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HIGH ACOUSTIC INSERTION LOSS FACADE DEVICES THAT ALLOWS NATURAL VENTILATION IN A DENSELY POPULATED HIGH-RISE BUILT ENVIRONMENT

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Ph.D

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2016

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High Acoustic Insertion Loss Facade Devices that Allows Natural Ventilation in a Densely Populated High-Rise Built Environment

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A thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy

JULY, 2015

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Tong Yean Ghing

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* Dedicated to my husband, Mr. Beh Loong Fatt (Ailang) &*

********* my lovely daughter, Beh Yi Xin *********

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ABSTRACT

Rapid population growth and economic development have led to serious noise pollution in densely populated cities. As the noise level keeps on increasing, opening windows for natural ventilation has become nearly not possible, especially in urbanized residential areas. Mechanical ventilation can be used but this may increase the energy consumption of the city. This thesis deals with the design of a façade devices of high acoustical insertion loss which can yet allow certain degree of natural ventilation across it.

The study begins with an investigation of a façade device that has been believed to be an effective self-protecting building form under the exposure of traffic noise. It consists of a window and a balcony. Unfortunately, this device does not provide significant protection to the façade compared with the conventional opened window. Thus, investigation on an alternative façade device, which is modified from a partially opened double glazing window system formed by staggering the inlet and outlet window openings, named as plenum window, is then conducted. The acoustical protection, in term of insertion loss, of this façade device is investigated both experimentally and theoretically. Laboratory measurements have been carried out to evaluate the effectiveness of the device in reducing sound transmission. Further analysis has been made to examine the effects of noise source directions on the acoustical protection of the device. The results reveal that the acoustical insertion loss of the device is more sensitive to the change in device configuration when the façade device is located at “favourable” propagation condition.

A series of on-site measurements have also been conducted to address the effectiveness of this device when it is applied to the real noisy built environment. An empirical formula for the prediction of the acoustical insertion loss of the façade devices has also been proposed. It is hoped that this study can provide a useful baseline on the recent status of acoustical protection of plenum window which can be applied as a noise-blocking façade device for the dwellings located close to noisy traffic roads, without forfeiting the chance of natural ventilation.

Keywords: Façade devices; Insertion loss; Plenum window

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PUBLICATIONS

Some ideas and figures have appeared previously in the following publications:

Tong, Y. G. and Tang, S. K. (2011). "Full scale model investigation on the acoustical protection of a balcony-like façade device (L)". Journal of Acoustical Society of America, 130(2), 673-676.

Tong, Y. G. and Tang, S. K. (2013). "Acoustical performance of plenum windows in the presence of a line source – a scale model study". Journal of Acoustical Society of America, 133(3)1458-1467.

Tong, Y. G. et al. (2015). "Full scale field study of sound transmission across plenum windows". Applied Acoustics, 89(March 2015) 244-253.

Tong, Y. G. and Tang, S. K. "Acoustical insertion loss of plenum window at different sound incidence angles". *Proceedings of the 20th International Congress on Acoustic (ICA),* Sydney, Australia, 2010.

Tong, Y. G. and Tang, S. K. "Scale model study on acoustical benefits of plenum window at various azimuthal sound incidences". *Proceedings of the 3rd International Postgraduate Conference on Infrastructure and Environment,* Hong Kong PRC, 2011.

Tong, Y. G. and Tang, S. K. "The insertion loss of plenum window with non-parallel line sources". *The 162nd Meeting of Acoustical Society of America,* San Diego, 2011.

Tong, Y. G. and Tang, S. K. “A study on acoustical protection effects of plenum windows”. *ACOUSTICS 2012 HONG KONG,* Hong Kong PRC, 2012.

Wong, H. K., Yung, C. N., Tang, S. K. and **Tong, Y. G.** “On site performances of ventilation windows”. *ACOUSTICS 2012 HONG KONG,* Hong Kong PRC,2012.

Tong, Y. G. and Tang, S. K. “Acoustical performance of plenum window at various azimuthal sound incidences”. *EURONOISE,* Prague, Crezh Republic, 2012.

Tang, S. K., **Tong, Y. G.** and Tsui, K. L. “The sound transmission loss across ventilation window under active noise cancellation”. *Proceedings of the 43rd International Congress on Noise Control Engineering: Improving the World Through Noise Control (INTERNOISE 2014),* Melbourne, Australia, 2014.

ACKNOWLEDGEMENT

First and foremost, I would like to express my highest gratitude to my supervisor, Professor Tang Shiu-keung for his extensive assistance, guidance and valuable advice in my research work.

Many thanks to my husband, mother and all family members for their kindly support, entirely care and love. Their encouragement made my study possible.

Also, I would like to acknowledge Malaysia's Ministry of Higher Education for financial support and University Tun Hussein Onn Malaysia for giving me study leave to pursue my study in The Hong Kong Polytechnic University.

Finally, sincere gratitude goes to all the lecturers and staff in Department of Building Services Engineering for their guidance and suggestions. Special thanks to all building & environment acoustic research group members for their helping hands.

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GLOSSARY TERMS

Abbreviation

CFD	Computational fluid dynamics
CRTN	Calculation of Road Traffic Noise
dB	Decibel
dB(A)	A-weigthed noise level in decibel
D_{nT}	Standardized level difference
EPD	Environmental Protection Department, HKSAR Government
Eq.	Equation
FEM	Finite element method
hr	hour
I	Acoustical intensity
IL	The difference of indoor sound levels before and after installation of plenum window
IL_A	The difference of band noise level inside the receiver room after replacing conventional side-hung window by plenum window
IL_B	The difference of band noise level at 1 meter in front of the closed window with and without the balcony
IL_{EF}	Empirical formula of insertion loss
IL_R	The average noise level reduction inside the receiver room with and without the balcony when the window is opened.
Hz	Hertz
ISO	International Standards Organization
m	meter
min	minutes
MLS	Maximum Length Sequence
mm	millimeter
MPA	Micro-perforated panel
NR	Noise level difference

PDF	Probability density function
Q	Directivity factor
R	Noise reduction
R'	Apparent sound reduction index
sec	second
SPL	Sound pressure level
STC	Sound transmission class
SWL	Sound power level
TNI	Traffic noise index
WHO	World Health Organization

Notations

d	Air gap width of plenum window
H	Height of plenum window
L	Length of plenum window
L_{10}	Sound pressure level exceeded for 10% of the measurement duration
L_{50}	Sound pressure level exceeded for 50% of the measurement duration
L_{90}	Sound pressure level exceeded for 90% of the measurement duration
L_{Aeq}	A-weighted equivalent sound pressure level
$L_{Aeq,\ T}$	Equivalent continuous A-weighted sound pressure level over a period of time, T
$L_{eq,\ T}$	Equivalent sound pressure level over a period of time, T
L_{NP}	Noise pollution level
v	Overlapping length of plenum window
w_i	Inner side opening of plenum window
w_o	Outer side opening of plenum window

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CHAPTER 1 INTRODUCTION

1.1 Background

Environmental noise, especially that generated from road traffic, is the major noise pollutant that has affected surrounding populations in a high-rise compact city. This urban noise annoyance bring outs various effects to the human daily activities and health (Ouis, 2001). Many social-acoustic surveys were carried out over the century to evaluate the effects of traffic noise exposure to the nearby residents. In several studies, traffic noise is found to be the most critical effects on human sleep disturbances (Öhrström, 2006a, 2006b; Robinson, 1970; Skånberg & Öhrström, 2006) and could lead to deterioration of subsequent daytime life quality such as tiredness, sleepy and low working performance (Muzet, 2007). Excess exposure to long-term high level of traffic noise can increase the risk to health diseases (Babisch, 2008; Sørensen et al., 2011; Wagner et al., 2010) as well as health problems. Sørensen et al. (2011) showed that increasing exposure to traffic noise could lead to higher probability of stroke risk especially for elderly persons who are over 65 years old.

From the social survey in London, the critical threshold for acceptable noise level based on the residents live near the traffic roads was range between 65 to 75 dB(A) L_{10} (Langdon, 1976). WHO has recommended the limit of noise level (L_{eq}(A)) outside dwellings for daytime to be 55dB(A) while 45 dB(A) is suggested as the limit during the night time to protect people from being seriously annoyed (Berglund & Lindvall, 1995). The growth in population and the business activities in the last few decades, which are also anticipated for the years to come, have increased the demand on the mass transport systems and this makes the noise environment even worse. In European Union countries, about 40% of the population are exposed to traffic noise levels $L_{Aeq,T}$ above 55 dB(A) and 20% of the population are exposed to traffic noise level exceed 65 dB(A) (European Environment Agency, 2011).

This urban noise becomes severe in densely populated cities such as Hong Kong where large numbers of residential dwellings are required to build alongside the main traffic networks to satisfy the housing demands of the communities. When buildings are situated near traffic roads, environment noise from transportation system becomes source of nuisance in the city. Since last four decades, Hong Kong can be considered the noisiest city in the world with the average of measured L_{10}, L_{50} and L_{90} as 81 dB(A), 75 dB(A) and 69 dB(A), respectively (Ko, 1978). The guideline sets out the limit of road traffic noise L_{A10},(1hr) at 1 meter from all new building façades is 70 dBA to protect residents in Hong Kong. However, previous survey shown that 1/7 (more than one million) of the Hong Kong population are living in areas where the highest traffic noise level exceed 70 dBA (HKSAR, 2006). This indicates that strategies to mitigate this urban noise are urgently needed.

There are three main methods of controlling the impact of traffic noise on communities (Garcia, 2001). The first approach is to reduce noise at its source either by designing quiet vehicles or reduce the traffic flow in those areas. The second way involves different strategies to limit the spread of noise whereby control the sound transmission path from the source to receiver. The third approach refers to the use of noise protective devices at the receiver such as the acoustic insulation of existing building to minimize the transmission of road traffic via sensitive zones. The second method which blocks the propagation of noise from the source to the receiver is the common solution used to tackle traffic noise in most countries.

Over the past few decades, roadside barriers are the common structures used in many urban areas to reduce human noise exposure due to the noisy road networks in the residential areas (Ekici & Bougdah, 2003). Experimental and theoretical studies on barriers have been conducted over a century. Various improvements on geometries and materials that used for barriers also have been made over few decades to enhance the performance of the barriers (Watts, Crombie, & Hothersall, 1994; Watts, 1996; Fujiwara, 1998; Auerbach, Bockstedteb, & Estorff, 2010; Koussa, Defrance, Jean, & Blanc-benon, 2013). There are researches on the insertion losses of roadside noise barriers (Lam & Roberts, 1993; Li & Wong, 2005). The use of active control together with noise barriers has also been explored (Omoto, Takashima, Fujiwara, Aoki, & Shimizu, 1997). In Hong Kong, noise barriers have been built along new major trunk roads since 1990 to reduce the excessive traffic noise exposure to the residents. The guideline of designing noise barrier has also been issued by the Hong Kong government to address this community noise (HKSAR, 2003).

As barrier is built near residential building areas, it becomes part of the neighbourhood landscape. Even though the noise level is reduced because of the shadow zone created by the barrier, the residents living behind the barrier is experiencing the restriction of views, reduction of sunlight and air circulation to their households (Arenas, 2008). Nevertheless, the effectiveness of noise barriers that used in the densely vertical city like Hong Kong is limited (Lam & Ma, 2012). Some other noise mitigation methods have been taken to reduce propagation of noise from outside into the indoor environment. Enclosures are also adopted in some highly problematic cases. In addition, setbacks and extended podia are suggested (Bradley, 1977; HKSAR, 1993). However, nearly all these measures are not cost-effective and must be designed at the time the whole built environment is planned. Besides, construction land in a hilly and congested city like Hong Kong is very limited and expensive. Crowded tall buildings with very narrow traffic roads can be found in many areas in Hong Kong. There are many cases where massive structures cannot be built due to site constraints. To this point, an alternative noise mitigation form is vital to deal with this serious problem.

Since noise from transportation system mainly propagates from outdoor into the indoor environment through building facades, the treatment on the devices at the façade could be great solutions to deals with traffic noise. Besides the external walls, large portions of building façades are covered by windows which are designed to admit natural daylight and ventilation into the buildings. This makes window a weak point of the facade because window constitutes the primary path of traffic noise enters into built environment. Double glazing windows are well known devices that can be used as a mitigation measure (Harris, 1979). In order to obtain good sound insulation, various passive noise controls have been carried out. For glass windows, factor contributing to the sound insulation of glazing windows are its mass, air-tightness, the number of glaze panels and gap width of the window cavity. Previous study has been carried out to predict the sound transmission loss dependence of glass thickness and air cavity inside window (Tadeu & Mateus, 2001). From their study, double and triple glazed windows with larger air gaps contribute to high sound insulation of more than 40 dB at higher frequencies. There are efforts to deal with limitation of passive controls of glazed windows by using active noise treatments (Jakob & Möser, 2003a, 2003b; Naticchia & Carbonari, 2007). Active noise control can improve the transmission loss of window in the low frequency range; reduction of noise in total sound pressure level of 7 dB for feedforward controller and 3 - 6 dB with the feedback controller.

Nevertheless, most of works mentioned are not designed for the natural ventilation applications. In urban residential areas with serious noise pollution, natural ventilation becomes nearly not possible. Natural ventilation and noise control are two conflicting issues. When natural ventilation is provided across the facade, windows will become the main noise transmission path for external noise ingress. Residents living in the city with high traffic noise levels then prefer to close all the windows and use air conditioning system. The use of mechanical ventilation increases electricity demand, energy consumption and environmental problems. Recent years, the issue of sustainability has been concern in many new urban development areas. Natural ventilation has become an increasingly important and prominent aspect of building design as an alternative way to reduce the use of air conditioning in the cities. Therefore, the study of façade devices which can provide good acoustical protections while allowing natural ventilation is required when the conventional mitigations may not adoptable. The research would be beneficial to the buildings (and people) especially those in the high densely cities of tropical and sub-tropical regions as it enhances the development of façade devices for traffic noise protection and indoor natural air circulations.

1.2 Overview of Façade Devices with Natural Ventilation

Recently, sound insulation of façade devices that allow natural ventilation become popular research area among acoustic researchers and engineers. Balcony is believed to be an effective self-protecting building form that can be used as alternative method for tackling traffic noise pollution in cities while allowing natural ventilation across it. The configuration of balcony itself can shield and reduce the exterior direct noise from entering into the interior of a building through façade opening or window. Figure 1.1 shows the common elements of a closed balcony which consists of a floor, a ceiling (slab of upper floor's balcony), a front parapet and two side walls. In traditional design of building, balconies normally were built for aesthetical and panoramic view. Due to limitation of lands, residential houses become extremely expensive and very rare in urbanized cities. As a results, buildings in the cities are built in the vertically direction to optimize the usage of lands. Therefore, balcony at residential building in the city becomes the only outdoor space of a high-rise residential unit. Residents like to use balcony as their recreation area, sky garden or even use as place for drying their clothes. In Hong Kong, balcony is to be exempted from the calculation of 'Gross Floor Area' and 'Site Coverage' with the maximum of area of $3m^2$ to encourage the adoption of this green feature to residential buildings (HKSAR, 2011). Since balcony is welcomed among residents, this façade device is likely to be suitable as urban noise mitigation measure.

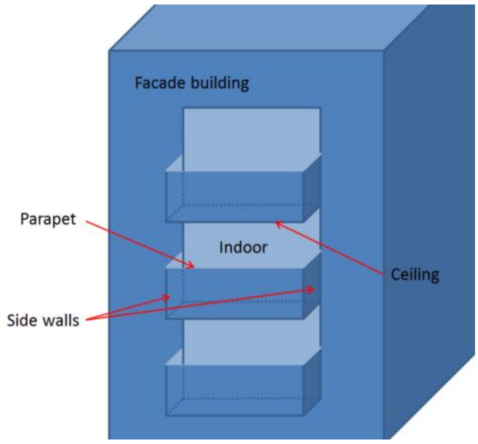


Figure 1.1 Basic components of closed balcony at façade building.

The acoustical performance of balcony attached to a building façade has been investigated over the past few decades. The effects of different balcony forms, balcony depths and ceiling configurations on the acoustical protection of this façade device have been studied by numerous researchers (Hossam El Dien & Woloszyn, 2004, 2005; Ishizuka & Fujiwara, 2013; Mohsen & Oldham, 1977; Oldham & Mohsen, 1979; S K Tang, 2005; S.K. Tang, 2010). Introduction of sound absorption materials to the device has also been proposed to increase the acoustical protection of balcony (Hothersall, Horoshenkov, & Mercy, 1996; Kropp & Berillon, 2000; May, 1979).

Another approach that is believed to be an effective and suitable façade device to mitigate the urban noise problem in densely high –rise city like Hong Kong is plenum window, a ventilation window with staggered inlet and outlet openings. The window is designed based on elongated plenum chamber concept originated from a partial opened double glazing window (Ford & Kerry, 1972). The inlet and outlet openings of the proposed window system were designed in the zigzag configuration to block direct sound path from the outdoor to the indoor environment. Efforts have made to increase sound attenuation of this type of window by introducing thin transparent micro-perforated panels (referred as MPA hereafter) into the window system (Kang & Brocklesby, 2005). It is showed that this ventilation window of the right dimensions lined with micro-perforated panels can produce an acoustical protection better than a closed single glazing window.

1.3 The Research Gaps

Normally, balconies at residential buildings are connected together with opening or window. However, most of the previous studies are focused on the noise reduction at the façade behind the balcony concerned. Measurement points at balcony cavity adopted in many studies are not practical since the receiver positions normally are inside the buildings. Besides, there still is shortage of knowledge regarding the sound transmitted into the residential flat in the presence of a balcony and window. Sound insertion loss of façade devices on window is a significant study because opening behind the balcony constitutes the primary path through which traffic noise enters into the indoor built environment when natural ventilation is required in the design of building envelopes. In addition, numerical and scale down model studies to predict the acoustical protection of balcony especially in the presence of sound absorption material may not truly reflect the performance of a full scale balcony and window.

Lately, many researchers have switched their focus to plenum window. This modification of ventilation window has received attention of many researchers because it is able to provide good sound insulation and reasonable natural ventilation. The acoustical protection of this window is believed to depend on the sound incident angles because of its staggered inlet and outlet design. However, only Kang and Li (2007) have studied the acoustical performance of this façade device for different sound incidence angles. Unfortunately, three incidence angles that considered in their study, 0 (normal), 45 and 75° may not sufficient to give a full picture of the sound transmission mechanisms in this staggered design. Also, it is important to explore whether plenum window can be successfully mitigate the urban noise problem for residential dwellings. Thus, the field test with real traffic noise will be more appropriate to examine the applicability of this façade device under the real condition. Furthermore, at the time being, there is no theoretical works on plenum window available for estimating the acoustical benefits of this façade device.

1.4 Objectives and Research Scope

The major aim of the present study is to address current issues on acoustical protection of high-rise residential buildings in urban areas. Investigation on the acoustical insertion loss of various devices that can be attached to building façade is the first objective of this study. Development of a theoretical model for the prediction of the acoustical performance of the façade devices then follows.

The aims and main objectives of this study are as follows:

i. To investigate the acoustic insertion loss of various devices that can be attached to building façade.

ii. To analyse the effects of device's configurations on its sound insertion loss.

iii. To develop theoretical model for the prediction of the acoustical performance of the façade devices.

1.5 Outline of Thesis

This dissertation contains seven chapters. They are briefly described as follows.

Chapter 2 starts with providing literature reviews of balcony which is a self-protecting building form that can be used as noise screening device at façade buildings. Then, an approach of window system that adopts the principle of plenum chamber is described and reviewed.

In chapter 3, investigation on combination of balcony and window, named as balcony-window device was carried out experimentally. This façade device was tested by using full-scale measurement which was carried out in the laboratory. The setups of the experiment and configurations of the tested devices are described. The benefit of the balcony-window device is compared with the conventional casement window. Sound absorption materials were used to increase the effectiveness of the device. Acoustical protections of balcony-window device before and after installation are discussed. The effects of location of sound absorption materials are reported.

Chapter 4 focus on the scale model experimental study of the staggered design windows, named as plenum window. The setup of experiments is described in details. Then, the effects of sound incident angle to the mentioned façade devices were tested. Various openings and air gap widths were also tested to investigate the effective acoustical protection of the device.

Chapter 5 extends the study of plenum window from the previous chapter. The investigation of plenum window when it was applied to a real housing flat is presented.

Site location and the setting of mock-ups are described first then followed by details of tested windows. Comparison of acoustical benefits of plenum windows and conventional windows used in Hong Kong public housing flats is made.

The investigations of various combinations of full–scale plenum windows were presented in chapter 6. The effects of important parameters include air gap width, opening sizes and overlapping lengths of the plenum windows to the performance of plenum windows were present. Finally, an empirical formulation of plenum window insertion loss was proposed.

The major findings of the present study are summarized in chapter 7 together with recommendations to improve the current design of façade device and on the direction for future works.

CHAPTER 2 LITERATURE REVIEWS OF FACADE DEVICES

This chapter start with review the development of balcony that used as façade device to screen traffic noise. Then, another façade device which incorporated a plenum chamber to control noise transmission from outdoor into the building interior through ventilation openings is discussed. Besides, the background and the basic principle of sound attenuation of plenum chamber are reviewed.

2.1 Introduction

As mentioned in the previous chapter, treatment of façade is considered an alternative method for tackling traffic noise pollution in cities. Building form designed to shield or screen the primary path of exterior direct noise from entering into the interior of a building can be described as self-protective. Balcony is an example of self-protective building configuration that can reduce the noise level intruded into living environment. Other alternative method included modification of window system so the device itself can screen outdoor noise effectively and enable natural airflows to maintain the indoor air quality of the living spaces. Plenum window, the window system that used the concept of plenum chamber become popular recently because it can attenuate noise effectively and at the same time provide some natural ventilation across it.

2.2 Balcony as Façade Device

There are numerous studies on the potential of using the balcony as façade device to improve sound transmission loss of the building. Mohsen and Oldham (1977) have carried computer simulations and scale model measurements on balconies studying its potential applications as noise screen to block direct traffic noise to the windows and doors at building facades. Different combinations of measurements were conducted which include different types of balcony (with and without front parapet), depth of balcony, floor heights, distance from sound source and types of window. However, they only discussed the comparison between experiment and simulation and have not presented the relationship of measured configurations in detail. They used traffic noise index (TNI) and noise pollution level (L_{NP}) as acoustical benefit estimations and the tested balcony provided protections of 10 dB and 7.5 dB, respectively.

They then published another paper later and described more about the results from the mentioned investigations (Oldham & Mohsen, 1979). From their investigations, balcony without parapet and longer projection (2 meter deep) gave higher attenuation when the façade was located near traffic road, while at remote source position, closed balcony with 1 meter depth produced higher sound attenuation. They also observed that attenuation increased when the balcony was at higher floor levels. Another variable tested in Oldham and Mohsen's study was the shape of window located behind the balcony. They observed that vertical shape gave larger value of attenuations compared to horizontal window.

Balconies and combination of different types of screen (splitter and thnadner) have been investigated using scale model in order to increase the sound protection of the façade devices (Hammad & Gibbs, 1983). The corresponding screens could be assumed as parapets of the balconies which provided better sound protections especially at lower floor levels when the depth of balconies were equal or less than 2 meter. From their study, balcony with side walls and without parapet provided additional acoustical protections of 3 dBA with every increment of balcony depth in meter.

There are efforts to increase sound protection of balcony by installing sound absorption materials. May (1979) conducted field-measurement to investigate balconies at high-rise building by introducing sound absorption treatments into balcony cavity. About 4 to 5 dBA of noise reduction could be achieved by a balcony when the ceiling was treated. An average of 8 dBA noise reduction was obtained by adding sound absorption materials on the ceiling and the back wall of balcony. Noise reductions of 10 dB could be provided by balcony with all internal walls treated by absorption materials.

Hothersall et al. (1996) have carried out a two-dimensional numerical study on the improvement of balcony insertion loss by different positioning of sound absorption linings inside the balconies. It is found that there would be about 5 to 8 dBA of noise reduction when the ceiling or the rear wall of the balcony was treated with sound absorbers. The maximum insertion loss measured in their study was 10 dBA when the absorption materials were lined on the ceiling, inner side of the parapet and the back wall of the balcony.

A three-dimensional numerical study has also been carried out in an attempt to increase the insertion loss of balconies by putting sound absorption materials at different locations (Kropp & Berillon, 2000). A 1:10 scale model measurements were carried to validate their predictions. Besides, the models were used to investigate the effects of absorbing material distribution within a balcony in the lower range frequencies from 20 to 200 Hz. Introducing the absorption materials only gave additional 2 to 3 dB attenuations compared to rigid balcony but no significant attenuation patterns were found for different positions of sound absorbing materials. By putting absorbing materials on the ceiling and the back wall of a balcony, Kropp and Berillon (2000) also investigated acoustical protection offered by balcony with opened window to the indoor space. Two kinds of insertion losses were considered; partial insertion loss and global insertion loss. Partial insertion loss was the difference between sound fields in the room alone and room with balcony. The effect of balcony itself can be studied in this comparison. However, global insertion loss was compared bare façade to the room with balcony. In this estimation, acoustical benefit combines the protection offered by the room and balcony. The later comparison gave higher insertion loss values with the maximum insertion loss obtained was 7 dB.

Another architectural concept was proposed by changing ceiling configurations to protect the balcony back wall from the traffic noise nuisance (Hossam El Dien & Woloszyn, 2004). A pyramid ray tracing three dimensional model was used to investigate balcony with different inclined ceiling angles (5, 10 and 15°) and depths (1, 2 and 3 meter) at a total of 17 floors. Results showed that the balcony with 1 meter depth only provided a maximum acoustic protection of 2 dBA for both 10 and 15° inclined ceiling. At same balcony depth, protection levels obtained with 5° inclined ceiling were not significant at all investigated floor levels. However, 5° angle provided better acoustic protection at higher floors (after tenth floor) when the balcony depth was increased to 2 and 3 m with a maximum protection level of 6 dBA. Additional noise attenuation at lower floors could be obtained by increasing the balcony depth. Although the 10° and 15° inclined ceilings did not provide higher protection levels at higher floor levels than the 5° inclined ceiling, the noise attenuation levels at a wider range of floor levels were obtained.

Hossam El Dien and Woloszyn (2005) further investigated the effects of acoustic benefits of inclined parapets (15 and 30°) with the same projection depths as in their previous study (Hossam El Dien & Woloszyn, 2004). They used pyramid ray tracing technique to predict the protection levels of balcony. A 1:10 scale model measurement with total height of eight floor levels was carried out for validation. From their study, almost all the predicted protection levels are higher than the measured values. The average reduction levels obtained by various projection depths were between 4 to 8 dB(A). Balcony with 1m projection depth performed better than those with 2 and 3 m depths. The inclined parapets provided additional reduction values between 0.5 and 4 dBA. Parapet with inclined angle of 15° was more effective at higher floor levels when the projection depth was 1 meter. When the projection depth was increased to 2 and 3 m, parapet with 30° inclined angles provided better performance.

Two-dimensional numerical analyses and scale model measurements have been carried out to examine the benefit of balcony with ceiling-mounted reflectors (Ishizuka & Fujiwara, 2012). The balcony was modified by installing an inclined reflector at the front part of ceiling to reduce the direct sound wave from traffic noise and a concave reflector at the back in order to weaken diffraction wave from the front parapet. Other configurations including installation of glass wool on the flat ceiling and inclined reflector at front part of ceiling were also tested. Traditional closed window without any modification on ceiling was used as the reference case. All balconies were investigated at incident angles of traffic noise at 30°, 45°, 60°, and 75°. Results obtained from the authors showed that the modified ceiling performed effectively only at higher floor levels of a building. Compared with normal balcony, addition of reflectors provided 7 to 10 dBA additional sound reductions. Even though the introduction of reflectors on ceiling gave some attenuation, the performance depended significantly on the sound incident angle.

Investigation of different types of common balconies found in Hong Kong has been carried out using 1:10 scale model (Tang, 2005). Tested balconies included closed balcony (floor, parapet and two side walls), ‘front-bottom’ type balcony (only floor and parapet), ‘side-bottom’ balcony (floor with two side walls) and ‘bottom’ type balcony (floor only) with 4 different horizontal distances (0.5, 1, 1.5 and 2 m) from the line source. Tang (2005) investigated the screening effects of balconies at different positions by using a 3 x 3 matrix balcony array. For the top balconies, better sound attenuation was obtained when the building was located near the line source which was 0.5 m based on his investigation. Balconies with front parapet included closed and front-bottom forms obtained maximum insertion loss of 8 dBA. However, these types of balconies did not provide any protections when they were located at middle and bottom parts of façade with the distance from line source was 0.5 m. These balconies were exposed to strong reflections from the ceiling and parapet, and therefore noise was amplified within the balconies especially at lower frequencies. When the distance of line source was increased, the insertion loss of bottom balconies with parapets in general increased a little bit while balconies without parapets did not provide any screening benefits.

The author (Tang, 2010) continued the investigation of balconies by examining the effects of different azimuthal angles of line source to the protection of four types of balcony forms as presented in his previous paper (Tang, 2005). A total of 25 points were measured at the central top, middle and bottom balconies. Balconies were tested with sound incidence of angles at 0°, 30°, 60° and 90°. The contours of insertion loss behind the balcony were presented to observe the screening effects of different balcony forms. Similar to his previous study's results, closed balcony provided better overall sound attenuation than other form of balconies. When balcony was located perpendicularly to the line source, the side panel provided acceptable protections at the area near to it. At this azimuthal angle (90°), all forms of top balconies basically provided protections against traffic noise. The protection was reduced when the location of balconies moved to middle and bottom parts of façade because of the existence of ceilings. Noise amplifications can be found behind all bottom balconies except the closed type balcony. At smaller azimuthal angles except at normal incidence, the insertion losses were generally increased. Again, closed window performed the best among the four types of balconies.

With the same balcony forms and array, a 1:3 scale model measurements were carried out to study the effects of ceiling and wave interaction of balconies (Tang, Ho, & Tso, 2014). Balconies at azimuthal incidence of angles of 0°, 15°, 30°, 45°, 60°, 75° and 90° were considered. Top balconies without ceiling again provided protections across all the tested grazing angles. Significant reductions of insertion losses were found for all forms when ceilings were installed to the top balconies. When the balconies with ceiling were located at lower floor levels of the building, only slight changes of insertion losses were observed over the variation of azimuthal angels. Similar to previous studies (Tang, 2005 and 2010), closed type balcony provided better protection compared to the other balcony forms. The insertion losses of balconies depended on frequency characteristics which included direct sound and reflections from ceiling and ground surface.

Prediction of noise level inside balcony by adapting the CRTN (Department of Transport Welsh Office, 1988) scheme and ray tracing technique has been proposed (Li, Lui, Lau & Chan, 2003). On-site measurements have also been carried out for prediction validation. Noise levels at 1 m outside balcony parapet were compared with those points inside the cavity to assess the screening effects. Li et al. (2003) compared their prediction and measurements results based on positions with different heights from the balcony floor. For the measurement at 1.5 m and above from the floor, the predicted insertion losses were about 0.5 to 3 dBA higher than the measurements. At lower part of measured positions, the difference between predicted and measured insertion losses ranged from 0 to 6 dBA. The results implied that their prediction method that has not concerned about multiple reflections and diffraction at the balcony especially at lower part of cavity was not accurate enough for predicting acoustic benefit at balcony.

A comprehensive review on methods and benefits of balcony used as façade device to screen off the traffic noise has been performed by Naish & Tan, (2007). They then predicted the effects of balcony located in the street canyon using theoretical models (Naish & Tan, 2008). Direct sound path, specular reflection path and radiosity path were considered in their models with a balcony placed at the center of a long building façade canyon. In order to investigate the protections offered by balcony when the receiver point was located in the center of cavity, various combination of configurations were taken into account. Solid parapet with absorptive materials on the ceiling contributed better sound protections in specularly reflected traffic noise while the parapet was found to be significant for reducing the diffuse effects of radiosity paths.

Previous studies investigated balcony at stand-alone building while Lee et al. (2007) carried out measurements within a group of buildings. The effects of balconies located in a complex apartment estate were tested by carrying out field tests and 1:50 scale model measurements. A total of six treatment configurations were tested for the common balcony used in Korea, which consists of solid hard side walls with fence at the front of balcony. The treatments of tested balconies included additional 50 cm and 100 cm of lintel, 50 cm and 100 cm of parapet, 15° inclined ceiling, sound absorption materials on inclined ceiling, 100 cm parapet with absorber at inclined ceiling and treatments at both parapet and inclined ceiling. Longer lintel reduced the performance of balcony since it extended the ceiling for the lower level balcony which increased the reflection of sound into the cavity of lower level balcony. Parapet of balcony could screen traffic noise at the lower levels and higher levels of balconies. However, in the middle levels of building, direct sounds from traffic noise could not be screened by parapet; sound reflected from ceiling to the cavity and rebounded to the receiver. From their results, balcony with the treatments on inclined ceiling and parapet gave the highest sound attenuations where the noise reduction obtained by balcony in an apartment complex was about 23 dB. The authors have also conducted computer simulation using RAY-NOISE to validate their scale model measurement.

Application of different source and measurement methods has also been proposed. Kim and Kim (2007) carried out field measurement consisted of 15 units in 9 apartment complex using three methods which were element loudspeaker method, element road traffic method and global loudspeaker method to test sound insulation of balcony windows. Measurements were carried out in Seoul at both newly constructed and occupied apartments that located close to roads. Three sizes of balcony windows at new apartments and 8 sizes at occupied apartments were tested. The tested balcony windows were double glazing windows that had the thickness of 16 mm with combination of 5 mm thick outer glaze, 6 mm wide air gap and 5 mm thick inner glaze. Balcony windows in their study used two sliding double glazed window systems with large cavity between indoor environment and façade. Two sound insulation estimations were used based on different measurement methods. Apparent sound reduction adopted in the estimation of element loudspeaker and element road traffic methods while standardized sound level difference was estimated from global loudspeaker measurement method. From their results, measurements using loudspeaker noise gave higher value of acoustic benefits than road traffic noise, range between 1 to 5 dBA. The maximum sound attenuation obtained from this façade device was about 36 dBA.

2.3 Plenum Window as Façade Device

There have been continual efforts made in the past few decades to find out alternative solutions that can cater with both noise control and natural ventilation issues. Modifications of window system to improve the sound insulation of the building against traffic noise have been proposed. Cotana (1999) proposed high sound insulation ventilation window by installed a fan inside an aerator to allow fresh air flow through the window. Sound reduction index of 30 dB can be obtained from Cotana’s window design.

Further evaluations of this type of window have been carried out by introducing filters into the aerator unit to purify the incoming ventilation (Asdrubali & Cotana, 2000) and by installing rolling shutter box to maintain the airflow rate (Asdrubali & Buratti, 2005). In addition, another modification of window system has been proposed by introducing muffler and fans in the double glazed window to improve its sound insulation and ventilation efficiency (Huang & Lai, 2012). Muffler and a series of small fans were located at the top of the window system facing the outdoor environment to increase inlet airflow while another muffler was placed at the bottom of the window facing to the indoor space. Ventilating air from outdoor travelled from the top inlet (fans and muffler) of window to the indoor passing through the opening at the bottom part of window system. They showed that their inventions can be achieved more than 30 dBA sound insulation. However, all mentioned modifications of the window systems are still not desirable in practice because of maintenance issue even though the devices provide excellent attenuations.

Since early 1970s, the idea of elongated plenum chamber concept was proposed to be used in window system (Ford & Kerry, 1972). Double glazed windows with horizontal and vertical staggered opening design have been introduced. The inlet and outlet openings of the proposed window system were designed in the zigzag configuration to block direct sound path from the outdoor to the indoor environment. The study was conducted to look at the feasibility of sound insulation of the window with partially natural ventilation. From the study of Ford & Kerry (1972), window with staggered openings in the horizontal direction gave better sound insulation than its vertical staggering counterpart and the maximum sound insulation provided by partially opened window against traffic noise was about 9 dBA. Even though they showed that this ventilation window provided high sound insulation, but the openings sizes of their window were too small compared to the length of the window. Yet, this modification of window has still attracted many researchers and has brought a new hope to the residents in noisy and densely cities and as it can provide high sound insulation while allowing natural ventilation across it.

Efforts have made to increase sound attenuation of this type of window by introducing thin transparent micro-perforated panels (referred as MPA hereafter) into the window system (Kang & Brocklesby, 2005). The MPA was placed at the void or air gap between the two glass panes to attenuate exterior noise before it propagated into the indoor environment. Investigations of MPA at various air gap widths of the window system were carried out. The use of MPA was found to be more effective in the window with a wider air gap. In addition, Kang & Brocklesby (2005) showed that ventilation windows of the right dimensions lined with micro-perforated panels can produce an acoustical protection better than a closed single glazing window.

