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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.

Keywords: Piezoelectric polymer; Transparent speaker; Active noise mitigation; Window

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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 loud-speakers 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 loud-speakers 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 loud-speakers 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., 140×140 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 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 cancelation 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 filed 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

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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 figure 1(c)). 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)).

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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 hr using a direct-immersion titanium horn (Sonics VCX500, 20kHz, 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 mm^2 and 230 × 430 mm^2 respectively, are shown in Fig. 1(c) and (d).

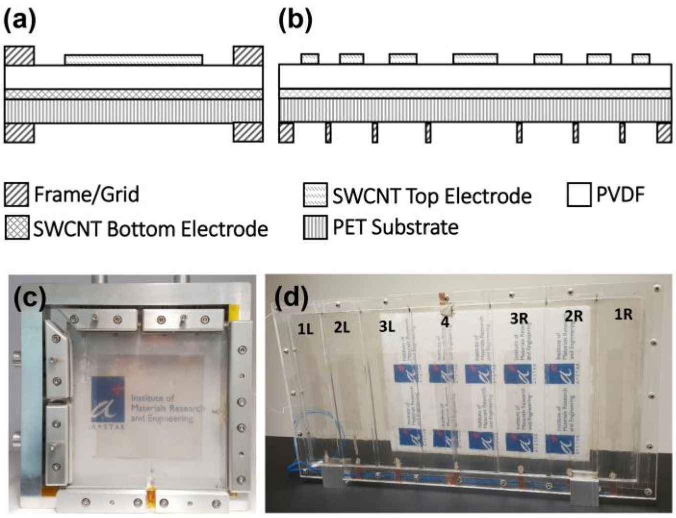

Fig. 1. Cross section view of the structure of (a) single-cell and (b) multi-cell transparent piezoelectric film speakers; A photograph of an obtained prototype of the (c) single-cell and (d) multi-cell transparent piezoelectric film speaker with dimensions of 200 × 200 mm^2 and 230 × 430 mm^2 respectively.

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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.

2.2.1. Top hung window

Fig. 2(a) illustrates the schematic diagram of the conventional top hung window with the integrated speaker. The multi-cell transparent piezoelectric film speaker was attached on the window glass. The schematic and implemented experimental ANC test setup for the top hung window, as shown in Figs. 2(b) and 4(a) respectively, consisted of a source room (2.6 × 3 × 2.6 m^3) and a receiving room (5 × 3 × 2.6 m^3). The two rooms were separated by a window comprising three top-hung sashes and 3 casements. One of the top-hung sashes was tilted at an angle of 30° to provide an opening for ventilation between the two rooms. All other casements and top-hung sashes were kept close. The transparent piezoelectric film speaker was attached to the tilted top-hung sash and the error microphone was placed at the center of the opening.

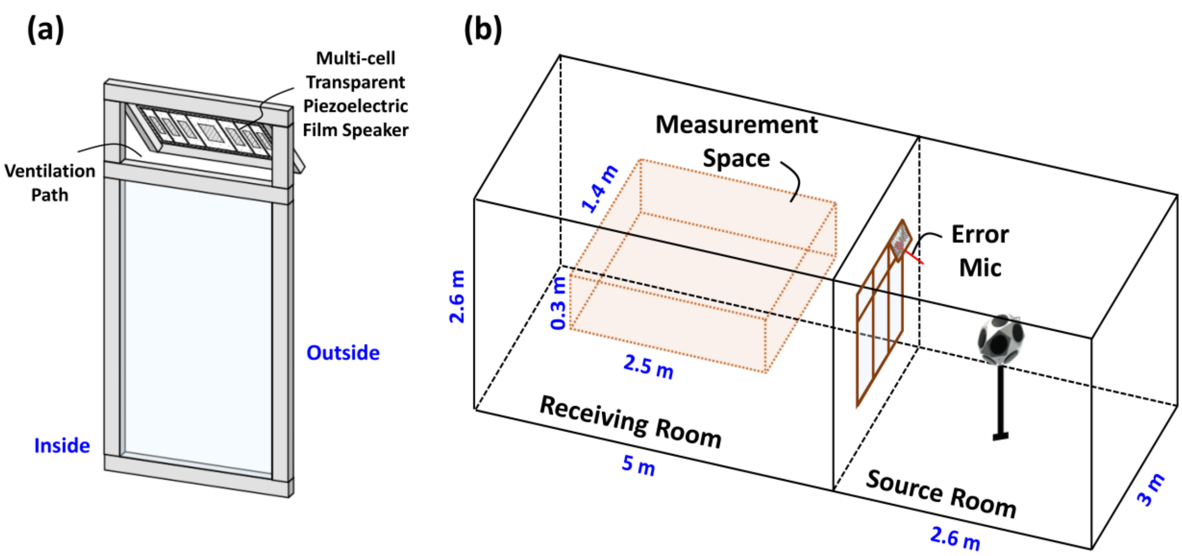

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Fig. 2. (a) Schematic diagram, and (b) the experimental test setup of the top hung window for evaluation of ANC performance of the multi-cell transparent piezoelectric film speaker.

