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ACTIVE NOISE MITIGATION WITH TRANSPARENT PIEZOELECTRIC FILM SPEAKERS

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Noise disturbance among residence in urban areas is often generated from various external sources (road traffic, aircraft, etc). The building envelop particularly windows often constitutes to the primary path for external noise sources to travel into the buildings. Passive noise mitigation technologies have been used to improve the acoustic comfort in urban life today. However these passive technologies are not very effective at low frequencies of most noise present in urban areas, and they also cannot be applied when transparency is required. For active noise mitigation technologies, discrete bulky and non-transparent electromagnetic speakers are typically installed at selected locations, but with limited global noise cancellation effect over a large area. Implementation of the conventional speakers for window applications also has aesthetical acceptance issue. In this work, we have designed and produced transparent piezoelectric film speakers aiming at active noise mitigation effect over increased area for window applications. The performance properties of our transparent speakers, the active noise control method, and the simulation and experimental results of the effectiveness for active noise mitigation in a window sash structure are reported. The potential and challenges of applying large area transparent piezoelectric film speakers for noise mitigation windows are analysed.

Keywords: active noise mitigation, transparent speaker, piezoelectric speaker.

1. Introduction

A major challenge for reducing noise transmission through windows is to effectively reduce noise across all the window area while keeping it transparent and aesthetically acceptable. Passive noise mitigation methods like double-glazed technology are mainly effective at high frequencies and lack natural ventilation. The lack of ventilation affects the air quality indoors and results in heavy use of air-conditioning systems and thus more power consumption.

Improved low frequency noise mitigation performance has been achieved by embedding active noise mitigation elements in windows [1-4]. For example, electromagnetic loud-speakers can be embedded within the air gap of the double glazed windows or discretely installed on single layer window glass, connected to driver circuits to realize active noise control, particularly for low frequency noise. However such windows are bulky and costly, and not aesthetically acceptable.

Such windows with the discrete electromagnetic loud-speakers are not able to achieve uniform noise mitigation over a large area. The reduction of noise varies significantly at different locations. Analysis results show that uniform noise mitigation 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., 0.14×0.14 m^2 for frequencies up to 500 Hz) [5, 6]. 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 piezoelectric film speakers have been explored for replacing the conventionally used electromagnetic speakers in windows with active noise mitigation function. Yu et. al. demonstrated effective active noise mitigation using transparent piezoelectric speakers mounted on a closed window [6]. 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 [7, 8]. To realize effective active noise mitigation at low frequencies, it is required to enhance low-frequency sound pressure level of the transparent piezoelectric film speaker. Various efforts have been made in literature to improve the sound pressure level of the transparent piezoelectric speakers through various designs [9-11]. However, their low frequency performance and size need to be further improved for more effective noise mitigation for window applications.

In a previous publication [12], we have reported improved performance of a transparent piezoelectric film speaker with a uni-morph structure comprising piezoelectric polymer film and a supporting layer. In this paper, we have designed and fabricated transparent piezoelectric film speakers comprising multiple speaker cells. Active noise cancellation performance of the multi-cell transparent speakers integrated within a duct type ventilation window with staggered opening has been evaluated through numerical simulation and experimental measurement.

2. Multi-cell transparent piezoelectric film speaker

Piezoelectric polymers are very suitable for producing transparent piezoelectric speakers with their flexibility and low cost. As off-resonance sound pressure level for transparent piezoelectric speaker is substantially lower than the resonance, resonances may be possibly explored for a piezoelectric speaker to enhance sound pressure level, although this could bring frequency dependent issues. We have designed a multi-cell transparent piezoelectric film speaker comprising multiple cells of different sizes and hence 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 speaker was composed of a top single walled carbon nanotube (SWCNT) electrode, a piezoelectric poly(vinylidene fluoride) (PVDF) film, a SWCNT bottom electrode, a poly(ethylene terephthalate) (PET) sheet as a supporting layer, and a grid to clamp the boundaries of each of the speaker cells (Figure 1(a)). A prototype of the fabricated multi-cell transparent piezoelectric film speaker with dimension of 230×430 mm^2 is shown in Figure 1(b).