Further investigations of staggered ventilation window has been carried through three dimensional numerical study (Kang & Li, 2007). Besides lining MPA on the inner surfaces of the two glass panes, Kang & Li (2007) also investigated the window system with louvers inside the air gap and external hood installed in front of the outer side opening. In their paper, various combinations of parametric study have been studied. This window with louvers inside the ventilation path was only effective when louvers were covered with sound absorption materials. Although the hood outside the exterior opening of the window provided a better sound attenuation, this design might significantly reduce the natural ventilation rate across the device.

In addition, active control method has been applied to the staggered ventilation window in an attempt to enhance the performance of the device at lower frequencies (Huang, Qiu & Kang, 2011). Huang et al. (2011) proposed an analytical model and validated their predictions using the scale model measurements. Even though the results of both numerical and experimental showed a good agreement, the idealized conditions assumed in their study was not practical.

2.4 Attenuation of Rectangular Plenum Chamber

One of the devices that can relate to the noise control in the presence of ventilation is the silencer commonly used in the air conditioning system. There are two types of silencers - namely the dissipative (absorptive) and reactive silencers. A dissipative silencer is a lined device that employs some porous materials to dissipate sound energy into heat. Plenum chamber is a well-known reactive silencer used in the air conditioning system to attenuate noise (Sharland, 1979). The common geometry of a plenum chamber used to interconnect duct systems is shown in figure 2.1. The sudden expansion and contraction of the device resulting in the pressure loss of the propagating sound. Sound energy enters from the inlet will be attenuated after passing through a chamber before leaving from the outer opening.

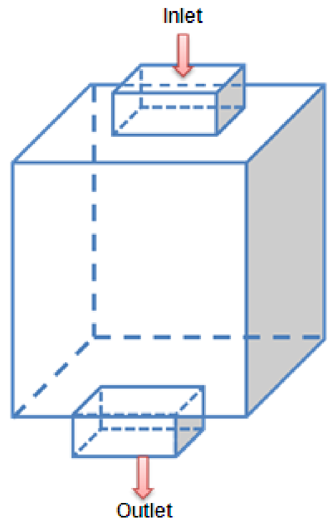


Figure 2.1 Geometry of plenum chamber.

Common plenum chambers used in the mechanical ventilation system are of the circular or rectangular shapes. In order to derive a device which can be used at the building façade to screen traffic noise and at the same time allows for natural ventilation, a rectangular plenum chamber would be a more appropriate choice. Numerous studies on sound attenuations of rectangular plenum chambers have been explored.

Since the mid-twentieth century, estimation of noise attenuation offered by plenum design has been proposed (Wells, 1958). Referring to the common room constant equations, Wells (1958) derived a formula for the calculation of plenum attenuation based on the geometry of the device as shown in Figure 2.2:

$$SWL_{in} - SWL_{out} = 10\log_{10} S_{out}\left(\frac{\cos\theta}{2\pi d^2} + \frac{1}{R_c}\right) \qquad \text{Eq. 2.1}$$

where *in* and *out* represent inlet and outlet respectively; *SWL* is sound power level; ℓ is slant distance from the inlet to outlet opening ($\sqrt{(L-d)^2 + H^2}$); cos θ is H/ ℓ; R_c is the plenum room constant and *S* is the cross-sectional area of outlet (*wd*).

In his work, this geometrical approximation was compared with scale down plenum chamber experimental measurements. The results revealed that this simple calculation only gave reasonable agreement at higher frequencies and at smaller size of openings. From his measurement results, when the ratio of the inlet or outlet opening width (*w*) to the length of the plenum chamber (*L*) was 0.5, the attenuation provided by this device about 10 dB in average. More attenuation can be obtained when the ratio *w*/*L* was smaller as expected.

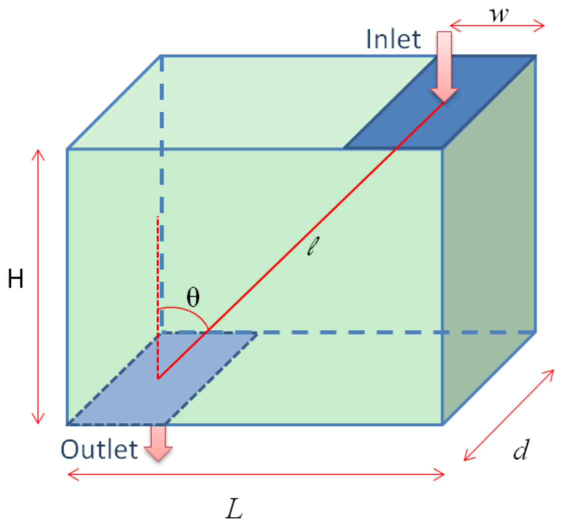


Figure 2.2 Details of plenum chamber notation.

As plenum chamber always attenuate noise at higher frequencies, Cummings (1978) had proposed theoretical approaches for its transmission loss at lower and higher frequencies. He used mode-matching technique to solve the low frequency acoustic attenuations by splitting the chamber into several regions so the sound field was expressed in eigenfunctions, the acoustic pressure and particle velocity then were matched at the interfaces of these regions. The rectangular plenum chamber was assumed to be lined with locally reacting materials, made of rigid structures and the mean air flow in duct system was neglected. For the high frequency condition, ray acoustic model was used for estimating the transmission loss.

A year later, Cummings together with Wing-King, published a paper on experimental measurements of plenum chamber to compare with his theoretical models (Cummings & Wing-King, 1979). Single and three-pass plenum chambers were tested in their investigations. For lower frequency single plenum chamber, experimental results only agreed with the prediction models at frequencies below cut-on frequency of the first cross-mode of inlet of the duct. All the measurement results at higher frequencies obtained in their investigations were higher than those estimated by theoretical models. Maximum measured transmission loss was about 30 dB at frequency 800 Hz.

Over the decades, a great number of studies has been done to predict the transmission losses offered by plenum chambers. Transfer matrix method was the most common approach in which the plane wave theory was used. A simple numerical method using four-pole parameters (same as the transfer matrix method) of rigid walls to evaluate three dimensional plenum chamber has been studied (Munjal, 1987a). The estimation involved notionally dividing a plenum chamber, which included inlet, chamber and outlet, into several segments based on area ratio to generate algebraic equations. Finite element method has been used to evaluate the proposed method in term of accuracy and speed of computation. Obviously, the computation using the method proposed by Munjal was much faster than finite element method, which about 60 times faster for simulation with a symmetric square chamber and about 130 times faster for the computation with an offset-inlet offset-outlet chamber. However, the transmission losses prediction suggested by Munjal did not agree so well with computed results from the finite element method at higher frequencies. Besides, this method was only restricted to simple expansion chamber (rectangular and circular) and not applicable to the irregular geometry cases compared to the finite element method that do not suffer from limitation of geometry.

Theoretical formulations that modelled unlined plenum chamber as pistons of end-in and end-out using transfer matrices also were suggested (Ih, 1992; Venkatesham, Tiwari, & Munjal, 2009). Ih (1992) derived the analytical formula by using eigenfunction expansion technique while Venkatesham et. al. (2009) adopted Green's function in their calculations. Some assumptions had made in both studies included no sources inside the chamber and the mean flow was neglected. In Ih (1992), all chamber's walls were assumed acoustically rigid. The transmission loss and insertion loss of different configurations of reactive plenum chambers were considered in the predictions. Various lengths of chamber and location of inlet/outlet ports of end-in/ end-out were also studied. A three dimensional numerical prediction for fully lined plenum chamber using the same piston-driven models was also studied (Kim & Ih, 2006). Rayleigh-Ritz method that did not require meshing and converged faster than the finite element method was adopted in the numerical scheme. The predicted transmission losses showed good agreement with the measurement results.

Various approaches have been studied on the noise attenuations of plenum chambers in the duct system. Efforts have made to compare various prediction models of acoustical benefits of plenum chamber (Bilawchuk & Fyfe, 2003; Li & Hansen, 2005). Bilawchuk and Fyfe (2003) compared the accuracy, computation time and ease of use in calculating transmission loss values using the traditional laboratory methods, the four-pole transfer matrix method and the three-point method. The traditional laboratory method mentioned in their work was the difference between sound pressure levels of the incident sound before the installation of chamber and the transmitted sound levels after installation of chamber. In the four-pole method, sound pressure and normal particle velocity at inlet and outlet of chamber were evaluated. For the three-point method, Bilawchuk and Fyfe (2003) calculated the transmission loss using the difference of sound pressure levels between the incoming sound wave and that at the exit of the chamber. Both finite element method (FEM) and boundary element method (BEM) of two dimensional models were computed. From their investigations, all methods agreed with the theoretical predictions until about 340 Hz. The three-point method required shorter computation time and was easier to apply when compared to the traditional four-pole methods.

Li and Hansen (2005) compared several popular prediction models (Wells, 1958; Cummings, 1978; Cummings & Wing-King, 1979; Ih, 1992). Experiments with unlined and lined plenum chambers were carried out to evaluate these prediction models. Calculation of transmission loss were done by measuring the transfer functions between two microphones at each inlet and outlet of the chamber. For the unlined plenum chamber, Ih's prediction models gave very good agreement with the measurement results below frequency 1 kHz, while the predicted transmission losses above 1kHz were generally lower than the measurement results. Li and Hansen (2005) showed that sufficient number of chamber modes of the Ih's prediction models should be included in the calculation in order to get correct estimations. Comparisons of Cummings's models and Wells's model were made for the lined plenum chamber. Mode matching technique suggested by Cummings for low frequency model was more suitable where the model gave fairly good results up to the frequency of 3150 Hz. Cummings's predictions were lower than the experimental data at higher frequencies with the range between 7 to 10 dB.

If the plenum chamber is adopted in a façade device, noise source orientation has to be considered in the evaluations. Along a duct system, the noise which is blocked by the plenum chamber propagates in the directions of the air flow and is usually in a direction normal to the cross-section of the plenum chamber. However, traffic noise comes from many directions and thus, the performance of the plenum chamber when it is attached at a building façade will be different from that applied in the mechanical ventilation ducting system. An evaluation of the effectiveness of a device consists of a plenum chamber is needed.

2.5 Summary

In this chapter, balcony and plenum window have been reviewed extensively. Difference types of balconies have been studied. Among of all these balconies, closed balcony provides better sound insulation to the building. Sound absorption materials have been suggested to be used inside the balcony cavity to increase the performance of this façade device. Besides, sound absorption materials lined at different positions of balcony has also been studied. However, up to now, there is no full scale measurements of this façade device have been carried out. Even the full-scale laboratory measurement require higher cost and spaces, better control of important parameters can be made during the measurement and the results outputs can direct reflected the acoustical performance of full-size balcony. After that, the development of plenum window has also described. The concept of plenum chamber and the attenuation of the common rectangular plenum chamber then are reviewed. The study on this type of façade devices still limited. Investigations of plenum windows should be carried out to top-up the shortage information of this façade device.

CHAPTER 3 BALCONY-WINDOW DEVICE – FULL SCALE MODEL INVESTIGATIONS

This chapter describes the investigation of the façade device which combines conventional window with closed balcony. Configuration of this mentioned façade device and the setup of the experiment are described first, followed by discussing the acoustical benefits of this device over the standalone conventional window.

3.1 Introduction

The acoustical insertion losses produced by a balcony-like structure in front of a window on a building façade were examined experimentally inside the acoustics chambers. In the present study, artificial sound absorption materials were put on different locations of the device to improve the broadband insertion loss. The insertion loss of the device was defined by the difference between the average noise level inside the receiver room with and without the balcony. A plain window was installed behind the balcony. The effects of the locations of the sound absorption materials on the acoustical insertion loss of the balcony-window configuration were experimentally tested. It is hoped that the present results can reveal the actual performance of balcony in the presence of sound absorption materials.

3.2 Test Chambers

The measurements were carried out inside the multi-purpose building acoustic testing chambers of the Department of Building Services Engineering, The Hong Kong Polytechnic University. The test chambers were two coupled but isolated chambers originally used for the ISO 10140-2 tests (BS EN ISO 10140-2, 2009) for sound transmission loss of building materials. They were located in FJ002 of the Hong Kong Polytechnic University and were isolated from the building structure. The bigger chamber had a volume of about 240 m^3 and a height of 5 m, while the smaller one, usually used as the receiver room, had a floor area of ~21 m^2 and a volume of ~84 m^3. Figure 3.1 shows the plan and dimensions of the mentioned chambers.

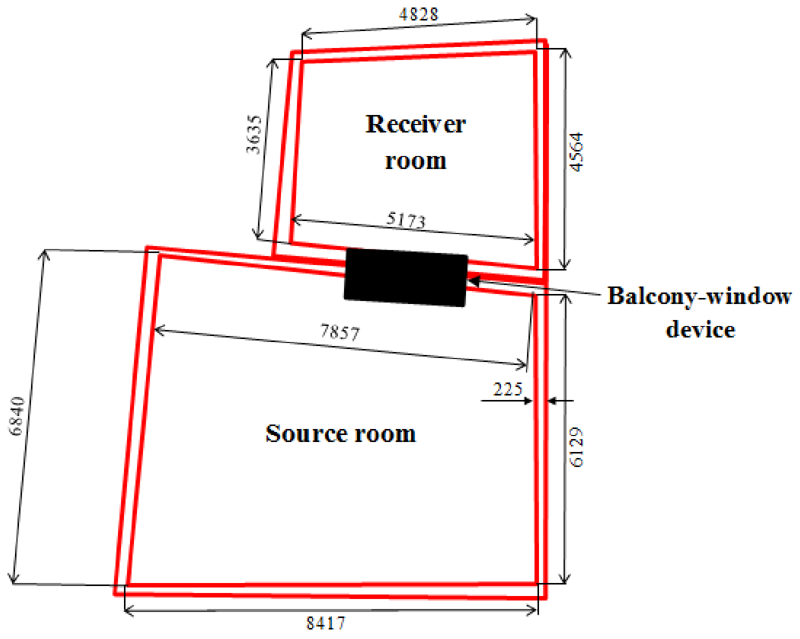


Figure 3.1 Plan of the coupled chambers (in mm).

The reverberation inside the source room tended to equalize the sound field inside the room and was thus undesirable for the present investigation as the location of sound source was undefined under the strong reverberation. Therefore, the source room was converted into a semi-echoic chamber by putting up 2-inch thick fibreglass curtains at about 1 m away from the rear wall and the side walls, and at similar distance below the room ceiling. No treatment was made to the floor and the separating wall. The receiver room remained reverberant. The setup was made similar to the Kang's study (2006). The workable size of the room was reduced to 5 m by 4.5 m by 4m high. The reverberation times inside the source room after the installation of the fibreglass curtains were less that 0.2 second at frequency bands above that of 250 Hz and was ~ 0.5 second within the 100 Hz one-third octave band. The source room therefore should be a good approximation of the free field condition.

3.3 Sound Source

Since traffic noise is the most serious source of noise pollution in a congested high-rise city, the sound source adopted in the present study has to have similar characteristics as this noise. In practice (Department of Transport Welsh Office, 1988), traffic noise is regarded as a line source formed by many incoherent point sources. A 5m long line source consisted of 25 six-inch aperture loudspeakers was used to simulate road traffic noise. In the present study, one-third octave band frequency range from 100

Hz to 5 kHz was considered. A constant magnitude of white noise signals were supplied by Brüel & Kjær 1405 Noise Generator, which was connected to a power amplifier to drive the loudspeakers. Figure 3.2 shows the loudspeaker array which the angles of the loudspeakers were pointing toward the middle height of the façade device. The loudspeaker array was placed on floor and located at 5 m horizontally away from the specimen.

Figure 3.2 Loudspeaker array

The property of loudspeaker array used as sound source was tested for its directivity and uniformity. The directivity of the loudspeaker array was measured at a radius of 2 m on the spanwise central plane of the array. The measurement angle was from 17° to 31° which covered the opening of the wall where the balcony-window device was located. The directivities and standard deviations of measured sound pressure levels at different frequencies are tabulated in Table 3.1. The average standard deviation of sound pressure levels from 100 Hz to 5 kHz is in general within 1 dB. Although the directivity variations at 1.25 kHz and 5 kHz were more than 1 dB (1.5 dB and 1.7 dB respectively), these values did not have significant effect on the overall calculation. The directivity variation after applying the A-weighting adjustment was 1.8 dB.

Test for uniformity of loudspeaker array was carried at 2 m away from the loudspeaker array and 1.2 m from the ground. Based on the centre line of loudspeaker array, measurements were carried out at both left and right side at 0.2, 0.4 and 0.6 m from the central plane of the loudspeaker array. Table 3.2 shows the results of uniformity tests for one-third octave band spectral level. Uniformity variations within the frequency range were in general within 2dB about the mean level. Though the adopted loudspeaker array was not producing a perfect two dimensional sound field, it was good enough for the study of traffic noise which is A-weighted in practice. After applying the A-weighting adjustment, the uniformity variation was 1.2 dB.

The repeatability tests were done using 5 trials done at different times when all the windows were closed using the sound spectra measured at a location 2.5 m from the wall and 1.6 m from the ground at the source room. The power amplifier and the noise generator were both switched off and disconnected from the power supply before they were switched on for each trial test. The results as tabulated in Table 3.3 show that the repeatability of the source was very good and was within 1dB at the low frequency end and was much less than that as frequency increases.

3.4 Balcony-window and Measurement Setup

The cross section of the balcony-window setup adopted in the present study and the dimensions of the essential components are illustrated in Figure 3.3. The balcony-like façade device consisted of a window of size 1.5 meter (wide) by 1 meter (high) which is the typical dimension of the windows adopted in Hong Kong public housing buildings attached together with closed balcony. The balcony was made of concrete brick of thickness 120 mm. The internal dimensions of the balcony cavity were 2.5 m high, 1.5 m deep and 1.9 m wide (horizontal span). The balcony parapet had a height of 1.2 m. Its edge was at the height level of the window sill. The side walls of the balcony covered the whole height of the balcony as shown in Figure 3.4. One inch fibreglass of density 32 kg/m^3 was installed at different internal surfaces of the balcony to investigate the acoustical performance of this façade device when it was exposed to traffic noise.

Table 3.1 Directivity tests of the sound source.

Frequency (Hz)	Sound level at different elevation angle (dB)				Standard deviation (dB)
	31°	27 °	22 °	17 °	
100	73.0	72.7	73.1	73.3	0.2
125	75.6	76.1	76.1	76.7	0.5
160	78.5	79.1	79.2	79.3	0.4
200	79.7	80.0	80.3	81.1	0.6
250	82.3	83.2	84.0	84.1	0.8
315	83.3	84.1	84.5	84.7	0.6
400	82.2	82.3	82.6	82.8	0.3
500	80.0	80.9	81.8	82.2	1.0
630	79.6	80.8	80.8	81.3	0.7
800	84.3	85.5	85.5	85.2	0.6
1000	84.5	82.9	84.3	84.2	0.7
1250	87.0	85.4	85.8	88.8	1.5
1600	78.3	78.6	78.0	78.1	0.3
2000	81.7	80.7	81.2	81.3	0.4
2500	79.6	77.8	77.9	78.2	0.8
3150	79.1	79.7	78.8	78.0	0.7
4000	71.6	71.3	69.9	71.1	0.7
5000	69.4	70.1	66.7	67.0	1.7
				Average	0.7

Table 3.2 Uniformities of line source.

Frequency (Hz)	Sound level at distance from the centre of loudspeaker array (dB)						Standard deviation (dB)
	Left side			Right side			
	0.6 m	0.4 m	0.2 m	0.2 m	0.4 m	0.6 m	
100	69.7	69.5	70.0	69.7	69.7	69.3	0.2
125	76.6	76.9	77.0	76.5	75.6	74.7	0.9
160	76.3	76.0	76.3	76.3	75.7	74.3	0.8
200	81.2	81.1	80.4	81.0	79.0	77.2	1.6
250	80.8	81.6	81.9	82.0	80.1	78.1	1.5
315	81.7	83.3	83.4	82.9	82.2	79.4	1.5
400	79.3	81.8	82.4	83.6	82.6	81.5	1.5
500	79.5	78.9	80.4	82.3	83.3	82.6	1.8
630	79.1	78.2	77.1	78.4	82.0	77.5	1.8
800	80.2	80.6	81.3	85.0	82.4	82.1	1.7
1000	78.3	84.1	84.3	85.9	83.6	81.2	2.7
1250	84.2	87.3	86.3	85.8	86.5	83.2	1.5
1600	80.0	78.5	78.2	77.9	81.1	77.7	1.4
2000	80.0	80.4	78.3	79.5	80.0	80.4	0.8
2500	77.4	76.0	75.4	79.1	78.5	80.1	1.8
3150	77.3	74.9	79.1	76.2	81.4	80.1	2.4
4000	68.2	71.7	69.6	71.5	71.4	67.6	1.8
5000	65.1	65.7	65.6	67.0	67.3	69.2	1.5
					Average		1.5

Table 3.3 Repeatability tests of loudspeaker array.

Frequency (Hz)	Trials (dB)					Standard deviation (dB)
	1st	2nd	3rd	4th	5th	
100	65.4	65.0	64.2	64.9	64.8	0.4
125	74.1	74.5	72.1	72.0	72.1	1.2
160	75.3	75.9	74.7	76.4	77.3	1.0
200	80.6	81.0	81.0	81.2	80.0	0.5
250	79.6	78.9	79.6	79.5	79.0	0.3
315	81.3	82.5	81.7	81.6	81.8	0.4
400	84.4	85.1	83.3	83.8	84.3	0.7
500	81.3	81.2	81.4	81.9	81.8	0.3
630	82.0	81.7	81.3	80.8	81.2	0.4
800	83.1	83.2	82.9	83.2	83.3	0.2
1000	84.1	83.2	83.6	83.0	83.5	0.4
1250	86.2	86.0	86.4	85.3	85.6	0.4
1600	81.3	81.0	81.6	81.7	81.1	0.3
2000	83.5	83.5	84.0	83.5	83.2	0.3
2500	78.9	79.7	79.6	80.0	79.4	0.4
3150	78.3	77.9	78.1	78.6	78.4	0.3
4000	73.0	73.2	72.9	73.2	73.0	0.1
5000	66.7	67.2	67.2	67.0	67.3	0.2
					Average	0.4

Table 3.4 summaries the different scenarios that were adopted in the present study. In order to estimate the acoustical benefits of the balcony-window device, the case without the balcony, but with the window alone was used as the reference case. Figure 3.5 and Figure 3.6 show the conventional casement windows (act as reference cases) setup for both opened and closed window cases, respectively. Balcony-window device with balcony attached to the opened window was compared with the opened stand-alone window case (Figure 3.5, scenario O0). While the benefit of balcony-window device that fixed with closed window was estimated by comparing the results obtained with the stand-alone closed casement window case (Figure 3.6, scenario C0). Figure 3.7 shows the balcony with all internal surfaces treated by absorption materials (scenarios C1 and O1). Figure 3.8 shows the condition of balcony when all internal

surfaces were treated except front parapet (scenarios C3 and O3). Table 3.5 summarizes the sound absorption properties of the fibreglass and the concrete brick surfaces used in the present study.

A rectangular array consisted of 12 equal-spaced ¼ inch Brüel & Kjær Type 4935 microphones which spanned over the window opening was used to measure the noise level at 1 meter away from the window in the source room. Nine Brüel & Kjær Type 4935 microphones spanned over the whole volume of the receiver room (at least 1 m away from walls) were used to capture the transmitted sound level. Inside the source room, a reference microphone was used to check any variation in the sound source spectral strength and derive the corresponding spectral corrections to the measurements if necessary. Figure 3.9 illustrates the locations of these microphones. The Brüel & Kjær 3506D PULSE system, which was capable of sampling 25 channels simultaneously sampled at a rate of 32000 samples per second per channel, was used as the data acquisition system.

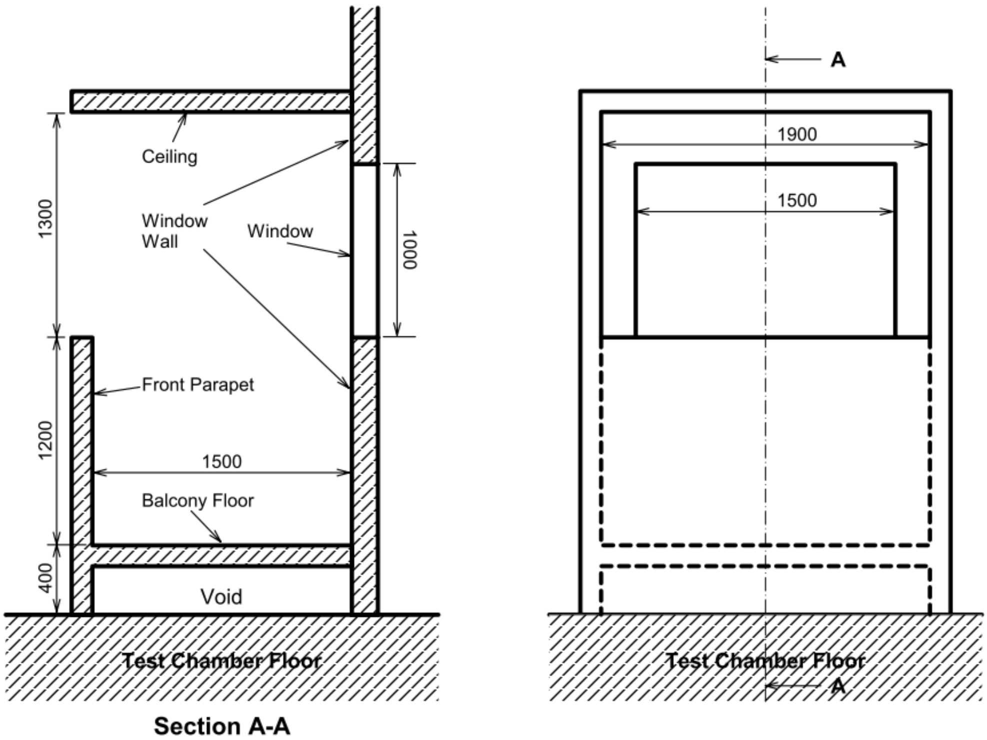


Figure 3.3 Cross section and dimensions of the present balcony-window (in mm).

Figure 3.4 Experimental setups viewed from the source room for balcony-window.

Figure 3.5 Experimental setups of reference case window (opened).

Left: view from source room; Right: view from receiver room.

Figure 3.6 Experimental setups of reference case window (closed).

Left: view from source room; Right: view from receiver room.

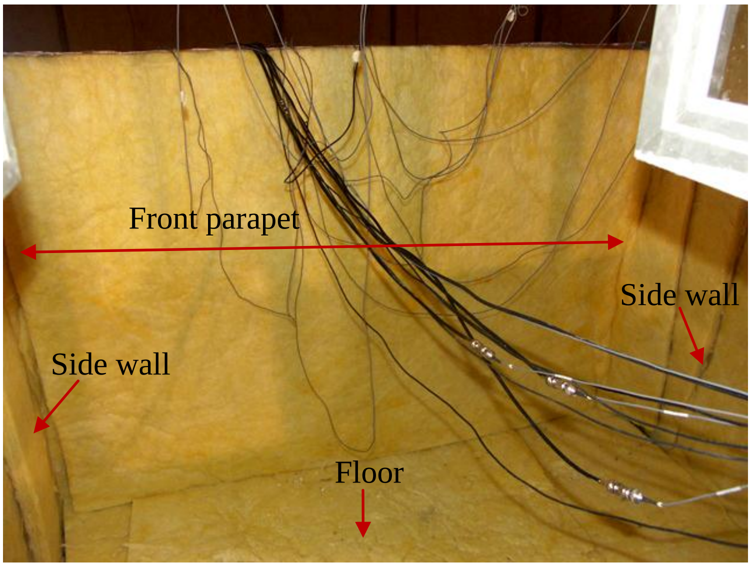


Figure 3.7 Sound absorption materials were lined on all balcony surfaces.

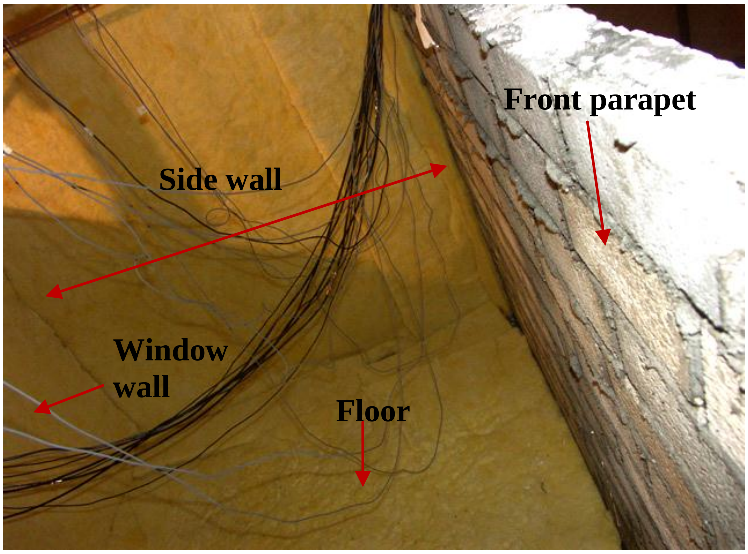


Figure 3.8 Balcony surfaces treated by fibreglass except front parapet.

Table 3.4 Scenarios of the balcony-like façade device treatments

Scenario	Window (1.5 m x 1 m) high)		Balcony surface treated by absorption materials				
	Closed	Opened	Ceiling	Window wall	Balcony side walls	Balcony floor	Front parapet
C0	√				No	Balcony	
C1	√		√	√	√	√	√
C2	√		√	√	√	√	
C3	√		√	√	√		
C4	√		√		√		
C5	√		√				
C6	√						
C7	√				√		
O0		√			No	Balcony	
O1		√	√	√	√	√	√
O2		√	√	√	√	√	
O3		√	√	√	√		
O4		√	√		√		
O5		√	√				
O6		√					
O7		√			√		

Table 3.5 Sound absorption coefficient of fibreglass installed inside balcony

Material	Octave Band Centre Frequency (Hz)					
	125	250	500	1000	2000	4000
25mm Fibreglass of density 32kg/m^3 from Owens-Corning	0.15	0.31	0.65	0.85	0.91	0.93

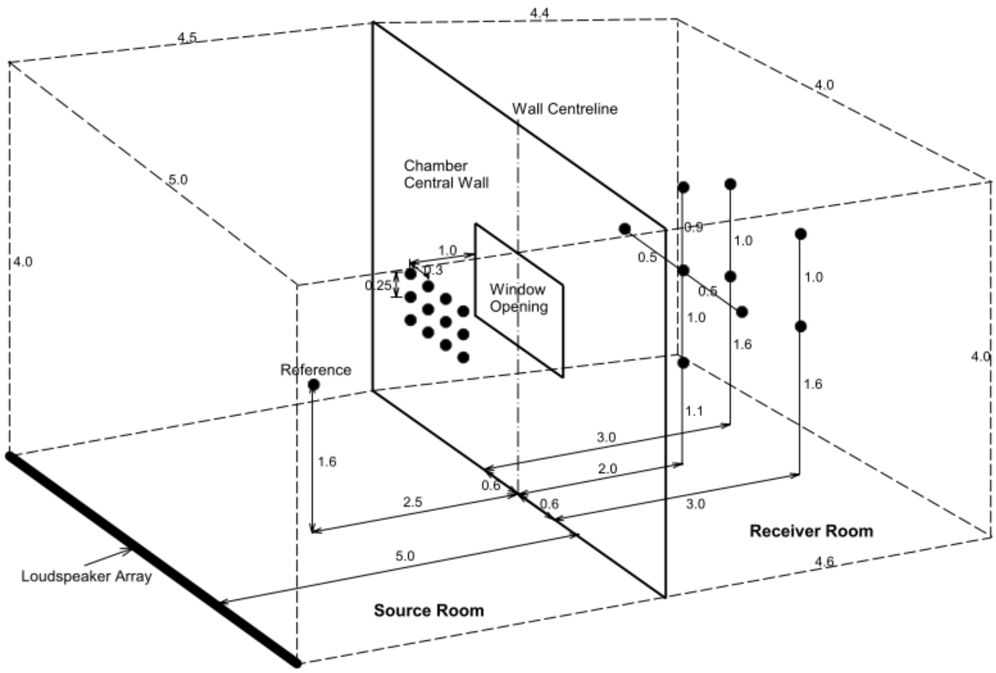


Figure 3.9 Microphone locations during the measurement (dimensions in m).

●: measurement points; -----: approximate chamber boundaries.

3.5 Balcony-window Experimental Results

Since one of the major objectives of the present study is to estimate the acoustical protection of the balcony-window in the presence of traffic noise, the performance indicators described below, apart from the one-third octave band data, are all rated by a normalized noise spectrum as in some existing literature such as Moshen and Oldham (1977), Hothersall et al. (1996), Buratti (2002) and Garai and Guidorzi (2000). The normalized traffic noise spectrum of the standard BS EN 1793-3 (1998) was used in the estimation of the insertion losses in term of a single rating. The normalized traffic noise spectrum used for the present experiment is shown in Table 3.6.

*Table 3.6 Normalized noise spectrum**

Frequency	Level (dB)
	BS EN 1793-3
100	-20
125	-20
160	-18
200	-16
250	-15
315	-14
400	-13
500	-12
630	-11
800	-9
1000	-8
1250	-9
1600	-10
2000	-11
2500	-13
3150	-15
4000	-16
5000	-18

(*Retrieved from BS EN 1793-3, 1998)

Two broadband indicators are used in the present study to describe the acoustical protections. The first one is the balcony insertion loss (*IL_B*) which is obtained from the differences of band noise levels at 1 m in front of the window (closed) with and without the balcony. This is also the parameter focused by many researchers such as May (1979), Hossam El-Dien and Woloszyn (2004), Hothersall et al. (1996) and Tang (2005). The other indicator adopted is the average noise level reduction inside the receiver room with and without the balcony when the window is opened (IL_R). This IL_R should already include, if there was any, the effects of reverberation strength variation in the receiver room after opening the window. Open window is the preferred mode of operation in Hong Kong.

3.5.1 Closed Window Scenarios

Figure 3.10 shows the one-third octave band sound levels obtained by averaging the noise spectra measured on the source side of the window (within the balcony) for the test scenarios with a closed window. The corresponding spectrum obtained without the balcony is also presented for the sake of easy comparison. One can observe that the installation of the balcony has resulted to some extent of noise reduction even without the application of sound absorption materials. However, the sound level reduction in Scenario C6 is much less compared to those in other scenarios. The mild reverberation created by the balcony even results in slightly higher sound levels, especially in the low frequency side of the spectra. The installation of sound absorption materials on the balcony side walls (Scenario C7) leads to a higher noise reduction as expected, but the improvement is not significant. The noise levels decrease as more and more sound absorption is put into the balcony cavity. However, the treatment at the ceiling gives rise to a relatively large noise reduction (from C7 to C4) and further increasing the sound absorption in the balcony cavity basically has no significant effect on the noise reduction. The ceiling treatment appears to be the most effective one for improving the insertion loss of a balcony.

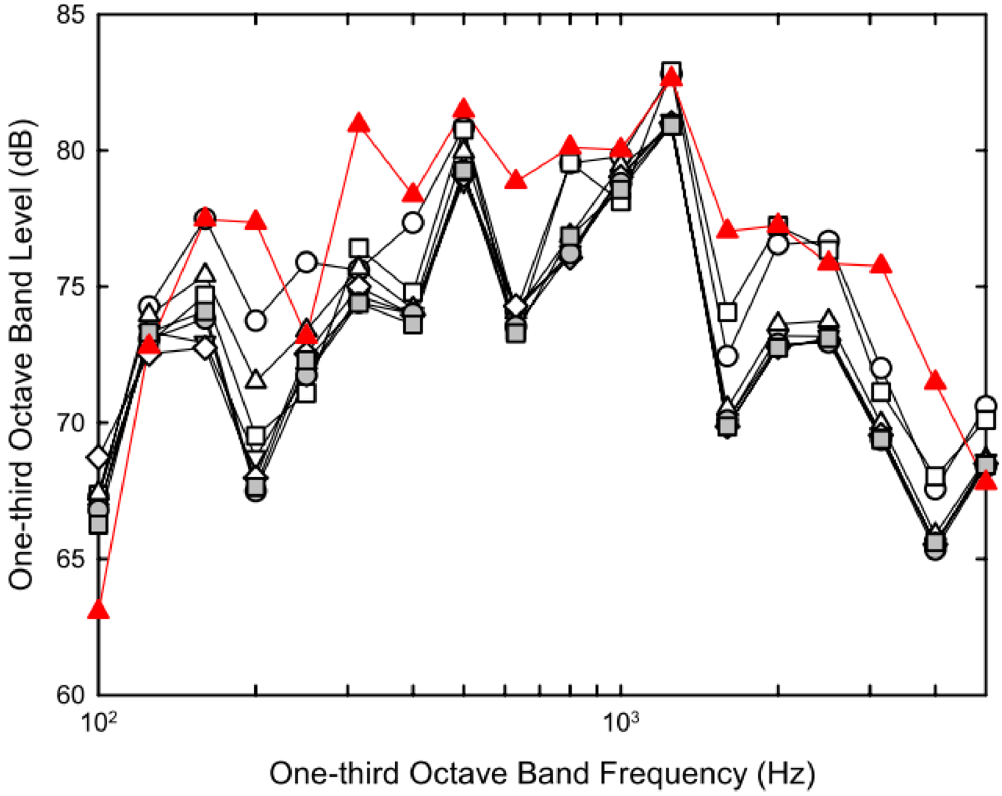


Figure 3.10 Average sound levels measured on the source side for the test scenarios with window closed.

