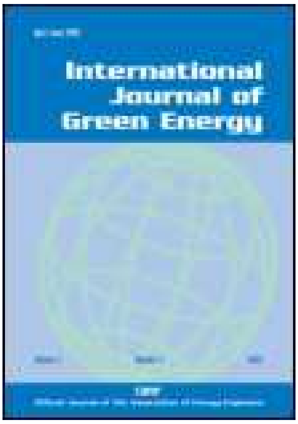

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AIR-INFILTRATION MEASUREMENTS IN BUILDINGS USING SOUND TRANSMISSION LOSS THROUGH SMALL APERTURES

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The objective of this investigation is to determine air infiltration in buildings using sound transmission loss (STL) through various types of holes and cracks. The method is based on the use of a sound source that radiates sound waves at a known frequency inside the building and two sound level meters, which measure sound pressure level inside and outside the building. To develop a correlation between STL and air infiltration, experiments have been performed using various types of materials. A test chamber was divided in two sub-chambers to simulate interior and exterior air conditions. Various materials, each with a small hole of varying shapes and sizes, were positioned between the two sub-chambers. A pressure difference has been generated between the sub-chambers and air infiltration in each experiment was measured through each hole. Filed testing in several buildings has been performed to determine air infiltration. The results of field measurements compared with the blower door readings show that the proposed method has promise to be used to measure air infiltration in buildings.

Keywords: ***Sound transmission loss; Air infiltration; Heat loss***

INTRODUCTION

Due to scarcity and increasing prices of almost all fuels, preventing heat loss from buildings has become an important area of research. Efforts are being made to save or optimize energy consumptions in various fields (Kulakowski 1999; Aries and Newsham 2008; Varshney, Rosa, and Shapiro 2011; Varshney et al. 2011). Forty-one percent of the total energy produced in the United States is consumed in residential and commercial buildings (U.S. Energy Information Administration 2010). Heat is primarily lost from buildings in two ways, (a) through thermal conduction, and (b) via air infiltration. Air infiltration can have a powerful impact on heat loss, comfort, expense, and air quality. Air infiltration is defined by Liddament (1986) as an “uncontrolled flow of air through penetrations in the building fabric caused by pressure differences generated across these openings by the action of wind and temperature.” It has a profound influence on both the internal environment and the energy needs of buildings. It is an intriguing task to estimate the air infiltration energy consumption of a building because of the uncontrolled nature of air infiltration.

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Pettersson (1978) performed testing in a single family house and reported that air infiltration accounted for 30–40% of heat loss. Orme (1998, 2001) estimated that one-eighth of energy is used in residential and service sector industries to meet ventilation and air infiltration requirements. Outside air entering into the building needs to be heated or cooled according to the inside temperature of the building, thereby increasing the energy costs over the lifetime of the building. Air infiltration occurs through gaps in building materials themselves and in joints in and around windows, doors, walls, etc. Air infiltration is conventionally minimized by using techniques such as weatherstripping and sealing/caulking (Sherman and Modera 1988).

The most common method to detect and measure air infiltration is the blower door method (Meier 1994). In the blower door test, measurements are taken by increasing the speed of a fan placed in a building doorframe until the pressure difference between the building interior and exterior becomes 50 Pascal (Pa). The amount of airflow measured in cubic feet per minute (CFM) for a pressure difference across the enclosure of 50 Pa is expressed as CFM/50. The blower door is used to quantify air infiltration and the resulting heat loss, and is also used to pinpoint specific locations of leaks. In general, the higher the airflow the more air infiltration through the holes in the building, indicating poor building quality. This method is widely used in small domestic buildings, and is a recognized test in many countries, for instance, under the Swedish building standards (Sonoda and Peterson 1986). It is often referred as a ‘steady’ method as it provides an air infiltration measurement at one pressure (Carey and Etheridge 2001). Bahnfleth, Yuill, and Lee (1999) compared two test standards, ASTM E779 (ASTM 2003), which specifies test conditions for blower door tests, and Canadian CGSB 149.15 (CGSB 1999), which specifies test conditions for a fan pressurization test using a building’s own air handling system, in two multi-zone, multi-story buildings. The researchers found that neither method was easy to implement. Wind and stack effects were difficult to control in multi-story buildings. Further, the sealing of leakage paths between floors via shaft penetrations was challenging. Therefore, the results of the fan pressurization tests may be inaccurate. A blower door method is based on using a powerful variable speed fan, mounted in an adjustable panel that temporarily fits in a doorway that is used to move air through the building in a controlled fashion. Once a building is depressurized, air leaks can be located by walking from room to room, feeling for drafts, or by waving a smoke pencil near likely problem areas. However, finding these leaks is a cumbersome process, requires experience and persistence. Furthermore, the blower door testing can be expensive, requires large and expensive equipment, and so is often not available to energy auditors. In addition, for buildings having significant air leakage, one blower door may not be big enough to generate the required 50 Pa pressure difference, and therefore more than one blower door is required, and more often the test is simply not done in large buildings. Furthermore, the blower door test is difficult to apply to a single building component, such as a single window or door, in order to disaggregate infiltration for a single component or group of similar components. It can be done, for example by running the test before and after sealing one component, but the resolution, and therefore accuracy, of the test is poor for one small infiltration site in a whole building.

