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REMOTE DETECTION OF BUILDING AIR INFILTRATION USING A COMPACT MICROPHONE ARRAY AND ADVANCED BEAMFORMING METHODS

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ABSTRACT

In the United States excess air infiltration is estimated to account for approximately 23% and 14% of the total amount of energy used for heating and cooling in all residential and commercial buildings, respectively. The overall goal is to use a non-intrusive acoustic phased array with beamforming techniques to remotely detect specific envelope leaks in buildings. Pressure fluctuations associated with the leakage flow can be localized by using a compact, noninvasive microphone array with advanced beamforming algorithms.

1 INTRODUCTION

Air leakage from window drafts and infiltration in commercial buildings are problems that can have several negative consequences. These consequences include reduced thermal comfort, interference with the proper operation of mechanical ventilation systems, degraded indoor air quality, moisture damage of building envelope components, and particularly <u>increased energy consumption</u>. This "drafty building problem" is the "opportunity" for our innovative technology. The problem is compounded because air leakage sites are often difficult to locate because air flows may be small compared to the size of the room or enclosure. There is also a lot of dissatisfaction with current leak detection techniques. Most local leak detection techniques such as smoke tracer, anemometer, bubble detection and tracer gas techniques are time consuming for large surfaces. Standard practices for using these detection techniques in building envelopes and air barrier systems are detailed in ASTM E1186 – 03 (2009). The method being proposed in the current study will help detect air leakage in large buildings efficiently and non-intrusively. Detecting and sealing leaks will in turn improve the energy efficiency of the building. Our leak detection method could be used by construction and engineering firms as a commercial tool for detecting air leakages quickly and sealing them. Currently it is estimated that space heating in buildings consumes up to 13

\$/m^2/year and with a 30% savings we could save up to 4 \$/m^2/year. In a city of roughly 10 million square meters (built-up space) the energy savings per year could be 30-40 million dollars per year. Considering two big cities for every state in the US (on average) the savings are in the 3-4 Billion dollar range per year. This provides us a compelling reason to pursue this opportunity.

There have been a few studies that use sound to characterize the air leakage in buildings [1,2]. They use single microphone measurements and to our best knowledge no remote acoustic localization of leakage spots in buildings has been done before. Therefore, the method proposed in the current study is designed to improve non-intrusive air leakage detection methods in buildings using advanced acoustic sensing. The method has the potential for allowing for envelope leak detection and location in a wider range of buildings than is currently practical, including large residential and commercial buildings that are impossible to measure with existing methods. The method may also be used to more rapidly detect envelope leaks, which will improve our ability to apply targeted air sealing retrofits and improve the energy efficiency of larger numbers of buildings in the U.S.

1.1 Current methodology for quantifying and locating air leakage in buildings

A Blower Door is a device used to measure air tightness of buildings. This is a standardized technique for measuring air leakage rates and the blower door is capable of pressurizing or depressurizing a building. The generic term for the blower door method is `Fan Pressurization' technique. The building leakage is described by the empirical Power-Law equation of flow through an orifice [3]. The orifice flow equation is given by

$$Q = C \cdot \Delta P^n \tag{1}$$

here, Q is the measured volume flow rate, ΔP is the measured pressure difference between the inside and outside of the room, C is the leakage area and n is the leakage coefficient (represents the characteristic shape of the orifice, ranging from 0.5 to 1 i.e., perfect orifice to very long thin crack). By taking the log of Eq. 1 we get,

$$\ln(Q) = \ln(C) + n \cdot \ln(\Delta P) \tag{2}$$

By plotting the ln(Q) Vs ln(ΔP) and calculating the coefficients of a linear fit to the data one could calculate the values of C and n. The physical paradigms that are applied to the power law equations are as follows:

- If the aspect ratio (AR) of the crack is low then the frictional forces can be neglected and the leak may be treated as an orifice wherein the flow is proportional to the square root of the pressure drop. If the Reynolds number/flow rate is higher, then even a crack with a higher AR can be treated as an orifice. This case corresponds to an exponent of 0.5.
- If the Reynolds number is low enough, there will be domination of laminar frictional losses in the flow. Hence a linearity between the flow and the pressure drop is observed. This case corresponds to an exponent of 1.

The main metric used to quantify air leakage across the building envelope is to have a standard reference pressure. The conventional reference pressure is 50 Pa ever since the blower door method became popular. This pressure is easily reachable by the blower fans and is high enough to suppress the wind drifts and stack effects. In order to normalize the air leakage, one of the three quantities can be taken into consideration: Building Volume, Envelope Area or Floor Area.

