Detection and quantification of building air infiltration using remote acoustic methods

Ganesh RAMAN[1]; Kanthasamy CHELLIAH[1]; Manisha PRAKASH[1]; Ralph T. MUEHLEISEN[2]

[1] Illinois Institute of Technology, Chicago, Illinois, USA. 60616
[2] Argonne National Laboratory, Argonne, Illinois, USA. 60439

ABSTRACT

Air infiltration in residential and commercial buildings of the United States are estimated to cost approximately 23% of the total amount of heating energy used (for cooling, this estimate is approximately 14%). The aim of the current work is to apply non-intrusive acoustic techniques to detect and quantify specific envelope leaks in buildings. Noise sources associated with the leakage air flow can be localized using a compact microphone array with advanced beamforming algorithms. Also, an idea of using a synthetic acoustic source inside the building instead of pressurization of the building is discussed. Finally, attempts are made in a laboratory level to quantify leakages using the nearfield acoustic holography technique.

Keywords: Infiltration, Beamforming, Energy.

1. INTRODUCTION

Consequences of air leakages from window drafts and infiltration in commercial buildings 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 *increased energy consumption*. This important economic/environmental problem is the motivation for the current innovative work. Detecting leakages is the first and cumbersome step in the process of sealing the leakages in buildings. Often, the air leakage sites are difficult to locate because of their size compared to that of the building. Current leak detection techniques such as smoke tracer, anemometer, bubble detection and tracer gas techniques are laborious and time consuming for large surfaces. ASTM E1186-03 (2009) details the standards for using these detection techniques in building envelopes and air barrier systems. The current need is a modern technique to detect and quantify the leakages in large buildings efficiently and non-intrusively.

The energy efficiency of a building can be improved significantly by detecting and sealing the leaks. The proposed leak detection method could be used by construction and engineering firms as a commercial tool for detecting air leakages quickly and sealing them. Current estimation of space heating in buildings is up to 13 $\$/\text{m}^2$/year and with a 30% savings we could save up to 4 $\$/\text{m}^2$/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 attractive reason motivates us to pursue this opportunity.

In the past, acoustic methods with single microphone measurements have been used in a few studies to characterize the air leakage in buildings (1, 2). To the authors' best knowledge, remote acoustic localization of leakage spots in buildings has not been performed before. The proposed acoustic sensing method in the present study is designed to address most of the shortcomings of the currently used methods in leakage detection. The method would allow for envelope leak detection methods in a wider range of buildings than is currently possible. The time and labor consumed in the process of leakage detection could also be reduced significantly by using the proposed method.

1.1 Current methodology

One of the standard building leakage detection methods currently available is blower door test (also called fan pressurization method). This method works by pressurizing or depressurizing a building/room. The building leakage is described by the empirical Power-Law equation of flow through an orifice (3). The orifice flow equation is given by:

---

[1] raman@iit.edu

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

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,

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

By plotting the $ln(Q)$ Vs $ln(\Delta P)$ 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:

- An exponent of 0.5 corresponds to higher Reynolds number/flow rate, i.e., the frictional forces can be neglected. This is applicable even for higher aspect ratio (AR) cracks.
- An exponent of 1.0 corresponds to lower Reynolds number/flow rate. Dominant laminar frictional losses in the flow creates linearity between the flow and the pressure drop.

The main metric used to quantify air leakage across the building envelope is to have a standard reference pressure. The conventional reference pressure has been 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.

The method has following major drawbacks:

1. The method is susceptible to weather conditions such as wind, atmospheric temperature, etc.,
2. During the pressurization, the building has to be sealed at any opening such as ventilation locations.
3. The method quantifies the leakage rate. However, this method cannot inherently locate the leakages. Locating the leakages is usually performed using manual smoke tracers in front of the pressurized building which is time consuming and laborious for large buildings.

1.2 Proposed Method for Leakage Detection

The method proposed in this study to localize the leakage spots in buildings is to use a compact microphone array combined with advanced beamforming algorithms. Some initial tests were performed by pressurizing the building using the blower door method and localizing the air flow noise generated at the leakage spots using a microphone array. However, this method is still laborious as pressurization is still required. To avoid this necessity, a new technique was introduced. A synthetic acoustic source (loudspeaker) was placed inside the building and the sound leakage spots were localized using the microphone array. A schematic of this concept is shown in Fig. 2. This concept is based on the assumption 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. To prove this concept a series of tests were conducted on a real building. The experimental setup can be seen in Fig. 1(a). 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 leakage spots were successfully located using the microphone array located outside the room. This is evident from Fig. 1(b) which shows the beamforming map calculated using the microphone array measurement. 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 the reference (4).

