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COMBINED IMAGING TECHNOLOGIES FOR DETECTION OF AIR LEAKS IN MODERN AIRTIGHT CONSTRUCTIONS

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The aim of this study is to develop a combined imaging system for the diagnosis of air leaks and diagnosing thermal and sound transfer through leaks and ventilation in modern homes. This paper will present the results of a collaborative, interdisciplinary project exploiting two unique world-class sets of expertise and experimental facilities from the University of Salford: the Acoustics Test Laboratories and the Energy House. Conventional air-tightness testing procedures for homes are proposed by building regulations for the detection of air leakage paths. By introducing sealing measures, the heat loss and noise break-in inside homes through such air leaks can be reduced. These tests are usually time consuming and do not provide any information on the heat and sound transfer through the leaks. The technology proposed here is a combined measurement and analysis solution utilising the Microflown PU acoustic sensor and the FLIR thermal imaging camera. The FLIR thermal camera is used for localising weak thermal insulation areas. However from the thermal image, it is not always clear if the weak areas represent a structural path or an air leak in the structure. Using the Microflown PU acoustic probe, the particle velocities on a structure can be mapped thus separating areas with high and low particle velocities, so that areas with high particle velocity can be diagnosed as leaks. Additionally, the nature of noise break-in can be assessed as the PU probe can also measure different sound transfer properties. The results show sound transfer through a retrofit window with and without a curtain covering. A clear reduction in the pressure and velocity levels with the curtain covering to simple window reference case is observed. It is concluded that the combined imaging system can be especially of interest for diagnosing the sound transfer through ventilation.
Keywords: façade sound insulation, internal environmental quality, ventilation, overheating, thermal comfort

1. Introduction

Awareness of the impacts of climate change, rising energy prices, fuel poverty and a demand for energy security have prompted significant changes in design thinking, construction practice, building materials and building legislation aimed at reducing energy use and carbon dioxide emissions. A particular example of this is the fabric first approach and increasing requirements for air-tightness in housing. Whilst this achieves a primary objective of reducing heat loss through ventilation, there is growing evidence that the requirements for healthy ventilation have not kept pace with these developments, and there is emerging evidence of poor indoor air quality and inadequate ventilation.

Poor ventilation in buildings has been linked to a multitude of public health issues, particularly for conditions such as asthma and chronic obstructive pulmonary disease (COPD) that are all known to be exacerbated by poor air quality. The long term objective of this project is to devise a novel applications of remote sensing and imaging techniques to facilitate the bringing together of public health and building professionals together with architects and their clients to investigate shared research questions, with the overall aim of supporting the design of healthy, low energy homes.

2. Aims and Concept

The study was conducted to use imaging techniques for the investigation of noise and thermal transfer through a retrofit window. The following imaging techniques were investigated tested and analysed by post processing techniques.

2.1 Acoustic Imaging –Beamforming and Nearfield holography

Acoustic imaging and localisation in the far field is usually done by beamforming a number of signals recorded by a microphone array known as the acoustic camera. The beamforming can be done in 2D or 3D manner depending on the location of sound sources and direction of incoming sound. Raman et al. [1] utilised 2D beamforming in the outdoors for locating air leakages in a window of a room and compared leak detection method used in standard airtightness testing. Our previous work [2] showed that 2D beamforming in a reverberant environment (inside the room) did not give satisfactory results due to reflection issues from the walls. Schröder et. al. [3] demonstrated an approach using the 3D spherical acoustical camera to evaluate the interior surroundings of a room. Different properties such as RT, absorption and reflection, and sound isolation were measured which showed the weak spots or the noise leakage in a door of the room they tested. Barre et. al. [4] demonstrated the use of time domain beamforming using impulse responses (sine-sweep) to analyse leaks in a plate installed between two rooms at high frequencies. From these studies, use of 3D Beamforming seems reasonable to investigate for leakage detection in buildings.