Table 1 lists the first three resonant frequencies for individual cells in a multi-cell transparent piezoelectric film speaker as shown in Figure 1(b), determined by numerical simulation. Sound at the varied resonant frequencies can be generated for use in noise mitigation by using the multi-cell transparent piezoelectric film speaker.

Table 1: List of resonant frequencies from simulation for individual cells of the multi-cell transparent piezoelectric film speaker as shown in Figure 1(b).

Speaker Cell	1R/1L	2R/2L	3R/3L	4
Mode 1 (Hz)	173.6	111.7	78.0	24.8
Mode 2 (Hz)	177.7	116.0	82.6	31.0
Mode 3 (Hz)	184.9	123.8	91.2	42.4

To fabricate the prototype, SWCNT thin film electrodes were deposited on a PVDF film having dimensions of 230×430 mm^2. A suspension of SWCNT powders in de-ionized (DI) water was sprayed on the PVDF film through aerosol spraying process. One single bottom SWCNT electrode was formed continuously on one side of the PVDF film while multiple top SWCNT electrodes were patterned using a shadow mask to form the optimized top electrode coverage of 27% on each cell. After the electrode coating process, the PVDF film was laminated on a PET transparent sheet as the supporting layer using transparent epoxy. After curing process of the epoxy, the PET/SWCNT/PVDF/SWCNT laminated structure was attached to a transparent grid made of acrylic to form the multi-cell transparent piezoelectric film speaker (Figure 1(b)).

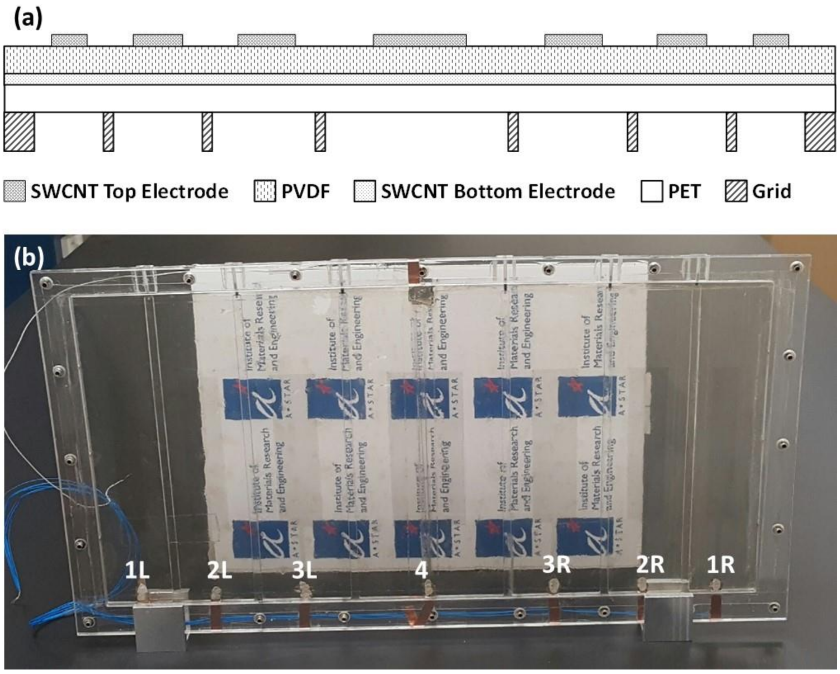

Figure 1: (a) Cross section view of the structure of the multi-cell transparent piezoelectric film speaker, and (b) photograph of the prototype of the multi-cell transparent piezoelectric film speaker.

Figure 2 presents the overall frequency response (when all of the speaker cells are active) as well as frequency response of each individual cell (only one speaker cell is active) of the multi-cell transparent piezoelectric film speaker, as shown in Figure 1(b). The results show that when all of the speaker cells are active, an improved SPL is found at most frequencies. Broader frequency response range compared to single cell is observed when all cells are active due to the collective effect of individual cells, each having different sets of resonance frequencies. Reduction of SPL at some frequencies is attributed to destructive interaction of sound waves among individual speaker cells due to their phase miss-match. This can be resolved by individually tuning the phase of driving voltage of each speaker cell.

