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BUILDING ENVELOPE ASSESSMENT OF AIRTIGHTNESS USING AN ACOUSTIC CAMERA: A CASE STUDY IN VALLADOLID, SPAIN

Ahmed Elsaei[1,3*] **Maria Machimbarrena**[2] **Alberto Meiss**[1]
Sergio Herguedas[4]
[1] Dpto. Construcciones Arquitectónicas I.T. y M.M.C.T.E, E.T.S. de Arquitectura, Universidad de Valladolid, Spain
[2] Dpto. Física Aplicada, Universidad de Valladolid, Spain
[3] Architecture, Built Environment and Construction Engineering Department (ABC), Politecnico di Milano, Italy
[4] HEAD acústicas GmbH, 08940 Carnella de Llobregat, Barcelona, Spain

ABSTRACT

Assessment of the building envelope quality in terms of airtightness and sound insulation is a critical factor to properly design an optimal retrofitting action plan. Therefore, the development of reliable and non-destructive measurement techniques for assessing these factors pre- and post-retrofitting is a crucial milestone, impacting costs, precision, and time efficiency. This study explores the use of an acoustic camera in evaluating airtightness performance in residential buildings. A measurement campaign was conducted across two houses in Valladolid, Spain, integrating blower door tests, smoke generator, and acoustic camera methods to assess air leakage and its interplay with sound transmission. The main goal of this research case study is to better understand the interplay between airtightness and acoustic performance within a real building façade.

Keywords: *building retrofitting, airtightness, sound insulation, acoustic camera.*

*[*]**Corresponding author**: ahmedelsaei@uva.es*

1. INTRODUCTION

One of the main goals of building retrofitting is to improve a building's energy performance. Air infiltration is widely recognized as a major cause of energy loss, typically occurring through façade cracks or construction defects. According to recent European studies, air leakage may account for 30–50% of the total energy consumption in the building sector [1]. Therefore, addressing infiltration points is essential during the renovation process. Accurately identifying the location of these cracks and quantifying their impact is critical to planning effective retrofitting strategies, and post-retrofit evaluations help determine the success of such interventions. Currently, no single method exists that can both quantify and localize air infiltration in building envelopes. Traditional methods such as the blower door (fan pressurization) test are commonly used to estimate the volume of air leakage under an artificial pressure difference [2]. However, this method cannot pinpoint the specific locations of leaks, often requiring additional tools like smoke generators or tracer gases [3]. These combinations are not only time-consuming and costly but also require technical expertise for proper setup and analysis.
In recent years, research has increasingly focused on alternative, non-invasive methods to assess airtightness. One promising approach is the use of acoustic-based methods, which are generally quicker, non-destructive, and potentially more precise. For instance, [4] and [5] used sound pressure level measurements in building acoustic frequency range to assess airtightness and conclude an empirical equation. However, significant

research efforts have been devoted to leak detection and localization, spanning from early work by [6] to recent contributions by [7] and [8]. These efforts have evolved from utilizing basic acoustic equipment to employing modern acoustic cameras and advanced beamforming techniques. Acoustic cameras, based on beamforming technology, offer the added advantage of visualizing leak locations in real time. However, while promising for detection, these methods face challenges in quantifying the infiltration rate. This quantification might be achieved by studying the interplay between sound transmission characteristics and airflow behavior through openings. Although previous studies highlight the complexity of this relationship [9], [10], [11], advances in acoustic technology may pave the way toward a practical solution. To explore this potential further, experimental campaigns must be conducted to test modern tools like acoustic cameras in real-world settings. The present study aims to contribute to this effort by demonstrating the effectiveness of acoustic methods in evaluating airtightness. Our work follows the direction of earlier studies and contributes modestly to ongoing efforts aimed at improving diagnostic tools for building envelope assessment.

2. METHODOLOGY

The method consisted in using an acoustic camera as measurement device to identify the potential air leak points, assuming that air leaks, under special conditions, should produce sound. Although the type of sound produced at air leak points could be different depending on the physical origin (forced air or real sound) the position of the air leak points should be coincident.

2.1 Overview

The measurement campaign was conducted in two occupied residential buildings located in Valladolid, Spain. These buildings were selected to represent typical Spanish multi-family housing stock, with conventional building envelopes and standard terrace window installations.
House 1 was a two-story family home in a residential compound. This unit served as a baseline scenario, without any specialized ventilation features as shown in Fig.1 and Fig.2. **House 2**, was a second floor of typical apartment in a mid-high residential building in Valladolid City, as depicted in Fig.3, featured micro-ventilation openings integrated into its terrace window frames. Both houses underwent a full testing sequence including pressurization, depressurization, and sound transmission analysis using both sides of the façade internally and externally. For House no.2 the measurements were performed with the micro-ventilation openings in both open and closed positions to study their impact. A smoke generator test was also performed in both houses to visually confirm major leakage points identified acoustically.