Active noise mitigation performance of the multi-cell transparent piezoelectric film speaker was measured in the frequency range of 200-900 Hz. SPL of the source and the transparent speaker were kept the same at the error microphone position in all of the frequencies. Phase of the transparent speaker was manually tuned to minimize the SPL at error microphone. A measurement microphone was used to record SPL of 10 different locations within the receiving room in ANC control ON and control OFF conditions. The measurement locations covered a volume of $2.5 \times 1.4 \times 0.3$ m^3.

2.2.2. Duct type window with staggered openings

Schematic diagram of the duct type window with staggered openings employing the multi-cell transparent piezoelectric film speakers is illustrated in Fig. 3(a). Fig. 3(b) and 4(b) present the schematic and implemented experimental ANC test setup respectively. The window consisted of 3 front sliding panels and 3 rear sashes. The inner dimensions of the window were $0.12 \times 1.8 \times 0.4$ m^3. The transparent speakers were attached on the rear sashes of the window. One of the rear sashes was kept open at an angle of about 30^o. The sound source was placed inside an enclosure attached to the open rear sash. The error microphone was positioned at the center of the opening on the sliding panel of the window. The opening was about 10 cm. The whole setup was placed in a room with dimensions of $2 \times 2.4 \times 2.4$ m^3. A tonal noise of 650 Hz was used for the measurement. The amplitude and phase of the transparent speaker were manually tuned to minimize the sound pressure level at the error microphone.

The average noise mitigation performance of the transparent speaker was evaluated by measuring sound pressure levels of 96 measurement locations within a space of $0.9 \times 1.5 \times 0.8$ m^3. The test was conducted in both single-channel (only one transparent speaker closest to the source was used for ANC) and multi-channel (three independent transparent speakers were used for ANC) configurations. To compare the noise mitigation performance of the transparent piezoelectric film speaker (area speaker) with the conventionally used electromagnetic speakers (point speaker), an electromagnetic speaker was used to replace the transparent speaker located closest to the source.

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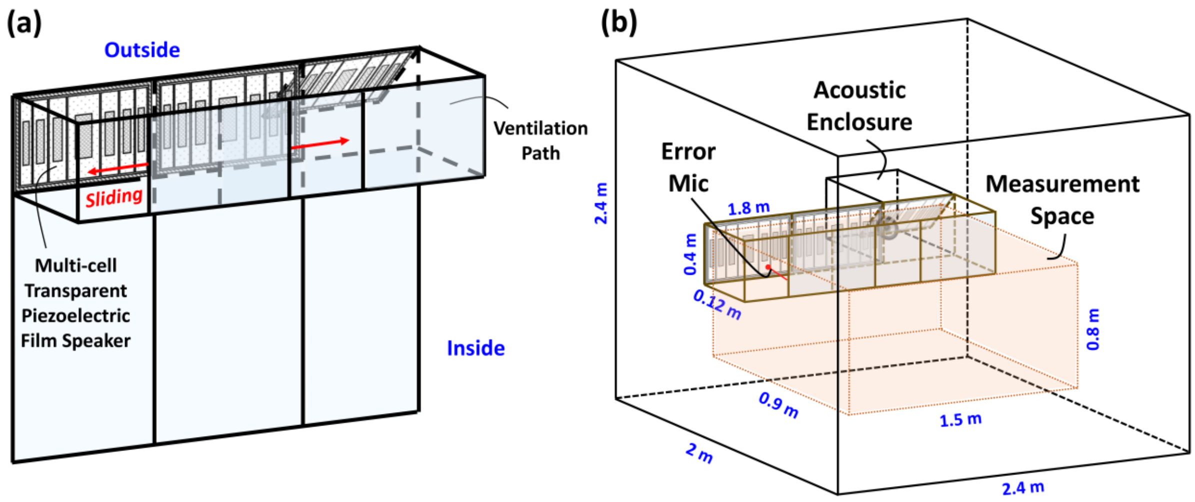

Fig. 3. (a) Schematic diagram, and (b) the experimental setup of the duct type window with staggered openings used for evaluation of ANC performance of the multi-cell transparent piezoelectric film speaker.

