Passive Noise Attenuation Methods for Apartments Part 2

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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.

2 ATTENUATION TECHNIQUES EXAMINED

We assessed the attenuations produced by twelve types of techniques which are shown in Table 1. The attenuations can be grouped into four acoustical categories according to whether the inputs and outputs are sound pressure (SPL) or sound power (SWL). Four techniques are described in Part 1 with another four techniques being described in this paper (Part 2).

Table 1 – Attenuation methods examined. (* ND not described in this paper | ^ See Part 1)

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	^
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	^
4	Ducts lined with insulation.	facade SPL to SWL	^
5	Incorporation of acoustically lined duct between the balcony opening and the room behind.	facade SPL to SWL	^
6	Lined external recess with internal louvre opening	façade SPL to SWL	3.3
7	Wintergarden with an internal opening	facade SPL to SWL	3.4
8	Downturns above balconies	facade SPL to SPL	ND
9	Horizontal and vertical fin-like projections beside windows	facade SPL to SPL	3.5
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	3.6

3 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.

3.1 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

3.2 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.

3.3 Louvred Recess on Façade

The method uses a recess in the building façade to provide a lined cavity with a ventilation louvre on one side as shown in Figure 1 and Figure 2. The recess is intended to fit into a region between a wardrobe and a wall. Attenuation of sound is produced by the sound absorption lining of the cavity. In essence, it is a tall, short, lined duct. Figure 3 shows the distribution of sound pressure level at 490 Hz over the louvre system. Salient details of the FEM model are:

- ventilation opening at the façade w/h: 400 mm x 2700 mm (excludes insulation)
- ventilation depth d/h 900 mm x 2700 mm (exclusions insulation)
- opening located 4 m above the road with line source of noise
- thickness of insulation in the recess: 100 mm on two sides
- insulation flow resistivity of 8,300 Rayls/m with the Allard Champoux model
- internal louvre opening w/h: 585 mm x 2700 mm
- receiver room has i) 100% reflecting floor, ceiling, and walls beside the louvres and ii) 100% absorption on the remaining two outer walls

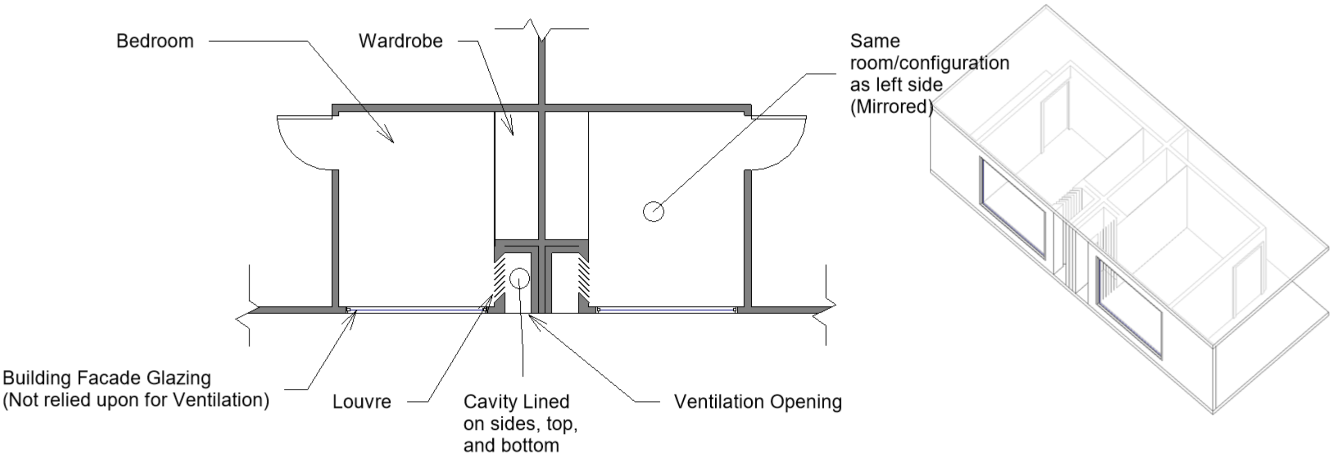


Figure 1. Arrangement of louvres behind acoustic opening and within a building.