▲ : C0; ■ : C1; ● : C2; ◇: C3; ▽ : C4; △ : C5; ○ : C6; □ : C7

Table 3.7 summarizes the IL_B estimated when the balcony-window is exposed to traffic noise. The average elevation angle of the measurement points from the sound source in the present study is roughly 28°. Under this relatively small angle, which is relevant to receivers at the lower floors of a building (Hothersall et al., 1996; Lee et al., 2007) or for a source quite far away from the receiver, the balcony without sound absorption material basically produces no acoustical benefit. The highest insertion loss is about 3 dB. This value is about 2 dB higher than that of Hothersall et al.(1996) at a similar elevation angle after the façade reflection correction of +2.5 dB (Department of Transport Welsh Office, 1988) is included into their level differences (~ 0.3 dB insertion loss for ceiling treatment only and ~1dB for the case where treatment is done to all surfaces except the balcony floor). The acoustical fin / noise barrier effect of the side walls is probably the reason for such difference.

Table 3.7 Insertion losses (IL_B) for all tested scenarios with window closed.

	Scenario						
	C1	C2	C3	C4	C5	C6	C7
Surface area of sound absorption material (m^2)	18.8	16.6	13.7	10.4	2.9	0	7.5
IL_B by BS EN 1793-3(dB)	3	3	2.8	2.9	2.4	0.8	1.3
IL_B by A-weighting (dBA)	3.2	3.3	3.2	3.1	2.8	0.9	1.2

The IL_B results shown in Table 3.7 also suggest that the parapet, the balcony floor and the wall under the window are not suitable for the acoustical treatment in term of noise reduction as one can observe that the nearly six times increase in the sound absorption in Scenario C1 compared to that in Scenario C5 can only produce an improvement of 0.6 dB. The side walls, which have a total area about three times that of the ceiling, can improve the IL_B by 0.5 dB already (C5 to C4). Therefore, while the balcony ceiling is the most important location for acoustical treatment, the side walls are the next.

The insertion losses estimated using simple A-weighting noise levels are also depicted in Table 3.7 for the sake of completeness. They show the same trend as those obtained using the normalized noise spectrum as the spectral power level of the source sound was kept fairly unchanged throughout the present study.

3.5.2 Opened Window Scenarios

For the purpose of natural ventilation, most of the windows in a residential flat should be openable. Therefore, the insertion loss of the whole balcony-window setting experienced inside the receiver room is important, but this has not been studied in detail previously at least to the knowledge of the author. Since the reverberation characteristics inside the receiver room when the window was opened did not vary much from Scenarios O0 to O7, the IL_Rs in the present study, which are the differences in the average noise levels inside the receiver room with and without the balconies, represent the change in the transmitted sound intensity due to the presence of the sound absorption materials and the balconies.

Figure 3.11 illustrates the one-third octave band insertion losses IL_R for various balcony-window settings studied in the present investigation. The reference case is the single opened window scenario O0. As expected, the balcony without any sound absorption material gives the least insertion loss. From the results, negative insertion losses at frequencies lower than 160 Hz are observed and it indicates that the balcony cavity amplification is significant even all the internal balcony cavity surfaces are covered with the sound absorption materials. It can be observed that the IL_R of the tested devices with sound absorption materials are increasing from 100 Hz to 315 Hz. At frequencies below 200 Hz, the trend of acoustic benefits increment do not show any relationship with the amount of sound absorption inside the balcony cavity. However, the trend of the IL_R shows increment with increasing amount fibreglass lined inside the balcony cavity at frequencies higher than 200 Hz.

At the frequencies between 200 Hz and 315 Hz, three regions of insertion losses can be observed. Balcony-window without any treatments gives the least benefits, devices with treatments on ceiling and side walls provide the highest sound insertion losses and the third region is balcony-window with absorption materials inside the cavity except on ceiling or on side walls whose insertion losses are between two mentioned groups. For the scenarios that sound absorption materials lined inside the balcony cavity (except scenario O6), balcony-window without treatment on ceiling (O7) gives the lowest insertion loss values at the frequencies higher than 630 Hz band. At some frequencies, this setting of balcony-window performs even worse than balcony-window without any treatments inside the cavity. One can also observe that the side walls only help improving the insertion loss at frequencies below the 1600 Hz band. The insertion losses of balcony-window with treatment on ceiling in general are unchanged at frequencies greater than the 1250 Hz band.

From Figure 3.11, insertion loss peaks can be observed at the 315 Hz and the 1600 Hz one-third octave bands, while troughs at the 100 Hz, 500 Hz, 1000 Hz and 2500 Hz one-third octave bands. The troughs at the 100 Hz and the 2500 Hz one-third octave bands are very significant. Since the depth of the balcony is 1.5 m, resonance at ~ 100 Hz between the window wall and front parapet and between both openings of window and balcony could take place. The mentioned resonance caused the dips (negative values) of IL_R for all measured balcony-window devices. Longitudinal resonance due to the openings of both balcony and window caused greater sound level inside the receiver room. Resonance of this type may take place at the harmonics, but the more effective sound absorption and stronger barrier effect of the balcony could have compensated the adverse resonance effect.

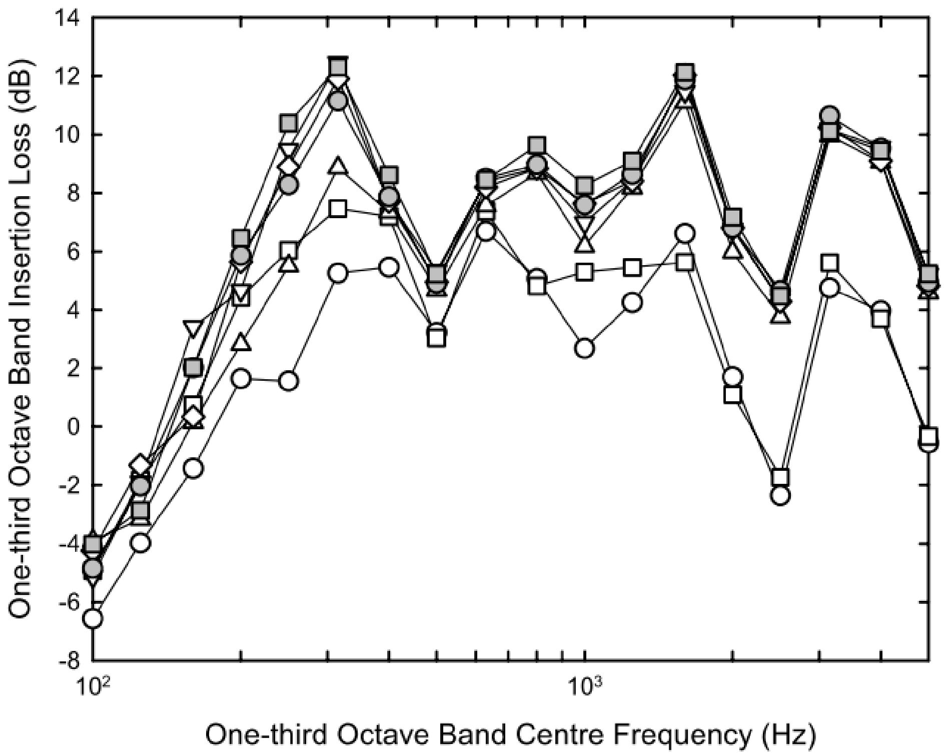


Figure 3.11 One-third octave band insertion loss for balcony-window scenarios with opened window cases.

■ : O1; ● : O2; ◇: O3; ▽ : O4; △ : O5; ○ : O6; □ : O7.

Insertion losses (IL_R) of balcony-window devices for the opened window cases are tabulated in Table 3.8. When opened balcony-window device without treatment (O6) is exposed to traffic noise, this device provides 2.5 dB acoustical benefit compared to the stand-alone opened window. The increment of about 1 dB in IL_R can be achieved when the internal side walls of balcony are treated with fibreglass. About 3 dB acoustic benefit can be achieved by installing sound absorption materials on the ceiling of the balcony-window device (O5). The ceiling absorption effectively weakens the reflection of sound into the balcony or that onto the window (image source effect) due to the presence of the ceiling. The 3 dB increment in the IL_R is therefore theoretically justified. Installation of sound absorption materials at both ceiling and internal side walls of the balcony-window raises the benefits of this device in term of broadband insertion loss to about 7 dB. However, further lining sound absorption materials at other internal surfaces of the device such as balcony floor, front parapet and window wall do not provide any additional acoustical benefit. The maximum IL_R for the present setup is 7 dB which is obtained when the balcony reverberation (and the resonance strength) is the minimum.

Table 3.8 Insertion losses (IL_R) for all tested scenarios with window opened.

	Scenario						
	O1	O2	O3	O4	O5	O6	O7
Surface area of sound absorption materials (m^2)	18.8	16.6	13.7	10.4	2.9	0	7.5
IL_R by BS EN1793-3 (dB)	7.0	6.7	6.7	6.6	5.9	2.5	3.5

Assuming that the array loudspeakers are incoherent, but closely packed identical point sources and each of them has an acoustic power of P, the overall acoustical intensity at the centre of the window I is

$$I \propto \int_{-\phi}^{\phi} \frac{P}{2\pi r^2} \cos^2 \theta d\theta = \frac{P}{2\pi r^2}\left[\phi + \frac{\sin(2\phi)}{2}\right], \qquad \text{Eq. 3.1}$$

where r is the shortest distance of the window centre from the loudspeaker array and ϕ the largest view angle of the array from the window centre. Considering an infinite long noise barrier placed at the same distance between window and balcony with height is the same as the front parapet of balcony-window device, $\phi = \pi/2$. Therefore, the insertion loss of the side wall portion due to the direct line of sight obstruction is:

$$IL = 10\log_{10}\left(\frac{I_{\phi=\pi/2}}{I}\right) = -10\log_{10}\left\{\frac{2}{\pi}\left[\phi + \frac{\sin(2\phi)}{2}\right]\right\} \qquad \text{Eq. 3.2}$$

The largest view angle in the present study is ϕ = 0.541 rad (~31°) and thus the estimated fin effect is 2 dB noise reduction. One should note that the IL_R for Scenario O6 where no sound absorption material is installed inside the balcony cavity will vary with the incident angle of the sound.

3.6 Summary of Balcony-window Devices

A full-scale experimental study of a balcony-window device on a building façade was carried out inside an indoor testing facility that originally established for the ISO 10140-2 sound transmission loss testing (consisted of a source and a receiver room). The source room was converted into a semi-echoic facility. A long loudspeaker array consisted of twenty five 6” aperture loudspeakers was used to simulate a line source. Measurements were carried out inside the receiver room and inside the balcony structure with sound absorption materials mounted artificially on different balcony internal surfaces. The case without the balcony structure was conducted as the reference case. A detailed analysis on the insertion losses was performed. For practical reason, the broadband insertion losses were rated by the normalized traffic noise spectrum.

As in some previous studies, the results from the present investigation reveal that treatment at balcony ceiling offers the most effective protection to the façade against traffic noise. However, those on the side walls, which have not been included in many previous studies, comes the second. In general, no additional acoustic protection offered by balcony-window with further covering sound absorption materials inside the balcony cavity after the ceiling and side walls are treated. Comparing the insertion loss produced by an infinitely long vertical noise barrier at the same distance away from the window and at the same height of the current balcony parapet, the side walls result in 1 to 2 dB additional noise reduction by obstructing the direct line of sight between the noise source and the window.

The balcony-like device can provide better sound reduction from the outdoor transportation noise compared to the conventional window. However, the maximum insertion loss of about 7 dB only is achieved when both ceiling and side walls are acoustically treated. The benefit of the balcony-window device without any extra sound absorption materials is still not satisfactory. This façade device only provides about 3 dB in broadband insertion loss compared with that of the conventional opened window. The noise reduction offers by the façade device itself is insignificant.

CHAPTER 4 PLENUM WINDOW – A SCALE-MODEL INVESTIGATIONS

This chapter describes the investigation of plenum window at different sound incidence angles. The setups of the measurement will be described first, followed by the scenarios and details of tests. Then the measurement procedures and test results will be introduced and discussed.

4.1 Introduction

As presented in the previous chapter, balcony-window devices do not provide significant acoustic benefits compared to the conventional window unless additional sound absorption materials are installed inside the balcony cavity. Thus, modification of façade device should be made so that the device itself can screen outdoor noise effectively without any additional acoustical treatments. Besides, the device should enable natural airflows to maintain the indoor air quality of the living spaces.

4.2 Experiment Facility

All the measurements were carried out inside the semi-anechoic chamber of the Department of Building Services Engineering, The Hong Kong Polytechnic University. The chamber setups and sound source used in this investigation were the same as those in the previous balcony-window device's experiments, which have been described in the previous chapter (section 3.2). The sound power input to the loudspeaker array was kept unchanged during the whole measurements. In the present study, a 1: 4 scale down model was selected to investigate the acoustical performance of plenum windows at different incident angles. One-third octave band frequency range from 400 Hz to 20 kHz, which corresponds to the range of 100 Hz to 5 kHz in the full scale condition, was considered. In order to avoid confusion, the frequencies presented in the dissertation are scaled back to the full scale plenum window case.

4.3 Scale Model and Measurement Setup

The scaled down model used was made of 18 mm thick varnished plywood. It was geometrically similar to the receiver room of the coupled reverberant chambers in laboratory (in 1:4 ratio). A window with dimension of 500 mm length (*L*), 250 mm height (*H*) was presented at the front-side of the model. The model was placed on a portable platform for easy movement. Window sill was at 0.5 m above the chamber concrete floor. Two 3 mm thick Perspex panes were staggered at the window to create an air gap width (*d*) between the Perspex panes to form an air passage. The purpose of Perspex panes is to stimulate the glass panes of the full size plenum window. Figure 4.1 shows the dimensions of the present scale model and the openings of the plenum window. There are two openings of plenum window, which are defined as outer side opening (w_o) and inner side opening (w_i). The outer side opening was facing sound source while the other opening was facing the simulated chamber.

Table 4.1 summarizes the configurations of plenum windows for the current investigation. Three different window opening sizes of 50 mm, 125 mm and 150 mm with 250 mm height were tested. The test configurations were coded for the sake of easy reference. “P” denotes the opening sizes of the test windows and “A” denotes the air gap width of window to allow ventilation. The case of fully opened window as shown in Figure 4.2 was used as reference case for determining the acoustical performance of plenum window (Figure 4.3). Fully closed window as shown in Figure 4.4 was also tested. The closed window case was stimulated by sealing a 5 mm thick Perspex pane to the window frame.

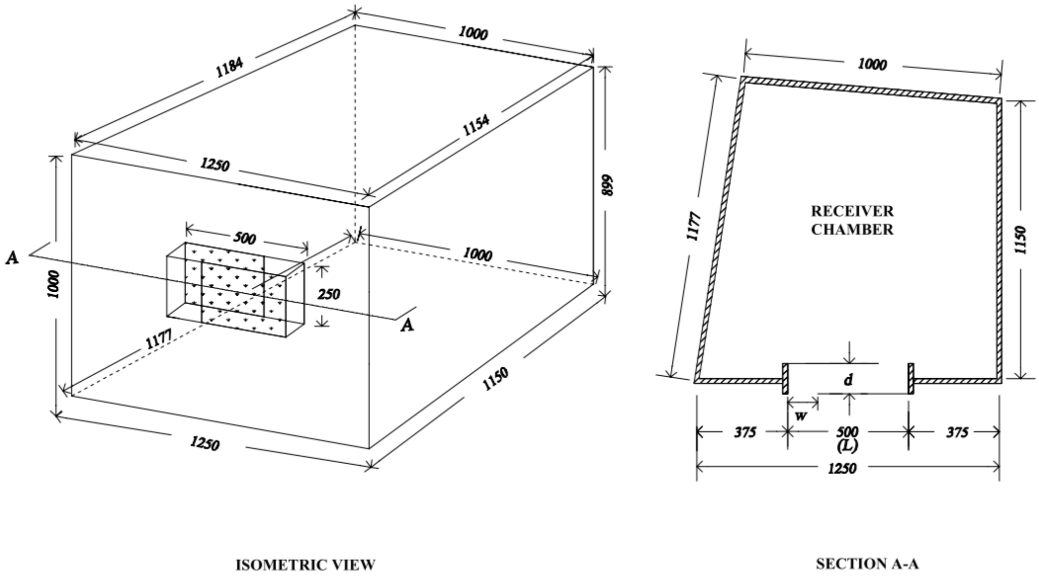


Figure 4.1 Isometric view and section A-A of scale model (in mm).

Table 4.1 Scenarios of scale model plenum windows.

Scenario, S_j	Outer / inner side opening (mm) w_o, w_i^*	Air gap width (mm) d^*	*w/L*	*d/L*
Opened		–		
Closed		–		
P250A100	250	100	0.5	0.2
P250A075	250	75	0.5	0.15
P250A050	250	50	0.5	0.1
P125A100	125	100	0.25	0.2
P125A075	125	75	0.25	0.1
P125A050	125	50	0.25	0.1
P050A100	50	100	0.1	0.2
P050A075	50	75	0.1	0.15
P050A050	50	50	0.1	0.1

Figure 4.2 Opened window (Reference case)

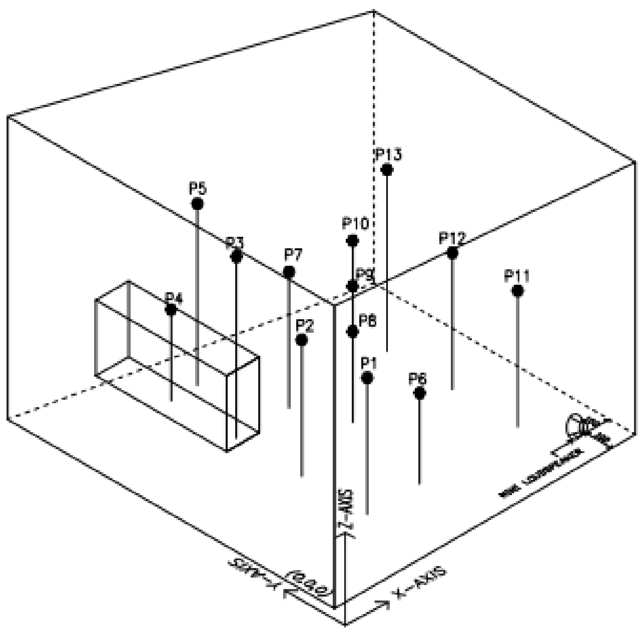
Figure 4.3 Plenum window

Figure 4.4 Closed window

Reverberation times inside the receiver room of the scaled down model were measured to determine the sound field condition of simulated chamber. These reverberation times are important for the calculation of the acoustical insertion loss. The source was placed at the corner of the receiver chamber and a 1/4" Brüel & Kjær Type 4951 microphone was used to capture the data. A total of twelve points irregularly spaced within the receiver room were selected to measure the average reverberation time using DIRAC system with MLS signal. Figure 4.5 summarizes all the measurement points and location of sound source.

The reverberation times of scale model (stimulated receiver chamber) were obtained by connecting the soundcard's line output to a 2-inches mini loudspeaker through a power amplifier Brüel & Kjær Type 2706 and input line to 1/4" Brüel & Kjær Type 4951 microphones through Brüel & Kjær NEXUS conditioning amplifier. One-third octave band reverberation time measurements were carried out in the model at various opening sizes (*w*) of the window. All reverberation times inside the scale model were less than 3.5 seconds throughout the frequency range of interest as shown in Figure 4.6. As the model was a 1:4 scale down model, this implies that the simulated receiver chamber was reverberant.

The model was placed at 3 m away from the line source where the centre of window was set as a base point. Six 1/4" microphones (Brüel & Kjær Type 4951) were used to measure the sound intensity fell on the plenum window on the source side. Another six microphones were spanned within the reverberation chamber to capture the transmitted sound level in the receiver chamber. Figure 4.7 is a schematics showing the location and coordinate of measurement points inside the receiver room and at outside the plenum window. The signals of these 12 microphones and the output of noise generator were recorded using a data acquisition system (Brüel & Kjær 3506D PULSE). Air temperature and relative humidity inside both source room and receiver room were maintained at around 26 °C and 55 % respectively throughout the measurements.



SIGNALS	COORDINATES (x, y, z)
P1	(375,250,450)
P2	(375,500,450)
P3	(375,750,600)
P4	(375,1000,300)
P5	(475,1000,600)
P6	(575,250,450)
P7	(575,750,500)
P8	(650,580,300)
P9	(650,580,450)
P10	(650,580,600)
P11	(950,250,450)
P12	(950,500,450)
P13	(950,750,600)

Figure 4.5 Reverberation time measurement points (coordinates in mm).

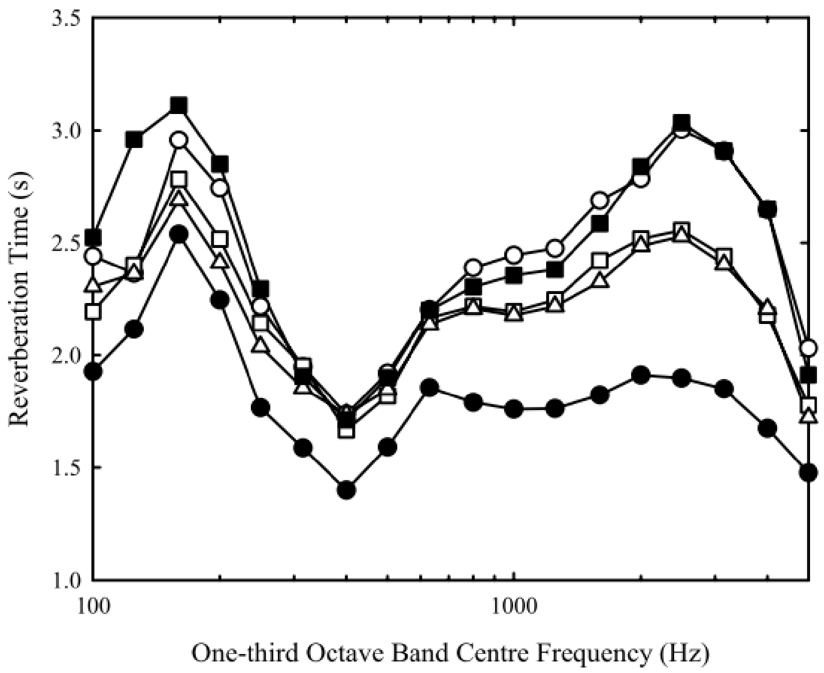


Figure 4.6 Average sound decays inside receiver chamber.

○: *w/L* = 0.1; □: *w/L* = 0.25; △: *w/L* = 0.5; ●: window opened; ■: closed window.

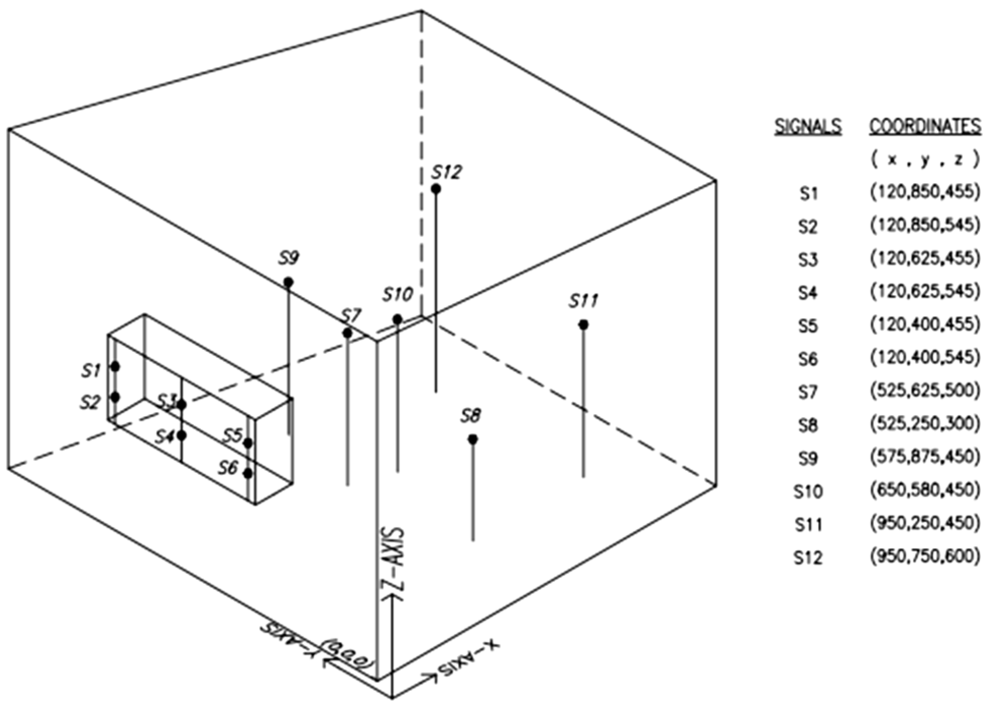


Figure 4.7 Location and coordinate of measurement points (coordinates in mm).

Building facades are not always parallel to the traffic road. The performance of window may change due to the different incidence of angles and reflections (Kang & Li, 2007; Viveiros, 2002). The effect of source orientation to the performance of plenum window was investigated in the present study. The present scale down model, which was placed on a portable platform, could be turned to adjust for different relative source orientations. Figure 4.8 shows the orientation of scale model in the chamber. Different sound incidences onto plenum window are shown in Figure 4.9. The orientation of model was at -90° incidence of angle when the window was perpendicular to loudspeaker array with the outer opening (sound side opening) closer to the sound source. The orientation angle was varied from -90° to 90° with 10° increment. At 0° of orientation angle, the window (and thus the model front wall) was parallel to the loudspeaker array. The angle of 90° indicates that the window was placed perpendicular to noise source with the outer side opening turned away from the road.

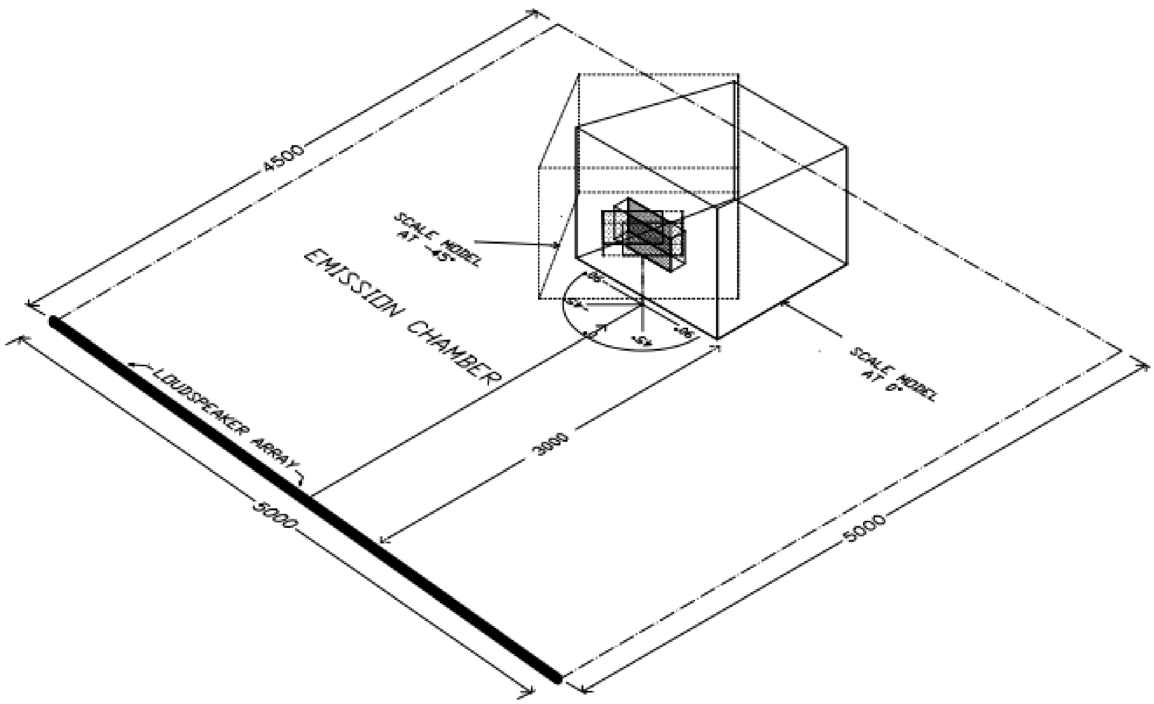


Figure 4.8 Layout of orientation of window to the sound source (in mm).

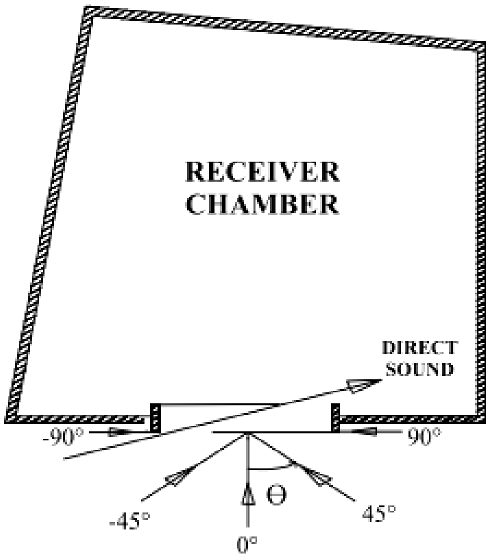


Figure 4.9 Different sound incidences onto plenum window

Since the objective of the present study is to estimate the acoustical protection of the plenum window in the presence of traffic noise, the normalized traffic noise spectrum of the standard EN 1793-3 (1998) was again adopted. The BS EN 1793-3 for traffic noise case was often used in the estimation of the acoustic benefits in term of a single rating. For this purpose, the difference between average acoustical levels, *L*, inside the model box before and after installation of plenum window was evaluated and the opened window case was used as the reference. Since the reverberation times inside the reverberation box did change with the window opening width, the effect of room constant is included in the calculation of the noise reduction as follows:

$$R_i = L_{i,S_{Opened}} - L_{i,S_j} - 10\log_{10}\left(\frac{RC_{i,S_j}}{RC_{i,S_{Opened}}}\right) \qquad \text{Eq. 4.1}$$

$$IL = 10\log_{10}\left(\frac{\sum_{i=1}^{18} 10^{0.1(N_i - R_i)}}{\sum_{i=1}^{18} 10^{0.1N_i}}\right) \qquad \text{Eq. 4.2}$$

where i represents the ith one-third octave band data, from 100 Hz to 5 kHz, RC_i the room constant and L_{Sj} the average band level obtain in the receiver chamber in scenario S_j and N_i the normalized noise band level. The room constant RC_i is obtained from the following equations:

$$RC_i = \frac{A_i}{1 - A_i / S_t}$$ Eq. 4.3

and $$A_i = \left(\frac{0.161V}{RT_i} \right)$$ Eq. 4.4

where A_i the sound absorption, S_t the total sound absorption, V the volume of the chamber, RT_i the average reverberation time inside the receiver chamber.

4.4 Results of Scale Model Measurements of Plenum Window

In practise, the orientation of the windows attached to the building facades can be restricted or flexible. Sometimes the orientations of windows are restricted because of the site constraint and or view issue, especially for the buildings located near the coastline. Another possible way is that the building façade and windows are freely oriented. So, there are two possible reference cases for the estimation of the plenum window insertion losses. When the orientation of the building is fixed, opened window with same orientation angle is used as the reference case. For the cases where the orientation of the building is not restricted, opened window case at θ = 0° is a better reference. The insertion loss of the second scenario is contributed by the plenum window itself and also the change in window orientation relative to the source.

4.4.1 Fixed Building Façade Orientation

Figure 4.10 illustrates the effects of orientation on the acoustical protection of plenum windows under different combinations of opening sizes (*w*) and air gap width (*d*) when the orientation of window relative to the transportation line is fixed. The insertion loss of closed window is also presented in the figure for the sake of easy comparison. As expected, closed window gives the highest *IL* , which is ~ 20 dBA. Besides, the trend of *IL* variation with orientation angle is symmetrical about θ = 0°.

For *w/L* = 0.5, plenum windows with various air gap widths (*d*) show the similar trends throughout the angular variation. At this *w/L*, additional of average ~ 1 dBA *IL* can be obtained with every 25 mm reduction of gap width (*d*) when device is located at same direction from the traffic noise (normal to the line source). The angle θ_{max} is between 10° and 20°. Highest sound protection of this *w/L* is not obtained at ~ $\theta = 0°$ because direct sound can propagate when the window is in normal position to the line source and oriented at negative θ. The present investigation shows that plenum window with *w/L* = 0.5 can provide at least 12 dBA acoustical benefit when window is located at $\theta = 0°$ which is higher than that Well's experiment result (Wells, 1958). For the same opening sizes, *w/L* = 0.5, plenum window at *d/L* = 0.1 provides highest acoustic protection of about 15 dBA at roughly $\theta = 15°$. From the figure, one can be observed that *IL* increases more rapidly when window is moved from $\theta = -90°$ approaches to $\theta = 0°$ than from $\theta = 90°$ approaches to $\theta = 0°$. At positive θ, plenum window offer better sound insulation where direct sound waves from the traffic roads are blocked or reflected by the outer pane of the device (refer to the Figure 4.9). Sound is transmitted into receiver chamber mostly through indirect reflections and diffractions.

When the opening sizes of plenum window are reduced to *w/L* = 0.25, the trends of *IL* throughout the angular variations do not change much from the trends of *w/L* = 0.5. For this *w/L*, higher *ILs* can be observed especially at large negative θ. However, the acoustical benefits at small θ are not so affected. The *d* becomes less "sensitive" when *w/L* is reduced to 0.25 where only small changes of acoustic benefits can be obtained by modifying gap widths of the window especially when window approaches to $\theta = \pm 90°$. It can be seen from the figure that *IL*s in all *d*/*L* for $|\theta| > 40°$ are very closed except for the *d*/*L* = 0.1. At this *w/L*, maximum *IL* obtained at θ between 0° to 10°.

As expected, further reducing the opening sizes to *w/L* = 0.1 is resulting in higher sound protections. The protection of plenum window reaches about 16 dBA compared to the opened window. The angle θ_{max} at this *w/L* is shifted to the negative side of sound incident which is about - 20°. The maximum *IL* at the orientation angle, θ_{max} becomes more dependent on *d* at this *w/L*. One can be noticed that the θ_{max} shows tendency to move to about - 20° when *d* of the window is reduced. At $|\theta| < 30°$, the *ILs* of plenum window with larger *d/L* are very closed. Since the opening sizes are small, the trends of *IL* of the windows are nearly same to that of closed window (symmetrical at nearly $\theta = 0°$). The direct sound waves at negative θ also less effective and multiple reflections within the plenum cavity may take placed which increased the sound energy losses. The ways sound propagates into the simulated chamber through the plenum window for positive and negative θ cases are different, thus the sound protection mechanisms at peak *IL* for the large and small window opening cases are expected to be different. This will be discussed further in the section 4.5. It can be seen that faster increase of *IL* at negative θ because at these orientations windows are in the "favourable" propagation condition.

It can be observed that when *d*/*L* was fixed, the peaks of *IL* nearly at the same θ. Besides, changing the opening sizes (*w*) of the plenum window will only significantly affect the *ILs* at negative θ. Apart from *w/L* =0.1, the *ILs* of the plenum window with same *d*/*L* are very close at positive θ. For the cases *d*/*L* = 0.2, the *ILs* for *w/L* = 0.25 are somewhat between *ILs* of *w/L* = 0.5 and *w/L* = 0.1. The *ILs* pattern across angular axis when *d*/*L* change from 0.2 to 0.1 are invariant where the *ILs* only moved upward (approach closed window) when *d*/*L* is reduced. One can notice that fast increase in *IL* at *d*/*L* = 0.1 when *w/L* changes from 0.25 to 0.1

Figure 4.11 (a) illustrates one-third octave band noise reduction R *for the cases with* w/L *= 0.5 and the numerical values are tabulated in*

Table 4.2. In general, the noise reduction *R* increases with frequency. It can be noticed that there are two regions of *R* trends at the higher frequencies. *R* is gradually increases across one-third octave band frequency range at θ = -90°, 90° and -45°. However, for all studied *d/L*, rapid increased of *R* can be observed at θ_{max} and θ = +45. There are peaks at around 160 Hz to 200 Hz for all *d/L* which may due to the longitudinal harmonic resonance of the plenum window. This mentioned harmonic resonance took placed at ~ 170 Hz. Besides, acoustic modes can be clearly seen at the lower frequencies and these fluctuations become smaller at frequencies greater than 1000 Hz. At frequencies lower than 630 Hz, the values of noise reduction *R* that obtained from *d/L* = 0.15 and 0.1 are almost the same. However, at higher frequencies, the variation of *R* between these two gap widths become larger especially at θ = -45° where the plenum windows are located at favourable propagation orientation.

