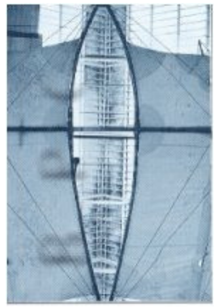

THE BUILDING PERFORMANCE CENTRE

SCHOOL OF THE BUILT ENVIRONMENT

NAPIER UNIVERSITY

NANR116: 'OPEN/CLOSED WINDOW RESEARCH'

SOUND INSULATION THROUGH VENTILATED DOMESTIC WINDOWS

Submitted to:

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Executive Summary

Planning guidance is required to advise on appropriate standards against which the suitability of development can be assessed. Consideration is needed of the locale, its existing character and of future residential amenity. In the noise context, advice is primarily required to define threshold exposure levels relative to extraneous sources of environmental noise. A thorough knowledge of the acoustic transmission characteristics afforded by the building envelope is therefore desirable to assist in the setting of threshold levels and to aid in the design and verification of development proposals.

The insulation of an open window has been generally accepted as being 10-15 dBA although its precision and affect on opening style, open area and window size, are not readily available. A programme of laboratory measurements have been undertaken by the Building Performance Centre at Napier University on behalf of the Department for Environment, Food and Rural Affairs, in order to quantify the sound insulation provided by a variety of window types, opening styles, areas of opening and ventilator devices.

Open Windows: The test regime measured the sound insulation provided by seven separate windows, with a combination of twelve different opening styles. The variation in weighted level difference, D_w, across the different opening styles for approximately equivalent area openings has been consistently measured as between 4 and 6 dB.

The range of measured insulation ratings, for window with a free open area of 0.05 m^2, is D_w 14 – 20 dB. This translates to the following dBA level differences, due to variations in the source noise characteristics:

- Road Traffic Noise 12 –18 dBA
- Railway Noise 12 –18 dBA
- Aircraft Noise 14 – 19 dBA
- Amplified Music 15 –20 dBA

The window results do not show any one opening style which provides significantly better insulating characteristics. In general the set of windows with an outward opening light performed well.

The windows with no extending opening lights, namely the internal turn and tilt and the sliding sash, were also among the best performing open units; particularly when the source of noise was neither random nor normal incidence.

Variations in the window size, frame material and glazing type have little significance on the insulating performance of an open window.

Closed Window. The introduction of a ‘closed’ 4000 mm^2 slot ventilator within the window frame reduced the overall weighted insulation performance of the window by 6 dB. This reduction increased to 11 dB when the vent was in its ‘open’ condition.

Proprietary over frame vents gave a marked improvement in the high frequency acoustic performance; however the weighted insulation rating is generally dominated by low-frequency transmission which is not substantially improved over that of a slot vent.

Sound Directivity: Rotation of source incidence away from the normal, within a non-diffuse acoustic environment, is found to consistently improve the resulting open window façade insulation.

Chapter 1 Introduction

1.1 Introduction to study

This report presents the findings from a set of laboratory measurements undertaken as part of a contract let by the Department for Environment, Food and Rural Affairs to investigate the sound insulating performance of residential windows in their open and closed conditions and to provide additional guidance on related physical factors.

The overall aim of the study is to provide rigorous guidance on the acoustical properties of residential facades allowing for the requirements of natural ventilation, through either open windows or background ventilators. The guidance is intended to be of particular use at the planning stage for residential developments; where it can be used in combination with acoustic criteria to assess the scope of noise mitigation works.

1.2 Brief for study

The following is taken from Section 3 of Defra's Invitation to Tender document and summarises the project brief:

'Defra is interested in developing a solid scientific base for the treatment of windows in acoustic predictions and a research contract is to be let to review the acoustic properties of windows. The project will include a thorough review of current knowledge on acoustic losses through windows (open and closed). It will then involve acoustic testing of the relevant practical situations encountered, including: window type, size, glazing, construction; and the extent to which the window is opened. The data will be summarised in a manner consistent with the use of PPG-24 and other relevant noise guidance (including unambiguous and relevant parameters).'

The project goals are summarised as follows:

- *Undertake a thorough review of current knowledge/literature of acoustic losses through windows (open and closed), and produce a detailed summary of the findings.*

The above goal is covered in Chapter 2 of this report.

- *Construct a methodology and programme for acoustic testing of the relevant practical situations, including, but not limited to: window type, size, glazing, and construction; and the extent to which the window is opened. It is expected that the testing will be performed under laboratory conditions, and in accordance with BS EN ISO 140-3:1995 as appropriate.*

The above goal is covered in Chapter 3 of this report.

- *To provide a clear set of information and figures for the average acoustic loss of windows over a variety of conditions.*
- *To provide information that may assist in updating future noise guidance.*

The above goals are covered in Chapters 4 to 6 of this report.

1.3 Background

The sustained demand for housing over recent years has led to higher density development within urban centres; typically on brown-field sites previously occupied by industry or located in close proximity to transport corridors. Policy outlined in 2000 by the Office of the Deputy Prime Minister's Planning Policy Guidance Document 3, Housing (PPG 3)[1] commits to sustainable patterns of development through the concentrated use of previously developed land whilst ensuring that homes are decent and are capable of improving quality of life.

The development of brown field sites for residential purpose present particular challenges. In terms of acoustics, brown field sites are generally exposed to high levels of noise from a combination of retained industrial neighbours, concentrated transport infrastructure, adjacent entertainment venues or utility plant.

Noise Exposure Categories (NEC's), determined on the development site, are presently used in Planning Policy Guidance 24 (PPG24) (England & Wales)[2] and Planning Advice Note 56 (PAN56) (Scotland)[3] to assess the acoustic suitability of residential development relative to the external environment. PAN56 additionally recommends that satisfactory internal noise levels be ordinarily achievable with windows sufficiently open for ventilation purposes. An acoustic requirement for closed windows to achieve a satisfactory noise environment is recommended only in 'exceptional circumstances';

Control of material planning issues, such as noise, are controlled by the Local Authority through the use of Planning Conditions. Whilst guidance such as PPG 24, and PAN 56 are frequently followed there are numerous other methodologies and criterion that are additionally used. This variation in approach, particularly over façade elements such as windows, window openings and ventilation devices, their assumed use and appropriate performance standards is significant and has generally occurred due to a lack of concise prediction and measurement guidance.

It is proposed to replace PPG 24 with a new Planning Policy Statement 'PPS 24' for England and Wales. This provides an opportunity to produce detailed advice on acoustic prediction methodologies suitable for the planning process.

1.4 The historic performance of open windows

The existing published research, which touches on sound insulation issues of façades and windows is generally related to the optimisation of acoustic performance of closed windows with advice pertinent to the insulation performance of partially open windows being limited. Of the applied papers available, they are limited by their scope and methodologies.

Table 1.1 provides an overview of the pertinent documents providing either guidance or a research report. The numerical results highlighted by Table 1.1 of the assumed / measured insulation rating of an open window are generally in agreement as being approximately 10-15 dBA.

Information Source	Summary of Findings
PPG 24 (1994) [2]	A reduction of 13 dB(A) from the facade level is assumed for an open window
WHO (1999) [4]	A reduction of 15 dB from the facade level is assumed for a partially open window. (no reference)
BS 8233 (1999) [5]	Windows providing rapid ventilation and summer cooling are assumed to provide 10 - 15 dB attenuation (no specific reference)
BRE Digest 338 (1988) [6]	A partly open window has an averaged level difference, $D_{1m,av100\text{-}3150}$ of 15 dB
DoE Design Bulleting 26 (1972) [7]	A reduction of 5 dB(A) with a window wide open
Nelson - Transportation Noise (1987) [8]	Sound insulation of an open single window is 5 – 15 dB. (theoretical)
Mackenzie & Williamson DoE Report (1972–73) [9],[10]	A vertical sliding sash window open 0.027 m^2 (summer night-time ventilation) and 0.36 m^2 (daytime summer ventilation) provided a sound level reduction of 16 and 11 dB(A) respectively. (Lab Study)
Kerry and Ford (1973 – 74)[11], [12]	A horizontal sliding sash window open 25 mm and 200 mm provided averaged sound reduction indices, R_{av} of 14 and 9 dB respectively. (Field Study)
Lawrence and Burgess (1982 – 83) [13][14]	A vertical sliding sash open 9% of the total façade provided a sound reduction index R_w 10 dB. (Field study)
Hopkins (2004) [15]	Road traffic noise reductions through window openings resulted in reductions of between $D_{2m,n,T}$ 8 and 14 dB. (Field Study)

Table 1.1 Summary of open-window acoustic transmission literature

1.5 Alternative ventilation solutions

Designers of residential developments are often forced to work around acoustic site constraints which cannot be satisfactorily overcome by the use of acoustic barriers, e.g. raised transport corridors, high rise development or close proximity noise sources.

In such situations it is the building envelope, principally through exposed windows and ventilators that are required to make up any insulation shortfall. Whilst the basic measures required to upgrade the acoustic insulation characteristics of a façade are well understood, i.e. sealing penetrations, increasing surface mass and providing panel isolation, these measures are not appropriate for façade elements required to allow fresh air into the building.

The ventilation requirements of the Building Regulations are currently similar across the UK, however a significant change is being proposed with the introduction of a performance based standard, outlined in the draft 2006 revision of Part L for England and Wales[15]. The primary motivation for the change from the prescriptive 1995 edition[17] is the policy of reducing ventilation heat loss whilst maintaining adequate indoor air quality. Thermal improvements are to be effected through improvements in the air-tightness standard[18] of the overall build, such that uncontrolled leakage through the building fabric are reduced in favour of controlled, device based ventilation.

The principles of natural ventilation are however contradictory to the principles of sound insulation although it is the preferred option for new build residential development. The largest sector of the domestic ventilator market is maintained by background trickle vents which have significant economic and sustainability advantages; derived from lower manufacturing and installation costs when compared to factored maintenance, large-footprint, and high cost mechanical plant.

The current regulations allow a minimum openable free area of background ventilation of 4000 mm^2 per room. The introduction of the draft Part L proposals will result in an increase in the size and number of external ventilation devices installed within the external building envelope. Estimates of the minimum increase, for a basic background ventilation strategy, are 60 %, however the precise ventilation performance will be determined by the size and layout characteristics of the dwelling.

1.6 Requirements for acoustic assessment

The accurate assessment of internal noise levels from external sources is complex and affected by a host of parameters. A summary of factors commonly affecting the transmission of noise through a façade are shown here, divided into effects related to the source, propagation and receiver environment.

Source	Propagation	Receiver Environment
constancy	separation	façade build-up
size	line of sight	workmanship of build
directionality	reflective surfaces	internal volume
spectral characteristic	relative geometries	surface finishes
meteorology	meteorology	location

It is not the intention of this report to provide recommendations on appropriate threshold noise exposure levels or to cover the detailed theory of sound propagation. The brief provided for the project does however touch on many of the factors outlined above. It is also recognised that the conclusions of the study can have application for planning guidance and therefore all of the conclusions drawn from the study are conservative to ensure an appropriate level of certainty is provided in the findings.

1.7 Study focus

To aid the progression and focus of the project, the outline aims of the project have been re-written into the form of questions, the answers to which should coincide with the main requirements of the study brief.

Q1 Define open, partially-open and closed windows?

Q2 How is the level of sound insulation provided by an open window affected by the opening style?

Q3 How is the level of sound insulation provided by an open window affected by the frame material?

Q4 How is the level of sound insulation provided by an open window affected by the window area?

Q5 How is the sound insulation of an open window affected by the area of opening?

Q6 How is the level of sound insulation provided by an open window affected by the glass specification?

Q7 Is there any benefit in fitting proprietary acoustic seals to windows?

Q8 What impact does the introduction of a ventilation slot in the window frame have on window performance?

Q9 Which single position within the receiving room best represents the average sound pressure level within the room?

Q10 How does the angle of incidence of the noise source to the window affect sound insulation?

Q11 Is there a significant variation in open window insulation from different sources of environmental noise?

Chapter 2 Literature Review

2.1 Introduction

A survey of the current literature has been reviewed to assess the relevance of previous research and to collate their associated empirical data for the sound insulation of open windows.

2.2 Guidance documents

Annex 6 of PPG 24[2] states that the "insulation provided by any type of window when partially open will be in the region of 10 - 15 dBA". The source of this guidance appears to be BRE Digest 338 [6] which gives average sound level differences (100 - 3150 Hz) based on field measurements for various types of window set in a brick/block wall, window area one third of total façade area and room reverberation time of 0.3 seconds. For a *'small window (e.g. roof light) partly open'* the average sound level difference (insulation) is stated to be 15 dB. This document also states *'when windows are open, only the area of opening is significant; if this is 10% of the total area, the basic noise reduction will be about 10 dB whatever type of window or wall construction occupies the remaining 90%'*.

The only reference to open windows in the WHO Guidelines for Community Noise[4] gives similar guidance (but in terms of sound reduction index) *'…completely open windows would have a sound reduction of 0 dB. If window openings make up 10% of the area of a wall, the sound reduction index of the combined wall and open window could not exceed 10 dB.'*

Annex 2 of PAN 56 [3] explains the derivations of the Noise Exposure Categories. Like PPG 24, it asserts that 10 - 15 dBA is usually assumed for the sound insulation qualities of a partially open window. So, for the purposes of calculating a façade level to achieve the 35 dBA recommended as a maximum internal night-time noise level by WHO, (based on the noise reduction due to a window opened to provide adequate ventilation), a sound insulation value of 13 dBA has been adopted.

Design Bulletin 26[7] (which predates BRE Digest 338) states that '*Normally constructed entrance doors and windows have a similar resistance, about 5 dBA when wide open, 10 - 15 dBA when partly open, and 18 - 20 dBA when closed.*'

Section 11.2.5 'Sound insulation of building elements' of the Transportation Noise Reference Book[8] gives typical values for the sound insulation of windows: single window open 5 - 15 dB; single window closed 20 - 25 dB. These values are labelled as 'dB' but are presumably 'dBA'. There is also a graph depicting how rapidly sound insulation decreases with open area and how a staggered window opening arrangement is 7 - 10 dB better than for a direct opening. A. B. Lawrence [13] is referenced as the source.

Section 6.7 of BS 8233:1999[5] presents both a simple calculation and a more rigorous calculation for internal noise in a dwelling. The simple calculation assumes an insulation of '*about 10 dB or 15 dB*' if the windows are open to provide rapid ventilation and summer cooling. The more rigorous calculation uses the method given in EN 12354-3:1999 Building acoustics - Estimation of acoustic performance of buildings from the performance of products - Part 3: Airborne sound insulation against outdoor sound. [19] In Section 8.4.7 'Windows', a table of R_w values is given: any type of window in a façade when partially open: 10 - 15 dB R_w; single glazed windows closed (4 mm glass): 22 - 30 dB R_w.

The reference material summarised here is generally in accordance with the 10 - 15 dB noise reduction 'rule' but there are discrepancies as to whether this is: an average level difference from 100 to 3150 Hz, an A-weighted level difference or a weighted sound reduction index, R_w. No reference to window type or frame material is made.

2.3 Experimental research

Two of the earliest relevant projects were carried out by Mackenzie R.K and Williamson J.J. for the Department of the Environment in 1972 and 1973 [9], [10] as background research in connection with the preparation of the Noise Insulation Regulations[20].

The first project tested five primary types of single glazed units, with and without various secondary glazing arrangements. The primary glazing units involved two sizes of timber casement, two sizes of steel casement and a timber double-hung sash and case window. A cavity brick wall separated the source and receiver test rooms; when tested in isolation this separating partition provided a sound level difference of 44.5 dBA. The primary purpose of the testing was to investigate the cost and performance effectiveness of remedial solutions, therefore windows were generally appraised in their closed position, although two open conditions were tested for each type of window.

It was found that a window opening of 0.027 m^2 (summer night-time ventilation) reduced the sound insulation to 16 dBA and an opening of 0.36 m^2 (daytime summer ventilation) reduced the performance to 11 dBA for all windows irrespective of their overall size. Secondary window systems were also tested (hinged and sliding, proprietary and DIY) with staggered openings of 0.027 m^2 and 0.36 m^2. The inclusion of the stagger improved the window insulation to 19 dBA (vertical sliding proprietary secondary and double-hung sash and case windows) for the 0.36 m^2 opening.

The more detailed laboratory study undertaken in 1973 gave the following dBA sound level difference results from measurements conducted with a white noise source.

	Closed	Bottom sash open 0.4 m	Top sash open 0.4 m	Bottom sash open 0.8 m
Road traffic	24.4	16.9	17.0	10.2
White noise	25.2	16.3	16.4	10.8

Table 2.1 - Level Difference Performance of Pre 1918 wooden sash and case (dBA)

	Closed	Lower sash open 0.15 m	Both sashes open 0.15 m	Lower sash open 0.3 m, top sash open 0.15 m
Road traffic	28.0	17.5	10.7	7.6
White noise	31.3	18.9	11.5	8.0

Table 2.2 - Level Difference Performance of vertically sliding aluminium window (dBA)

	Closed	Bottom hung bottom light open	Centre pivoted centre part open	Bottom hung and centre lights open	Bottom hung top light open
Road traffic	21.4	12.9	4.0	2.9	9.3
White noise	25.4	13.1	5.3	3.6	9.1

Table 2.3 – Level Difference Performance of Steel casement window (dBA)

Ford and Kerry[11], [12] undertook comparative field and laboratory studies at a similar time, for the investigation of window insulation and natural ventilation. The tests were primarily on secondary glazing, on a 25 - 200 mm air space, with and without absorbent reveals. In addition, open single glazing was also tested.

The laboratory measurement results [11] are presented as the average sound reduction index (SRI) over the frequency range of 100 to 3150 Hz and as calculated dBA level differences for aircraft and road traffic noise. A summary of the single glazing insulation results is given in Tables 2.4 and 2.5.

	Closed	25 mm opening	200 mm opening
Average SRI, R_{av} (dB)	23	14	9
Aircraft noise dBA	26	16	11
Road traffic dBA	25	16	11

Table 2.4 - Horizontal sliding unit, aluminium framed, 4 mm glass, 2.4 x 1.3 m

	Closed	25 mm opening	200 mm opening
Average SRI, R_{av} (dB)	23	11	7
Aircraft noise dBA	25	14	9
Road traffic dBA	25	14	9

Table 2.5 - Vertical sliding unit, aluminium framed, 4 mm glass, 2.4 x 1.3 m

The secondary glazing results established that even with windows open, absorbent reveals are beneficial and insulation increases with frame separation. It was concluded that, in general, open double windows are about 10 dBA better than open single windows. The authors stressed that these results were from tests using random incidence sound whereas in a real situation the incident sound is often at a particular angle. In addition, it is noted that there was no significant difference in insulation found using a traffic or aircraft noise source.

The field measurements reported in the second paper [12] were performed on a house near Manchester Airport. Due to supply difficulties, the secondary glazing was a mixed arrangement of vertical sliding outer glazing and horizontal sliding inner glazing. The single glazing was the same thickness as that used in the vertical sliding outer glazing. Tape recorded measurements were made inside and outside the house simultaneously during aircraft or traffic movements. The inside microphone was mounted on a tripod positioned approximately in the centre of the room.

The external levels were measured with the microphone at the end of a 1 m pole, clamped under the eaves of the house adjacent to the window. The paper provides detailed information about the external noise spectra, the room dimensions, the room reverberation time and the ventilation rates for the various glazing arrangements. In summary, the dBA level differences for the single glazing were:

	Closed	100 mm opening
Aircraft noise dBA	30	22
Road traffic noise dBA	-	21

Table 2.6 - Vertical sliding unit, aluminium framed, 4 mm glass, 1.75 x 1.5 m

The secondary glazing results are also given in the paper. In order to compare the laboratory results [11] with the field-based measurements the lab-based SRIs were converted to dBA level differences based on the Manchester house room size, room absorption and window size. The single glazing sound insulation comparison is as follows:

		Closed	100 mm opening
Aircraft noise dBA	Calc'd	27	16
	Meas'd	30	22
Road traffic noise dBA	Calc'd	28	16
	Meas'd	-	21

Table 2.7 - Vertical sliding unit, aluminium framed, 4 mm glass, 1.75 x 1.5 m

The authors concluded '*The field measurements show an increased insulation over the predictions based on the laboratory experience. This is attributed not only to the more discrete angle of incidence of the sound waves experienced in practice compared with the random noise used in the laboratory, but also to the acoustic state of the measuring room. Other discrepancies are thought to be due to the different type and layout of the windows and to the position of the measuring microphone in a semi-reverberant room.'*

Similar field-based measurements were undertaken by Lawrence and Burgess in an experimental building in an industrial suburb of Sydney in 1983 [13]. Two types of façade were tested: timber stud (external cement sheet and internal plasterboard) and "brick-veneer" (external sheet replaced by brick). Road traffic noise was recorded simultaneously outside and inside two rooms (north and south facing). The outside microphone was located at 1 metre from the façade and the internal microphone was either placed centrally in the room or in up to five independent positions, in which case the results were subsequently averaged. Tests were performed with the rooms either empty or furnished and all results were normalised to take into account façade area and room absorption.

A summary of the L_{A10} sound level differences from the "brick-veneer" and open/closed window arrangement is as follows:

	Closed		Open 7-8% (rel. façade)	
	North	South	North	South
Horizontal sliding single glazed 3 mm glass	23	21-22	10	-
Horizontal sliding single glazed 6 mm glass	-	22	-	9
Horizontal sliding double glazed 100 mm spacing	26	-	11	11

Table 2.8 - L_{A10} sound level differences in road traffic noise

With staggered openings, the 100 mm double glazed unit reached 16 dB L_{A10} level difference.

The next significant investigation of noise reduction via open windows appears to be by Irvine in 1993 [26]. The main aim of the work was to experiment with different methods of natural ventilation to obtain optimum sound insulation. Laboratory and field-based measurements were conducted. However, unlike the previous field measurement studies, the outside microphone was placed 10 m from the façade so the dBA level differences are not directly comparable.