One of the main drawbacks of the 'fan pressurization' technique is that for large buildings the method becomes impractical. The method is also susceptible to weather conditions such as wind speed, temperature etc. This method provides only the overall air leakage rate from the room/building and does not provide the location of these leaks. Before one can perform this test known leakage spots such as the ventilation ducts into the room should be sealed off. Once the room has been pressurized another technique known as the tracer gas or smoke stick method is used to detect the location of the leaks. We can see how this technique could become fairly laborious and time consuming when the building floor area to be surveyed becomes large.

1.2 Proposed method for detecting air leakages in buildings

The method we propose to detect air leakages in buildings is to use a microphone array in conjunction with sophisticated beamforming algorithms. As a first step we propose using the blower door method to pressurize the building. Next, the flow noise generated at the leaks is localized using a microphone array. This technique would work when the building floor area is relatively small. However the method will still be laborious as we have to seal the room and pressurize it using blowers. In order to avoid this time consuming process we propose an improved method where we use a sound source inside the room instead of pressurizing the room. The principle behind this method is that the sound generated by the source will leak out of the same leakage spots in a building through which the air leaks out when using the pressurization method. By locating this we could locate the air leakage spots on the building façade. An initial proof of concept test was conducted to validate this technique. A dual cone 4 Ohm speaker was placed inside a room facing the window and a white noise signal was fed through an amplifier. The microphone array which was located outside the room facing the window (see Fig. 1(a) for setup) was able to locate the leakage spots on the window clearly. This can be observed in Fig. 1(b) which shows the beamform map calculated from the microphone array data.

(a)

(b)

Fig. 1. (a) A picture of the experimental setup showing the microphone array(OptiNav 24) system facing the window of room. (b) Beamform map of acoustic noise source leaking through the window obtained from the microphone array data.

A brief description of the phased array system and the beamforming algorithms is given in the next section. A more detailed description can be found in reference [4].

2 EXPERIMENTAL METHOD

A standard Minneapolis Blower Door is used for the test to pressurize the room. The system consists of a blower/fan, Model 1, which is a variable speed control fan which can easily maintain a constant building pressure ranging from 0-75 Pa. This fan provides actual flow measurements up to 6100 CFM. There are different flow rings, namely A, B, C, D and E which can be installed on the blower to adjust the flow rate so as to maintain a particular pressure inside the room. DG-700 Pressure and Flow Gauge by The Energy Conservatory is used to measure both pressure and flow rate. It consists of two independent differential pressure channels, A and B. Pressure measurements up to 1250 Pa can be made with an accuracy 1% of pressure reading. This device is programmed to calculate and display air flow readings for particular rings installed on the blower. This is also incorporated with the time averaging options, 1, 5 or 10 s average or continuous average. A door mounting system which also acts as the seal for the door is used to mount the blower. The complete setup is shown in Fig. 2. The microphone array used for this experiment is an OptiNav 24 array with 24 microphones arranged in a log spiral pattern (0.72 m diameter) with a centrally located camera to capture the image of the object. The signal from the microphone array is acquired by an A/D converter which has 24 I/O audio interfaces. A MAGMA express box handles the task of interfacing the PCI 424 card to the computer. The microphone data is then processed using various beamforming algorithms. Classical beamforming is performed in both the frequency domain as frequency domain beamforming (FDBF) and in the time domain as Delay and Sum (DAS). Other algorithms include Deconvolution Approach for the Mapping of Acoustic Sources (DAMAS), developed by Brooks and Humphreys [5], CLEAN algorithm based on spatial coherence (CLEAN-SC), developed by Sijtsma [6], and TIDY developed by Dougherty [7]. Two rooms at the Illinois Institute of Technology were used for the tests. Both pressurization and acoustic noise source tests were performed in these rooms and the results are presented in the next section. A picture of the microphone array system facing the window on a room is shown in Fig. 1(a).