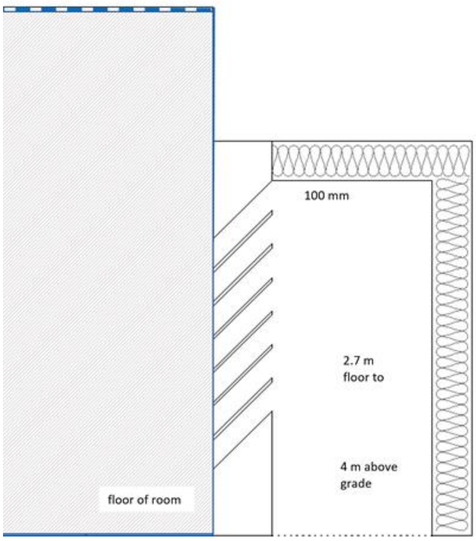


Figure 2 Details of recess with louvre

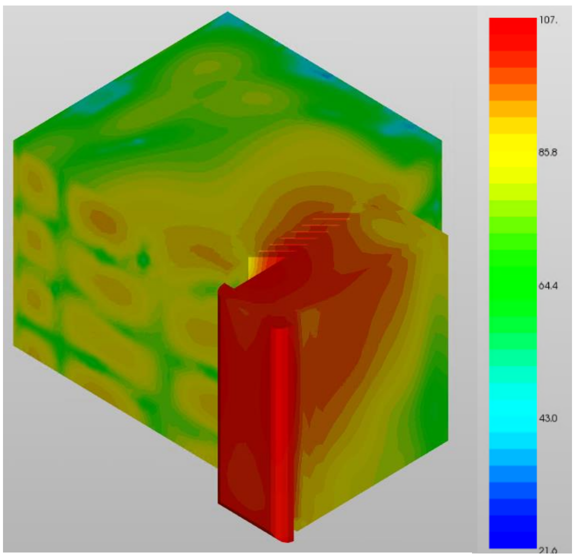


Figure 3. SPL distribution at 490 Hz over the louvre system.

Figure 4 shows the relationship between the free-field SPL incident on the building façade and the SWL transmitted into the room.

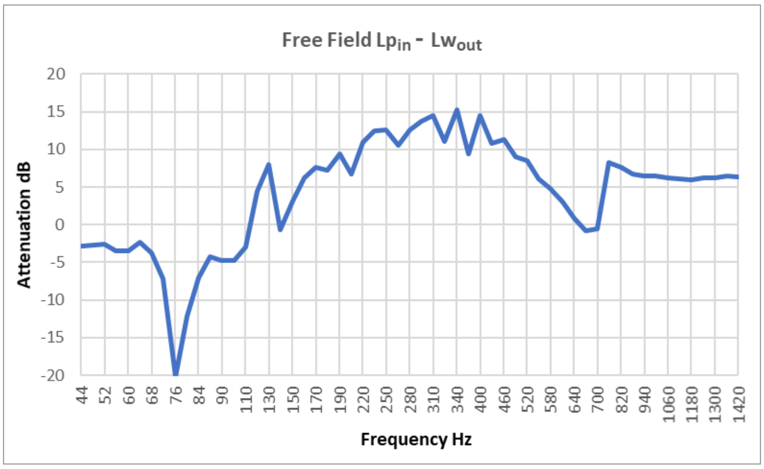


Figure 4. Relationship between free-field incident SPL and SWL transmitted to the room. External opening of 400 mm x 2700 mm and internal opening of 585 mm x 2700 mm.

The following points are noteworthy:

- The SPL and SWL levels have been logarithmically averaged over the entry and exit areas.
- Below 100 Hz, the relationship is negative, implying an increase in level. One component of this increase is the input SWL associated with the SPL plus 2.1 dB (due to the area of 12.62 m^2), and the other is a floor to ceiling resonance at 76 Hz. Interestingly, the resonance frequency is significantly higher than the room-mode frequency of 63 Hz (at which the aperture height and the floor-to-ceiling distance of 2.7 m produces the first standing wave).
- The presence of the blade-like louvre structure increases the insertion loss by between 1 dB and 2 dB over the frequency range of 150 Hz to 300 Hz. Above and below this range, the louvre had little effect.
- If the aperture area were decreased, the insertion loss would increase, however the frequency response of the insertion loss would also change.
- Computation time precluded modelling of the attenuation above 1 kHz, and the results have been simply estimated based on the absorption by the aperture for random incident sound.