The external noise source during the field measurements was from rail traffic, which was in the same horizontal plane and approximately perpendicular to the test façade (since the results are in terms of L_{Amax} during a train pass-by). The openable section of the window was an aluminium framed upper light, which was bottom hung and opened inwards. Tests were carried out with and without ceiling absorption. When the upper light was closed, the level difference was 35 dBA (including 10 m distance correction). With the upper light open at increasing angles, the performance varied from 20 to 25 dBA (without absorption) and from 22 to 27 dBA (with absorption).

The lab test method on aluminium and timber framed versions of the same window followed '*BS 2750 as closely as possible*'. The receiver test chamber was reverberant and the source test chamber was semi-anechoic to simulate outdoor conditions in the absence of any reflecting objects. Aluminium sheets were fitted over the semi-anechoic wall, 1 m beyond the window, to simulate the effect of a normal building façade. The window system was installed in an opening between the two test chambers. Unfortunately, the measurements were affected by flanking transmission between the window frame and the opening perimeter.

The test results were corrected to allow for this, but for this reason, the test method only is described here. The measurements in the receiver room complied with BS 2750. The sound pressure incident on the window was determined by fixing the microphone to the window itself in six different positions and averaging the results. This averaged result was used for all subsequent tests. The sound source was a loudspeaker, 3.1 m from the façade at an angle of incidence 36° below the horizontal. The vertical angle of incidence was 0° for most tests but other angles were also tested.

The effect of an external baffle mounted in line with the upper openable light showed a marked increase in sound insulation performance above 630 Hz which implies that it is more suitable at reducing noise sources with a significant high frequency content, e.g. trains and fast flowing traffic. Adding absorption around the reveals gave a further small improvement of 1 to 3 dB. The performance dropped markedly at source noise angles of incidence more than 40°, with respect to the vertical plane perpendicular to the window. For the aluminium window with lightshelf, reveal absorption and 15° opening the R_w falls from 22 dB at 0° to 20 dB at 40° and 13 dB at 80°.

More recently, in 2002, Buratti [26] carried out an extensive series of lab-based measurements in order to "attain a single-numbered index which characterises the indoor noise reduction with open windows". The hypothesis was that the reverberant component of the received sound was a significant factor, particularly the reflection contribution from the ceiling. Therefore, a parameter was defined to evaluate the dBA noise reduction (via an open window) produced by a sound absorptive suspended ceiling for road and railway traffic.

The source signals were road traffic, low speed and high speed rail traffic, recorded in the city of Perugia, Italy. The source playback in the laboratory was by an omni-directional source in a reverberation room so no directional characteristics of the incident sound were evaluated. Two types of suspended ceiling were tested. For road traffic noise, the ceiling with greater absorption at mid-high frequencies gave a 4 dBA improvement compared to the less absorptive ceiling. Similarly, for rail traffic noise, the improvement was about 5 dBA (for both low and high speed rail traffic).

A recent paper by BRE entitled 'Aligning the aims of the new DfES Building Bulletin on natural ventilation with those of Building Bulletin 93 Acoustic design of schools' [15] states that there '…*is little information available in the literature on the airborne sound insulation of open windows*', and then quotes the relevant clauses in BS 8233 and PPG 24.

BRE have recently measured the façade airborne sound insulation of a few school classrooms with open windows as part of an EU project (RANCH) on road traffic noise, aircraft noise and children's cognition and health. The façade measurements were taken according to ISO 140-5 using a loudspeaker outside the classroom to give results in terms of the standardised level difference, $D_{2m,nT}$. Five schools were tested with various window and opening arrangements. The conclusions were that '*For traffic noise, window openings can give a reduction in the external A-weighted noise level of between 8 dB and 14 dB, a difference of 6 dB. For some schools this will be the deciding factor as to whether natural or mechanical ventilation is used'* Unfortunately, only a few measurements were available to make this initial assessment. The availability of more ISO 140-5 measurement data would allow DfES to issue guidance about the sound insulation of open windows that should be assumed when calculating the indoor ambient noise level.

Recently, there have been several papers proposing theoretical models of noise transmission via open windows. Some of these papers such as Zhang [27] are part of the progress towards active noise control of external noise. At the moment, they are only attempting to model low frequency noise transmission (below 200 Hz) and so are of limited interest. Other theoretical models are dealing with the noise transmission between two adjoining rooms via the external façade, in order to calculate flanking transmission due to open/closed windows.

An extensive review of noise control strategies used in passive ventilation systems is provided by De Salis[29]. This paper outlined the acoustic treatment of ventilator products which is typically addressed by increasing the air-path tortuosity and including absorbtion. The net effect is to increase the flow resistance through the system, thereby reducing ventilation efficiency. This performance reduction is not however currently addressed by the Building Regulations[17], which specifies background ventilation in terms of the openable free area of the air path. A change is however proposed[15], with a move away from the geometric requirement to a performance based 'equivalent area' specification.

The standard method of measuring the equivalent area for an air transfer device, derived from its air-flow performance at 1 Pa pressure difference, is given in BS EN 13141-1[21], however as an approximation, the draft approved document advises that the free area of a trickle ventilator is typically 25% larger than its equivalent area. The level of passive background ventilation required to meet the draft regulation is calculated for the whole dwelling taking account of the floor area, number of habitable rooms and height characteristics.

Chapter 3 Test Methodology

3.1 Measurement objectives

The aim of the laboratory measurements was to facilitate the project objectives empirically. The methodology has therefore been designed to provide comparative data on the variables anticipated to have an influence on the acoustic transmission characteristics of domestic windows. The specific parameters considered are:

a. window type/opening style
b. area of open window
c. size of window area
d. angle of source incidence
e. vent specification
f. vent type
g. window frame/seal materials
h. acoustic room condition

The standard test methodology for laboratory sound insulation testing on panel assemblies is contained within BS ISO EN 140 Part 3 'Laboratory measurements of airborne sound insulation of building elements' [22]. This method uses a test aperture between two highly reverberant environments. The use of a reverberant source environment however would not allow for the investigation of source location nor any influence from angled window openings. Therefore it was decided at an early point within the project that the test methodology provided in BS ISO EN 140 Part 5 'Field measurements of airborne sound insulation of façade elements and facades' [23] to be more appropriate; although based within a laboratory environment i.e. anechoic chamber.

A drawback to the use of a directional source is a higher level of measurement uncertainty and larger result variation. The use of the standard diffuse field method allows the sound pressure measurement to the source side to be spatially averaged, whilst any insulation measurement made within the direct field needs to be categorised by the source location and measurement position.

The potential for result scatter is illustrated in the predicted transmission losses of a 4.7 mm glass plate presented in Figure 9.19 of Beranek [31]. The insulation predictions are shown for four test conditions: plane wave normal incidence, plane wave at 45° incidence, plane wave at 85° incidence and for random incidence. The predicted single figure ratings, for the same homogenous sheet material, are

$R_{0°,w}$ 37 dB

$R_{45°,w}$ 34 dB

$R_{85°,w}$ 13 dB

$R_{random,w}$ 29 dB

The insulation rating specified from a test methodology needs to be appropriate to the intended application. The above example highlights the potential theoretical variations possible from small experimental deviations e.g. 21 dB difference in insulation rating for plane wave incidence at 45° or 85°.

The use of a standard reverberant source room enables a single figure insulation rating to be defined for any test condition and whilst it would provide a simplified approach for the project; as the glass panel predictions illustrate acoustic transmission loss is highly dependent on the source angle and is not satisfactorily encapsulated by a single figure diffuse-field measurement, particularly when applied to external, non-diffuse sources of noise. This problem is acknowledged in the prediction standard BS EN 12354-3:2000 [19] which provides the following comment in discussion of its limitations '*4.5 The difference in sound field between the various situations in the field and the assumption of a diffuse field for the prediction as in the laboratory situation, causes some systematic difference. The average of these differences is taken into account, thus reducing the systematic error, leaving some increase in the inaccuracy of the prediction due to random error*'.

Following careful consideration of the project aims it was agreed that the laboratory set-up should consist of an anechoic source room connected via the test aperture to a receiver room of residential character. The actual laboratory consisted of a 300 m^3

anechoic chamber, connected via a 12 m^2 test aperture, to a 210 m^3 reverberation chamber.

Laboratory sound insulation measurements tend to overestimate test results relative to field assessment due to measurement variation and the suppressed flanking conditions designed into test chambers. As this study is primarily concerned with the characterisation of low insulation systems, for which flanking transmission is anticipated to contribute only marginally, variation between comparable results obtained from this study and in-situ conditions are expected to be small.

Field measurements will additionally be exposed to a higher degree of meteorological variation than the controlled environmental conditions within the laboratory. Such variations are however outside the scope of this report.

3.2 Details of the facilities

Preliminary arrangements were necessary to adapt the acoustical laboratories to suit the test programme. Initial preparation works required the removal of the anechoic wedges across the full width of the separating wall to a height of 4m together with the removal of the anechoic chamber's composite steel lining, between the two test areas.

The rooms were both structurally isolated and were only coupled at the test aperture. The initial test suite layout is shown in Figure 3-1. The facilities also included an external control room with installed cabling runs to/from the anechoic and reverberation chambers.

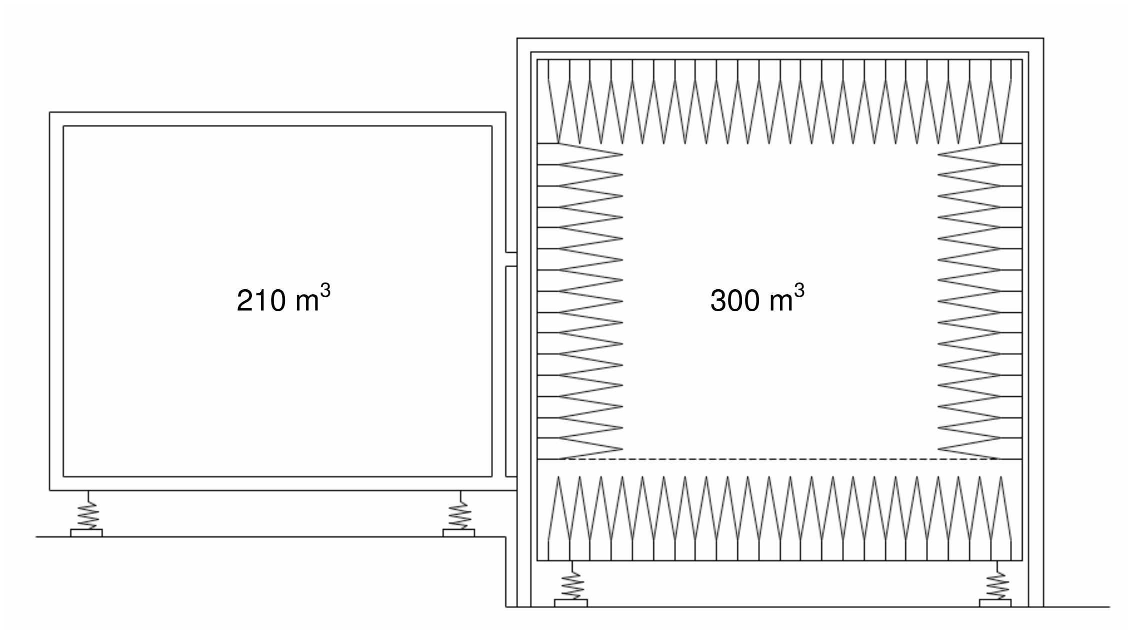


Figure 3-1 Initial laboratory layout (section view)

3.3 Choice/Specification of window assemblies

A questionnaire survey of window manufacturers and construction companies was undertaken to identify the range and styles of window units currently being installed in the UK. The response to this survey largely steered the choice of test units. The units selected were predominately PVCu frames, excepting one timber and one aluminium frame.

All window units were specified with sealed double-glazed units of 4 mm glass – 16 mm air space – 4 mm glazing specification, with one frame also having a heavier 4 mm glass – 18 mm air space – 6.4 mm laminated replacement pane. A total of five different manufacturers were used to source the test units. The range of windows included the most popular frame sizes, materials, opening types, seals and ventilation arrangements. Table 3.1 shows the physical properties of each window sample included in the test programme.

Sample	Description	Frame dimensions (mm) (area)	Frame depth (mm)	Glass dimensions (mm)	Mass (kg)	Seals
A	Vent + side hung (double)	2400 x 1050 ($2.52 m^2$)	60	424 x 834 560 x 600 464 x 194 424 x 834 560 x 600 464 x 194	75.6	foam
B	Reversible	1200 x 1050 ($1.26 m^2$)	71	1004 x 854	35.2	rubber
C	Tilt & turn (inwards)	900 x 1050 ($0.95 m^2$)	70	696 x 846	29.2	rubber
D	Sliding sash	900 x 1200 ($1.08 m^2$)	135	725 x 485 725 x 485	34.8	double brush
E	Top hung London	600 x 1050 ($0.63 m^2$)	70	452 x 493 403 x 362	16.9	rubber
F	Top hung London (Aluminium)	600 x 1050 ($0.63 m^2$)	48	530 x 473 487 x 430	16.9	rubber
G	Side hung (Timber)	600 x 900 ($0.54 m^2$)	94	414 x 695	18	foam, nylon sheath

Table 3.1 - Properties of window samples

Several window units were able to open in different configurations, the range of potential openings are shown in Table 3.2. Several frames had additional locking hardware enabling the window to be secured in an ajar position.

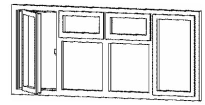
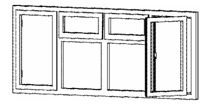
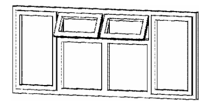
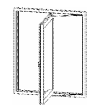
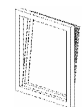
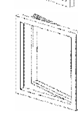
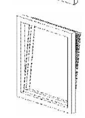
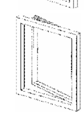
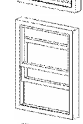
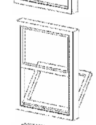
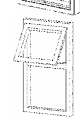
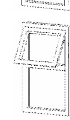
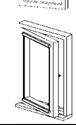
Term	Description	Configuration
A-1	Window A, outward opening casement - left hand side	
A-2	Window A, outward opening casement - right hand side	
A-3	Window A, top hung outward opening casements	
B	Window B, side swing reversible	
C-1	Window C, horizontal inward tilt	
C-2	Window C, vertical inward turn	
C-3	Window C, laminate glass, bottom hung inward tilt	
C-4	Window C, laminate glass, side hung inward tilt	
D-1	Window D, sliding sash upper section open	
D-2	Window D, sliding sash lower section open	
D-3	Window D, bottom hung inward opening	
E	Window E, top hung outward opening (PVC-U)	
F	Window F, top hung outward opening (Aluminum)	
G	Window G, side hung outward tilt (timber)	

Table 3.2 – Window test configurations

3.4 Test Procedure

The laboratory setup followed the requirements of BS EN ISO 140-1:1998 as far as was reasonably practicable, except where the project objectives required a different setup to that given in the standard.

The test methodology followed the functional requirements of BS EN ISO 140-3:1995 as closely as possible, with deviations only where integral to the aims of the project. A *Brüel & Kjær Pulse* nine channel data acquisition system was used for the testing, with 3 fixed microphones used to characterise the source noise levels and 6 fixed microphones used within the receiver room. A 30 second pink noise signal, generated by the data acquisition system was used as the acoustic excitation, fed through amplifying loudspeakers. The test signal arrangement is shown in Figure 3.2.

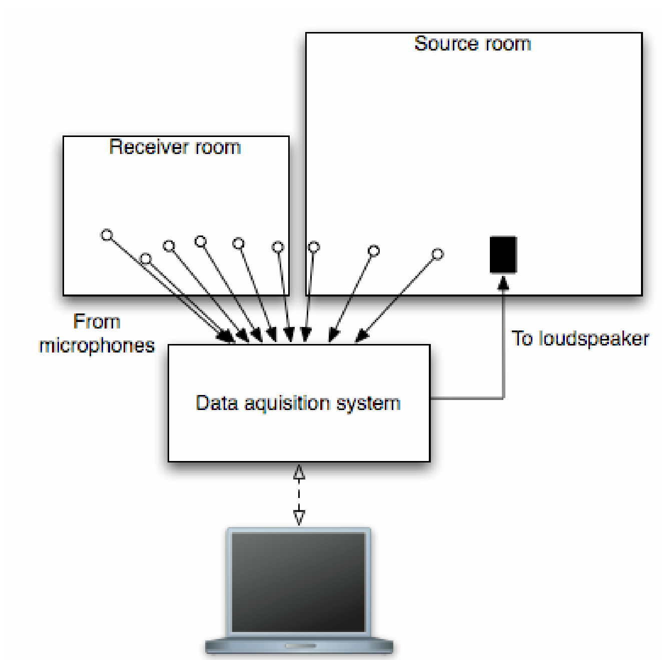


Figure 3.2 - Test system schematic diagram

The six microphones in the receiver room, R1 to R6, were positioned at heights between 1.2 m and 1.5 m and were all, with exception of R1, at least 700 mm away from any other surface or measurement position. The positions are shown graphically in Figure 3.3, with their respective distances shown in Table 3.3.

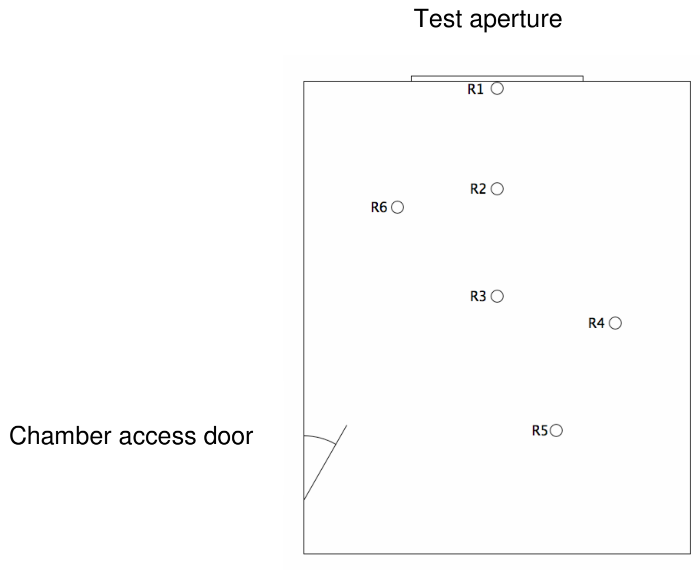


Figure 3.3 - Receiver room microphone positions (plan view)

Microphone	Height (m)	Distance from centre of window (m)
R1	1.5	0.01
R2	1.35	1
R3	1.2	2
R4	1.35	2.5
R5	1.5	3.3
R6	1.35	1.5

Table 3.3 - Receiver room microphone positions

The three microphones located in the source room, S1 to S3, were positioned at heights between 1.2 m and 1.5 m. These microphones were rotated around the centre of the test window at fixed radii, depending on the location of the source loudspeaker.

Five loudspeaker configurations (L1-L5) were used at a distance of 2.72 m from the centre of the window specimen and at angles to the facade of 15º, 55º, 90º, 125º and 165º. In addition, a coherent line source provided by four parallel loudspeakers, was positioned opposite the façade at a separation of 2.72 m. The final loudspeaker position (L6) was located 5 m directly in front of the test window, this location is in accordance with BS EN ISO 140-5.

The positions of the source microphones and loudspeaker are shown in Figure 3.4, with their respective distances shown in Table 3.4.

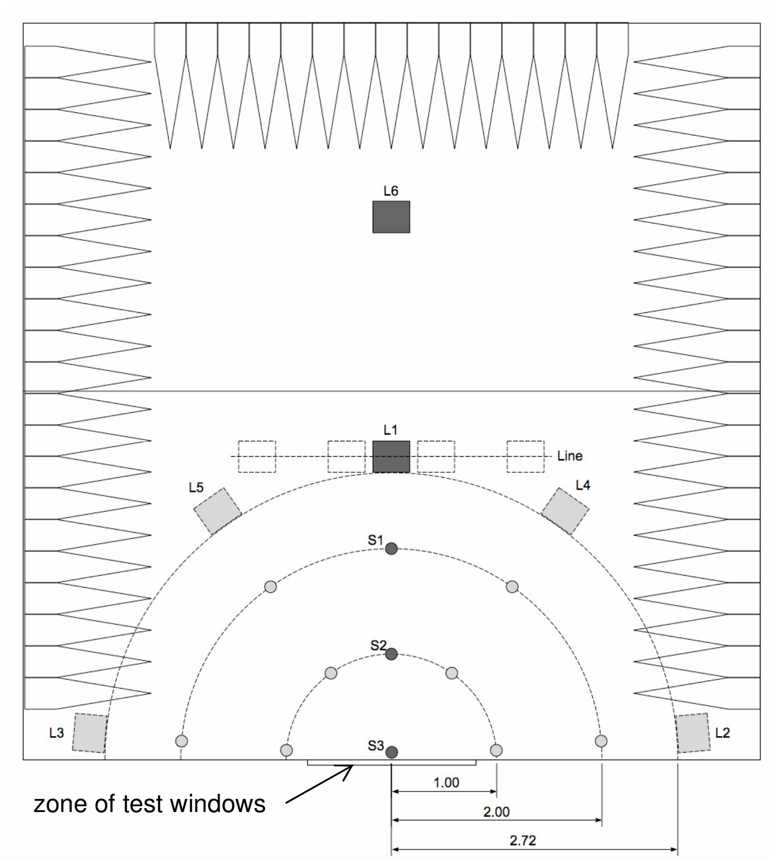


Figure 3.4 - Source room microphone and loudspeaker positions (plan view)

Microphone/loudspeaker position	Height to mic/speaker centre (m)	Distance from centre of window (m)	Horizontal angle with façade
S1	1.20	2.00	-
S2	1.35	1.00	-
S3	1.50	0.02	-
L1	1.07	2.72	90º
L2	1.07	2.72	15º
L3	1.07	2.72	165º
L4	1.07	2.72	55º
L5	1.07	2.72	125º
L6	1.07	5.00	90º
Coherent Line source	1.07	2.72	90º

Table 3.4 - Source room microphone and loudspeaker positions

The floor of the anechoic chamber was lined with chipboard flooring directly in front of the test wall. The boarding was used to simulate the ground in front of a façade. Additional measurements were also made without the chipboard to look at ground affect.