2.2 Equipment

The experimental campaign employed three main types of equipment: a blower door and an omnidirectional sound source as "exciting devices" and an acoustic camera as measurement device. Additionally, a portable smoke generator was used to visualize air leaks.
The blower door system used combined with a DG-700 digital pressure gauge as shown in Fig.4. This system allowed for controlled pressurization and depressurization of the interior space by creating artificial pressure differentials of 50 Pa and 80 Pa, thereby forcing air infiltration through leaks and enabling airflow quantification through the envelope which could then be localized using the acoustic camera.
An omnidirectional sound source, as depicted in Fig.2, was also used during the measurement campaign to try to identify airborne sound leakage paths. This device emitted broadband white noise within a range of 40 Hz to 16 kHz and was placed strategically inside or outside the dwellings depending on the test configuration. The noise served as a reference signal to help determine the extent and location of sound transmission paths through the façade.
To localize potential leakage paths and visualize sound transmission, the HEAD VISOR 7500ff acoustic camera was utilized shown in 3 and a schematic drawing of it illustrated in Fig.5. This high-resolution beamforming system consists of a 56-microphone spiral array paired with three synchronized industrial cameras. The system operates over a wide frequency range from 300 Hz to 20 kHz, offering both real-time and post-processed visualization of sound sources. The portable smoke generator was used to release non-toxic visible smoke into the interior space during pressurization / depressurization. Leakage paths were identified by observing smoke escaping through façade discontinuities from the exterior / interior. This method provided a qualitative visual reference to complement the acoustic recordings.

2.3 Measurement procedure

In both houses the same measurement protocol was followed to ensure comparability between test cases. For House 2, the measurement protocol was performed twice to analyze the impact of window micro-ventilation features: first with window micro ventilations closed and then with window micro ventilations open. This enabled a comparative analysis of acoustic and airflow behavior under varying boundary conditions, offering insight into how these small architectural features influence both airtightness and sound insulation

The measurement protocol was the following:

The Acoustic Camera (AC) was placed outside the house in front of the terrace window (as in Fig.1 and Fig.3) and measurements were made under different excitation conditions:

- No forced excitation: This set up was chose to assess environmental noise and thus establish baseline acoustic conditions. These preliminary recordings helped identify uncontrollable ambient noise sources—such as birds, street traffic, or nearby recreational areas—and allowed later to filter them out during analysis. In each configuration, at least two or three random baseline recordings were performed to improve the robustness of the dataset.
- Blower door mounted to force air in/out potential leak paths: the blower door was installed in the main entrance of the apartment to enable full control over the internal pressure. Blower door tests were then conducted in both pressurization and depressurization modes at pressure differentials of 50 Pa and 80 Pa. During each steady-state phase, the acoustic camera recorded for 30 seconds to capture noise emissions through the façade.
- Omnidirectional speaker placed inside the house and activated to emit white noise, simulating real-world sound transmission while the acoustic camera recorded also for 30 seconds to capture noise emissions through the façade.

Additionally, for House 1 the measurements related to the blower door tests were repeated placing the acoustic camera inside the house to assess the influence of directionality on leak detection and source visualization.

Figure 1. House 1 Terrace Window. AC outside

Figure 2. House 1. Sound source inside. AC outside

Figure 3. House 2 Façade. AC outside.

Figure 4. Blower Door setup – House 1

Figure 5. Microphone arrays and the camera setup

3. RESULTS

All the images shown in this section correspond to a specific moment within a preselected short time period (2 to 3 seconds) and within a selected limited frequency range. The acoustic camera software allows to analyze the video recording filtering both according to a selected frequency range and to a selected time period. Results shown have consistently been observed over time and over different frequency ranges as it will be explained hereinafter.

3.1 SPL peaks spots within House 1

Fig.6 and Fig.7 show persistent SPL peaks in the same position (upper right section of the terrace window frame), in different moments and under blower door pressurization 50 Pa conditions. This position is also seen when performing the smoke generator test integrated with blower door as shown in Fig.8. These SPL peaks points were found across multiple frequency bands and are shown for the following intervals: 580–715 Hz and 1647–1829 Hz. Due to its position on the edge of the window frame, these spots are preliminary identified as potential air leakage spots.

