Applications of the in-situ Airborne Transfer Path Analysis (TPA) technique in the diagnosis of sound transmission paths of a building element

Nikhilesh PATIL; Andrew ELLIOTT; Andy MOORHOUSE
Acoustics Research Centre, University of Salford, Manchester, UK

ABSTRACT
For airborne sound transmission through building elements, the sound insulation of a building element is given by its Sound Reduction Index (SRI). SRI quantifies the overall sound transfer through the element but gives no information about how the transfer takes place and what are the contributions of different sound transfer paths involved. Here we investigate the use of Transfer Path Analysis (TPA) techniques, which are fairly common to the vehicle acoustics industry, to provide additional diagnostic information. This paper formulates an in-situ Airborne TPA technique based on blocked forces to quantify the contributions of different sound transfer paths to the transmitted pressure. The application has been tested on cavity backed single leaf and dual leaf partitions excited by airborne and structure borne sources. A simplification of the method is discussed by means of measuring airborne contact forces which may be used to diagnose airborne sound transmission through single leaf walls.

Keywords: Sound Reduction Index, Transfer Path Analysis, Blocked forces. I-INCE Classification of Subjects Numbers: 51.3, 51.4

1. INTRODUCTION
For building elements, airborne sound insulation, impact sound insulation and sound absorption can be measured by standard ISO tests which then rate the element by a single number quantity. In case of airborne sound insulation of building partitions, such single number rating obtained by ISO 10140 (1) is often not descriptive of the diagnostic properties of the sound transfer paths in the partition. Such diagnostic information can be important for stiffening elements in the partition such as ribs, point connections, isolators, etc. If the pressure contributed by these different paths is known, one can make suitable modifications at design stage to improve the resultant sound insulation of the partition in specific frequency regions or use this information to diagnose any sound transfer issues in-situ. Such diagnostic exercises have been nontraditional in building acoustics but they are fairly common to the vehicle acoustics industry at NVH (Noise, Vibration, and Harshness) refinement stage of the vehicle. For these purposes, TPA techniques are usually applied to calculate the source contributions to the sound in the vehicle interior and the noise sources can be acoustically ranked. For airborne sound transfer in building partitions, these TPA methods can instead be adapted to diagnose sound transfer paths in building partitions which could be ranked for their respective sound insulation. In the following section a TPA method is formulated for diagnosing airborne sound transmission through different sound transfer paths of a partition.

2. AIRBORNE TRANSFER PATH ANALYSIS
2.1 Blocked forces
In applying TPA method, at first the system is discretised into a source-path-receiver model where the source is the active component of the system exciting the receiver. The next step involves measuring the Frequency Response Functions (FRF’s) at the source receiver interface when the source is inactive. In-situ approaches (2, 3) also known as iTPA have been fairly common now so that source is not required to be separated for FRF measurements. The active test is the operational phase where the source excites the system and operational responses are measured. In iTPA, the
blocked forces are then found as per equation (1).

\[ f_{bt} = [A]^{-1}a' \]  \hspace{1cm} (1)

In equation (1), ‘A’ is the accelerance matrix formed from FRF measurements, and \( a' \) is the operational acceleration vector; capital letters denote a matrix and lower case letters a vector. In the case of an airborne sound transmission, the air is effectively the source which results in continuum of transfer paths on the partition. With careful sampling assumptions, the incident wavefield can then be approximated by discrete blocked forces on discrete square paths shown in Figure 1.

![Figure 1 – Approximating incident wavefield (left, blue) with discrete blocked forces (right, blue)](image)

2.2 Path contributions by TPA

Once the blocked forces are found, they can be combined with the path FRF’s to determine the path contributions as well as predict the final pressure in a receiver cavity if all the paths are characterised. Other approaches make use of acoustic FRF (pressure to volume velocity) to represent the source can be found in literature (4, 5), such as ‘Panel Contribution Analysis’ or ‘Source Path Contribution Analysis’, but this method differs because the structure borne TPA, or rather iTPA is used to analyse the transfer of airborne noise through a partition. This Airborne TPA method was tested on a cavity backed plate where the plate represents a single leaf partition. The schematic of the experiment is shown in Figure 2.