There are several other methods used to detect and measure air infiltration through a building, including envelope air leakage techniques, air velocity measurements, tracer gas techniques and thermal imaging (McKenna and Munis 1989). An inexpensive fog machine can pinpoint air leaks but cannot measure actual air infiltration rates. Furthermore, due to the fog, the building has to be vacant, which makes the testing difficult if people are in the building. In making a precise measurement of air leakage, the tracer-gas method has been investigated and developed during the last few decades using CO, SF_6, and perfluorocarbon (Russell and Edgar 1982; Murakami and Yoshino 1983). Moreover, the thermography method, with the aid of an infrared camera, is useful for detecting insulation defects and air leaks in a building (Pettersson 1978). However, this requires a relatively expensive camera and also information obtained by this method does not give quantitative results, but only relative, qualitative features for the building envelope. Thus, another technique must be employed simultaneously so as to make the data quantitative.

The literature shows that a correlation between the STL and air infiltration is at present not well characterized. This correlation may be obscured by large uncertainties in the measurements and other effects present during the time of experiments. Some issues remain open, such as whether the STL is a function only of the area of holes or whether it changes with the shape as well. The present study aims to establish a relationship between air leakage and STL through holes and gaps of different sizes, to overcome these problems.

EXPERIMENTAL SET-UP

Experiments have been carried out in the Taitem Engineering test facility to attempt to correlate air infiltration and sound transmission loss (STL) through various types of holes and slits (Figure 1). The test chamber is divided in two sub chambers, where different interior and exterior test conditions can be simulated. The outside walls of the test chamber are insulated by R-17.50 rigid insulation panels. Various types of material panels with different hole and slit sizes were mounted in the test chamber (Table 1). All test specimens of size 36 × 22 inch (91.4 × 55.9 cm) were mounted between the interior and exterior chambers. Holes were created at the center of the test specimens, which were approximately 4 ft (1.22 m) above the floor.

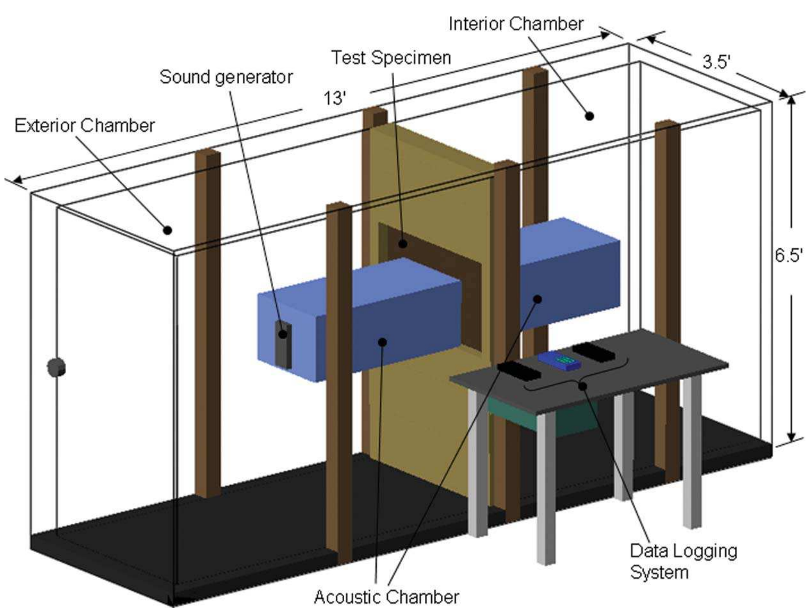

Figure 1 The experimental setup: Sound generator, acoustic chambers, data logging system, and interior and exterior chambers. (color figures available online)

Table 1 Sizes of Circular Holes, Annular Holes, and Rectangular Slits for Lab Testing (O.D. is Outer Diameter, I.D. is Inner Diameter)