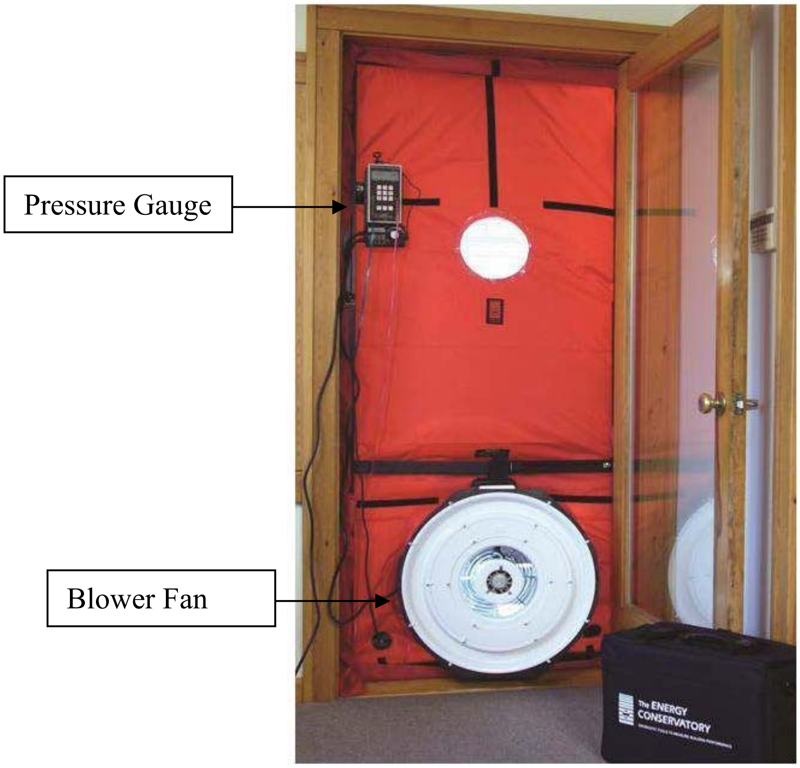


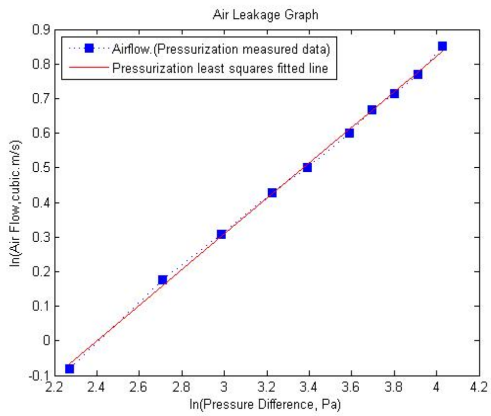
Fig. 2. A picture of the experimental setup showing the pressure gauge and blower fan mounted on the door sealing and mounting kit.

3 RESULTS AND DISCUSSION

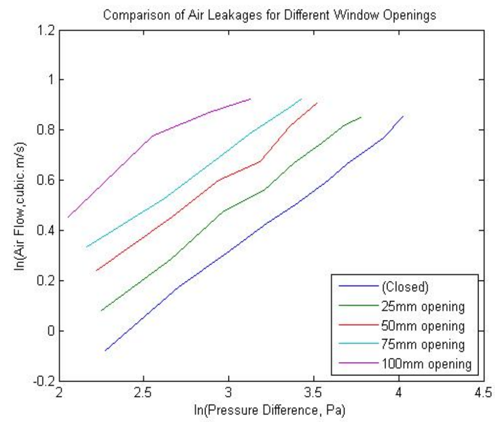
The experimental results are presented in this section. First we will look at the results from the blower door test and then we will discuss the results from the microphone array tests with both flow as the noise source and then the use of an acoustic noise source.

3.1 Blower door tests

The pressurization test was performed using the blower door equipment described in the earlier section. The known openings in the room (such as ventilation and exhaust ducts) were sealed. The room had one window which could be opened to vary the leakage rate of the room. Five different cases were tested namely, when the window was completely closed and when opened by 25 mm, 50 mm, 75 mm and 100 mm. For each case the pressure inside the room was maintained at a particular constant value by changing the flow ring and speed setting on the blower fan. The pressure difference and the flow rate measurements were made and the flow coefficient n and leakage area C are calculated as outlined in Section 1.1. The result of the closed door case is shown in Fig. 3(a). Figure 3(b) shows the comparison of the different window opening gap sizes. The average value of coefficient n calculated is 0.5. The leakage area C calculated for different gap sizes is shown in Fig. 4. It was observed that the theoretical leakage area calculated based on the window dimensions is consistently lower than the measured value. It is speculated that since the air vents were sealed there could have been a significant leakage to another room through the cracks in the ceiling of the room.



(a)



(b)

Fig 3. Graphs showing the air flow rate Vs the measured pressure difference (a) for the closed door case and (b) for different window opening sizes (the top line indicates 100 mm opening case and the bottom line indicates closed case).

