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IN-SITU TRANSFER PATH ANALYSIS OF A ROOF MOUNTED AIR SOURCE HEAT PUMP

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ABSTRACT

To combat carbon emissions and move towards Net Zero, many EU countries have begun phasing out fossil fuel domestic heating in favour of air source heat pumps. The UK government has set a target of installing 600,000 air source heat pumps per year from 2028.Though restrictive installation guidelines for air source heat pumps have been revised, this does not negate the issue of suitable unit placement for retrofit in existing UK housing stock. In many cases, the existing homes are attached, terraced homes with little outdoor space to accommodate a heat pump. An option is to mount the heat pump in the attic space, by attaching to the roof. This provides a reasonable alternative to using up potentially limited outdoor space and may utilise unused interior space. This approach presents its own challenges, however, notably the potential for structure-borne noise transmission to the dwelling and adjoining homes, due to the attachment to the roof, and potentially airborne noise transmission, due to the proximity of bedrooms etc. With the aim of better understanding – and therefore mitigating – these potential issues, this paper explores the benefits of in-situ Transfer Path Analysis – a method normally employed for vehicles and mechanical structures – for this application.

1. INTRODUCTION

As retrofit becomes a realistic prospect for the development of net-zero heating in domestic homes using Air Source Heat Pumps (ASHPs), suggestions for options of ASHP placement within the loft space of homes has become a popular idea. Due to the comparatively large existing housing stock in the UK, retrofit is necessary to meet the UK government targets for becoming carbon neutral. Many of these houses have limited outdoor space, or have close borders to neighboring dwellings, which creates challenges for external ASHP placement when considering existing noise and boundary regulations. As roof mounting an ASHP is a relatively new concept, especially in the UK, a method for the determination of structure and air-borne noise transmission is required for the analysis of the acoustic impact of the system. This paper proposes an in-situ methodology for the characterization of structural transmission paths of a roof-mounted ASHP. Using a Transfer Path Analysis (TPA) [1] approach, which is commonly applied to all manner of structural problems and applications, such as in vehicles [2] and buildings [3]. The blocked forces are measured at the frame from to which the ASHP is attached, with excitation by a pair of shakers within the ASHP external case at the mounting positions. Noise predictions are made for response positions at remote accelerometers on the adjacent roof structure, remote microphones in the loft space, and microphones in the bedroom and the bedroom below.

2. THEORY

The methodology proposed in this paper is based on the in-situ TPA method [4]. This involves the characterisation of a coupled structure in terms of a source and receiver, with an interface. The blocked forces are the for which is

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needed to constrain the velocity of the device under test to zero [5].
The method does not require the separation of source and receiver and, as no assumption is required for the behaviour of the receiver structure, the in-situ method is most likely more reliable than the previous TPA approaches. Another advantage of the in-situ approach is that the operational blocked forces are independent of the receiver structure, meaning that they remain valid for different assemblies by re-measuring or modelling the transfer function for a different assembly [6].

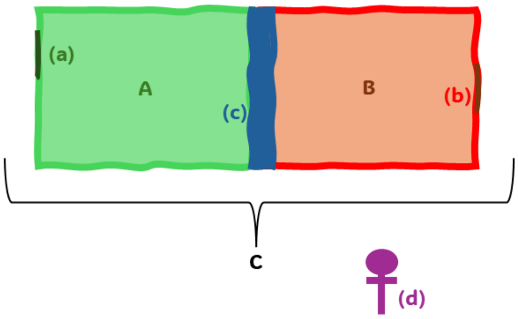

Figure 1. Schematic diagram illustrating the source (A), receiver (B), and couple assembly (C).