No.	Material	Hole/Slit Type	Size of Hole/Slit
1	Sheetrock and plywood (0.5 inch (1.27 cm) thick), and rigid insulation (1 inch (2.54 cm) and 2 inch (5.1 cm) thick)	Circular	1/8 inch (0.32 cm), ½ inch (1.27 cm), ¾ inch (1.91 cm) (diameter)
		Rectangular	2 × 1/16 inch (5.1 × 0.16 cm), 4 × 1/16 inch (10.2 × 0.16 cm), 6 × 1/16 inch (15.3 × 0.16 cm), 8 × 1/16 inch (20.4 × 0.16 cm), 2 × 1/8 inch (5.1 × 0.32 cm), 4 × 1/8 inch (10.2 × 0.32 cm), 6 × 1/8 inch (15.3 × 0.32 cm), 8 × 1/8 inch (20.4 × 0.32 cm)
		Annular	1.5 inch (3.81 cm) O.D. and ½ inch (1.27 cm) I.D., 1.5 inch (3.81 cm) O.D. and ¾ inch (1.91 cm) I.D., 1.5 inch (3.81 cm) O.D. and 1 inch (2.54 cm) I.D.
2	Wall assembly (inside to outside) ½ inch (1.27 cm) sheetrock 3 inch (7.6 cm) fiberglass Insulation ½ inch (1.27 cm) plywood	Circular	1/8 inch (0.32 cm), ½ inch (1.27 cm), ¾ inch (1.91 cm) (diameter)
		Rectangular	2 × 1/16 inch (5.1 × 0.16 cm), 4 × 1/16 inch (10.2 × 0.16 cm), 6 × 1/16 inch (15.3 × 0.16 cm), 8 × 1/16 inch (20.4 × 0.16 cm), 2 × 1/8 inch (5.1 × 0.32 cm), 4 × 1/8 inch (10.2 × 0.32 cm), 6 × 1/8 inch (15.3 × 0.32 cm), 8 × 1/8 inch (20.4 × 0.32 cm)
		Annular	1.5 inch (3.81 cm) O.D. and ½ inch (1.27 cm) I.D., 1.5 inch (3.81 cm) O.D. and ¾ inch (1.91 cm) I.D., 1.5 inch (3.81 cm) O.D. and 1 inch (2.54 cm) I.D.
3	Double pane, vinyl frame window	N.A.	N.A.

In order to determine the STL through the holes/slits, a sound source and a sound level meter (Extech Instruments, Nashua, NH, USA, Model No. 407760-Sound level data logger) were mounted in the exterior chamber and a few sound level meters were mounted in the interior chamber at different distances from the test specimen. The sound level meters can measure and record sound pressure levels wirelessly over a frequency range from 32 Hz to 8000 Hz, and sound pressure level between 30 dB and 130 dB with an accuracy of ± 1.4 dB. The frequency of the sound source was 6000 Hz.

A hot-wire air velocity sensor (Onset computers, Bourne, MA, USA, Model: T-DCI-F900-L-P) in conjunction with a data logger (Onset Computers, Model: Energy pro H22-001) was used to measure air leakage through a hole under interior–exterior pressure difference of 50 Pa created by the blower door equipment (Energy Conservatory, Minneapolis, MN, USA). Both velocity and sound intensities in the sub chambers were sampled at 1 Hz. Signal processing of the acquired data such as calculating mean, covariance, etc. and filtering out undesirable frequency signals have been performed as described in Varshney and Panigrahi (2005) and Cramer et al. (2006). In these tests, the effect of temperature on STL was assumed negligible and the temperature in both chambers was kept same. The blower door equipment was used to induce airflow to obtain the relationship between STL and air infiltration. The air infiltration was calculated by multiplying measured velocity with the cross-sectional area of the hole. Four sound level meters in the interior chamber were positioned at different distances from the hole and the velocity sensor was positioned in front of the hole so that airflow through the hole could be measured. It is known that the slits/holes in a building, such as cracks around windows and doors can be of many sizes and shapes. Therefore, it is difficult to come up with a "model" hole. However, in order to mimic cracks in windows and doors, long and thin slits of different length and width have been constructed and tested. In addition, holes of various geometries such as rectangular, circular, and annular (representing the hole around a wall penetration for a pipe or electrical conduit) have also been tested.

The sound pressure level of sound waves is commonly measured on a logarithmic scale, called the decibel (dB) scale, and is defined as,

$$\mathrm{SPL} = 20 \log(p/p_0)\mathrm{dB}, \tag{1}$$

where p_0 is the pressure amplitude of a reference sound. By measuring the SPL, STL can be obtained from the following equation:

$$\mathrm{STL} = 10 \log(I_1/I_2)\mathrm{dB}, \tag{2}$$

where I_1 and I_2 are the incident sound energy intensity on the hole in the interior chamber and transmitted sound energy intensity near the hole in the exterior chamber, respectively. I_1 and I_2 are obtained by using sound pressure level data measured by sound level meters. Figure 2 shows the schematic view of the experimental setup for sound pressure level measurements.