3.5 Wall construction

A cavity masonry wall, similar to that commonly used in dwellings, was built as the core wall within the test aperture separating the source and receiver test rooms. The construction consisted of two leaves of 100mm concrete blockwork, rendered on the source face with 13mm cement and on the receiving room face with 12.5mm plasterboard on timber straps. The leaves were separated by a 50mm cavity, using butterfly wire wall ties. The wall was initially built across the whole test aperture and included a 2.4 m lintel supported on two masonry piles either side on the infill. The wall was then tested before it was knocked through in order to provide an aperture in which window specimens could be mounted. Throughout the processes of construction and knocking through the wall, care was taken that mortar and debris did not fall into the cavity and thereby cause unrepresentative bridging effects between the two masonry leaves.

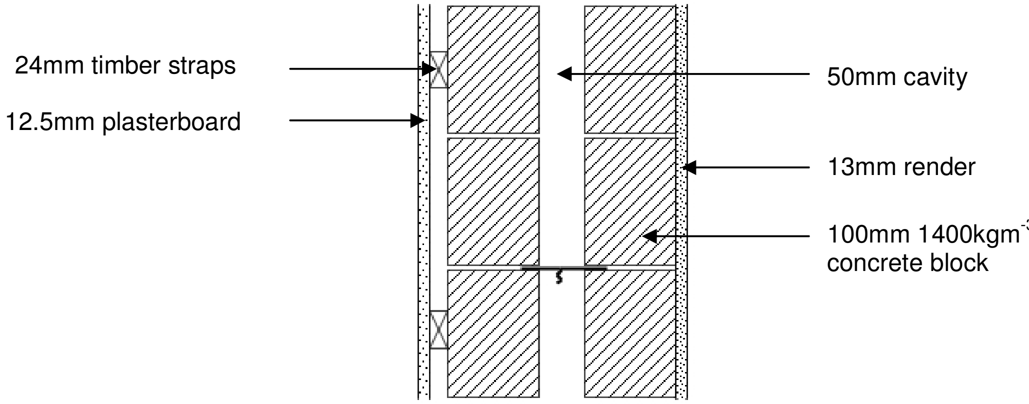


Figure 3.5 - Filler wall construction simulating external wall characteristics

3.6 Receiver room simulation

The reverberation time within the reverberation chamber was too long to simulate a domestic environment. A smaller test room was therefore constructed within the reverberation room to better simulate a typical residential room. The test room was constructed using a timber frame lined with plasterboard. The approximate internal dimensions of the test room were 4.4 m x 3.6 m x 2.4 m (38m^3). The laboratory test arrangement after modifications had been made is shown in Figure 3.6.

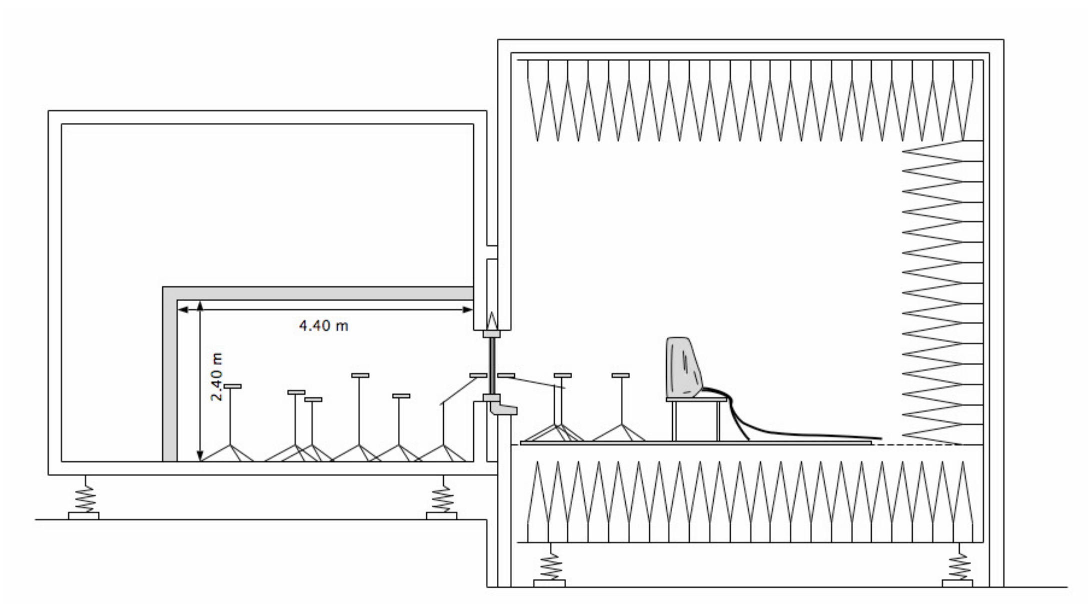


Figure 3.6 - Post-modifications laboratory setup

3.7 Measurement Precision

The accuracy of the sound level measurement equipment complied with accuracy class 1 defined in IEC 651 and IEC 804. At the start of each measurement sequence, all microphones were calibrated at a reference level of 94 dB at 1000 Hz. The calibrator complied with the requirements of accuracy class 1 defined in IEC 942.

The third-octave band filters in the data acquisition system complied with the requirements defined in ISO 354.

The reverberation time measurement equipment complied with the requirements defined in ISO 354.

The loudspeaker settings were adjusted to ensure a reasonably flat spectrum across the third-octave bands from 50 Hz to 5 kHz, when pink noise was used as an input to the system. Sound emitted from the loudspeaker(s) did not have differences in level greater than 6 dB between adjacent third-octave bands, measured 1 m from the loudspeaker centre.

Test specimens were stored for more than 24 hours at the test temperature, which was always between 17 ºC and 23 ºC.

3.8 - Window test arrangements

Testing of each window configuration was initially carried out with the window closed. The windows were then tested with the windows open, at five defined settings:

- untensioned (UT –window lightly closed seals uncompressed)
- ajar (window locked whilst allowing for ventilation);
- 0.05 m^2 (50,000 mm^2);
- 0.10 m^2 (10,0000 mm^2);
- 0.20 m^2 (20,0000 mm^2).

The size of the openings was measured perpendicular to the potential air flow in the plane of the opened light. A description of the terminology used to describe the window condition is given in Table 3.5.

Term	Description
Closed	Window was closed.
UT	The window catch was released such that the window seals were not compressed.
Ajar	If the mechanism was available, the window was opened a small amount to a secondary keeper set further out from the primary keeper, which allowed the window to be secured whilst still providing ventilation.
50K	The window was opened to an open area value of approximately 50,000 mm^2.
100K	The window was opened to an open area value of approximately 100,000 mm^2.
200K	The window was opened to an open area value of approximately 200,000 mm^2.

Table 3.5 – Window test condition terminology

An illustration of the scope of the laboratory testing is given below, indicating the basic parameters that were tested. These include the 14 openable window configurations (and test wall) which were each tested at 7 source locations with 6 distinct window conditions and with the data recorded by 9 microphone channels.

Test Unit	Source Position	Test Condition	Receiver Position
Wall	L1	Closed	S1
A-1	L2	Untensioned	S2
A-2	L3	Ajar	S3
A-3	L4	50,000 mm^2 Open	R1
B	L5	100,000 mm^2 Open	R2
C-1	L6	200,000 mm^2 Open	R3
C-2	Line		R4
C-3			R5
C-4			R6
D-1			
D-2			
D-3			
E			
F			
G			

Additional sets of measurements looked specifically at the effect of window ventilators, receiving room condition, effect of the external hard ground surface and the variation in the receiving room sound field.

Chapter 4 Results

4.1 Result format

The basic output from each measurement undertaken in the laboratory was nine individual sets of one-third octave sound pressure spectra across the frequency range 50 to 5000 Hz. The measurement dataset additionally included background noise spectra, receiver room reverberation time spectra, environmental data such as temperature, humidity and air pressure and general time-stamps, text descriptions and microphone calibration information. The single figure results presented in this section are not directly measured; rather they are calculated from combinations of sound pressure spectra to provide single integer, weighted level differences, D_w's, determined by level fitting a reference curve to the background corrected level difference spectra as described in BS EN ISO 717-7 [26].

A full set of standardised one-third octave level difference results (D_{nT}) are presented in an accompanying document; calculated for every experimental set-up for each source measurement position, relative to the averaged receiving room result, standardised to the receiver room reverberation and the 0.5 s T_0 reference. The reverberation time measurement results are tabulated in Appendix A.

Three level difference spectra, and their corresponding single figure results, were calculated from each test dataset. The calculations used each source microphone result (S_1, S_2 & S_3) in combination with the logarithmically averaged receiver spectrum at five receiver room measurement positions ($R_{2\text{-}6}$). These receiver room microphones R_2, R_3, R_4, R_5 and R_6 were located within the specification tolerance given within BS EN ISO 140 – 3 [22] for measurement of the receiver room sound field.

4.2 Test results

The full programme of the laboratory testing is outlined in Chapter 3, however the basic test regime used seven window samples (A – G), fourteen opening configurations (A-1, A-2… G), seven source locations (L1, L2… Line) and six basic window conditions (closed, untensioned (UT), ajar, 50k, 100k, 200k). The following tables (4.1 to 4.5) present the calculated weighted level difference results relative to the three source microphone locations S_1, S_2 and S_3 respectively.

4.3 Core wall performance

The initial test condition, prior to the installation of any of the test window units, was that of the core cavity block wall built within the entire test aperture. The derived single figure weighted level difference results are shown in Table 4-1 for each source angle configuration.

Loudspeaker position	$D_{w\,(S1)}$ (dB)	$D_{w\,(S2)}$ (dB)	$D_{w\,(S3)}$ (dB)
L1	58	51	52
L2	46	47	54
L3	45	46	53
L4	51	49	53
L5	51	48	52
L6	51	50	52
Line source	55	53	56

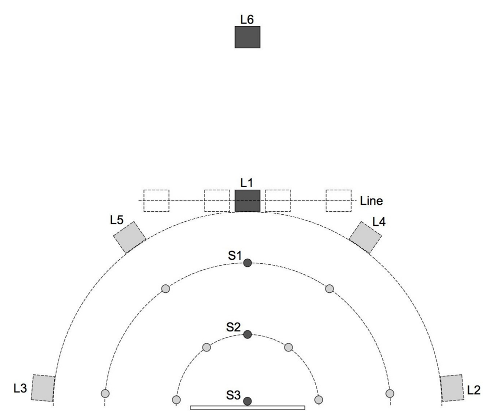


Table 4-1. Weighted level difference results for test wall, D_w (dB)

The results for the core wall measurements show significant variability, with the maximum spread in single figure results of 14 dB between loudspeaker's L1 and L3. In both instances the reference source microphone was S1, located directly between the source and wall centre, 0.72 m horizontally from each speaker and 2 m from the wall centre. The spread of results becomes progressively smaller for the S2 and S3 referenced measures. The grazing angle loudspeakers result in smaller insulation ratings for a combination of reasons. There is a greater influence from bending waves at grazing incidence, however a significant factor is the effect on the external sound field due to destructive interference between the direct and façade reflected sound, evidenced at the S1 and S2 grazing microphone positions although not exhibited to the same degree for S3. The location very close to the façade will be subject to reduced phase difference between the direct and reflected sound resulting in constructive sound reinforcement.

4.4 Window performance

Table 4-2 shows the weighted level difference result from each closed window unit installed in the masonry test wall. The masonry wall was re-built to accommodate each new test frame, with perimeter joints sealed, external wall face rendered and internal framing and plasterboard made good. The glazing specification is common for each window (4 – 16 – 4 mm) with the opening lights tensioned closed and the source at loudspeaker position L6. Window sample C was the only unit to incorporate a 4000 mm^2 trickle vent within the frame. These results correspond to the measurements made with a ventilator and canopy fitted although with the trickle ventilator closed.

Note that the D_w presented represents the composite insulation of the whole façade and not just the window insulation, although the window is the dominant sound transmission path.

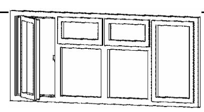
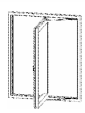
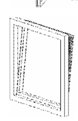
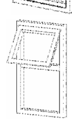
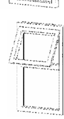
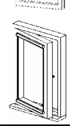
Window specimen	Frame Area (m^2)	Diagram	$D_{w\,(S1)}$ (dB)	$D_{w\,(S2)}$ (dB)	$D_{w\,(S3)}$ (dB)
A	2.52		35	35	34
B	1.26		36	37	38
C	0.95		36	36	36
D	1.08		40	39	36
E	0.63		45	45	46
F	0.63		43	42	44
G	0.54		43	43	43

Table 4-2. Weighted level difference of closed window samples. (L6, $R_{2\text{-}6}$) D_w (dB)

4.5 Window result tables

The core results from the measurement programme are presented in Table 4-3, Table 4-4 and Table 4-5. These extensive tables present results as the weighted level difference relative to each source microphone, located 2m from the façade ($D_{w\,(S1)}$), 1m from the façade ($D_{w\,(S2)}$) and 0.01 m from the façade ($D_{w\,(S3)}$).

The Tables show the effect for each window sample and opening configuration of changing source incidence angle and of the increased area of window opening.

To assist in reviewing the tables a colour scheme has been used whereby upper levels of sound insulation are shown by yellow and lower insulation levels by red.

L1	A-1	A-2	A-3	B	C-1	C-2	C-3	C-4	D-1	D-2	D-3	E	F	G
Closed	41	41	41	42	40	40	38	38	43	43	43	50	49	47
UT	35	33	36	28	27	27	26	28	43	43	43	45	32	40
Ajar	27	26	26									28	27	40
50K	22	22	21	18	20	21	20	21	20	17	20	22	22	20
100K	21	21	20	17	20	20	20	20	19	16	18	20	20	19
200K	19	19	17	15	19	19	19	20	17	14	16	18	18	18

L2	A-1	A-2	A-3	B	C-1	C-2	C-3	C-4	D-1	D-2	D-3	E	F	G
Closed	41	41	41	42	42	42	43	43				52	50	49
UT	35	32	38	29	31	34	35	35				52	39	43
Ajar	28	25	31									33	30	27
50K	25	19	26	22	25	28	25	28				27	26	24
100K	24	17	24	21	24	26	24	27				26	25	24
200K	22	16	22	20	22	24	23	25				24	23	25

L3	A-1	A-2	A-3	B	C-1	C-2	C-3	C-4	D-1	D-2	D-3	E	F	G
Closed	44	44	44	41	44	44	43	43	46	46	46			48
UT	37	36	41	28		33		30	46	46	46			37
Ajar	28	32	34											29
50K	23	28	29	22		25		21	30	27	29			21
100K	21	27	28	21		24		21	28	25	26			19
200K	19	26	25	20		22		21	25	23	25			16

L4	A-1	A-2	A-3	B	C-1	C-2	C-3	C-4	D-1	D-2	D-3	E	F	G
Closed	42	42	42	42	38	38	38	38				49	48	48
UT	33	34	35	25		30	26	30				44	37	41
Ajar	25	26	26									29	27	25
50K	22	21	22	19		23	21	22				22	21	21
100K	21	19	21	18		23	21	22				21	20	21
200K	20	17	18	17		22	20	21				19	18	21

L5	A-1	A-2	A-3	B	C-1	C-2	C-3	C-4	D-1	D-2	D-3	E	F	G
Closed	42	42	42	40	38	38	38	38	43	43	43			47
UT	35	32	37	28	27	28		28	43	43	43			40
Ajar	26	25	26											25
50K	21	22	21	18	22	20		22	23	19	22			19
100K	19	21	20	17	20	20		21	21	18	20			18
200K	17	20	18	16	19	19		19	19	15	18			16

L6	A-1	A-2	A-3	B	C-1	C-2	C-3	C-4	D-1	D-2	D-3	E	F	G
Closed	35	35	35	36	36	36	35	35	40	40	40	45	43	43
UT	29	28	31	23	21	22	22	23	40	40	40	44	35	40
Ajar	21	22	21									23	23	20
50K	18	18	16	14	17	18	17	17	18	16	20	17	18	15
100K	17	17	16	13	16	17	16	17	16	14	17	16	16	14
200K	15	15	13	12	15	15	15	15	13	10	14	15	15	14

Line	A-1	A-2	A-3	B	C-1	C-2	C-3	C-4	D-1	D-2	D-3	E	F	G
Closed	36	36	36	37	33	33	33	33	41	41	41	48	45	44
UT	30	28	32	24	20	21	21	24	41	41	41	48	35	40
Ajar	24	22	22									27	21	24
50K	19	18	16	15	15	15	16	16	19	16	19	20	17	20
100K	18	17	15	14	15	16	16	15	17	15	17	18	15	19
200K	16	15	12	13	13	15	14	14	15	13	15	16	13	18

colour key:

43	39	35	31	27	23	19	15	11	7

Table 4-3 Open area D_w insulation results (dB) (Source microphone S1)

L1	A-1	A-2	A-3	B	C-1	C-2	C-3	C-4	D-1	D-2	D-3	E	F	G
Closed	37	37	37	37	35	35	34	34	38	38	38	46	44	43
UT	30	28	31	23	23	23	22	23	38	38	38	41	28	37
Ajar	22	22	21									25	23	37
50K	18	17	17	13	15	15	15	15	15	13	16	18	18	16
100K	16	16	16	11	15	14	15	14	14	12	13	16	15	14
200K	15	14	12	10	13	13	13	14	12	9	11	14	14	13

L2	A-1	A-2	A-3	B	C-1	C-2	C-3	C-4	D-1	D-2	D-3	E	F	G
Closed	35	35	35	36	36	36	36	36				45	43	41
UT	28	26	32	22	25	27	28	27				45	32	36
Ajar	22	20	25									26	24	20
50K	19	13	19	14	19	21	19	21				20	19	17
100K	18	12	18	14	17	20	17	20				19	18	17
200K	16	10	16	13	15	18	16	18				17	16	18

L3	A-1	A-2	A-3	B	C-1	C-2	C-3	C-4	D-1	D-2	D-3	E	F	G
Closed	35	35	35	34	36	36	36	36	38	38	38			43
UT	28	27	32	21		24		23	38	38	38			32
Ajar	19	23	25											24
50K	14	19	20	15		17		14	22	20	21			16
100K	12	18	18	14		15		14	20	17	18			14
200K	10	16	16	13		14		14	18	15	16			11

L4	A-1	A-2	A-3	B	C-1	C-2	C-3	C-4	D-1	D-2	D-3	E	F	G
Closed	36	36	36	35	33	33	34	34				45	42	42
UT	27	28	30	20		25	22	26				40	32	36
Ajar	21	22	22									26	23	20
50K	16	16	17	14		18	17	18				19	17	17
100K	15	14	16	13		18	17	18				18	15	16
200K	14	12	13	12		17	16	17				16	14	16

L5	A-1	A-2	A-3	B	C-1	C-2	C-3	C-4	D-1	D-2	D-3	E	F	G
Closed	36	36	36	34	34	34	34	34	39	39	39			42
UT	30	27	32	23	23	24		22	39	39	39			35
Ajar	22	21	22											22
50K	16	16	17	14	18	16		17	19	16	18			15
100K	15	15	16	13	16	15		16	17	14	16			14
200K	12	14	13	11	15	14		14	14	12	14			13

L6	A-1	A-2	A-3	B	C-1	C-2	C-3	C-4	D-1	D-2	D-3	E	F	G
Closed	35	35	35	37	36	36	34	34	39	39	39	45	42	43
UT	28	27	31	24	21	22	21	23	39	39	39	43	34	40
Ajar	21	22	20									22	22	20
50K	17	17	16	14	17	18	17	16	16	15	19	17	16	15
100K	16	16	15	12	15	16	16	16	14	13	15	15	15	14
200K	15	15	12	11	14	13	14	13	12	9	13	14	13	13

Line	A-1	A-2	A-3	B	C-1	C-2	C-3	C-4	D-1	D-2	D-3	E	F	G
Closed	36	36	36	36	33	33	33	33	38	38	38	44	42	41
UT	30	27	31	22	20	21	21	23	38	38	38	44	34	36
Ajar	22	20	20									23	21	23
50K	17	17	16	12	15	16	15	15	17	14	17	16	16	17
100K	17	16	15	10	15	16	14	15	15	13	14	14	14	16
200K	15	14	11	9	13	15	13	13	13	10	12	13	12	15

colour key:

43	39	35	31	27	23	19	15	11	7

Table 4-4 Open area D_w insulation results (dB) (Source microphone S2)

L1	A-1	A-2	A-3	B	C-1	C-2	C-3	C-4	D-1	D-2	D-3	E	F	G
Closed	36	36	36	37	36	36	34	34	35	35	35	46	45	42
UT	30	28	31	23	23	22	22	23	35	35	35	40	28	35
Ajar	21	20	20									23	23	35
50K	17	17	16	13	14	14	14	14	14	10	13	18	20	17
100K	15	16	14	11	14	13	14	13	13	9	12	16	17	17
200K	13	13	12	10	12	11	11	11	12	7	10	14	16	16

L2	A-1	A-2	A-3	B	C-1	C-2	C-3	C-4	D-1	D-2	D-3	E	F	G
Closed	38	38	38	37	38	38	37	37				47	45	42
UT	32	30	35	24	26	29	29	29				47	35	37
Ajar	26	23	28									29	25	19
50K	21	16	22	17	18	21	18	20				23	21	17
100K	20	15	21	16	16	19	15	19				21	20	17
200K	16	13	19	15	13	15	14	15				20	19	17

L3	A-1	A-2	A-3	B	C-1	C-2	C-3	C-4	D-1	D-2	D-3	E	F	G
Closed	38	38	38	36	38	38	37	37	38	38	38			45
UT	31	30	35	24		26		24	38	38	38			34
Ajar	22	25	28											24
50K	16	20	22	17		17		13	22	19	21			18
100K	14	19	21	16		15		12	21	17	18			14
200K	13	16	18	15		12		12	19	15	17			9

L4	A-1	A-2	A-3	B	C-1	C-2	C-3	C-4	D-1	D-2	D-3	E	F	G
Closed	37	37	37	38	34	34	34	34				46	45	42
UT	29	29	31	22		26	22	26				42	35	37
Ajar	20	21	22									27	25	19
50K	18	16	17	15		17	16	15				20	20	18
100K	17	15	17	12		17	15	14				18	18	17
200K	15	13	14	11		14	14	14				17	16	17

L5	A-1	A-2	A-3	B	C-1	C-2	C-3	C-4	D-1	D-2	D-3	E	F	G
Closed	37	37	37	36	35	35	34	34	36	36	36			44
UT	31	28	33	25	24	25		24	36	36	36			37
Ajar	22	21	23											23
50K	17	17	17	12	19	16		18	17	12	14			18
100K	15	17	17	11	17	15		16	15	10	13			17
200K	13	15	14	12	14	14		14	13	8	12			16

L6	A-1	A-2	A-3	B	C-1	C-2	C-3	C-4	D-1	D-2	D-3	E	F	G
Closed	34	34	34	38	36	36	34	34	36	36	36	46	44	43
UT	28	27	31	25	21	22	21	23	36	36	36	44	35	40
Ajar	19	20	20									23	24	17
50K	16	17	16	14	16	17	15	14	15	13	17	17	19	16
100K	15	16	15	11	14	15	14	14	13	10	15	16	17	16
200K	13	13	12	10	13	12	13	12	11	8	12	14	15	12

Line	A-1	A-2	A-3	B	C-1	C-2	C-3	C-4	D-1	D-2	D-3	E	F	G
Closed	36	36	36	36	36	36	35	35	35	35	35	46	45	44
UT	29	26	31	22	23	24	23	26	35	35	35	46	35	34
Ajar	20	18	19									24	22	18
50K	16	15	15	12	17	16	18	17	14	11	12	18	18	15
100K	16	15	15	11	17	16	18	16	12	9	10	17	17	14
200K	13	12	12	11	14	14	15	14	10	8	10	15	15	15

colour key:										
	43	39	35	31	27	23	19	15	11	7

Table 4-5 Open area D_w insulation results (dB) (Source microphone S3)

The closed window results clearly illustrate the effect of the window area on the façade insulation, with smaller windows achieving higher levels of sound insulation.