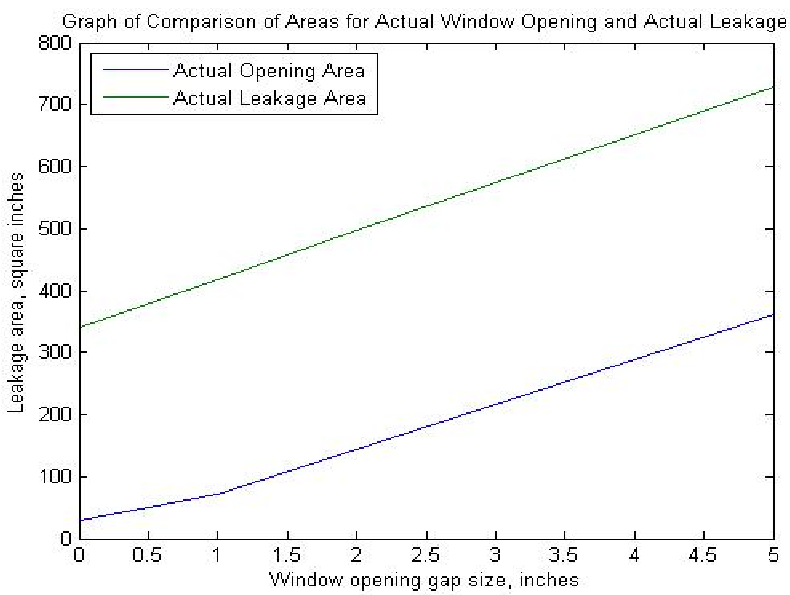
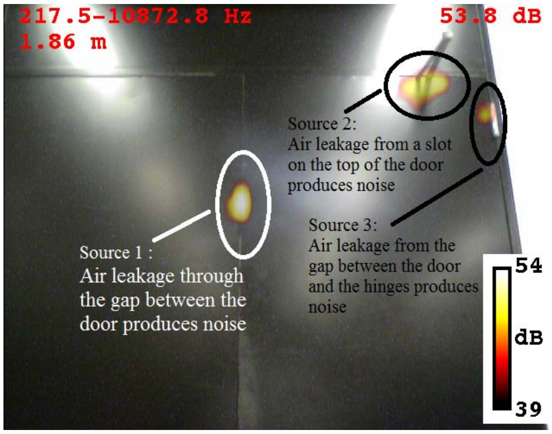


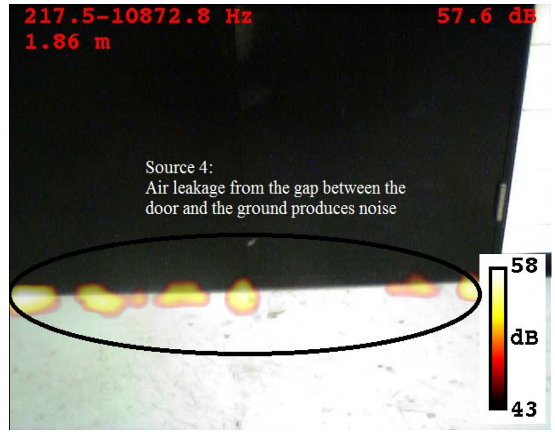
Fig 4. Graph showing the calculated leakage area and the theoretical leakage area for different window opening sizes. The top line shows actual leakage area and the bottom line shows the actual opening area.

3.2 Microphone array tests

The microphone array measurements were made first in a room with significant air leakage through known cracks. An imbalance in the building's ventilation system caused a pressure difference (about 100 Pa) between the room and the external hallway. Gaps in the door of the room contributed most of the air leakage into the room. Figure 5 shows the door of the particular room in question. It also shows the possible locations for maximum air leakages (i.e., large gaps). Tests were performed on the two halves of the door: the upper and the lower half. Fig. 6(a) shows the beamform map of the upper half of the door using the TIDY algorithm. In this we clearly observe the three sources of leak on the door. The pressure unsteadiness and sound associated with the airflow from these leaks could be detected by the array. The source for leak 1 was the vertical gap between the two doors. Leak 2 occurred at the slot opening on the top of the door provided for the swivel mechanism and the source for leak 3 was at the gap between the door and the upper right hand side hinge. Fig. 6(b) shows the beamform map of the lower half of the door using TIDY. We observe the source for leak 4 that occurred at the gap between the doors and the floor. Results from this test suggest that at a minimum, this acoustic method could be used in conjunction with fan pressurization techniques to identify specific leakage areas for subsequent rapid, targeted air-sealing measures.