UNCERTAINTY ANALYSIS

The measurement uncertainty has been assessed by identifying and quantifying both bias and precision errors. In this study, the uncertainty analysis was performed for various parameters such as the STL, air velocity, and air infiltration in a building according to the method presented by Coleman and Steele (1995). The overall uncertainty can be calculated using the following equation:

$$e_y^2 = \left(\frac{\partial Y}{\partial Y_1}\right)^2 e_{x_1}^2 + \left(\frac{\partial Y}{\partial Y_2}\right)^2 e_{x_2}^2 + \ldots + \left(\frac{\partial Y}{\partial Y_J}\right)^2 e_{x_I}^2, \tag{3}$$

where e_Y represents the overall uncertainty, Y_J are the calculated results, $Y = Y(X_1, X_2, \ldots X_I)$, and represent the individual uncertainties in the variables $x_{I \ldots I}$. The instrumentation ranges and their uncertainties are presented in Table 2.

The total uncertainties of the measurements are estimated to be $\pm$ 1.4 dB for the sound pressure level measured by sound level meters, $\pm$ 1% for the air velocity sensor, and $\pm$ 3% for the blower door equipment. The uncertainty of the STL for all the holes tested is calculated on the basis of the uncertainties of measured sound pressure levels, which are used to calculate sound energy intensities. The uncertainty of air infiltration measurements in the field is calculated using the uncertainties of sound pressure level meters and the velocity sensor.

$$\left.\begin{array}{c}\mathrm{STL} = \mathrm{f}(\mathrm{I}_1, \mathrm{I}_2) \\ \text{Air infiltration measured in the field using the propose method} = \mathrm{f}(I_1, I_2, V)\end{array}\right\} \tag{4}$$