Figure 1 illustrates an arbitrary source- receiver assembly, where in this case the source 'A' is the ASHP, and the receiver 'B' is the frame attached to the roof. The responses (d) are remote accelerometers on other structural roof beams, and microphones in the loft space and the bedroom below the ASHP. The blocked forces are calculated by:

$$\dot{\bar{f}}_{A,c} = Y_{C,cc}^{-1} \dot{v}_{C,c} \quad (1)$$

Where $Y_{C,cc}^{-1}$ is an inverted matrix of mobilities, measured using a force hammer at the accelerometer positions on the frame. These excitations were made either side of the accelerometers and were averaged due to a lack of access for direct excitation. $\dot{v}_{C,c}$ is a vector of operational mobilities, measured when the source (in this case, a pair of shakers) is running, and is the transfer function between the shaker voltage and the acceleration measured at the frame accelerometers.
The predicted pressure is then given by:

$$\dot{P}_{C,d} = H_{C,db} \dot{\bar{F}}_{A,c} \quad (2)$$

In this paper, the transfer functions used for $H_{C,db}$ are referred to as H_{pf}, as they are the acoustic transfer function between the response and the hammer excitation, as pressure due to force. For the remote validation measurements, these are acceleration due to force, but for consistency the transfer function name remains the same.

3. METHODOLOGY

The experiment was conducted in Energy House 2.0, a climatic chamber at The University of Salford. The facility consists of two climatic chambers, which can produce a multitude of environmental conditions and temperatures. The HVAC system of the chamber was deactivated during the course of this measurement.

Figure 2: The Future Home at Salford University's Energy House 2.0

The ASHP is mounted in the loft space of a detached brick house, as shown in **Figure 2.** The roof frame where the ASHP attaches to the rafters was instrumented with 15 accelerometers; 5 on each of the 3 accessible sides, which are shown in **Figure 3** and **Figure 4**.

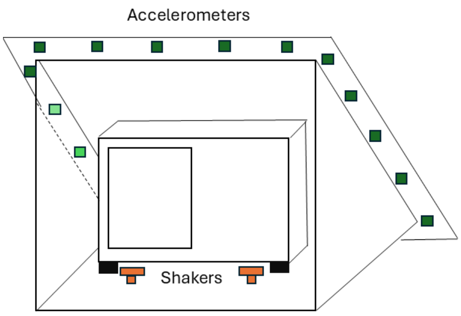

Figure 3. Diagram of ASHP in housing, with accelerometers and shakers shown.

Due to access limitations, only three sides of the frame were accessible for measurement. However, the rear side of the frame does not have a beam and does not appear to be rigidly connected to the ASHP housing.

Figure 4. Photograph of accelerometers

The ASHP was enclosed in plastic housing, with a hatch for access inside. The external roof above the ASHP had a large vent for airflow. Due to logistical restrictions, it was not possible to use the ASHP as an operational source during this measurement. Instead, two small shakers were mounted next to the connecting feet at the base of the ASHP inside the plastic casing, shown **in Figure 5.**

Figure 5. Photograph of one of the shakers

The shakers were measured in various operational combinations using both pink and white noise, and a voltage reference was taken from the supplying noise source. Two accelerometers were attached to struts in the loft space as remote validation points. These were vertical beams attached to the floor and ceiling, and not directly in contact with the ASHP housing. Three microphones were located in the loft space as illustrated in **Figure 6**.

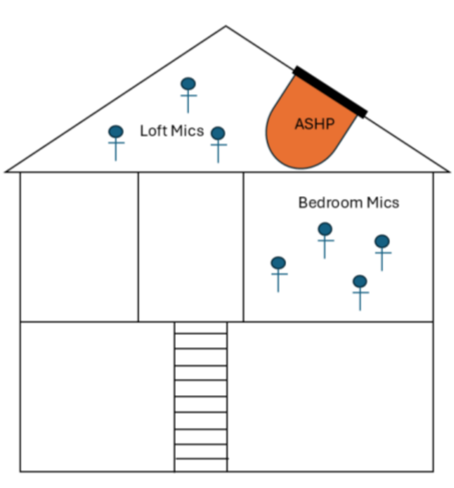

Figure 6. Diagram of microphone placement

A further four microphones were located in the bedroom immediately below the ASHP, as shown in **Figure 7**. These were located to the left side of the room near the window directly below the ASHP, in the centre of the room, at the right hand side of the room near the door, and at a position just above the pillow area of the bed.