3. Active noise mitigation using the multi-cell transparent piezoelectric film speaker

3.1 Numerical Simulation

The feasibility of achieving low frequency sound cancellation by using the proposed transparent piezoelectric film speaker is investigated by conducting numerical simulation. Figure 3(a) illustrates the simulation model, where the film speaker is used as the secondary cancelling source in a window structure with staggered openings. The inner dimensions of window were 0.40×1.80×0.12

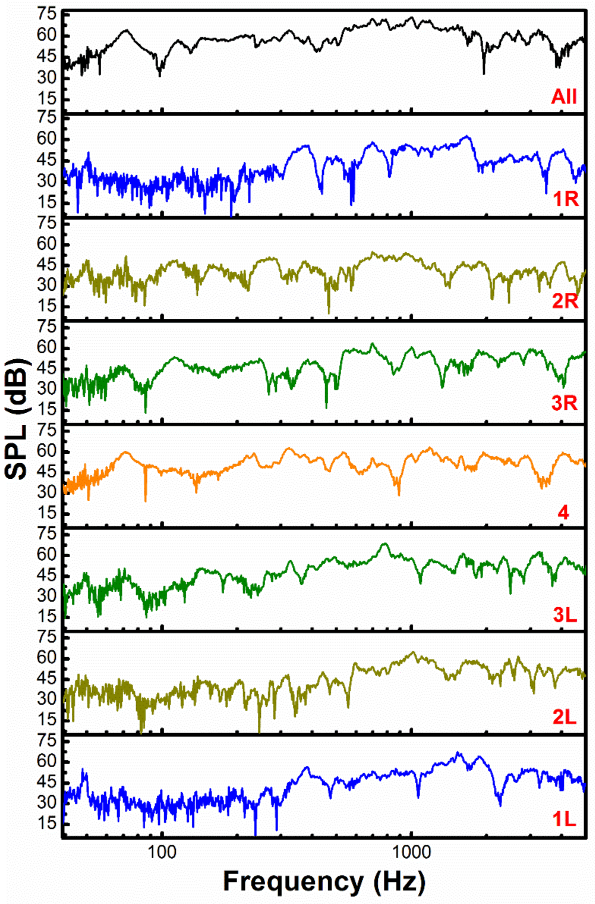

Figure 2: Overall frequency response as well as frequency response of each individual cell of the multi-cell transparent piezoelectric film speaker prototype.

m^3. Plane wave excitation is assumed at the window inlet opening, and the acoustic field is solved by using finite element method based on COMSOL. To control the secondary speaker, a measurement point is defined at the centre of the outlet opening, as the error sensor. The control target is to minimize the sound pressure received at this error sensor by matching the primary sound field (due to the plane wave excitation) and the secondary field (due to the transparent piezoelectric film speaker). In the simulation, the amplitude and phase of the secondary speaker are tuned based on the transfer function obtained from two simulations conducted for the primary and secondary fields separately. The averaged Sound Pressure Level (SPL) in a representative receiving region connected to the outlet opening is considered for the control effect.

In Figure 3(b), the averaged SPLs before and after including the piezoelectric speaker, namely the control off and control on conditions, are presented in the frequency range from 200 Hz to 1400 Hz. It can be seen that the theoretical control effect is more significant at lower frequencies, where the acoustic wavelength is long so that the secondary sound field can better match with the primary field. As frequency increases, the plane wave sound propagation inside the window duct becomes more complicated as multi-dimensional waves. The cut-off frequency determined by the window width (0.12 m) is around 1400 Hz. The simulation result shows to achieve active noise mitigation below this cut-off frequency is possible, while the control effect is deteriorated close to it. It should be noted that Figure 3(b) is purely based on ideal simulation conditions. In reality, the frequency spectrum of the film speaker, the capability of the control circuit and also sound leakage from various window components need to be carefully considered.