On the other hand, when using the sound source as an excitation signal, a sound peak is detected close to the previous location across the frequency band of 1016–1211 Hz as shown in Fig.9. Due to its position slightly away from the frame edge and directly on the window (curtains behind the sound peak shown in figure 10), it is not considered a potential air leakage spot but rather an external sound reflection or glass vibration.

When the tests were performed with the blower door under depressurization conditions (50 Pa and 80 Pa) and the acoustic camera was placed inside the house, SPL peaks were detected exactly between window frames 1 and 2, as shown in Fig.10 and Fig.11, notably in higher frequency band: 4833–5695 Hz. Other sound peaks have been identified within different time periods and across different frequency bands as summarized in Tab.1. All these spots shown in Tab.1 are potential air leakage spots due to their position.

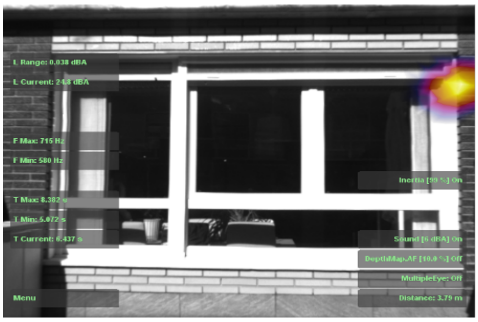


Figure 6. SPL peak located in upper right window frame in House 1. (50 Pa pressurization. AC outside)

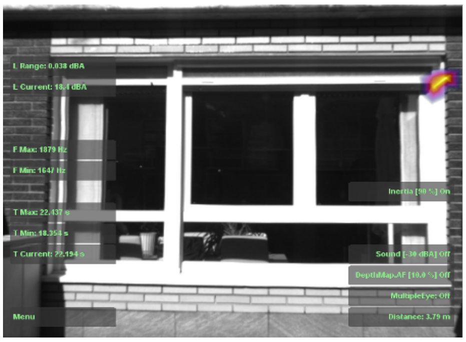


Figure 7. SPL peak located in in upper right window in House 1 (50 Pa pressurization. AC outside)

Figure 8. Visual identification of air leakage locations in House 1 using smoke generator

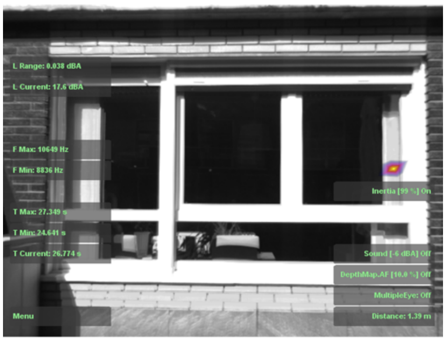


Figure 9. SPL peak located on the glass (curtain behind), close to the right side of the window frame in House 1. (Sound source inside. AC outside.)

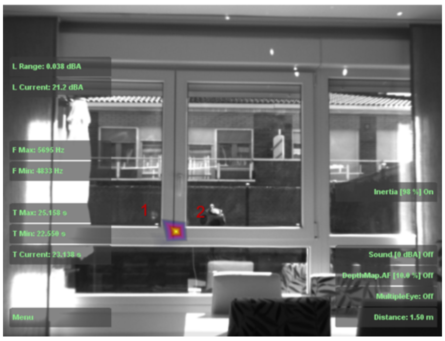


Figure 10. SPL peak located between adjacent window frames in House 1. (50 Pa depressurization. AC inside)

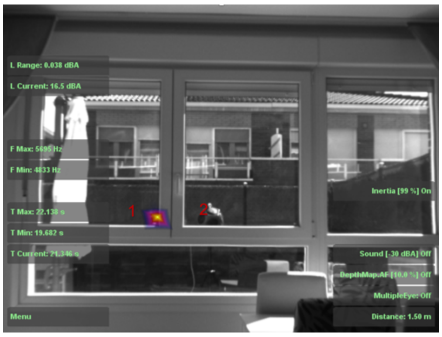
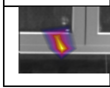
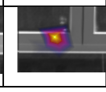
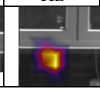
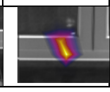
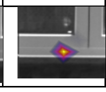
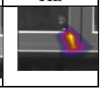


Figure 11. SPL peak located between adjacent window frames in House 1 (80 Pa depressurization. AC inside)

Table 1. SPL peaks near window frames 1 and 2 during blower door depressurization of 50 Pa and 80 Pa, across multiple frequency bands in House 1. (AC inside)

50 Pa	80 Pa	50 Pa	80 Pa	50 Pa	80 Pa
1759 – 2143 Hz	1759 – 2143 Hz	2169 - 2750 Hz	2169 - 2750 Hz	2699 - 3836 Hz	2699 - 3836 Hz
					

3.2 SPL peaks spots within House 2

The evaluation of House No. 2 focused on verifying and analyzing air leakage detected visually via smoke generator. Fig.12 shows two key locations where fog was observed to come out when the fog generator was used inside the house. Fig.13 identifies the upper frame area as position A and the lower frame zone between adjacent window segments as position B. In fact, position B corresponds to the position of a small open/close micro-ventilation opening.