Fig 5. Schematic of the door with major air leakage spots indicated. A mechanically-driven pressure difference existed across the door under normal building operation.





(a) *(b)*

Fig 6. Beamform map of success at locating leakages from doors using the advanced wideband beamformer, TIDY of, (a) the top half of the door and (b) the bottom half of the door. The circled regions show the location and size of air leakage superimposed on the photograph of the door.

In order to validate our leak detection technique the experiments were repeated in the same room where the blower pressurization test was conducted. Since the room had no imbalance in the ventilation system that caused a leak, the blower was used to pressurize the room and the five cases with window closed and four different openings were tested again with the microphone array. The aim of this experiment was to identify leakage spots on the window and study the characteristics of noise generated by the leaks for various opening sizes. The pressure difference was set to 50 Pa and the microphone array measurements were taken. Figure 7 shows the SPL frequency spectra of the window closed case and the 25 mm window opening size case measured using the array. It can be observed that the window closed case shows an increase (relative) in the noise level at high frequency (above 3500 Hz) whereas the 25 mm open case shows an increase in noise level at low frequency (below 2000 Hz). It is believed that the closed case still exhibited a slight gap that resulted in the high frequency noise and the low frequency noise was due to the 25 mm gap.

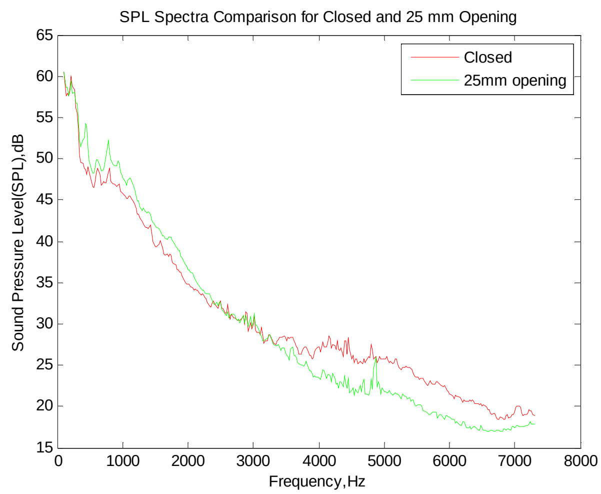
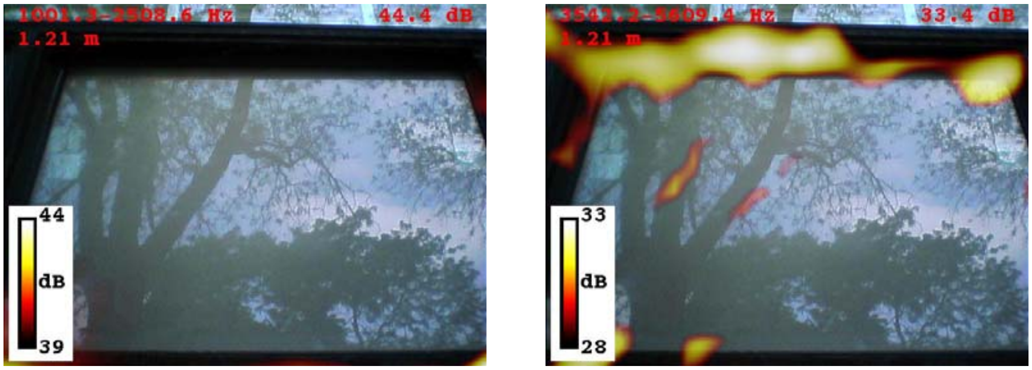


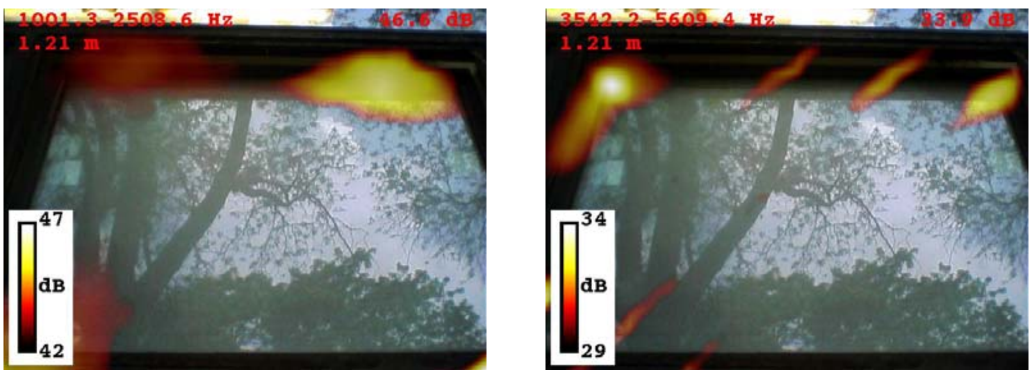
Fig. 7. SPL frequency spectra comparing the window closed and window open by 25 mm cases.

