Passive Noise Attenuation Methods for Apartments

Glenn Leembruggen FIOA (1) and Joel Parry-Jones (2)

(1) Acoustic Directions, Sydney Australia
(2) PKA Acoustic Consulting, Sydney Australia

Abstract - The NSW Apartment Design Guide mandates that a percentage of apartments in a development have natural cross ventilation. In areas near busy roads, the need to provide this ventilation whilst maintaining low internal noise levels from the ingress of traffic noise provides a difficult challenge for acoustic engineers.

The authors recently undertook a detailed investigation for the City of Sydney into the attenuations that can be achieved with a range of passive devices that can allow natural ventilation in apartments.

For the attenuation methods in which wave acoustics were dominant, attenuation predications were made using finite element analysis, while in the remaining situations, sophisticated ray-tracing software was used. Among the attenuation devices explored were i) balcony areas with varying sound absorption linings and lined-ventilation ducts fed from these balconies, ii) louvred apertures with absorption, iii) open wintergardens, iv) gradual setbacks of balconies, v) shielding structures and vi) open windows into various sized apartments. The attenuations produced by these method can be combined (with appropriate conversions to sound power) to develop a net outside-to-inside attenuation of sound pressure level.

The project won the H. Vivian Taylor Award for excellence from the Association of Australasian Acoustical Consultants in 2021.

1 INTRODUCTION

Acoustic consultants Acoustic Directions and PKA Acoustic Consulting working in association recently undertook a project for the City of Sydney Council to investigate passive attenuation techniques that can produce low internal noise levels inside apartments in suburban/urban areas when openings are provided to allow natural and natural cross-flow ventilation.

An extensive literature search was initially conducted with some eighty journal papers being examined. Unfortunately, these papers were not directly useful for our work for the following reasons:

- the methods were not deemed practical given the current Australian marketplace
- results presented were based on the total A-weighted level and lacked spectral information
- frequency range of the analysis was not sufficiently extended to cover the traffic spectrum
- papers were academic in nature with little guidance for developing engineering solutions
- insufficient ventilation area to be of use
- insufficient information to use in a design context

Given the outcomes of this literature search, it was apparent that we needed to develop attenuation methods using a first-principles approach that ultimately would yield attenuation data that was both comprehensive and straightforward to use.

Based on the NSW Interim Guideline for Busy Roads, the overarching acoustic requirements are to ensure that:

- The L_{Aeq} noise levels do not exceed 35 dBA in bedrooms (9 hr night) and 40 dBA (15 hr day) in all other habitable rooms with windows closed and alternate opening(s) providing natural ventilation airflow

- The L_{Aeq} noise levels do not exceed 45 dBA in bedrooms (9 hr night) and 50 dBA (15 hr day) in all other habitable rooms with windows open providing natural ventilation airflow.

2 VENTILATION REQUIREMENTS

A report by Flux Consultants for the City of Sydney recommends the minimum open areas for ventilation shown in Table 1.

Table 1. Minimum Open Area (m²) per façade for standard-size apartments

Natural Ventilation Type		Number of Noise Impacted Facades	Required Area per Façade (m²)			
			One Bedroom	Two Bedroom	Three Bedroom	Four Bedroom
Cross-though		One	0.17	0.25	0.33	0.42
		Per habitable room	0.17	0.125	0.11	0.1
		Two	0.21	0.31	0.41	0.52
Non cross though	Corner	One	0.38	0.57	0.77	0.96
		Two	0.40	0.61	0.81	1.01
	Single sided	One	0.60	0.90	1.20	1.50
Non cross though	Single sided	Per habitable room	0.60	0.45	0.40	0.38

3 ATTENUATION TECHNIQUES EXAMINED

We assessed the attenuations produced by twelve types of techniques which are shown in Table 2. The attenuations can be grouped into four acoustical categories according to whether the inputs and outputs are sound pressure (SPL) or sound power (SWL). Seven of these techniques are described in this paper.

*Table 2 – Attenuation methods examined. (** ND not described in this paper | ^see complete paper*)*

Method No.	Description	Acoustical Category	Section in this Paper
1	Building siting— example of reflections causing an increase in level within a notionally shielded courtyard.	facade SPL to SPL	5.1
2	Building siting—opening in façade at 90º to the street with the noise source.	facade SPL to SPL	ND*
3	Using a balcony with sound absorption to provide attenuation of noise to an opening at the rear of the balcony.	facade SPL to SPL	5.2
4	Ducts lined with insulation.	facade SPL to SWL	5.3
5	Incorporation of acoustically lined duct between the balcony opening and the room behind.	facade SPL to SWL	5.4
6	Lined external recess with internal louvre opening	façade SPL to SWL	^
7	Wintergarden with an internal opening	facade SPL to SWL	^
8	Downturns above balconies	facade SPL to SPL	ND
9	Horizontal and vertical fin-like projections beside windows	facade SPL to SPL	^
10	Increasing façade height	facade SPL to SPL	ND*
11	Setback of apartment facades	facade SPL to SPL	ND*
12	Rooms with openings (windows or ducts)	facade SPL to SPL SWL to in-room SPL	^

4 PREDICTION METHODS

Predictions of the attenuations provided by a range of methods were undertaken using virtual ray-tracing and finite element modelling for the frequency range 63 Hz to 8 kHz.