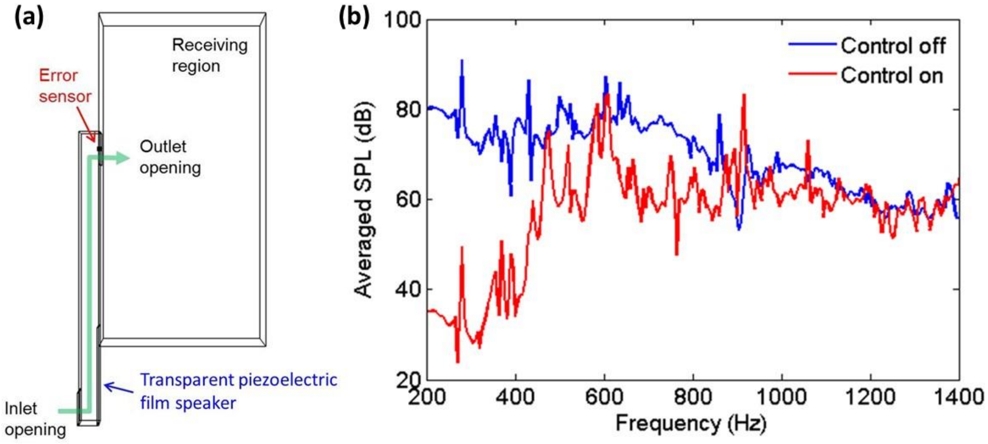

Figure 3: (a) Schematic diagram of the simulation model of a window (inner dimension: 0.40×1.80×0.12 m^3) with staggered opening and employing transparent piezoelectric film speaker as the secondary cancelling source. (b) Numerical simulation results, representing the active noise mitigation performance of the structure, within the receiving region, in the frequency range from 200 Hz to 1400 Hz.

3.2 Testing configuration

For active noise mitigation testing, a duct type window with staggered opening (similar to the numerical simulation) was fabricated, as shown in Figure 4. The window consisted of 3 front sliding panels (facing inside the room) and 3 rear sashes (facing outside the room). The sound source was placed inside the window while the error microphone was positioned at the centre of the opening on the opposite side of the window. The opening was about 10 cm. Multi-cell transparent piezoelectric film speakers were attached on the rear sashes. To measure the average noise mitigation performance of the transparent speaker, SPLs of 96 measurement points within a space of 1.5×0.9×0.8 m^3 were measured using a measurement microphone in control ON and control OFF conditions. A tonal noise of 650 Hz was used for the measurement. Three different scenarios were considered for the testing:

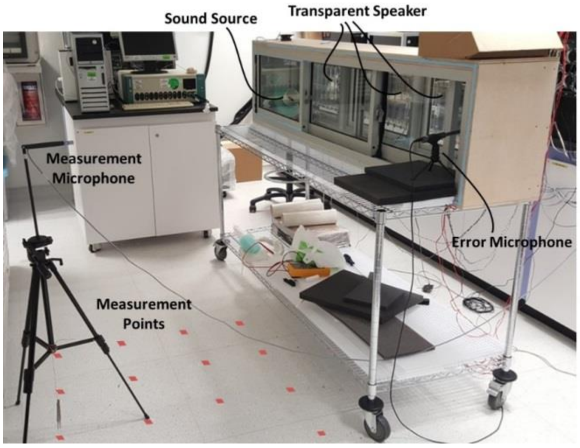

Figure 4: Testing set up for active noise mitigation performance of the multi-cell transparent piezoelectric film speakers in a duct type window.

3.2.1 Scenario 1: Single-channel area speaker

In this scenario, one multi-cell transparent piezoelectric film speaker (closest to the sound source) was used as the secondary speaker for active noise mitigation. Figure 5(a) presents the active noise mitigation effect achieved in this condition. An average SPL reduction of -5.1 dB was achieved within the measurement space. At 14.6% of the total 96 measurement points, SPL amplification (in the range of 1-16 dB) was also observed. The amplification may be partially due to the leakages in the structure.