The sound insulation is reduced as the window is progressively opened, with the largest single decrease in insulation occurring between the Untensioned to Ajar conditions.

For most window types there was a 1 dB reduction from the 50K to the 100K position and a 1 to 2 dB reduction from the 100K to 200K position. The exception is the sliding configurations of window D, which exhibits a slightly larger reduction of 2 to 3 dB for each doubling of open area.

The furthest source microphone position (S1) records a range of 10dB across the window types and the closest microphone position (S3) records a range of 12dB.

The results presented in the following sections 1.6 to 1.14 concentrate on the measurement configuration of speaker L6, located normal to the façade at a distance of 5 m, and source microphone S1, set 2 m from the façade towards the speaker. This position corresponds closest to that recommended in BS EN ISO 140—5 ‘Field measurements of airborne sound insulation of façade elements and facades’.

4.6 Glazed area

The effect of the glazed on measured level difference results are highlighted in Table 4-6.

Glazed area (m2):	1.56			0.7		0.37
L6	A-1	A-2	A-3	D-1	D-2	E
Closed	35	35	35	40	40	45
50K	18	18	16	18	16	17

Table 4-6. Glazed area D_w insulation results (dB)

The sample tests shown in Table 4.6 identify that a doubling of window area (with windows closed) causes a reduction in the D_w insulation results of approximately 5 dB for the dataset considered. The influence of the glazed area is negligible once the windows are open, indicating the insulation result for the opening is significantly less than that of the other façade components such that the dominant sound transmission path is through the opening.

4.7 Glazing specification

The effect that the glazing specification has on the measured level difference is shown in Table 4-7. Measurements were carried out on Window C (tilt & turn) with standard 4-16-4 glass. They were repeated for the upgraded specification of 4-18-6.4 laminated glass.

Glazing:	4-16-4		4-18-6.4		
L6	C-1	C-2	C-3	C-4	
Closed	36	36	35	35	D_w
Closed	33	33	34	34	$D_w + C_{tr}$
50K	17	18	17	17	D_w

Table 4-7 Glazing specification D_w insulation results (dB)

Table 4-7 presents three sets of results involving the closed condition D_w and D_w+C_{tr} result and the D_w result for the open 50,000mm^2 open condition. Due to the reinsertion of the upgraded glass (Specimens C-3 and C-4) it was discovered after testing that there had been leakage at the seal. This primarily affected the high frequencies, which is demonstrated by the poorer performance for the D_w values when compared to (C-1 and C-2).

However, the leakage did not adversely influence the lower frequency performance as demonstrated by the D_w+C_{tr} values, which incorporate a low frequency spectrum adaptation term.

It is noticeable that once the window is opened the influence of the glazing specification is nullified.

4.8 Frame type

The effect of frame type on the measured level difference is shown in Table 4-8. Types tested included PVC-U, aluminium and timber frames. At the time of testing it was not possible to test a timber window of the exact same type as the PVC-U and aluminium frame types. Therefore a timber window of similar size but of different opening type was used.

Frame:	PVC-U	Alu	Timber
L6	E	F	G
Closed	45	43	43
50K	17	18	15

Table 4-8. Frame type D_w insulation results (dB)

It can be seen that the influence of the window frame material when the window is closed and once the window has been opened is insignificant. The frame type may however have more influence on the performance of a window fitted with very high performance glazing.

4.9 Seals

The condition of window seals is known to have a significant effect on the acoustic performance of a closed window assembly. Windows E and F were tested with their seals progressively removed. The results are shown in Table 4.9. The term 'light seals' refers to the seals present on the opening section of the window. 'Frame seals' refers to the seals present on the window frame.

Window type	Closed	Untensioned	Opening light seals	Frame seals	D_w (dB)	
E	?		?	?	45	Frame & light seals
E	?			?	43	Only frame seals
E	?				25	No seals
F	?		?	?	43	Frame & light seals
F	?			?	41	Only frame seals
F	?				29	No seals
E		?	?	?	44	Frame & light seals
E		?		?	41	Only frame seals
E		?			26	No seals
F		?	?	?	35	Frame & light seals
F		?		?	30	Only frame seals
F		?			29	No seals

Table 4-9 Seal removal D_w insulation results (dB)

When the window conditions are closed or untensioned and both light and frame seals are in place the results are consistent. The removal of light seals results in a 2 to 3dB reduction in performance. However, the removal of both light and frame seals leads to a significant and consistent drop in insulation performance.

The effect of upgrading the seals by fitting an additional set of proprietary seals was tested, using window C closed. The D_w insulation results are shown in Table 4-10.

Window type	Original frame seals	Original light seals	Additional proprietary seals	D_w (dB)	
C	✓	✓		35	Frame & light seals
C	✓	✓	✓	41	Frame & light & proprietary seals
C				21	No seals

Table 4-10. Proprietary seals D_w insulation results (dB)

The adoption of proprietary seals in addition to the light and frame seals increased the insulation performance of the test window by 6dB. As with other parameter changes the influence of the additional proprietary seals are negligible once the windows are opened.

4.10 Ventilator performance

A range of ventilator products were also tested. The tests were performed using window C which was factory prepared with two 2000 mm^2 slots in the frame. A range of trickle ventilator inserts and external canopies were tested within the slots. Tests were also performed using a fitted over-frame vent, for which Window C needed to be re-installed, with a taller aperture size, into the test wall. A section of typical window head conditions are shown in Figure 4-1, showing a window frame with no vent fitted, with an open over-frame ventilator product installed and with an open slot ventilator installed.

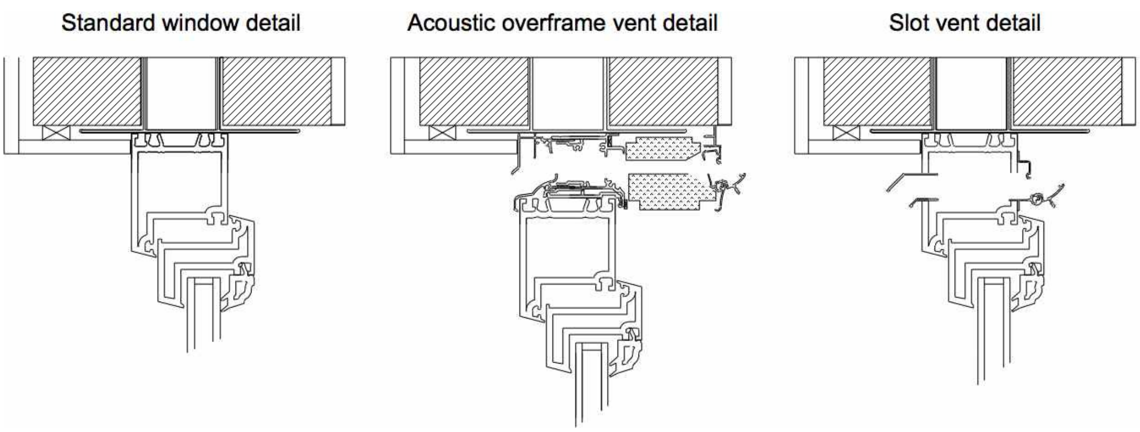


Figure 4-1 Standard ventilator details

The single figure results of the ventilator measurements are shown in Table 4.11, with the results divided into ventilator closed and ventilator open datasets. The first column in Table 4.11 shows the highest insulation result is achieved for this window with all vents blocked. The results with the ventilators unblocked are very consistent across the range of products; however it is clear that there is a significant drop in the level of façade when any of the ventilators tested are installed, even in the closed position.

	Vent slots sealed	Vent closed	Vent closed	Vent closed	Vent closed	Vent closed	Vent closed	Vent closed	Acoustic vent closed	Vent closed	Vent closed	Overframe vent closed
Canopy	-	-	-	-	-	1	2	3	4	6	7	-
Vent	-	1	2	4	5	1	2	3	4	1	7	-
Closed	41	35	34	36	36	35	36	33	36	35	35	36
UT	-	23	24	25	25	24	24	26	25	25	25	26
50K	-	-	-	-	-	18	-	-	-	-	-	18
Open area (mm^2)	0	4000	4000	4000	2000	4000	4000	4000	4000	4000	4000	6880

	Vent slots open	Vent open	Vent open	Vent open	Vent open	Vent slots open	Vent open	Vent open	Vent open	Vent slots open	Acoustic vent open	Vent slots open	Vent slots open	Vent open	Vent slots open	Vent open	Overframe vent open
Canopy	-	-	-	-	-	1	1	2	3	4	4	5	6	6	7	7	-
Vent	-	1	2	4	5	-	1	2	3	-	4	-	-	1	-	7	-
Closed	29	29	29	30	33	29	29	30	30	29	30	29	29	29	-	30	31
UT	23	24	23	24	25	-	23	25	25	-	25	-	24	24	24	24	25
50K	-	-	-	-	-	-	18	-	-	-	-	-	-	-	-	-	18
Open area (mm^2)	4290	4000	4000	4000	2000	4290	4000	4000	4000	4290	4000	4290	4290	4000	4290	4000	6880

colour key:										
	43	39	35	31	27	23	19	15	11	7

Table 4-11 Ventilator performance D_w insulation results (dB)

The upper table shows the results with the ventilators closed whilst the lower table shows the results of the ventilator products tested in their open condition. Also included within the table is a measurement performed with the windows closed although with the slot empty. This measurement result is effectively the baseline against which the acoustic performance of the slot ventilators is judged. It can however be seen that the results for the 'vent open' condition show little improvement over this baseline performance.

4.11 Receiver room characteristics

Five distinct room conditions were used to assess the variation in the sound insulation result for the façade. The condition of the room, whilst not altering the flow of sound energy coming from the source room through the façade, does change the receiver room sound-field, thereby appearing to alter the measured insulation result. The room changes were created by introducing soft material into the receiver room from condition D0, corresponding to the base condition with only bare surfaces exposed. D1 included a soft floor covering, D2 and D3 included curtains whilst Condition D4 incorporated absorptive material usually used within the anechoic chamber. Table 4-12 summarises the various absorbent conditions used in these tests.

Condition	Soft floor covering	Light curtains	Curtains closed	Heavy curtains	Absorbent wedges
D0					
D1	✔				
D2	✔	✔			
D3	✔	✔	✔		
D4	✔		✔	✔	✔

Table 4-12 Description of receiver room conditions

The change in acoustic conditions affected in the receiver room are apparent from the reverberation time measurement spectra shown in Figure 4-2.

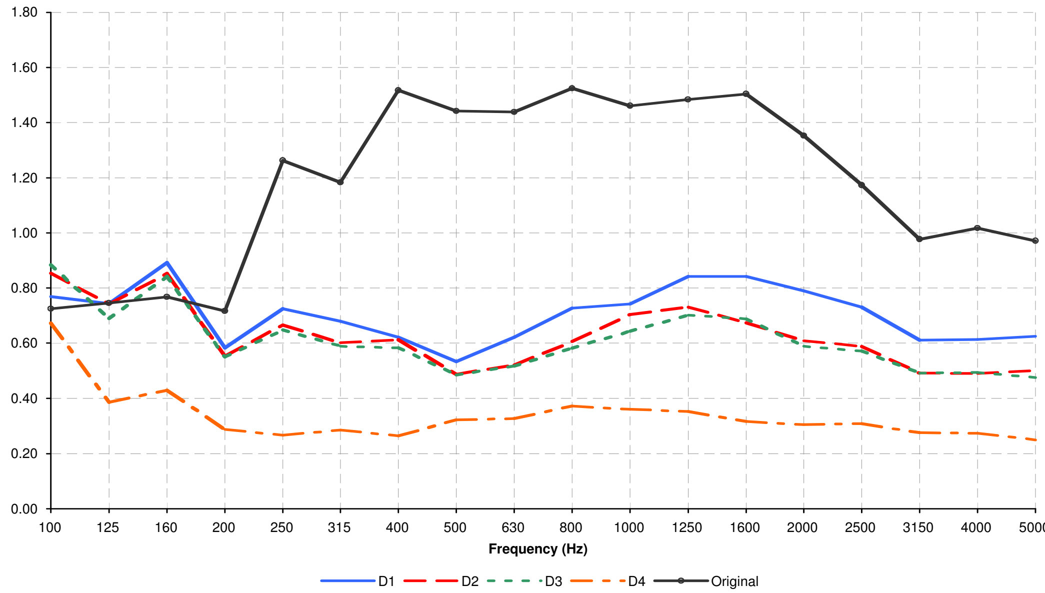


Figure 4-2 Reverberation time each room condition

Table 4.13 shows the D_w insulation results for each room test condition together with the average reverberation time result.

Room condition:	D0	D1	D2	D3	D4
L6					
Closed	40	42	43	44	44
50K	16	17	-	19	20
Average RT (s) $10\log_{10}$(RT)	1.43 1.56	0.72 -1.45	0.61 -2.11	0.60 -2.11	0.32 -4.88

Table 4-13 Effect of room condition on measured D_w insulation results (dB)

The results of the measurements clearly demonstrate that the increase in absorptive material in the receiving room increases the D_w insulation result. Examination of the raw data reveals corresponding reductions in the receiving room sound field.

4.12 Receiver location

The results presented so far have used the average result of five receiver microphone positions. A logarithmic average obtained from the 30 second averaged time signal recorded at each of the spatially varied positions. The spatial distribution of the microphones ensured a minimum 0.7 m between individual locations and 0.5 m clearance to room boundaries. The extent of the variation between the signals depended on the acoustic modal conditions within the room. The results shown in

Figure 4-3 indicate the spatial variation of level within the receiving room. The measurement shown is from the test with loudspeaker position L6 and window configuration D-2, where the window open area was 50,000 mm^2. The location of the measurement microphones are described in Section 3.4.

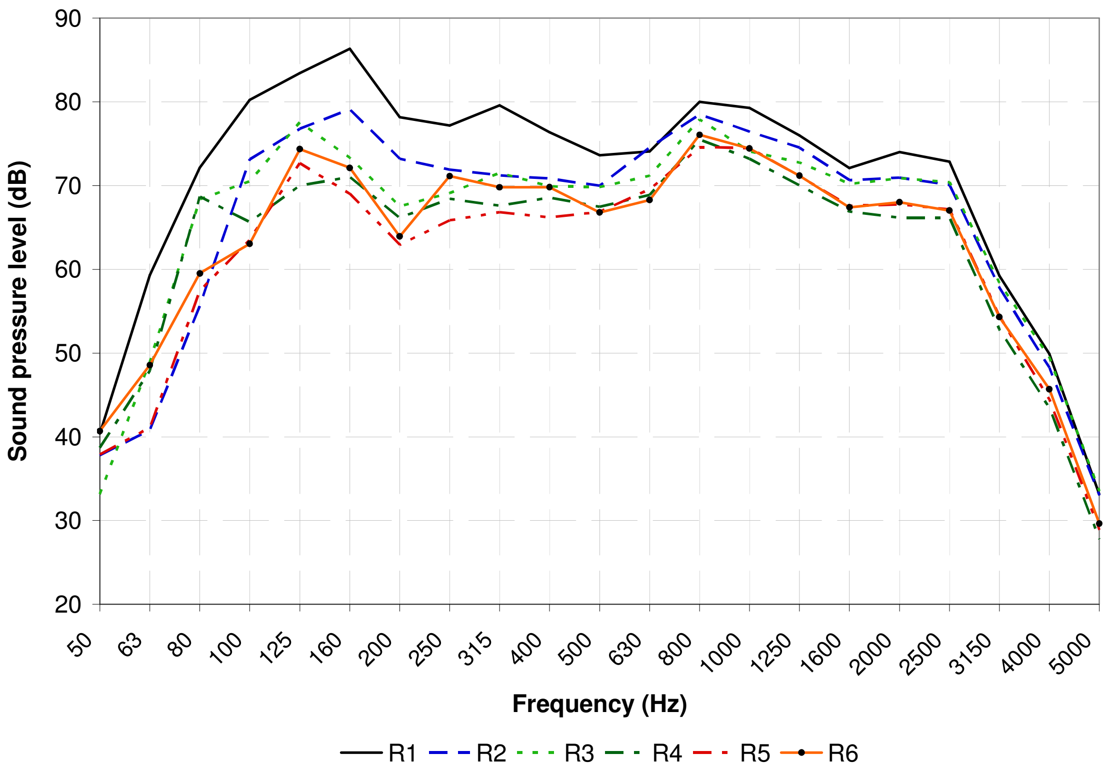


Figure 4-3. Spatial variation in level in receiving room

The level recorded at receiver microphone R1 was consistently greater than at any of the other receiver microphone positions. This is due to the placement of the microphone very close to the window in the receiver room, and is not representative of the average sound pressure level in the room. All other receiver microphones exhibit a fairly close relationship to each other over the frequency range shown, with R2 giving the upper bounds of the average and R5 giving the lower bounds. This shows that a reasonable diffuse field exists in the receiving room at frequencies higher than around 250 Hz.

4.13 Source room characteristics

Reverberation time measurements were additionally undertaken in the anechoic source room. The result spectrum is shown in Figure 4-4.

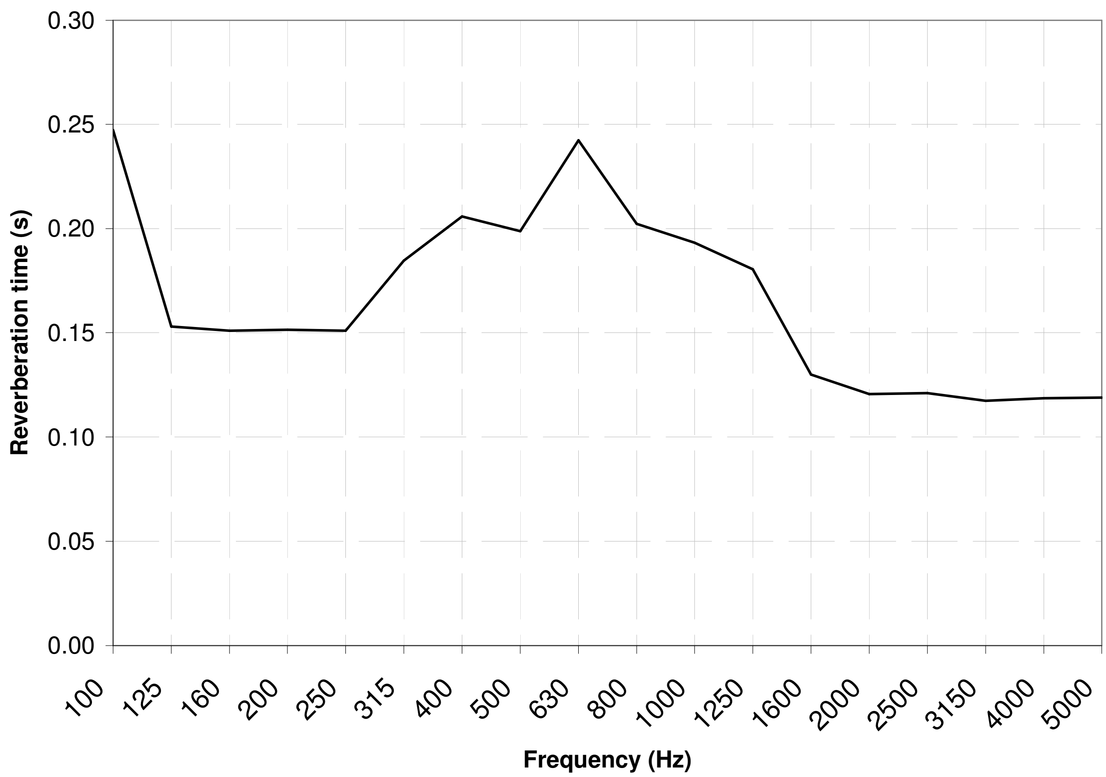


Figure 4-4 Source room reverberation time (s)

It is seen from Figure 4-4 that the source room's reverberation time is low, with a calculated average surface absorption coefficient $\overline{\alpha}$ of approximately 0.5.

