locations. Uniform noise mitigation with the discrete electromagnetic loudspeakers can be achieved only when the length of the window glass is less than one-fifth of the wavelength of sound in air (e.g., $140 \times 140\,\text{mm}^2$ for frequencies up to 500 Hz) [8,9]. Such a small window glass is not practical for real applications; or use of many of such speakers on window glass greatly increases the overall cost and affects the transparency and aesthetics.

Transparent speakers using piezoelectric films have been explored for replacing the conventional electromagnetic speakers in windows with active noise mitigation function. For example, active noise cancellation using transparent piezoelectric speakers mounted on a closed window was demonstrated by Yu et. al. [9]. Hu et. al. developed

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algorithms to enhance noise mitigation performance of the transparent piezoelectric speakers on closed windows and to further allow their use as audio play-back devices [10,11].

In ANC problems for buildings, since the size of the primary source (for example traffic noise) and its distance from the secondary source (cancellation speaker in window) are large, the wavefronts of the primary sound at the cancellation region usually have a very large curvature. However, wavefronts generated by an electromagnetic speaker as a secondary point source (within the cancellation region) have much smaller curvature compared to the primary source. As a result it is not likely to perfectly superposition the sound fields of the primary and the secondary sources. The consequence of such mismatch is creation of regions where noise is amplified and regions where noise is reduced. In contrast, the transparent piezoelectric film speakers cover a significantly larger area (potentially whole window), and hence can generate a secondary sound field distributed over a large area with relatively flat wavefronts (area speaker). Such characteristic of the transparent piezoelectric film speakers enables a better overlap between the primary sound field and the secondary sound field and hence is promising for achieving a more uniform noise reduction within the building.

The bottleneck of active noise mitigation using the piezoelectric film speakers in the literature is their low frequency performance [12–14]. To realize effective active noise mitigation at low frequencies, it is required to enhance low frequency sound pressure level of the transparent piezoelectric film speakers. Despite the efforts in literature to improve sound pressure level of the transparent piezoelectric speakers through various designs [15–19], their low frequency performance and size need to be further improved for more effective noise mitigation for window applications. Another question is how effective transparent piezoelectric film speakers are for noise mitigation in a window with ventilation function.

Despite the efforts reported in literature, there is big room to improve the speaker structure and characteristics for more effective noise mitigation. Piezoelectric speakers are often a type of piezoelectric unimorph. Hence basic design rules of piezoelectric unimorphs apply to the transparent piezoelectric film speakers. To maximize bending of the unimorph, specific conditions should apply. Firstly, the ratio of piezoelectric actuator's area to that of substrate should be optimized. In transparent piezoelectric film speakers, this is relevant to the top electrode coverage, i.e. the ratio of the area of the top electrode deposited at the center of the transparent piezoelectric element (A_1) over the area of the piezoelectric element (A) (inset of Fig. 6(b)). Secondly, the thickness of substrate should be selected such that neutral line of the structure lies within the substrate. Such structure of a transparent piezoelectric film speaker will result in improved performance of the speaker.

In this paper, we have designed and fabricated transparent piezoelectric film speakers using piezoelectric polymer materials. The effects of presence of a substrate as well as the top electrode coverage on sound pressure level of our obtained transparent piezoelectric film speaker are investigated through numerical simulation as well as experimental measurement. Further, improvement of low frequency performance of the speakers is investigated by fabricating a transparent speaker comprising multiple speaker cells. Active noise cancellation (ANC) performance of the multi-cell transparent speakers is evaluated by integrating them with two types of windows: a conventional top hung window and a duct type window with staggered opening, both with ventilation function. The numerical simulation and experimental measurement results are presented.

2. Materials and methods

2.1. Fabrication and characterization of transparent piezoelectric film speakers

Two different types of speakers were investigated, a single-cell transparent piezoelectric film speaker consisting of one speaker cell, and a multi-cell transparent piezoelectric film speaker consisting of multiple speaker cells with different sizes. Structure of the single-cell transparent piezoelectric film speaker was composed of a top single walled carbon nanotube (SWCNT) electrode, a piezoelectric polyvinylidene fluoride (PVDF) film with thickness of 110 μm, a SWCNT bottom electrode, a polyethylene terephthalate (PET) sheet as substrate, and a frame to clamp the edges of the speaker (Fig. 1(a)). The multi-cell transparent piezoelectric film speaker was composed of multiple patterned transparent top electrodes, a piezoelectric PVDF film, a transparent bottom electrode, a supporting layer, and a grid to clamp boundaries of each cell of the speaker (Fig. 1(b)).

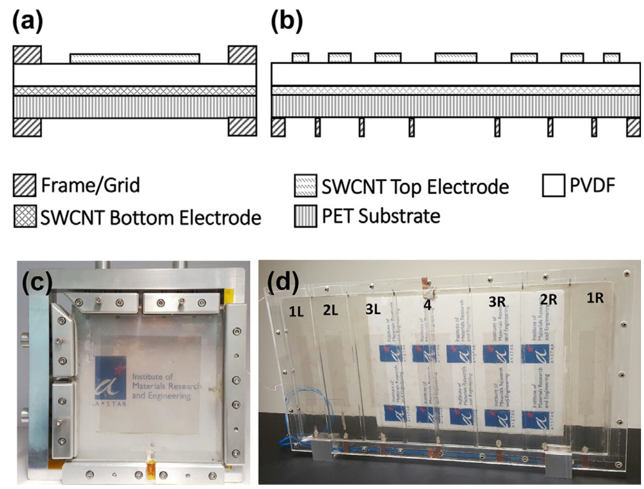

Fig. 1. Cross section view of the structure of (a) single-cell and (b) multi-cell transparent piezoelectric film speakers; A photograph of an obtained prototype of the (c) single-cell and (d) multi-cell transparent piezoelectric film speakers with dimensions of 200 × 200 mm² and 230 × 430 mm² respectively.

To fabricate the top and bottom electrodes, first a suspension of SWCNT powders in 1 wt% solution of DI water and sodium dodecyl sulfate (SDS) surfactant was prepared. The suspension was made by ultrasonic treatment of the mixture for 1 h using a direct-immersion titanium horn (Sonics VCX500, 20 kHz, 500 W, Sonics & Materials Inc., Newtown, CT) at an ultrasonic power of 40 W. During the ultrasonic treatment, the temperature of the suspension was controlled by a temperature thermocouple at 50 °C. The suspension was sprayed on the PVDF film using aerosol spraying process. Bottom SWCNT electrode was formed continuously on one side of the PVDF film while top SWCNT electrodes were patterned using a shadow mask. A sheet resistance of about 400 Ω/□ was achieved for the electrode layers.

After coating the electrodes, the PVDF film was laminated on a 65 μm-thick PET transparent substrate using a transparent epoxy. The laminated PET/SWCNT/PVDF/SWCNT structure was then clamped using a frame to form the transparent piezoelectric film speakers. Prototypes of the fabricated single-cell and multi-cell speakers, with dimension of 200 × 200 mm² and 230 × 430 mm² respectively, are shown in Fig. 1(c) and (d).

Characterization of the fabricated speakers was conducted using PULSE Basic Electroacoustic software (Brüel & Kjaer) interfaced with a calibrated microphone. The microphone was placed 10 cm away from the center of the speaker. Frequency responses of the fabricated speakers were measured within the audible frequency range of 40 Hz–20 kHz.

2.2. Experimental setup for active noise control

Feasibility of achieving ANC was investigated using the multi-cell transparent piezoelectric film speaker integrated with two types of windows: a conventional top hung window and a duct type window with staggered openings, both with ventilation function.