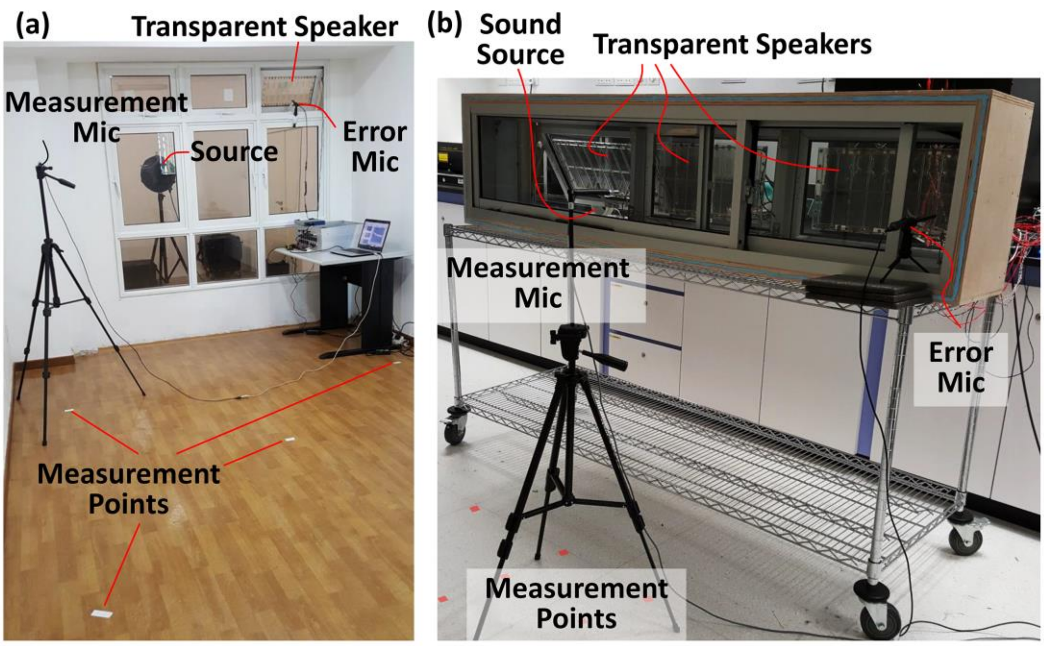

Fig. 4. Implemented ANC test setup for evaluation of noise mitigation performance of the multi-cell transparent piezoelectric film speaker using (a) conventional top hung window and

(b) duct type window with staggered openings.

2.3. Numerical simulation

2.3.1. Transparent piezoelectric film speaker

The structure of the transparent piezoelectric film speaker, as described in Section 2.1, is analogous to a piezoelectric unimorph. To achieve the optimal performance of the speaker, optimal PET substrate thickness and CNT top electrode coverage (area of piezoelectric actuator) of transparent piezoelectric film speaker were identified through numerical simulations with ANSYS (Version 15.0).

Substrate thickness and top electrode coverage were varied to achieve the largest displacement of the speaker under an applied voltage; the sound pressure level of the transparent piezoelectric speaker will be largest when the displacement of the speaker is maximized. ANSYS elements SOLID226 and SOLID186 were used for simulating piezoelectric layer and the substrate layer, respectively. The piezoelectric layer was polarized in the thickness direction. The top and bottom electrodes were modelled by coupling the voltage degree-of-freedom for top and bottom surfaces of the piezoelectric layer, respectively. The physical geometry of SWCNT electrodes was not modelled considering its small thickness in comparison with the piezoelectric layer and the substrate. 36-volt electric potential was applied across the top and bottom electrodes and the maximum displacements of different speaker designs were recorded. To determine the optimal top electrode coverage, a transparent piezoelectric film speaker with PET substrate thickness of 65 μm and varied top electrode coverage was simulated.

The optimal substrate thickness and top electrode coverage values obtained from numerical simulations were used for fabrication of the transparent piezoelectric film speakers.

2.3.2. Active noise control

Top hung window: Numerical simulation was conducted using commercial software COMSOL to show the possible control effect under ideal situation. Fig. 5(a) illustrates the finite element modeling (FEM) model, where a top hung window with single sash is opened at

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an angle of 30°. A source room was considered to generate acoustic excitation to the window. The receiving room was assumed to have rigid surfaces with dimension similar to experiments. The transparent speaker which is attached to the receiving side of the window sash is modeled as a vibrating surface.