Figure 7. Microphones in bedroom

A modal hammer was used to make excitations either side of the accelerometers and averaged using the finite difference approach to measure the Frequency Response Functions (FRFs) for the interface. A voltage reference was used to measure the shakers.

4. RESULTS

For the results presented here, both shakers were operational using a pink noise signal, as this most resembled the ASHP noise. Firstly, the raw data is shown in terms of Power Spectral Density (PSD) to establish that the signal is sufficiently above the background noise.

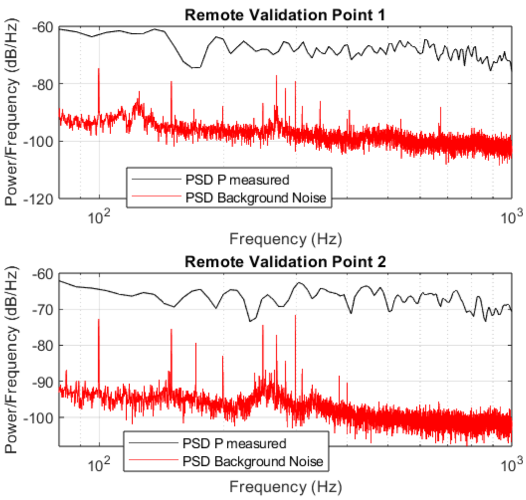

Figure 8. PSD of measured acceleration, in black, and background noise, in red, for remote validation points 1 and 2, from 80 Hz to 1kHz.

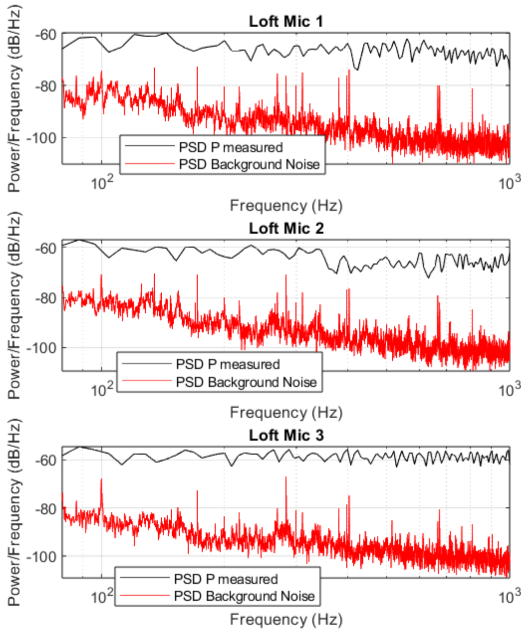

Figure 9. PSD of measured pressure in black, and background noise, in red, for loft microphones, from 80 Hz to 1kHz.