1.3 Proposed Method for Leakage Quantification

Although, the beamforming technique was able to successfully locate the leakages in the building, quantifying leakages using this method was difficult. Therefore, another remote acoustic sensing method called nearfield acoustic holography (NAH) is proposed to locate and quantify the leakages. Nearfield acoustic holography was introduced by Williams and Maynard (5) in early 1980s as a powerful noise source localization method. NAH removed many of the limitations of conventional acoustic holography which is based on the optical holography methods. Maynard *et al* (6) and Williams (7) explain this method in detail. The NAH method discussed in the present work is based on two dimensional spatial Fourier transform technique. More advanced numerical methods based NAH treatments are available in literature such as boundary element method based NAH (8) and equivalent sources method based NAH (9). The quantification tests have been conducted in a model building with known leakage areas. The experimental methodology of this technique is discussed in the next section. Various methods of NAH applied to leakage detection is discussed in a more detailed fashion by Chelliah *et al.* in (10).

2. EXPERIMENTAL METHOD

To pressurize the room a standard Minneapolis Blower Door is used. 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. DG-700 Pressure and Flow Gauge made by The Energy Conservatory is used to measure both pressure and flow rate. 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. 3. A detailed description of this setup can be found in (11). 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 used in this study include Deconvolution Approach for the Mapping of Acoustic Sources (DAMAS), developed by Brooks and Humphreys (12), CLEAN algorithm based on spatial coherence (CLEAN-SC), developed by Sijtsma (13), and TIDY developed by Dougherty (14). Two rooms located 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 experimental setup to perform nearfield acoustic holography analysis to quantify the leakages is shown in Fig. 4. A single microphone (B & K (model 4338)) is mounted on a traversing mechanism in front of a scaled building model which houses a loudspeaker inside. Single frequency tones are played in the loudspeaker and using the measurements taken at various points with the microphone, the acoustic pressure and particle velocity at a plane near the wall can be reconstructed. The details of this technique and setup (including the dimensions of the model and measurement aperture) can be found in our previous paper (10).

3. RESULTS AND DISCUSSION

This section provides and discusses some of the key experimental results of the proposed methods. Leakage detection results on a real building using the microphone array and beamforming combination (for both air and sound leakage measurements) are first discussed followed by the leakage quantification results using a traversing microphone in conjunction with NAH for a scaled building model.

3.1 Leakage Detection

A room with significant air leakage through its door gaps due to an imbalance in the building's ventilation system was chosen for our first set of experiments. The pressure difference between the room and the hallway to which it is connected to was found to be approximately 100 Pa. The microphone array was placed near this leaky door and measurements were made. Figure 5 shows the door of the particular room under study. The significantly larger gaps in the door installation are circled in the Figure. The beamform map of the upper half of the door using TIDY algorithm is shown in Fig. 6 (a). In this beamforming map, one can clearly observe the noise sources created by the air flow at the gaps of the door. 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. Figure 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. These positive results suggest that this acoustic technique can be used in conjunction with the fan pressurization method to locate the leakages (replacing the laborious smoke tracer method).

Next, a room was chosen at a building located on the campus of the Illinois Institute of Technology and was pressurized using the blower door setup described in the previous section. The pressure difference between the atmosphere and the room interior was maintained constant at 50 Pa throughout the experiment. Microphone array measurements were made outside the building facing the window for four different opening sizes of the window. The beamforming maps corresponding to this case is shown in Fig. 7 (a). It is evident that the technique successfully locate the leakage spots using the noise sources created by the leaking air flow. In order to avoid the complexity of pressurizing the room, two loudspeakers (10-inch, 4-ohm Dual Voice Coil Subwoofers) were placed inside the same room (see Fig. 2) and the blower door setup was removed. White noise signals were fed through the amplifiers to the loudspeakers. The microphone array measurements were repeated for the same opening sizes of the window and the results are plotted in Fig. 7 (b).