When the opening sizes of plenum window are reduced to *w/L* = 0.25, the trend of frequency variation of noise reduction *R* is shown in Figure 4.11 (b). The numerical data of this plenum window are present in Table 4.3. It can be noted that *R* at the higher frequency side of the spectrum increased more rapid and it makes two separate regions of noise reduction trends that observed in *w/L* = 0.5 getting closer. Similar to that figure in w/L = 0.5, peaks at 200 Hz one –third octave band can be observed for all studied d/L of plenum windows at orientation θ = +45°. When plenum window is placed at θ = -90° and 90°, it can be seen that R peaks have shifted to 250 Hz band which are likely to be due to combination of longitudinal and transverse resonances at ~ 257 Hz.

Figure 4.11 (c) shows the noise reduction R for plenum window with opening sizes of w/L = 0.1. The numerical values of this w/L are shown in

Table 4.4. For the frequencies between 630 Hz and 800 Hz, noise reduction R is not significantly influenced by changing gap width (d) of the plenum. For these small window opening sizes with small gap width (d/L = 0.1), R is increased rapidly at higher frequencies. At w/L = 0.1, widen the gap width (d) resulting increase of noise reduction R at lower frequency ranges while decreased the performance of R at higher frequencies. One can be noticed that sharp deep of R at 5 kHz for almost all orientations at d/L = 0.2 and 0.15 which probably due to the great transmissions of high frequency sound. Since the present experiment is scale down model, 20 kHz in the experiment is corresponded to the 5 kHz of full scale window. These dips of R at this part the frequency spectrum are unimportant as the A-weighted traffic noise (BS EN 1793-3, 1998) is the main concern of the current study.

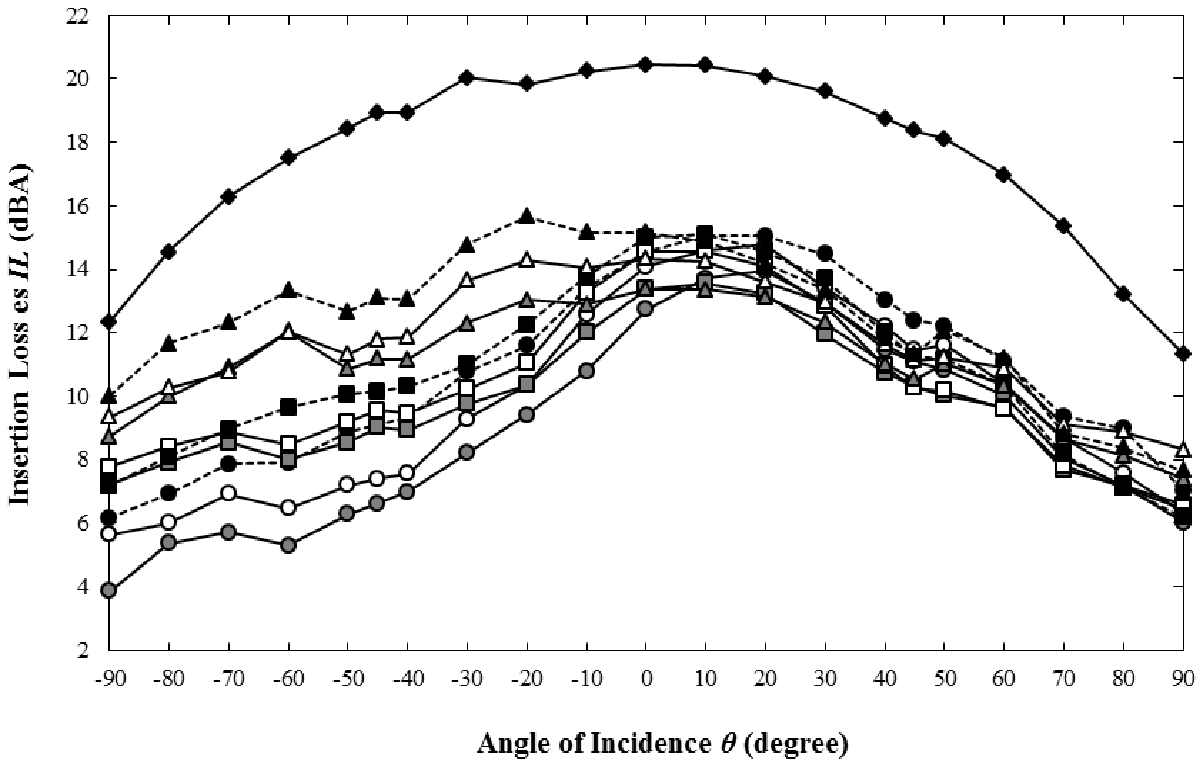


Figure 4.10 The effects of IL on variation angles for the restricted plenum window orientation relative to the line source cases.

○ : *w/L* = 0.5; □ : *w/L* = 0.25; △ : *w/L* = 0.1; ◇ : Closed window; Grey symbol : *d/L* = 0.2; Opened symbol : *d/L* = 0.15; Closed symbol with - - - line: *d/L* = 0.1.

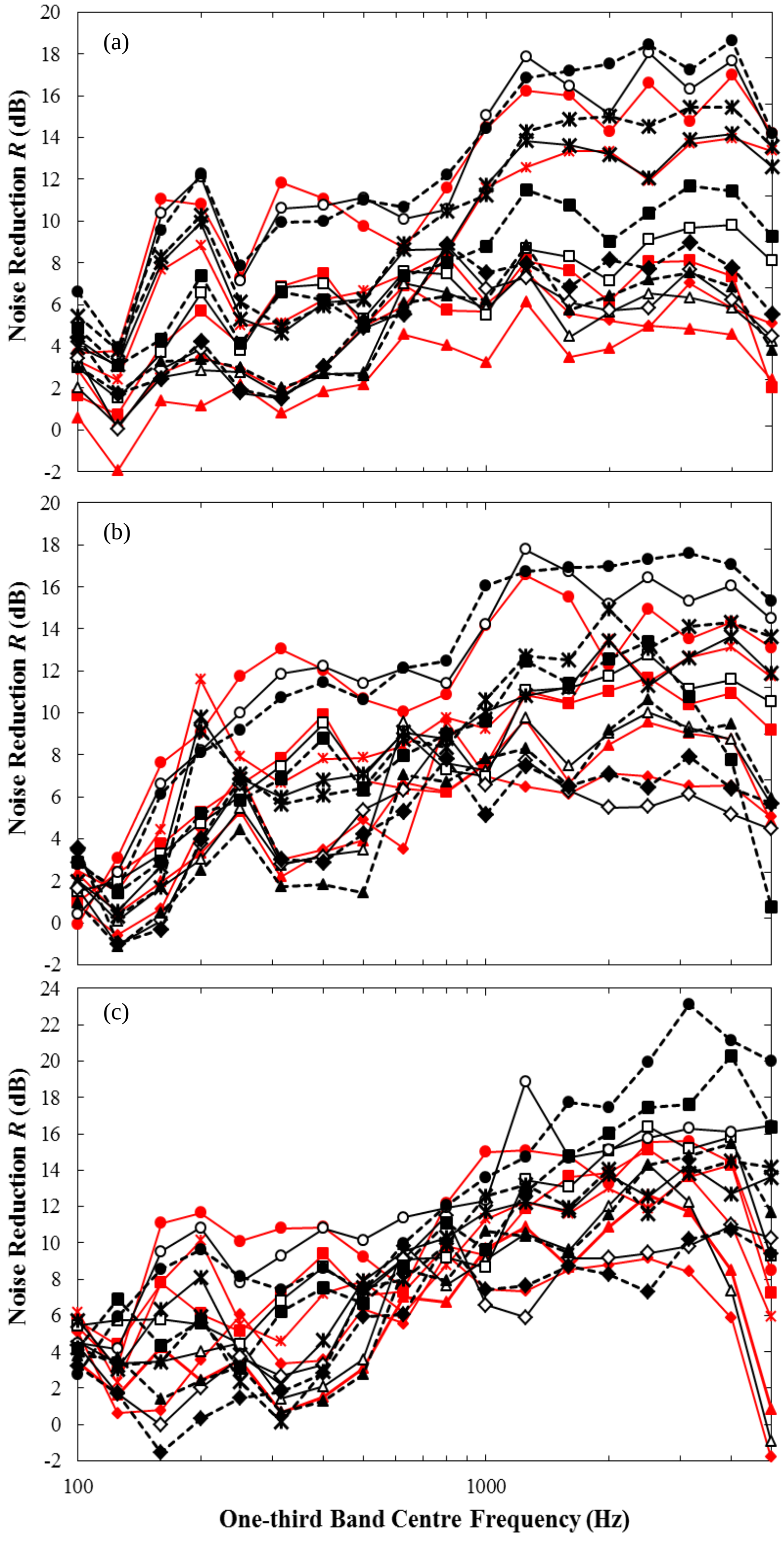


Figure 4.11 Noise reduction for cases with fixed window orientation relative to the line source.

(a) w/L = 0.5; (b) w/L = 0.25; (c) w/L = 0.1.○ : θ = θ_{max}; □ : θ = –45°; △ : θ = –90°; ✳ : θ = +45°; ◇ : θ = +90°. Red symbol: d/L = 0.2; Open symbol: d/L = 0.15; Closed symbol with - - - line: d/L = 0.1.

Table 4.2 Numerical data of noise reduction R for the fixed orientation of plenum window with w/L = 0.5.

Orientation angle, θ (°)	***d/L***	**Symbol**	**One-third octave band noise reduction, *R* (dB)**																	
			Frequency (Hz)																	
			100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
	0.2	●	3.7	3.8	11.0	10.8	7.3	11.8	11.1	9.8	8.7	11.6	14.5	16.2	16.0	14.3	16.6	14.8	17.0	14.2
θ_{max}	0.15	○	4.3	3.0	10.4	12.1	7.2	10.6	10.8	11.1	10.1	10.5	15.0	17.9	16.5	15.1	18.0	16.3	17.7	13.9
	0.1	●	6.6	3.9	9.5	12.3	7.8	10.0	10.0	11.0	10.7	12.2	14.4	16.9	17.2	17.5	18.4	17.3	18.6	14.2
	0	■	0.6	-2.0	1.4	1.1	2.1	0.8	1.8	2.2	4.6	4.0	3.2	6.1	3.5	3.9	5.0	4.8	4.6	2.4
- 0 °	0.15	□	2.0	0.2	2.5	2.8	2.8	1.7	2.7	2.7	7.0	6.6	5.8	7.6	4.5	5.6	6.5	6.3	5.9	4.3
	0.1	■	3.0	1.8	3.3	3.4	3.0	2.0	2.7	2.6	6.1	6.4	6.2	8.8	5.7	6.4	7.2	7.5	6.9	3.8
	0.2	▲	1.6	0.7	4.0	5.7	4.1	6.9	7.5	4.9	6.9	5.7	5.7	8.1	7.6	6.1	8.1	8.1	7.3	2.0
-45 °	.1	△	3.0	1.5	3.7	6.5	3.8	6.8	7.0	5.3	7.6	7.5	5.5	8.7	8.3	7.2	9.1	9.7	9.8	8.1
	0.1	▲	4.8	3.1	4.3	7.4	4.1	6.6	6.2	5.0	7.4	8.0	8.8	11.5	10.8	9.0	10.4	11.7	11.4	9.3
	0.2	*	3.3	2.4	7.7	8.8	5.0	5.1	6.3	6.6	7.5	8.5	11.6	12.6	13.3	13.3	11.9	13.7	14.0	13.4
+45 °	0 15	*	4.0	3.1	8.0	9.9	5.3	4.6	6.1	6.3	8.6	8.6	11.7	13.8	13.6	13.2	12.1	13.9	14.2	12.6
	0.1	- * -	5.4	3.8	8.3	10.3	6.1	5.0	5.9	6.2	8.9	10.5	11.2	14.3	14.9	15.0	14.5	15.5	15.4	13.6
	0.2	♦	2.9	0.2	2.7	3.5	2.9	1.8	3.0	5.0	6.0	8.3	6.1	7.6	5.6	5.2	4.9	7.0	5.8	5.1
+90 °	0.15	♦	3.4	0.0	2.9	3.9	1.8	1.5	3.0	4.8	5.6	8.8	6.7	7.3	6.1	5.7	5.8	7.7	6.2	4.5
	0.1	- ◊ -	4.5	1.7	2.4	4.3	1.9	1.5	3.0	5.2	5.5	8.9	7.5	8.0	6.8	8.1	7.7	9.0	7.8	5.6

Table 4.3 Numerical data of noise reduction R for the fixed orientation of plenum window with w/L = 0.25.

Orientation angle, θ (°)	***d/L***	**Symbol**	**One-third octave band noise reduction, *R* (dB)**																	
			Frequency (Hz)																	
			100	125	16	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
	0.2	●	-0.1	3.1	7.6	9.1	11.8	13.0	12.0	10.7	10.0	10.9	14.2	16.6	15.5	12.3	14.9	13.5	14.3	13.1
θ_{max}	0.15	○	0.4	2.4	6.6	8.2	10.0	11.8	12.2	11.4	12.1	11.4	14.2	17.8	16.7	15.2	16.5	15.3	16.1	14.5
	0.1	●	2.8	1.6	6.1	8.1	9.2	10.7	11.4	10.7	12.1	12.5	16.0	16.7	16.9	17.0	17.3	17.6	17.1	15.3
	0	■	2.3	0.4	2.0	3.3	5.3	2.2	3.4	3.9	6.7	6.3	7.6	9.7	6.7	8.5	9.6	9.0	8.8	4.8
-90 °	0.15	□	1.9	0.1	1.7	3.0	5.5	2.8	3.2	3.4	9.6	7.6	7.3	9.8	7.5	9.0	10.0	.3	8.7	5.7
	0.1	■	0.9	-1.1	0.5	2.5	4.4	1.7	1.8	1.4	7.1	6.7	7.8	8.3	6.5	9.2	10.6	9.1	9.5	5.9
	0.2	▲	1.0	2.4	3.7	5.3	6.6	7.8	9.9	6.8	6.4	6.2	7.5	10.9	10.5	11.0	11.7	10.4	10.9	9.2
-45 °	0.15	△	1.5	2.0	3.3	4.7	6.1	7.4	9.5	6.9	9.1	7.3	7.0	11.1	11.2	11.8	12.8	11.1	11.6	10.5
	0.1	▲	2 9	1.4	3.0	5.2	5.8	6.8	8.8	6.3	8.0	9.0	9.6	12.5	11.4	12.6	13.4	10.8	7.8	0.7
	0.2		2.5	1.5	4.5	11.6	7.9	6.7	7.8	7.9	8.4	9.8	9.2	11.0	10.5	13.5	11.5	12.7	13.1	11.7
+45 °	0.15	∗	2.0	0.5	2.7	9.8	6.9	6.0	6.8	7.1	9.1	8.8	10.1	10.8	11.2	13.4	11.3	12.6	13.6	11.9
	0.1	- ∗ -	3.2	0.3	1.7	9.1	7.1	5.6	6.1	6.4	8.7	8.3	10.6	12.7	12.5	14.9	13.1	14.1	14.3	13.6
	0.2	♦	0.8	-0.6	0.7	4.5	7.1	3.0	3.5	4.9	3.5	9.6	7.0	6.5	6.1	7.1	7.0	6.5	6.5	5.0
+90 °	0.15	♦	1.6	-1.0	0.1	3.8	6.6	2.8	3.1	5.4	6.3	9.0	6.6	7.7	6.3	5.5	5.5	6.1	5.2	4.5
	0.1	- ◊ -	3.6	-1.0	-0.3	4.0	6.9	3.0	2.9	4.2	5.3	7.8	5.2	7.5	6.5	7.1	6.5	7.9	6.4	5.7

Table 4.4 Numerical data of noise reduction R for the fixed orientation of plenum window with w/L = 0.5.

Orientation angle, θ (°)	***d/L***	**Symbol**	**One-third octave band noise reduction, *R* (dB)**																	
			Frequency (Hz)																	
			100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
	0.2	●	5.3	3.2	11.1	11.7	10.1	10.8	10.9	9.2	7.5	12.2	15.0	15.1	14.8	13.2	15.5	15.6	14.4	8.5
θ_{max}	0.15	○	4.5	4.2	9.5	10.8	7.8	9.3	10.8	10.1	11.4	11.9	12.3	18.8	14.7	15.1	15.8	16.3	16.1	16.4
	0.1	●	2.7	5.9	8.5	9.6	8.1	7.4	8.6	7.4	10.0	12.0	13.6	14.7	17.7	17.5	20.0	23.1	21.1	20.0
	0	■	3.4	1.6	4.2	2.4	3.6	0.7	1.5	3.1	7.0	6.7	9.7	10.9	8.7	10.9	12.6	11.7	8.5	0.8
-90 °	0.15	□	4.5	3.3	3.5	4.0	4.5	1.4	2.1	3.6	9.9	7.6	9.1	10.5	9.6	12.0	14.3	12.2	7.3	-0.9
	0.1	■	3.8	3.7	1.4	2.4	3.2	0.7	1.3	2.8	8.5	7.9	10.6	10.3	9.4	11.6	14.3	14.8	15.5	11.7
	0.2	▲	5.7	4.4	7.8	6.1	5.1	7.2	9.4	7.1	7.3	9.8	9.3	11.9	13.6	13.8	15.1	13.6	14.3	7.2
-45 °	0.15	△	5.4	5.7	5.8	5.5	4.4	6.8	8.7	7.2	9.1	9.2	8.6	13.5	13.1	15.1	16.4	15.2	15.8	9.3
	0.1	▲	4.2	6.9	4.3	5.7	3.1	6.2	7.5	6.7	8.7	11.1	9.6	12.8	14.8	16.0	17.4	17.6	20.3	16.4
	0.2	*	6.2	2.3	7.8	10.1	5.5	4.6	7.2	7.9	6.1	8.7	11.3	12.2	11.6	13.0	11.9	13.7	10.9	5.9
+45 °	0.15	*	5.7	3.0	6.3	8.1	3.8	2.2	4.6	7.9	9.5	10.3	11.7	12.2	11.8	13.7	12.5	14.3	12.7	13.6
	0.1	- * -	4.3	3.3	3.4	6.0	2.4	0.1	2.9	7.5	8.0	9.9	12.6	13.2	12.0	14.0	11.6	13.8	14.5	14.2
	0.2	♦	5.1	0.6	0.8	3.5	6.0	3.3	3.6	6.4	5.5	9.4	7.5	7.3	8.5	8.8	9.2	8.4	5.8	-1.8
+90 °	0.15	♦	4.3	1.7	0.0	2.0	3.7	2.7	3.3	7.4	9.1	11.5	6.6	5.9	9.2	9.1	9.4	9.8	11.0	10.3
	0.1	- ◊ -	3.2	1.7	-1.5	0.3	1.4	1.8	2.8	5.9	6.0	10.1	7.4	7.6	8.7	8.2	7.3	10.2	10.7	9.4

Figure 4.12 (a) shows the average narrow band sound spectra inside the stimulated receiver chamber for some plenum window cases and opened window. It can be seen that there are several sharp peaks at frequencies below 150 Hz in both plenum windows and reference window which are probably due to the simulated receiver chamber. The sharp peaks ~ 160 Hz and ~ 200 Hz octave band in the Figure 4.11 confirmed due to the harmonic resonance of plenum window where the dip at ~ 85 Hz can be observed in this narrow band spectra. When opening sizes (*w*) and gap width (*d*) of plenum window become smaller, sharper longitudinal resonance can be seen. Since the current study is to evaluate plenum window in the present of traffic noise which corresponds to the frequency range of 100 Hz to 5 kHz, peaks and dips at very lower frequencies can be negligible.

The narrow band insertion losses for the cases discussed in Figure 4.12 (a) are shown in Figure 4.12 (b). There are fluctuations of insertion loss at lower frequencies which probably due to the mode effects. The trends of these *IL* fluctuations appear more constant at higher frequencies. From the figure, the insertion loss peaks can be noticed at ~ 300 Hz of both plenum windows which may due to the combination of transverse and longitudinal resonances of the plenum window. Higher peak of insertion loss can be clearly seen for the case larger opening sizes (*w*) and gap width (*d*).

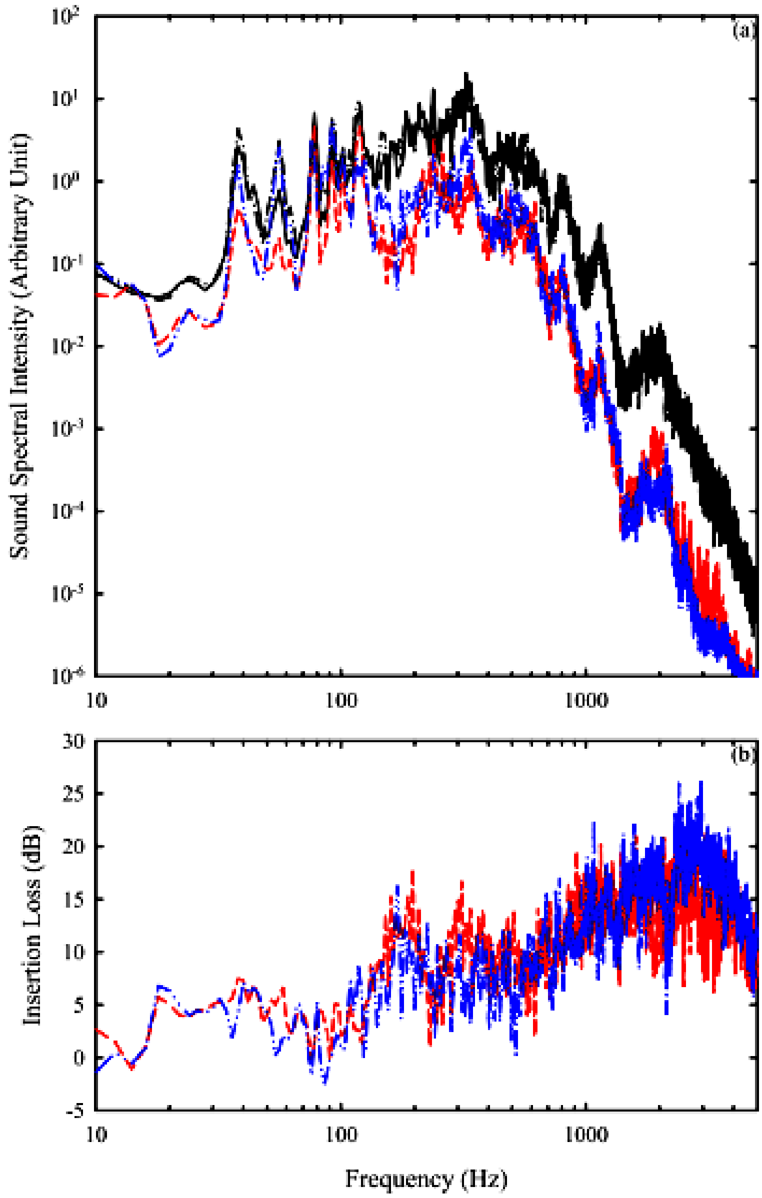


Figure 4.12 (a) Average narrow band sound spectra inside the stimulated receiver chamber. (b) Example of some narrow band insertion losses.

——— : Opened window, θ = +20 °; — · — : Opened window, θ = –20 °;
– – – – : *w*/*L* = 0.5, *d*/*L* = 0.2, θ = +20 °; — ·· — : *w*/*L* = 0.1, *d*/*L* = 0.1, θ = –20 °.

4.4.2 Unrestricted Building Façade Orientation

The acoustic protections of plenum windows for the cases when the orientation of window can be adjusted are also investigated in the present study. Sometimes the orientation of windows that attached to the building façade can be flexible, for instance, a new built environment. The estimation of *IL* for this condition is done by comparing plenum windows at difference sound incident angles with opened window at normal incidence ($\theta = 0°$). The acoustical benefits obtained in this situation not only consist of protection of plenum window itself but also the change of view angle of the traffic noise. Figure 4.13 illustrates the angular variations of *IL* for the cases that the orientations of plenum window relative to the line source are unrestricted. The *ILs* trends of current situation are increased compared to the fixed orientation condition (Figure 4.10) because of the source view reduction. However, it can be seen that the variation of *ILs* are not much affected by the change in source view for the $|\theta| < 30°$. The results of closed window can be clearly seen the reduction of source view effects.

From the angular variation of IL, it can be noticed that the effects of source view to the *ILs* become significant when the plenum windows are placed at larger θ. In general, after $|\theta|$ larger than 45^o the *ILs* are increased with the increasing of $|\theta|$ while the inverse trends are observed in the previous situation (Figure 4.10). Highest *ILs* always obtained at $|\theta| = 90^o$ where at these orientations plenum windows are perpendicular to the line source and no direct sound waves can be entered into receiver chamber. Minimum *ILs* are obtained at θ between -40^o to -45^o where the stimulated line source paths can directly propagate into receiver chamber via outer side opening. There are also small dips at $\theta \sim 45^o$ can be observed in the figure. For the case $w/L = 0.5$, the magnitudes of dips at $\theta \sim -45^o$ are much larger than those at $\theta \sim 45^o$. However, when the opening sizes of plenum window are changed from $w/L = 0.5$ to 0.25, the difference between these two sides of dips become smaller. As opening sizes further reduced to $w/L = 0.1$, the dips at $\theta \sim -45^o$ and $\theta \sim 45^o$ are nearly same. Similar to the Figure 4.10, the *IL* is more sensitive at negative θ because direct sound propagation may take placed at these orientations. The ILs at negative θ is lower than those at positive θ for the cases of large *w*. However, at small *w* and *d*, the ILs at negative θ is higher than that at positive θ. Besides, there are not much difference on *ILs* at $\theta > 40^o$ after further narrower gap width of the plenum windows. Reduced the gap width *d*/*L* only dominant at larger *w*/*L* which is similar to the fixed façade orientation cases.

At *w*/*L* = 0.5, the effectiveness of plenum window is increased when the gap width of device is reduced. The acoustical benefits obtained by the plenum window with smaller opening sizes, *w*/*L* are higher. When *w*/*L* reduced, the influence of air gap width becomes insignificant. At *w*/*L* = 0.1, the orientations of façade building that exposed to the traffic noise are considered do not give big impact on acoustic performance of the devices because of the small opening sizes. The rate of *ILs* are invariant at θ = - 10^{o} to 30^{o}. Consider that *d/L* are fixed with varies *w*/*L*, the effects of sound insertion losses of devices show substantial effects between θ = -90° to 0° owing to the sound incident angles that imposed to opening of windows at such angles. There are about 1.5 dBA to 5 dBA of *IL* variation when opening sizes are changed from *w*/*L* = 0.5 to *w*/*L* = 0.1 in the abovementioned angle range. On the other hand, at the right side of studied angle range (positive θ), *ILs* for three different openings sizes are not much affected.

Figure 4.14 illustrates the effect of view angle on the insertion loss of plenum window. This source view effects can be obtained by getting the differences of *ILs* between fixed orientation (from Figure 4.10) and unrestricted orientation (from Figure 4.13) cases. The results for all the studied cases show that the angle effect is independent with the plenum window configurations. This adds to the reliability of measurements. The data from the measurements are fitted well with fourth order polynomial regression line with the correlation coefficient R^2 = 0.997 and standard error ε = 0.15 dB. Besides, the line $\Delta IL = 10\log_{10}|\cos\theta|$ also present in the figure where it shows the reduction of sound intensity that falling on the windows due to the change in the source view. At $|\theta|$ < 70^{o}, there was only small differences between the line $\Delta IL = 10\log_{10}|\cos\theta|$ and measurement data. After $|\theta|$ > 70^{o}, the effect of change in the source view angle on insertion loss of plenum window is slowly increased compared to the line $\Delta IL = 10\log_{10}|\cos\theta|$. The differences may due to the sound diffraction when windows are approaches $|\theta|$ = 90^{o}

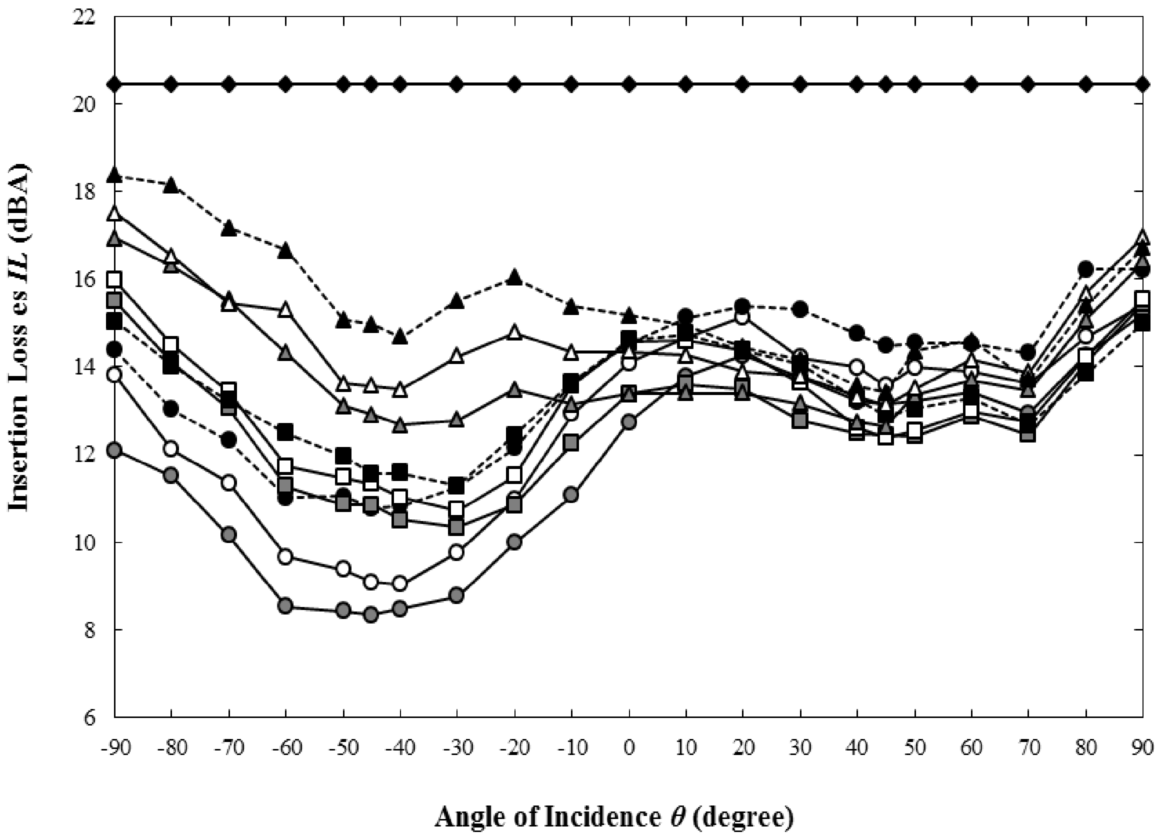


Figure 4.13 The effects of IL on variation angles for the unrestricted plenum window orientation relative to the line source cases.

○ : *w/L* = 0.5; □ : *w/L* = 0.25; △ : *w/L* = 0.1; ◇ : Closed window; Grey symbol : *d/L* = 0.2; Opened symbol : *d/L* = 0.15; Closed symbol with - - - line: *d/L* = 0.1.

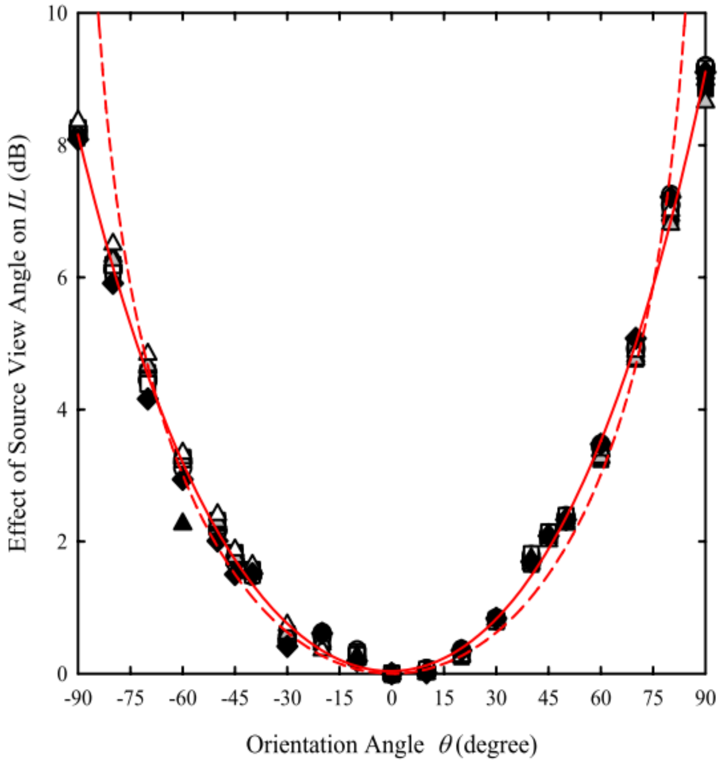


Figure 4.14 Effect of source view angle on the insertion loss (IL).

○ : *d/L* = 0.2; □ : *d/L* = 0.15; △ : *d/L* = 0.1; Closed symbol : *w/L* = 0.5;
Grey symbol : *w/L* = 0.25; Open symbol : *w/L* = 0.1;
——— : Regression line; – – – – : $\Delta IL = 10\log_{10}|\cos\theta|$.

Figure 4.15 (a) illustrates one-third octave band noise reduction *R* for the *w/L* = 0.5 with different *d/L* cases when the orientation of window is unrestricted. The numerical data are shown in Table 4.5. Similar to the condition that the orientation of building is fixed (Figure 4.11), the noise reduction *R* of the plenum windows are increased with the increasing of frequency. Besides, peaks can be observed at ~ 160 Hz and 200 Hz due to the resonance of plenum window which has been described in the previous section. After 630 Hz one-third octave band, one can be noticed that plenum window at position θ = - 45° obtained lowest noise reduction especially for the wider gap width *d* cases. However, noise reduction *R* for the large $|\theta|$ are higher because direct sound waves that can propagate into the receiver cavity and sound transmission by diffraction are relatively reduced.

The frequency variation of noise reduction for *w/L* = 0.25 was shown in Figure 4.15 (b) and the numerical values are tabulated in

Table 4.6. When the opening sizes are reduced from w/L = 0.5 to w/L = 0.25, it can be seen that the *Rs* at θ = - 45° are increased more rapidly at higher frequencies. Peaks at 200 Hz one–third octave band can be observed for all studied d/L at positive θ (45° and 90°) while at negative θ (- 45° and - 90°) the peaks are shifted to the ~ 250 Hz. At this opening sizes, noise reduction R at θ =- 45° for the smaller gap width d/L = 0.1 is decreased dramatically at 5 kHz.

When the opening sizes are further reduced to w/L = 0.1, the corresponding noise reduction R is shown in Figure 4.15 (c). Table 4.7 shows the numerical values of this opening sizes plenum window. In general, R increased more rapidly across the frequency especially for the d/L = 0.1 cases. Higher R again can be observed at large $|\theta|$ for this w/L. From the figure, peaks still can be observed at ~ 200 Hz which may be due to the resonances. Fast drop of R at 5 kHz which also happened in the Figure 4.11 (c) can be seen for all plenum windows.