This was confirmed by the beamform maps for these cases. Figure 8 shows the beamform maps obtained using TIDY for the closed window case at the low and high frequency ranges. It can be observed that at high frequency the closed window results in air leakage at the top of the window as indicated in Fig. 8(b). Similarly, Fig. 9 shows the beamform maps obtained using TIDY for the window open (by 25 mm) case for the low and high frequency ranges, We observe that in this case at the air leakage at the top of the window is dominant at the low frequency as indicated in Fig. 9(a). At high frequency the leakage at the edges of the window at dominant.



(a) *(b)*

Fig. 8. Beamform maps obtained using TIDY for the closed window case for the frequency ranges: (a) 1000 Hz – 2500 Hz, and (b) 3500 Hz – 5600 Hz.



(a) *(b)*

Fig. 9. Beamform maps obtained using TIDY for the window 25 mm open case for the frequency ranges:(a) 1000 Hz – 2500 Hz, and (b) 3500 Hz – 5600 Hz.

Through these tests we were able to successfully show that using a microphone array in conjunction with the blower door we could locate the air leakage spots in the building façade. As a next step in order to eliminate the blower door completely we proposed using an acoustic noise source, such as a loud speaker. Two 10-inch, 4-ohm Dual Voice Coil Subwoofers were used inside the room replacing the blower door setup. The schematic of this setup is shown in Fig. 10. A white noise signal was fed to the speakers. Two speaker locations were selected for the study, one close to the window at 1.12 m (4 ft) and another away from the window at 2.74 m (9 ft). The results of this test are presented next.

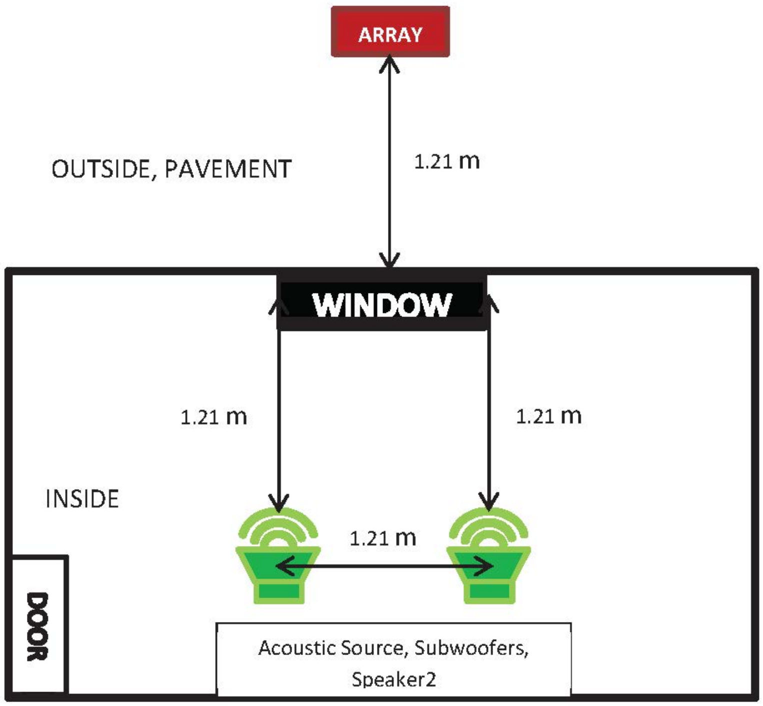


Fig. 10. Schematic of the experimental setup to measure sound leakage through the window produced by loud speakers using the microphone array.