4.1 Ray Tracing

For the situations that were more straightforward in acoustic terms, acoustic modelling was undertaken using the ray tracing software ODEON (https://odeon.dk). This software is a world leader in the acoustic simulation of interior and short-distance outdoor areas. ODEON uses the image-source method combined with a modified ray tracing algorithm. Theoretical models for single and double diffraction around structures are included in Odeon (Rindel J.H., 2009).

In the ODEON models, approximately 250,000 sound rays are emitted from the source, which are diffracted and reflected from various surfaces according to their sound absorption properties, and eventually arrive at the receiver point where they are gathered. A map of the distribution of sound pressure level over a grid of receivers is produced, along with the levels at a nominated set of receiver points. Fifty point-sources were used to simulate a line of traffic on the road beside an apartment block

4.2 Finite and Boundary Element Methods

For situations involving the sound being transmitted through openings and ducts with dimensions that are small relative to a wavelength, analysis was undertaken using PAFEC vibroacoustic software (http://pafec.eu) which implements the finite element (FEM) and boundary element (BEM) methods. The use of FEM/BEM provides accurate modelling of ducts, openings and balconies in which the dimensions are smaller or commensurate with the wavelength of low and mid frequencies. Factors which are accurately modelled by FEM include the end-reflections from ducts and resonance modes in the balcony, duct and receiving room.

FEM and BEM work by dividing a relatively complicated acoustic situation into a large number (thousands to hundreds of thousands) of finite mesh elements, such as little cubes. Mathematical equations then predict the behaviour of each element, and the algorithm sums the individual behaviours to compute the overall behaviour of the situation. Figure 1 shows an example of the mesh structure of a lined duct connecting a balcony to a room.

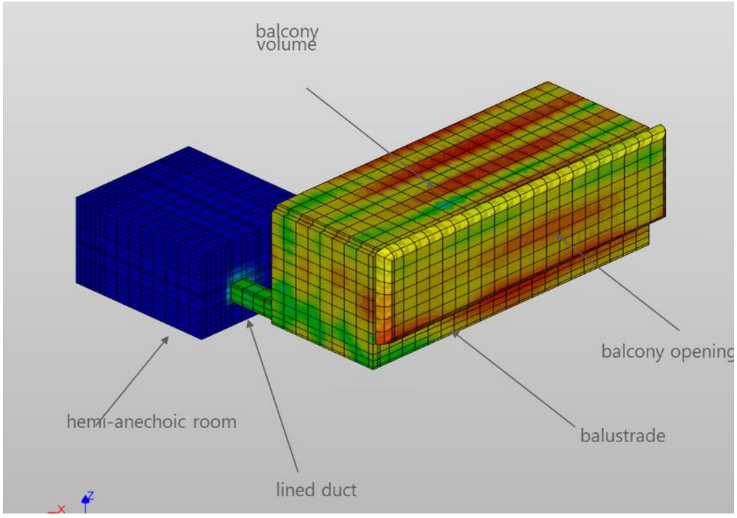


Figure 1. Example of a FEM model of lined duct connecting the balcony to the room showing the mesh structure.

5 ATTENUATION RESULTS

5.1 Building Siting

Figure 2 shows three examples of how the siting of buildings can exacerbate or attenuate noise from traffic that is incident on building facades. The noise irradiated onto the facades of the building complex at the lower left of Figure 2 was modelled in Odeon with a line source of vehicles on the street. Figure 3 shows the mapped SPLs at

500 Hz on the facades of the rooms facing the traffic and courtyard. The average SPL on each façade is stated. The attenuations of the direct field of the traffic noise produce by shielding are degraded by reflections within the semi-enclosed courtyard.

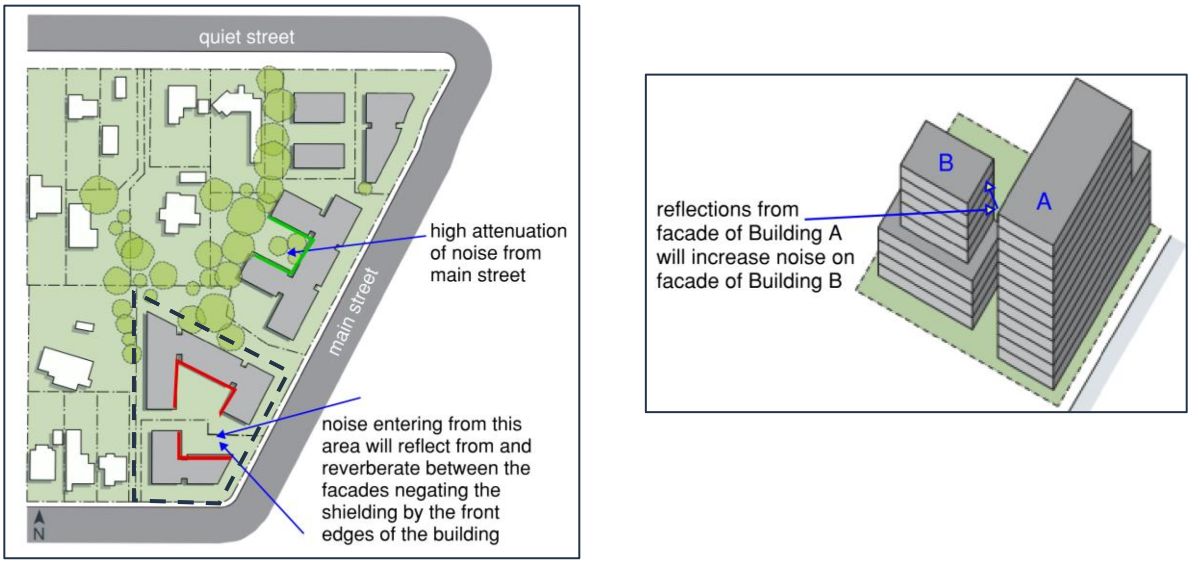


Figure 2. Examples building siting issues.