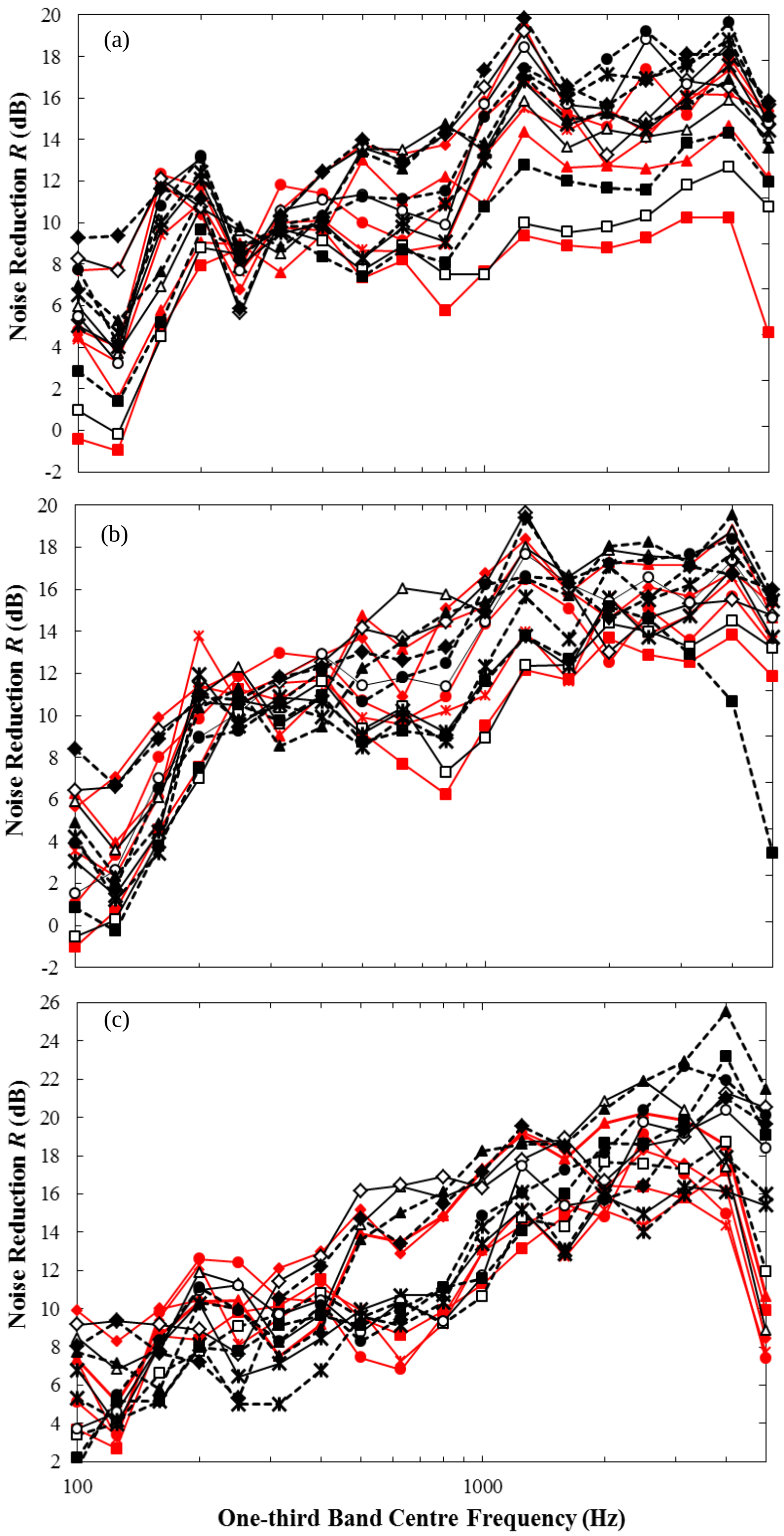


Figure 4.15 Noise reduction of plenum windows for cases window orientation relative to the line source unrestricted.

(a) w/L = 0.5; (b) w/L = 0.25; (c) w/L = 0.1.○ : $\theta = \theta_{max}$; □ : θ = –45 º; △ : θ = –90 º; ✳ : θ = +45 º; ◇ : θ = +90 º. Red symbol: d/L = 0.2; Open symbol: d/L = 0.15; Closed symbol with - - - line: d/L = 0.1.

Table 4.5 Numerical data of noise reduction R for the unrestricted orientation of plenum window with w/L = 0.5.

Orientation angle, θ (°)	***d/L***	**Symbol**	**One-third octave band noise reduction, *R* (B)**																	
			Frequency (Hz)															
			100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	315	0 0	5000
	0.2	●	4.8	4.0	12.3	11.8	7.8	11.8	11.4	10.0	9.1	10.9	15.1	16.8	15.2	14.6	17.4	15.2	18.0	15.1
θ_{max}	0.15	○	5.4	3.2	11.6	13.1	7.7	10.6	11.1	11.3	10.6	9.9	15.7	18.4	15.7	15.5	18.8	16.7	18.7	14.8
	0.1	●	7.7	4.1	10.8	13.2	8.4	9.9	10.3	11.2	11.1	11.5	15.1	17.4	16.4	17.8	19.2	17.6	19.6	15.1
	0	■	4.5	1.5	5.8	9.0	9.0	7.6	9.5	13.0	11.0	12.2	10.9	14.3	12.7	12.7	12.6	13.0	14.6	12.2
-90 °	0.15	□	5.9	3.7	6.9	10.7	9.6	8.5	10.3	13.6	13.5	14.7	13.4	15.8	13.6	14.5	14.1	14.5	15.9	14.1
	0.1	■	7.0	5.3	7.6	11.3	9.8	8.9	10.3	13.4	12.6	14.6	13.8	17.1	14.9	15.3	14.8	15.7	16.9	13.6
	0.2	▲	-0.4	-1.0	4.9	7.9	8.8	9.8	9.6	7.3	8.2	5.8	7.7	9.4	8.9	8.8	9.3	10.2	10.2	4.7
-45 °	0.15	△	1.0	-0.2	4.5	8.8	8.5	9.7	9.1	7.7	8.9	7.5	7.5	10.0	9.5	9.8	10.3	11.8	12.7	10.8
	0.1	▲	2.8	1.4	5.2	9.6	8.8	9.5	8.4	7.4	8.7	8.1	10.8	12.8	12.0	11.7	11.6	13.8	14.3	12.0
	0.2	*	4.4	3.3	9.4	11.0	7.6	10.0	10.1	8.7	8.6	8.9	13.3	15.5	14.4	15.5	14.4	15.8	17.4	15.2
+45 °	0.15	*	5.0	4.0	9.8	12.1	7.9	9.5	10.0	8.3	9.8	9.1	13.4	16.8	14.7	15.3	14.5	16.0	17.6	14.4
	0.1	- * -	6.5	4.7	10.0	12.4	8.8	9.8	9.8	8.3	10.1	10.9	12.9	17.2	16.0	17.1	16.9	17.6	18.8	15.4
	0.2	♦	7.7	7.8	11.9	10.4	6.8	10.6	12.4	13.7	13.3	13.7	15.8	19.5	15.3	12.8	14.1	16.2	16.1	15.4
+90 °	0.15	♦	8.3	7.7	12.1	10.7	5.7	10.3	12.4	13.6	13.0	14.2	16.5	19.2	15.8	13.3	15.0	16.8	16.5	14.7
	0.1	- ◊ -	9.3	9.4	11.6	11.1	5.8	10.3	12.4	14.0	12.9	14.3	17.3	19.8	16.6	15.7	16.8	18.1	18.1	15.8

Table 4.6 Numerical data of noise reduction R for the unrestricted orientation of plenum window with w/L = 0.25.

Orientation angle, θ (°)	***d/L***	**Symbol**	**One-third octave band noise reduction, *R* (dB)**																	
			Frequency (Hz)																	
			100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
	0.2	●	1.0	3.3	8.0	9.8	11.9	13.0	12.7	10.7	9.7	10.9	14.4	16.5	15.1	12.5	15.1	13.6	15.7	13.3
θ_{max}	0.15	○	1.5	2.6	7.0	9.0	10.1	11.8	12.9	11.4	11.8	11.4	14.4	17.7	16.3	15.4	16.6	15.4	17.4	14.7
	0.1	●	3.9	1.8	6.5	8.9	9.2	10.7	12.1	10.7	11.8	12.5	16.2	16.6	16.5	17.2	17.4	17.6	18.4	15.5
	0	■	6.3	3.9	6.3	11.2	12.1	9.0	11.1	14.7	13.2	14.4	15.2	17.9	15.9	17.3	17.2	17.2	18.8	14.6
-90 °	0.15	□	5.9	3.6	6.1	10.9	12.3	9.6	10.9	14.3	16.0	15.8	14.9	18.0	16.6	17.9	17.6	17.5	18.8	15.5
	0.1	■	4.9	2.4	4.8	10.4	11.3	8.5	9.5	12.2	13.5	14.9	15.4	16.5	15.7	18.0	18.3	17.2	19.5	15.7
	0.2	▲	-1.0	0.7	4.6	7.5	11.2	10.7	12.0	9.2	7.7	6.3	9.5	12.2	11.7	13.7	12.9	12.5	13.8	11.9
-45 °	0.15	△	-0.5	0.3	4.1	7.0	10.7	10.3	11.6	9.3	10.4	7.3	8.9	12.4	12.4	14.4	14.0	13.3	14.5	13.2
	0.1	▲	0.8	-0.3	3.8	7.5	10.5	9.7	10.9	8.7	9.2	9.0	11.6	13.8	12.7	15.2	14.6	12.9	10.7	3.4
	0.2	*	3.5	2.4	6.2	13.8	10.5	11.5	11.7	9.9	9.6	10.2	10.9	14.0	11.6	15.6	13.9	14.8	16.5	13.5
+45 °	0.15	*	3.1	1.4	4.5	12.0	9.5	10.9	10.7	9.1	10.2	9.2	11.8	13.8	12.3	15.6	13.7	14.7	17.0	13.7
	0.1	- * -	4.2	1.2	3.4	11.3	9.7	10.5	9.9	8.5	9.9	8.8	12.3	15.7	13.6	17.1	15.5	16.2	17.7	15.4
	0.2	♦	5.6	7.0	9.9	11.4	11.0	11.8	12.9	13.7	10.9	15.0	16.7	18.4	15.9	14.6	16.1	15.7	16.8	15.3
+90 °	0.15	♦	6.4	6.6	9.3	10.6	10.5	11.6	12.5	14.1	13.7	14.4	16.3	19.6	16.0	13.0	14.7	15.3	15.5	14.7
	0.1	- ◊ -	8.4	6.6	8.9	10.9	10.8	11.8	12.3	13.0	12.6	13.2	14.9	19.4	16.2	14.6	15.6	17.1	16.7	16.0

Table 4.7 Numerical data of noise reduction R for the unrestricted orientation of plenum window with w/L = 0.1.

Orientation angle, θ (°)	*d/L*	Symbol	One-third octave band noise reduction, ***R*** (dB)																	
			Frequency (Hz)																	
			100	125	160	200	2 0	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
	0.2	●	5.1	3.4	9.8	12.6	12.4	10.5	10.3	7.4	6.8	9.6	13.0	14.4	15.4	14.8	19.1	17.0	14.9	7.4
θ_{max}	0.15	○	3.7	4.6	8.2	11.0	11.2	9.7	10.4	8.7	10.4	9.3	11.7	17.5	15.4	15.7	19.7	19.2	20.4	18.4
	0.1	●	1.7	5.5	8.4	11.1	9.9	8.3	10.2	8.3	9.5	11.1	14.9	16.1	17.2	18.1	20.4	22.7	21.9	20.1
	0	■	7.4	5.1	8.6	10.3	10.4	7.5	9.2	13.9	13.5	14.9	17.3	19.1	17.8	19.7	20.2	19.8	18.5	10.6
-90 °	0.15	□	8.5	6.8	7.9	11.9	11.3	8.2	9.7	14.4	16.4	15.8	16.7	18.7	18.8	20.9	21.9	20.4	17.4	8.9
	0.1	■	7.7	7.2	5.8	10.3	10.0	7.5	8.9	13.6	15.0	16.1	18.2	18.6	18.6	20.4	21.9	22.9	25.5	21.5
	0.2	▲	3.7	2.7	8.6	8.4	9.8	10.1	11.5	9.5	8.6	9.9	11.3	13.2	14.9	16.5	16.3	15.8	17.2	9.9
-45 °	. 5	△	3.4	4.0	6.6	7.8	9.1	9.7	10.8	9.6	10.4	9.2	10.6	14.8	14.3	17.7	17.6	17.3	18.7	12.0
	0.1	▲	2.2	5.2	5.1	8.0	7.8	9.1	9.6	9.1	10.0	11.1	11.6	14.1	16.0	18.7	18.6	19.8	23.2	19.0
	0.2	*	7.2	3.2	9.6	12.3	8.1	9.4	11.1	9.9	7.3	9.2	13.0	15.2	12.7	15.2	14.3	15.8	14.3	7.7
+45 °	0.15	*	6.8	3.9	8.1	10.3	6.5	7.1	8.5	9.9	10.7	10.7	13.4	15.2	12.9	15.9	15.0	16.4	16.1	15.4
	0.1	- * -	5.3	4.2	5.2	8.1	5.0	5.0	6.8	9.6	9.1	10.3	14.3	16.1	13.1	16.2	14.0	15.9	17.9	16.0
	0.2	♦	9.9	8.3	10.0	10.4	9.9	12.1	13.0	15.2	12.9	14.8	17.2	19.2	18.3	16.3	18.3	17.6	16.2	8.5
+90 °	0.1	♦	9.2	9.4	9.2	8.9	7.6	11.4	12.7	16.2	16.5	16.9	16.3	17.8	18.9	16.7	18.5	19.0	21.3	20.5
	0.1	- ◊ -	8.0	9.3	7.6	7.2	5.3	10.6	12.2	14.7	13.4	15.5	17.2	19.5	18.4	15.8	16.4	19.3	21.0	19.6

4.5 Two-dimensional Numerical Simulations of Plenum Window

In order to understand the dynamics of the sound waves when they engaged with the plenum windows, numerical simulations were performed in the present study. The finite-element method and the wave equation solver implemented by the software COMSOL was used. As the three dimensional computation is very demanding on computer resources, two-dimensional simulations with anechoic source and receiver regions were carried out instead under the current resource constraint. The outgoing wave boundary condition was adopted at the boundaries of the computation domain, while all the window surfaces and the walls separating the source and receiver regions were rigid. Since the horizontal cross section of the plenum window is more important in the control of sound propagation, the wave dynamics or transmission mechanisms revealed in the present two-dimensional computation are relevant to the scale model study, though an exact comparison is not possible and it is also not the present purpose.

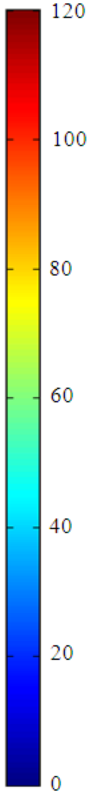
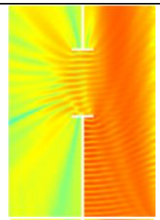
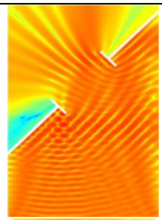
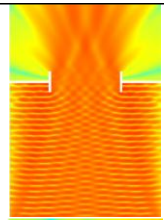
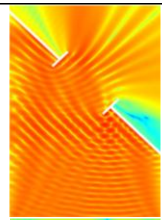
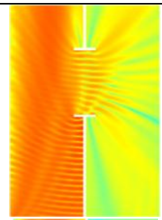
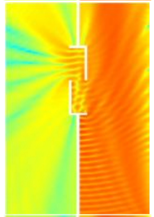
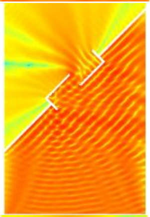
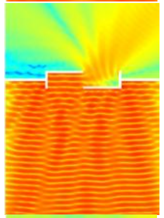
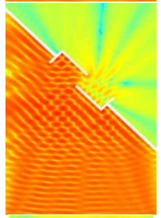
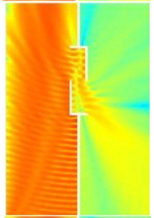
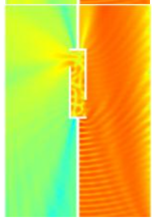
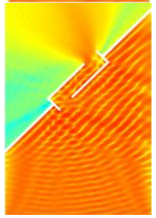
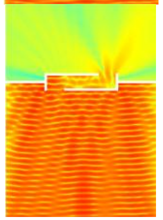
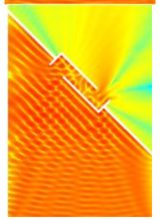
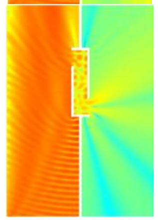
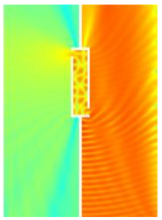
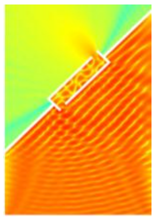
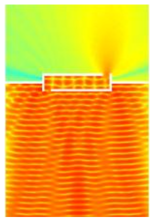
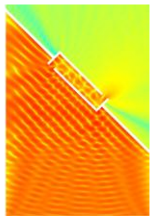
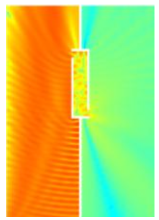
The computations were done on a server with Dual X5650 Xeon Processors (12 cores $\times$ 2.66 GHz) and 192 GB memory space. Meshes with at least six elements over a wavelength were set for all regions to ensure the accuracy of calculations. The total number of elements differed from setting to setting, but was kept not less 790,000 and a further refinement of the meshes did not give rise to noticeable differences in the computed results. Full dimensions of the plenum windows (except the height) were used in the computations.

Table 4.8 shows the wave mechanics across plenum windows with different w/L and θ while d/L = 0.2. The opened window cases are included for comparison. A mono-frequency line source generating a 1 kHz sound is set at the bottom of each sub-figure. The 1 kHz sound is chosen here for detailed discussion as it and the frequencies around it have the most significant contribution to the A-weighted insertion losses (BS EN 1793-3, 1998). The sound propagates upward and interacts with the plenum windows. Strong reflection of sound in the source region can be observed unless θ is closed to ±90°. For the opened window cases, standing wave patterns can be observed, confirming the possibility of longitudinal resonance across the width of the opening.

For the plenum window with w/L = 0.5 facing the normal incident sound (θ = 0°), it can be noticed that standing wave pattern parallel to the window pane is observed on the left half of the window, while another standing wave pattern which is parallel to the window side panels is found on the right half of the plenum window cavity. Sound energy is also transmitted from the left half of the window cavity into the receiver region through diffraction. Owing to such diffraction, the orientation of maximum transmission loss θ_{max} for this window configuration will take a slightly positive value as shown in Figure 4.10. With the same w/L, the wave dynamics at $\theta = +45°$ are very different from those at $\theta = -45°$. For the case of $\theta = -45°$, one can find the standing wave patterns and diffraction similar to those observed at $\theta = 0°$, except that a stronger standing wave is set up across the width of the window. It is likely that a direct sound transmission across the inclined window has also occurred. Much of the sound energy is reflected back into the source region by the left half of the window at $\theta = +45°$. A much weaker standing wave than that found at $\theta = -45°$ is then created inside the right half of the window cavity as the kind of direct transmission observed in the case of $\theta = -45°$ is not possible. A higher sound transmission loss then follows. This is largely in-line with the results shown in Figure 4.10 and Figure 4.13. Similar phenomenon takes place at glazing incidence ($\theta = \pm 90°$). Again direct sound transmission is likely for $\theta = -90°$, resulting in lower insertion loss compared to its $\theta = +90°$ counterpart.

The three rows sound pressure level maps at the bottom of Table 4.8 illustrate the effect of reducing w/L on the wave dynamics. The reduction of w/L from 0.5 to 0.1 does reduce significantly the amount of sound energy that can enter the window cavity. As direct sound transmission is no longer possible under this configuration and the sound intensities reaching the inlets of the windows inclined at $\theta = -45°$ and $\theta = +45°$ are very similar, the difference between the *IL*s with $\theta = -45°$ and $\theta = +45°$ is small. This applies to all other values of θ. This is also in-line with the scale model experimental results shown in Figure 4.13. One can observe that the sound field inside the window cavity is dominated by strong higher acoustic modes at this small w when forced by a 1 kHz sound. The effects of reducing d/L on the wave dynamics are very similar to those of reducing w/L and thus they are not presented.

Table 4.8 Examples of simulated sound pressure level distribution maps.

Window cases	Sound pressure level (dB)	Orientation, θ (degree)				
		-90°	-45°	0°	+45°	+90°
Opened window						
Plenum window *w*/*L* = 0.5 *d*/*L* = 0.2						
Plenum window *w*/*L* = 0.25 *d*/*L* = 0.2						
Plenum window *w*/*L*= 0.1 *d*/*L* = 0.2						

4.6 Summary of Scale Model Experiments

A 1:4 scale down model experiment was conducted in a semi-echoic chamber in the present study to investigate acoustical protection of plenum window in the presence of a line source. The line source that has been adopted in balcony-window experiments (chapter 2) was used in the current investigation. Plenum window with different configurations and sound incident angles were tested. The effect of the orientation of line source relative to the plenum window on the acoustical insertion loss was evaluated. In this experiment, window size of 500 mm (*L*) by 250 mm (high) which corresponded to a window of 2 m by 1 m in full scale size was adopted. The normalized traffic noise spectrum has been applied to estimate the acoustical protection of plenum window in the presence of traffic noise.

There are two types of insertion losses *IL* have been adopted in the present study. The first one is for the case where the building façade orientation is fixed relative to the road traffic. Fully opened window at same orientation with plenum window is used as reference case for the insertion loss estimation. For this situation, the A-weighted insertion loss is the highest when the plenum window is oriented at small angle relative to the line source. As this angle is increased, the insertion loss decreases quickly. Plenum window can be considered at "favourable" propagation condition at negative θ where direct sound wave can propagates into receiver chamber. Faster reduction of insertion loss is observed as orientation angle θ approaches -90° than as θ approaches 90°. When the window opening (*w/L*) became smaller or when the plenum gap width (*d/L*) became narrower, smaller reductions of insertion loss can be obtained when the plenum window orientation angle θ approaches -90°. When plenum window orientation is not in the "favourable" propagation condition, the acoustical insertion loss is not significantly affected by changing the window configurations. The maximum insertion loss recorded in the present study is about 16 dB. The minimum insertion loss is found at the position where the line source is in a direction perpendicular to the plenum window.

Another type of insertion loss *IL* is the case where the building façade orientation relative to the traffic is unrestricted. The reference case for the insertion loss estimation is the fully opened window that parallel to the line source (at $\theta = 0°$). In this case, the estimated insertion loss therefore consists of the effects of the plenum window itself and the source orientation. The maximum traffic noise insertion loss for this case appears when the line source is in a direction perpendicular to the plenum window which is opposite to the previous case. The insertion loss is not much affected by the change in source view at smaller sound incident angles ($|\theta| < 30°$). At larger angles θ, the effects of source view become dominant. About 18 dB insertion loss can be achieved using the studied plenum window configurations. Minimum traffic noise insertion loss recorded is ~ 8 dBA at θ = -45° where the window orientation is in the “favourable” propagation condition. Similar to the previous situation, the insertion loss is much less sensitive to the change in window configuration when the window orientation is not in the “favourable” propagation condition.

From the preliminary scale model investigation, this plenum window shows better acoustic performance compared with the balcony-like device in the previous chapter (chapter 2). The better protections offered by plenum windows warrant their application in densely cities as façade devices. Thus, the rest of this thesis will concentrate on further detail investigations of plenum window.

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CHAPTER 5 ON-SITE FULL SCALE PLENUM WINDOW MEASUREMENT

This chapter describes the investigation of plenum window when it is applied to real condition using on-site full scale device. The setups of the mock-up units will be described first, followed by the configurations and details of tested windows including conventional side-hung window (casement) and plenum window. Then the measurement procedures and tested scenarios will be introduced. On-site traffic spectrum and different approaches of acoustical benefits of plenum window will also be discussed.

5.1 Introduction

From the scale model experiment described in the previous chapter, it is known that plenum windows can provide a significant acoustical protection to the indoor environment. According to the previous scale model tests, a fixed orientation plenum window parallel to the traffic road can offer an insertion loss of more than 10 dBA in the laboratory environment. However, it is believed that the actual acoustical benefits of plenum window can be more representatively studied on-site with the road traffic being the noise source.

In the present study, on-site full scale measurements were conducted close to a heavy traffic road to find out the traffic noise impact to the residents after adopting the plenum windows. A full scale model consisted of two identical modular public housing residential flats built up next to the traffic road. One of these model flats was equipped with two ventilation windows, while the other with conventional windows having side-hung window panes. Noise measurements were carried out simultaneously inside the both flats and at the façades of these model flats. The acoustical benefit of replacing side-hung windows (conventional windows) with plenum windows was investigated.

5.2 Mock-up Units

Full scale on-site tests were adopted in the present study to investigate the noise reduction offered by plenum windows for residential flats. Subject site was located at San Po Kong Flatted Factory area which was planned to be re-developed via a public housing development project of Hong Kong Housing Authority. Two mock-up flats were built next to the Prince Edward Road East, which is a very busy urban traffic road with traffic noise level L_{A10} exceeding 80 dBA in general as shown in Figure 5.1. Mock-up was consisted of two identical side-by-side modular public housing residential flats which were built next to a noisy traffic road for concurrent in-situ test. The study involved two different window designs installed in mock-up flats. One mock-up flat was used as a control case by installing conventional casement windows, while the other mock-up flat was equipped with plenum windows. Mock-up flats were built 3 m away from the road carriageway to ensure the traffic noise was the dominant noise during the measurements. A cavity was also constructed on one side of the flat in order to make the surroundings of the two mock-up flat units identical as shown in the figure 5.2. The test flat façades were parallel to the traffic road and the slabs were raised at 3 m above the ground. At this setting, the mock-up flats were representing the first floor of the public dwelling and all tested windows were facing directly to traffic roads. Figure 5.3 illustrates the condition of mock-up sites. The Prince Edward Road East is shown in Figure 5.4.

Two identical flats were built based on typical layouts of future public housing residential units to stimulate the actual dwelling condition as shown in Figure 5.5. Similar to the future dwelling, mock-up flats were built with a 2.54 m headroom. Walls, floor and ceiling of mock-up units were made of three layers of 20 mm thick plywood and a layer of 12.7 mm thick gypsum board panel with rockwool as the in-fill. The overall sound transmission class of the mock-up walls was around STC 43. Internal partitions of the mock-up dwellings were made of two layers of plywood with rockwool as the in-fill, while indoor surfaces were made of gypsum board. Table 5.1 shows the sound absorption coefficient of rockwool and gypsum board adopted in this study.

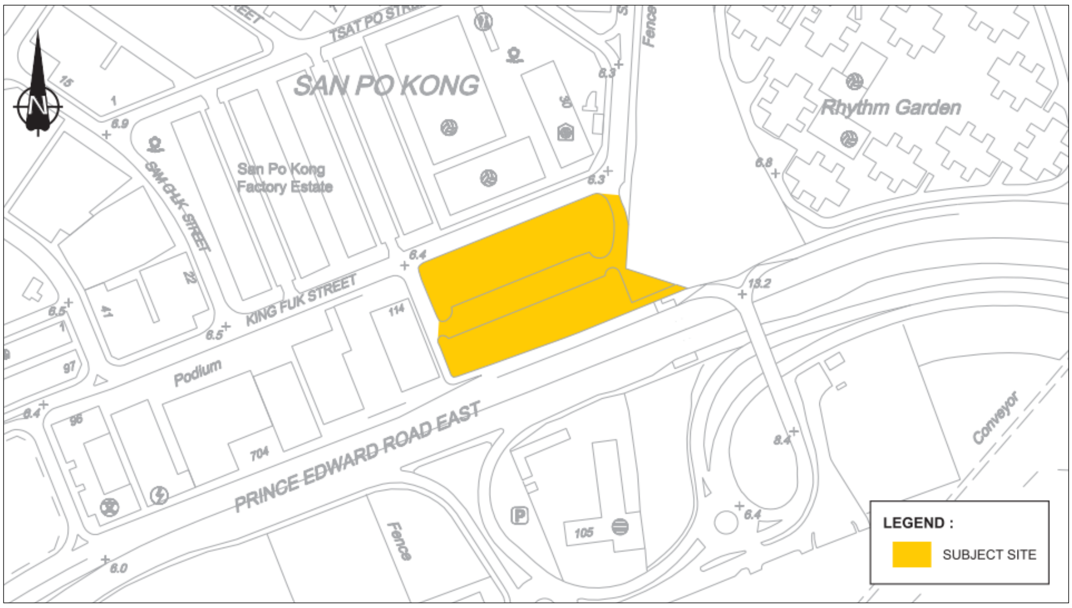


Figure 5.1 Location of subject site.

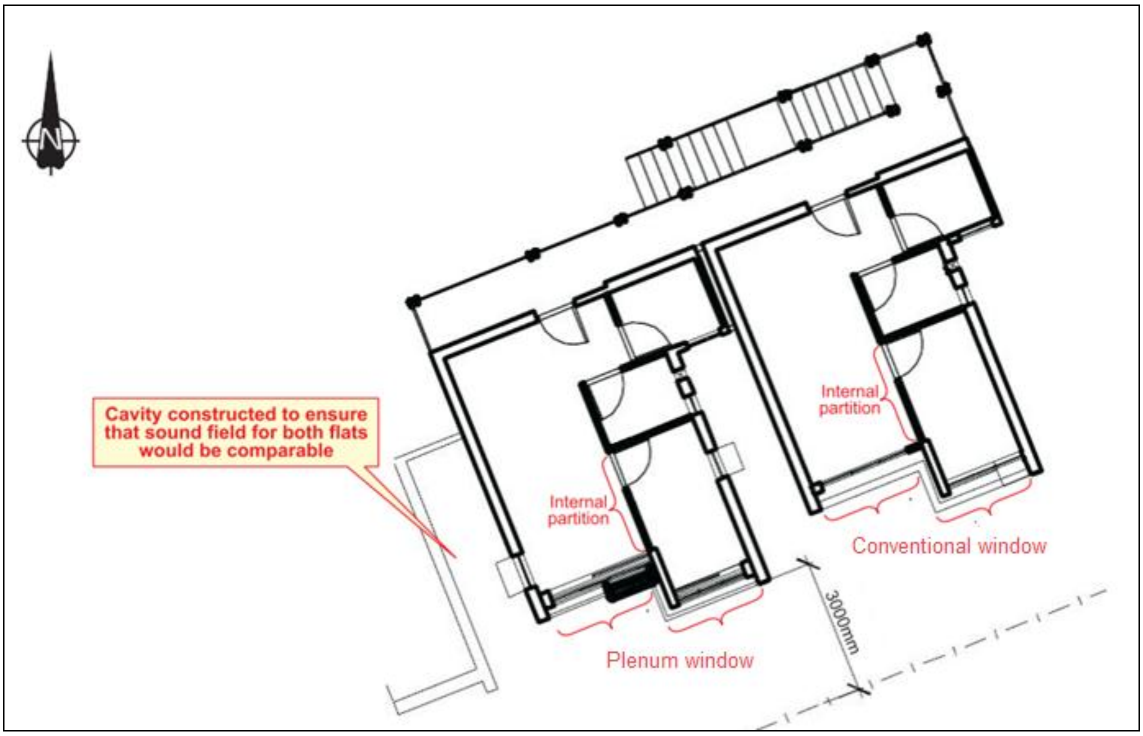


Figure 5.2 Layout of the mock-up flats.

Figure 5.3 View of mock-up flats from outside.

Figure 5.4 Traffic road condition of Prince Edward Road East.

Table 5.1 Mock-up flats material sound absorption coefficients

Material	Octave Band Centre Frequency (Hz)					
	125	250	500	1000	2000	4000
50mm rockwool (density 80kg/m^3)	0.36	0.91	1.19	1.2	1.07	1.05
1/2 inch gypsum board with 2x4 inch studs, spaced 16 inches OC	0.29	0.1	0.05	0.04	0.07	0.09

The living room and bedroom in the typical modular flats were the major investigation spaces for the present study. During the measurement, all windows in the kitchen and bathroom were kept closed. A corridor at the rear side of the mock-up flats was adopted in the present study in order to reduce the possibility of noise intrusion from the rear side of the mock-up units.

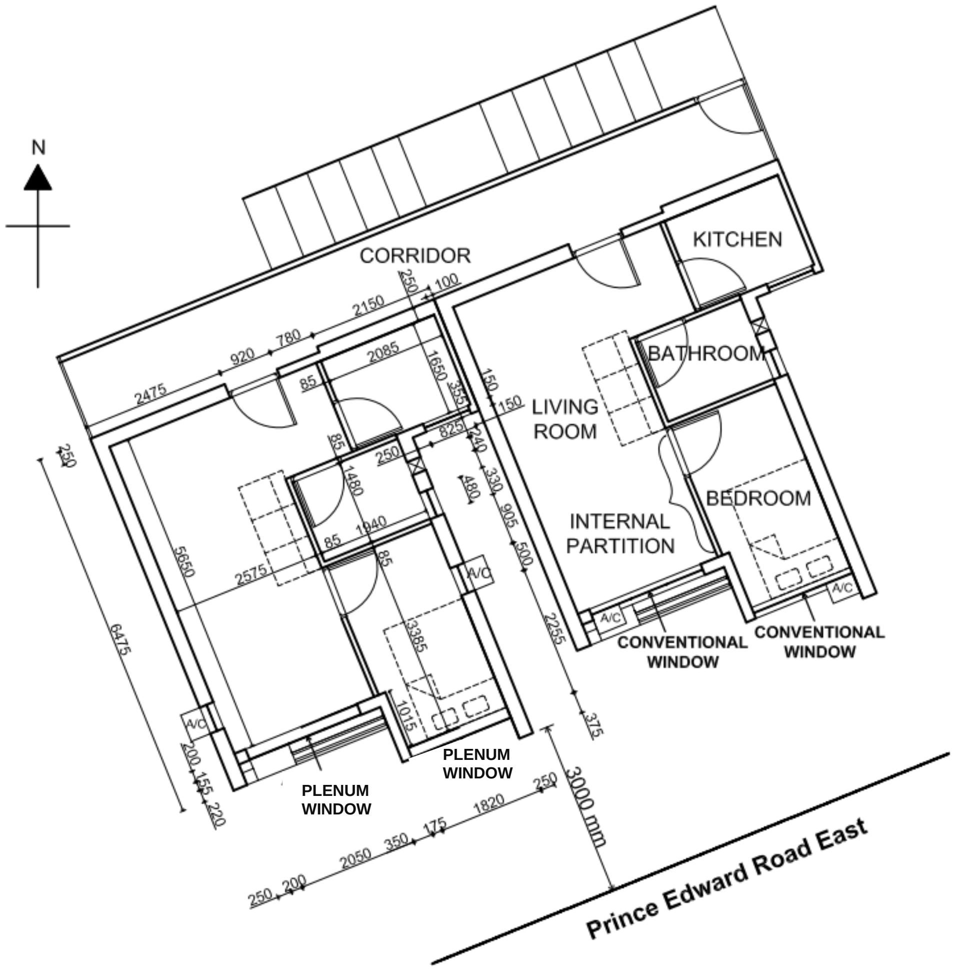


Figure 5.5 Typical layout plan of mock-up dwelling.

5.3 Tested Windows

Two different window systems, conventional and plenum design were tested simultaneously in the present study. Each window system consisted of two sets of windows which were mounted at the façade of living room and bedroom area, respectively. All windows were made of 6 mm thick single glass glazing with aluminium frame. The conventional window system consisted of top-hung, casement and fixed glazed windows. The configuration details and dimensions for this ordinary window are shown in Figure 5.6. The conventional window adopted in this study is commonly used in public flats in Hong Kong. Therefore, this conventional design was used as the base case to estimate the acoustical benefits of the plenum window when it is attached to the dwellings.

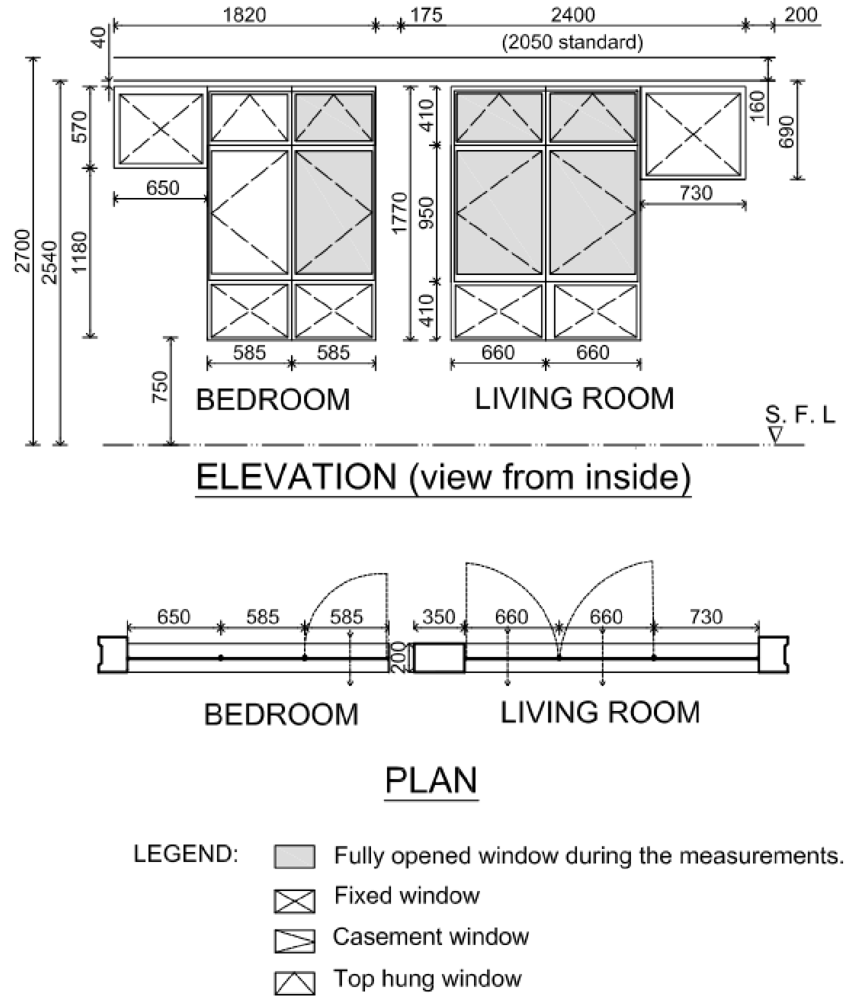


Figure 5.6 Dimensions and details of conventional window system.