4.14 Ground effects

The effect of the hard ground surface in the source room was tested. The results with and without the hard surface are shown in Table 4-14. The measurements were carried out using window configuration D-2 in both the closed and open 50,000 mm^2 positions.

Floor:	with	without
L6	D-2	D-2
Closed	36	35
50K	16	15

Table 4-14 Effect of hard floor surface in source room on measured level difference

The hard floor surface shows a 1 dB reduction in the D_w insulation result, due to the increase in the source side sound field with the reflective surface in place.

4.15 Speaker location

The effect of the angle of incidence on the resulting insulation was tested using five loudspeaker positions arranged over a 150º angle, from 15º to 165º. The results are shown as contour plots in Figure 4-5 to Figure 4-10. For Window D, tests were not carried out for all speaker positions. Data has therefore been repeated for angles beyond 90º, with the assumption that the response exhibited a symmetric pattern.

The patterns observed in the diagrams shows the apparent façade insulation to be strongly dependent on the source angle and, for the closed window case, that the response is symmetric with insulation minima generally observed at normal incidence.

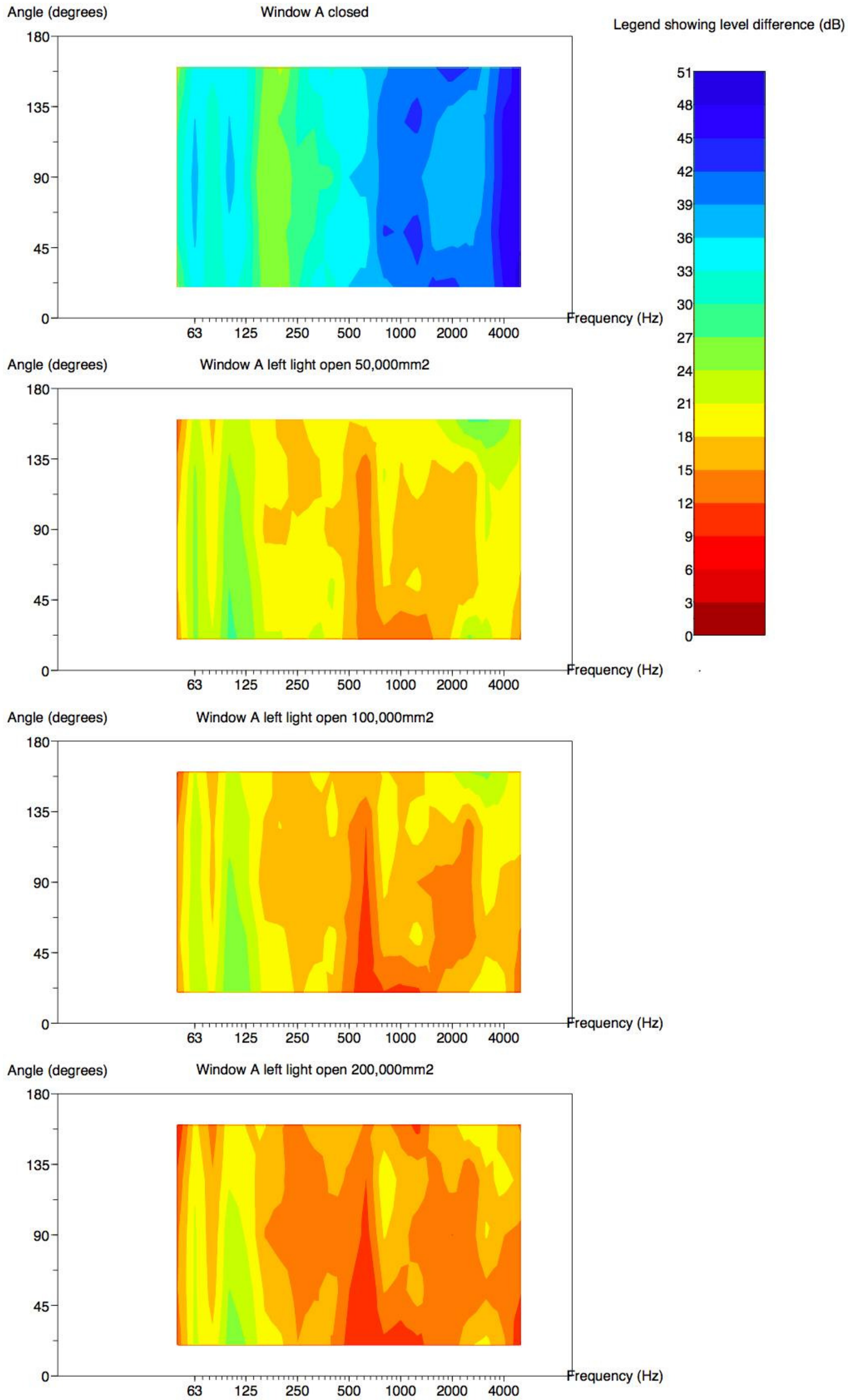


Figure 4-5. Angle of incidence level difference results for window configuration A-1 (dB)

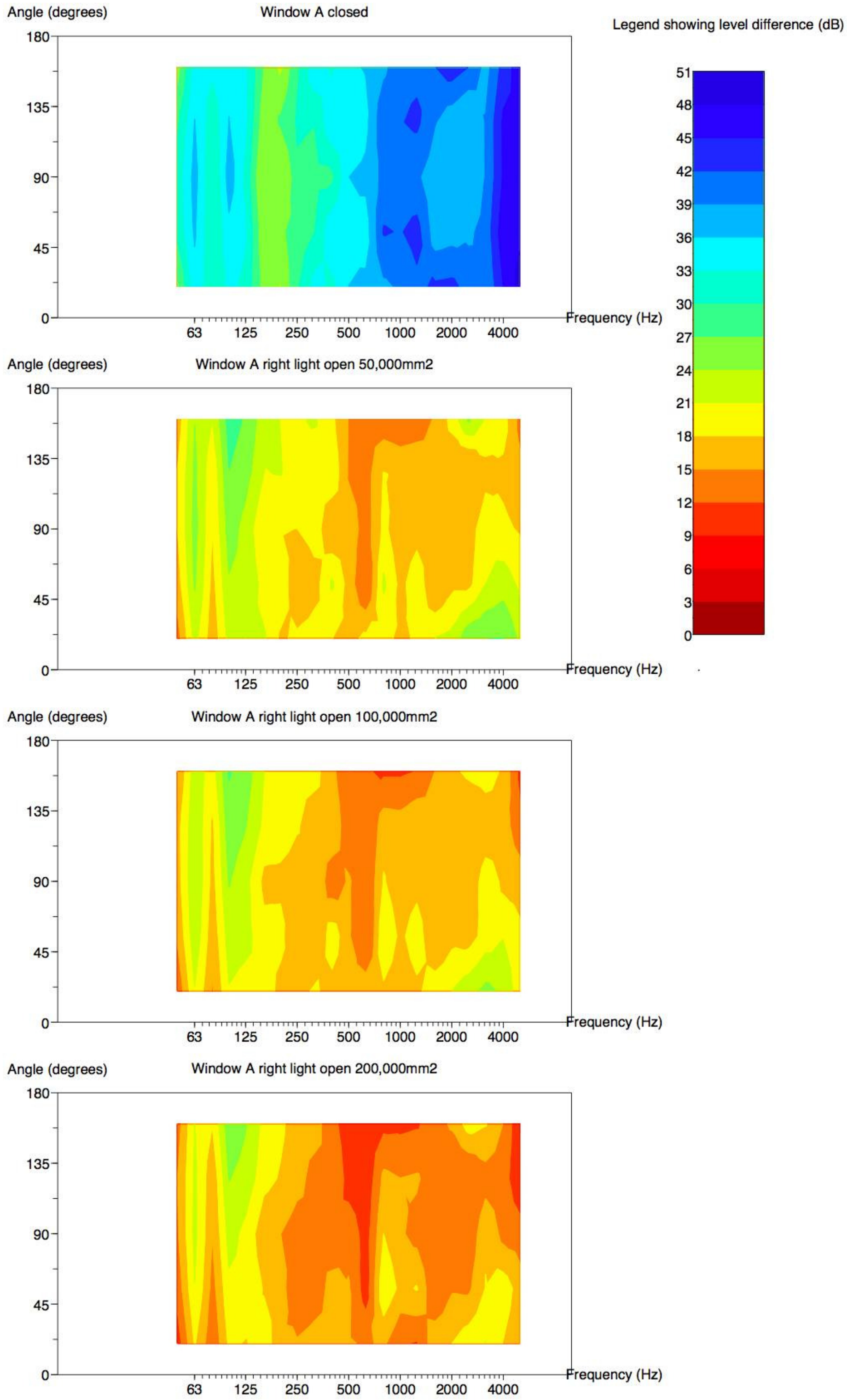


Figure 4-6. Angle of incidence level difference results for window configuration A-2 (dB)

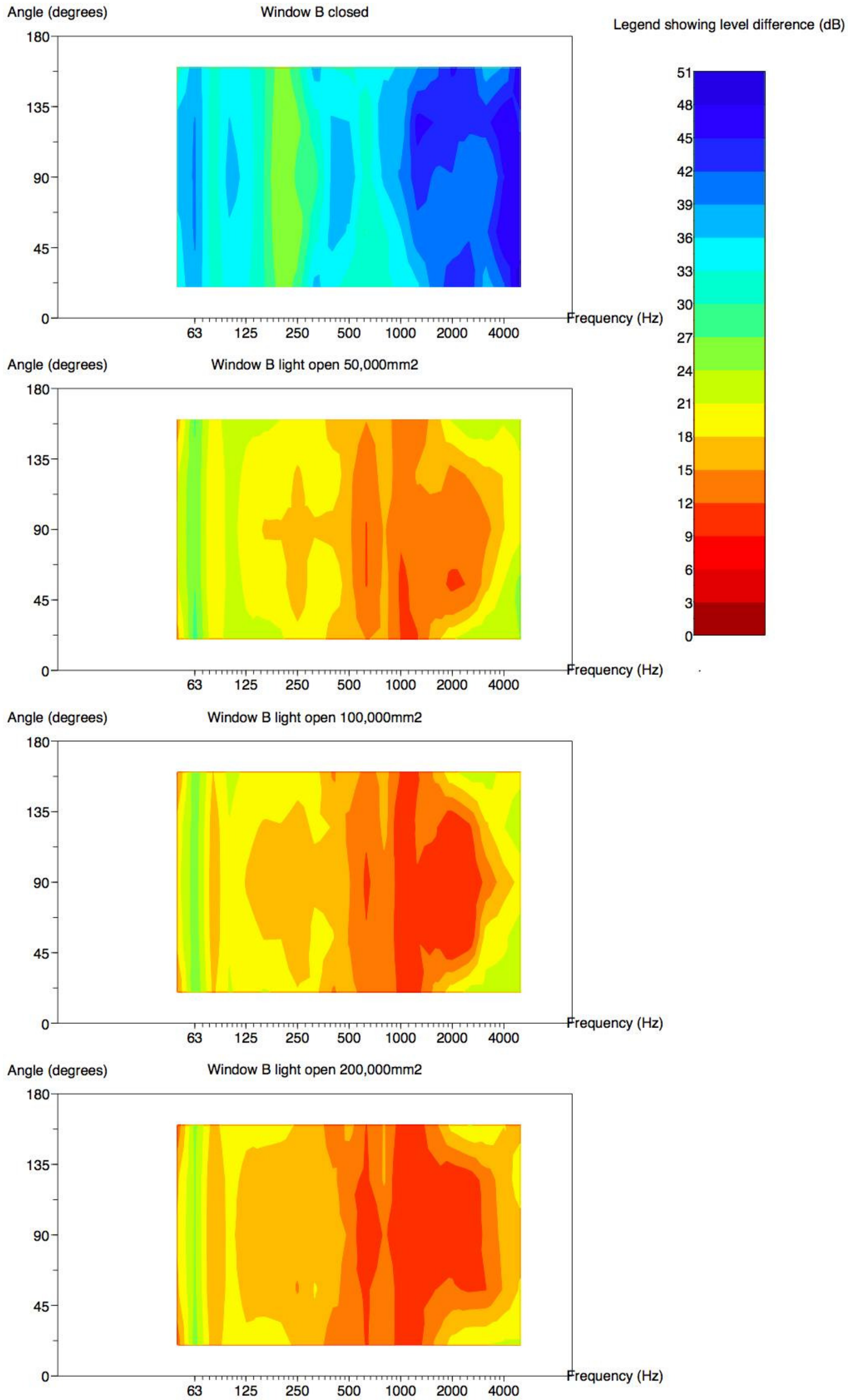


Figure 4-7. Angle of incidence level difference results for window configuration B (dB)

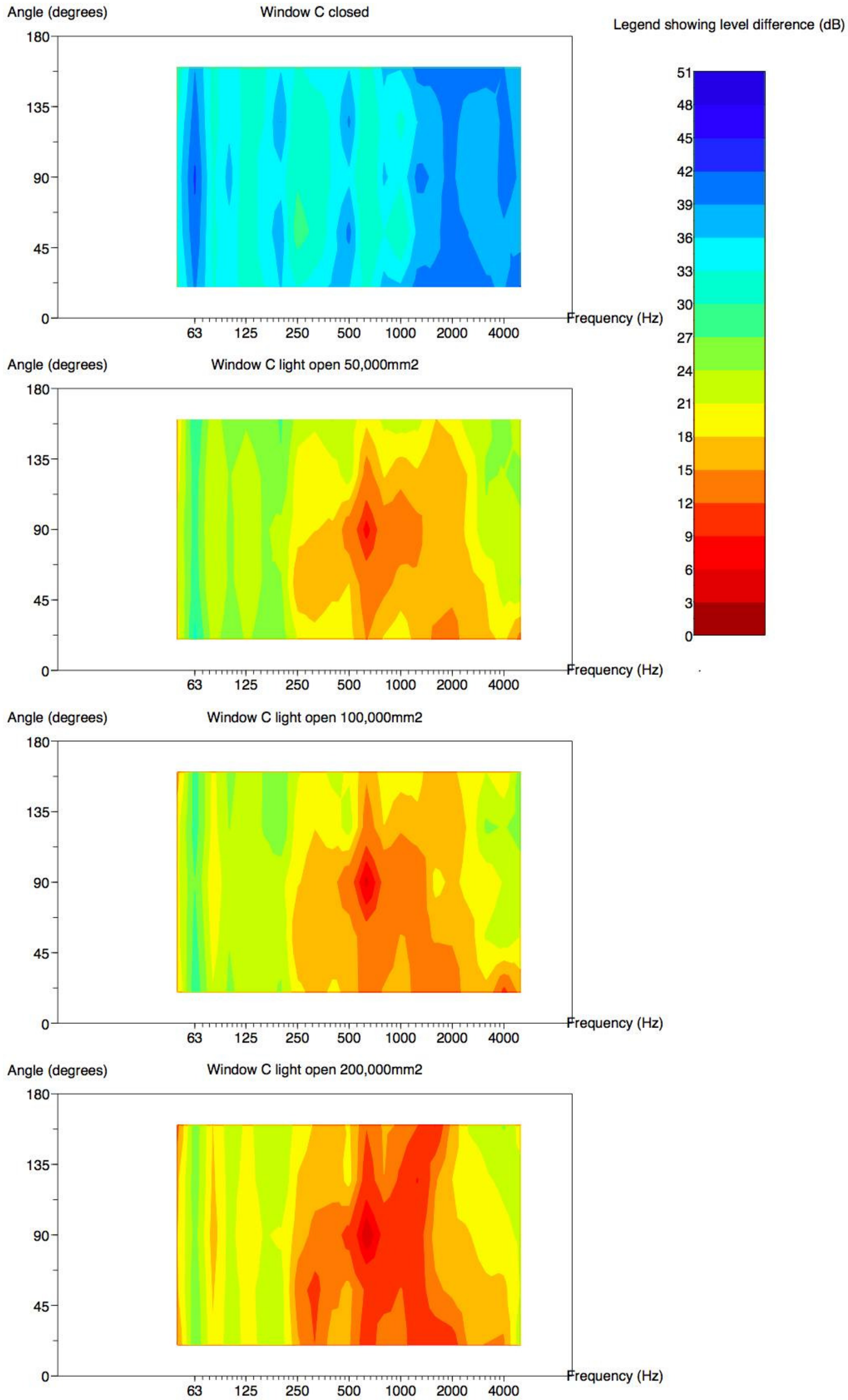


Figure 4-8. Angle of incidence level difference results for window configuration C-2 (dB)

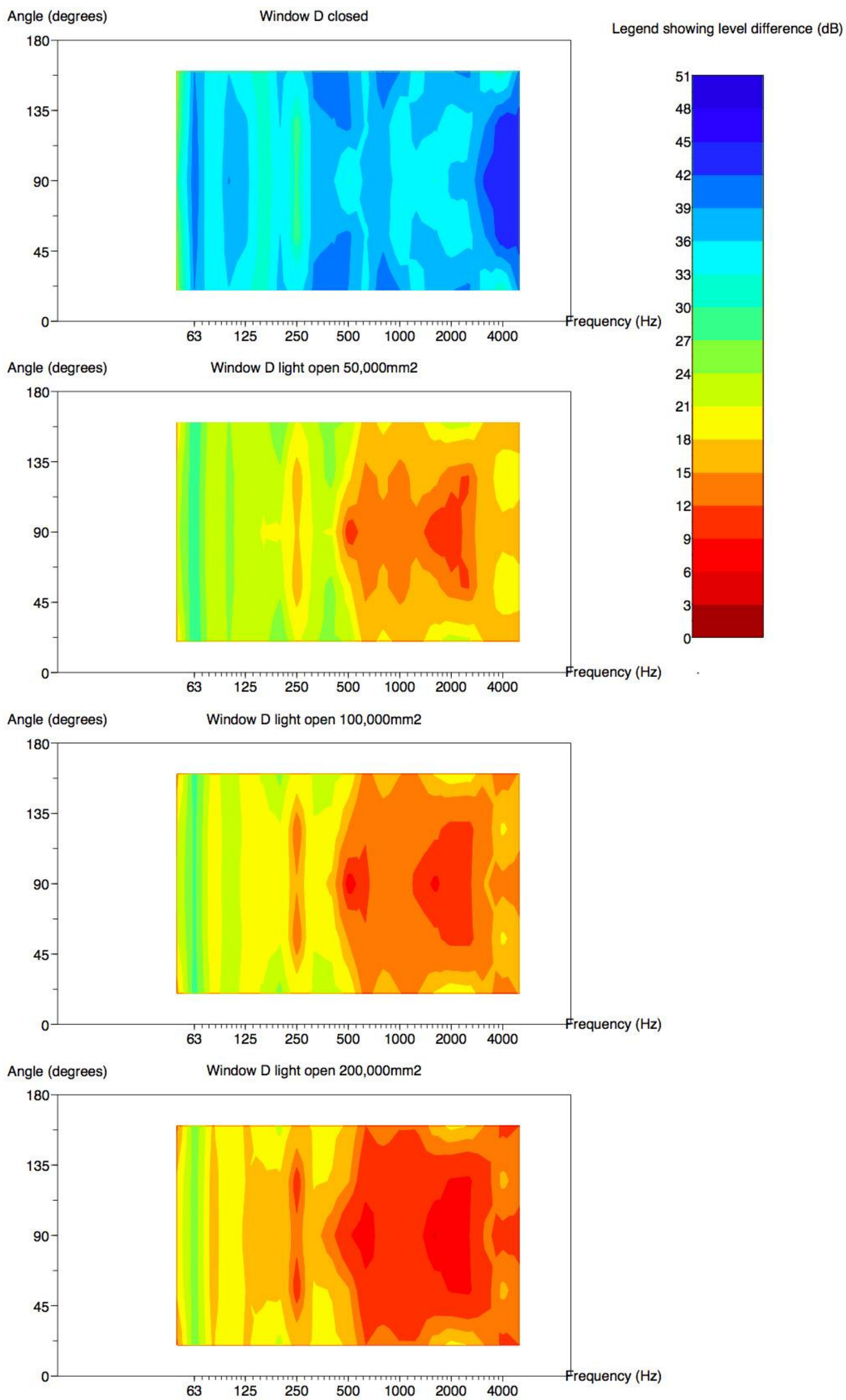


Figure 4-9. Angle of incidence level difference results for window configuration D-2 (dB)

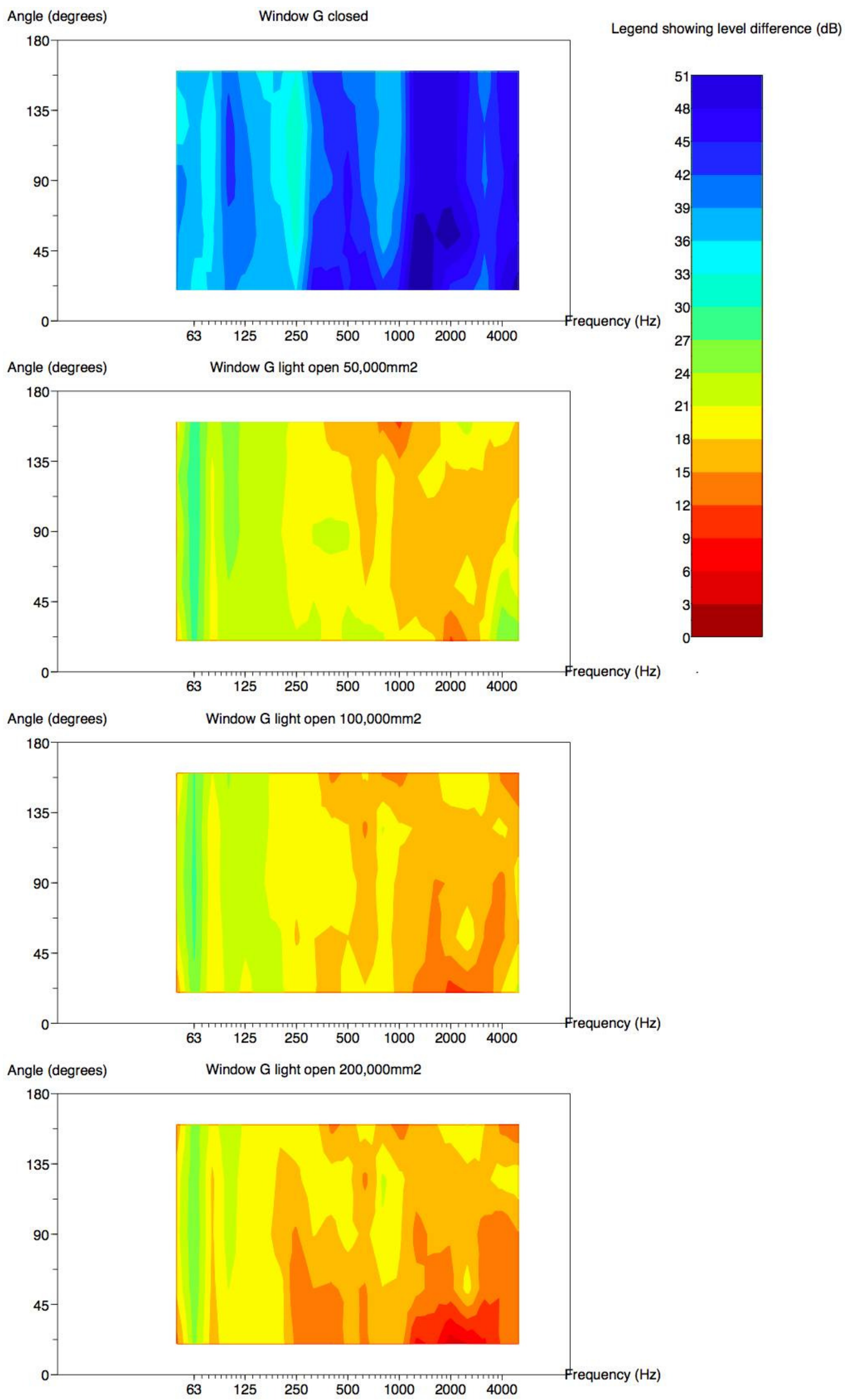


Figure 4-10. Angle of incidence level difference results for window configuration G (dB)

Chapter 5 Analysis

5.1 Aim of analysis

Analysis has been performed on the measurement results to rationalise them into a more functional format and to better quantify each physical variable under consideration i.e. window opening size, source directivity and frequency content of the source.