The Microflown P-U probe used for the study is a nearfield solution for analysing the sound fields and localising sources. It measures the pressure and the particle velocity in three directions using the principle of a hot wire anemometer. For compressed air leaks, Microflown first demonstrated the application to detect a leak as low as 7x10-6 bar l/s, however this was possible by using a nozzle attachment at the particle velocity probe [5]. Instead of using compressed air sound waves can be transmitted through leaks which can also be measured with the probe. Vecchio et. al. [6] used the Microflown probe to detect an artificially generated acoustic leakage in the sealing of a car lateral window at high frequencies. Comesana et. al. [7] demonstrated the use of Scan & Paint technology with the Microflown probe. Scan and Paint creates a colour map of the acoustic properties on the image of the scanned structure. The authors performed broadband mapping (50 to 5000 Hz) of sound pressure, particle velocity, and acoustic intensity on a door excited by airborne sound. It was observed that, while the pressure roughly indicates where the noise is coming from, particle velocity mapping shows even the weaknesses at the door profile, demonstrating the high spatial resolution of the measurement method.

The acoustic camera would require a detailed CAD model of the room or a laser scan to use 3D beamforming in reverberant room. As the room is reverberant 2D beamforming does not work, hence the Microflown sensor was chosen for detecting leakages. Additionally it is faster and provides us with different acoustic properties such as the acoustic particle velocity and sound intensity.

2.2 FLIR Thermal Imaging Sensor

The instrument used for the thermal imaging experiments was a Flir B425 thermal imaging camera. This device has an accuracy of +/- 2 degrees Celsius and a sensitivity of 50mK. This device functions on the principle of detection of radiative heat exchange which is present in all materials above absolute zero. This principle can be used to collect visual data on the surface temperature of elements; this can be useful when comparing scenarios such as insulated and uninsulated structures, or detecting gaps in insulation measures [8]. The thermal imaging camera is not applicable for recording surface temperatures of reflective materials such as glass; the equipment was only used when the windows were covered with curtains

2.3 U-value measurement

U-values are a well-defined internationally recognised unit of measure for the thermal transmittance of a building element, in this case a window. The unit gives a measure of the number of Watts (W) passing through a square metre (m^2) of the material for a given difference in temperature in Kelvin (K) and it units are W/m^2K [9]. To estimate a U-value three measurements are needed; heat flux, internal temperature and external temperature.

3. Test Methodology

The tests were carried out in the Energy house at University of Salford. The Energy House at University of Salford (Fig. 1) is a full scale house built inside an environmental chamber. The environmental chamber is controlled and different environmental conditions can be simulated, for ex., rain, wind and sub-zero temperatures. The building in the chamber can then be tested with different materials under a controlled environment.

3.1 Scan and paint using Microflown P-U probe

To diagnose the sound transmission through the window, the Energy house compound was excited by a loudspeaker driven by pink noise excitation. A sound field is set up around the energy house and this causes the sound to be transmitted to the bedroom from paths such as the window and any leaks/openings in the window. Using the P-U probe, a scan was conducted over the window to measure the pressure and acoustic particle velocity normal to the window inside the room. Using Scan and Paint technology, these scanned quantities were mapped on the window. At first, the window was scanned fully closed (to detect leaks) and then with 3 window openings (5, 15 and 24 cm) with and without curtain to measure the sound transfer. The window chosen for the study is shown with the loudspeaker outside the house in Figure 1.

Figure 1: the energy house (left), the window tested (centre) and the loudspeaker in the house compound (right)

3.2 Thermal imaging methodology

For the thermal tests a temperature difference inside and outside of the house is produced. If this is of greater than 10 degrees Celsius then thermal imaging is able to suggest dominant paths of heat transfer into the enclosed space. This is also a commonly used method to identify air leakage paths at weak points and gaps in the structure. The thermal camera was set up to capture thermal images of the internal face of the window covering. The images were taken at the end of the test when a steady state temperature had been reached at the curtain surface.