In this investigation, the plenum window is composed of two layers of window systems where the outer layer is a combination of casement window and fixed glazed window while the inner layer is a movable sliding glass pane as shown in Figure 5.7. This window design allows either direct opening or offset opening configurations by adjusting the position of the inner layer of the sliding glass pane. The window system was remained in the offset opening condition throughout the test.

In order to fulfil the requirement under the Building Regulations of Hong Kong, window opening sizes were kept at the minimum prescribed values, which is one sixteenth of the space floor area (Buildings Department HKSAR Government, 2005). For conventional window system, all windows in the living room area except fixed glazing were opened while only a casement and a top-hung window in the bedroom were opened during the test. On the other hand, for the plenum window side, two layers of window systems were kept in the offset opening condition during the measurement as shown in Figure 5.7.

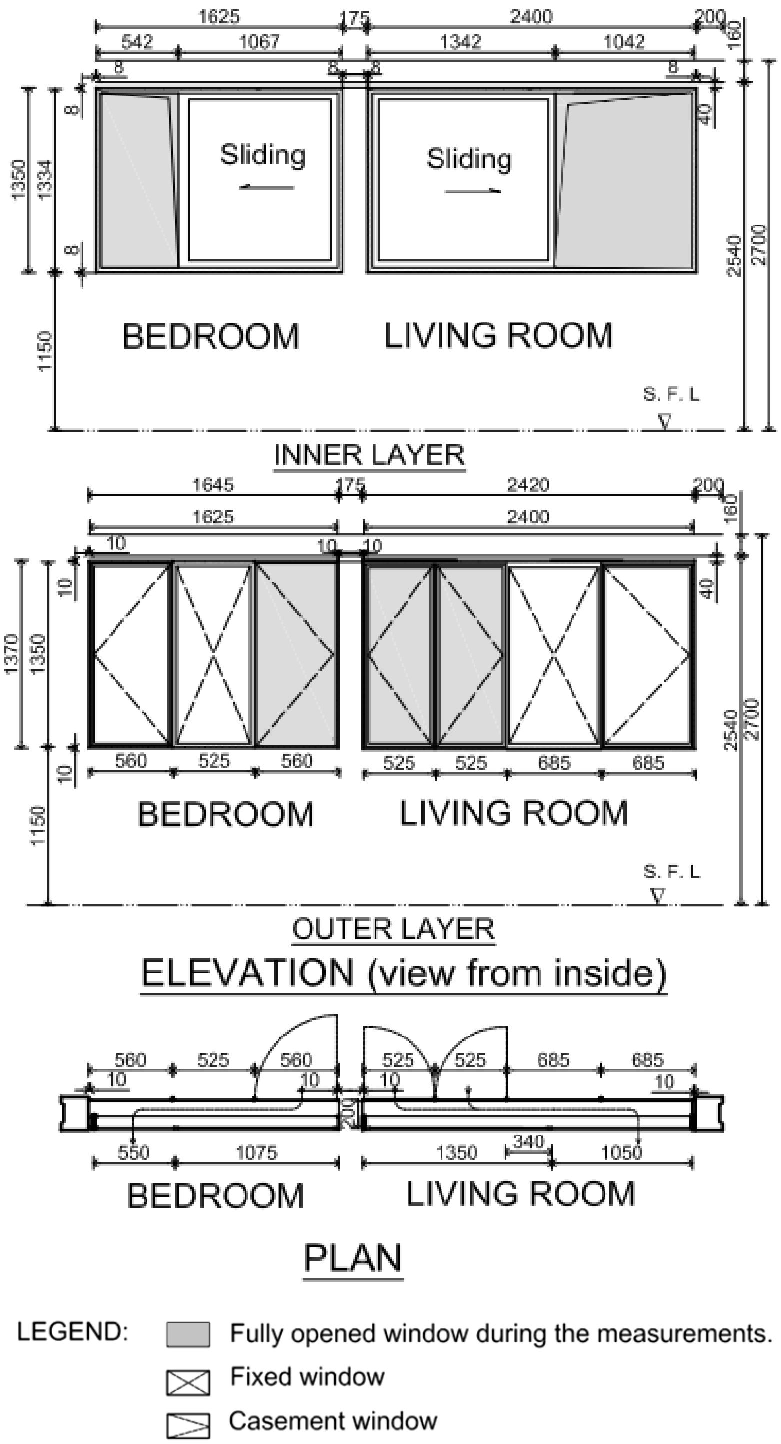


Figure 5.7 Setup and dimensions of plenum window system.

5.4 Measurement Procedure

A total of 34 Brüel & Kjær Type 4935 microphones were used in the present on-site measurements. Figure 5.8 shows the microphone setting and their locations during the measurement. The noise levels inside each test flat were measured by 8 microphones regularly spaced inside the living room and 3 microphones inside the bedroom, but at least at 1 m away from reflecting surfaces. These microphones spanned basically over the entire living volume of the flat. Three microphones were located at 1 m away from the mock-up facade outside each window opening to capture the incident noise levels as well as to provide correction of incident sound intensity differences. All microphones were fixed on slender metal rods as shown in Figure 5.9. Sound pressure levels for all measurement points were recorded simultaneously by the Brüel & Kjær Type 3560D PULSE system.

There was a microphone well below each window sill (E1 for opening at bedroom area and E4 for opening at living area) which captured sound level with façade reflections were used as reference. The difference between the noise levels of the measurement points under the window sills can also provide the necessary corrections. Tests were carried out in normal weekdays (excluding public holiday) during the peak traffic hours. Two periods of time were chosen to assess the noise impact of the façade windows: 08:00 to 10:00 hour in the morning and 18:00 to 20:00. Each test lasted for 30 minutes. All measurements were carried out on non-rainy days with local wind speed not more than 5 m/s. The traffic along the main road was under free-flow condition throughout the measurements.

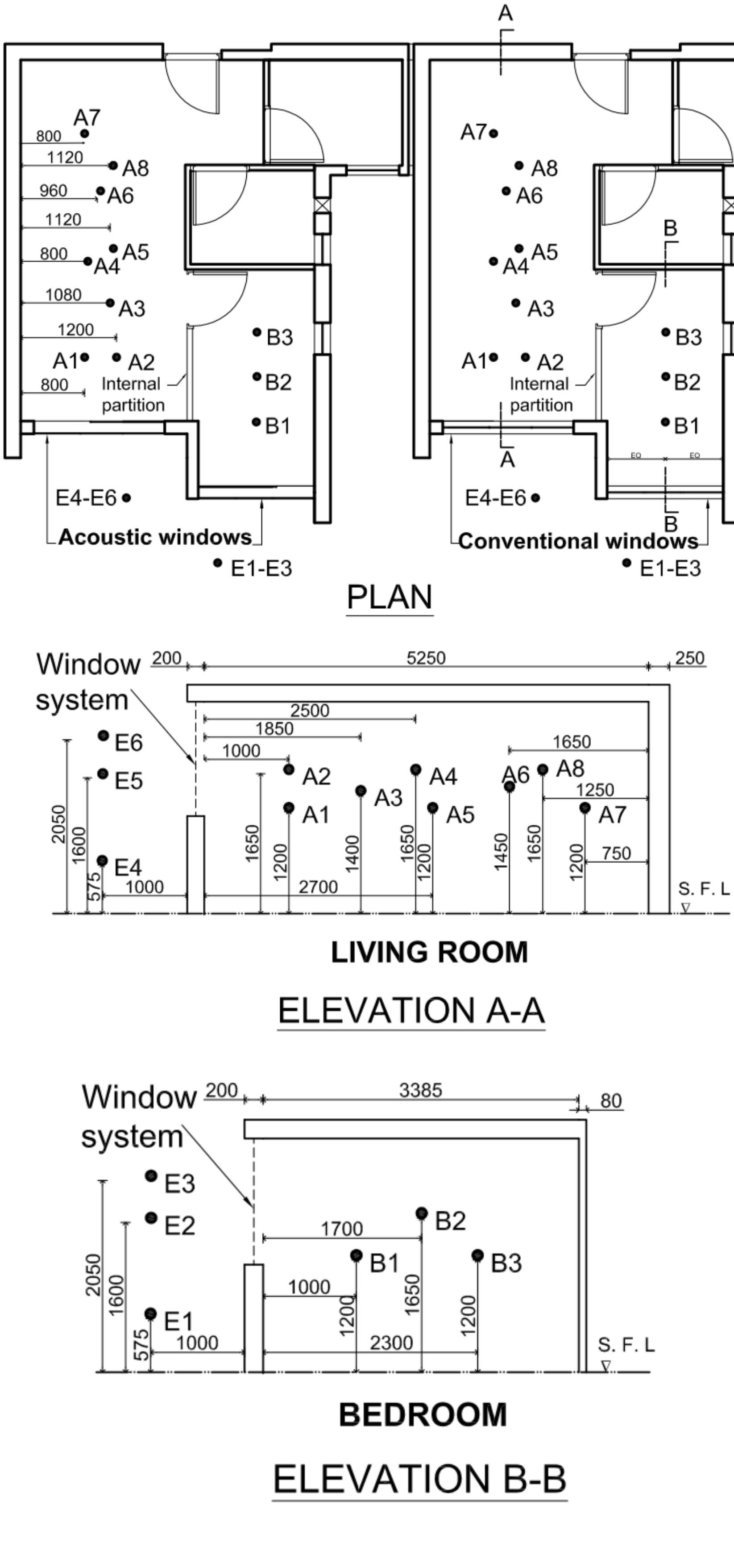


Figure 5.8 Schematic layout of measurement points (dimensions in mm).

Figure 5.9 Microphones setup. (top): Outside façade; (bottom): Indoor area.

5.5 Scenarios Tested

Twelve scenarios were identified to test the in-situ performance of plenum windows as shown in Table 5.2. In order to improve acoustical performances of plenum window, sound absorption materials were put on top and at the mullions of the plenum window cavity. Perforated panels were also used in the present study to cover sound absorptive materials as shown in Figure 5.10. Since the future residents may install their own partition to separate bedroom and living room area, scenarios for both with partition and without partition walls between these two habitable areas were tested. Figure 5.11 shows the test scenarios with and without partition. In order to mimic the real condition of future dwelling, furniture was put in the flats in some test scenarios as shown in Figure 5.12. The furniture included a fabric two-seat sofa and bed with mattress.

Table 5.2 Difference configurations of ventilation window

Type	Scenarios	Descriptions			
		Partition	Furniture	Perforated panels	Rockwool
A	S1	✓			
	S2	✓		✓	
	S3	✓		✓	✓
B	S4			✓	✓
	S5			✓	
	S6				
C	S7		✓		
	S8		✓	✓	
	S9		✓	✓	✓
D	S10	✓	✓	✓	✓
	S11	✓	✓	✓	
	S12	✓	✓		

Figure 5.10 Plenum window with perforated panels.

Figure 5.11 Mock-up units' indoor conditions. (top) With partition; (bottom) Without partition.

Figure 5.12 Flat was equipped with furniture (bed and sofa).

5.6 Reverberation Time

The reverberation times inside both rooms (living room and bedroom) were measured for four different conditions of flats. The reverberation times are important in the later calculation. The tests were carried out in the following situations:

i) Type A: Flat with internal partition separating the bedroom and the living room, and no furniture in the dwelling. Reverberation times were measured in the case of scenario S1 in this room environment.

ii) Type B: Flat without internal partition and no furniture in the dwelling. For this type of room condition, the sound decays of scenario S4 were measured.

iii) Type C: Flat without internal partition but equipped with sofa and bed. Scenario S8 was selected.

iv) Type D: Flat with internal partition between the bedroom and the living room, and equipped with furniture. Reverberation time in scenario S12 represent the reverberation in this type D flat condition.

Measurements were carried out according to ISO 3382 (BS EN ISO 3382-2, 2008) by using Brüel & Kjær Type 4296 omni-directional sound source and the DIRAC system with the MLS signal. Three points were randomly chosen to measure the sound decays of the flat. Two points with 1.6 m and 1.2 m height from the floor were measured in the living room to obtain the average decay time. Since the bedroom size is small, only one point was chosen for measuring the reverberation time. It was located at the center of the bedroom with the height of 1.2 m above the floor. All measurement locations are schematically shown in Figure 5.13. Figure 5.14 gives some site photographs that illustrate the microphone (sound level meter) and the sound source in the bedroom and one of the measurement points in the living room.

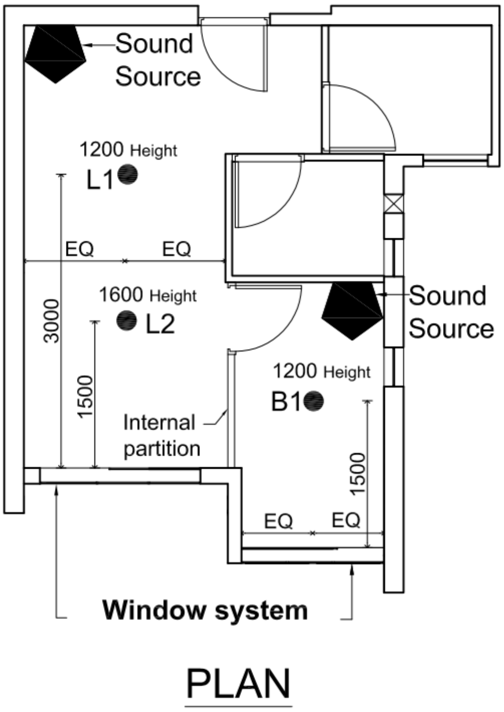
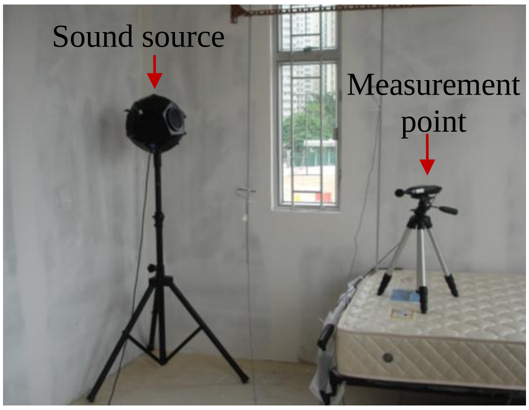


Figure 5.13 Schematic of reverberation time measurement locations.



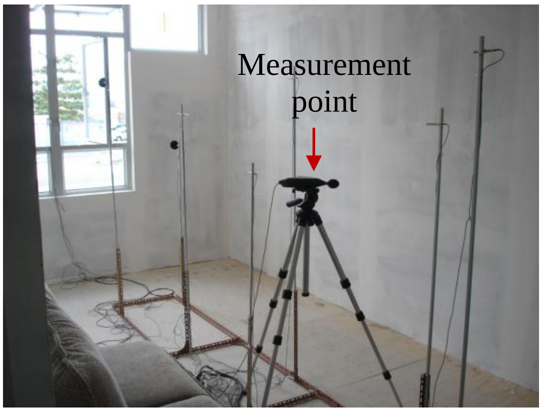


Figure 5.14 Reverberation time measurements. (left) Bedroom; (right) Living room.

Figure 5.15 (a) shows the average reverberation times measured inside the bedroom of both mock-up flats. In general, sound decay inside the bedroom with plenum window is longer than bedroom that equipped with conventional window. This may due to the fact that plenum window allows more sound reflections inside the cavity. One can be noticed that the reverberation time is influenced by the presence of furniture. The differences of sound decay between these two rooms become smaller when bed and mattress (furniture) are introduced into the test rooms. Since the sound absorption inside the test rooms are increased after introduction of furniture, a decrease in the reverberation times can be observed. However, such decrease becomes smaller when internal partitions separating the bedroom and the living room are installed inside the test rooms. The presence of the partitions increase the overall sound absorption of the bedroom surfaces and also reduce the acoustical contribution of the furniture in the test rooms, resulting in small decrease of sound decays.

The average reverberation times measured inside the living room is shown in Figure 5.15 (b). In general, the reverberation times inside living room are higher than bedroom due to the bigger room volume. From the figure, one can be observed that the situation of living room is different from that in the bedroom (refer to Figure 5.15 (a)). For the test room equipped with plenum window, living room with internal partition separating bedroom and living room, and in the absence of furniture obtained higher reverberation time which the opposite situation occurs in the bedroom. When sofa (furniture) is introduced into living room, such increment becomes smaller. For the furnished test rooms without internal partition, the living room reverberation is significantly stronger than that of the bedroom.

For the furnished mock-up flat equipped with conventional side-hung window, sound decays in living room and bedroom are nearly same at frequency higher than the 500 Hz when these two spaces are separated by the internal partition. The reverberation time trends at the lower frequencies of the test rooms in the presence of partition can be observed that affected by the lower order spanwise acoustic modes and these eigen-frequencies are likely to be below 200 Hz. These eigen-frequencies fall out the frequency range of current study when the partition is removed. The absence of internal partition in the unfurnished test room with conventional window enhances the reverberation times in both living room and bedroom.

5.7 Outdoor and Indoor Traffic Noises

In the present investigation, a microphone located outside the façade, right below the bedroom’s window sill of each mock-up unit (points E1 from Figure 5.8) was used as a reference. At these points, microphones were considered directly exposed to traffic road and were not affected by the reflection from the windows and the interiors of mock-up flats. The duration for each measurement was 30 min and sound pressure levels were logged every second during each measurement. For each test case, eight 30-minute measurements, four in the morning and four in the evening, were carried out. Altogether, there are 96 sets of 30-minute measurement data for analysis. Since the data from the four intervals are similar, only data collected within one 30-minute interval were presented in this thesis.

Figure 5.16 shows time variation (second by second) of noise level outside the mock-up flat installed with conventional side-hung windows during morning and evening measurement intervals for all scenarios. From the figure, it can be seen that the traffic was very steady during the whole measurements. The L_{Aeq} for 30 minutes for all the measurements were around 80 dBA.

In the previous laboratory tests of plenum window in CHAPTER 4 , normalized traffic spectrum (BS EN 1793-3, 1998) was adopted to simulate traffic noise effect. In this section (chapter 5), traffic noise spectrum was measured on-site during the measurements. Figure 5.17 illustrates the average normalized traffic noise spectrum measured by the reference microphone in front of the bedroom equipped with side-hung windows (all 96 measurements included). The upper and lower boundaries of the spectrum are also presented. The normalized traffic noise spectrum of BS EN1793-3 is given for the sake of comparison. The traffic noise level (in term of L_{Aeq}) at the façade of the mock-up varied between 78.4 dBA to 80.7 dBA with an average of 79.7 dBA.

Figure 5.18 (a) and (b) illustrate the indoor noise spectra of the bedrooms and the living rooms respectively. Same symbols with different colours are used for the scenarios where the indoor conditions are the same for sake of easy comparison (room conditions of type A, B, C and D as shown in Table 5.2). Sound level inside bedroom of plenum window system’s flat is lower than that inside the conventional window system’s flat except at frequencies between the 125 Hz and 200 Hz one-third octave bands as shown in Figure 5.18 (a). For the side-hung window, transmitted traffic sound levels at frequencies higher than the 200 Hz one-third octave band are reduced when the indoor condition of the flat is changed from type B to type A, type C and type D. With furniture inside the bedroom, the noise level inside bedroom with conventional window is reduced especially between 250 Hz to 315 Hz one-third octave band. Flat installed with plenum window performs better at high frequencies. The frequency variation of the transmitted noise level inside this bedroom area can be separated into two groups: one with furniture and the other without furniture. The noise levels are almost similar for all tested cases at lower frequencies, at 100 Hz and 125 Hz one-third octave bands. The furnished bedroom gives a larger noise reduction at frequency from the 160 Hz to the

2.5 kHz one-third octave band. There are very clear noise level dips at the 315Hz one-third octave band for all tested cases involving the plenum window. These reductions are due to the effect of plenum design, which will be discussed further later.

Figure 5.18(b) shows the transmitted sound pressure levels inside the living room spaces of tested flats. Lower indoor sound pressure level is obtained between the 160 Hz to 1.6 kHz one third octave band when furniture (sofa and bed) are put inside the living space. When the flat is installed with plenum window, the transmitted traffic noise level is reduced. Sound pressure level inside the living space of plenum window flat also drops quickly at the 315 Hz one third octave band, but this reduction is not as sharp as that in the bedroom for the same flat type (Figure 5.18 (a)).

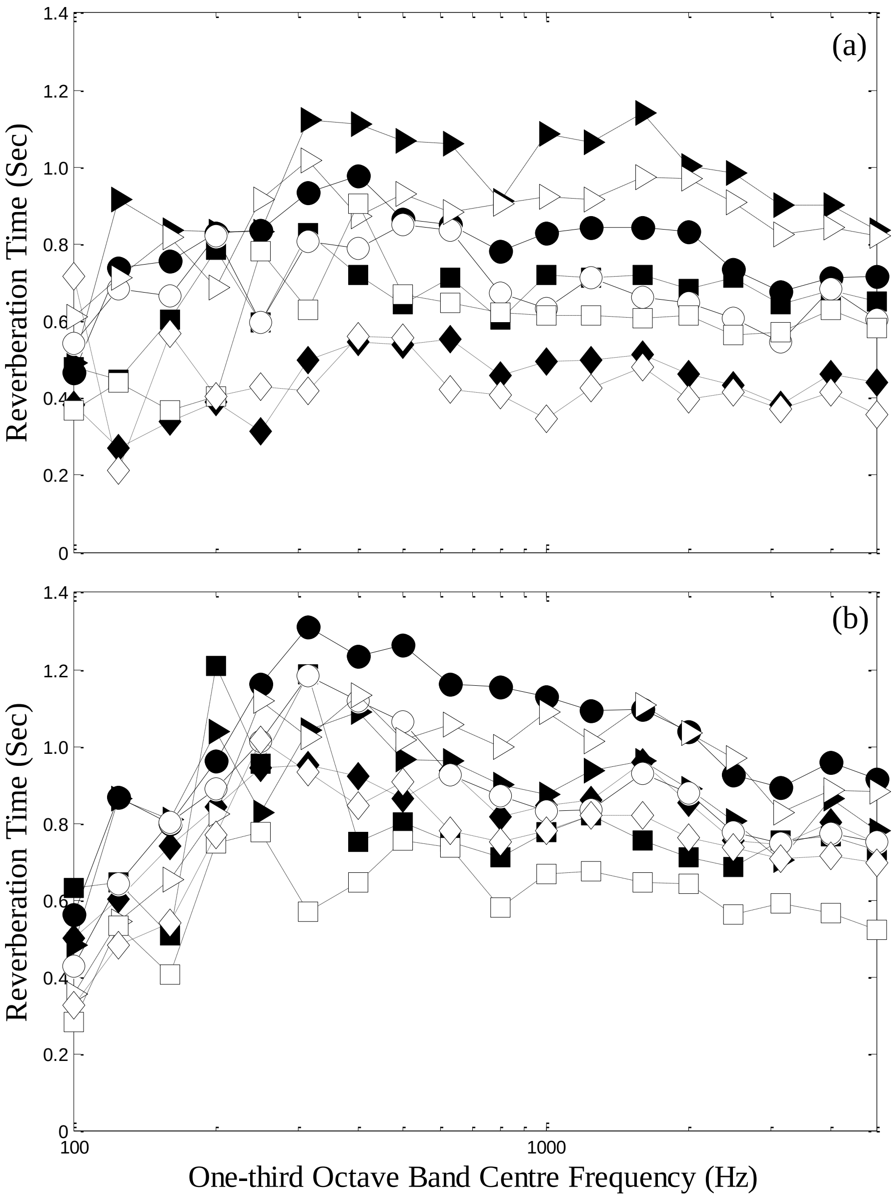


Figure 5.15 Measured average reverberation times of mock-up flats. (a) Bedroom; (b) Living room

● : Scenario S1 (plenum window); ▶ : Scenario S4 (plenum window);
■ : Scenario S8 (plenum window); ♦ : Scenario S12 (plenum window);
○ : Scenario S1 (conventional window); ▷ : Scenario S4 (conventional window);
□ : Scenario S8 (conventional window); ◊ : Scenario S12 (conventional window).

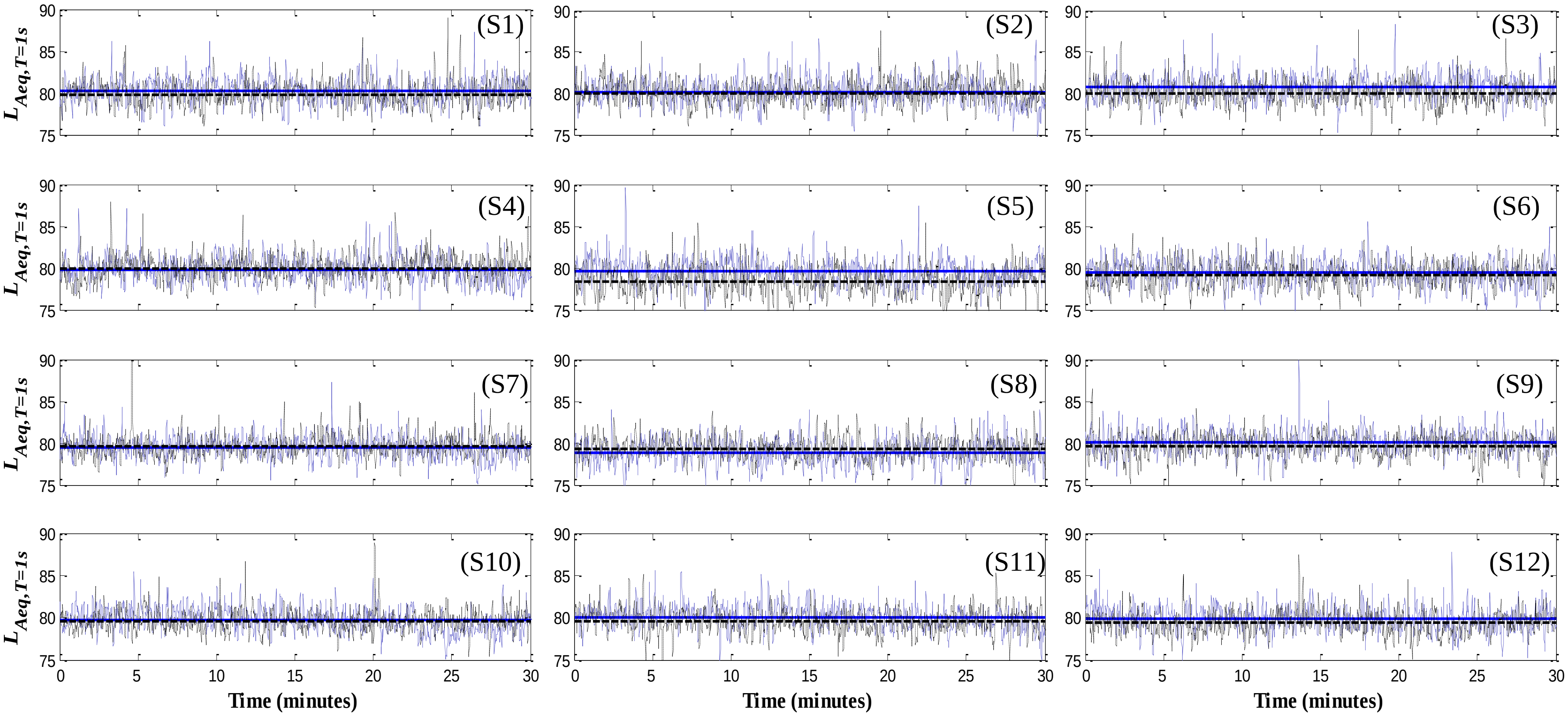


Figure 5.16 Time variations of recorded traffic noise level.

—: Morning $L_{Aeq,T=1\ sec}$; -·-: Evening $L_{Aeq,T=1\ sec}$; —: Morning $L_{Aeq,T=30min}$; ---: Morning $L_{Aeq,T=30min}$

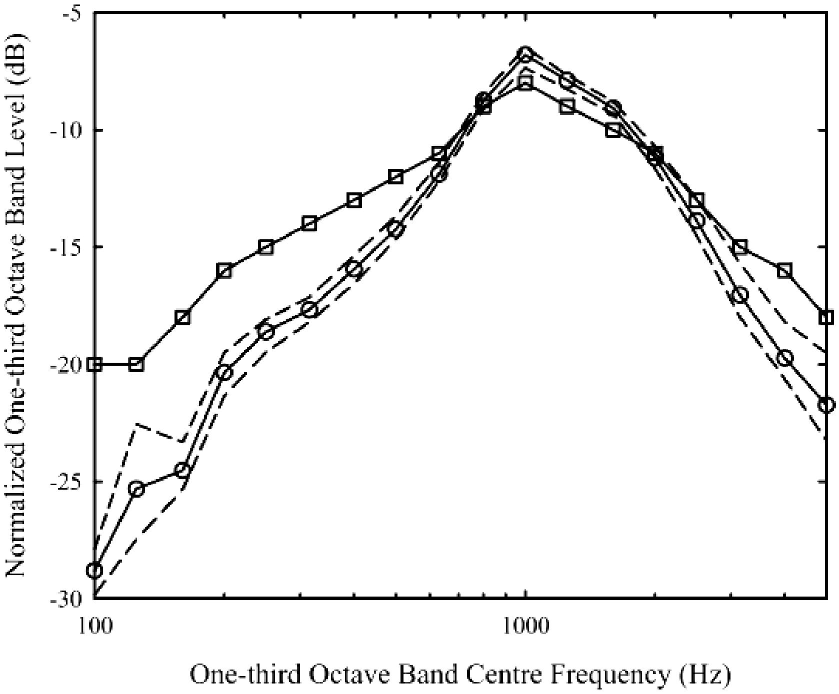


Figure 5.17 Traffic noise spectra at mock-up façade (conventional window).

○: Average normalized spectrum in this study; □: normalized traffic noise spectrum.
– – – – : Upper and lower bounds of normalized spectrum fluctuations.

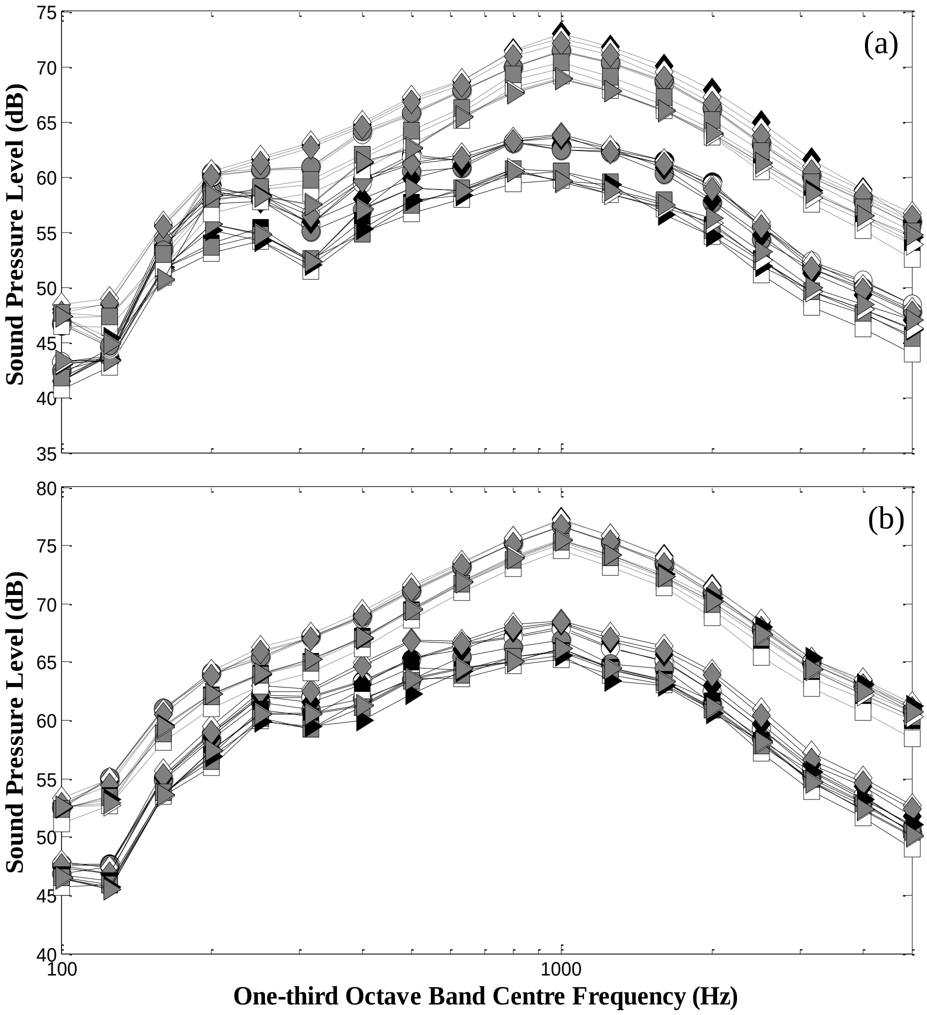


Figure 5.18 Transmitted sound pressure level inside tested flats.(a) Bedroom; (b) Living room.

● : S1; ○ : S2; ● : S3; ◆ : S4; ◇ : S5; ◆ : S6; ■ : S7; □ : S8; ■ : S9;▶ : S10; ▷ : S11; ▶ : S12;—— : Flat equipped with plenum window; · · · : Flat equipped with conventional window.

Figure 5.19 shows the examples of the noise level fluctuation cumulative distributions at the reference points and inside the mock-up units. These distributions actually mainly affected by the furnishing and floor layout of the mock-up unit, so only the results from the morning interval of S1, S6, S7 and S12 are presented. In order to show how the windows are affecting the noise level fluctuation inside the mock-up units, the abscissas that relative to the L_{Aeq}s are adopted. The individual noise level time series of second-by-second are average logarithmically to obtain the corresponding indoor noise time series that used in the current statistical distributions. One can observe from Figure 5.19 that the windows, be they are of the side-hung design or the plenum window design, and the test unit internal layouts, have not practically changed the noise level cumulative distributions during the sound transmission process. The change inside the living room of the test unit installed with the side-hung casement window appears to be the largest. However, the indoor reverberations, at the present strength levels (Figure 5.15), can only at the most reduce the L_{A90} and increase the L_{A10} by ~0.2 dBA, which is insignificant in practice.

Though the noise level cumulative distributions do not tell much about the sound transmission across the side-hung and plenum windows, the noise level probability density distributions (PDF), do reveal some differences in such process across these two types of windows. Figure 5.20 illustrates the probability density distributions (PDFs) corresponding to the cumulative distributions presented in Figure 5.19. It can be observed from the Figure 5.20 that when furniture introduced into test units to reduce the reverberation strength, the indoor PDFs are likely to be flattening out regardless the window design. However, the reverberation strength of test unit with plenum windows is higher than mock-up unit with conventional side-hung windows. For the mock-up unit without internal partition and furniture as shown in Figure 5.20 (b), the probability density distribution of noise level inside the test units equipped with plenum window shows nearly same trends with the reference points. From the Figure 5.20, it can be observed that the PDFs inside the bedrooms of both test units are nearly close to each other. When the indoor reverberation is stronger for a fixed window design and internal room condition, the indoor noise level PDFs are close to the reference signals.

If the indoor space becomes more reverberant, the indoor noise climate (L_{A10} – L_{A90}) is expecting smaller than those at outdoor ones. While the opposite situation may occurs if the indoor unit becomes more ‘dead’. Thus, residential unit with too much absorption may not be desirable in term of aural comfort. It is because the traffic noise index (Scholes, 1970) could be increased due to the anticipated stronger noise level fluctuations through the L_{Aeq} is reduced.