Both air leaks have been consistently detected by the acoustic camera independently of the type of excitation used (pressurization/depressurization at 50/80 Pa or loudspeaker). The leaks are seen at specific frequencies which need to be identified among the full data set. For example, sound pressure level peaks were consistently identified at position A in the frequency band of 1412 - 2120 Hz and at position B in the 1000 - 1841 Hz band. Some of these findings are summarized in Tab.2 and Tab.3, which compile results across various test conditions. Similar images are found at different moments within the full recording periods.

When the sound source is used as excitation signal, a SLP peak is also observed at the same location but at a higher frequency band of 3387 - 4112 Hz as shown in Fig.14.

As mentioned earlier, in some of the acoustic camera tests conducted in House 2, the micro-ventilation feature on the window was intentionally left open. As it can be seen in Tab.4, the SPL values increase in all cases when the micro-ventilation is open, as it was expected.

Figure 12. Visual identification of air leakage locations in House 2 using smoke detection

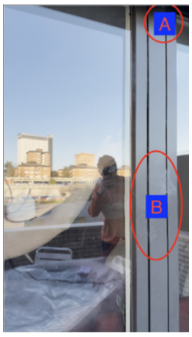


Figure 13. Positions A and B (micro-ventilation)

Figure 14. SPL peak at Position A in House 2. (Sound source inside. AC outside.)

Table 2. SPL peaks at Position A. Frequency range 1412 - 2120 Hz. Various testing conditions. AC outside

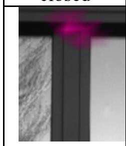
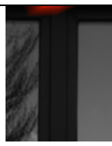
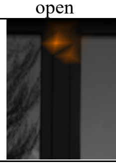
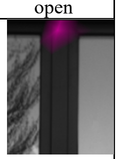
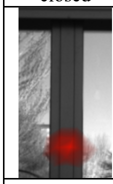
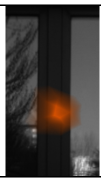
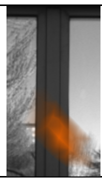
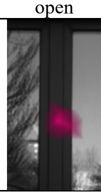
50 Pa Press Microvent closed	50 Pa Press Microvent open	Speaker Inside Microvent closed	Speaker Inside– Microvent open	80 Pa Press. Microvent open
				

Table 3. SPL peaks at Position B. Frequency range 1000 - 1841 Hz. Various test conditions. AC outside.

50 Pa Press Microvent closed	50 Pa Press Microvent open	Speaker Inside Microvent closed	Speaker Inside– Microvent open	80 Pa Press. Microvent open
				
37.2 dBA	41.2 dBA	42.3 dBA	46.5 dBA	34.1 dBA

4. DISCUSSION

4.1 House 1

The results from House 1 can be used to discriminate whether a SPL peak corresponds or not to an air leakage path. To support this type of classification, we refer to the study by Schiricke et al. [12], which introduced the Acoustic Assessment Score (ASS). This score ranges from 0 to 3 and is used to assess the likelihood that a detected peak corresponds to a real leakage point—helping distinguish between unlikely and likely leakage sources. In this case study three different SPL peaks spots have been identified:

The SPL peaks shown in Fig.6 and Fig.7 (upper right corner of the window façade) is located on the edge of the frame and aligns with the smoke generator results, strongly supporting the conclusion that, at this location, there is an air leakage path.

On the contrary, the SPL peak observed in Figure 10 is located over the glass. Since the glass was visually inspected and confirmed to be intact with no cracks or defects, this signal is likely the result of structure-borne sound or vibration rather than air leakage.

Lastly, another SPL peak zone was consistently identified under depressurization conditions, at a location which was not observed with the smoke generator. This is around the lower edge of the frame, near the junction of both frames. This SPL peak zone was detected very consistently at middle frequencies as shown in Tab.1, but it was more precisely spotted at higher frequencies as shown in Fig.10 and Fig.11. According to its position, it is very likely an air leak path. If we assume this is a crack or infiltration path, it is likely very narrow—possibly too thin to be detected by the smoke method and better detected at higher frequencies. This suggests that the acoustic method is particularly sensitive to small or layered cracks that may not be visible using smoke or fog-based techniques. Lower frequency bands (as shown in Tab.1) also detected the signal, but with less accurate localization.