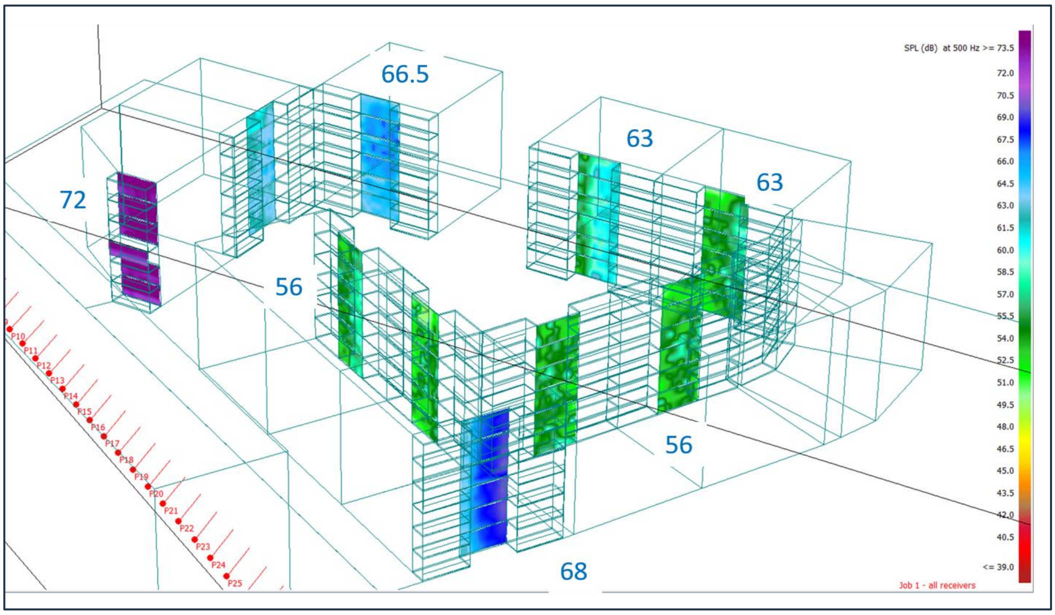


Figure 3. Mapped SPLs at 500 Hz on the facades of the rooms facing the traffic and courtyard. The average SPL on each façade is stated.

5.2 Balconies

Four attenuation techniques were investigated for apartments with balconies using FEM and ray-tracing. The reference condition is the acoustic shielding provided by a solid balustrade only, but as this attenuation is degraded by reflections within the balcony, sound absorption is required within the balcony to reduce the reflected sound energy.

Figure 4 shows dimensional plan details of the balcony in relation to the road and building opposite. The following parameters were used in the FEM model.

- Floor-to-soffit height of 2.7 m.
- Width of the balcony is 6.0 m.
- Balcony depth of 2.2 m.
- The balustrade is assumed to be continuous from side wall to side wall with height of 850 mm

- Front of building is 10.7 m from the noise source (line source of traffic on the closest lane).
- Traffic modelled as a 25 m long line array of point-sources at 100 mm intervals
- Reflections of traffic noise in the road are modelled as image sources with strength equivalent to an absorption co-efficient of 0.15.
- The building opposite (shown as the purple rectangle in Figure 4), being 24 m from the balustrade, has reflections modelled as an image source at twice the distance from the road with strength equivalent to an absorption co-efficient of 0.15.

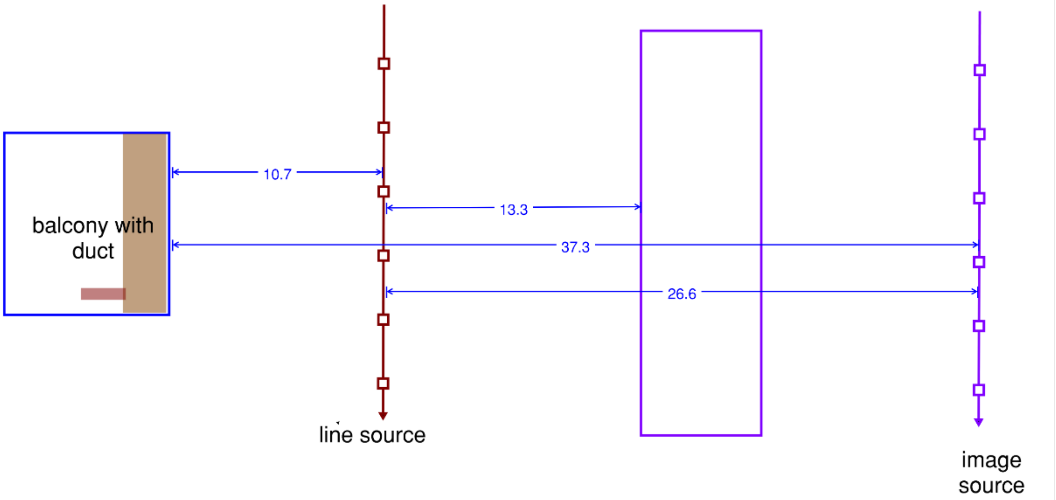


Figure 4. Dimensional details of balcony system modelled with PAFEC.