![Figure 2 – Phase 1-Passive test (left), Phase 2-Operational test (right)](image)

With impact testing, the accelerance for the partition and vibroacoustic FRF’s from the paths to receiver points inside the cavity are measured. In the second phase, operational measurements of accelerations over the plate and pressures inside the cavity are measured. After finding the blocked forces over the plate, they can be used with the vibroacoustic transfer functions to predict the pressures inside the cavity and their individual path contributions.

2.3 Pressure validation test: setup & measurements

There are two important assumptions in this experiment: first, that an incident airborne wavefield can be decomposed into discrete blocked forces over the plate and secondly, that the sound transfer is dominant through the plate and minimal through the walls of the box. If these assumptions hold true, then the total pressure contributions from the plate to the cavity should be almost equal to the pressure measured inside the cavity. This serves as a good criterion to test the methodology of this in-situ TPA technique. The wooden box representing the cavity (79x79x82 cm³) and the plate on top representing a plate backed cavity is shown in Figure 3. Silicone sealant was used between the plate and box edges to minimize any flanking transmission from the walls to the plate. However some structure borne and/or airborne flanking could be expected, especially at low frequencies, through
the walls of the box.

![Figure 3 – Test setup- the wooden box cavity (left), Perspex plate assembled with the box (right)](image)

Accelerometers were placed over the plate surface and Type MCE 212 (free field) microphones were used inside the box. With impact testing on the plate, the FRF measurements yield an accelerance matrix as,

\[
[A_{ij}] = \begin{bmatrix}
\frac{a_1}{f_1} & \cdots & \frac{a_i}{f_j} \\
\vdots & \ddots & \vdots \\
\frac{a_i}{f_1} & \cdots & \frac{a_i}{f_f}
\end{bmatrix}
\] (2)

‘\(A_{ij}\)’ represents the FRF matrix with transfer functions (a/f). ‘a’ is the acceleration and ‘f’ is the impact force applied at each point in turn, ‘i’ are the response points and ‘j’ the excitation points. Simultaneously the vibroacoustic FRF’s were measured for the forces on the plate and pressures inside the box with the help of pressure microphones.

\[
[H_{kj}] = \begin{bmatrix}
\frac{p_1}{f_i} & \cdots & \frac{p_i}{f_j} \\
\vdots & \ddots & \vdots \\
\frac{p_k}{f_i} & \cdots & \frac{p_k}{f_f}
\end{bmatrix}
\] (3)

\(H_{kj}\) represents the vibroacoustic FRF matrix with transfer functions (p/f). ‘p’ is the pressure at a point inside the cavity and ‘f’ is the impact force over the plate, ‘k’ is the number of pressure points.

A loudspeaker with pink noise excitation acts as an airborne sound source which excites the plate, which in turn excites the cavity. The operational accelerations and pressures were measured with respect to the driving voltage of the noise generator which ensures that the signals are synchronous. With the operational accelerations over the plate, the blocked forces are calculated as

\[
f_{bl} = [A_{ij}]^{-1} a_i'
\] (4)

‘\(f_{bl}\)’ represent the blocked forces over the plate and ‘a’” the operational accelerations. These blocked forces map the sound field on the plate by using vibration responses instead of pressure responses. The pressure inside the box can thus be predicted as

\[
p_p = [H_{kj}]f_{bl}
\] (5)

‘\(p_p\)’ is the pressure predicted at microphone positions inside the cavity. These predicted pressures were then compared with the operational pressures at same positions to check the validity of the applied TPA method. The pressure contributions ‘\(p_c\)’ of a path ‘n’ can then be calculated as

\[
p_{cn} = H_n f_{bln}
\] (6)

### 2.3.1 Pressure Validation Results

For the single plate backed cavity experiment, accelerometer grids of 4x4 and 8x8 (yielding 16x16 and 64x64 accelerance matrix sizes respectively) were used. From the methodology outlined in section 2.3, the prediction of sound transmitted through the partition inside the cavity was compared with the measured cavity pressure. It was initially found by Patil (6) that the matching between this prediction and measurement is valid for wide frequency range as the grid size is made finer. Results in Figure 4 show the pressure validation for an 8x8 grid.