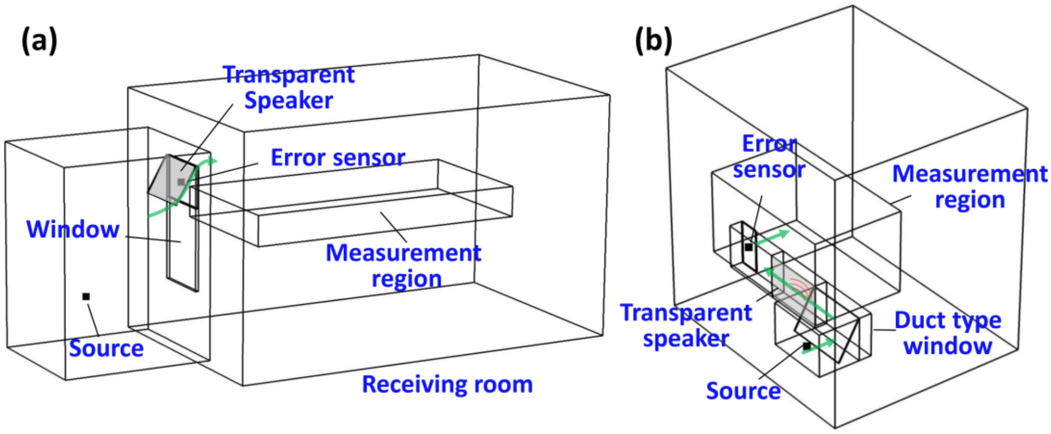

Fig. 5. FEM simulation model for (a) conventional top hung window and (b) duct type window with staggered opening.

To simulate the ANC effect, the primary sound field due to the source room and secondary sound field due to the transparent speaker with an arbitrary input strength were first calculated. The control target is to minimize the sound pressure received at the single error senor location, which is assumed at the center behind the single window sash. The complex sound pressures obtained at the error sensor due to primary and secondary fields determine the correct input speaker strength [3]. The averaged SPL in a representative measurement region with dimensions of $2.5 \times 1.4 \times 0.3$ m^3 is considered for the control effect.

Duct type window with staggered openings: Fig. 5(b) illustrates the simulation model where a duct type window with staggered opening configuration, similar to the experiments, is considered. An acoustic enclosure with a point sound source is connected to the window inlet as the noise excitation. A receiving room ($2 \times 2.4 \times 2.4$ m^3) with rigid walls was considered in the model. The SPL was averaged over a representative measurement region (0.9 × 1.5 × 0.8 m^3) to evaluate the control effect.

The secondary speaker is controlled using the same approach as introduced in the top hung window case, with a measurement point being defined at the center of the outlet opening, as the error sensor. The control target is to minimize the sound radiated to the duct outlet by matching the primary sound field (due to noise source) and the secondary field (due to transparent piezoelectric film speaker). The transparent speaker in Fig. 1(d), as the secondary source, is modeled as a vibrating surface with uniform normal velocity.

It should be noted that the simulation results are purely based on ideal simulation conditions. In reality, the frequency spectrum of the film speaker, the capability of the control circuit, sound leakage from various window components and non-ideal boundary conditions of the excitation and receiving rooms will all affect the actual measurement outcome.

3. Results and Discussion

3.1. Transparent piezoelectric film speaker

Fig. 6(a) shows the numerical simulation results for determination of optimal PET substrate thickness for a 200 × 200 mm^2 transparent piezoelectric film speaker with top electrode coverage of 100% and varying PET substrate thickness. A strong dependence of maximum displacement of the speaker on PET substrate thickness was found. The optimal PET substrate thickness for the speaker under simulation was about 65 μm, resulting in the largest displacement. The numerical simulation results of the optimum top electrode coverage are shown in Fig. 6(b). The displacement of the speaker was strongly dependent on top electrode coverage. Compared to full coverage ($A_1/A = 1$), the maximum displacement of the speaker significantly increased (by a couple of orders of magnitude) with decrease of the top electrode coverage to 27%, and then dropped with further decrease.

Fig. 7(a) presents the frequency response of the fabricated single-cell speaker with PET substrate and optimized top electrode coverage within the audible frequency range of 40 Hz - 20 kHz. For comparison, frequency response of a fabricated conventional transparent piezoelectric film speaker (with 100% top electrode coverage and no substrate) with same

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dimensions as our transparent piezoelectric film speaker is also presented.