Four techniques labelled as B to E are created and use a cumulative combination of barrier shielding and sound absorption are listed in Table 3. The attenuations occurring on the façade in the centre of the balcony behind the balustrade are shown in each octave band for two positions; Figure 5 shows the attenuations in SPL above the balustrade height while Figure 6 shows those at the position of a vent located at floor level. In each figure, the attenuations are given for levels on the apartment buildings spanning the ground floor to Level 5 and are relative to the SPLs incident on the façade without a balcony at each height. The building reflections (Opp Bldg) have been included to simulate an urban apartment scenario. Note that negative values denote amplifications.

Table 3. Attenuation techniques B to E using shielding and absorption within the balcony

Technique	Combination			
	B	C	D	E
Attenuation from solid balustrade	❖	❖	❖	❖
100 mm thick insulation on the balcony soffit		❖	❖	❖
100 mm thick insulation on the left-hand balcony wall (as viewed from the street)			❖	❖
100 mm thick insulation on inner face of balustrade				❖

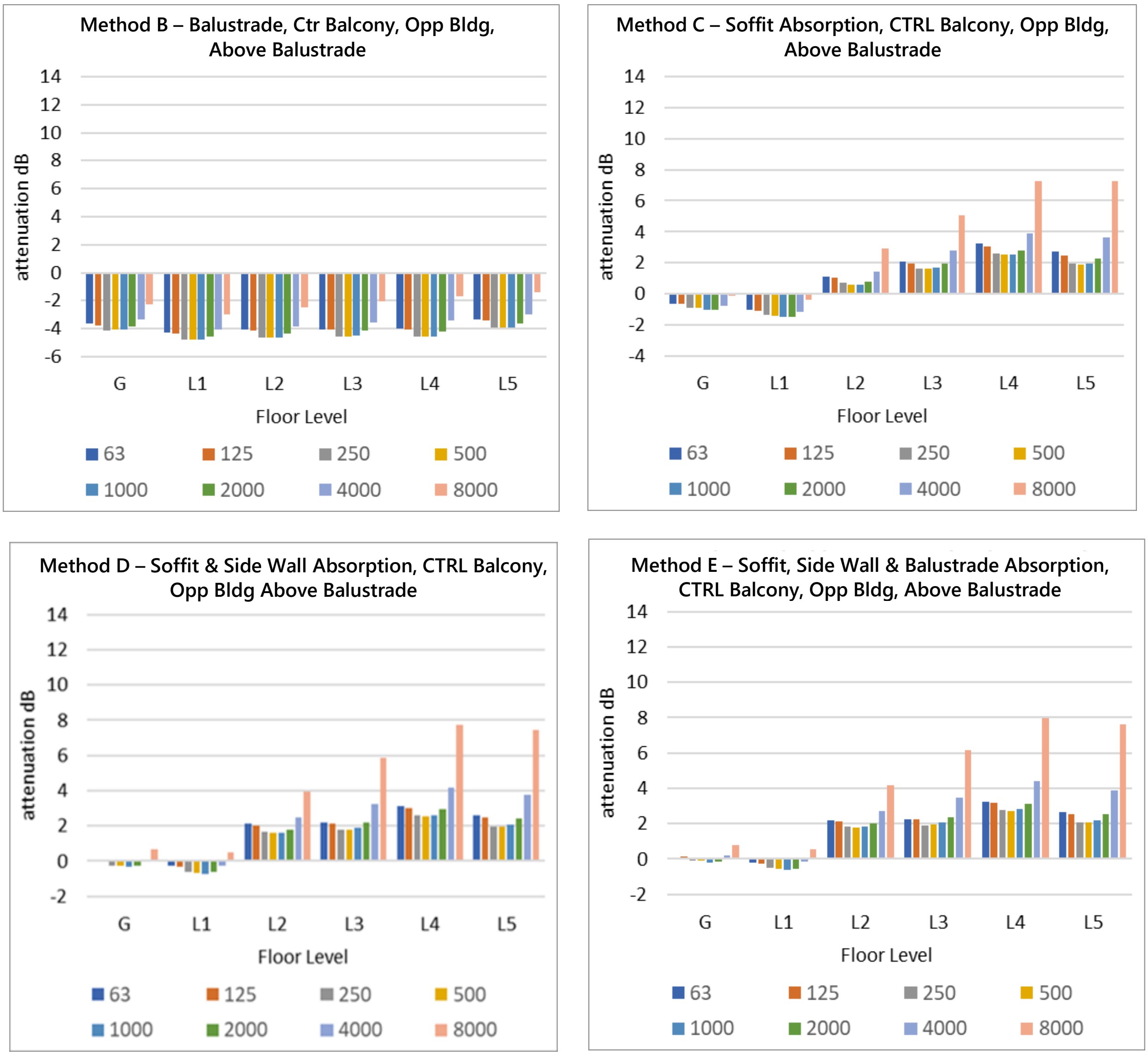
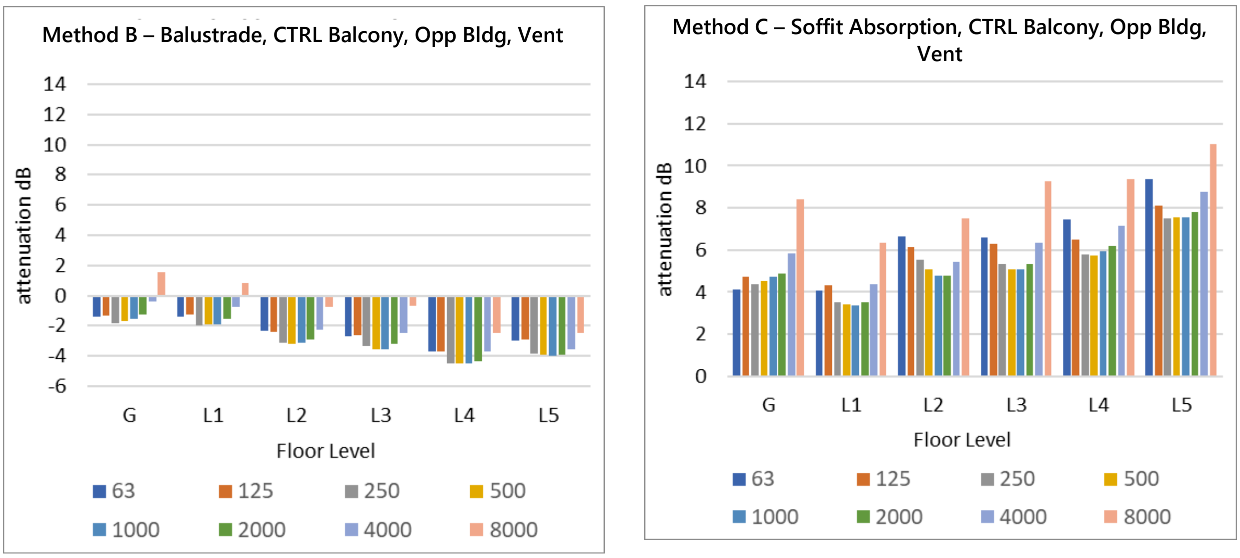