The top plot in Figure 4 shows the narrow band matching while the bottom plot shows the matching of the one third octave band averaged results. The results look convincing and verify the TPA methodology up to 1 kHz except the difference in 80-120 Hz region which might be attributed to the sound transmission through the walls at low frequencies as mentioned earlier. Once this methodology was validated, it could be applied to diagnose the sound pressure contributions of a complex partition as shown in the following section.
3. APPLICATION OF AIRBORNE TPA TO A POINT CONNECTED PARTITION

3.1 Dual leaf construction

Having verified the TPA approach by the cavity backed plate experiments, the approach was then applied in the diagnosis of sound transfer paths of a point connected partition subject to structure borne and airborne excitation separately. Figure 5 shows the point connected partition with mineral wool infill installed on top of the box.

![Point connected partition](image)

Figure 5 – Point connected partition (left) fitted with the box (right)

The point connection represents a sound bridge for sound transmission between the top plate and bottom plate. As such, the point connection could provide higher sound transmission at some mid/high frequency region which is also reported by Hongisto (7). Therefore with the application of Airborne TPA, the sound pressure contribution of the point contribution can be quantified and ranked with respect to the contributions of other paths. Following the TPA approach outlined in section 2, the accelerances and vibroacoustic transfer functions were measured over discrete locations on the top plate and pressure positions inside the cavity respectively.

3.2 Structure borne excitation case

For structure borne excitation case, a shaker was used on the top plate driven with pink noise. The shaker excitation was applied at a different location than the point connection location. Using equations (2-5), the pressure validation is done which is shown in Figure 6. The results appear satisfactory in the given frequency range from 200 Hz to 1 kHz. For the structure borne excitation described above, only one external point force acts on the top plate through the shaker and accordingly the blocked force at the shaker position is dominant (see Figure 7). Interestingly, it can...
also be seen that the blocked forces on rest of the plate are not zero in spite of the external forces being zero there. As the accelerance and operational accelerations are not zero, the blocked forces obtained as per equation (4) will have some finite value.

![Figure 6 – Pressure validation results for point connected partition with structure borne excitation](image)

This presents an interesting potential of the blocked force technique in identifying the source location. As the inputs (accelerance and operational accelerations) are obtained purely from measurements, this technique may offer a better alternative for source localisation than other approaches which use computational methods reported by Pezerat (8).

![Figure 7 – Blocked forces (top) and sound pressure contributions (bottom) for different paths on the top plate](image)

The sound pressure contributions for different paths in Figure 7 show that the shaker path contribution (the path where the shaker is attached to the plate) is highest till 1 kHz. This is expected as the blocked force at shaker position is considerably higher as discussed above. The point connection path contribution increases with frequency and is the second most dominant path above 800 Hz. However that is not the case with the blocked force there. So even if the blocked force is not ranked similarly, its path contribution is still dominant. Following the trend, the point connection may become the most dominant path at higher frequencies above 1 kHz and a finer grid size could be used to investigate and improve the method.

### 3.3 Airborne excitation case

For this case, the dual leaf partition was installed with a solid plasterboard structure in the reverberation chambers at Uni. of Salford. The plasterboard structure consists of stacks of
plasterboard sheets lined on top of each other to fill the cavity between the main brick aperture and dual leaf partition. A facing wall was then applied from both sides on to the plasterboard stacks. The final construction is shown below in Figure 8. A loudspeaker driven by white noise in the source room was used which simulates the airborne excitation.