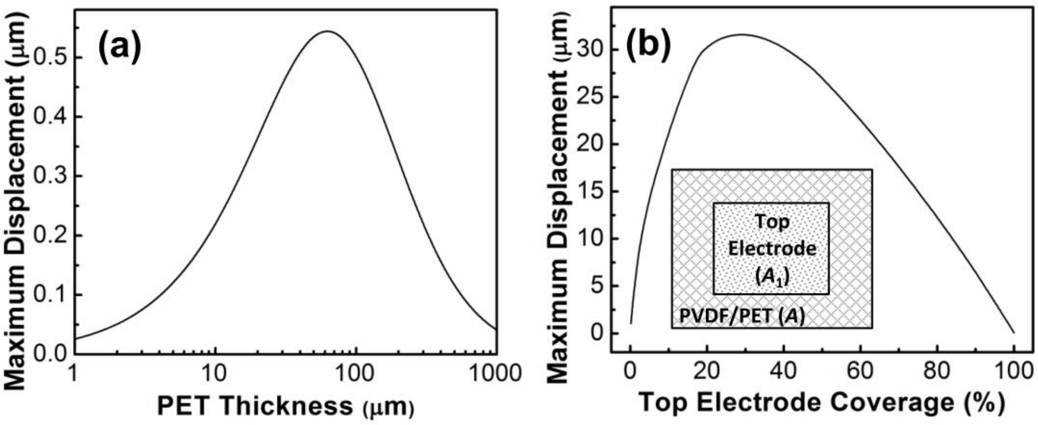

Fig. 6. Numerical simulation results for determination of (a) optimal PET substrate thickness (65 μm) and (b) optimal top electrode coverage for a single-cell transparent piezoelectric speaker with 110 μm thick PVDF.

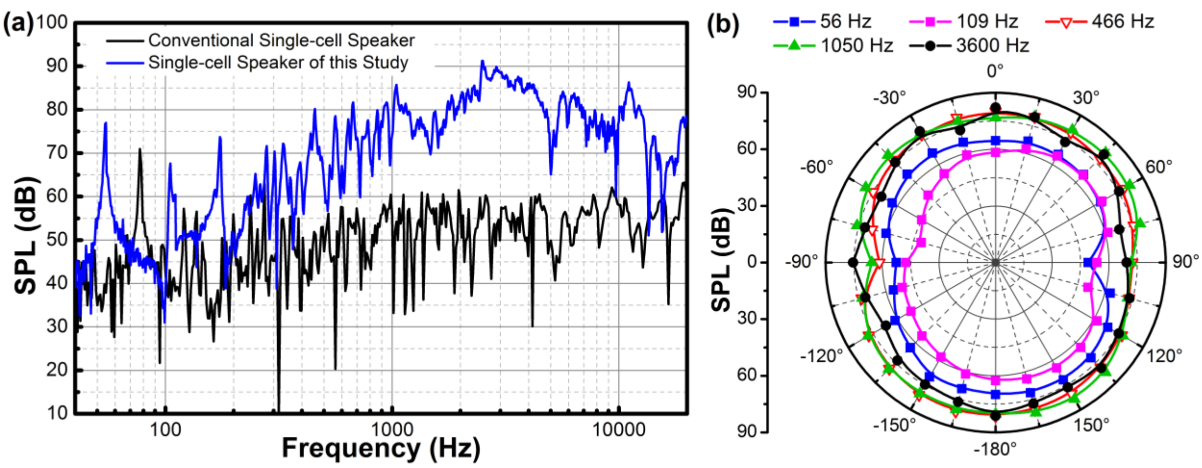

Fig. 7. (a) Frequency response of the conventional single-cell transparent piezoelectric film speaker and single-cell transparent piezoelectric film speaker with PET substrate and optimized partial top electrode coverage; (b) Polar diagrams representing radiation pattern of the single-cell transparent piezoelectric film speaker with PET substrate and optimized partial top electrode coverage.

It was found that the SPL of the single-cell transparent piezoelectric film speaker with PET substrate and partial top electrode coverage was significantly larger (by 10-30 dB) than that of the conventional single-cell speaker with 100% top electrode coverage and without PET substrate. An exception was at the frequency of 75 Hz, where a resonance happened in the conventional speaker. The increased SPL of the single-cell transparent piezoelectric film speaker with PET substrate and partial top electrode coverage is due to the enhanced vibration displacement due to optimization of design parameters as indicated by simulation.

Radiation pattern of a speaker is defined as angle of coverage of speaker output and is a characteristic of how a speaker sends sounds in different directions. For effective noise mitigation, it is desired that the speaker generates sound equally in all directions so that uniform noise mitigation within a space can be achieved. Polar diagrams of radiation pattern of the transparent piezoelectric film speaker with PET substrate and partial top electrode coverage at different frequencies are presented in Fig. 7(b). It was found that at all of the measured frequencies (56 - 3600 Hz), the speaker generated almost equal SPL in all directions indicating that our fabricated piezoelectric film speaker is omnidirectional, which is promising for uniform ANC effect.