4.2 House 2

In this house, the analysis focused on validating the leakage locations identified by the smoke generator method using the acoustic camera. The two-leakage points A and B detected with the smoke were confirmed across multiple frequency bands. Additionally, the consistency of such detections within specific frequency ranges suggests a potential link to the type or characteristics of the cracks when analyzing the sound spectral properties at these locations. This needs to be further explored.

Concerning the effect of the window micro-ventilation system whether in open or closed configuration, the results shown in Tab.3 indicate that, even when the feature is closed, there is measurable sound transmission with relatively high sound power. This suggests that air leakage may still occur through the micro-ventilation component even when it is closed. While the system appears to function as intended, the observed sound peaks while not activating it and the difference in sound power between closed ad open cases should be taken into account when evaluating the need for potential renovation or design improvement.

Overall, the acoustic data aligned well with the visual smoke-based observations while offering a more detailed and frequency-sensitive picture of infiltration behaviour, reinforcing the value of acoustic camera data both as confirmatory and diagnostic tool in complex façade assessments.

4.3 General insights

The combined findings from House 1 and House 2 strongly support the feasibility and added value of using acoustic cameras for airtightness evaluation. In both case study, the acoustic camera successfully detected leakage spots confirmed by smoke and, in some cases, it was possible to identify additional narrow leak paths which were visually undetectable with smoke. This detection was observed at high-frequency bands which most likely can provide information about the thin and narrow nature of the leak path. Overall, the findings confirm that acoustic imaging can complement or even exceed traditional air leakage localization methods, especially when visual cues are weak or absent.

The results further emphasize that it is not possible to identify all leakage points in a single acoustic image, as leakage signatures appear at different locations depending on the frequency band. Therefore, it is necessary to have a multi frequency band visualization, where the sound peaks are distributed across the façade, varying between lower and higher frequencies. This observation aligns also with findings reported by Schiricke et al. [12], confirming that a sequence of images across third-octave or narrow-band frequency bands is necessary to detect all potential leakage areas. Therefore, comprehensive leakage visualization requires multi-frequency acoustic analysis to account for the variability in spectral responses caused by differences in geometry, crack size, and flow behavior.

4.4 Further research

Finally, these findings support the work of Schiricke et al. [12], who demonstrated that acoustic cameras could detect small leakage points that are often missed by traditional tools such as blower door tests, smoke generators, or gas tracer methods. However, Kölsch and colleagues highlighted that additional knowledge is still required to reliably distinguish between true leak sources, reflected signals, and airborne sound transmission, especially in complex real-world settings. This remains an open research question and presents a critical avenue for further development.

Therefore, one of the key ongoing tasks in our study is to analyze the spectral characteristics of each confirmed leakage point, with the goal of establishing acoustic signatures or spectral patterns that may correlate with leak size, type, or severity. This spectral approach could form the basis for developing more automated or semi-automated leakage classification tools using acoustic data. As also discussed by Schiricke et al. [12], the spectral fingerprint of a leak may offer valuable diagnostic insight, and future work will aim to explore this potential in depth.

5. CONCLUSIONS

House 1 demonstrated the potential ability of the acoustic camera to show sound pressure peaks that could correspond to subtle air leaks where the smoke testing failed to produce a visual cue. The existence of the sound peak at relatively high frequencies and between the frames most likely corresponds to a fine or narrow leak. This highlights a key advantage: acoustic tools offer higher sensitivity to narrow or complex leakage paths, especially in the mid to high frequency range. House 2 provided an opportunity to evaluate the influence of micro-ventilation features. The integration of multiple source types (blower door and speaker) revealed consistent detection at smoke-identified positions.

Overall, this study shows the potential use of acoustic beamforming as a complementary, or in some cases with further research as independent, tool to traditional diagnostic techniques. Their ability to visualize, localize, and interpret leak behavior in real time provides a user-friendly and highly effective solution for both researchers and practitioners. Importantly, the integration of sound-frequency analysis with pressure-based testing opens the door to more detailed diagnostics that could evolve into hybrid quantification models in the future. Our findings confirm that single-frequency images are insufficient for capturing all leakage paths. A multi-frequency approach is necessary to visualize the full range of leakage behavior.

6. ACKNOWLEDGMENTS

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