![Figure 8](image)

Figure 8 – The dual leaf partition (grey) installed in a plasterboard structure with the facing wall (blue)

On applying the pressure validation methodology outlined in section 3, it was observed that the predicted pressure was lower than the measured pressure, 4–5 dB lower in most frequency regions (Figure 9). Two reasons were considered for this mismatching—either there are inversion errors in the calculation of blocked forces or there is considerable flanking through the plasterboard structure which shows up as the higher measured pressure. The first reason was dispelled because the accelerance matrix showed good reciprocity. The operational data was referenced to the excitation voltage to prevent any phase mismatching between different measurement sessions. Flanking can be considered as a reason for the mismatching as the facing wall is connected to the frame of the dual leaf partition and could provide some structure borne flanking. Also some airborne flanking could be expected at low frequencies through the solid plasterboard construction.

![Figure 9](image)

Figure 9 – Pressure validation for airborne excitation case, narrow band (top plot) and third octave band (bottom plot)

It should be noted that a mismatch in pressure validation does not imply that the Airborne TPA is wrong, provided the FRF and operational measurements are correct. It simply means that there may be additional flanking sources which contribute to the increase in pressure at the receiver point. In the current case, as the FRF measurements are correct, the sound pressure contributions are valid and can be used to rank the sound transfer paths. Using equation (6), the sound pressure
contributions of each path was calculated which are shown in Figure 10.

![Graph showing sound pressure contributions](image)

Figure 10 – Sound pressure contribution of different paths on the partition plotted in narrow band (top plot) and third octave band (bottom plot).

From Figure 10, it can be seen that the point connection’s contribution is higher after 300 Hz and increases steadily compared to other paths. In this way, the point connection could be ranked as a weak path for sound insulation as compared to other paths. This shows the true potential of the Airborne TPA method where one can quantify the sound pressure contributions of individual paths on the partition as well as rank them. Further investigations are being carried out to obtain a perfect pressure validation for the partition.

4. AIRBORNE CONTACT FORCES

4.1 Blocked forces and pressure field around the partition

For Airborne TPA, the frequency range of application is closely tied to the number of measurement point or in other words, the number of blocked forces considered. If the dimensions of the path considered are less than quarter trace wavelength of the incoming wave on the partition, then the incident pressure field can be assumed constant over the area. Thus the excitation on that path can simply be represented by a single blocked force. Likewise, from this wavelength the frequency range of the blocked force assumption can theoretically be deduced.

Due to the nature of airborne excitation which is continuous over the partition surface, a number of transfer paths exist leading to a number of measurement positions over the partition surface. Additionally at higher frequencies, the wavelength becomes small which calls for more number of measurement positions for the Airborne TPA to be valid. Thus the measurement of the acclerance matrix and the ensuing blocked forces can be quite tedious. As the blocked forces are a source quantity, one can look for direct measurement of these forces. For structure borne sources this is often not feasible as access to the source receiver interface is limited. For airborne excitations, this interface is accessible as air is effectively the source. The air applies a sound pressure on to the partition (receiver) which can simply be measured by microphones. Therefore, if the net pressure excitation on the partition can be measured then the blocked forces could be theoretically calculated by multiplying the net pressure with the path area.

As the solid partition is excited into bending vibration, the equation of motion for the partition can be written as,

\[ Z_p v_p = p_s - p_r \]  

\[  \text{(7)} \]

‘\( Z_p \)’ and ‘\( v_p \)’ are the impedance and the velocity of the partition respectively. The right hand side of the equation represents the source quantity; ‘\( p_s \)’ and ‘\( p_r \)’ are the source side and receiver pressures acting on the partition. Therefore in general, the net pressure or the net force acting on the partition is related to the pressure difference around the partition. Hence the blocked force which is also the source quantity should be directly measurable if this pressure difference can be measured.
Measuring the contact pressures on both sides of a partition path and multiplying it with the path area should then give the blocked force. This contact pressure is also been referred to as the blocked pressure by Bobrovitskii (9) but an experimental validation wasn’t provided.