Figure 11 shows the beamform maps using TIDY for the cases where speakers were both close to the window and away from the window for various window gap sizes. The frequency of interest was chosen to be 3500 Hz- 5600 Hz. It was observed that for both the speaker locations the microphone array was able to locate the noise escaping through the window openings. For the closed case the noise escaping at this frequency range was minimal and with increase in the gap size the location estimates got better. Figure 12 compares the location estimates from the pressurization test to the estimates from the acoustic source test. We observed that the location estimates from the acoustic source test are similar to that observed from the pressurization test. This shows that the acoustic source method has good potential in locating the air leakage spots on a building façade. It should also be noted that our tests were conducted on days when background noise levels were high (from road traffic, construction and insects). No steps were taken to eliminate background noise as this technique adequately detects leaks without background noise removal.

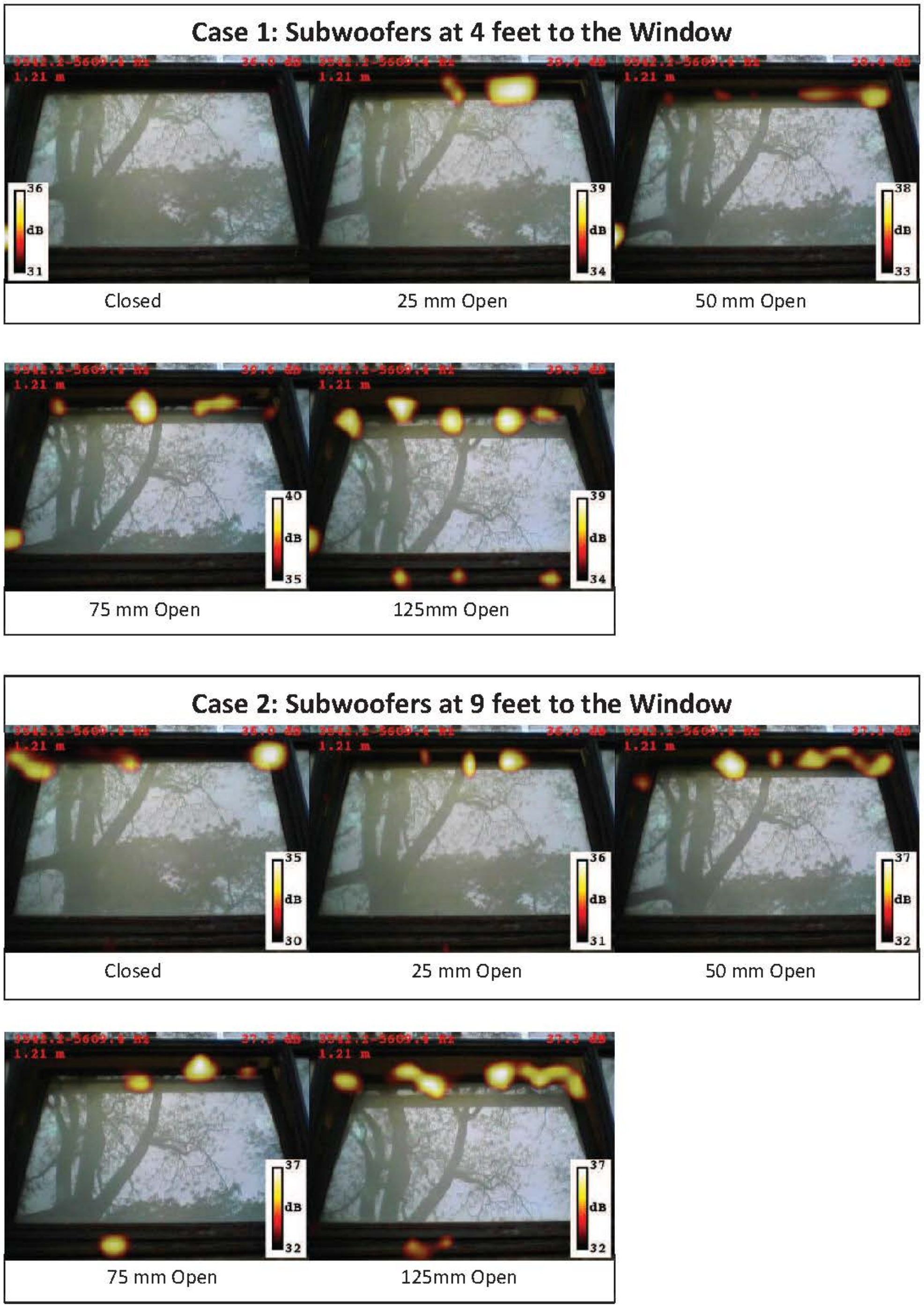
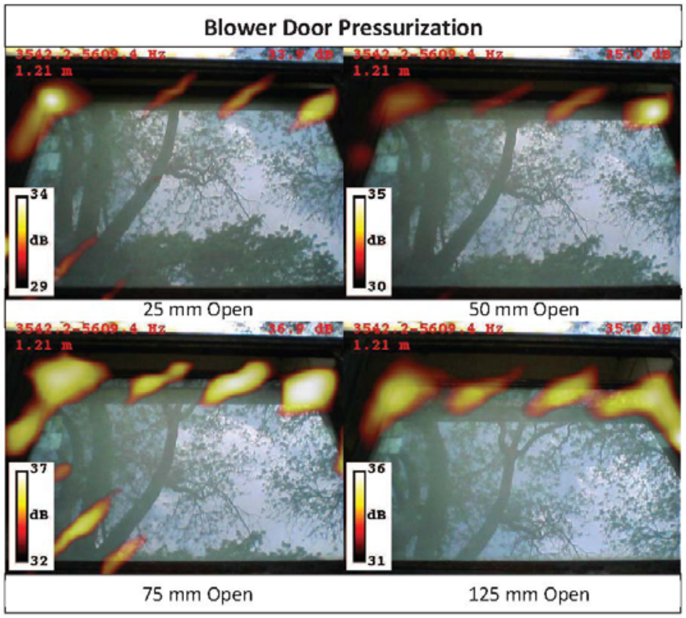
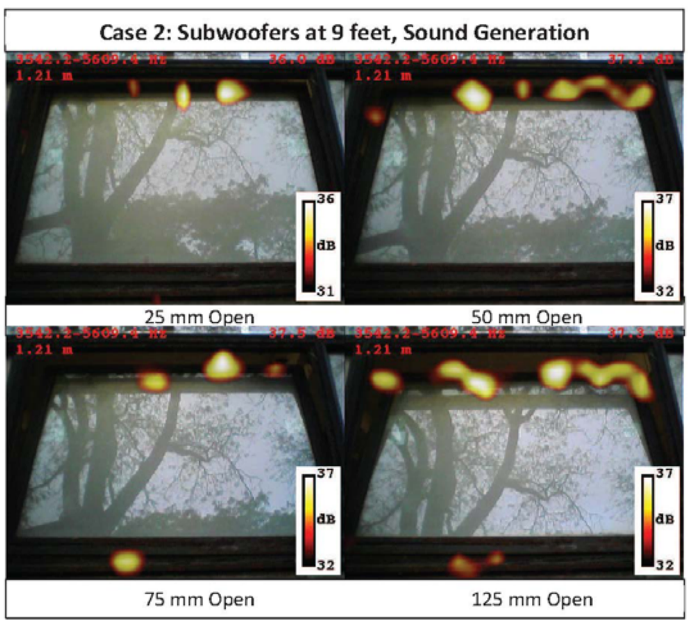