Table 2 states the relationships between free-field input SPL and total output SWL in octave bands.

Table 2. Octave-band Relationships between free-field input SPL and total output SWL.

Octave Band Centre Frequency (Hz)							
63	125	250	500	1000	2000	4000	8000
-11	-1	10.5	4	6.5	10	10	10

3.4 Wintergardens

A closed balcony is often called a wintergarden and creates a room in front of a habitable room. A wintergarden can form an acoustical plenum, which allows sound entering in part of the closed space to be partly absorbed before it leaves another part of that space. An image of the model used for the wintergarden in ODEON is shown in Figure 5.

Figure 5. Wintergarden as implemented in ODEON. The 0.76 m^2 opening is shown

Salient details of the wintergarden model are:

- Dimensions: w/d/h: 5.3 m/2.2 m/2.7 m (floor area of 11.7 m2)
- Openings on the façade of 0.72 m^2 (1800 mm x 400 mm) and 0.36 m^2 (900 mm x 400 mm)
- The SWL over an internal opening of 200 mm x 300 mm was computed and represents the entry to a lined duct leading to a habitable room.
- Distance of 4.7 m between centres of facade and ventilation openings.
- Ceiling of the wintergarden covered with sound absorption with coefficients of 0.9 at all frequencies.
- Sound absorption coefficients of all other surfaces in the wintergarden assumed be less than 0.1.

The differences between the sound power levels at the external opening of the wintergarden and the internal opening into the living area of the apartment were computed in octave bands. Table 3 lists the attenuations in octave frequency bands from a free-field SPL at the façade to the SWL at the internal ventilation opening resulting from the transmission of sound through the wintergarden. The benefit of sound absorption on the ceiling of the wintergarden is substantial.

Table 3. Attenuations produced by transmission through a wintergarden opening to a ventilation opening of 0.06 m^2 .

Façade Opening m^2	Soffit Absorption	SPL minus SWL Octave Band Centre Frequency (Hz)							
		63	125	250	500	1000	2000	4000	8000
0.72	No	17	17	14	14	13	13	14	16
	Yes	24	24	23	23	22	22	22	23
0.36	No	19	19	16	16	15	15	16	18
	Yes	28	29	28	27	27	26	27	29

3.5 Building Projections

Various projections from the building that are intended to provide some shielding are shown in Figure 6. Table 4 lists the attenuations produced by projections from the side façade of a building which is orientated 90° to the street with an opening 8.8 m located from the street. Attenuations are relative to the free-field level on the street-facing façade, which is 4.8 m from the line of traffic. The area of the opening is 0.95 m^2 and it is located 18 m from a building opposite.

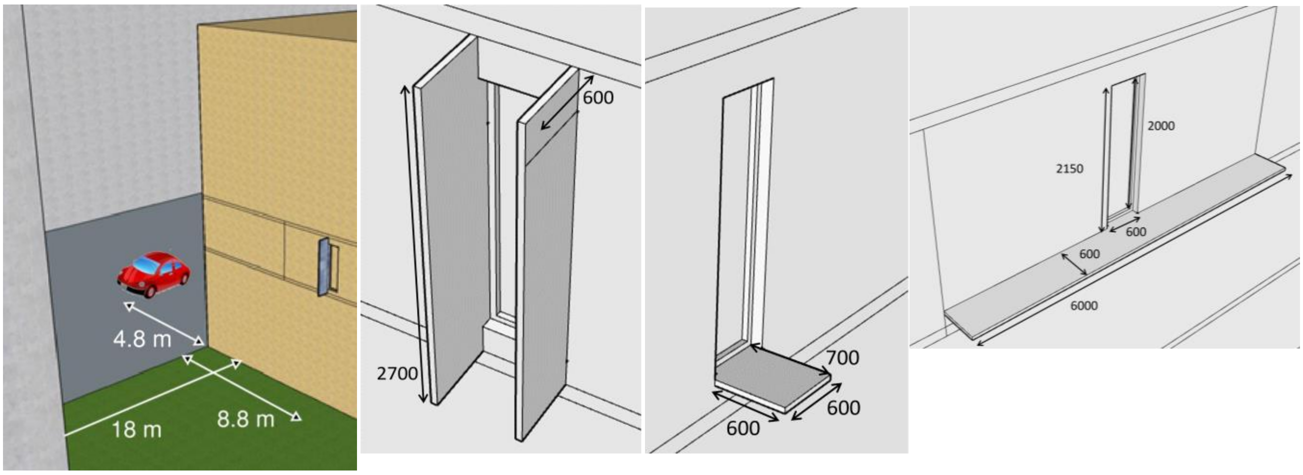
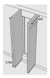
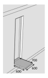
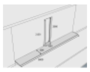
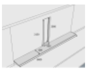