Piezoelectric polymers are very suitable for producing transparent piezoelectric speakers with their flexibility and low cost, but they exhibit much smaller piezoelectric strain coefficient. As a result, the off-resonance sound pressure level (SPL) of a transparent piezoelectric speaker fabricated from a polymer film is low. Hence resonances may be possibly explored for a polymer-based piezoelectric film speaker to enhance its sound pressure level, although this could bring frequency dependent issues.

A multi-cell transparent piezoelectric speaker comprising multiple cells of different sizes and geometries would possess varied sets of resonance frequencies. Such structure of the speaker possesses multiple resonance frequencies and hence a relatively flattened frequency response with potential for realizing active noise mitigation over a broader frequency range.

The overall frequency response of the fabricated multi-cell transparent piezoelectric film speaker, as well as frequency response of each cell is presented in Fig. 8. Speaker cells with the same dimensions (1L and 1R, 2L and 2R, and 3L and 3R respectively) exhibited similar frequency response and hence only the representative data are presented in Fig. 8. The

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resonance frequencies shifted to higher frequencies by reducing the dimensions of the speaker cell. Further, when all of the speaker cells were active, an improved SPL and a broader and relatively flattened frequency response compared to individual cells were obtained. This originates from the collective effect of individual cells, each having different sets of resonance frequencies. Reduction in SPL at some frequencies is attributed to destructive interaction of sound waves among individual speaker cells due to their phase mismatch.

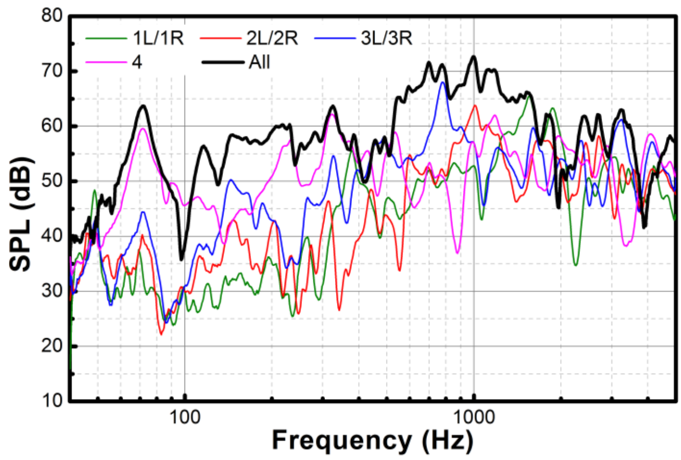

Fig. 8. Frequency responses of the multi-cell transparent piezoelectric film speaker prototype, and the individual cells.

It was also noted that the multi-cell transparent piezoelectric film speaker exhibited significantly improved SPL at frequencies below 300 Hz when all of the speaker cells were active, which is an advantage in ANC application for cancelling low frequency noise. The potential of the multi-cell transparent piezoelectric film speaker for application for active noise mitigation will be evaluated in the next section.

3.2. Active noise control using the multi-cell transparent piezoelectric film speaker

3.2.1. Top hung window

Fig. 9 presents the control effect, in the top hung window configuration, at the error sensor and averaged over the representative measurement region obtained from numerical simulation and its comparison with experimental measurement. The numerical simulation results show that ANC could reduce the SPL at the error sensor, but global control over the receiving room is only effective at frequencies between 200 to 500 Hz. The reason could be due to random noise excitation, since the incident sound waves could be multi-directional. In such a case, spatial matching to the primary sound field by using secondary speaker is very challenging, and standing-wave modes inside the rigid receiving room further deteriorates the global control effect. It is further found from Fig. 9 that trend of the experimentally measured average SPL reduction is in good agreement with numerical simulation. It was found from the experimental measurements that the average SPL reduction ranged between 1-12 dB over a large frequency range, while amplifications as much as 2 dB occurred at some frequencies. ANC was most effective within the frequency range of 250-500 Hz within which an average SPL reduction of 4.4 dB was achieved.