Fig. 11. Beamform maps using TIDY showing a comparison of the cases with speakers close and away from the window for the frequency range 3500 Hz – 5600 Hz for various window gaps.



(a)



(b)

Fig. 12. Beamform maps using TIDY comparing the ability of microphone array to locate noise generated by (a) flow due to pressurization, and (b) noise due to acoustic source for frequency range 3500 Hz- 5600 Hz for various window gaps.

4 CONCLUSIONS

In this study we propose a unique method to locate air leakage from buildings. The methods currently used as the industry standard are laborious and impractical for survey of large buildings. We propose a method which is both quick to perform and relatively simpler than the existing blower door and smoke stick method. The initial study performed in a room which had a mechanically driven air leakage showed the potential for locating air leakage spots by localizing the noise generated by the flow through the gaps between the door and the floor (also door frame). The pressurization test showed that the microphone array can successfully locate the air leakage spots on the window of a building facade. In order to avoid the pressurization process an acoustic source was used to replace the pressurization equipment. On testing we observed that the noise leaking through the window gaps were successfully located by the microphone array. This technique is much simple to use and will also work for large building floor area. Currently this technique will provide only the location estimates of the air leakage spots and for the leakage area we have to still use blower door technique. Efforts are currently underway to devise a new method to estimate the leakage area.

In summary it should be noted that our proposed technique using the microphone array has two variations. One variation uses the blower door of the standard methods and the other substitutes subwoofers (acoustic sources) for the blower door. Both variations are effective and simpler than earlier methods. The second variation that uses the subwoofers (acoustic source) is simpler to implement than the first variation.

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