Figure 6. Projections from buildings assessed.

Table 4. Attenuations produced by building projections at third and sixths storeys (6 m above street) and long horizontal base on the sixth storey (15 m above street) with the façade facing the street.

Façade orientation to street	Scheme	Attenuation (dB) Octave Band Centre Frequency (Hz)							
		63	125	250	500	1000	2000	4000	8000
0º	Reference: No projections on façade	0	0	0	0	0	0	0	0
90º	Single vertical projection (street side) 3rd storey	10.7	11.1	11.7	12.2	12.6	13.0	14.2	17.6
90º	Dual vertical projections 3rd storey 	5.6	5.4	5.5	5.6	5.7	5.8	6.3	8.0
90º	Short horizontal projection 3rd storey 	5.5	5.6	5.8	5.9	5.9	6.0	6.2	7.2
90º	Long horizontal projection 3rd storey 	5.3	5.4	5.6	5.7	5.8	5.9	6.2	7.6
90º	Long horizontal projection 6th storey 	5.7	5.6	5.7	5.8	5.9	6.0	6.1	7.2

We make the following comments:

- With a building opposite the façade facing the street, the 90° orientation of the façade with the opening produces a reduction of approximately 5 dB on that façade relative to the street-facing façade.
- This attenuation is slightly increased with the installation of horizontal projections below the opening on the 90° façade.
- A single vertical projection on the street side of the opening increases the attenuation by 6 dB or more, due to acoustic shielding.
- However, where dual vertical projections are used, the successive reflections between the projection produce sufficient level to nullify the benefit of the shielding produced by the street-side projection.

3.6 Rooms with Duct Openings

After traffic noise has passed through the noise-attenuating structures, it eventually reaches a habitable room such as a living room or bedroom in which the sound power of the attenuated noise is converted into sound pressure by reflections and reverberation. This conversion of sound power to sound pressure is the final stage in the attenuation chain. In broad terms, the relationship between sound power and sound pressure at each frequency is determined by the reverberation time and the refection patterns of the room into which that sound power is radiated.

The relationships between SWL and SPL in typical apartment rooms were computed using ODEON for a generic living room and bedroom at multiple positions in these rooms. The rooms are furnished to some extent and have typical surface finishes. The living room has a rug on the floor, while the bedroom is carpeted. Figure 7 shows a view of these rooms. ODEON was used to calculate the T30 reverberation times, which are shown in Table 5.