3.3 U-value measurement

An array of Hukseflux HFP01 heat flux plates are fixed to the internal surface of the glass. On both internal and external surfaces are thermocouples which record the temperature; data is collected at intervals of 1 minute. The method for calculating U-value, as used by Wood et. al. [10], combines heat flux, surface temperatures and surface thermal resistances, as set out for the average method in [9]. Each experiment observes the U-value across a test period during which heat is applied to the room. A heater is situated to the rear of the room so as to allow heat to circulate around the room. This is done to initiate steady state conditions within the room and thus through the tested element. A set point of 22^{o}C is used for the room, while the external temperature is regulated to approximately 5^{o}C using a dedicated HVAC system. This temperature difference of above 10K was used to promote mono-directional heat flow through the element.

$$U = \frac{1}{\left(\frac{T_I - T_E}{Q}\right) + R_{SI} + R_{SE} + \Phi} \quad (1)$$

Where T_I is the internal surface temperature (K), T_E is the external surface temperature (K), Q is the heat flux through the element (W m^{-2} K^{-1}), R_{SI} is the internal surface thermal resistance (m^2 KW-1), R_{SE} is the external surface thermal resistance (m^2 K W^{-1}), φ is the resistance of the heat flux plate (6.25x10-3 m^2 K W^{-1}).

Figure 2: U-value measurement setup showing position of heat flux sensors (left) and with tweed curtain (right)

4. Results

With the loudspeaker active, the probe was scanned on the window in all configurations and the particle velocity and pressure were mapped using the Scan and Paint technology. Figure 3 shows the scans for the window closed case to detect areas of leakage in the frequency range of 1-2 kHz. From the scans it is evident that the leakage areas are present between the junctions of the two window frames. It is also evident that while pressure mapping can show areas of the leakage, the localisation with acoustic particle velocity is more precise thus demonstrating a high signal to noise ratio compared to the pressure map. This is also in line with the conclusion of Bree et al. [11] on using velocity mapping for better signal to noise ratio.

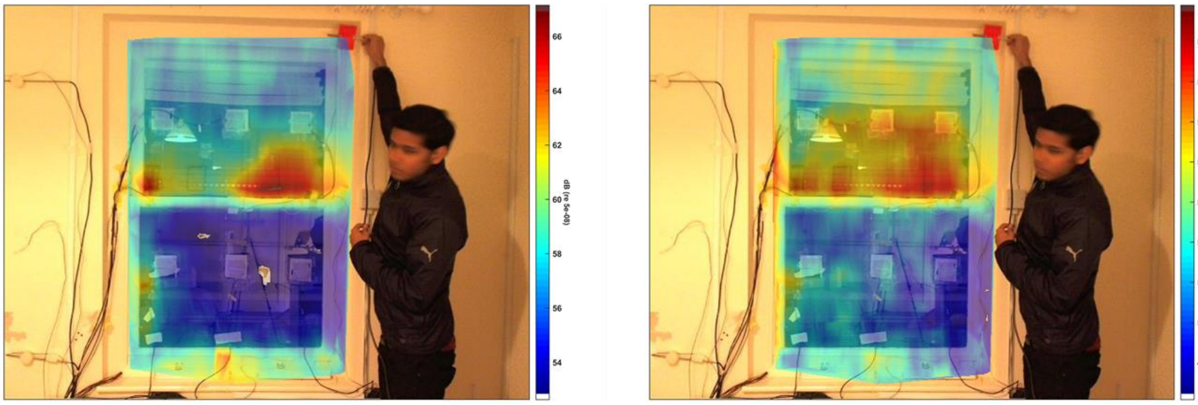

Figure 3: Acoustic particle velocity map (left) and the sound pressure map (right) of the closed window

4.1 Sound transfer without and with the curtain on open window

Figure 4 and 5 show the maps for particle velocity and pressure respectively for the open window case. The window opening in this case was 24 cm. The open window case is also compared with the case when the tweed curtain is on (opening is unchanged). The results are presented for the frequency range 1-2 kHz and show a clear reduction in the pressure and velocity levels around the window opening. This is also the region where the maximum levels are observed which can be clearly seen to have reduced for the curtain case, about 20 dB in the velocity level and 9 dB in pressure level. It is also interesting to see that the sound does not leak from the sides of the curtain but rather still transmits most through the region covering the opening of the window. Again it can be seen that the velocity maps display a high signal to noise ratio.