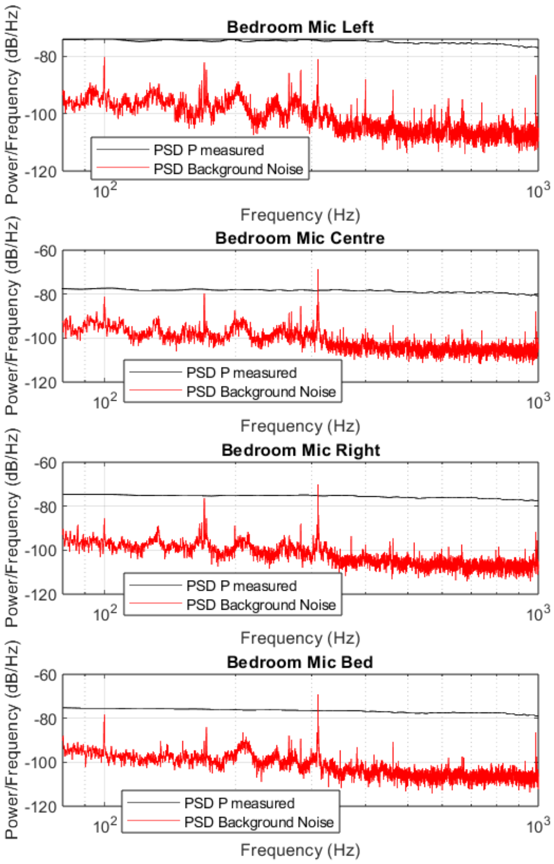

Figure 10. PSD of measured pressure in black, and background noise, in red, for bedroom microphones, from 80 Hz to 1kHz.

Seen in **Figure 10,** there are some erroneous peaks visible in the background noise spectra in three of the bedroom mics, at around 310Hz, which are a higher in magnitude than the measured as seen in **Figure 10**. This could be due to some interfering noise being present during the background noise recording, due to another system in the house such as ventilation, which was outside of operational control during the experiment. The measured signal is out of the noise floor for the remote validation accelerometers and the loft microphones at this frequency range, as seen in **Figure 8** and **Figure 9.**

Using Equations 1&2, predictions at the response positions due to excitation by both shakers are presented here.

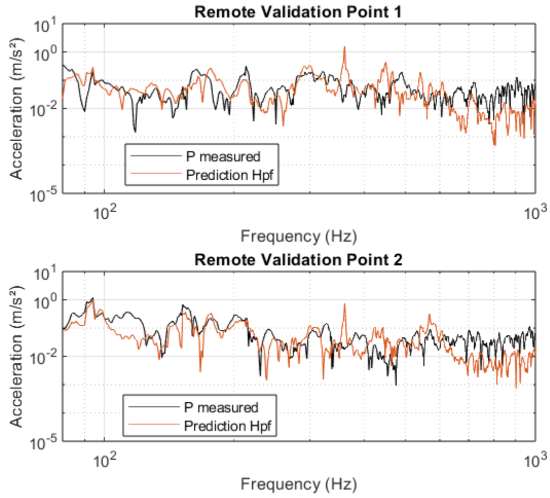

Figure 11. Predicted acceleration at remote validation points using the Hpf transfer function, compared to the measured acceleration, from 80 Hz to 1kHz.

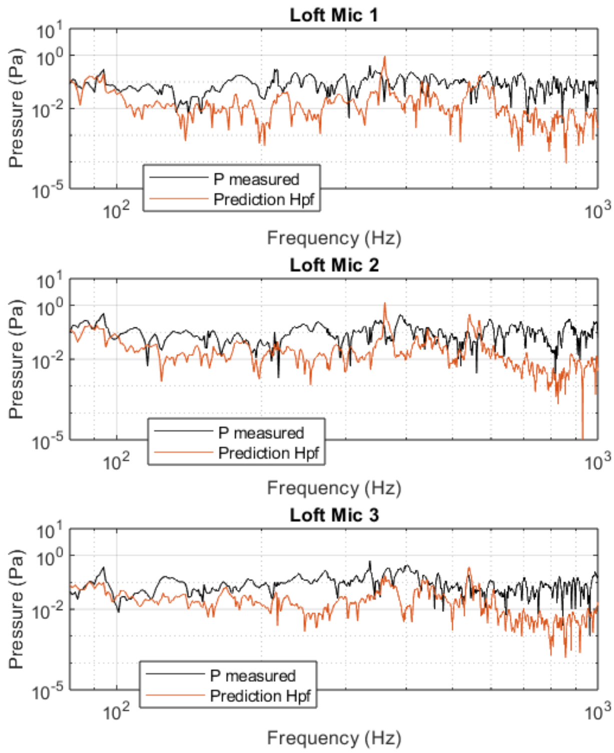

Figure 12. Predicted pressure at loft microphones using the Hpf transfer function, compared to the measured acceleration, from 80 Hz to 1kHz.