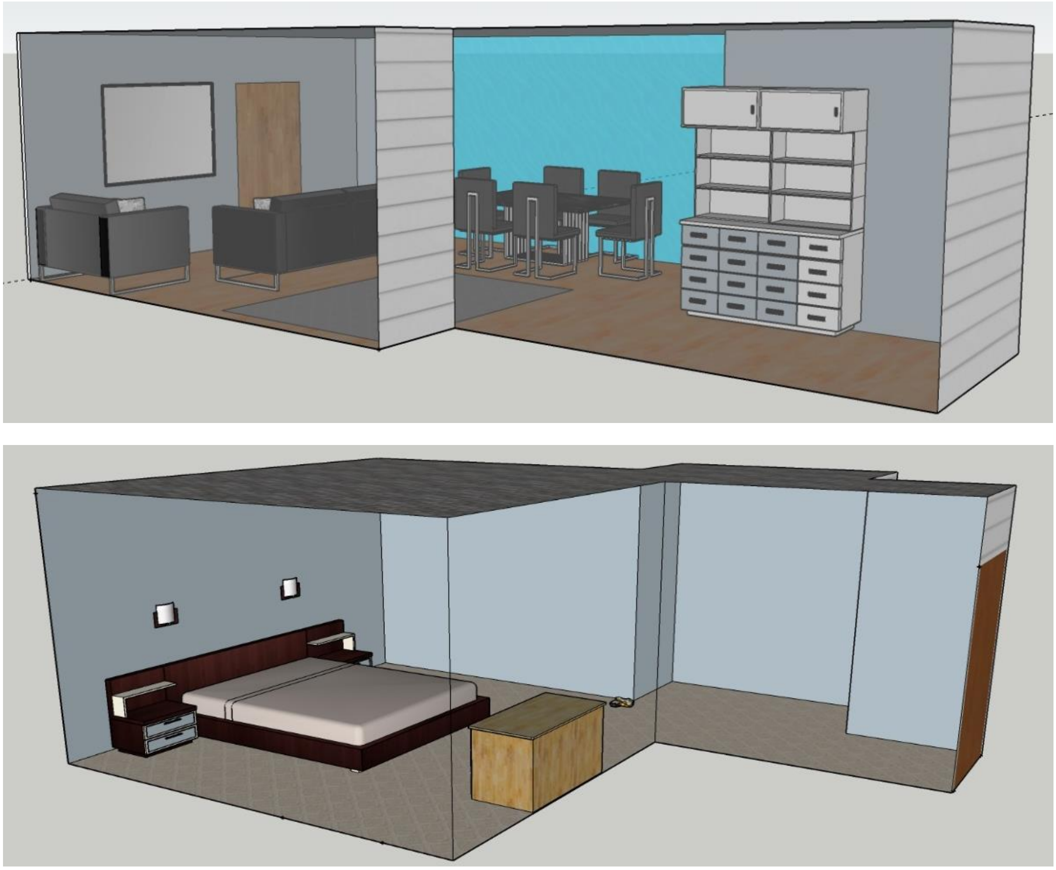


Figure 7. View into generic living room (upper figure) and bedroom (lower figure) used to determine a typical relationship between sound power and sound pressure in a bedroom.

An opening of 300 mm x 400 mm (0.12 m^2) from a lined duct is located in one corner of the room and emits a sound power level of 0 dB into the room. The resulting sound pressure levels were computed using ODEON at eight or six receiver positions distributed throughout the rooms. The difference between the SWL leaving the duct and the SPL at the receiver point at each frequency was then calculated.

Table 5. Size data and reverberation times for receiving rooms used to assess the conversion of SWL to SPL.

Room	Room Volume m^3	Floor Area m^2	Reverberation Time (s) Octave Band Centre Frequency (Hz)							
			63	125	250	500	1000	2000	4000	8000
Living Room	108	40	0.43	0.43	0.55	0.71	0.73	0.82	0.69	0.50
Bedroom	50	18.5	0.43	0.41	0.39	0.53	0.51	0.56	0.48	0.38

3.6.1 Predicted Levels in Living Room

Table 6 presents the room levels predicted by Odeon at positions between 2.2 m and 5.6 m from the vent.

Table 6 Living room – attenuations of SWL to SPL computed by ODEON

Attenuations dB	Attenuation (SWL - SPL) Octave Band Centre Frequency (Hz)							
	63	125	250	500	1000	2000	4000	8000
Spatial Average (8 positions)	12	12	11	10	10	9	10	11
Maximum / minimum	9/16	9/16	8/15	8/12	7/12	7/11	7/12	8/14

It is informative to compare the ODEON levels inside the living room with those predicted with the commonly used Hopkins Stryker equation (Equation 2) which combines the direct and reverberant fields. The room constant is derived from the Eyring equation and the reverberation times computed by ODEON.

$$L_p = L_w + 10\log\left(\frac{Q}{4\pi r^2} + \frac{4}{R}\right) \tag{2}$$

Figure 8 presents the sound pressure levels predicted by ODEON and the Hopkins Stryker equation with a total sound power level of 0 dB entering the room at the ventilation opening. Although the spectral shape of the total statistical sound pressure levels is similar to that of ODEON, the Hopkins Stryker method overpredicts the levels in the room with a range of 0.7 dB to 7 dB, with an average overprediction of 3 dB.