Figure 5. Attenuations (SPL to SPL) produced by Methods B to E on the facade above the balustrade.



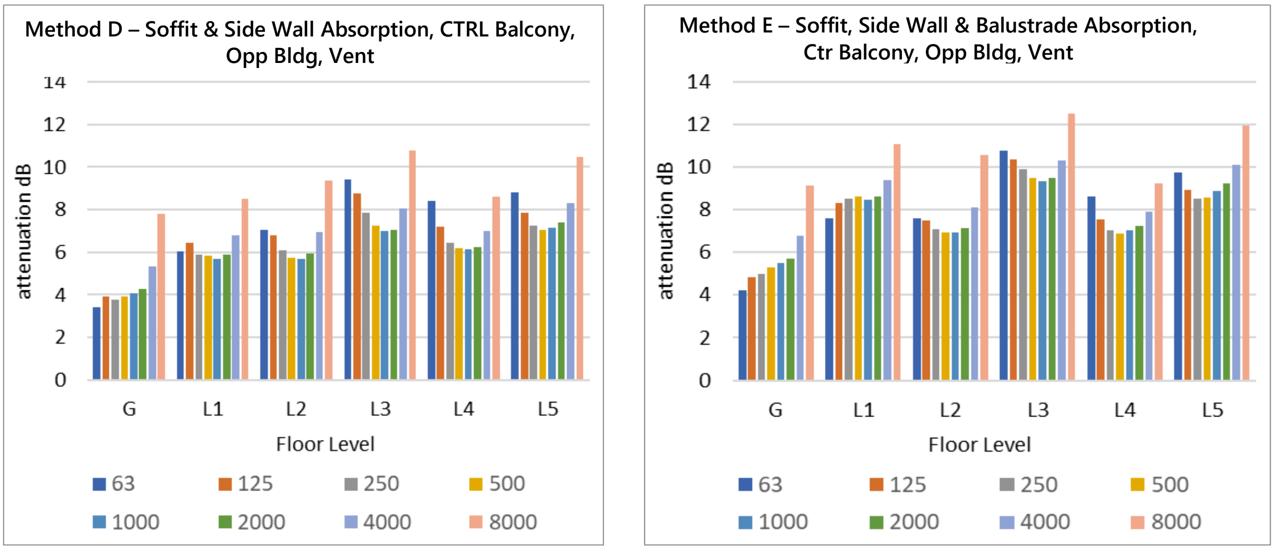


Figure 6. Attenuations (SPL to SPL) produced by Methods B to E at height of vent above the balcony floor.

The following trends are clear from the results:

- In the untreated balcony, despite the presence of the solid balustrade acting as an acoustic barrier, reverberation inn the balcony area amplifies the noise.
- The solid balustrade reduces the levels in the region near the balcony floor compared to the region above the balustrade.
- At frequencies between 125 Hz and 4 kHz, the use of sound absorption on the balcony soffit provides between 6 dB and 10 dB reduction in noise level near the floor compared to no absorption.
- The presence of absorption on one side wall and the front of the balustrade yields further attenuation, but as expected, the increase in attenuation is not as high as with the introduction of soffit absorption into the bare balcony.

5.3 Lined Ducts

5.3.1 PAFEC Modelling from 63 Hz to 700 Hz

Figure 7 shows the meshed structure used to compute the attenuation of a combination of line ducts. D1 to D4 indicate the four lined ducts used in the model.