The analysis is principally based on the measurement results from speaker L6, located 5 m normally from the façade in conjunction with the S1 source microphone position set 2 m from the façade. This position provides the best correlation to the test methodology outlined in of BS EN ISO 140—5.

In the absence of contributory flanking components, the sound transmission coefficient, τ, is the ratio of sound power transmitted through a system to the sound power incident on it. The definition is provided in Equation 5-1, shown as a function of source angle and frequency. Equation **5-2** shows the sound reduction index, R, as a function of the sound transmission coefficient.

$$\tau(\phi,\omega) = \frac{W_{transmitted}\ (\phi,\omega)}{W_{incident}(\phi,\omega)}$$

Equation 5-1

$$R(\phi,\omega) = -10\,Log_{10}(\tau(\phi,\omega))$$

Equation 5-2

Where the façade is composed of multiple elements the overall insulation is dependent of the sound transmission coefficient of each component as shown by **Equation 5-3**.

$$R = -10\lg\left(\sum_{i=1}^{n}\tau_{e,i}\right)$$

Equation 5-3

The standard BS EN 12354-3:2000 [19] specifies a calculation model to estimate the sound insulation of a façade from constituent performance ratings. It uses Equation 5-4 for a plane façade to link the composite apparent sound reduction index to the field measured normalised level difference parameter (Equation 5-5).

$$D_{2m,nT} = R' + 10Log_{10}\left(\frac{V}{6T_0 S}\right)$$

Equation 5-4

$$D_{2m,nT} = L_{1,2m} - L_2' + 10Log_{10}\left(\frac{T}{T_0}\right)$$

Equation 5-5

where $L_{1,\ 2m}$ is the external sound pressure level 2 m in front of the façade from a non-diffuse sound source, L_2 is the spatial and temporally averaged sound pressure level in the receiving room (dB), S is the area of the building element (m^2), T is the reverberation time in the receiving room (s) with T_0 the reference reverberation time (0.5 s).

The analysis of the results has been addressed by reversing the BS EN 12354-3:2000 calculation method, through the deconstruction of the overall façade results into constituent parts.

Equation **5-6** is fundamental to the calculation method, providing a relationship between the apparent sound reduction index and the element normalised sound level difference $D_{n,e}$. The use of this 'small element parameter' is considered appropriate for the characterisation of 'holes', that is areas of very low insulation for which an accurate definition of its surface area is not possible.

$$\tau_{e,i} = \frac{S_i}{S} 10^{-R_i/10} \quad \text{or} \quad \tau_{e,i} = \frac{A_0}{S} 10^{-D_{n,e,i}/10}$$

Equation 5-6

Where:

S is the total façade area (m^2), as seen from the internal position.
S_i is the area of element i.(m^2).

A_0 is the reference equivalent sound absorption area, for dwellings given as 10 m^2.

The standard test method for the assessment of small building elements in terms of the element normalised sound level difference parameter, $D_{n,e}$, is given in BS EN ISO 140-10 [25]. The application of the standard is stated as general building elements with an area less than 1 m^2 that occur in a number of discrete sizes and which transmit sound between one room and the environment. Whilst the definition excludes windows, it suggests transfer air devices are suitable. For the purpose of the analysis a open window has been considered as an air transfer device.

5.2 Determination of façade sound reduction index

Preliminary tests established the levels of flanking sound between the source and receiver rooms to be negligible, such that the measured sound pressure levels within the receiver room were principally due to sound transmitted only through the façade

The apparent sound reduction was directly calculated for appropriate test conditions (i.e. test arrangement of distant source L6 combined with the 2 m source measurement microphone) from Equation 5-7, derived from the formulations given in BS EN 12354-3:2000.

$$R' = L_{1,2m} - L_2' + 10Log_{10}\left(\frac{TS}{0.16V}\right)$$

Equation 5-7

Calculation results are presented as octave band spectra, however the conversion from one-third octaves has been performed as the last step of the calculation, with the single figure results calculated from the one third octave results.

Table 5.1 presents the derived sound reduction indices from the measurements performed on the “closed” facades, with all windows and ventilators (window C only) closed. The results have been corrected for the background noise level, where appropriate.

	Element Area (m^2)	Octave Band Centre Frequency (Hz) 63Hz	125Hz	250Hz	500Hz	1kHz	2kHz	4kHz	$R'_W(C;C_{tr})$
Wall	8.64	34.5	34.6	40.6	51.9	61.1	70.9	72.1	53 (-2, -7)
Window A	2.52	31.2	22.8	22.2	37.1	40.4	42.6	40.6	37 (-2; -6)
Window B	1.26	33.0	27.1	25.6	38.2	36.0	45.5	42.7	39 (-2; -5)
Window C1	0.95	31.3	27.0	28.6	37.4	36.7	42.2	38.8	39 (-2; -4)
Window C3	0.95	30.8	29.0	37.5	36.6	33.4	41.8	40.5	38 (-2; -3)
Window D	1.08	29.6	27.9	32.5	40.9	40.4	47.8	42.2	42 (-1; -4)
Window E	0.63	33.2	32.5	29.6	48.7	49.7	49.9	53.5	47 (-3; -8)
Window F	0.63	33.9	30.6	26.5	43.6	45.8	53.0	50.6	45 (-4; -9)
Window G	0.54	34.4	32.4	36.0	42.7	45.2	51.2	47.0	45 (-1; -4)

Table 5-1 Apparent sound reduction for test façade with closed window (L6, S1, R2-6) (dB)

It can be seen that the overall insulation of the façade is strongly influenced by the size of the window aperture, with the smallest windows contributing to the highest overall insulation ratings. The reduction in insulation relative to the non window condition has been empirically linked to the percentage area coverage of the window within the facade, as shown by Equation 5-8.

$$\Delta R' = -10 Log_{10}(Glass\ Ratio) \quad where\ Glass\ Ratio = \frac{S_{glass}}{S} \times 100$$

Equation 5-8

The relationship is expected to be additionally influenced by the insulation performance of the glass, therefore a correction will need to be incorporated within Equation 5-8, however the logarithmic nature of this relationship with or without an additional constant will ensure a 3 dB degradation in wall insulation for each doubling of glazed area.

5.3 Empirical estimate of closed window performance

The sound insulating performance of the individual closed window components has been derived though an empirical subtraction technique using the core wall measurement result. This assessment provides useful information on the application of the prediction method promoted by BS EN 12354-3 whilst also providing an indication of the individual, non-dimensionally constrained window properties. The derivation process in shown in Equation 5-9.

$$R'_{Element} = -10Log_{10}\left[\frac{1}{S_{Element}}\left(S_{Facade}10^{\left(-\frac{R'_{Facade}}{10}\right)} - S_{Wall}10^{\left(-\frac{R'_{Wall}}{10}\right)}\right)\right]$$

Equation 5-9

The derived insulation ratings for the isolated closed window elements are shown in Table 5-2.

	Octave Band Centre Frequency (Hz)							
	63Hz	125Hz	250Hz	500Hz	1kHz	2kHz	4kHz	R'_W ($C;C_{tr}$)
Window A	26.6	17.6	16.9	31.8	35.1	37.4	35.4	32 (-2; -6)
Window B	26.1	19.4	17.4	30.0	27.7	37.5	34.7	31 (-2; -6)
Window C1	22.6	18.1	19.2	28.0	27.1	32.7	29.3	29 (-1; -4)
Window C3	22.0	20.6	30.4	27.1	23.8	32.3	31.1	28 (-1; -2)
Window D	21.2	19.8	24.1	32.2	31.5	39.3	33.5	34 (-2; -5)
Window E	23.4	24.0	18.5	38.5	38.9	39.5	45.7	37 (-4; -8)
Window F	24.6	21.2	15.2	32.9	34.6	44.0	41.2	34 (-4; -9)
Window G	24.7	22.8	24.5	30.7	33.4	40.6	36.3	34 (-2; -4)
BS EN 12354:3 sample data	-	21	17	25	35	37	31	29 (-1; -4)

Table 5-2. Derived Apparent insulation for closed window units (L6, S1, R2-6) (dB)

The final row includes reproduced sample data from BS EN 12354:3 for a window unit comprising 4–(6-16)-4 mm double glazed glass. The derived results show reasonable agreement across the calculation set, with differences potentially attributable to variations in the panel sizes, aspect ratio, and sealing systems.

The results for window C, which included a sealed trickle vent within the measurements, gave comparably lower results within the mid to high frequency octave band than the other complete window units. The inclusion of the vent, or more specifically the aperture within the frame does appear to degrade the overall acoustic insulation of the window unit.

5.4 Open window analysis

To assess the effect of the window opening on the façade insulation, similar empirical estimates were performed to those described above. The deductions were however performed in terms of the small element parameter; the element normalised level difference $D_{n,e.}$ The data used for the assessment was again taken from the BS EN ISO 140-5 comparable measurements i.e. 5 m source distance, 2 m 'external' microphone and with the 'internal' microphone array consisting of R2 to R6 inclusive. The calculation method is summarised by Equation 5-10.

$$D_{n,e,i} = -10 Log_{10}\left[\frac{1}{10}\left(S\ 10^{\left(-\frac{R'_{Facade}}{10}\right)} - S_{Wall}10^{\left(-\frac{R'_{Wall}}{10}\right)}\right)\right]$$

Equation 5-10

Where S_{wall} is the wall area appropriate to the measurement i.e. $S\text{-}S_{Element.}$.

The results of the insulation prediction for the open window situation is provided in Table 5-3 for the 50,000 mm^2 window openings; Table 5-4 for the 100,000 mm^2 window openings and Table 5-5 for the 200,000 mm^2 window openings.

	Octave Band Centre Frequency (Hz)							
	63Hz	125Hz	250Hz	500Hz	1kHz	2kHz	4kHz	$D_{n,e,W}$ (C;C_{tr})
Opening A-1	21.8	16.6	17.1	21.6	18.9	23.0	24.5	21 (0; -1)
Opening A-2	21.3	17.5	16.7	21.7	19.2	23.2	24.5	22 (-1; -2)
Opening A-3	22.0	15.7	19.2	20.4	16.0	21.4	24.5	20 (-1; -2)
Opening B	23.4	16.2	17.3	20.5	13.9	20.1	23.6	18 (-1; -2)
Opening C-1	25.5	19.8	23.8	20.3	17.9	22.0	26.2	21 (-1; -1)
Opening C-2	25.9	19.9	22.6	22.5	18.9	23.2	27.8	22 (-1; -1)
Opening C-3	25.5	20.9	26.5	20.4	18.5	22.5	27.0	21 (0; -1)
Opening C-4	24.6	19.3	23.2	20.4	16.2	23.5	27.2	21 (-1; -2)
Opening D-1	25.1	18.9	23.0	19.1	18.4	23.5	24.5	21 (0; -1)
Opening D-2	26.0	18.0	17.0	23.7	15.4	19.5	21.5	19 (-1; -1)
Opening D-3	26.7	19.0	18.9	22.5	17.4	26.0	24.6	23 (-2; -3)
Opening E	25.7	19.9	21.3	20.3	19.2	22.0	23.6	21 (0; -1)
Opening F	27.0	19.4	21.5	20.4	20.4	22.5	25.1	22 (-1; -1)
Opening G	25.1	18.6	20.5	19.6	18.7	17.9	20.1	18 (0; 1)

Table 5-3 Derived $D_{n,e}$ result for "50,000 mm^2" open windows (L6, S1, R2-6) (dB)

	Octave Band Centre Frequency (Hz)							
	63Hz	125Hz	250Hz	500Hz	1kHz	2kHz	4kHz	$D_{n,e,W}$ (C;C_{tr})
Opening A-1	20.6	15.7	15.5	20.2	18.7	22.0	23.0	21 (-1; -2)
Opening A-2	20.2	16.6	15.2	20.2	18.6	21.6	23.0	21 (-1; -2)
Opening A-3	21.3	15.1	18.5	19.0	15.9	20.7	23.6	20 (-1; -2)
Opening B	22.1	14.9	15.5	19.2	12.5	18.4	23.6	17 (-1; -2)
Opening C-1	24.0	18.4	22.5	17.9	16.4	21.8	25.1	19 (0; -1)
Opening C-2	24.4	18.3	20.6	20.1	15.8	23.0	26.9	21 (-2; -3)
Opening C-3	24.1	19.2	24.8	18.0	16.9	22.3	26.0	20 (-1; -1)
Opening C-4	24.4	19.0	22.9	20.1	15.9	23.2	27.1	21 (-1; -3)
Opening D-1	23.7	17.3	20.8	16.9	19.7	19.8	21.1	19 (0; 0)
Opening D-2	24.8	16.5	14.4	21.5	13.7	17.7	18.6	17 (-1; -1)
Opening D-3	25.0	16.8	15.6	21.0	18.0	20.2	22.1	20 (-1; -1)
Opening E	24.4	18.6	19.6	18.7	19.0	20.6	21.9	20 (0; -1)
Opening F	24.7	17.8	19.2	18.6	19.6	20.2	22.7	20 (0; -1)
Opening G	24.0	17.5	18.8	18.1	18.5	17.6	19.6	18 (0; 0)

Table 5-4 Derived $D_{n,e}$ result for "100,000 mm^2" open windows (L6, S1, R2-6) (dB)

	Octave Band Centre Frequency (Hz)							
	63Hz	125Hz	250Hz	500Hz	1kHz	2kHz	4kHz	$D_{n,e,W}$ (C;C_{tr})
Opening A-1	18.7	14.0	12.0	18.7	17.4	19.9	21.4	19 (-1; -2)
Opening A-2	18.3	15.1	12.1	18.5	18.0	19.5	21.3	19 (-1; -2)
Opening A-3	19.7	13.7	17.1	14.9	13.9	18.7	21.5	17 (-1; -2)
Opening B	20.8	13.3	12.9	18.1	12.0	18.3	20.5	16 (-1; -2)
Opening C-1	22.9	17.0	21.2	17.0	15.4	21.1	25.6	19 (-1; -2)
Opening C-2	22.3	16.0	17.8	18.3	14.9	20.4	25.0	19 (-1; -2)
Opening C-3	23.0	17.7	23.3	17.1	15.9	21.5	26.6	19 (0; -1)
Opening C-4	22.5	16.8	20.2	18.5	15.6	20.6	25.7	19 (0; -1)
Opening D-1	21.9	15.2	17.5	15.0	15.1	17.2	18.8	16 (0; 0)
Opening D-2	23.1	14.6	11.5	20.6	10.2	14.9	14.2	14 (-1; -2)
Opening D-3	23.5	15.2	13.0	21.3	16.8	17.3	17.9	18 (-1; -1)
Opening E	23.1	17.4	18.4	17.2	17.7	19.1	19.5	18 (0; 0)
Opening F	23.2	16.5	17.9	17.0	18.1	18.7	20.6	18 (0; 0)
Opening G	22.7	16.1	16.6	17.3	18.5	16.6	17.8	18 (-1; -1)

Table 5-5 Derived $D_{n,e}$ result for "200,000 mm^2" open windows (L6, S1, R2-6) (dB)

The empirical results given in Table 5-3 to Table 5-5 show reasonable agreement across each opening style. The standard deviations are 1.4, 1.3 and 1.5 dB for the 50,000, 100,000 and 200,000 mm^2 openings respectively. The overall trend reflects the intuitive result of decreasing acoustic protection with increased window opening. Improved insulation performance corresponds to those window styles which provide a physical shield when open. Conversely the worst performing opening style is the sliding sash window which provides an unobstructed path from external to internal environments.

In order to provide simplified data on the insulating performance of the window openings, the combined results have been reduced into a single set of results for each opening condition. This statistical selection is based on a two-tailed test at a 5% significance level in order to provide results, from the octave band data population shown, within the 95% confidence interval. The 95% confidence level was chosen to provide a conservative estimate considered as being appropriate for guidance documentation, the statistical calculation results are additionally rounded down to their integer value as shown in Table 5-6.

	Octave Band Centre Frequency (Hz)							
Opening size	63Hz	125Hz	250Hz	500Hz	1kHz	2kHz	4kHz	$D_{n,e,W}$ (C;C_{tr})
50k (mm^2)	23	17	19	20	16	21	23	19 (0; -1)
100k (mm^2)	22	16	17	18	15	19	21	18 (-1; -1)
200k (mm^2)	20	14	14	16	14	17	19	16 (0; -1)

Table 5-6. Statistically Derived $D_{n,e}$ insulation ratings for window openings (dB)

5.5 Example noise source characteristics

Further assessment has been performed to compare the dBA level difference between external and internal environments through an open window for typical sources of environmental noise. The comparison uses the level difference measurement results for the open window (50,000 mm^2) test condition with the speaker located 5 m normal to the façade, the external microphone 2 m from the window and using spatially average internal sound pressure level.

The source spectra for the transportation sources are derived from BS 8233:1999 *Sound insulation and noise reduction for buildings* [5]. The music noise spectrum has been taken from the BPC measurement library from measurements made outside a nightclub façade. The octave band spectra used for the calculations are shown in Table 5-7.

		Octave Band Centre Frequency (Hz)						
Data Source	Noise Source	63Hz	125Hz	250Hz	500Hz	1kHz	2kHz	4kHz
[5] Figure 1	Road	-7	-14	-9.7	-6.7	-3.3	-6.1	-11.1
[5] Figure 4 (Mk 3)	Rail	-8	-10	-14	-11	-3	-5	-15
[5] Figure 3 (Landing)	Air	-3	-6	-4	-4	-7	-5	-8
BPC Library	Music	18	8	3	-2	-13	-19	-26

Table 5-7. Environmental Noise source spectra (dB)

The analysis has been performed using the measured level difference data for the 'open 50,000 mm^2' window condition in combination with the various source spectra given in Table 5-7. The A-weighted difference between the source and resultant level was subsequently entered into Table 5-8.

The results indicate that the sound insulation of the partially open windows, given the specific receiving room characteristics, are between 12 to 18 dBA for road and rail traffic noise, 14 to 19 dBA for aircraft (landing) noise and 15 to 20 dBA for bass intensive music.

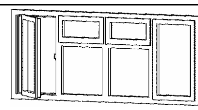
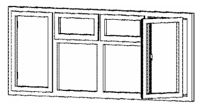
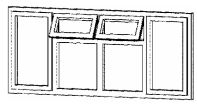
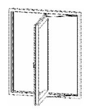
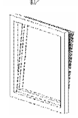
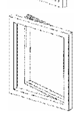
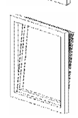
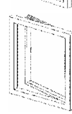
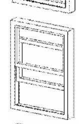
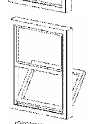
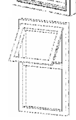
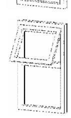
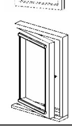
Window	**Measurement**	**Opening**	**Comparative Level Difference (dBA)**			
ID	D_w (C ; C_{tr}).	**Illustration**	$D_{A,road}$	$D_{A,rail}$	$D_{A,air}$	$D_{A,music}$
A-1	18(-1; -2)		17	17	18	16
A-2	18(-1; -2)		17	17	18	16
A-3	16(-1; -2)		14	14	16	16
B	14(-1; -2)		12	12	14	15
C-1	17(-1; -1)		16	16	17	19
C-2	18(0; -1)		17	17	19	20
C-3	17(0; -1)		16	16	18	19
C-4	17(-1; -2)		15	15	17	18
D-1	18(-1; -2)		16	16	18	18
D-2	16(-1; -2)		14	14	16	17
D-3	20(-3; -4)		16	16	18	18
E	17(0; 0)		17	17	18	18
F	18(0; -1)		18	18	18	18
G	15(0; 0)		15	15	15	17

Table 5-8 dBA level difference for different source characteristics (50k mm^2 open windows)

5.6 Ventilator analysis

The subtraction insulation analysis method has also been used to estimate the acoustic performance of the different ventilator products installed on Window C.