From Fig. 7, it is clear that the location estimates obtained from the acoustic source test are similar to that obtained from the pressurization test. This confirms that the beamforming technique with the artificial acoustic source inside the building could be a potential method to locate leakages in buildings. It should be noted that the tests were conducted on days when background noise levels were reasonably high (from road traffic, construction and insects). No special measures were taken to eliminate the background noise as this technique has inherent potential to detect leaks without a background noise removal requirement.

3.2 Leakage Quantification

As described in the introductory section, beamforming technique lacks the ability to quantify the detected leakages. More accurate measurements and analysis become necessary to quantify the leakages. This led to the use of nearfield acoustic holography methods in this study. The model building discussed in the previous section has a rectangular slot on its front face where inserts with various known crack shapes and sizes can be installed. Six different cracks (see Fig.8) have been considered for the present study. These cracks are rectangles of different areas.

Sine tones of $f = 5004Hz$ and $f = 317Hz$ are played through the subwoofer placed inside the building model and measurements are made on a two dimensional plane in front of the crack locations. These measured data are then used in NAH analysis to reconstruct the acoustic pressure and other quantities such as particle velocity on the surface near the wall of the building model. Figure 9 shows the reconstructed acoustic pressures on the building model surface. From this Figure, it is evident that the NAH is able to locate the leakages except for the least crack size considered. Also, one can notice that the sound pressure level increases with the increase in the crack area. This confirms that the NAH methods have the potential to be used as a leakage detection and quantification technique for buildings. In Figure 10, the maximum sound pressure levels detected ($p_{S,max}$) are plotted against the nondimensional area of the cracks. It is evident that the sound pressure levels increase monotonically with increase in area of the crack for both the input frequencies considered in this study.

4. CONCLUSIONS

In this study, a series of experiments were conducted to establish a unique, acoustics based method to locate and quantify leakages in buildings. The proposed remote acoustic method has the potential to replace the current laborious and time consuming leakage detection/quantification methods. A compact microphone array along with advanced beamforming algorithms was used to successfully locate the leakages (created by the imbalances in ventilation system) at a door of a room. The same technique was applied to a room in a building to locate the leakages on the window using the measurements made from outside. Blower door setup was used to pressurize the room to create air flow through leakages. To avoid the cumbersome process of setting up the blower door, a loudspeaker was used to generate sound inside the building (thereby removing the need to pressurize the building). Beamform maps of both tests show similar ability to locate the leakages. However, quantification of the spotted leakage area was not possible using the beamforming methods. Therefore, another acoustic method, namely, nearfield acoustic holography was tested with a scaled building model and was found to be successful in localizing and quantifying the leakage areas in terms of sound pressure levels.

ACKNOWLEDGEMENTS

This work was funded by NCIIA and Department of Energy, USA.

REFERENCES

1. Iordache V, Catalina T. Acoustic approach for building air permeability estimation. Building and Environment. 2012;57:18–27.

2. Sonoda T, Peterson F. A sonic method for building air-leakage measurements. Applied Energy. 1986;22(3):205–224.

3. Handbook A. Fundamentals. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta. 2001;111.

4. Ramachandran RC, Raman G, Dougherty RP. Wind turbine noise measurement using a compact microphone array with advanced deconvolution algorithms. Journal of Sound and Vibration. 2014;333(14):3058–3080.

5. Williams EG, Maynard J. Holographic imaging without the wavelength resolution limit. Physical Review Letters. 1980;45(7):554.

6. Maynard JD, Williams EG, Lee Y. Nearfield acoustic holography: I. Theory of generalized holography and the development of NAH. The Journal of the Acoustical Society of America. 1985;78:1395.

7. Williams EG. Fourier acoustics: sound radiation and nearfield acoustical holography. Academic Press: New York; 1999.

8. Bai MR. Application of BEM (boundary element method)-based acoustic holography to radiation analysis of sound sources with arbitrarily shaped geometries. The Journal of the Acoustical Society of America. 1992;92:533.

9. Sarkissian A. Method of superposition applied to patch near-field acoustic holography. The Journal of the Acoustical Society of America. 2005;118:671.