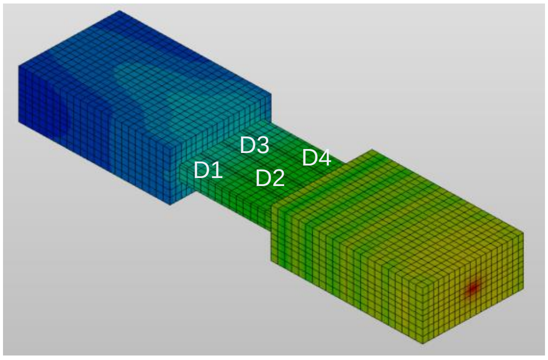


Figure 7. Meshed structure used to compute the attenuation of a combination of line ducts

Salient parameters in the FEM model to predict the attenuation in combinations of ducts are as follows:

a) To maintain a relatively-constant sound field across the face of the ducts, a point source located at 3 m from the duct wall was used. The input SPL is the free-field level that would strike the wall at the duct entry if the wall were not present. It is noted that the nominal level at the surface of the duct-entry wall is 6 dB higher than the free-field level, due to boundary reflection of the incoming sound wave.

b) Ducts are 1 m and 2 m long and 400 mm wide and 300 mm high. Ducts are lined on all sides with 50 mm thick insulation with a flow resistivity of 8,300 Rayls/m producing a free airway of 300 mm x 200 mm.

c) Ducts are stacked side by side with the short (200 mm) dimensions touching.

d) The complex acoustic impedance of the insulation was modelled using the Allard-Champoux formulation with 50 mm insulation on each side of the duct.

e) Ducts start and end in a large wall that is 100% reflective. i.e., each end of the duct is located in a hemi-anechoic environment (aka half space environment).

f) The actual SPL at the duct entry is produced by a complex set of interactions associated with i) reflections from each end of the duct, ii) standing waves inside the ducts, iii) the reflection of sound from the wall at the duct entry and iv) mutual coupling between the ducts. As such, it is not useful to report the actual SPL at the duct entry as it provides little information. Instead, a nominal free-field level at the duct entry is assumed.

g) Results were computed at a distance of 2 m from the ducts in 1/12th octave frequency intervals over the frequency range 44 Hz to 700 Hz and integrated into octave frequency bands. The levels are relative to the assumed free-field level at the duct entry.

h) The nominal sound power entering the duct can be computed using Equation 1.

$$SWL_{input} = SPL_{free-field} + 10 * \log(DuctArea) \quad (1)$$

i) Considerable directionality in the duct output sound can result from the side-by side stacking of the ducts. The directivity indices (DIs) for each duct arrangement were computed using the nomographs given by Molloy (Molloy, 1948) and are listed in Table 4.

Table 4. Approximate directivity indices in dB for the stacked duct situation in half space environment.

No of ducts	System Width mm	63 Hz	125 Hz	250 Hz	500 Hz
one	400	3.0	3.2	3.6	4.6
two	800	3.3	3.6	4.7	7.5
three	1200	3.4	4.1	5.9	9.1
four	1600	3.6	4.9	7.1	10.6

j) As FEM computes pressure at a point and not sound power, the sound power output from the ducts was computed from the pressures at 2 m from the duct outlets and the DIs. To produce a match of the calculated SWL with the SPL at 2 m of within 0.5 dB, it was necessary to increase the effective radiating area of the ducts to 115% of the actual duct opening area between the insulation faces.

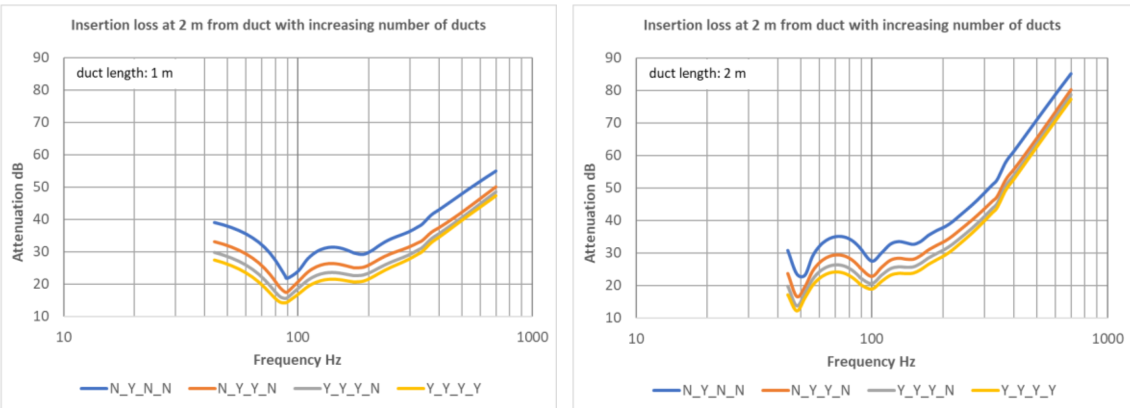


Figure 8. Attenuations of lined ducts 1 m and 2 m long when stacked together. The legend shows the open status of each duct, e.g. N_Y_N_N means that only Duct 2 was open.

The investigation showed that the duct attenuations at frequencies below 1 kHz were substantially higher than stated by standard tables such as ASHRAE and CIBSE. To ensure that our calculations of the attenuations produced by a combination of balcony techniques B to E with lined ducts leading to internal spaces were valid, we modelled one of the scenarios in the nomographs in Fig 9.20 in (D. Bies C.Hansen, 2003) (B&H).