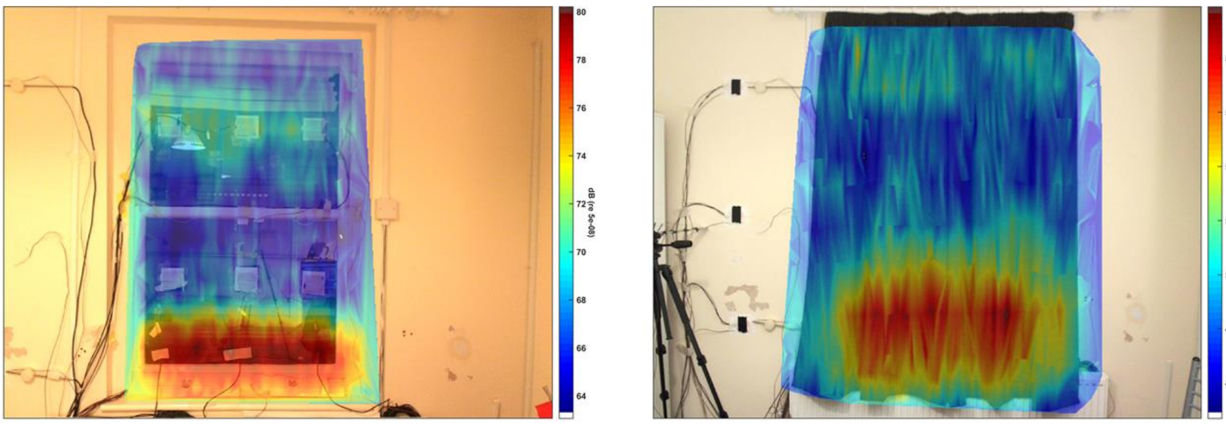

Figure 4: Acoustic particle velocity map for open window (left) and the window with curtain (right)

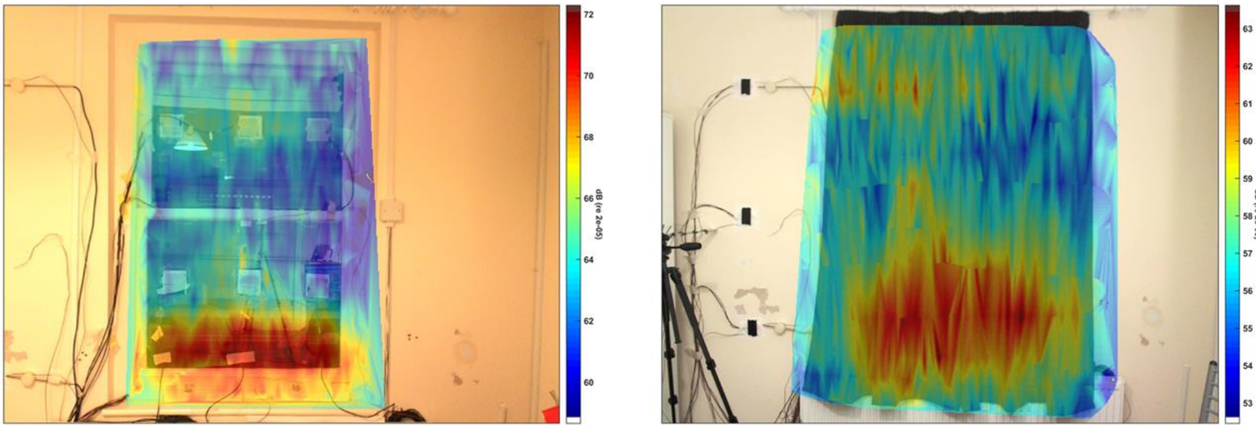

Figure 5: Acoustic pressure map for open window (left) and the window with curtain (right)

4.2 Thermal Imaging and U value results

Figure 6 shows the thermal imaging results for the closed window case (with and without curtain). It is important to note that thermography is not generally used on reflective surfaces; therefore the results for the naked window are illustrative. Thus any weak spots detected on the window may be inconclusive for leak detection.