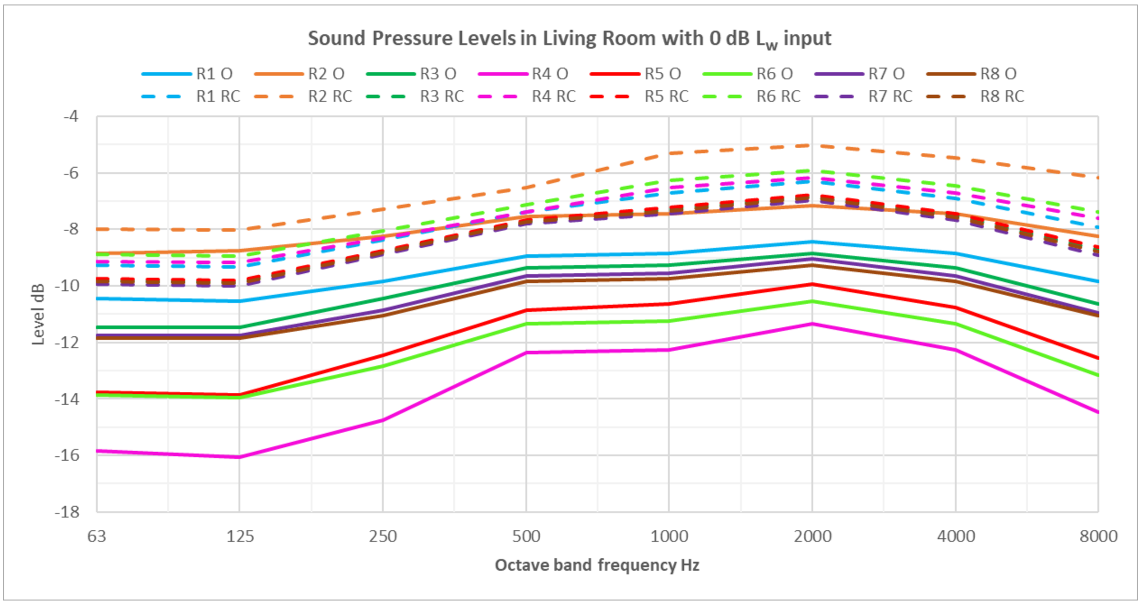


Figure 8. Relationship between input SWL and SPLs at eight receiver points computed by ODEON (e.g. R2 O) and the statistical method using the Room Constant (e.g. R2 RC).

To provide further insight into this mismatch, Table 7 states the reverberant and direct level at position R1 and the directivity indices (DI) for the sound power entering the room, which were estimated from the location of the vent relative to room boundaries in the ODEON model. The reverberant field dominates the total level at R1.

Table 7. Reverberant and direct field levels at R1 and estimated directivity indices for ventilation opening in the ODEON model. The input SWL is 0 dB.

Item	Octave Band Centre Frequency (Hz)							
	63	125	250	500	1000	2000	4000	8000
Reverberant Field Level	-10.4	-10.5	-9.3	-8.1	-8.0	-7.4	-8.2	-9.7
Estimated DI	6	6	6	6	9	9	9	9
Direct Field Level at R1	-15.7	-15.7	-15.7	-15.7	-12.7	-12.7	-12.7	-12.7
Total Level	-9.3	-9.3	-8.4	-7.4	-6.7	-6.3	-6.9	-7.9
Attenuation (SWL-SPL)	9.3	9.3	8.4	7.4	6.7	6.3	6.9	7.9

3.6.2 Predicted Levels in Bedroom

Table 8 presents the range of room levels predicted by Odeon at positions between 1.4 m and 4.4 m from the vent. Figure 9 shows the sound pressure levels predicted by ODEON and the Hopkins Stryker (Room Constant) method with a total sound power level of 0 dB entering the room at the ventilation opening. The Hopkins Stryker equation overpredicts the levels in the room with a range of 0.1 dB to 7 dB, with an average overprediction of 2.5 dB.