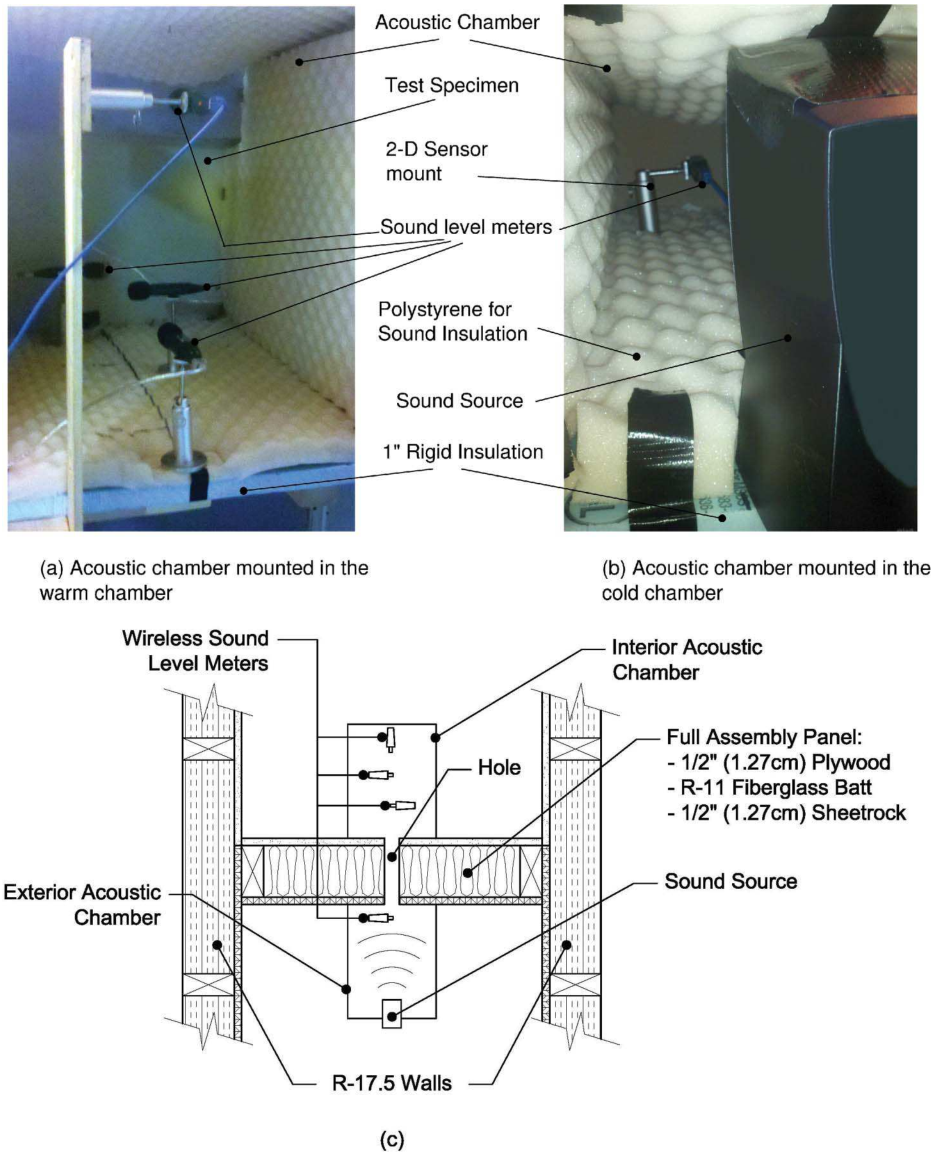

Figure 2 (a, b) Arrangement of testing hardware in the acoustic chambers. The testing hardware includes sound level meters, a sound source, a velocity sensor, and sensor mounts. (c) Position of the hardware and the full assembly. Various holes were made in the middle of the panel (Table 1) and STL was measured using the proposed method. (color figures available online)

Table 2 Instrumentation Range and Uncertainty

Instrument	Range	Uncertainty
1. Sound level meter	30–130 dB	± 1.4 dB
2. Velocity sensor	30–1969 fpm (0.15–10 m/s)	± 1%
3. Blower door	11–6300 CFM (18–10,700 m^3/h)	± 3%

RESULTS AND DISCUSSION

A series of tests was conducted under controlled lab conditions, with a goal of developing a reliable protocol for measuring air infiltration using STL. All experiments have been performed in quiet ambient conditions. A sound threshold was established, above which tests were not conducted if there was a risk of data contamination by sound other than the controlled sound source. During the experiments, interior and exterior test chamber doors were closed to minimize the noise level in the chambers.

Figure 2 shows the positioning of the sound level meters for the testing. Two acoustic chambers were built and mounted in the interior and exterior chambers. The walls of the acoustic chambers were made of 1 inch (2.54 cm) rigid insulation and on the inside surfaces of the walls, 1.5 inch (3.81 cm) thick polystyrene insulation was attached to provide sound insulation. A sound level meter and a sound source were positioned inside the exterior chamber (Figure 2) at 2.5 inch (6.35 cm) and 30 inch (76 cm), respectively, from the test specimen in front of the hole. Four sound level meters were positioned at 2.5 inch (6.35 cm), 12 inch (30.5 cm), and 24 inch (61 cm) in front of the hole, and 24 inch (61 cm), but 12 inch (30.5 cm) above the hole, in the interior chamber (Figure 2), so that STL at different locations could be determined. The reason for using the acoustic chambers was to detect as much of the transmitted sound through the slit/hole as possible. At the same time, the acoustic chambers were also used to eliminate undesirable sound such as that transmitted through other parts of the test specimen other than the slit/hole opening, different than the transmitted sound from the sound source itself, reflected sound or ordinary background noise. Lab experiments and field testing were performed at 6000 Hz sound source frequency.

In order to test various sizes and shapes, 60 different types of gaps in six different materials were tested. For these experiments, 0.5 inch (1.27 cm) sheetrock, 0.5 inch (1.27 cm) inch thick wood, 1 inch (2.54 cm) rigid insulation, 2 inch (5.1 cm) rigid insulation, full wall assembly that consists of 0.5 inch (1.27 cm) sheetrock on interior side and 0.5 inch (1.27 cm) thick wood on exterior side, and 3 inch (7.6 cm) fiberglass insulation in-between sheetrock and wood, and a double pane, vinyl frame, air-filled, clear window were tested. Various types of holes have been made in these materials and a correlation between STL and air infiltration through them has been made.

Figure 3 shows the variation in STL with various types of holes for different materials. It can be seen that STL decreased with an increase in the hole size. The variation of STL with distance is shown in Figure 4. It was found that for a given hole, STL increased as the distance of sound level meter increased from the test specimen in the interior chamber. After testing all different holes/slits in different materials as presented in Table 1, it was found that the sound level meter mounted at 12 inch (30.5 cm) distance from the test specimen was optimum for all types of holes and materials used in this study. For a given acoustic chamber dimensions, closer sound level meters were not able to measure total STL from a long slit, and farther sound level meters were not able to measure STL accurately for small holes. Therefore, during subsequent field testing, the sound level meter was mounted at 12 inch (30.5 cm) from exterior surface. Figure 5 shows a correlation between STL measured at 12 inch (30.5 cm) from the test specimen and air infiltration at 50 Pa pressure difference through various holes/slits. It can be noted that the STL decreased rather exponentially with an increase in air infiltration. Using all the points, a curve fitting by a fourth-order polynomial was performed to obtain a correlation function between STL and air-infiltration, which was used to convert measured STL into air infiltration in the subsequent field tests.