The results are shown in Table 5-9 and Table 5-10 for a range of trickle vents (T Vent) and an over-frame vent (F Vent). Two sizes of trickle ventilator were used, a 2000 mm^2 (T vent 9) and the more typical 4000 mm^2 range. The over-frame vent had an open area of approximately 6000 mm^2.

Vent configuration	63Hz	125Hz	250Hz	500Hz	1kHz	2kHz	4kHz	$D_{n,e,w}(C,C_{tr})$
0.02 m^2 slot (no vent)	38.9	33.7	41.9	35.7	40.5	36.0	34.3	38 (0; 0)
T Vent 9 open	39.5	33.8	42.3	36.0	41.0	37.1	36.2	39 (-1; -1)
T Vent 9 closed	42.2	36.7	45.3	37.7	43.1	42.4	44.6	42 (0; -1)
0.04 m^2 slot (no vent)	35.5	31.1	36.7	31.5	34.1	32.4	30.7	33 (0; 0)
T Vent 1 open	36.3	32.0	37.7	31.9	32.6	34.6	34.0	34 (0; -1)
T Vent 2 open	36.5	32.0	37.9	32.2	31.8	35.1	35.1	34 (0; -1)
T Vent 3 open	37.0	32.4	38.4	32.5	32.4	34.5	34.3	34 (0; -1)
T Vent 4 open	37.6	32.6	38.9	32.8	30.9	37.1	38.0	34 (0; -1)
T Vent 7 open	37.2	32.6	38.6	33.1	32.9	36.1	34.8	35 (0; -1)
T Vent 8 open	37.1	32.1	38.6	33.0	30.5	36.1	34.6	34 (-1; -1)
T Vent 1 closed	35.9	25.0	44.5	36.1	40.8	42.4	46.3	40 (-1; -4)
T Vent 2 closed	35.4	38.9	44.1	36.2	41.0	43.2	48.6	41 (0; -1)
T Vent 3 closed	35.0	36.1	41.5	33.8	36.3	38.7	48.4	37 (0; -1)
T Vent 4 closed	36.4	25.1	49.6	37.8	42.0	44.7	46.6	42 (-1; -5)
T Vent 7 closed	45.7	25.0	46.6	37.7	39.3	43.3	46.0	41 (-1; -4)
T Vent 8 closed	35.8	36.9	44.2	36.3	38.8	44.0	46.2	40 (0; -1)
Frame Vent open	35.7	30.8	32.0	28.7	35.7	45.7	47.7	35 (0; -2)
Frame Vent closed	35.0	34.8	43.0	35.0	39.5	51.2	47.6	40 (0; -1)

Table 5-9. Ventilator calculation (with external canopies fitted), $D_{n,e}$ (window C, L6, S1, R2-6)

5.7 Angle of Incidence

An investigation into the effect of the angle of the window relative to the noise source has been undertaken. This analysis examined the results from angle dependent measurements, made using the five source locations of 2.72 m radii, (15º, 55º, 90º, 125º and 165º), in conjunction with the source microphone position S2 (90º) sited 1 m from the facade. The change in the apparent sound reduction index from each angle and opening configuration was estimated by the subtraction method for each 50,000 mm^2 opening condition, relative to the normal wall result from source location L_1 (90º) . The resulting datasets provided effective third-octave band insulation spectra for each measurement angle per open window configuration.

To reduce the size of these data-sets the spectra were converted to octave bandwidths and further reduced through the use of a polynomial curve fitting routine. The fits were made against the cosine of the opening angle (for the side hinged window), taken from the line of the façade. This protocol required the measurement results for oppositely hinged opening units to be changed appropriately. The results are summarised in Table 5-10 as the variation in the estimated apparent sound reduction index, relative to normal value.

It can be seen that the effect of the source angle to opening has a varied effect across the range of window openings and that the size of the effect varies considerably across the frequency range, with the largest apparent insulation increase being seen at the extreme angles. The largest variation in estimated insulation rating is 5 dB relative to the normal incidence result.

	Horizontal Angle of incidence between window Centre and Source						
Opening	15^o	30^o	60^o	90^o	120^o	150^o	165^o
A-1	3.4	2.7	0.8	0.0	0.0	-1.5	-2.4
A-2	0.7	0.7	0.5	0.0	0.0	0.8	1.2
A-3	-0.4	0.3	0.8	0.0	0.9	2.4	2.7
B	2.2	1.8	0.7	0.0	0.2	0.9	1.1
C-1	1.8	2.0	1.1	0.0	1.1	2.0	1.8
C-2	5.0	3.0	-0.2	0.0	0.3	0.9	1.4
C-3	2.8	1.7	0.1	0.0	0.1	1.7	2.8
C-4	0.9	2.2	3.0	0.0	-0.8	1.1	1.9
D-1	1.4	1.6	1.0	0.0	1.0	1.6	1.4
D-2	1.6	1.7	1.0	0.0	1.0	1.7	1.6
D-3	2.5	2.2	0.9	0.0	0.9	2.2	2.5
E	0.9	0.7	0.2	0.0	0.2	0.7	0.9
F	-0.3	-0.2	-0.1	0.0	-0.1	-0.2	-0.3
G	2.4	1.9	0.6	0.0	0.4	1.2	1.4

Table 5-10 Variation in estimated open window (50k mm^2) R'_w relative to normal incidence

The trend from Table 5-10 shows that the insulation result for an open window at normal incidence provides the least acoustic protection, with generally a symmetric 2 to 3 dB improvement towards either grazing angle. The windows with a symmetric opening relative to the normal angle (e.g. sliding sash or turn and tilt) provided symmetric results. The pattern is not however consistent with some styles, notably opening A-1, showing a 5 dB variation between each grazing position, however the results for A-1 and A-2, whilst effectively the same window, have more significant variations due to the differential offsets between window and source.

The speakers were centred about the middle of each window unit sample such that the two extreme angle speakers were set at different distances from a non-central opening light, therefore whilst the distance between the left hand speaker and right hand opening will be the same as that between the right hand speaker and left hand opening for the symmetric 2.4 m long 'Sample A'; it will differ to the separation between the left hand speaker and left hand opening.

The largest improvement in insulation is seen for window opening C-2, which turns into the room and will therefore always have a form of barrier between the opening and extreme angled source locations.

5.8 Variation in external condition

Consideration of the source measurement location has been made for microphone positions S1 (1m), S2 (2m) and S3 (2.72m). The definition of the source microphone is of particular importance in the assessment of sound insulation from a non-reverberant sound field (such as an external environment), which unlike a truly reverberant environment will be position dependent. The effective sound insulation of the façade will therefore vary with the chosen source measurement location against which the internal noise environment, unchanged by the source-side measurement location, is referenced.

It is common practice to include a 2.5 – 3 dB façade correction positively when converting a free field measurement to a façade level or vice versa. The definition of a façade measurement is not however well defined, with common guidance recommending that free-field conditions are appropriate only with a separation greater than 3.5 m from reflecting surface. Figure 5-1 presents a set of normalised third octave source spectra from each source microphone from the defined source locations L6 (5 m from the façade), Line source (3 m) from the façade and L1 (2.72 m from the façade). Measurements were made simultaneously at microphone locations S1 (2 m), S2 (1 m) and S3 (façade). The octave band and single figure values are presented in Figure 5-1.

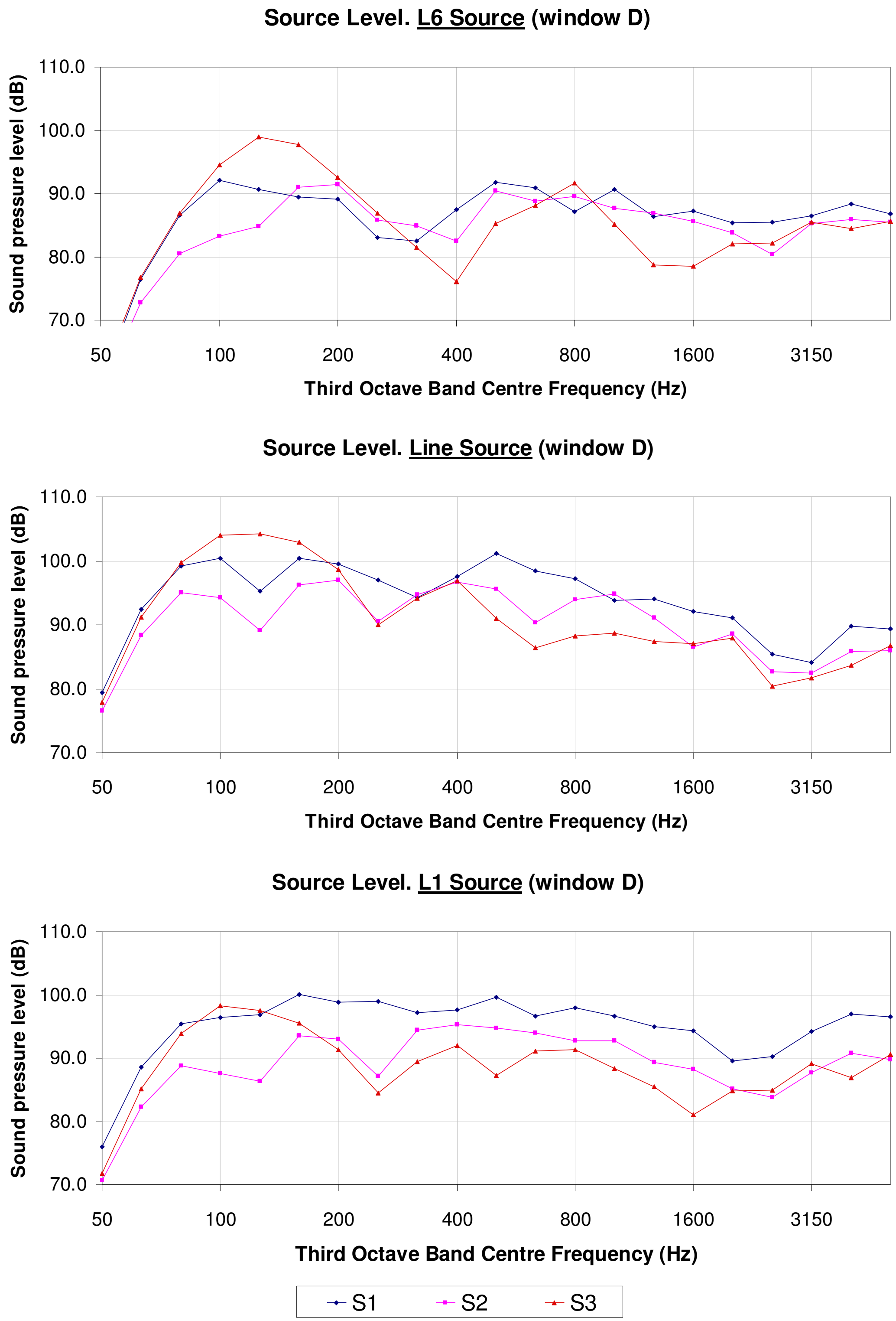


Figure 5-1. Variation in Sound Pressure Level at different source positions

The octave band sound pressure level data-set for Figure 5-1 is presented in Table 5-11 as the measured pressure spectra at the three external microphones and the spatially averaged internal receiver level.

	Octave Band Centre Frequency (Hz)							Overall Level		Insulation Rating
	63	125	250	500	1k	2k	4k	L_{Leq}	L_{Aeq}	D_w (C; C_{tr})
<u>L6 Source</u> Window D – Closed.										
S1	87.0	93.1	85.8	94.3	92.0	88.4	90.7	101	99	38 (-1; -3)
S2	81.2	92.0	88.4	92.7	90.4	85.4	88.7	100	97	37 (-1; -2)
S3	87.3	101.4	88.0	89.9	86.1	85.1	88.1	104	97	34 (-1; -2)
R_{2-6}	54.9	67.3	55.3	53.1	54.6	48.0	48.7	69	61	
Line Source Window D – Closed										
S1	100.0	101.5	98.9	103.0	96.9	92.1	92.6	110	105	43 (-1; -3)
S2	95.9	97.0	96.1	96.7	96.3	89.6	88.9	106	102	40 (-2; -4)
S3	100.3	106.6	95.6	92.3	91.1	88.6	88.5	110	100	37 (0; -1)
R_{2-6}	68.5	73.1	63.2	55.0	53.8	46.8	43.0	76	64	
L1 Source Window D – Closed										
S1	96.2	101.8	101.2	101.4	98.9	92.9	99.7	110	107	45 (0, -1)
S2	89.7	94.3	95.1	97.4	94.4	87.5	93.3	104	102	40 (-1; -3)
S3	94.4	99.6	90.6	92.6	90.2	87.9	92.1	105	99	37 (-1; -2)
R_{2-6}	62.6	66.0	57.3	55.2	55.2	47.9	46.9	70	61	

Table 5-11. Sound Pressure Level data. (dB re 2 x 10 $^{-5}$ Pa)

It can be seen that the source spectra characteristic is not only dependent on the type and relative location to the sound source but also on the proximity to the façade. For each sound source considered, the S3 microphone, located at the façade, exhibits a bass boost, likely due to the effect of pressure doubling, although at the higher frequencies the effect of this phase shift between the direct and façade reflected wave-fronts introduce deconstructive interference visible as localised minima.

The S1 spectra from the L1 speaker position is approximately 0.72 m from the sound source and will therefore be dominated by the direct source level, highlighted by the relatively flat frequency response and which provides the best indication of the original characteristics of the source spectra.

It is evident from the corresponding single figure results shown in Table 5-11 that a 3 dB correction is consistently seen in the corresponding insulation ratings between the S2 and S3 results although not for the low frequency weighted C_{Tr} spectrum adaptation result.

Further investigation of the reflective effects in evidence on the source side of the façade was made by comparing the source side spectra measured with and without a reflective floor in-situ. The general measurements were made with a chipboard floor in-situ under the window samples over the top of the normal wire mesh walking surface. One set of measurements were however undertaken with the floor sections removed. Figure 5-2 compares the source spectra from three test conditions, normalised to the source spectra obtained in the 'Anechoic' condition. This normalisation reveals the excess attenuation occurring due to each specific test condition, namely the effect of the floor, the full opening of the test window (removing the solid backing from behind microphone S3) and the combination of these effects. The third octave level difference results are shown on the following three plots divided between each source side microphone.

It can be seen from the almost constant 0 dB line that opening the window has very little effect for the S1 source microphone located furthest from the façade, although for the S3 microphone located at the façade the level drops by a reasonably constant 2 dB across the frequency range by removing the reflective backing.

The effect of incorporating the hard floor is however more significant with significant bass boosts in evidence at each microphone position together with a set of higher frequency interference maxima and minima in excess of 3 dB within the third octave band. The variation is clearly seen in the resulting insulation results for the conditions with the floor in place consistently 3 dB higher than the 'Anechoic' condition. The octave band and single figure results are presented in Table 5-12 and Figure 5-2.

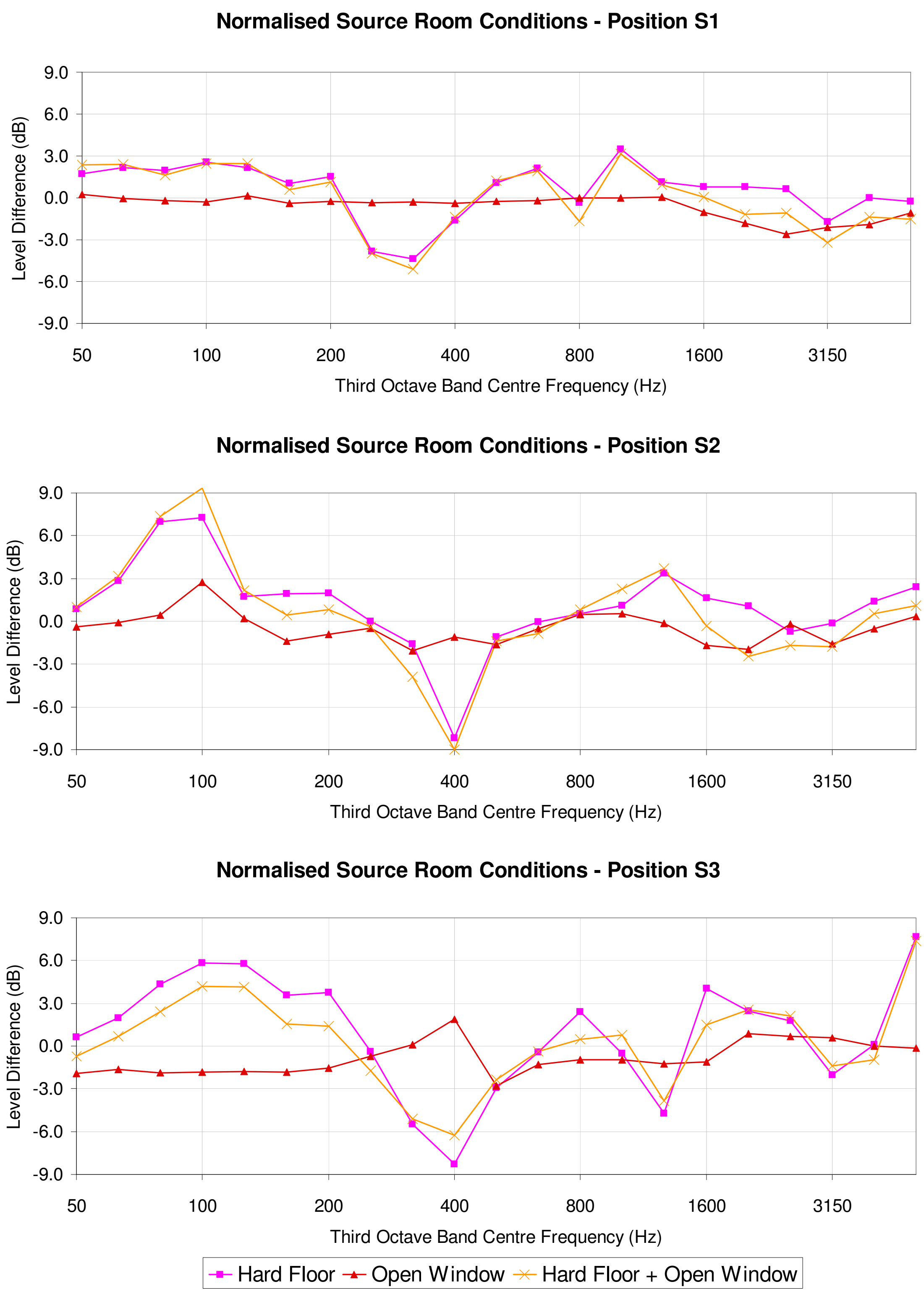


Figure 5-2. Normalised source spectra, relative to anechoic condition.

Sound Pressure Spectra Anechoic Floor Section. L6 Speaker: Window D – Closed. (dB re 2 x 10 $^{-5}$ Pa)										
	Octave Band Centre Frequency (Hz)							Overall Level		Insulation Rating
	63	125	250	500	1k	2k	4k	L_{Leq}	L_{Aeq}	$D_w(C; C_{tr})$
S1	83.6	89.5	87.8	91.1	87.5	86.2	89.2	99	97	36 (-1; -2)
S2	73.6	88.1	87.4	91.7	86.5	83.4	85.1	98	95	35 (-1; -3)
S3	81.8	94.7	88.0	89.6	85.8	81.6	83.9	99	94	33 (-2; -2)
R_{2-6}	49.2	60.7	53.2	49.9	48.3	44.4	40.7	63	56	
Sound Pressure Spectra Hard Floor Section. L6 Speaker: Window D – Closed. (dB re 2 x 10 $^{-5}$ Pa)										
	63	125	250	500	1k	2k	4k	L_{Leq}	L_{Aeq}	$D_w(C; C_{tr})$
S1	85.6	91.2	83.7	92.6	90.2	86.8	89.1	100	97	39 (-1; -4)
S2	79.7	90.0	86.6	91.0	88.6	83.8	87.0	98	96	38 (-1; -3)
S3	85.9	99.4	86.0	88.1	84.0	83.6	86.7	102	95	35 (-1; -2)
R_{2-6}	48.3	61.9	49.1	46.5	46.9	40.0	41.5	63	54	
Sound Pressure Spectra Anechoic Floor Section. L6 Speaker: Window D – Lower pane fully open. (dB re 2 x 10 $^{-5}$ Pa)										
	63	125	250	500	1k	2k	4k	L_{Leq}	L_{Aeq}	$D_w(C; C_{tr})$
S1	83.4	89.4	87.5	90.9	87.5	84.0	87.7	98	96	4 (0; 0)
S2	73.9	87.1	86.1	90.5	86.8	82.3	85.0	97	95	3 (-1; 0)
S3	80.0	92.9	87.7	87.6	84.7	82.3	83.9	98	94	1 (-2; -1)
R_{2-6}	63.5	75.4	76.1	81.4	78.8	76.9	75.9	87	86	
Sound Pressure Spectra Hard Floor Section. L6 Speaker: Window D – Lower pane fully open. (dB re 2 x 10 $^{-5}$ Pa)										
	63	125	250	500	1k	2k	4k	L_{Leq}	L_{Aeq}	$D_w(C_1, C_{tr})$
S1	85.3	91.2	83.2	92.6	89.9	85.0	87.7	99	96	7 (0, 0)
S2	80.1	89.0	85.4	90.5	89.4	81.3	85.9	98	95	6 (-1, 0)
S3	84.0	97.6	85.1	88.3	85.2	83.9	86.1	100	95	4 (-1, 0)
R_{2-6}	62.9	75.4	73.7	71.3	78.1	74.3	73.9	85	83	

Table 5-12. Source spectra with and without hard ground surface

The combined effects of the open window (anechoic condition) with the replaced floor are clearly seen in the result of the open window (floored condition) level difference results.