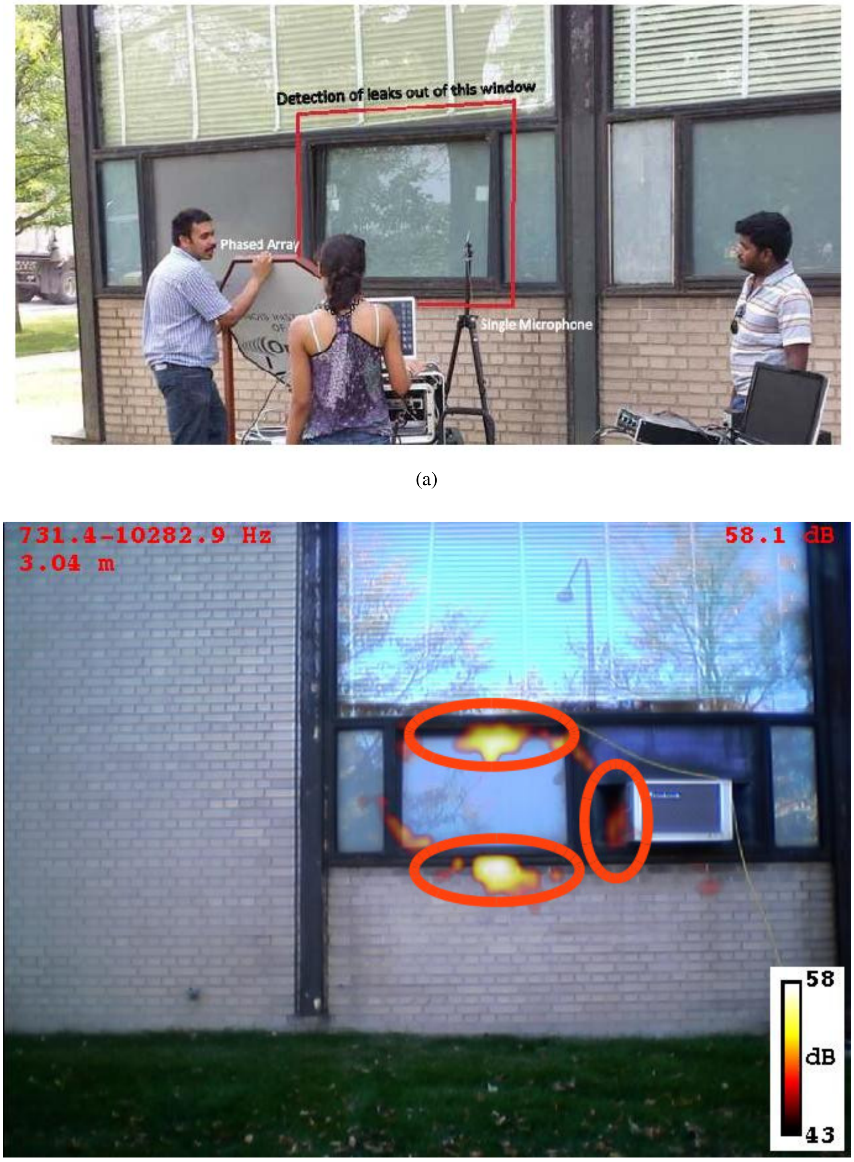
10. Chelliah K, Raman G, Muehleisen RT. Advanced aeroacoustic testing techniques using various methods of acoustic holography. In: 20th AIAA/CEAS Aeroacoustics Conference, Atlanta, Georgia, USA, June. AIAA 2014-3071; 2014. .

11. Raman G, Prakash M, Ramachandran RC, Patel H, Chelliah K. Remote detection of building air infiltration using a compact microphone array and advanced beamforming methods. In: BeBeC; 2014. .

12. Brooks TF, Humphreys WM. A deconvolution approach for the mapping of acoustic sources (DAMAS) determined from phased microphone arrays. Journal of Sound and Vibration. 2006;294(4):856–879.

13. Sijtsma P. CLEAN based on spatial source coherence. International journal of aeroacoustics. 2007;6(4):357–374.

14. Dougherty RP, Podboy GG. Improved phased array imaging of a model jet. In: 15th AIAA/CEAS Aeroacoustics Conference (30th AIAA Aeroacoustics Conference), Miami, FL, May. AIAA 2009-3186; 2009. p. 11–13.



(a)

(b)

Figure 1 – (a) A photograph of the experimental setup showing the microphone array (OptiNav 24) system externally facing a ground floor window. (b) Beamform map of acoustic noise source leaking through the window obtained from the microphone array data.