3.2.2 Scenario 2: Multi-channel area speakers

In this scenario, 3 independent multi-cell transparent piezoelectric film speakers were used as secondary speakers for active noise mitigation. The measurement results are shown in Figure 5(b). The average SPL reduction was larger than the single-channel area speaker (-6.3 dB). SPL amplification 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.

3.2.3 Scenario 3: Single-channel point speaker

For comparison, an electromagnetic speaker was placed within the window at the centre of the window sash close to the source speaker. Figure 5(c) presents the results for this scenario. The average SPL reduction was -3.4 dB, much smaller than the two other scenarios with piezoelectric film speakers, and the number of locations and the extent of SPL amplification were both much larger (27.1% and 1-20 dB, respectively).

Figure 5(d) has summarized the active noise mitigation testing results of the three scenarios. It was found that compared to the point speaker, when the area piezoelectric speaker is used as the secondary sound source for the cancellation purpose, more uniform noise mitigation with larger average SPL reduction can be achieved. Employing a multi-channel configuration for multiple area speakers can further enhance the noise mitigation performance of the window.

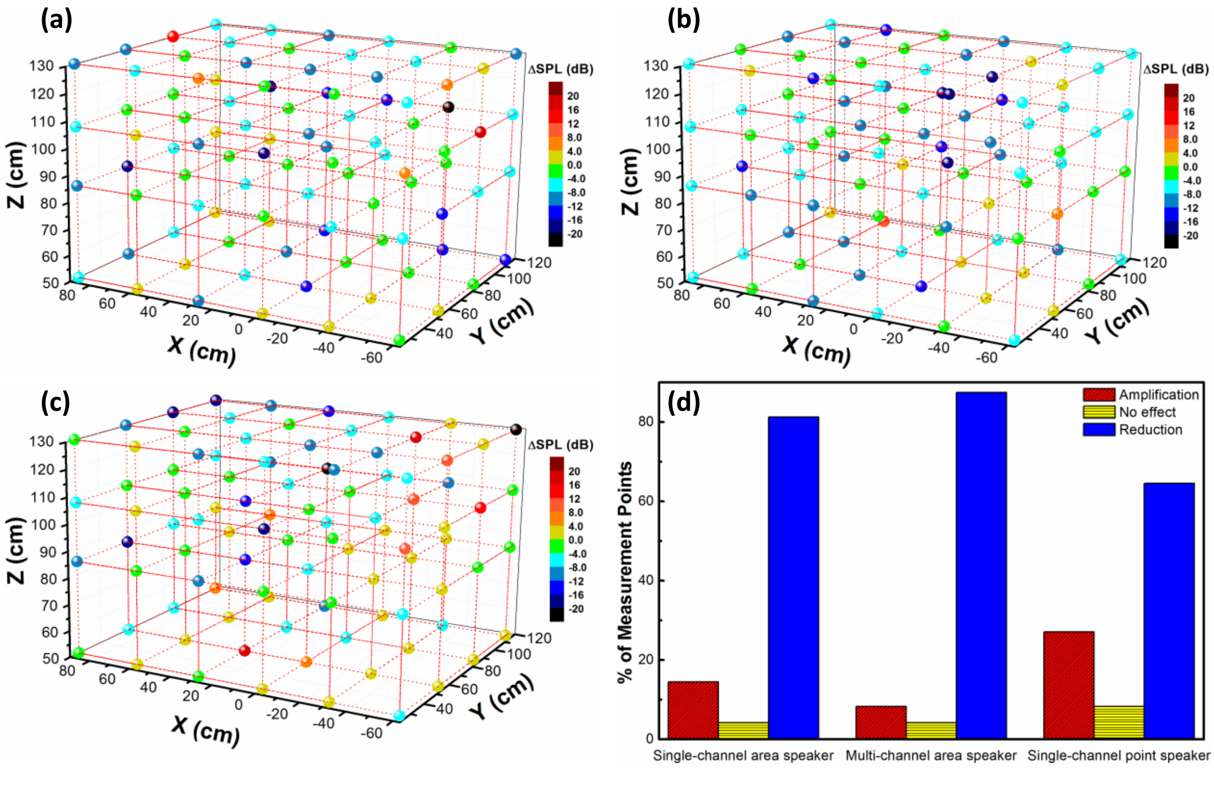

Figure 5: Active noise mitigation testing results at 650 Hz for a window with staggered opening and employing (a) one multi-cell transparent piezoelectric film speaker as an area secondary sound source (single-channel), (b) three independent multi-cell transparent piezoelectric film speakers as an area secondary sound source (multi-channel) and (c) on electromagnetic speaker as a point secondary sound source (single-channel). (d) Summary of active noise mitigation performance of the windows in (a), (b), and (c).

4. Active noise cancellation control system