5.9 Variation in internal room condition

The sound pressure level within the receiver room will not be equal throughout the space. Variation will occur due to source directivity, geometric spreading, absorption, resonant and focusing effects. ISO 140 describes the spatial requirement of the measurement as '*the surface average being taken over the entire room with the exception of those parts where the direct radiation of a sound source or the near field of the boundaries (wall, window etc) is of significant influence...*' however it recommends that this is achieved using a minimum of five microphones evenly distributed throughout the room although with the following constraints

- 0.7 m between microphone positions
- 0.5 m to room boundaries or other objects,

or to using a single moving microphone, having a minimum sweep radius of 0.7 m, taking at least 15 seconds for a full sweep and to be non parallel to any room surface.

The calculations presented within the report have been based on the logarithmic average of the five receiver microphones meeting the requirements of ISO 140. However, where compliance testing is to be undertaken on site it is unlikely that the stringent requirements outlined in ISO 140 will be considered. Instead it is likely that a single microphone position would be used, positioned close to the window such that the operator can visually verify the noise source as being active.

The deviation of the individual measurement positions from the calculated average have been calculated, with the follow findings made

1. The average standard deviation was approximately 3 dB for the receiver positions R 2-6, although with a marginally worse low frequency performance.
2. The size of the deviation depends on the room conditions, with the smallest spread in results achieved within the most reverberant room and the largest difference with more absorbent room conditions.

3. The largest range in internal sound pressure levels occurs with the windows open as there is a higher intensity level relative to the windows closed scenario.

4. For the microphone arrangement used within the study, position R3, located centrally within the room 2 m from the window and at a height of 1.2 m, gave the closest correlation to the averaged result.

5. The most extreme variation in level, from microphone R1 located at the window, ranged from 15 dBA, for the most absorbent room condition.

Figure 5-3 shows the sound pressure spectra measured at each microphone during three distinct measurements. The measurements compared the effects of changing the internal levels of absorption within the receiver room. The initial condition, a bare room with a mid-frequency RT of 1.3 s was altered by the introduction of a carpet with a resulting change in the mid-frequency RT to 0.6s. The final change was enacted by adding floor standing absorbent material to the room perimeter bringing the mid frequency RT down to 0.3 s. The microphones were arranged more uniformly at a height of 1.4 m along the longest room axis, bisecting the receiving room floor. The separations from the window were set at 0.1, 0.2, 0.4, 0.8, 1.6 and 3.2 m.

The results for the three conditions are very similar, with only the spread in receiver results obviously characterising the results. The source measurements are effectively the same across each measurement; otherwise the trend in each graph is the same identifying the highest level closest to the window with each consecutive position away from the window having additional attenuation.

The variation in each room condition are clearly seen in Figure 5.9, which shows the selected microphones at 0.8, 1.6 and 3.2 m compared against each room condition. (The source measurements for each data sets varied by less than 0.15 dB across each one-third octave band).

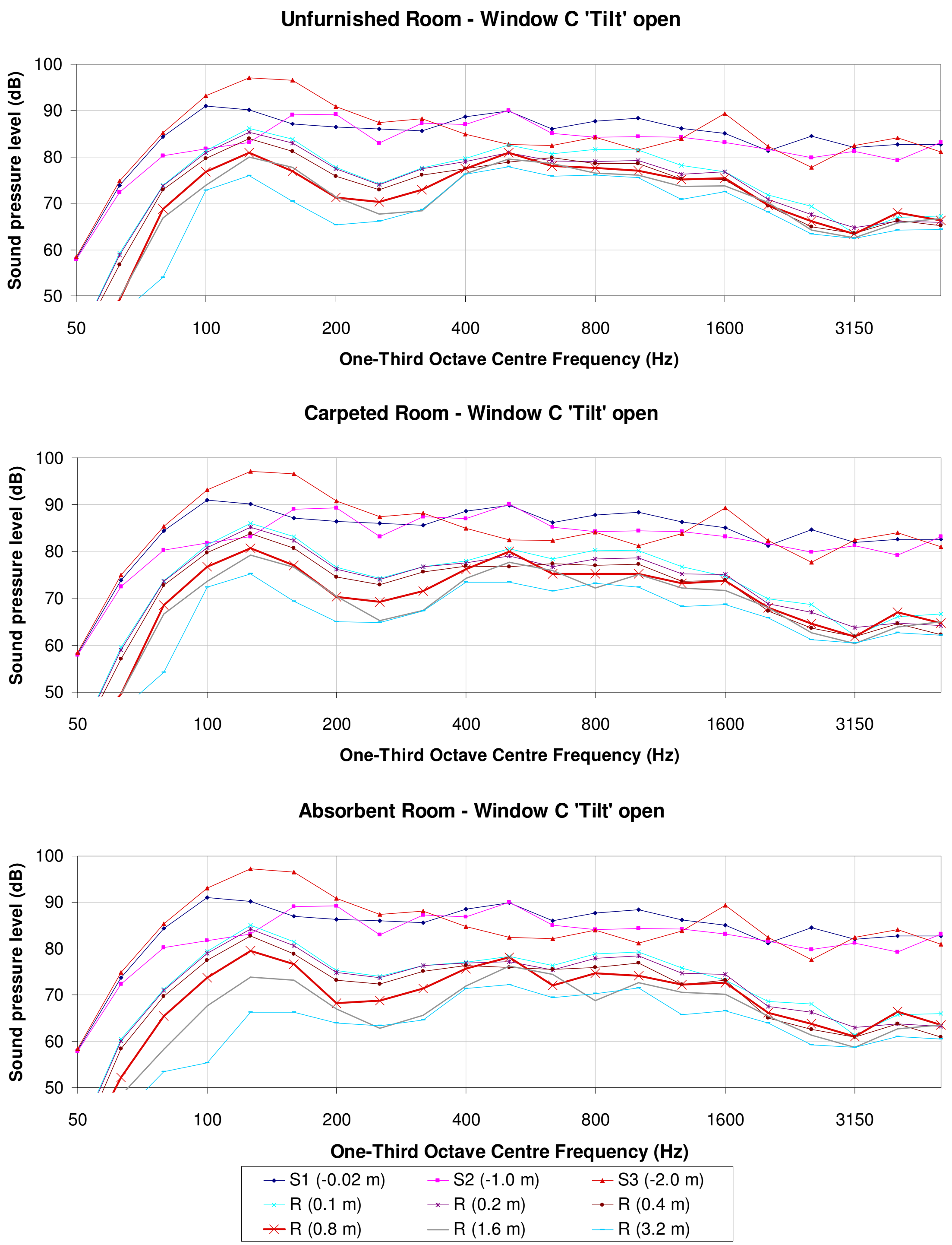


Figure 5-3. Source and receiver room sound pressure spectra

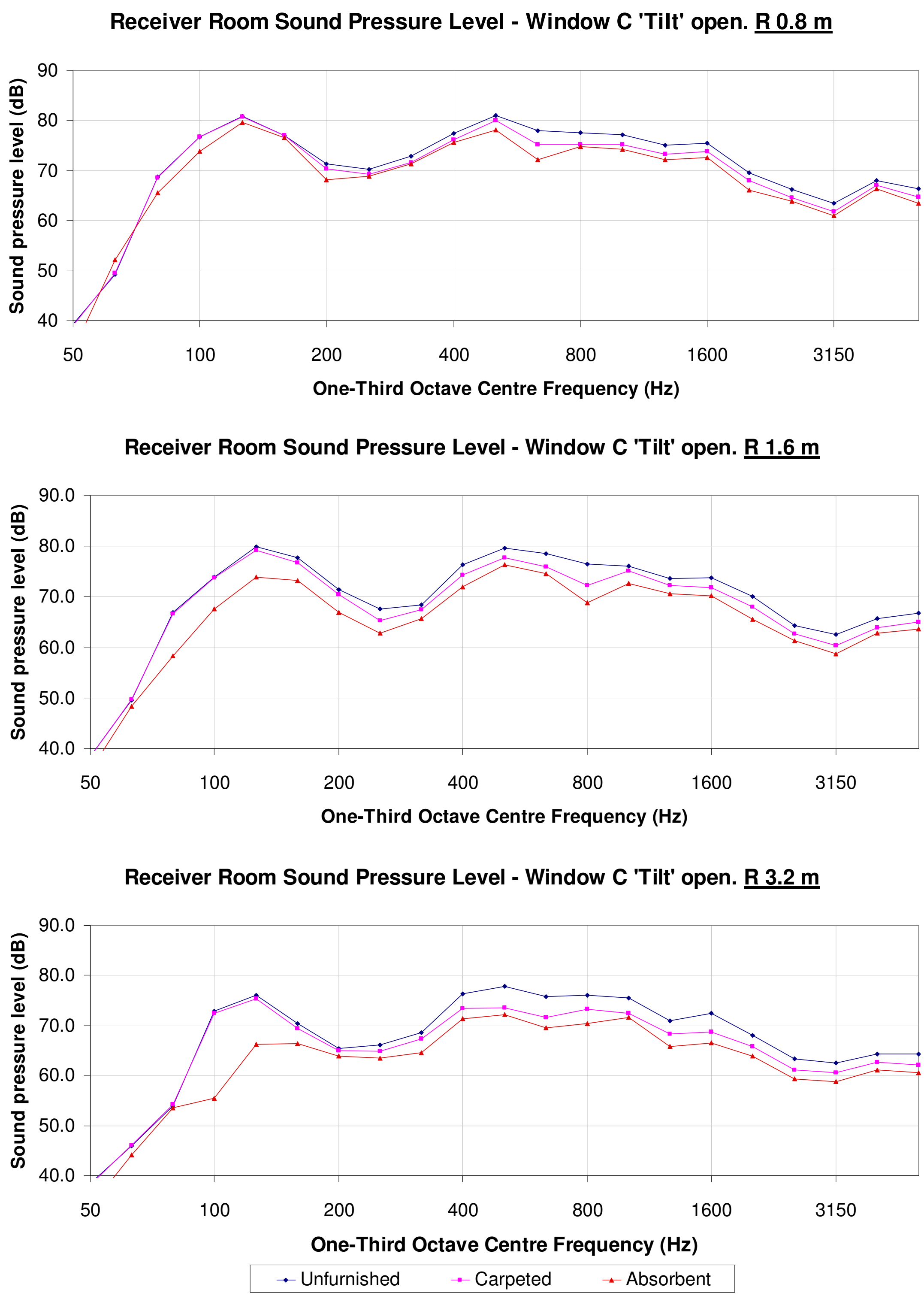


Figure 5-4. Variation in receiver room sound pressure spectra with room condition

Chapter 6 Conclusions

6.1 – Introduction

This study has involved a laboratory investigation of sound transmission through open and closed windows with a review of pertinent reference and research literature. Particular attention has been given to the evaluation of the relative effects of window type, material, size, glazing, opening style, area of opening, case seals, ventilation slots, measurement position and source characteristics.

The extensive test programme consisted of some 720 individual measurements, made simultaneously across nine microphone channels. The analysis has examined the resulting noise spectra by initially deriving single figure insulation ratings. Further analysis provided estimates of the component insulation ratings for the window openings.

Section 1.7 of the study introduction set out project aims as focused questions. The following paragraphs will address each of these questions.

6.1 An open window

Define open, partially-open and closed windows?

A definition of an open window area sufficient for room ventilation purposes is outside of the scope for this report; however there is increased awareness that the ability to open a window without suffering exposure to high noise levels is a positive indicator of the built environment.

The 1972 research published by Mackenzie and Williamson [9] defined appropriate window openings for day and night time summer ventilation of 0.36 and 0.03 m^2 respectively. This study however used three **open window** areas of 0.05, 0.1 and 0.2 m^2; the most appropriate of these for background ventilation is considered to be the 0.05 m^2 opening. The window openings have been calculated from the combined open areas between the opened light and static frame, perpendicular to the plane of the open window. This approach to the calculation of open area, for a simple side hinged window, is dependent only on the sum of the opening light's height and width, as shown by Equation 6-1.

$$Window\,Open\,Area \approx d(W + H)$$

Equation 6-1

Where d (m) is the opening depth of the window and W (m) and H (m) are the width and height dimensions of the opening light respectively. The calculation of an appropriate opening area is therefore relatively straightforward for simple window styles (i.e. those with the hinges fixed only to one side). An opening depth of 0.04 to 0.05 m is generally adequate to ensure commonly sized opening lights will have an open area in excess of 0.05 m^2.

Table 5-6 presents the empirically derived insulation ratings for the 0.05 m^2 open windows. The rating is provided in the form of the element normalised level difference, $D_{n,e}$, which provides reasonable consistency across the range of window opening styles. The single figure weighted rating for the 0.05 m^2 opening is $D_{n,e,w}$ 19 dB. The reduction in insulating performance when the size of the opening is nominally doubled to 0.1 m^2 was 1 dB with a further reduction in insulation rating of 2 dB for a further doubling of open window area.

A **partially open** window has been assumed to be a window physically secured on a window catch, although without compressing the seals. Locking mechanisms commonly have two settings one which compresses the seal and one, which does not. The small opening allows a low level of ventilation to occur whilst still providing window security.

Measurement results, Table 4-3, for the tests undertaken on the 'Untensioned' window condition show consistent results for each individual window although the least correlation across the combined 'window opening style'. The resulting insulation of a partially open window appears therefore to be dependent on the individual window configuration; with some units showing relatively large air paths past the open light whilst others show negligible daylight through the partial opening and subsequently exhibit better insulation performance, similar to those with the seals fully compressed. It is assumed that the ventilation performance of such partially open windows would show significant variation.

A **closed window** is readily defined by the tensioned closure of an opening light; however any closed window assumption, particularly if using high specification glazing, must also include information about any ventilator incorporated within the facade. The measured performance of the closed windows, in isolation to the block façade, have been empirically estimated. These results show reasonable agreement with published results, Table 5-2.

The effect of including a ventilator within a window frame is shown to significantly degrade the insulation performance of a façade[4.10].

6.2 Style of window opening

How is the level of sound insulation provided by an open window affected by the opening style?

The insulation of seven windows, with a total of twelve different opening styles, have been measured. The variation range in the single figure weighted insulation results across the different opening styles is consistently between 4 and 6 dB. There is therefore a significant affect attributable to the means of opening.

The window opening with the poorest sound insulating performance was Window B, a reversible centre pivoting window whose opening light twisted into the room to allow maintenance access. The method of opening creates the main air paths either side of the opening, these additionally form a channel with sound reflecting off the open light towards the room.

The results do not show any one opening style providing significantly better insulating characteristics. Instead the set of windows with an outward opening which protects the open void from direct sound generally performed similarly well.

The set of windows with no extending opening lights, namely the inwards turn and tilt Window C and the sliding sash Window D, were also among the best performing open units particularly with angled sources of noise; The lack of an extending opening is potentially advantageous by avoiding further in-bound reflections which effectively reduce the level of noise transmitted through the opening compared to the outward opening windows. The turn and tilt window bettered the ‘unprotected’ sliding sash window when the source was normal to the façade.

6.3 Frame material

How is the level of sound insulation provided by an open window affected by the frame material?

No discernible difference in sound insulation was measured between frames of different material whilst in the open position; a small difference was recorded between windows in the closed position with the PVCu frames recording a marginally better result than other materials (Table 4-8).

6.4 Window size

How is the level of sound insulation provided by an open window affected by the window area?

No discernible difference in sound insulation was measured between windows of different surface area whilst in an open position. The analysis of the acoustic performance of closed windows therefore used the area-independent element normalised level difference parameter, $D_{n,e}$ to characterise open window performance. The use of the apparent sound reduction index, R’, would require a relationship to exist between windows of different surface area and their sound insulation.

As expected, smaller closed windows recorded improved insulation ratings compared to the larger windows. Investigation of a potential relationship identified two distinct trends. Table 4-6 shows a variation of 5 dB per doubling of the glass area, however Section 5.3 which considers the whole window unit area identifies the relationship as being logarithmic with a resulting 3 dB variation per doubling of whole window unit area.

6.5 Opening size

How is the sound insulation of an open window affected by the area of opening?

There is a direct relationship between a windows area of opening and its characteristic level of acoustic insulation; larger openings provide poorer acoustic protection. This relationship does not however correlate to a logarithmic ratio of relative opening sizes, with measured weighted insulation differences in opening areas being limited to 1 and 2 dB for open area increases from 0.05 m^2 to 0.1 m^2 and from 0.1 m^2 to 0.2 m^2 respectively.

6.6 Glass specification

How is the level of sound insulation provided by an open window affected by the glass specification?

For open windows the level of sound insulation was not affected by the glass specification. The effect of glass type for closed windows is well documented in trade and research literature and has not been considered in this report.

6.7 Acoustic window seals

Is there any benefit in fitting proprietary acoustic seals to windows?

There was no apparent benefit of acoustic window seals once windows were open beyond the ‘Untensioned’ position.

The closed window results show the condition and presence of seals have a significant influence on closed window acoustic performance. Table 4-9 indicates the presence of full and partial sealing between the rebated frame and closed window light has a 14 – 20 dB influence on the weighted insulation rating.

An improvement in the weighted insulation of 6 dB was obtained by fitting proprietary acoustic seals to a closed test window (see Table 4-9).

6.8 Background façade ventilation

What impact does the introduction of a ventilation slot in the window frame have on window performance?

The inclusion of a slot ventilator within a window frame had a negligible influence on insulation levels once the window was open.

The introduction an open slot ventilator to a window frame reduced the weighted closed window acoustic performance by 11 dB. The comparative reduction with the vent closed was 6 dB. Proprietary over frame vents gave a significantly improved acoustic performance at high frequencies, the weighted insulation rating is however dominated by the low-frequency performance which do not substantially differ from slot vent performance.

There was very good correlation between different slot vent products. Typical closed window weighted level differences with a 4000 mm^2 slot ventilator were 32 dB with the vent open and D_w 38 dB with the vent closed.

'Acoustic' slot ventilators and external cowls showed no tangible performance difference to any other slot-vent product (see Table 4.11).

6.9 Field measurement position

Which single position within the receiving room best represents the average sound pressure level within the room?

The investigation has considered providing advice to practitioners undertaken field measurements using a single receiver measurement position. The conclusions of the assessment were that a position on the room's centre line, set back 2 m from the window and at a height of approximately 1.2 m above the floor provided a good representation of the spatially averaged room sound level (see Figure 4-3).

The variation in the sound-field distribution was most acute at the microphone measurement position located at the window. This position consistently recorded the highest receiver room noise levels with significant variations compared to the receiving room mean level. This result was excluded from further averaging and does not form any part of the main report findings.

6.10 Source angle

How does the angle of incidence of the noise source to the window affect sound insulation?

The analysis of source angle incidence found the weighted apparent sound insulation rating to have the lowest value with the source normal to the openings. The movement of the source to wider angles increased the level of insulation. The largest variation in estimated weighted insulation rating is +5 dB relative to the normal incidence effect.

6.11 Source Type

Is there a significant variation in open window insulation from different sources of environmental noise?

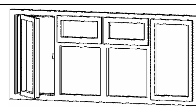
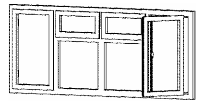
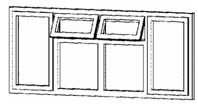
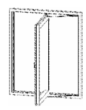
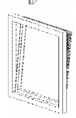
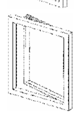
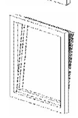
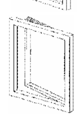
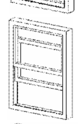
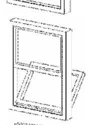
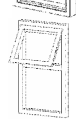
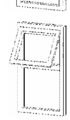
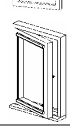
In order to assess the influence that different sources of environmental noise have on open window insulation noise break-in predictions were undertaken using four different source spectra. The results of the calculation are shown in Table 6.1, assuming open window transmission through a 0.05 m^2 opening.

The influence of road and rail traffic noise on the resultant overall internal noise level are identical; further correlation can be found with the weighted level difference rating adjusted with the C_{tr} spectrum adaptation term.

The influence of aircraft noise closely follows that of the weighted level difference insulation parameter.

Entertainment noise, specifically amplified music, does not show the same degree of correlation to the measured single figure insulation ratings as do the transport related noise sources. Their use in a prediction could not provide a robust result; although it would generally provide the more cautious estimate, generally underestimating the ability of an open window to reduce amplified music noise break-in.

The use of the weighted level difference parameter, D_w (C; C_{tr}) provides a useful tool for the prediction of noise from a variety of sources.

Window	**Measurement**	**Opening**	**Comparative Level Difference (dBA)**			
ID	***D_w (C ; C_{tr}).***	**Illustration**	$D_{A,road}$	$D_{A,rail}$	$D_{A,air}$	$D_{A,music}$
A-1	18(-1; -2)		17	17	18	16
A-2	18(-1; -2)		17	17	18	16
A-3	16(-1; -2)		14	14	16	16
B	14(-1; -2)		12	12	14	15
C-1	17(-1; -1)		16	16	17	19
C-2	18(0; -1)		17	17	19	20
C-3	17(0; -1)		16	16	18	19
C-4	17(-1; -2)		15	15	17	18
D-1	18(-1; -2)		16	16	18	18
D-2	16(-1; -2)		14	14	16	17
D-3	20(-3; -4)		16	16	18	18
E	17(0; 0)		17	17	18	18
F	18(0; -1)		18	18	18	18
G	15(0; 0)		15	15	15	17

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Appendix A. Receiving Room Reverberation Time

	Condition D_0	Condition D_1	Condition D_2	Condition D_3	Condition D_4
100	0.73	0.77	0.85	0.88	0.67
125	0.75	0.74	0.74	0.69	0.39
160	0.77	0.89	0.85	0.84	0.43
200	0.72	0.58	0.55	0.55	0.29
250	1.26	0.73	0.67	0.65	0.27
315	1.18	0.68	0.60	0.59	0.28
400	1.52	0.62	0.61	0.58	0.26
500	1.44	0.53	0.49	0.48	0.32
630	1.44	0.62	0.52	0.52	0.33
800	1.52	0.73	0.61	0.58	0.37
1000	1.46	0.74	0.70	0.64	0.36
1250	1.48	0.84	0.73	0.70	0.35
1600	1.50	0.84	0.67	0.69	0.32
2000	1.35	0.79	0.61	0.59	0.30
2500	1.17	0.73	0.59	0.57	0.31
3150	0.98	0.61	0.49	0.49	0.28

Table A.1 Reverberation time of receiver room (s)