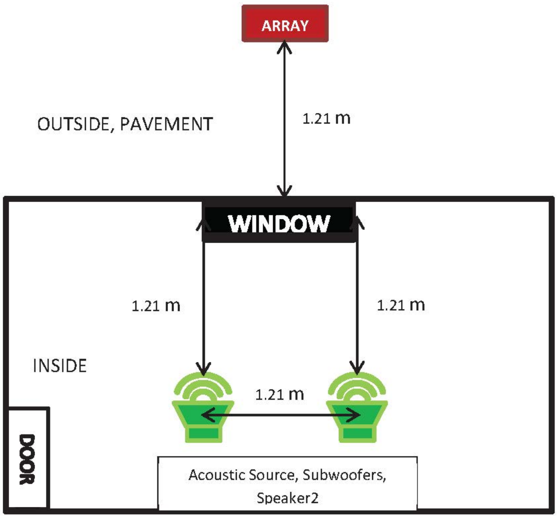
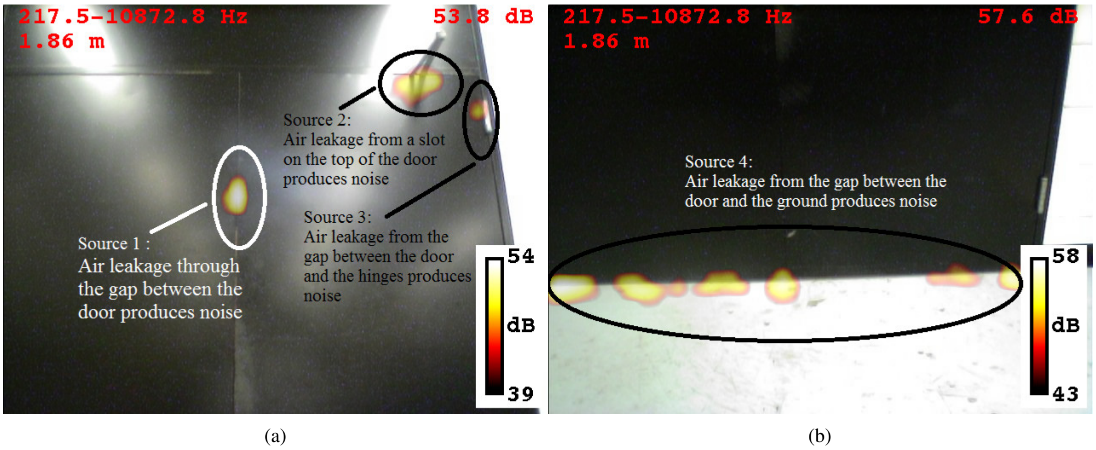


Figure 2 – Schematic of the experimental setup to measure sound leakage through the window. The sound in the room was produced by loud speakers and measured externally using a microphone array.

Figure 3 – A photograph of the experimental setup showing the pressure gauge and blower fan mounted on the door.