Table 8. Bedroom room – attenuations of SWL to SPL computed by ODEON

Attenuations dB	Attenuation (SWL - SPL) Octave Band Centre Frequency (Hz)							
	63	125	250	500	1000	2000	4000	8000
Spatial Average (8 positions)	8	8	8	7	7	7	8	9
Maximum / minimum	5/11	5/12	5/12	5/11	5/11	5/11	6/12	6/14

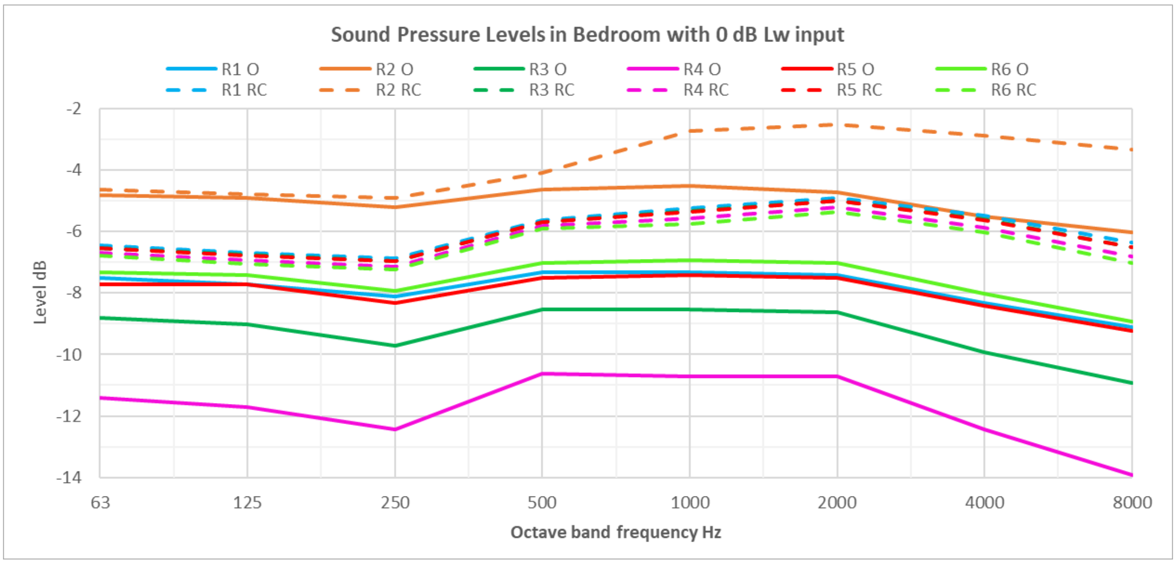


Figure 9. Relationship between input SWL and SPLs at six receiver points in the bedroom computed by ODEON (e.g. R2 O) and the Hopkins Stryker equation using the Room Constant (e.g. R2 RC).

3.7 Rooms with Open Windows

3.7.1 Living Room

Table 9 presents the average attenuations of SPL to SPL of sound entering a 40 m^2 living room through an open window of three sizes. The incident sound is free-field SPL the in-room level is the spatial energy-average over eight positions. The 5% of floor area represents the area requirement for natural cross-ventilation.

Table 9. Attenuations of free-field SPL entering living room via an open window of four sizes to average SPL in the room with/without a building opposite.

Scenario	Window Dimensions (m)	Percentage of floor area	Free-field SPL minus spatially averaged SPL Octave Band Centre Frequency (Hz)							
			63	125	250	500	1000	2000	4000	8000
Building Opposite	0.5 x 0.8	1.0%	13.2	13.4	13.7	12.8	13.2	12.9	13.7	14.8
	0.5 x 1.2	1.5%	10.8	10.9	11.1	10.1	10.4	10.2	11.0	12.4
	0.55*1.82	2.5%	9.9	10	9.6	9.3	9	9.2	9.4	10.4
	1 .1*1.82	5%	7.5	7.4	7	6.6	6.3	6.5	6.6	7.6
No Building Opposite	0.5 x 0.8	1.0%	14.2	14.6	15.0	14.0	14.3	13.8	14.3	15.1
	0.5 x 1.2	1.5%	12.6	12.9	13.1	12.1	12.3	11.9	12.3	13.1
	0.55*1.82	2.5%	11.3	11.4	11.1	10.7	10.4	10.5	10.3	10.7
	1 .1*1.82	5%	8.9	8.8	8.4	8.0	7.7	7.7	7.5	7.9