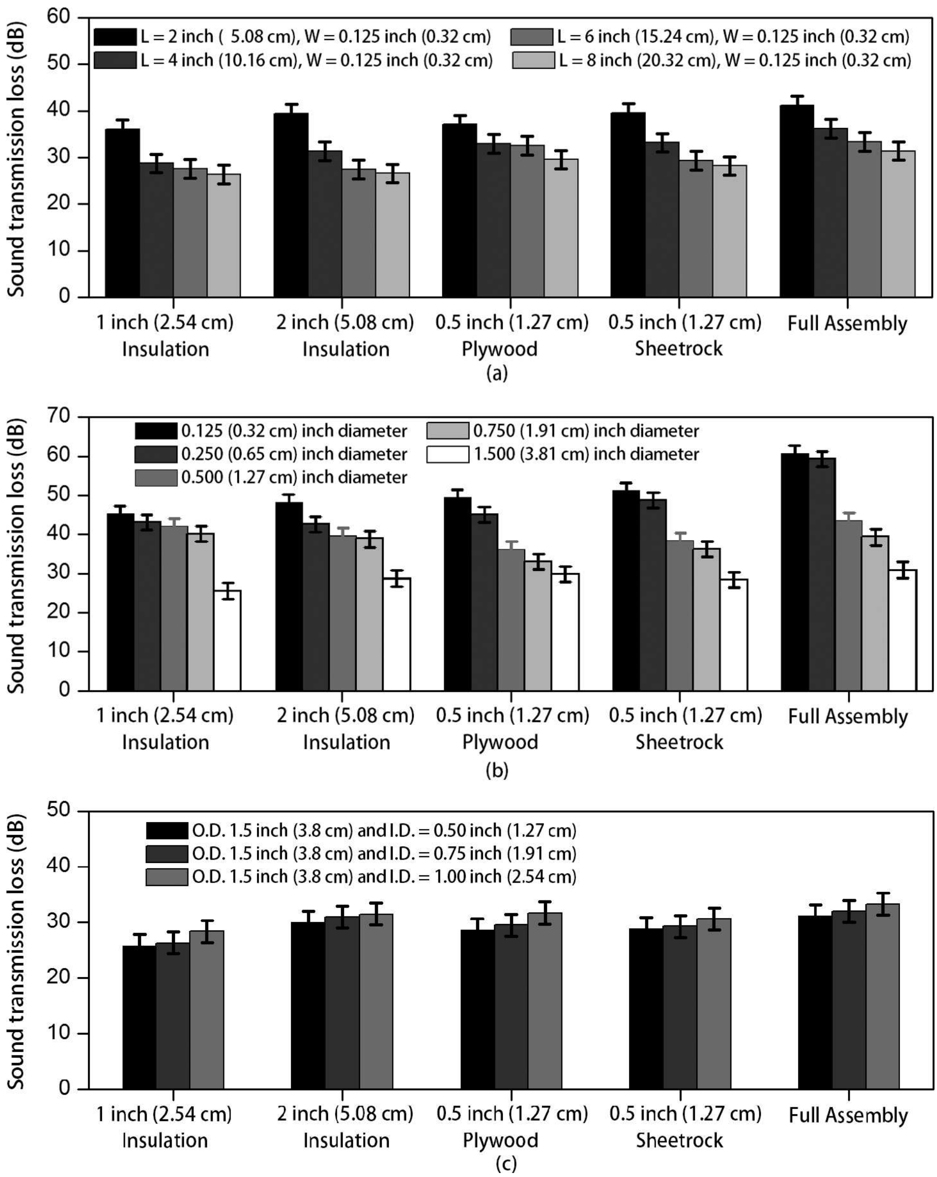

Figure 3 Variation in STL with the various types of holes for different materials: (a) Rectangular hole in different materials, (b) Circular holes in different materials, and (c) Annular holes in different materials.

Field Testing

Field testing was performed in five different buildings located in Ithaca, NY, which were office and residential two storey buildings. Specifications of the buildings are listed in Table 3.