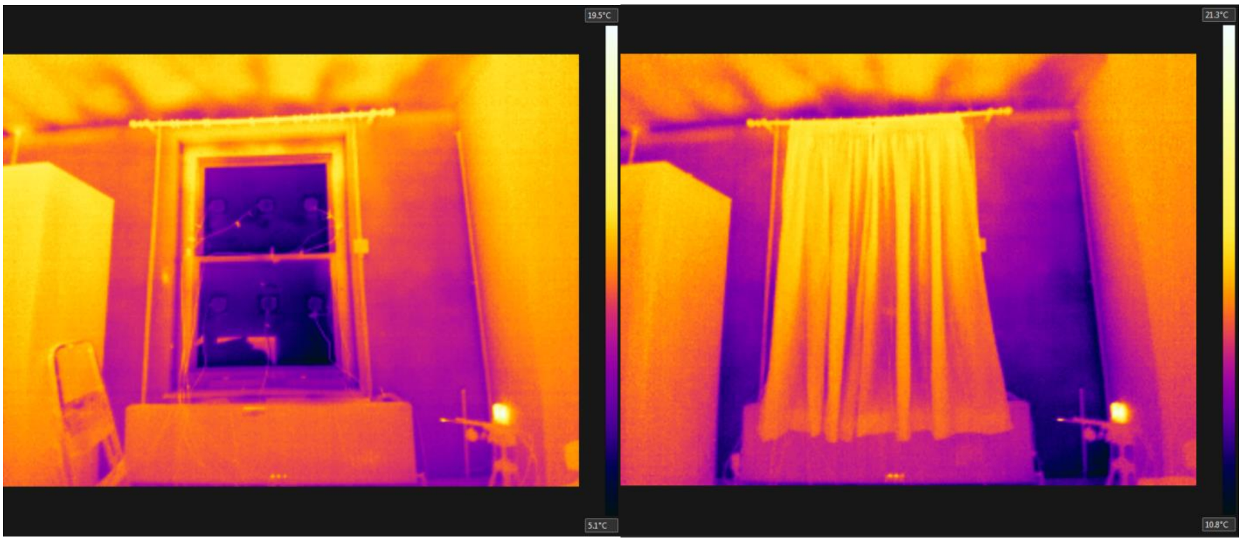

Figure 6: Thermal image of window with no curtains (left), thermal image of the tweed curtains (right)

Table 1 show the U-values of the window glazing with and without the curtains. The test setup can be seen in Figure 2. Again a clear reduction in U-values can be seen when the curtain is used demonstrating its effectiveness in reducing the thermal transfer in the room.

Table 1: U-value measurements with and without curtains

Test	Element	Average U-value Top (W/m^2K)	Average U-value Bottom (W/m^2K)	Average U-value Overall (W/m^2K)
1	Glazing with no curtains	4.6	4.4	4.5
2	Tweed Curtains	2.9	3.0	2.9

5. Conclusions

The aim of the study was to investigate combined acoustic and thermal imaging techniques to investigate the leakage and thermos-acoustic transfer through a retrofit building element –a window in this case. To detect leakage, although thermal imaging has been used in studies previously, it may give misleading results when thermal imaging is applied on a transparent structure. Also a temperature difference between indoors and outdoors has to be maintained. A simple way around this is to excite the structure with sound waves such that sound transfers through the leaks take place. Using the Microflown P-U probe, the leaks were detected using pressure and particle velocity mapping of the window. The particle velocity mapping shows more precise location of leaks and exhibits a higher signal to noise ratio. It is concluded that using the Microflown P-U probe as opposed to thermal imaging for leakage detection may be faster.