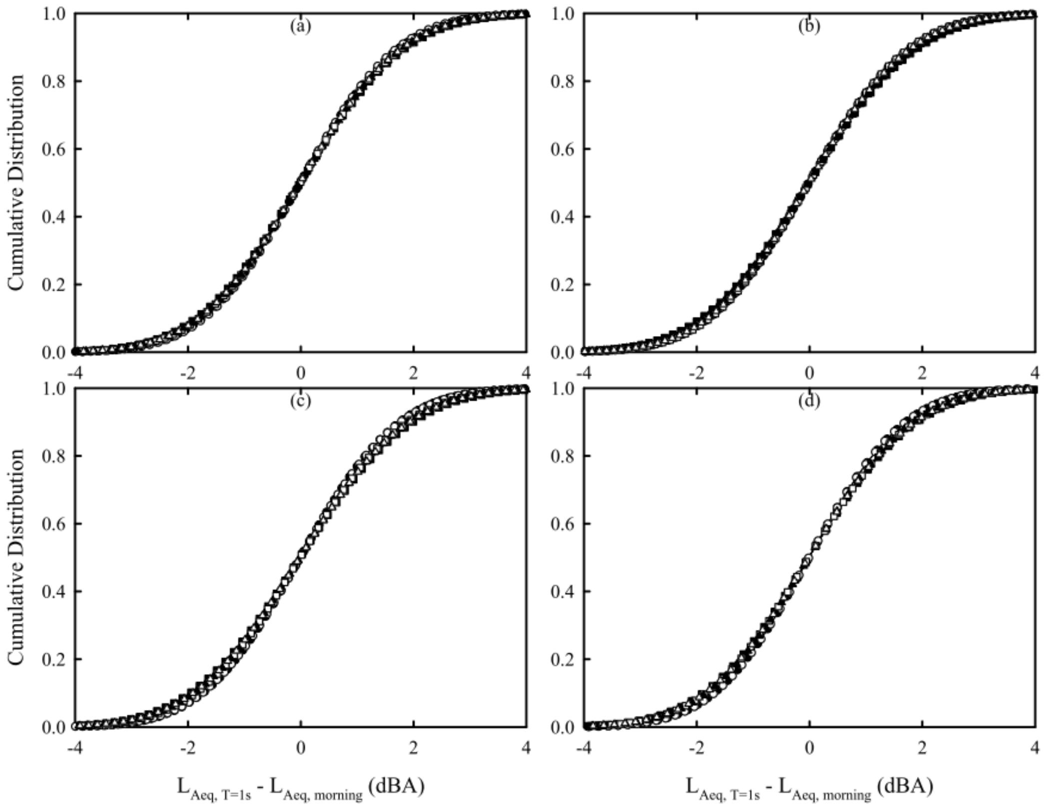


Figure 5.19 Example of cumulative distributions of the noise level ($L_{Aeq, T=1s}$) at the reference points and inside the test units.

(a) S1; (b) S6; (c) S7; (d) S12. ●: Reference points; ■: Living rooms; ▲: Bedrooms; Opened symbol: Unit with plenum windows; Closed symbol: Unit with conventional side-hung windows.

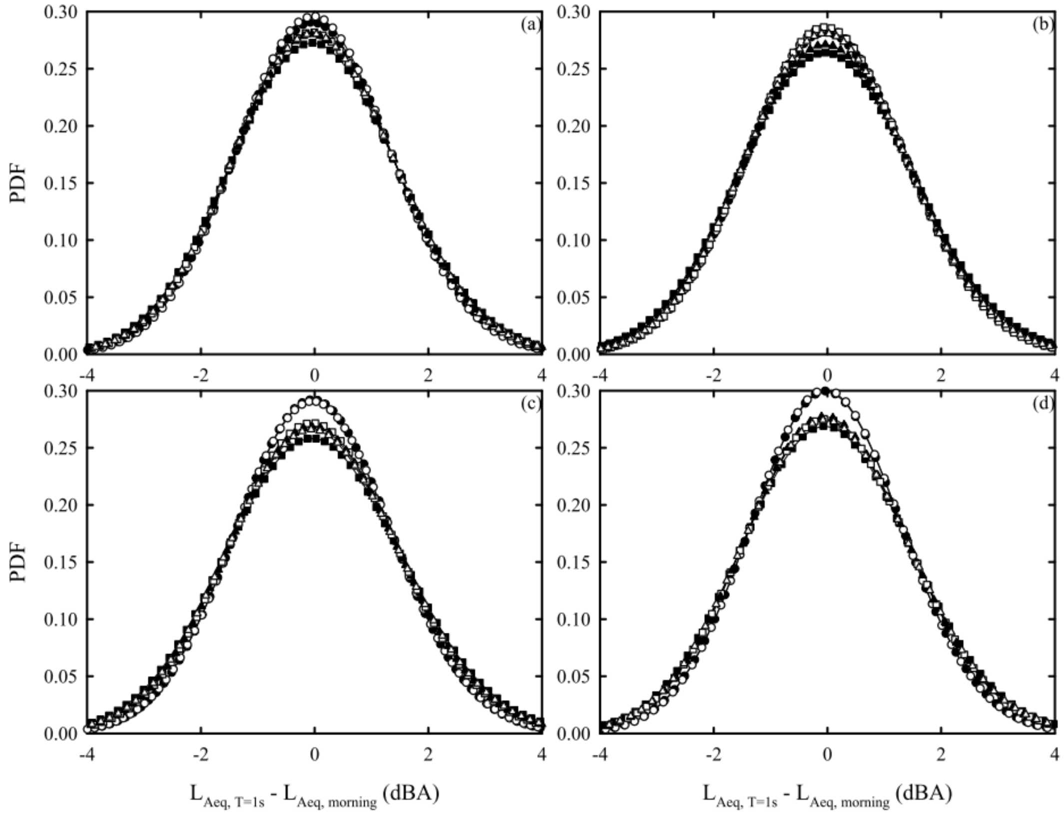


Figure 5.20 Noise level ($L_{Aeq, T=1s}$) probability density at the reference points and inside the mock-up units.

(a) S1; (b) S6; (c) S7; (d) S12. ●: Reference points; ■: Living rooms; ▲: Bedrooms; Opened symbol: Unit with plenum windows; Closed symbol: Unit with conventional side-hung windows.

5.8 Acoustic Benefits of Plenum Window

The acoustical benefit of plenum windows compared to the conventional side-hung casement window system is examined in details in this sub-section. Noise reduction (*NR)*, adopted in Wong et al. (Wong, Yung, Tang, & Tong, 2012) is used in the present estimation. *NR* is defined as the difference in the average A-weighted noise levels between the two tested units, adjusted by the noise level difference recorded at the reference points:

$$NR = (L_{conventional} - L_{conventional,reference}) - (L_{plenum} - L_{plenum,reference}) \qquad \text{Eq. 5.1}$$

where *L*s are the average A-weighted noise levels. The reference points for the living room and the bedroom calculations in the presence of the partitions are E4 and E1 (refer Figure 5.8) respectively. In the absence of the partition, the reference noise levels are obtained by averaging the noise levels at E1 and E4.

The *NR*s based on L_{Aeq} are depicted in

Table 5.10. One can notice that the *NR*s for the cases S2, S5, S8 and S11 are very similar to their corresponding ‘no perforated panel and no rockwool’ cases which are S1, S6, S7 and S12, respectively. While it is not surprising to see that the *NR*s are increased after rockwool is installed inside the plenum windows, the *NR* increase appears smaller if the receiver rooms are more absorptive to sound. Under the current plenum window design, the maximum *NR* achieved is around 8.4 dBA in the absence of the partitions. When the living room and the bedroom are decoupled, the plenum window in the living room gives better acoustical protection. It is probably because of the larger window opening of the corresponding side-hung casement window and the larger sound absorption surface in the plenum window cavity.

The *NR*s are affected by the reverberation inside the test units as well as the reference side-hung casement window design. Thus, it does not reflect truly the sound transmission losses across the plenum windows alone. In order to quantify the acoustical performance of adopting plenum window system on the building façade, noise reduction (R_i), adopted in Tong & Tang (2013) which includes the room constant of indoor spaces due to the change of window size (similar to Eq. 4.1) is used. This mentioned R_i can be defined as:

$$R_i = SPL_{i,Conventional} - SPL_{i,Plenum} - 10\log_{10}\left(\frac{RC_{i,Plenum}}{RC_{i,Conventional}}\right) \qquad \text{Eq. 5.2}$$

where *i* represents the *i*th one-third octave band (from 100 Hz to 5 kHz), *SPL* denotes average sound pressure level inside the tested flats, *RC* the room constant, and the suffices *Conventional* and *Plenum* denote noise level obtained inside flat installed with conventional side-hung window system and flat installed with plenum window system respectively. The same equations of room constant *RC* in Eq. 3.4 and Eq. 3.5 are used.

Figure 5.21 (a) illustrates one-third octave band frequency noise reduction of the tested bedroom. The maximum noise reduction achieved by installing plenum window is around 11dB (S9) when the gap of the window is lined by rockwool and perforated panels together with the furniture inside the bedroom. A relatively fast increase of noise reduction is observed within the 160 Hz to the 315 Hz band and the 500 Hz to the 1 kHz band except for scenarios with type B indoor situation. It is clearly seen that there are two dips which are at the 160 Hz and 500 Hz bands. The dips at 160 Hz one-third octave band is believed to be due to the harmonic longitudinal resonance inside the plenum window (1.075 m) whose frequency is ~ 80Hz. At 500 Hz, the effects become sharper when there are internal partition installed in the flats and no absorption materials lined in the plenum window system. These mentioned cases are referring to the scenarios of S1, S2, S11 and S12. With the same indoor environment, plenum window with rockwool gives better acoustical performance compared to those without treatment inside window system. These additional noise reduction levels which are contributed by the sound absorption materials inside the window can be observed in the frequency bands from 315 Hz to 500 Hz and from1.6 kHz to 3.15 kHz.

The frequency variation of noise reduction inside living spaces of the flats is shown in Figure 5.21 (b). All cases of living room fitted with plenum window show better acoustical performance compared to that equipped with conventional window system. The largest noise reduction level obtained in the living room is about 11 dB in S10. Similar noise level attenuation is observed for all tested cases at frequencies lower than the 250 Hz band. A peak of noise reduction can be observed at the 125 Hz one-third octave band, which is likely to be due to the harmonic resonance of an opened end longitudinal resonance of the plenum window at ~ 63 Hz and then at ~ 127 Hz. Within the frequency band from the 315 Hz to the 500 Hz, the *R* shows three trends of acoustical benefits. For the first one, when the plenum window system is installed at living room in the presence of the partition, putting absorption materials inside the window system enhances the noise reduction levels (S3 and S10). The second trend, when plenum window is placed at living room in the absence of the partition (when the living spaces and bedroom form a combined space), window without any treatment decreases the performance within the above-mentioned frequency range (S5, S6, S7 and S8). The rest of the tested cases can be categorized into the third trend. At the higher frequencies, unfurnished test units with no treatments inside the window system show lowest acoustic protection while the tests units with absorption materials lined inside the window cavity provide higher acoustical benefit. In general, noise attenuation level of the test units do not affected by the perforated panels that installed inside the window cavity.

One-third octave band noise reduction indices in BS EN ISO 16283-1 (2014), the apparent sound reduction index *R'* is also adopted in the current sound transmission analysis. The apparent sound reduction index of the *i*th one-third octave band, R'_i, of the sound transmitting façade can be estimated using the following formula:

$$R_i^{'} = L_{i,incidence} - L_{i,transmitted} + 10\log_{10}\left(\frac{S}{A_i}\right) \qquad \text{Eq. 5.3}$$

where L_i is the *i*th one-third octave band noise level, A_i the sound absorption in m^2 Sabine of the receiver room and *S* the area of the sound transmitting façade. The apparent sound reduction indices in present estimation is used the percentage area occupied by the window relative to the whole façade due to the façade wall's sound reduction indices are very large when compared to those opened windows. These ratios do not affect the frequency characteristic of sound transmission in the analysis because they are constants in the current study.

Another estimation that can be used to describe the noise reduction is the standardized level difference, D_{nT} (BS EN ISO 16283 -1, 2014):

$$D_{nT,i} = L_{i,incidence} - L_{i,transmitted} + 10\log_{10}\left(\frac{T20_i}{0.5}\right), \qquad \text{Eq. 5.4}$$

which define the acoustical benefit in the same way as given in Eq. 5.2. It should be noted that R'_i and $D_{nT,i}$ are numerically different, the acoustical benefits estimated by these two indices are the same as Sabine formula is applied to obtain A_i from $T20_i$. A single noise rating of R_i , R'_i and $D_{nT,i}$ can be obtained by using normalized traffic noise spectrum (BS EN 1793-3, 1998).

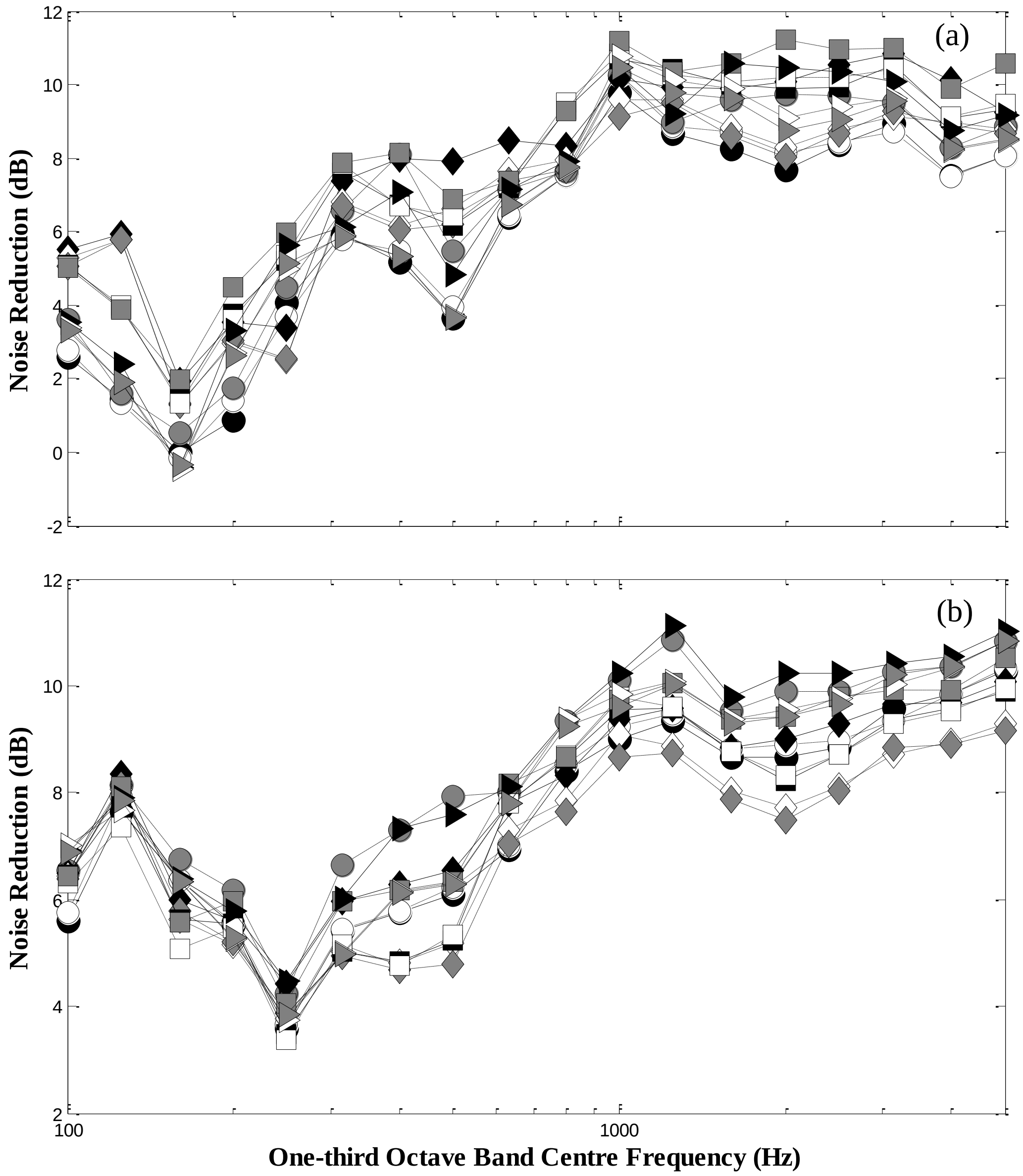


Figure 5.21 One-third octave band noise reduction of tested scenario. (a) Bedroom; (b) Living room.

● : S1; ○ : S2; ● : S3; ♦ : S4; ◊ : S5; ♦ : S6; ■ : S7; □ : S8; ■ : S9; ▶ : S10; ▷ : S11; ▶ : S12;

Figure 5.22 (a) shows the one-third octave band apparent sound reduction index, R'_i obtained in the bedroom. The numerical values of apparent sound reduction index are presented in Table 5.3. One can observe from the figure that sharp peak at the 125 Hz one-third octave band can be found regardless the window design. The high R'_{125Hz} is believed to be due to the low frequency resonance along the length of the bedroom (~ 3.4 m) with high acoustical pressure on the rear wall and high acoustical particle velocity at the window which will take place at ~ 76 Hz and 127 Hz. At frequencies above the 200 Hz one-third octave band, the frequency variations of R'_s are divided into two regions: test units with plenum windows and test units with conventional side-hung window.

For the mock-up units equipped with plenum windows, a relatively high peak can be observed at the 315 Hz one-third octave band. As the mean separation between outdoor and indoor opening of the plenum window in bedroom is 1.08 m (refer to Figure 5.7), a resonance within the window cavity in the spanwise direction is likely, which corresponds to a frequency of 318 Hz. A small peak at the 315 Hz one-third octave band can also be observed in the test room with the conventional side-hung windows. It is believed to be due to the resonance of bedroom window width. Given the width of bedroom side-hung window is 585 mm, resonance along this length will take place at 293 Hz. A dip at 500 Hz one-third octave band for bedroom with plenum windows that occurs in noise reduction, R_i (Figure 5.21) can also be observed in the apparent sound reduction index, R'_i. In general, at frequencies above the 500 Hz one-third octave band, the apparent sound reduction index increases with the frequency and also increases when the plenum cavity is lined with sound absorption materials.

The frequency variations of R'i.in the living room of the test units are presented in Figure 5.22 (b). Table 5.4 shows the numerical values of the apparent sound reduction index in the living spaces. Mock-up units with plenum windows obtained larger sound transmission losses compared to that test units with side-hung casement windows in whole studied frequency range. By comparing the results with the bedroom cases (Figure 5.22 (a)), the absence of high R'_{125Hz} and R'_{315Hz} peaks in the living room confirms that the bedroom acoustic modes are the main reason for the large sound reduction at frequencies of 125 Hz and 315 Hz.

One can observe that there is a small peak at the 200 Hz one-third octave band for all cases in the living room. An acoustic mode along the width of the living room between the bathroom wall and side wall of the mock-up unit at ~ 199 Hz is believed to be one of the reasons of this peak. Besides, a dip at 250 Hz one-third octave band can be found in both the two test rooms. The double-leaves side-hung casement windows that were installed in the living room complicate the sound transmission process. The resonance at ~ 250 Hz probably occurs in front of the window when the two window glass panes are opened. Besides, the resonance due to the separation between the outdoor and indoor opening of the living room window (1.38 m) may also occur. The corresponding resonance frequency is at ~ 249 Hz.

Figure 5.23 shows the one-third octave band apparent sound reduction index, R'_i for the test units without internal partition separating bedroom and living room. One can notice that the peaks and dips from those bedroom (Figure 5.22 (a)) and living room (Figure 5.22 (b)) alone appear in the current cases when both spaces are combined together. After 160 Hz one-third octave band, the trend of test units installed with plenum windows depends on the lining of absorptive materials inside the window cavity. For the mock-up units with conventional side-hung windows, peak at 125 Hz can be observed for the test units equipped with furniture. The reason for this peak is not exactly known.

The one-third octave standardized level differences, $D_{nT,i}$ for bedroom and living room are presented in Figure 5.24. The numerical values of standardized level difference of bedroom and living space are tabulated in Table 5.6 and Table 5.7, respectively. Although the peaks and dips of the current figure are the same as those of the apparent sound reduction index, R'i. (Figure 5.22), the values of the DnT,i are different. For the mock-up units in the absence of internal partition, the frequency variations of DnT,i is shown in Figure 5.25 and the numerical values are tabulated in

Table 5.8. One can observe that the trends of $D_{nT,i}$ for test units without partition across the frequency range are similar to that of the apparent sound reduction index shown in Figure 5.23. Since the basic features of the frequency variations of $D_{nT,i}$ resemble to those of the apparent sound reduction index R'_i., the results in both Figure 5.24 and Figure 5.25 are not discussed in details.

Table 5.9 summarizes the single rating of acoustical performance of test units obtained by using the normalized traffic noise spectrum (BS EN 1793-3, 1998). The suffix *w* in the table denotes that weighting has been applied. Comparison between rated noise reduction, R_i and the noise level difference, *NRs* can indicate how important is the change in space reverberation due to a change in the window design in affecting the acoustical benefit of the device by replacing the conventional side-hung window to the plenum window. One can observe from the table that all values of R_is are higher than the corresponding *NRs.* This may be due to the stronger reverberations and modal excitation in the mock-up units installed with plenum windows, which offer stronger sound fields inside the test rooms. Without the internal partition, the difference between R_is and *NRs* for unfurnished test unit varies between 0.3 and 1.1 dBA. In the presence of partition and without the furniture condition, the difference between R_is and *NRs* reduce to the range from 0.3 to 0.7 dBA. Introduction of furniture to increase the sound absorption of the test rooms makes the values of *NRs* closer to that of R_i (difference is between 0.1 to 0.4 dBA).

For the noise transmission of the facades in term of a single rating, in the absence of internal partition, mock-up facades with plenum windows offer 5.8 to 8.5 dBA higher than those with side-hung casement windows. When partition is introduced into the test units, the difference of noise reduction of the bedroom façades with plenum windows and conventional side-hung windows is between 6.2 to 6.9 dBA while the living room facades with plenum windows offer higher noise reduction of between 7.7 and 8.8 dBA than those with side-hung casement windows.

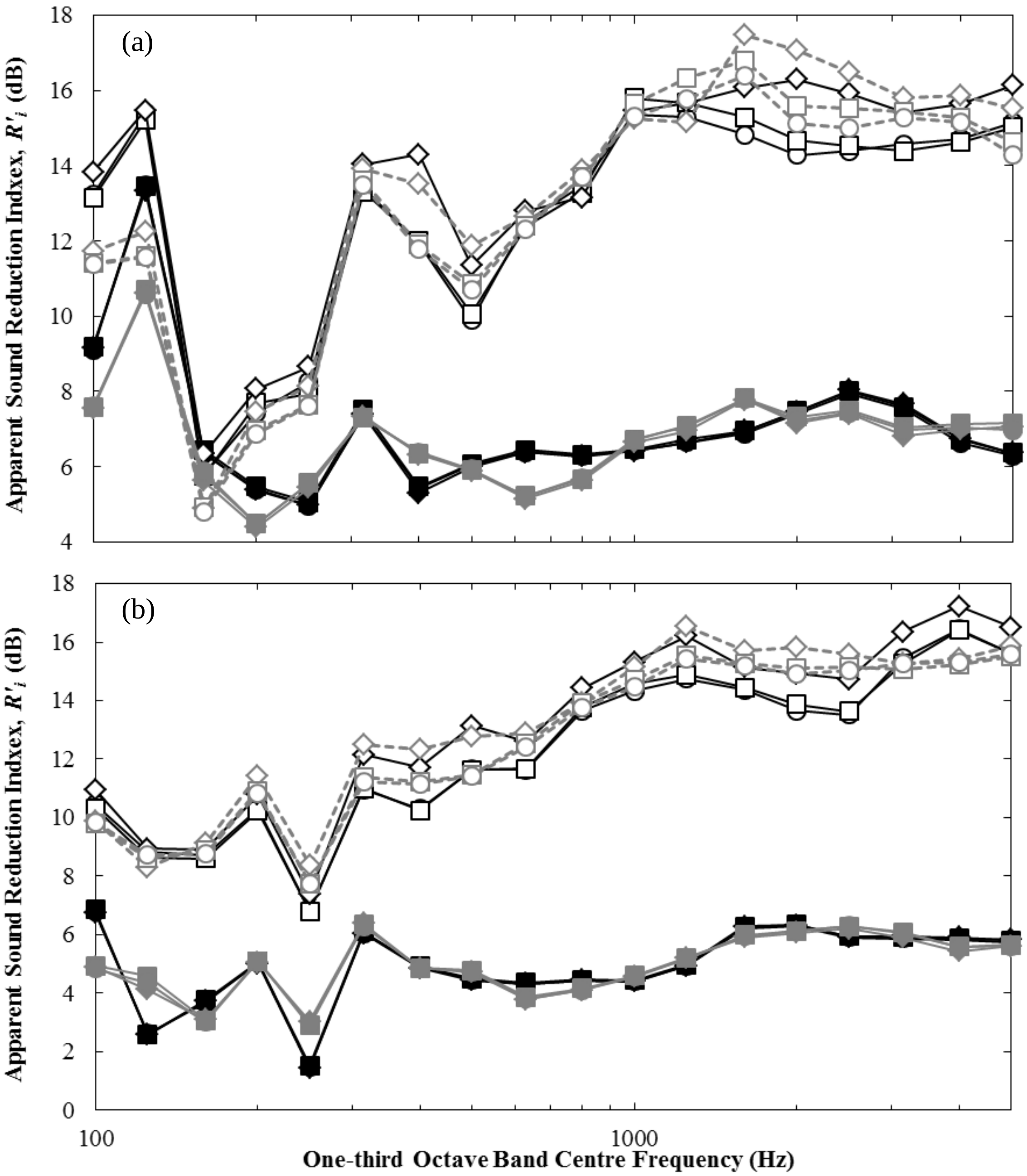


Figure 5.22 One-third octave band apparent sound reduction index, R'_i of mock-up facades. (a) Bedroom; (b) Living room

● : S1 with conventional windows; ○ : S1 with plenum windows; ■ : S2 with conventional windows; □ : S2 with plenum windows; ♦ : S3 with conventional windows; ◊ : S3 with plenum windows; ♦ : S10 with conventional windows; ◊ with - - - line : S10 with plenum windows; ■ : S11 with conventional windows; □ with - - - line: S11 with plenum windows; ● : S12 with conventional windows; ○ with - - - line: S12 with plenum windows.

Table 5.3 Numerical data of one-third octave band apparent sound reduction index of bedroom (Figure 5.22 (a)).

Scenarios	Type of windows	Symbol	One-third octave band apparent sound reduction index, R'_i (dB)																	
			Frequency (Hz)																	
			100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
S1	Conventional	●	9.1	13.5	6.3	5.4	5.0	7.4	5.4	6.0	6.4	6.3	6.4	6.6	6.9	7.4	7.9	7.5	6.6	6.3
	plenum	○	13.2	15.4	5.8	7.4	8.3	13.4	11.9	9.9	12.5	13.5	15.4	15.3	14.8	14.3	14.4	14.6	14.7	15.1
S2	Conventional	■	9.2	13.4	6.4	5.5	5.1	7.5	5.5	6.1	6.4	6.3	6.5	6.7	7.0	7.5	8.0	7.6	6.7	6.4
	Plenum	□	13.1	15.2	5.8	7.7	7.9	13.3	12.0	10.1	12.4	13.3	15.8	15.7	15.3	14.7	14.5	14.4	14.6	15.0
S3	Conventional	♦	9.2	13.3	6.4	5.4	5.0	7.4	5.3	6.0	6.4	6.3	6.4	6.7	7.0	7.5	8.0	7.7	6.8	6.4
	Plenum	◊	13.8	15.5	6.3	8.1	8.7	14.0	14.3	11.3	12.8	13.1	15.5	15.7	16.1	16.3	15.9	15.4	15.6	16.1
S10	Conventional	♦	7.5	10.6	5.6	4.4	5.4	7.3	6.3	5.9	5.2	5.6	6.6	7.0	7.8	7.2	7.4	6.8	7.0	7.1
	Plenum	- ◊ -	11.7	12.3	4.9	7.5	8.1	13.9	13.5	11.9	12.7	13.9	15.3	15.2	17.5	17.1	16.5	15.8	15.9	15.5
S11	Conventional	■	7.6	10.7	5.8	4.5	5.6	7.3	6.4	5.9	5.2	5.7	6.7	7.1	7.8	7.3	7.5	7.0	7.1	7.2
	Plenum	- □ -	11.4	11.6	4.9	7.0	7.7	13.6	11.9	10.8	12.4	13.7	15.7	16.3	16.8	15.6	15.5	15.4	15.3	14.6
S12	Conventional	●	7.6	10.6	5.9	4.5	5.6	7.3	6.4	5.9	5.2	5.7	6.7	7.1	7.8	7.2	7.4	7.0	7.1	7.0
	Plenum	- ○ -	11.4	11.6	4.8	6.9	7.6	13.5	11.8	10.7	12.3	13.7	15.3	15.8	16.4	15.1	15.0	15.3	15.1	14.3

Table 5.4 Numerical data of one-third octave band apparent sound reduction index of living room (Figure 5.22 (b)).

Scenarios	**Type of windows**	**Symbol**	**One-third octave band apparent sound reduction index, R'_i (dB)**																	
			Frequency (Hz)																	
			100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
S1	Conventional	●	6.8	2.6	3.7	5.1	1.5	6.0	4.9	4.5	4.3	4.4	4.4	4.9	6.2	6.3	5.9	5.9	5.8	5.7
	Plenum	○	10.5	8.8	8.7	10.3	6.8	11 0	10.3	1.7	11.6	13.6	14.3	14 7	14 4	13.6	13.5	15.5	16.4	15.6
S2	Conventional	■	6.9	2.6	3.8	5.1	1.5	6.1	4.9	4.5	4.4	4.5	4.4	5.0	6.3	6.3	5.9	5.9	5.9	5.8
	Plenum	□	10.3	8.6	8.6	10.2	6.8	11.0	10.2	11.6	11.7	13.8	14.6	14.9	14.5	13.9	13.6	15.3	16.4	15.6
S3	Conventional	♦	6.8	2.6	3.7	5 0	1.4	6.0	4.9	4.4	4.3	4.4	4.4	4.9	6.3	6.3	5.9	5.9	5.9	5.8
	Plenum	◊	10.9	8.9	8.9	10.8	7.4	12.1	11.7	13.1	12.6	14.4	15.3	16.2	15.1	14.9	14.7	16.3	17.2	16.5
S10	Conventional	♦	4.9	4.1	3.1	5.1	3.0	6.4	4.8	4.7	3.8	4.1	4.6	5.2	5.9	6.1	6.2	5.9	5.4	5.6
	Plenu	- ◊ -	9.9	8.3	9.1	11.4	8.4	12.5	12.3	12.8	12.9	13.9	15.1	16.5	15.7	15.8	15.6	15.3	15.4	15.9
S11	Conventional	■	4.9	4.6	3.1	5.1	2.9	6.3	4.9	4.8	3.9	4.2	4.6	5.2	6.0	6.1	6.3	6.1	5.6	5.6
	Plenum	- □ -	9.8	8.6	8.9	10.9	7.7	11.4	11.2	11.5	12.5	13.9	14.7	15.5	15.3	15.1	15.1	15.1	15.2	15.5
S12	Conventional	●	4.8	4.4	3.0	5.1	3.0	6.3	4.9	4.7	3.8	4.1	4.6	5.2	5.9	6.1	6.3	6.1	5.6	5.6
	Plenum	- ○ -	9.8	8.7	8.8	10.8	7.8	11.2	11.1	11.4	12.4	13.7	14.5	15.4	15.2	14.9	15.0	15.3	15.3	15.6

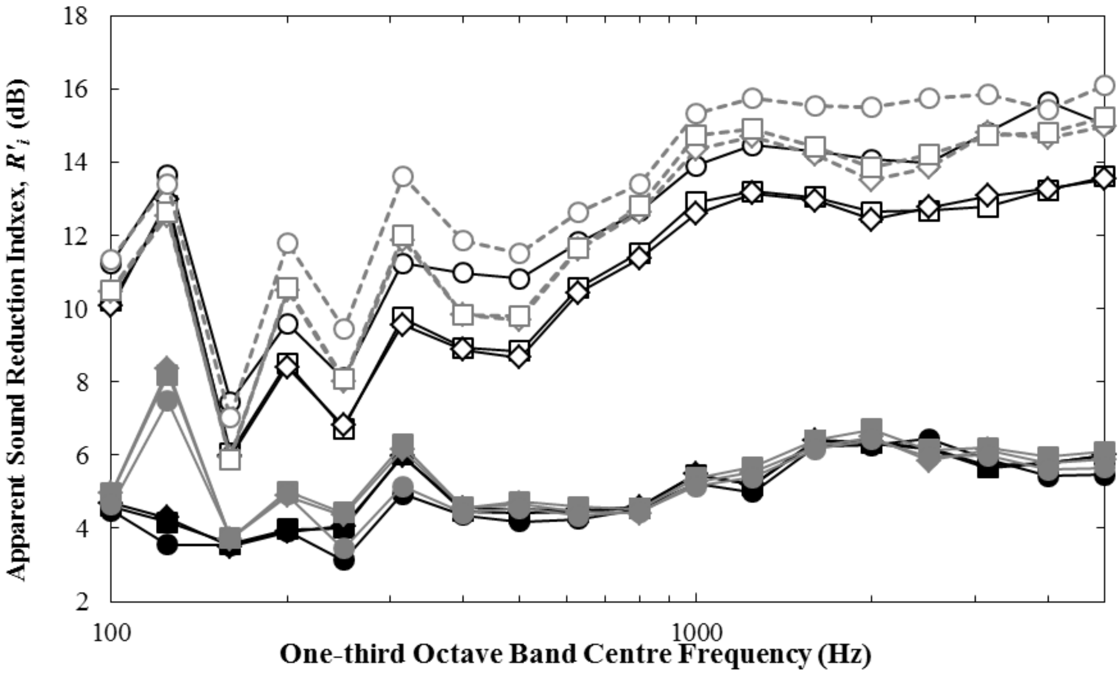


Figure 5.23 One-third octave band apparent sound reduction index, R'_i of mock-up facades for the units without internal partition.

● : S4 with conventional windows; ○ : S4 with plenum windows; ■ : S5 with conventional windows; □ : S5 with plenum windows; ♦ : S6 with conventional windows; ◊ : S6 with plenum windows; ♦ : S7 with conventional windows; ◊ with - - - line : S7 with plenum windows; ■ : S8 with conventional windows; □ with - - - line : S8 with plenum windows; ● : S9 with conventional windows; □ with - - - line : S9 with plenum windows.

Table 5.5 Numerical data of one-third octave band apparent sound reduction index of units without internal partition (Figure 5.23).