In the field testing, sound pressure levels inside and outside the buildings were measured for as many holes as we found at the sites. In these tests, the sound source was

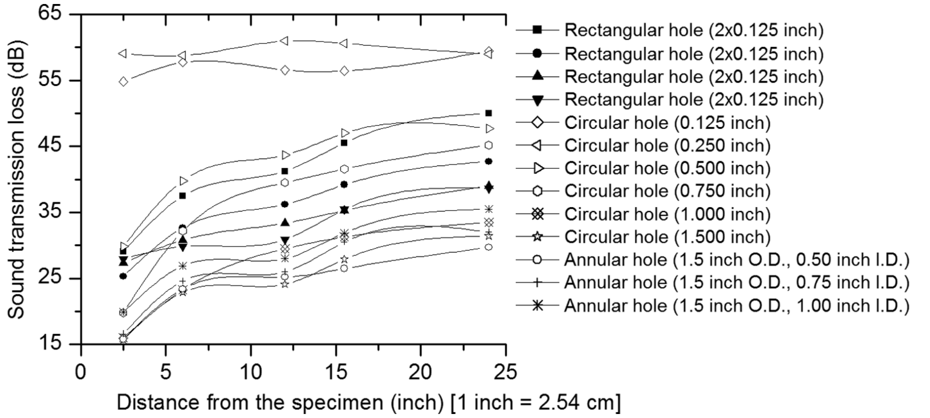

Figure 4 Variation of STL with distance for different types of holes are considered in this study. For each hole size, STL increases with the distance. Here, O.D. is the outer diameter and I.D. is the inner diameter of annular holes.

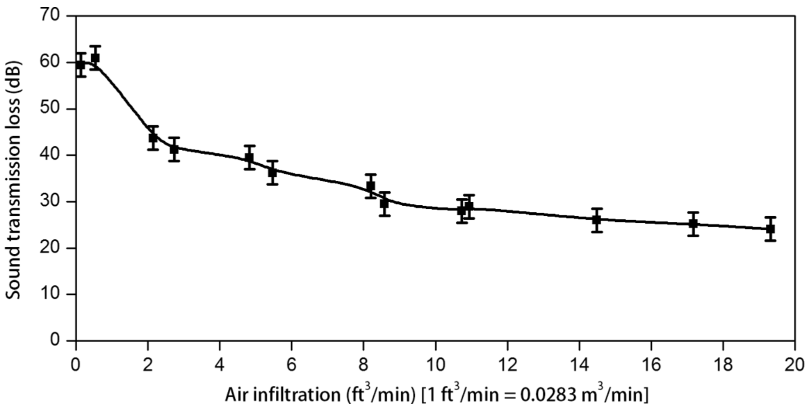

Figure 5 Correlation between STL and air infiltration at 50 Pa pressure difference (CFM) through various holes/slits.

Table 3 Specifications of the Buildings Used for Field Testing

Test Site	Year Built	No. of floors	Total conditioned area (ft^2)	Basement	No. of Windows	No. of Doors	Attic	Tightness
1	2006	2	1340	Yes	14	2	Yes	Very tight
2	1910	2	1748	Yes	26	2	Yes	Average
3	1955	2	1367	Yes	17	2	No	Average
4	1890	2	900	No	19	1	No	Leaky
5	2009	2	1500	No	31	3	No	Average

mounted inside the building and sound was radiated at 6000 Hz. Both the sound level meter, which was used to measure sound pressure level inside the building (2.5 inch (6.4 cm) from the interior surface) and the sound source, were mounted inside the acoustic chamber. Two sound level meters were mounted at 6 inch (15.2 cm) and 12 inch (30.5 cm) from exterior surfaces to measure sound pressure levels at these distances. The sound level meter mounted at 12 inch (30.5 cm) was used for calculations. Based on the lab testing, the obtained correlation between the STL and air infiltration was used to measure total air infiltration in each building component. The STL through different holes and gaps such as gaps between two sashes of a double pane window, gaps around a door, and annular gaps around pipes was measured separately. For a given fenestration (window or door), the testing was performed in a few steps because the size of the acoustic chamber was smaller than the size of a window or a door, and afterward all the STL measurements were added to determine a total air infiltration through a given fenestration. Air infiltration through various holes and gaps in a building were added to determine the total air infiltration in that building, through accessible holes. In order to measure STL through the second floor windows, a suction cup with a 24 inch (61 cm) long flat platform (Figure 6) was used. Blower door testing at 50 Pa pressure difference between the interior of the building and the outdoors was conducted at each site and readings of blower door testing were compared with the readings of the acoustic method.