Using the terminology of the B&H nomographs, the duct parameters modelled are:

- *l*/h = 0.5 for 200 mm dimension and 0.33 for 300 mm dimension
- R1l/ρc =1.0
- h_{width} = 100 mm
- h_{depth} = 150 mm
- For l/h = 0.33, the geometric mean of the attenuations for l/h = 0.5 and l/h = 0.25 was used.
- Attenuations for width and height are summed.
- The B&H attenuations have been adjusted upwards to account for the incident sound power over the small duct area which is used in the FEM calculations (adjustment of -10*log(0.3*0.2) = 12.2 dB).

Figure 9 compares the attenuations predicted by PAFEC with those derived from Fig 9.15 in B&H.

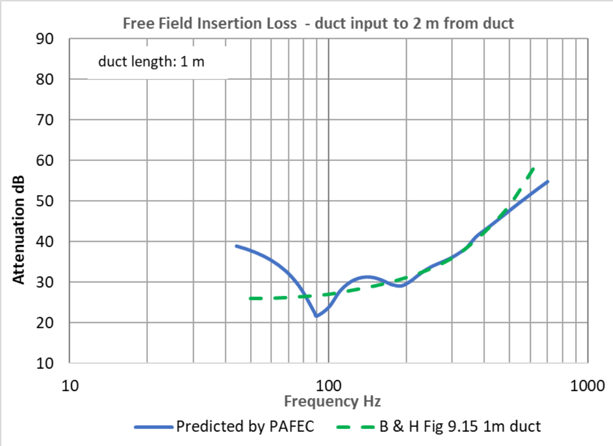


Figure 9. Comparison of single duct computed by PAFEC and via B&H for the stated duct parameters.

5.3.2 Duct Attenuations

Figure 5 lists the relationships between the free-field input SPL impinging on the ducts and total output SWL for ducts of 1 m and 2 m length when stacked together. The results for 63 Hz to 500 Hz were computed by FEM modelling, while those for 1 kHz, 2 kHz, and 4 kHz are taken from the 2016 Guide B4 issued by (CIBSE, 2016) for a duct of 200 mm x 300 mm with 50 mm insulation lining. As CIBSE do not state attenuations at 8 kHz, these have been estimated. For frequencies 1 kHz and above, the attenuations for the 2 m duct are simply twice those of the 1 m duct.

The output levels of the various duct arrangements are the summation of the output power of all the ducts in operation and the changes in attenuation due to mutual coupling effects between ducts. The mutual coupling between ducts changes the acoustic impedance presented to the output of each duct, resulting in reduced attenuation due to end-reflections. For example, at 63 Hz, the combined level with four ducts compared to one duct should equate to 9.7 dB (15.7 minus 6), but the mutual coupling decreases the attenuation to 6.6 dB.

B&H note that where the quantity 2*h*/λ exceeds unity, the attenuation cannot be described in terms of attenuation per unit length as in Figure 9.15. However, at these higher frequencies, the attenuation achieved in practice will in all cases be greater than that predicted by Figure 9.15. With the duct dimensions of 200 mm x 300 mm, the value of 2*h*/λ is unity at 1400 Hz.

B&H also note that with random-incidence sound impinging on the duct, additional attenuation will result for sound that repeatedly reflects from the duct walls just after the sound enters the duct. With the 200 mm x 300 mm, the additional attenuation is 10 dB above 2.2 kHz. Taking a conservative approach to the use of Fig 9.21 in B&H for the duct inlet correction, we have incorporated additional attenuations of 3 dB at 2 kHz, 6 dB at 4 kHz and 8 dB at 8 kHz to account for this effect.

Table 5. Relationships between free-field input SPL and total output SWL for stacked ducts.

Duct Length	No of ducts	System Width mm	SPL minus SWL Octave Band Centre Frequency (Hz)							
			63	125	250	500	1000	2000	4000	8000*
1 m	one	400	16	12	18	33	46	32	27	25
	two	800	10	8	15	30	40	26	21	19
	three	1200	8	7	14	28	36	22	17	16
	four	1600	7	6	13	27	34	19	15	13
	five	400	6	5	12	26	33	19	14	12
	six	800	5	4	12	25	32	19	14	13
	seven	1200	4	4	11	25	31	17	12	11
	eight	1600	4	3	10	24	31	16	12	10
2 m	one	400	14	17	26	51	79	48	36	30
	two	800	10	13	23	49	73	42	30	24
	three	1200	7	11	22	47	70	38	26	21
	four	1600	6	10	21	46	67	36	24	18
	five	400	5	9	20	45	66	35	23	17
	six	800	5	8	19	44	66	34	22	16
	seven	1200	4	8	19	44	65	33	21	16
	eight	1600	3	7	18	43	64	33	21	15

*Estimated

5.4 Balustrade Shielding with Balcony Absorption and Lined Ducts

Techniques B to E for balconies can be combined with lined ducts of different lengths to form Techniques F to I, as shown in Table 6. The flow resistivity of the insulation inside the ducts is 10,000 Rayls/m.

Table 6. Techniques for balcony attenuation combined with lined ducts.

Technique in combination with lined ducts	Combination			
	F	G	H	I
Attenuation from solid balustrade	❖	❖	❖	❖
100 mm thick insulation on the balcony soffit		❖	❖	❖
100 mm thick insulation on the left-hand balcony wall (as viewed from the street)			❖	❖
100 mm thick insulation on inner face of balustrade				❖

Figure 10 shows the attenuations of Techniques F to I with a duct opening 200 mm x 300 mm in Position 1 and lengths of 0.5 m and 1.5 m with a building opposite. The attenuations are input free-field SPL to output SWL.