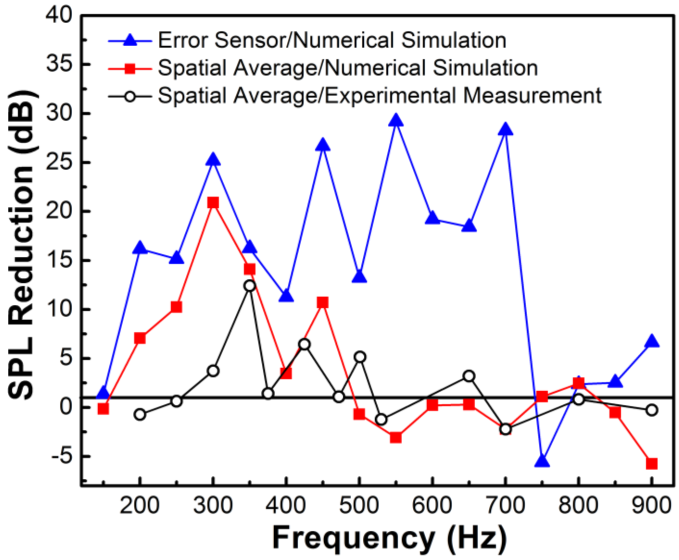

Fig. 9. The simulated and measured ANC effect of the transparent speaker integrated with a top hung window, at error sensor location, and spatially averaged over the measurement region.

3.2.2. Duct type window with staggered openings

The SPL reduction averaged over the receiving region, in the duct type window

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configuration with staggered openings, obtained by numerical simulation is presented in Fig. 10(a). The simulated result is capped at 30 dB as greater values become unrealistic in real test. The cut-off frequency determined by the window width (0.12 m) is around 1400 Hz below which ANC is theoretically possible [3]. At lower frequencies the acoustic wavelength is long so the secondary sound field can better match the primary field in ANC. The control effect is significant below 800 Hz except from 450 Hz to 600 Hz. The drop could be due to acoustic resonances of the source enclosure. As frequency increases, the plane wave sound propagation inside the window duct transforms to complicated multi-dimensional waves which deteriorates ANC effect.

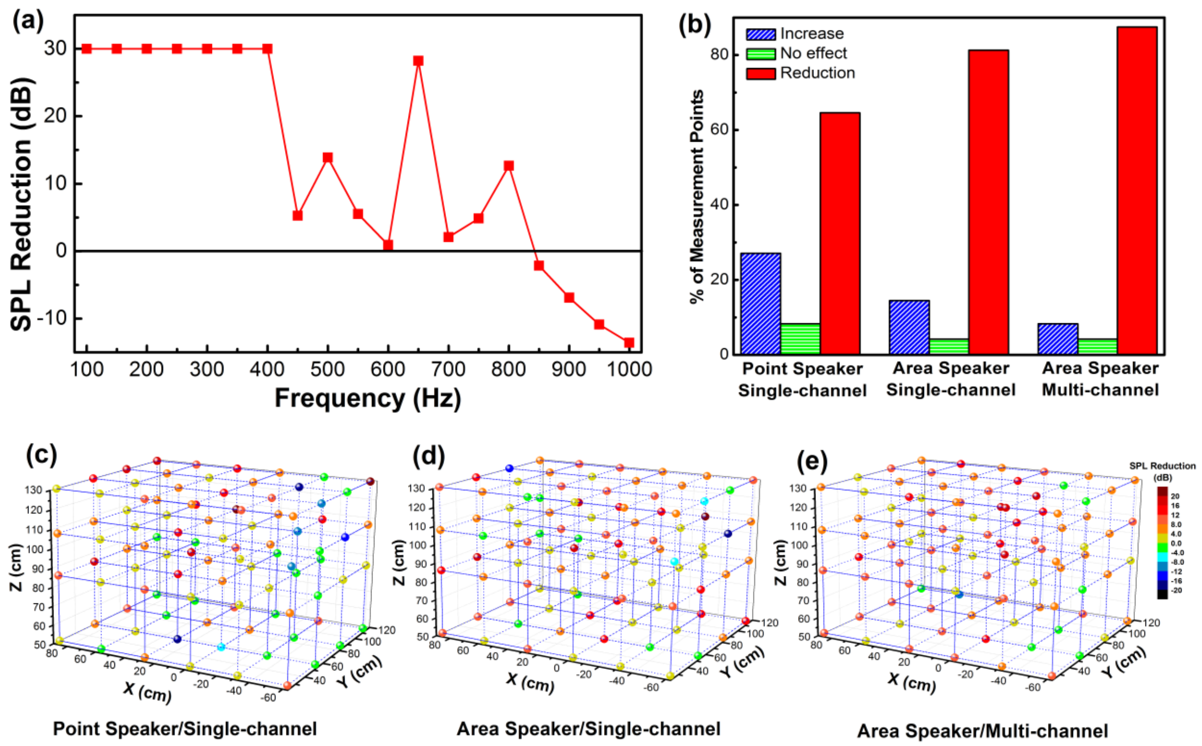

Fig. 10. (a) Numerical simulation results, representing the active noise mitigation performance of the multi-cell transparent speaker integrated with a duct type window, within the measurement area, in the frequency range from 100 to 1000 Hz; (b) Summary of active noise mitigation testing results at 650 Hz for a window with staggered openings and employing (c) one electromagnetic speaker as a point secondary sound source (single-channel), (d) one multi-cell transparent piezoelectric film speaker as an area secondary sound source (single-channel), and (e) three independent multi-cell transparent piezoelectric film speakers as area secondary

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sound source (multi-channel).