Figure 7 shows a comparison between blower door testing and the readings obtained using the acoustic method for all five buildings. It can be seen that both methods show high infiltration for leaky buildings and low infiltration for tight buildings, even if both methods do not produce identical results. It should be noted that at each building, readings obtained

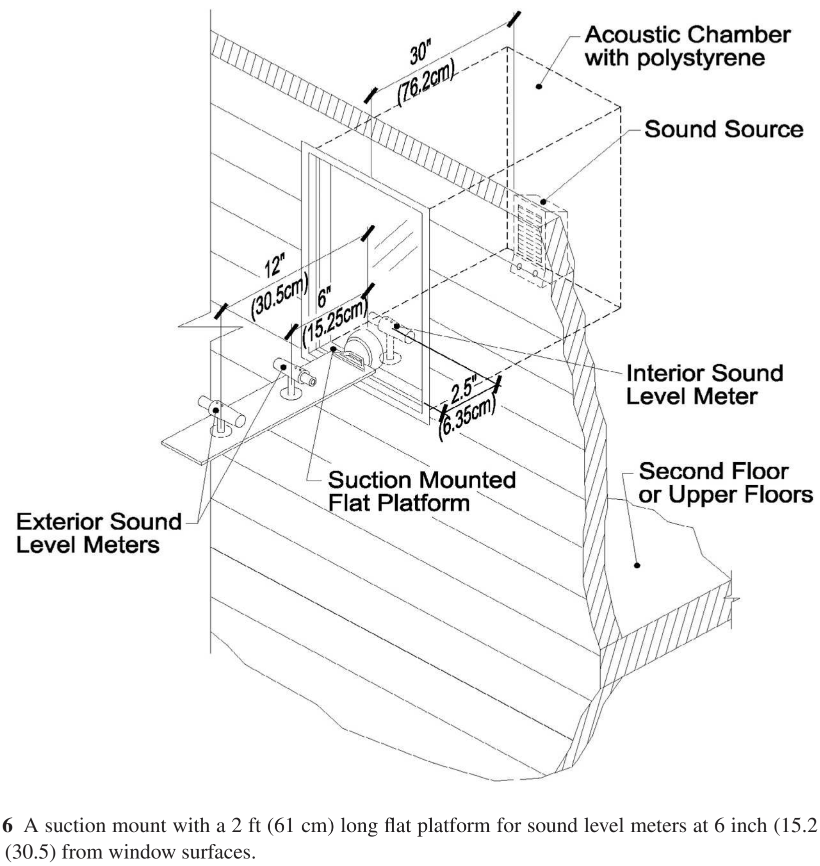

Figure 6 A suction mount with a 2 ft (61 cm) long flat platform for sound level meters at 6 inch (15.2 cm) and 12 inch (30.5) from window surfaces.

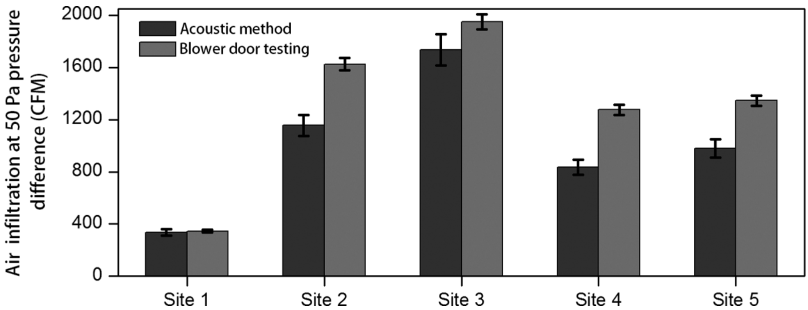

Figure 7 Comparison between blower door readings with the readings using acoustic method for five different buildings located in Ithaca, NY.

using the acoustic method is lower than that of the blower door method. A plausible explanation is that we could not reach each and every hole contributing to air infiltration in buildings, as that was the case with the acoustic method.

CONCLUSION

The purpose of this investigation was to experimentally obtain a correlation between air infiltration and STL through small apertures. Air infiltration was measured by applying a pressure difference of 50 Pa using the blower door method. The STL was measured by using the sound level meters, and a correlation between the air infiltration and STL was achieved. Based on the correlation obtained in the lab, air infiltration in five different buildings was measured and results were compared with the blower door readings. It was found that the air infiltration measured using the proposed method and blower door readings are close to each other, and therefore the proposed method has promise to be used to measure air infiltration. It can be concluded that the proposed nonintrusive technique is a potentially useful methodology for determination of air infiltration in building components.

The method does have some limitations. Although the method can be used to measure air infiltration through holes, there might be holes in the building, which are not easily visible or accessible and therefore air infiltration through them cannot be measured. In some cases, holes exist on one side of the envelope, but not on the other side. For example, pipes or electrical wires, which penetrate in the building from one side of the wall or ceiling, may not come out from the other side. In such cases, air infiltration cannot be measured using this method. Finally, measurements can likely not be performed in an environment where extraneous noises might interfere with the measurement.

ACKNOWLEDGEMENT

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