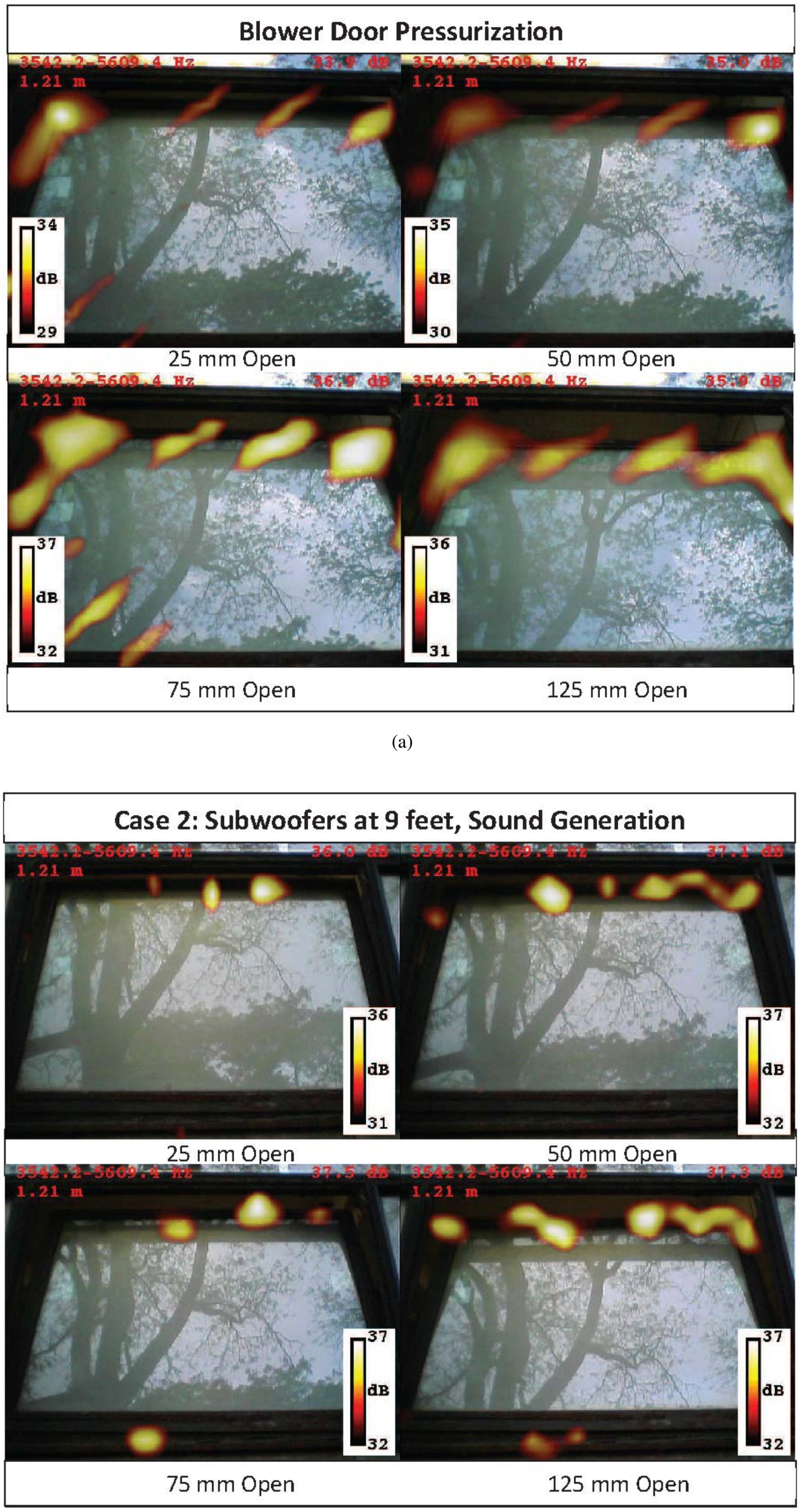
Figure 4 – Traversing single microphone setup in front of a model building located in an anechoic chamber for the accurate testing of NAH algorithms.

Figure 5 – Photographs of a door with major air leakage spots indicated. A mechanically-driven pressure difference existed across the door under normal building operation.



(a) (b)

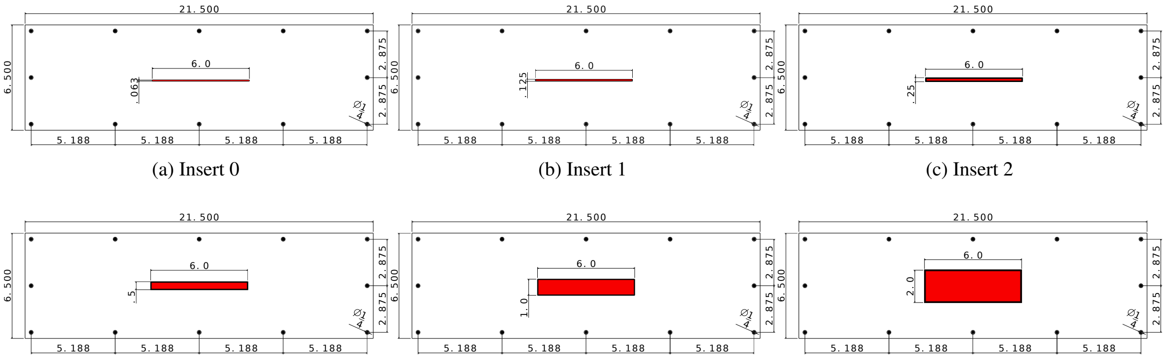
Figure 6 – Beamform map of success at locating leakages from doors using the advanced wideband beamformer, TIDY of, (a) the top half of the door and (b) the bottom half of the door. The circled regions show the location and size of air leakage superimposed on the photograph of the door.