In the experiments, ANC was conducted at 650 Hz and the results are summarized in Fig. 10(b)-(e) and Table I. It was found that when one multi-cell transparent piezoelectric film speaker (closest to the sound source) was used as the secondary area speaker for active noise mitigation, an average SPL reduction of 5.1 dB was achieved within the measurement space. However, at 14.6% of the total 96 measurement points, SPL increase (in the range of 1-16 dB) was observed. The increase may be partially due to the leakages in the structure.

Table I. Active noise mitigation performance of the multi-cell transparent piezoelectric film speaker and its comparison with conventional electromagnetic speakers.

Test Configuration	Speaker type	Average SPL reduction (dB)	Reduction points (%)	Increase points (%)	No effect points (%)
Multi-channel transparent speaker	Area	6.3	87.5	8.3	4.2
Single-channel transparent speaker	Area	5.1	81.3	14.5	4.2
Single-channel electromagnetic speaker	Point	3.4	64.6	27.1	8.3

Using 3 independent multi-cell transparent piezoelectric film speakers (multi-channel) as the secondary area speaker for active noise mitigation, resulted in a larger average SPL reduction (6.3 dB) than the single-channel area speaker. Furthermore, SPL increase happened in lesser points (8.3% of the total points) and was much smaller (in the range of 1-9 dB) than the single-channel configuration.

However, when a conventional speaker is used as the secondary point source for ANC, the average SPL reduction was much smaller (3.4 dB) than the two scenarios with piezoelectric film speakers, and the number of locations and the extent of SPL increase were both much larger (27.1% and 1-20 dB, respectively).

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These results show that compared to a point electromagnetic speaker, use of an area piezoelectric film speaker as the secondary sound source for ANC, more uniform noise mitigation with larger averaged SPL reduction can be achieved. Employing a multi-channel configuration for multiple area speakers can further enhance the noise mitigation performance. Our transparent piezoelectric film speakers can be fabricated in large area (potentially the size of whole window), which enables generation of a flatter sound field and hence provides a better superpositioning of primary and secondary sound fields with the potential for improving uniformity of ANC in many applications. Piezoelectric film speakers are further advantageous over the electromagnetic speakers due to their smaller thickness and transparency. They can be directly applied on windows with ANC function and reduce complexities arising from use of bulky electromagnetic speakers. Another advantage of transparent piezoelectric film speaker is that it can be positioned on window glass facing directly the incoming sound without blocking its field of view. It is reported in literature that in ventilation windows with duct structure, better sound attenuations can be achieved when the secondary source faces the incoming sound directly compared to when it faces the cavity towards the window outlet [20]. One disadvantage with the current transparent piezoelectric speaker over the electromagnetic speakers is the relatively higher harmonic distortion [21].

4. CONCLUSION

Transparent piezoelectric film speakers composed of SWCNT electrodes, PVDF polymer layer, PET substrate and clamping frame were designed and fabricated, with substantially improved sound pressure level after structural optimization guided by numerical simulation. The film speaker was found to have a significantly wide radiation pattern. Multiple cells of the piezoelectric film speakers with different dimensions were produced for further improving the overall SPL over broader frequency range. The ANC performance using the transparent piezoelectric film speaker was evaluated through both numerical simulations and experimental measurements. The numerical simulation showed that global noise mitigation may be achieved at wider frequencies (below 800 Hz) with the multi-cell transparent piezoelectric film speakers integrated within a duct type window with staggered openings for natural ventilation. Experimental measurements conducted at 650 Hz revealed an average SPL reduction of 6.3 dB while three independent multi-cell transparent piezoelectric film speakers were used. It was further found that compared to an electromagnetic speaker as a point secondary sound source, using the multi-cell transparent piezoelectric film speaker as an area source resulted in more uniform noise mitigation with substantially enhanced average SPL reduction. The results presented here show the advantages of large area transparent piezoelectric film speakers over conventional electromagnetic speakers for ANC applications, including their values for noise mitigation for building envelop structures.

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