At the remote validation accelerometers, which were mounted on wooden roof struts in the loft room, there is relatively close agreement between the measurement and prediction across the measured frequency range, though both positions have an overprediction at around 361 Hz, as shown in **Figure 11.**

There is less overall agreement for the predictions to the loft microphone positions, shown in **Figure 12.** Again, an overprediction is seen at 361 Hz in Loft Mic 1 & 2, as with the remote validation sensors.

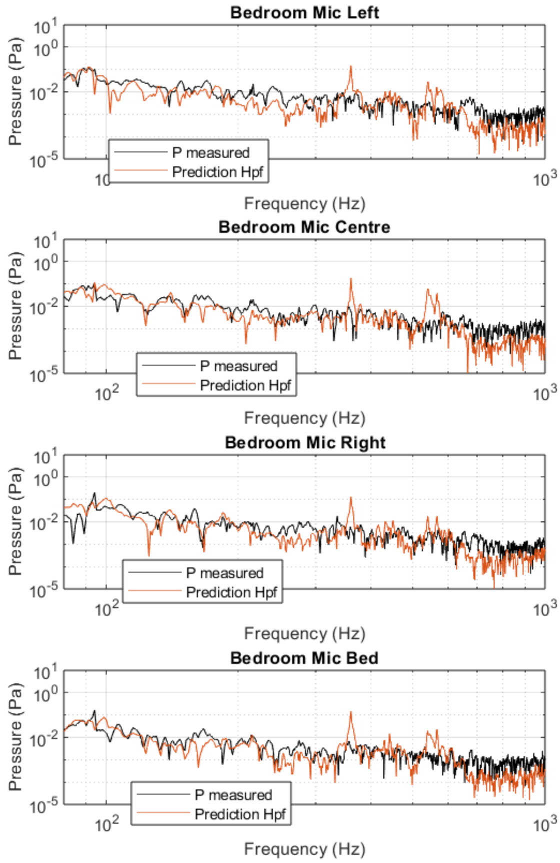

Figure 13. Predicted pressure at bedroom microphone using the Hpf transfer function, compared to the measured pressure, from 80 Hz to 1kHz.

As seen in the remote validation accelerometers and two of the loft microphones, the erroneous peak in the prediction is also present in the bedroom microphone predictions, seen in **Figure 13.**

5. DISCUSSION

The predictions have mixed accuracy. The remote validation accelerometers and the bedroom microphone predictions, both appear to have higher accuracy than the microphones in the loft. This may be due to the different frequency content of airborne and structural excitations within this frequency range. The loft space also has its own acoustic behaviour which may be contributory, and does not have the reassurance lent by laboratory conditions.

The results may be improved by refining the data, using methods such as singular value discarding, to remove noise. Although further analysis is required to be confident of the results, the blocked forces approach can be applied to the measurement of structure- and air-borne noise from a roof mounted ASHP.

6. CONCLUDING REMARKS AND FURTHER WORK

The in-situ TPA approach using blocked forces, which is commonly used in automotive engineering, has been used to evaluate vibroacoustic transfer paths in a home with a roof-mounted ASHP. Following this initial data analysis, there are further steps to be taken. Additional data measured using a volume velocity source will be used to make further blocked forces predictions, treating the entire loft room as the source. This may give clarity to some of the errors in predictions shown in this paper.

If logistics allow, it would be beneficial to repeat the measurement with the ASHP running, to provide verification that the dynamic behaviour and spectral content of the shakers is sufficient to emulate the operational state of the ASHP. Though every care was taken to reduce and mitigate interfering noise from other systems running in the house, any further experiments would take further steps to ensure minimal background noise from processes such as ventilation.

A further condition which may be desirable is to fully instrument around the aperture in which the ASHP hangs, as though the rear quarter of the frame does not appear to be coupled to the ASHP housing, it would be beneficial to ensure this and work towards a more complete interface characterisation.

7. ACKNOWLEDGMENTS

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