(a)

(b)

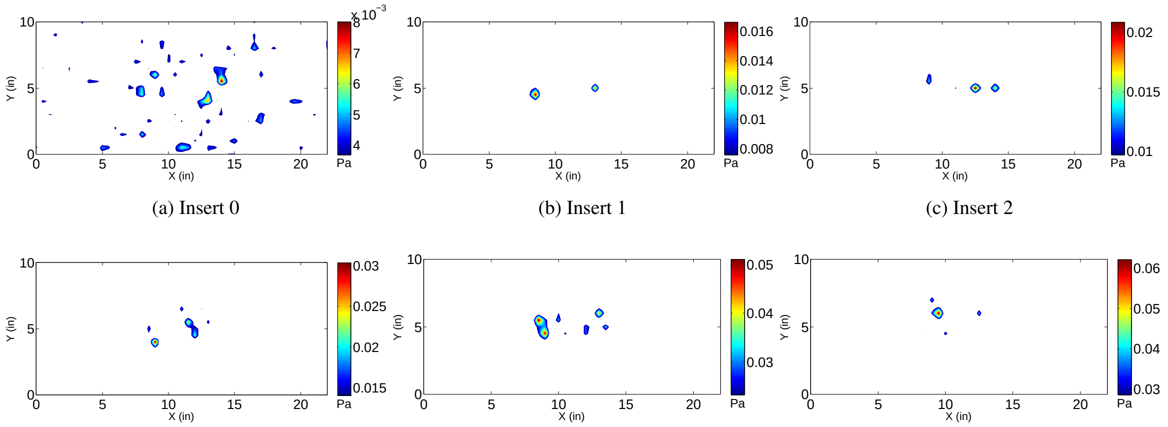
Figure 7 – Beamform maps using TIDY comparing the ability of microphone array to locate noise generated by (a) flow due to pressurization, and (b) noise due to acoustic source for frequency range 3500 Hz- 5600 Hz for various window gaps.



(a) Insert 0 (b) Insert 1 (c) Insert 2

(d) Insert 3 (e) Insert 4 (f) Insert 5

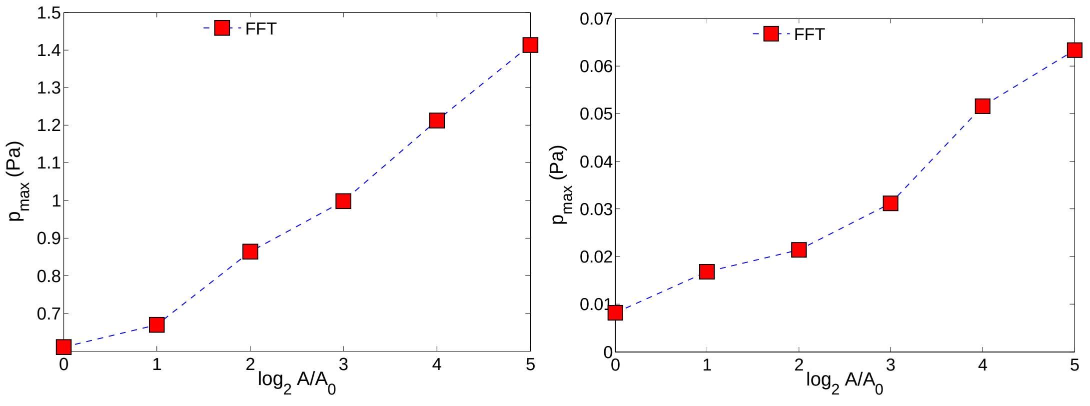
Figure 8 – Inserts with increasing area of opening (the rectangular openings are shown in red color).



(a) Insert 0 (b) Insert 1 (c) Insert 2

(d) Insert 3 (e) Insert 4 (f) Insert 5

Figure 9 – Reconstructed acoustic pressure field using NAH for various areas of leakage, $f = 5004Hz$.



(a) $f = 317Hz$ (b) $f = 5004Hz$

Figure 10 – Quantification: $p_{S,max}$ for various areas of leakage, calculated using NAH for two different frequencies.