The acoustic imaging was also used to measure the acoustic transfer properties of the open window and window covered with a tweed curtain. The test was done for 4 different window openings and the result is presented for the highest window opening case. From the particle velocity and pressure mapping of the curtain in 1-2 kHz range, the effect of level reduction can be seen. Further study is in progress to measure the sound intensities in both cases to give the approximate sound reduction of the curtain in-situ.

Thermal imaging offers a different technique to qualitatively detect locations for leakage and thermo-acoustic transfer by illustrating the relative difference in the intensity of infra-red radiation emitted by a surface element. In cases where a particular region on the surface of an element experiences higher thermal transmission than the surrounding areas – such as where leakage may be detected through air permeation or structural defects – the region would appear colder. Although this technique is suitable for the visualisation of data, it lacks the capacity for quantitative analysis and so quantification of fabric performance parameters, for example the U-value, relies on a more inclusive technique. Thermal imaging also faces an obstacle where reflective or transparent surfaces are considered, as infra-red radiation from other sources can be transmitted from and through the surface to give an inaccurate representation of the actual condition at that surface.

In order to explicitly differentiate between an unobstructed glazing element and one which incorporates tweed curtains, it is necessary to state the U-value of each glazing permutation. Following the method outlined in BS ISO 9869-2014, measurements of heat flow and internal / external temperatures were taken over a period of 14 hours under steady state conditions. The average method was then employed to calculate the average centre-pane U-values, as indicated in table 1. By quantifying the average thermal transmission across the centre-pane element with and without the curtain, a difference in this thermal transmission of 37% is identified. Rather than simply illustrating relative thermal transmissions and areas of leakage, the technique presents a figure for this disparity. The disadvantage of using thermal imaging and the average U-value method is inherent in each procedure, in that both methods require steady state conditions to be established. For leak detection then, acoustic imaging takes the advantage in providing rapidity of both measurement and result analysis.

REFERENCES

1 Raman G., Prakash M., Ramachandran R., Patel H., and Chelliah K. Remote detection of building air infiltration using a compact microphone array and advanced beamforming methods, *Proceedings of the Berlin Beamforming Conference,* Berlin, Germany, (2011).

2 Patil N., WongMcSweeney, Benjaber M., Fitton R., Elliott A., Waddington D., Feasibility study on using acoustic camera for acoustic imaging to detect air leaks in a structure, *Proceedings of the IOA conference,* Kenilworth, UK, (2016)

3 Schröder, R., Meyer, A., Döbler, D., Heilmann, G. and Ohm, M. Fields of application for three-dimensional microphone arrays for room acoustic purposes, *Proceedings of INTER-NOISE conference,* Osaka, Japan, 4–7 September, (2011).

4 Barré, S., Döbler, D., and Meyer, A., Room impulse response measurement with a spherical microphone array, application to room and building acoustics, *Proceedings of INTER-NOISE conference*, Melbourne, Australia, 16–19 November, (2014).

5 *The Microflown E-book*, [Online] available: http://www.microflown.com/library/books/the-microflown-e-book.html.

6 Vecchio, A., Valent, L., Berthe, A., and Debree H. The Microflown, a Novel Approach to Helicopters Interior Noise Testing, *Instrumentation and Measurement Technology Conference*, Sorento, Italy, 24-27 April, (2006).

7 Comesaña, D., Steltenpool, S., Pousa, G., Bree, H., and Holland K. Scan and Paint: Theory and Practice of a Sound Field Visualization Method, *ISRN Mechanical Engineering*, (2013).

8 BS EN 13187:1999 Thermal performance of buildings. Qualitative detection of thermal irregularities in building envelopes. Infrared method. London: BSI.

9 ISO 9869-1:2014 Thermal insulation -- Building elements -- In-situ measurement of thermal resistance and thermal transmittance -- Part 1: Heat flow meter method.

10 Wood C, Bordass B, and Baker P. Research Report. Researching into the thermal performance of traditional windows: timber sash windows, (2009).

11 de Bree, H. E., Svetovoy, V. B., and Visser, R. (2005). The Very Near Field II An introduction to Very Near Field Holography, (No. 2005-01-2446). *SAE Technical Paper*, (2005).