4.2 Measurement of contact forces

To check if the blocked pressures (blocked force/path area) are equal to the net contact pressure on the partition, Airborne TPA was first applied on a single unbaffled plate excited by airborne excitation. The plate is shown in Figure 11.

Figure 10 – Unbaffled plate used to validate contact pressure with blocked forces, areas with red boundaries constitute a sound transfer path on the plate

For the application of Airborne TPA, the accelerances on the plate were measured. For operational measurements, a loudspeaker driven by pink noise simulated the airborne excitation on the plate. Using equation (1), the blocked forces on the plate were measured. The net contact pressure was also measured with microphones as a difference of pressure above and below three randomly chosen paths on the plate. This contact pressure was compared to the measured blocked forces divided by the path area. The results are shown in Figure 11 and Figure 12.

Figure 11 – Narrow band comparison of blocked pressure and contact pressure over three paths

Figure 12 – One-third octave band comparison of blocked pressure and contact pressure over three paths
The results show that the contact pressure matches very well with the blocked pressures. The reasons for the small discrepancy being that there may be inversion errors in the blocked force calculation, and also different calibration of microphones and impact hammer as both contribute to measuring the force or pressure. A second validity check was applied in the form of on-board validation. In an on-board validation, the contact forces are used to predict a known quantity (operational acceleration at point ‘n’ due to ‘i’ measured contact forces ‘f_c’) using equation (8).

\[ a_n = \sum A_i f_c \]  
(7)

The predicted acceleration was then compared to the measured acceleration and the results are shown in Figure 13.

Figure 13 – On-board validation showing comparison of measured and predicted acceleration by contact forces in narrow band (top plot) and third octave band (bottom plot)

Figure 13 shows that the response of the plate can be well defined by using contact pressures. Thus directly measured contact pressure can be substituted for blocked pressures while applying Airborne TPA, provided that the source side and receiver side interface are accessible for the contact pressure measurement. This is usually the case for single leaf partitions however for multilayered partitions only one side of the first leaf is accessible while its other side is usually hidden in the cavity which is physically not accessible during measurements. Therefore currently contact forces Airborne TPA is currently limited in application to single leaf partitions and more investigations are needed for devising its application on multilayered partitions.

5. CONCLUSIONS

A novel application of TPA has been developed and tested for diagnosis of airborne sound transfer through building partitions. With this method, the incident airborne wavefield (source) can be mapped onto the partition (receiver) using blocked forces, which are then used for predicting the sound transfer through the partition inside a cavity according to section 2. A pressure validation has been successfully investigated for single leaf and dual leaf partition to validate the TPA methodology and the blocked forces. With finer sampling of blocked forces or finer grid size, the TPA method can be applicable in a wide frequency range.

In the case of dual leaf partition excited by a structure borne excitation, the blocked force at the structure borne source path is found considerably higher compared to other paths which show an interesting potential of the blocked forces in localising a structure borne source. For airborne sound transmission through dual leaf partition, a pressure validation allows to investigate if the partition under test is overall a dominant element of sound transfer compared to flanking transmission. Provided that the measured FRF and operational data is correct and phase matched, the sound pressure contributions of each path are a valid measure of ranking the paths for sound insulation, and not invalidated in presence of flanking. These point connected partition example displays the potential of the TPA technique in diagnosing airborne sound insulation paths of a partition by quantifying the path’s sound pressure contributions.
As the Airborne TPA method involves significant measurement time, the method can be simplified by measuring the contact forces instead of measuring the blocked forces. For airborne sound transmission through single panels, contact forces Airborne TPA is faster. This method however is currently limited to diagnosing sound transmission through single panels and investigated further for applications on to multilayered partitions.

REFERENCES