3.7.2 Bedroom

Table 10 presents the average attenuations of sound entering a 9 m^2 bedroom through an open window of two sizes. The incident sound is the free-field SPL and the in-room level is the average SPL over eight positions. The 5% of floor area represents the area requirement for natural cross-ventilation.

*Table 10. Attenuations of free-field SPL entering a bedroom via open window of three sizes to average SPL in the room with/without a building opposite. *excludes position near the window.*

Scenario	Window Dimensions (m)	Percentage of floor area	Free-field SPL minus spatially-averaged SPL Octave Band Centre Frequency (Hz)*							
			63	125	250	500	1000	2000	4000	8000
Building Opposite	0.275*0.8	2.5%	9.5	9.9	9.4	9.0	9.0	9.6	10.5	11.8
	0.54*0.8	5.0%	6.7	7.1	6.7	6.8	7.3	7.8	8.9	10.5
No Building Opposite	0.275*0.8	2.5%	10.4	10.9	10.5	10.3	10.4	10.9	11.6	12.3
	0.54*0.8	5.0%	8.1	8.6	8.3	8.5	9.0	9.4	10.2	11.1

3.7.3 Comparison with "10 dB rule"

Table 9 and Table 10 show that the attenuations in the living rooms range from approximately 6 dB to 14 dB and in the bedrooms from 7 dB to 11 dB. Both sets of attenuations depend on window area and the presence or other wise of a building opposite. On the basis of these results, we conclude that the 10 dB rule is unreliable and should not be used, particularly if code-compliance is critical.

4 EXAMPLE OF COMBINATION OF ATTENUATION METHODS

The total attenuation and resulting internal noise level produced by a range of attenuation methods was computed for two attenuation scenarios using the data presented above. The input to each scenario is the free-field SPL of traffic noise incident on the third-storey façade at a level of 67 dBA and the spectrum shown in Table 11. A tall building is located opposite on the street. The outputs are the spatially-averaged SPL in a bedroom of internal volume 50 m3 or a living room with a volume of 108 m^3.

Table 11. Assumed spectrum of free-field traffic noise at façade used for attenuation examples.

	Octave Band Centre Frequency (Hz) L_{Zeq}								Total dBA
	63	125	250	500	1000	2000	4000	8000	
Traffic noise level	72	66	66	63	63	59	51	43	67

Table 12 lists the total attenuation of noise between the input SPL on the façade and the resulting internal noise level.

Table 12 Details of attenuation scenarios with free field input SPL

Scenario	Parameter 1	Parameter 2	Parameter 3	Receiver Room	Attenuation dBA	Room Level dBA
1	100 mm absorption on balcony soffit	2 x 1 m ducts	Total duct entry area 0.12 m^2	Bedroom	32.3	34.3
2				Living room	35.7	30.9
3		8 x 1 m ducts	Total duct entry area 0.48 m^2	Bedroom	26.3	40.4
4	Wintergarden	Opening 0.36 m^2		Living room	36.6	30.0
5	Louvre	Opening 1.1 m^2		Bedroom	12	54.6
6	Projection 600 mm on street side	1.5 m long duct	Total duct entry area 0.24 m^2	Bedroom	34.6	32

5 CONCLUSIONS

Parts 1 and 2 of this paper present attenuations of eight different techniques (to allow openings for natural ventilation in apartments), which 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.

Although the results presented in this paper pertain to a set of specific situations and structures, they can be used to guide and inform a design process. However, caution should be used when applying these results to other situations that may appear similar but have important subtle differences. Accordingly, we recommend that computation of attenuations for other situations and structures is undertaken using a first-principles approach, as the authors have done.

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