We are in the process for developing an active noise cancellation control system based on the Filtered-x Least Mean Square (FxLMS) algorithm [13] implemented on a digital signal processor as shown in Figure 6. The ADAU1452 digital signal processor (Analog Devices, Inc.) is used to perform the calculation for the FxLMS algorithm. The analog-to-digital conversion of the signal from the reference and error microphones, and the digital-to-analog conversion of the signal for driving the speaker are done using the AD1938 audio CODEC (Analog Devices, Inc.) operating at 48 kHz sampling rate. The adaptive FIR filter has 1024 taps and the FIR filter for compensating the secondary-path effects has 256 taps. The DRV2700 amplifier (Texas Instruments Inc.) is used to drive the piezoelectric speaker. Further challenging developments are in progress to integrate the transparent piezoelectric film speakers with the developed control system for active noise mitigation testing.

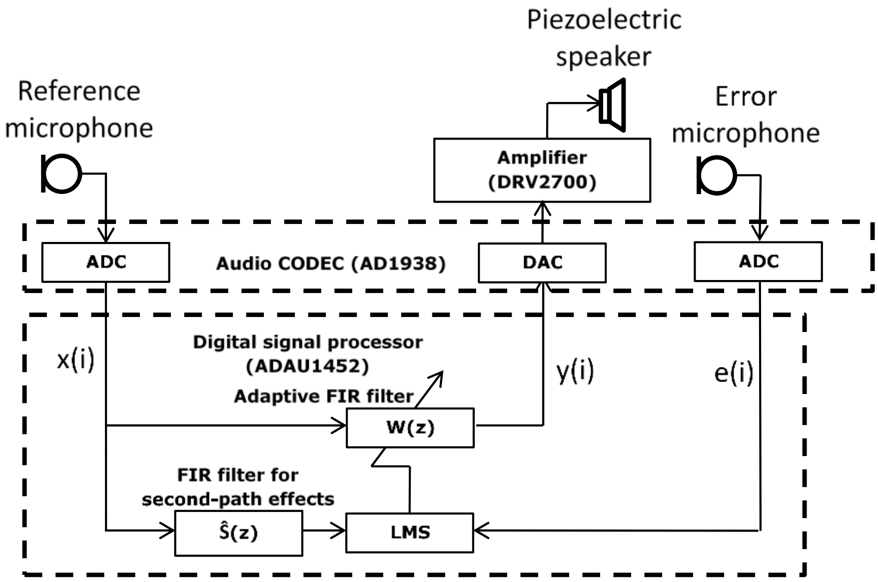

Figure 6: Schematic diagram of the active noise cancellation control system with FxLMS algorithm.

5. Conclusions

Multi-cell transparent piezoelectric film speakers were designed and fabricated as area secondary sound source for active noise mitigation for windows. Compared to individual cells, the multi-cell transparent piezoelectric film speaker exhibited enhanced overall SPL and broader frequency response range. Active noise mitigation performance of the transparent piezoelectric film speaker was examined in a duct type window with staggered opening through numerical simulation and experimental measurement. Numerical simulation results showed that noise mitigation was more effective at lower frequencies and deteriorated by approaching the cut-off frequency of the window at 1400 Hz. 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 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 larger average SPL reduction. The results presented here show the potentials and advantages of transparent piezoelectric film speakers for active noise mitigation in window structures.

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