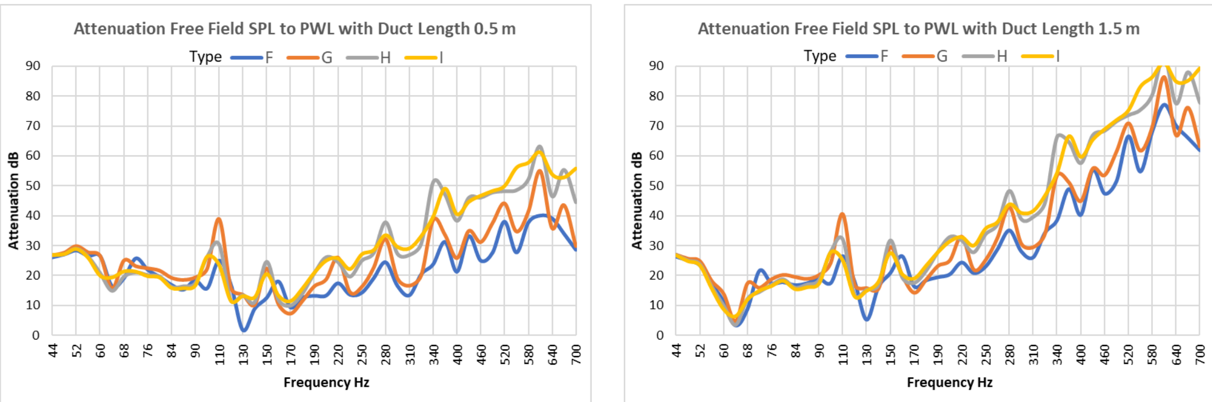


Figure 10 Attenuations of Techniques F to I with duct lengths of 0.5 m and 1.5 m with building opposite.

Figure 11 compares the octave-band attenuations with methods F to I and duct lengths of 0.5 m, 1.0 m and 1.5 m. The ducts were located at bottom-left corner of the balcony.

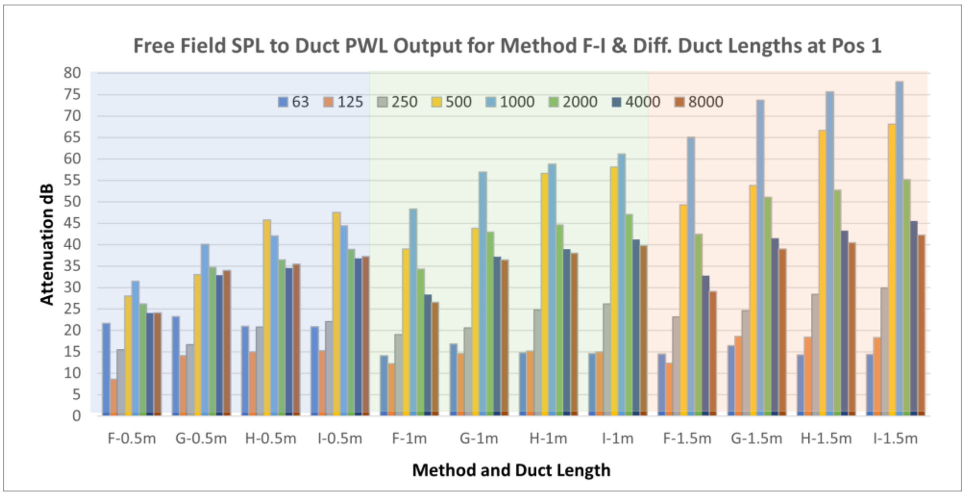


Figure 11. Attenuations of Methods F to I with three duct lengths with a building opposite.

The changes in attenuation with the position of the duct in the wall were explored and found to be relatively insensitive to position. Accordingly, to increase the ventilation area, the sound power output of one duct can simply be added to that of another duct beside it. Note that the interactions at low frequencies between ducts should also be considered.

6 CONCLUSIONS

The original version of this paper contained results for the techniques listed in Table 2; however, the conference page limit precluded presentation of all the techniques. Interested readers are invited to contact the author at Glenn@acousticdirections.com for access to the complete paper.

The attenuations of eight different techniques to allow openings for natural ventilation in apartments were examined using a combination of ray tracing in a 3D virtual model and the finite and boundary element methods (FEM/BEM). FEM/BEM was used when the dimensions of the structures were small relative to or commensurate with wavelength of the incident sound. Techniques include the use of a solid balustrade to provide acoustic shielding, sound absorption within the balcony, and lined ducts leading from the balcony into a room. Other attenuation techniques are wintergardens and projections on the building façade.

Attenuations for each technique can be combined to yield SPLs in receiver rooms, for a given external free-field SPLs incident on the apartment façade. Sufficient attenuation of traffic noise can be achieved to allow openings for natural ventilation whilst providing satisfactory internal noise levels in bedrooms and living rooms.

REFERENCES

CIBSE. (2016). The Chartered Institution of Building Services Engineers: Noise and vibration control for building services systems. *Guide B4*.

D. Bies C.Hansen. (2003). *Engineering Noise Control.* London: Spon Press.

Molloy, C. T. (1948). Calculation of the directivity Iindex for various types of radiators. *The Journal of the Acoustical Society of America,, 20*, 387.

Rindel J.H., N. G. (2009). Diffraction around corners and over wide barriers in room acoustic simulations. *16th International Congress - Sound and Vibration .* Krakow.