Scenarios	**Type of windows**	**Symbol**	**One-third octave band apparent sound reduction index, R'_i (dB)**																	
			Frequency (Hz)																	
			100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
S4	Conventional	●	4.5	3.5	3.5	3.9	3.1	4.9	4.4	4.2	4.3	4.5	5.2	5.0	6.2	6.3	6.4	5.9	5.4	5.5
	Plenum	○	11.2	13.6	7.5	9.6	8.1	11.2	11.0	10.8	11.8	12.7	13.9	14.5	14.3	14.1	1 .0	14.8	15.7	15.0
S5	Conventional	■	4.6	4.2	3.6	4.0	4.0	6.0	4.5	4.4	4.4	4.6	5.5	5.2	6.4	6.3	6.2	5.6	5.8	6.0
	Plenum	□	10.2	12.8	6.1	8.5	6.7	9.8	8.9	8.8	10.6	11.5	12.9	13.2	13.0	12.6	12.7	12.8	13.2	13.6
S6	Conventional	♦	4.7	4.	3.5	3.9	4.1	6.0	4.6	.5	4.5	4.6	5.5	5.2	6.4	6.4	6.2	5.7	5.8	6.0
	Plenum	◊	10.1	13.0	6.0	8.4	6.8	9.6	8.9	8.7	10.4	11.4	12.6	13.2	13.0	12.4	12.8	13.1	13.3	13.5
S7	Conventional	♦	5.0	8.3	3.7	4.9	4.4	6.1	4.6	4.7	4.4	4.4	5.3	5.5	6.2	6.5	5.8	6.1	5.8	5.9
	lenum	- ◊ -	10.4	12.5	5.9	10.5	8.0	11.9	9.8	9.7	11.6	12.6	14.4	14.7	14.2	13.5	13.9	14.8	14.7	15.0
S8	Conventional	■	5.0	8.2	3.7	5.0	4.4	6.3	4.6	4.7	4.6	4.5	5.4	5.7	6.4	6.7	6.2	6.2	6.0	6.1
	Plenum	- □ -	10.5	12.6	5.9	10.6	8.1	12.0	9.8	9.8	11.6	12.8	14.7	4.	14.4	13.9	14.2	14.	14.8	15.2
S9	Conventional	●	4.6	7.5	3.8	4.9	3.5	5.1	4.4	4.5	4.3	4.4	5.1	5.4	6.2	6.4	6.0	6.0	5.6	5.7
	Plenum	- ○ -	11.4	13.4	7.0	11.8	9.5	13.6	11.9	11.5	12.6	13.4	15.3	15.8	15.5	15.5	15.7	15.9	15.5	16.1

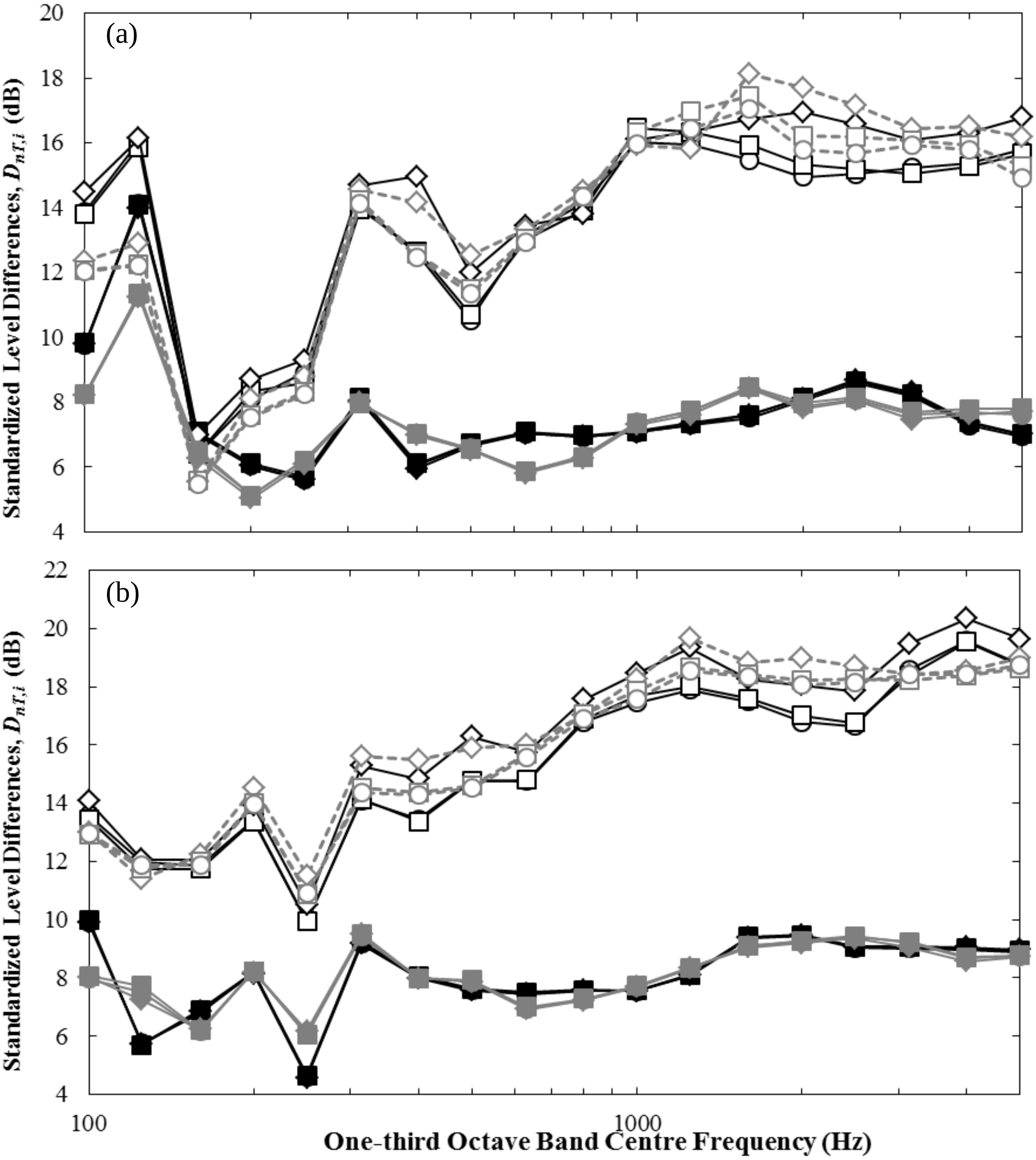


Figure 5.24 One-third octave band standardized level difference, $D_{nT,i}$ of mock-up facades. (a) Bedroom; (b) Living room

● : S1 with conventional windows; ○ : S1 with plenum windows; ■ : S2 with conventional windows; □ : S2 with plenum windows; ♦ : S3 with conventional windows; ◊ : S3 with plenum windows; ♦ : S10 with conventional windows; ◊ with - - - line : S10 with plenum windows; ■ : S11 with conventional windows; □ with - - - line: S11 with plenum windows; ● : S12 with conventional windows; ○ with - - - line: S12 with plenum windows.

Table 5.6 Numerical data of one-third octave band standardized level difference of bedroom (Figure 5.24 (a)).

Scenarios	**Type of windows**	**Symbol**	**One-third octave band standardized level difference, $D_{nT,i}$ (dB)**																	
			Frequency (Hz)																	
			100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
S1	Conventional	●	9.8	14.1	7.0	6.0	5.6	8.0	6.1	6.7	7.0	6.9	7.1	7.3	7.5	8.1	8.6	8.2	7.3	6.9
	Plenum	○	13.9	16.0	6.4	8.1	8.9	14.1	12.6	10.5	13.2	14.1	16.0	15.9	15.5	14.9	15.0	15.2	15.4	15.8
S2	Con entional	■	9.8	14 1	7.1	6.1	5.7	8.2	6.1	6.7	7.1	7.0	7.1	7.4	7.6	8.1	8.7	8.2	7.4	7.0
	Plenum	□	13.8	15.9	6.4	8.4	8.6	14.0	12.7	10.7	13.0	13.9	16.5	16.3	15.9	15.3	15.2	15.0	15.3	15.7
S3	Conventional	♦	9.8	14.0	7.0	6.0	5.6	8.0	6.0	6.6	7.0	6.9	7.1	7.3	7 6	8 1	8.7	8.3	7.4	7.0
	Plenum	◊	14.5	16.1	7.0	8.7	9.3	14.7	15.0	12.0	13.5	13.8	16.1	16.3	16.7	16.9	16.6	16.1	16.3	16.8
S10	Conventional	♦	8.2	11.3	6.3	5.0	6.1	8.0	7.0	6.5	5.8	6.3	7.3	7.6	8.4	7.8	8.1	7.5	7.6	7.7
	Plenum	- ◊ -	12.4	12.9	5.5	8.1	8.8	14.6	14.2	12.5	13.3	14.5	15.9	15.8	18.1	17.7	17.1	16.4	16.5	16.2
S11	Conventional	■	8.2	11.4	6.4	5.1	6.2	8.0	7.0	6.6	5.9	6.3	7.4	7.7	8.5	8.0	8.2	7.7	7.8	7.8
	Plenum	- □ -	12.1	12.3	5.6	7.6	8.3	14.2	12.6	11.5	13.1	14.4	16.3	17.0	17.4	16.2	16.2	16.1	15.9	15.3
S12	onventional	●	8.3	11.2	6.5	5.1	6.2	8.0	7.0	6.6	5.9	6.4	7.4	7.7	8.5	7.9	8.1	7.6	7.7	7.6
	Plenum	- ○ -	12.0	12.2	5.5	7.5	8.3	14.1	12.5	11.4	12.9	14.3	16.0	16.4	17.0	15.8	15.7	15.9	15.8	14.9

Table 5.7 Numerical data of one-third octave band standardized level difference of living room (Figure 5.24 (b)).

Scenarios	**Type of windows**	**Symbol**	**One-third octave band standardized level difference, $D_{nT,i}$ (dB)**																	
			Frequency (Hz)																	
			100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
S1	Conventional	●	9.9	5.7	6.8	8.2	4.6	9.2	8.0	7.6	7.4	7.6	7.5	8.1	9.4	9.4	9.0	9.0	8.9	8.9
	Plenum	○	13.6	12.0	11.8	13.4	9.9	14.1	13.4	14.8	14.8	16.8	17.5	17.9	17.5	16.8	16.7	18.6	19.6	18.8
S2	Conventional	■	10.0	5.7	6.9	8.2	4.7	9.2	8.1	7.6	7.5	7.6	7.6	8.1	9.4	9.5	9.1	9.1	9.0	8.9
	Plenum	□	13.5	11.8	11.7	13.4	9.9	14.1	13.4	14.8	14.8	16.9	17.7	18.0	17.6	17.0	16.8	18.4	19.5	18.7
S3	Conventional	♦	9.9	5.7	6.9	8.2	4.6	9.2	8.0	7.6	7.5	7.6	7.5	8.1	9.4	9.5	9.1	9.1	9.0	9.0
	Plenum	◊	14.1	12.1	12.0	13.9	10.5	15.3	14.8	16.3	15.7	17.6	18.4	19.3	18.3	18.1	17.8	19.5	20.4	19.6
S10	Conventional	♦	8.0	7.2	6.2	8.2	6.2	9.5	8.0	7.9	6.9	7.2	7.7	8.3	9.0	9.2	9.3	9.0	8.6	8.7
	Plenum	- ◊ -	13.0	11.4	12.2	14.5	11.5	15.6	15.5	15.9	16.0	17.0	18.3	19.7	18.8	19.0	18.7	18.4	18.6	19.0
S11	Conventional	■	8.1	7.7	6.2	8.2	6.0	9.5	8.0	7.9	7.0	7.3	7.7	8.3	9.1	9.3	9.4	9.2	8.7	8.8
	Plenum	- □ -	12.9	11.7	12.0	14.0	10.9	14.5	14.3	14.6	15.7	17.1	17.9	18.7	18.4	18.2	18.3	18.2	18.4	18.6
S12	Conventional	●	8.0	7.5	6.1	8.2	6.1	9.4	8.0	7.9	6.9	7.2	7.7	8.3	9.1	9.3	9.4	9.2	8.7	8.7
	Plenum	- ○ -	13.0	11.9	11.9	14.0	10.9	14.4	14.3	14.5	15.6	16.9	17.6	18.5	18.3	18.1	18.2	18.4	18.4	18.7

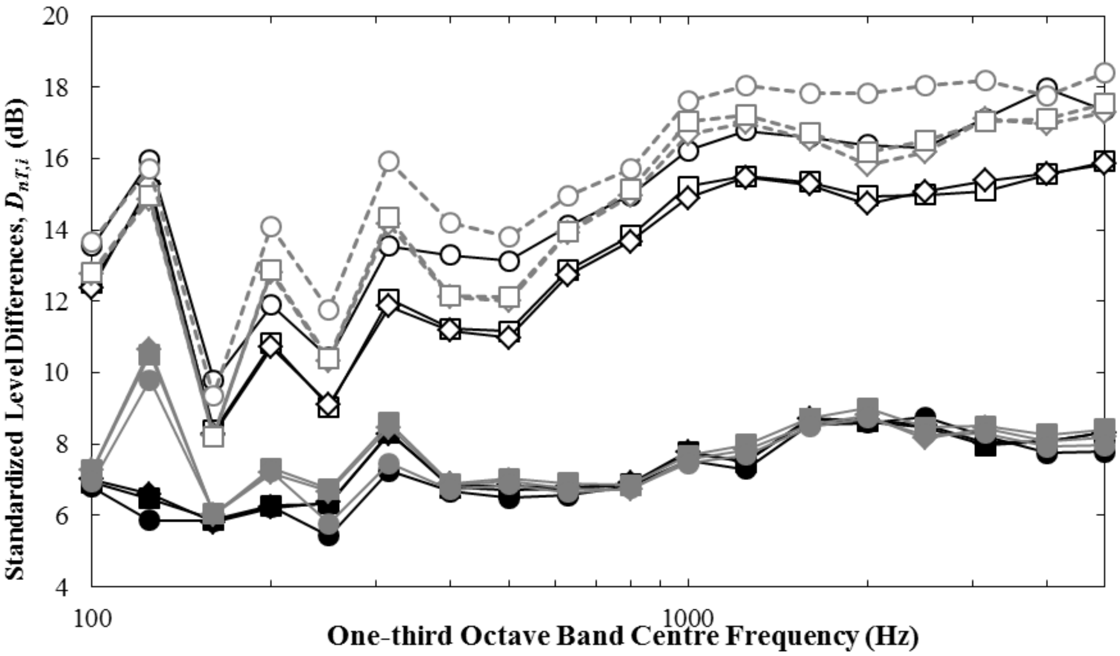


Figure 5.25 One-third octave band standardized level difference, $D_{nT,i}$ of mock-up facades for the units without internal partition.

● : S4 with conventional windows; ○ : S4 with plenum windows; ■ : S5 with conventional windows; □ : S5 with plenum windows; ♦ : S6 with conventional windows; ◊ : S6 with plenum windows; ♦ : S7 with conventional windows; ◊ with - - - line : S7 with plenum windows; ■ : S8 with conventional windows; □ with - - - line : S8 with plenum windows; ● : S9 with conventional windows; □ with - - - line : S9 with plenum windows.

Table 5.8 Numerical data of one-third octave band standardized level difference of units without internal partition (Figure 5.25).

Scenarios	**Type of windows**	**Symbol**	**One-third octave band standardized level difference, $D_{nT,i}$ (dB)**																	
			Frequency (Hz)																	
			100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
S4	Conventional	●	6.8	5.9	5.8	6.2	5.4	7.2	6.7	6.5	6.6	6.8	7.5	7.3	8.5	8.6	8.8	8.2	7.7	7.8
	Plenum	○	13.6	16.0	9.8	11.9	10.4	13.6	13.3	13.1	14.1	15.0	16.2	16.8	16.6	16.4	16.3	17.1	18.0	17.4
S5	Conventional	■	6.9	6.5	5.9	6.3	6.3	8.3	6.8	6.7	6.8	6.9	7.8	7.5	8.7	8.6	8.5	8.0	8.1	8.3
	Plenum	□	12.5	15.1	8.4	10.8	9.0	12.1	11.2	11.2	12.9	13.8	15.2	15.5	15.4	15.0	15.0	15.1	15.6	15.9
S6	Conventional	♦	7.0	6.6	5.8	6.2	6.4	8.3	6.9	6.8	6.8	6.9	7.8	7.5	8.7	8.7	8.5	8.0	8.1	8.3
	Plenum	◊	12.4	15.3	8.3	10.7	9.1	11.9	11.2	11.0	12.7	13.7	14.9	15.5	15.3	14.7	15.1	15.4	15.6	15.8
S7	Conventional	♦	7.3	10.7	6.0	7.2	6.7	8.5	6.9	7.0	6.8	6.7	7.6	7.8	8.6	8.8	8.2	8.5	8.1	8.2
	Plenum	- ◊ -	12.8	14.9	8.2	12.8	10.3	14.2	12.1	12.0	13.9	15.0	16.7	17.0	16.5	15.8	16.2	17.1	17.0	17.3
S8	Conventional	■	7.3	10.5	6.0	7.3	6.7	8.6	6.9	7.0	6.9	6.8	7.7	8.0	8.7	9.0	8.5	8.5	8.3	8.4
	Plenum	- □ -	12.8	15.0	8.2	12.9	10.4	14.3	12.2	12.1	14.0	15.1	17.1	17.2	16.7	16.2	16.5	17.0	17.1	17.5
S9	Conventional	●	6.9	9.8	6.1	7.2	5.8	7.5	6.7	6.9	6.6	6.8	.5	7.7	8.5	8.7	8.3	8.3	7.9	8.0
	Plenum	- ○ -	13.7	15.7	9.3	14.1	11.8	15.9	14.2	13.8	15.0	15.7	17.6	18.1	17.8	17.8	18.1	18.2	17.8	18.4

Table 5.9 Acoustical performance of mock-up units

Scenario	Acoustical Performance (dBA)																	
	$D_{nT,w}$						$R'w$						R_w			NR		
	Bedroom		Living room		Overall		Bedroom		Living room		Overall		Bedroom	Living room	Overall	Bedroom	Living room	Overall
	Side-hung	Plenum	Side-hung	Plenum	Side-hung	Plenum	Side-hung	Plenum	Side-hung	Plenum	Side-hung	Plenum	Plenum	Plenum	Plenum	Plenum	Plenum	Plenum
S1	7.2	13.4	8.0	15.7			6.6	12.8	4.8	12.5			6.4	7.7		6.1	7.1	
S2	7.3	13.5	8.0	15.7			6.6	12.9	4.9	12.6			6.6	7.8		6.2	7.2	
S3	7.2	14.1	8.0	16.6			6.6	13.5	4.8	13.5			7.4	8.8		6.7	8.2	
S4					7.3	14.8					5.0	12.5			8.2			7.9
S5					7.5	13.4					5.2	11.1			7.3			6.4
S6					7.5	13.3					5.2	11.0			7.2			6.1
S7					7.6	14.6					5.3	12.3			7.9			6.9
S8					7.7	14.7					5.4	12.4			8.0			7.0
S9					7.4	15.9					5.1	13.6			8.5			8.4
S10	7.1	14.0	8.0	16.8			6.5	13.3	4.9	13.7			7.6	8.8		7.3	8.5	
S11	7.2	13.6	8.0	16.3			6.5	12.8	4.9	13.1			7.1	8.2		6.9	8.1	
S12	7.2	13.5	8.0	16.2			6.5	12.8	4.9	13.0			7.0	8.2		6.6	8.0	

Insertion loss in term of a single rating has been used to describe the acoustical properties of frequency-sensitive acoustical devices (Buratti, 2002, 2006). In this section, two different definitions of insertion losses are adopted. The first one is the insertion loss (IL_A) which is obtained from the differences of band noise levels inside the flat after replacing a conventional side-hung window by a plenum window. A single rating of insertion loss (IL_A) of plenum window when exposed to traffic noise can be defined as followed expression.

$$IL_A(dBA) = 10\log_{10}\left(\sum_{i=1}^{18} 10^{0.1(SPL_{i,Conventional})} \Big/ \sum_{i=1}^{18} 10^{0.1(SPL_{i,Plenum})}\right) \qquad \text{Eq. 5.5}$$

The insertion loss same as Eq. 3.3 also adopted in the present investigation. This insertion loss (IL) is the difference of indoor sound levels before and after installation of plenum window which include the effects of reverberation strength variation inside the flats and normalized traffic noise spectrum of the standard EN 1793-3 (BS EN 1793-3, 1998).

Table 5.10 summarizes the IL_A and IL. It can be observed that both estimated IL_A and IL are very similar. The largest difference between two estimations is only ~ 0.2 dBA. The standard error of the estimation for two sets of insertion losses are 0.07 dBA and 0.09 dBA for the bedroom and living room, respectively. Mean of insertion losses for every second are also estimated. The results are compared with those calculated using averages over 30 minutes. The standard error of insertion loss using Eq. 5.5 for estimation second by second and average 30 minutes is 0.07 dBA and 0.09 dBA, respectively. Two sets data of IL for estimation by every second and average over 30 minutes give the standard error of 0.09 dBA for bedroom area and 0.06 dBA for living room. Thus, the insertion loss estimation either using $L_{eq,30\ minutes}$ or mean of $L_{eq,1\ second}$ are almost the same.

The IL_A and IL results shown in

Table 5.10 suggested that the acoustic treatments inside the plenum window systems increase the performance of the window compared to the conventional one with a maximum insertion loss of about 9 dBA for bedroom (S9) and living room (S3 and S10). A new unfurnished flat with installation of plenum window without any treatment on window system (S6) can achieve an insertion loss of about 7 dBA. Putting acoustic treatment into window system provides an additional benefit about 1 dBA (S4). When the residents install a partition of inside their new dwelling with no treatments inside the plenum window system, the insertion loss in the space of living room is increased, but that of the bedroom area decreased. Yet, the differences are small. When furniture is moved inside the new dwelling, corresponded to scenario S7, additional insertion losses of about 0.5 dBA to 1 dBA may be obtained due to the sound absorption of the furniture. Installation of internal wall between the two spaces in furnished mock-up flat in generally reduces the noise levels inside living room area, but increase noise levels inside bedroom area except for the flat installed with plenum window with sound absorption materials.

5.9 Summary of On-site Full Scale Measurements

A full-scale on-site investigation on the acoustical insertion loss of plenum window for use on future public residential flat facade was carried out. A pair of mock-up flats with different window systems, conventional side-hung casement window system and acoustic design window system was built next to noisy urban road. Each window system consisted of two sets of windows which were installed at the facade of living room and bedroom area. Different combination of room layouts and window systems were tested for both flats to simulate the real situation of future residential dwellings. Original layout of public flat was consists of an open space which connected living area and bedroom. An internal wall was constructed in consideration of future residents may be partitioned the bedroom and living area. The possible interaction between the room volume and the windows were discussed. Besides, the acoustical benefit of replacing conventional side-hung windows with the acoustic design window (plenum window) was also estimated.

Table 5.10 Different room conditions and insertion losses of tested scenarios.

Type	Scenario	Partition	Furniture	Perforated panels	Rockwool	Noise Reduction, *NR*(dBA)			IL_A (dBA)		IL(dBA)		Mean $IL_{A,30\text{mins}}$ * (dBA)		Mean $IL_{,30\text{mins}}$ * (dBA)	
						Bedroom	Living Room	Overall	Bedroom	Living Room	Bedroom	Living Room	Bedroom	Living Room	Bedroom	Living Room
	S1	✓				6.1	7.1		6.4	7.7	6.4	7.6	6.4	7.6	6.3	7.6
A	**S2**	✓		✓		6.2	7.2		6.6	7.8	6.7	7.8	6.6	7.7	6.5	7.7
	S3	✓		✓	✓	6.7	8.2		7.4	8.8	7.3	8.8	7.2	8.7	7.3	8.7
	S4			✓	✓			7.9	8.3	8.1	8.4	7.9	8.3	7.9	8.2	8.0
B	**S5**			✓				6.4	7.4	7.3	7.5	7.1	7.4	7.1	7.3	7.2
	S6							6.1	7.2	7.1	7.2	6.9	7.2	6.9	7.2	7.0
	S7		✓					6.9	8.2	7.6	8.1	7.7	8.0	7.7	7.8	7.7
C	**S8**		✓	✓				7.0	8.3	7.6	8.2	7.8	8.2	7.8	7.9	7.8
	S9		✓	✓	✓			8.4	8.7	8.2	8.6	8.3	8.5	8.3	8.4	8.4
	S10	✓	✓	✓	✓	7.3	8.5		7.6	8.8	7.6	8.9	7.5	8.9	7.5	8.9
D	**S11**	✓	✓	✓		6.9	8.1		7.1	8.2	7.2	8.3	7.1	8.3	6.9	8.3
	S12	✓	✓			6.6	8.0		7.0	8.2	7.1	8.2	7.0	8.2	6.9	8.2

**Mean value of the 30 minutes IL, $_{t=1\ second}$*

Two indices which describe the noise transmission of the façade were adopted in the present study which included the apparent sound reduction index and the standardized level difference. Since the effect of the room absorption is corrected in both estimations (the apparent sound reduction index and the standardized level difference), the furnishing in the test units did not affect much of the values of these sound reduction descriptors. For the mock-up unit equipped with conventional side-hung windows, the frequency variations of the sound transmission descriptors at frequencies higher than the 400 Hz one-third octave band are small which is between ~ 4 to ~ 6 dB. At lower frequencies, these variations are affected by the acoustic modes. When the internal partition is installed to separate bedroom and living room, the effects of these acoustic modes become more obvious. For the test room installed with plenum windows, the sound transmission of mock-up façade at frequencies below the 400 Hz one-third octave band are affected by the acoustic modes inside the plenum window cavities and the interior of the test room. At frequencies larger than 400 Hz one-third octave band, the mock-up facade with plenum windows offer ~ 10 dB higher noise reduction than those with conventional side-hung casement windows.

By comparing the normalized traffic noise weighted acoustical benefit (noise reduction, R_w) with average A-weighted noise level difference between the two test rooms, it is found that the change in the acoustical properties of the test room interior by replacing conventional side-hung window with plenum window result in 0.3 to 1.1 dBA reduction of insertion loss for the unfurnished test unit without internal partition. In the presence of partition and furnishing, the corresponding reduction is about 0.3 to 0.7 dBA.

Noise reduction and insertion loss are used to estimate the acoustical benefits offered by the plenum windows. About 7dBA traffic noise insertion loss is recorded for a new unfurnished flat installed with the plenum window system. The maximum acoustic benefit of replacing conventional windows with plenum windows is roughly 9 dBA. The present results suggest that plenum window with sound absorption treatment inside the plenum cavity is the most effective way to attenuate outdoor traffic noise regardless the room layout of the interior units. Furnished dwelling with treatment inside the plenum window system provides a further improvement of broadband insertion loss. Partitioned the spaces between bedroom and living room slightly improve the acoustic protection at living space but reduced the performance of plenum window inside bedroom area. The present investigation suggested possibilities of using plenum window as façade device in problematic high rise cities to screen traffic noise and can allow certain degree of natural ventilation across it. At the time being, a concrete mathematical development on the insertion loss due to these structures is lacking. Thus, further works may be needed on evaluate the design of plenum window to achieve optimum performance of devices in term of acoustical protection.

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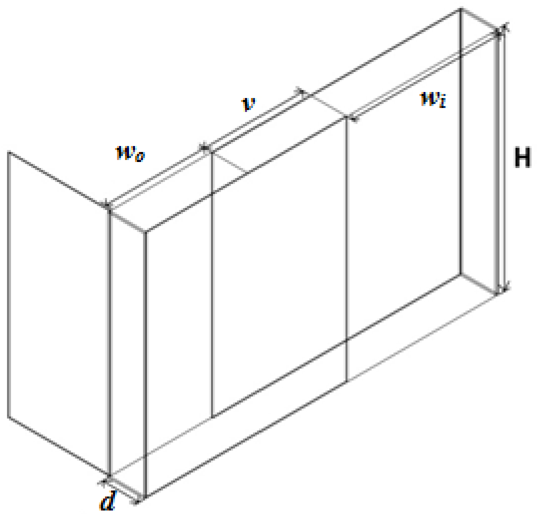
CHAPTER 6 PARAMETRIC STUDY OF PLENUM WINDOWS – FULL SCALE LABORATORY MEASUREMENTS

This chapter is divided into two parts. The first part is consists of experimental investigation of plenum windows with 24 different configurations. The second part of the chapter describes the empirical formula for the estimation of the acoustical insertion losses of the plenum windows.

6.1 Introduction

In the previous chapters, results from the scale model and on-site measurements suggest that plenum window can provide effective noise screening effects to a residential unit compared to the conventional windows. To the best knowledge of author, there is no study on the acoustic insertion loss estimation of plenum window at the time being. Its acoustical performance appears to depend on a number of configuration parameters (Kang & Brocklesby, 2005; Tong & Tang, 2013). Thus, parametric study is essential for better understanding as well as for the setting up of a prediction scheme.

A series of full-scale laboratory measurements were carried out in order find out the relationship between the important parameters and the performance of plenum window. Figure 6.1 illustrates the schematic diagrams of the plenum windows tested in this study. The performance of plenum window under different combinations of inner side window opening size (w_i), outer side window opening size (w_o), gap width (d) and overlapping length (v) were investigated. The total length of the windows depended on the window opening sizes and overlapping length. There were two different configurations of outer side window, namely the single-leaf (Figure 6.1(top)) and the double-leaf side-hung windows (Figure 6.1 (bottom)) included in this study.



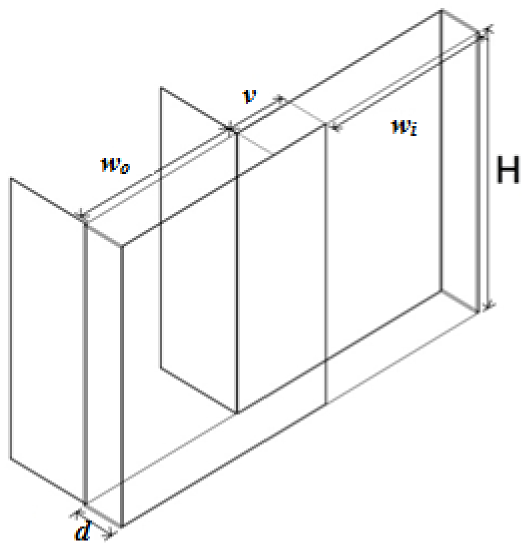


Figure 6.1 Plenum window schematics. (top) Single leaf window; (bottom) Double leaves window.

6.2 Tested Window Configurations

The laboratory works were carried out by investigating 24 different configurations of plenum windows with various opening sizes (w_i and w_o), gap widths (d) and overlapping lengths (v) with and without lining of sound absorption materials as shown in Table 6.1. Acoustical benefits of plenum window were compared with conventional side-hung windows based on its opening sizes. Plenum windows with and without absorptive materials lined inside the window cavity were also tested. Figure 6.2 shows plenum window setups with and without sound absorption materials lined at three sides of window frames. From Table 6.1, eight different configurations of plenum windows were to compare with a single set of side-hung window. The heights of all tested windows were 1350 mm which is the common window height of residential building of Hong Kong. The sliding window pane at the inner layer and the outer side-hung window were kept opened in staggered position as shown in Figure 6.3. All windows glass panes were made of 6 mm thick single glazing with aluminium frames.

Figure 6.2 Plenum window setups. (top) With sound absorption materials; (bottom) Without sound absorption materials.

Table 6.1 Test scenarios and window configurations

Scenario	Side-hung windows (Reference cases) (w)	Plenum windows			
		Opening sizes (w_o, w_i)	Overlapping (v)	Air gap (d)	Fibreglass
L1	430 (Single leaf)	320 (Single leaf)	100	145	√
L2					x
L3				205	√
L4					x
L5			700	145	√
L6					x
L7				205	√
L8					x
L9	660 (Single leaf)	600 (Single leaf)	100	145	√
L10					x
L11				205	√
L12					x
L13			70	145	√
L14					x
L15				205	√
L16					x
L17	1130 (Double leaves)	950 (Double leaves)	100	145	√
L18					x
L19				205	√
L20					x
L21			700	145	√
L22					x
L23				05	√
L24					

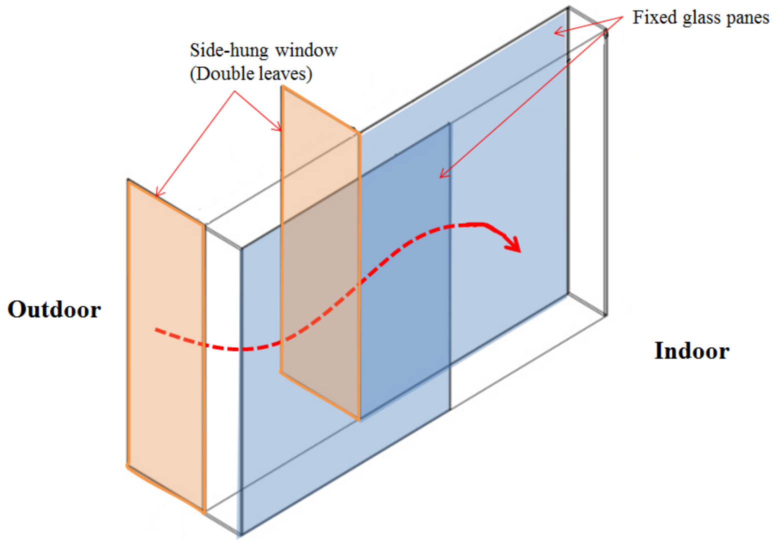


Figure 6.3 Plenum window setup (staggered).

6.3 Measurement Setups

All the experiments were conducted inside the building acoustics testing chambers in the Department of Building Services Engineering, The Hong Kong Polytechnic University. The chambers that used for the present measurements were the same as those used for full-scale balcony-like window. They have been described in Figure 3.1 (section 3.2). Tested windows were installed on the wall separating between two chambers. The 5 m long loudspeaker array as shown in Figure 3.2 used in the investigation of balcony-like window (in chapter 3) and the scale model study of plenum windows (in chapter 4) was adopted in this set of experiments.

The locations of reference point and microphone arrays in the receiver chamber for the current laboratory measurement were the same as those in the previous investigation of balcony-like window as shown in Figure 3.9. A total of nine Brüel & Kjær Type 4935 microphones spanned over the entire volume of the receiver chamber to estimate the transmitted sound pressure levels. Only the microphone positions at the source room of current measurement were different from the previous balcony-like window laboratory tests. The number of microphones for the current measurements depended on the window size as shown in Figure 6.4. These microphones were placed at 1 m horizontally from the tested windows to estimate the average sound pressure level falling onto the tested specimens. All microphone signals were recorded simultaneously by Brüel & Kjær 3506D PULSE system. Figure 6.5 shows the typical setup during the experimental investigation.

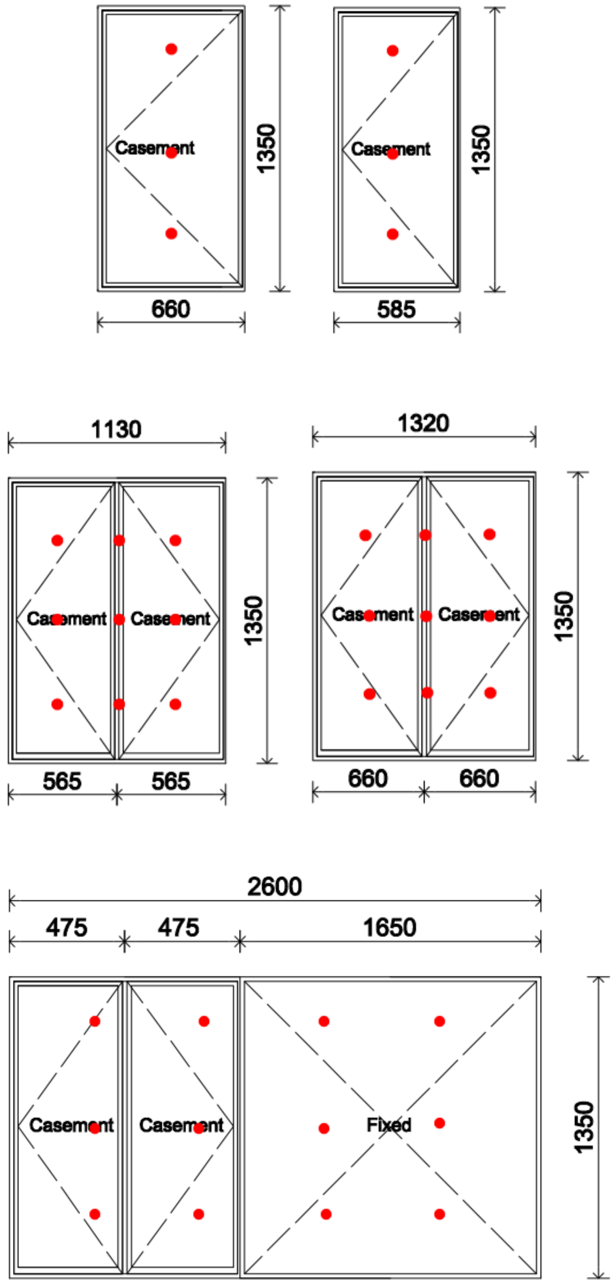


Figure 6.4 Measurement points for difference window sizes (views from receiver chambers). (top): Three microphones; (centre): Nine mircophones; (bottom): Twelve microphones.

●: measurement points

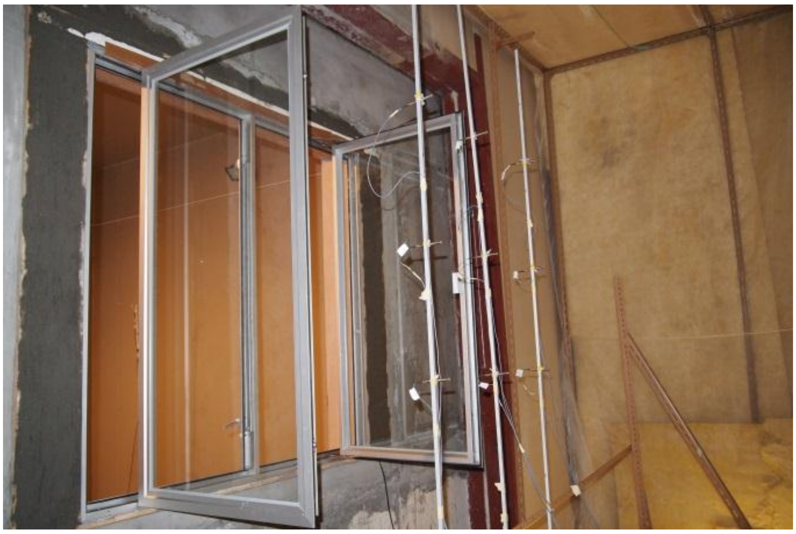


Figure 6.5 Typical microphone setups in the source room. (left) Plenum window; (bottom) Reference case.

Reverberation times of the chambers were measured for different window opening sizes according to the ISO 3382 (BS EN ISO 3382-2, 2008). The DIRAC system with an omni-directional sound source (Brüel & Kjær Type 4296 with a power amplifier) in the MLS mode was used to measure the average sound decays of the chambers. Figure 6.6 shows the schematic measurement setup of reverberation time measurements. Sound level meter was placed at three different positions in the source room and two locations in the receiver room to measure the decay sounds. At each point, reverberation times were measured for three times. A site photograph of reverberation time test in the receiver room is illustrated in the Figure 6.7.

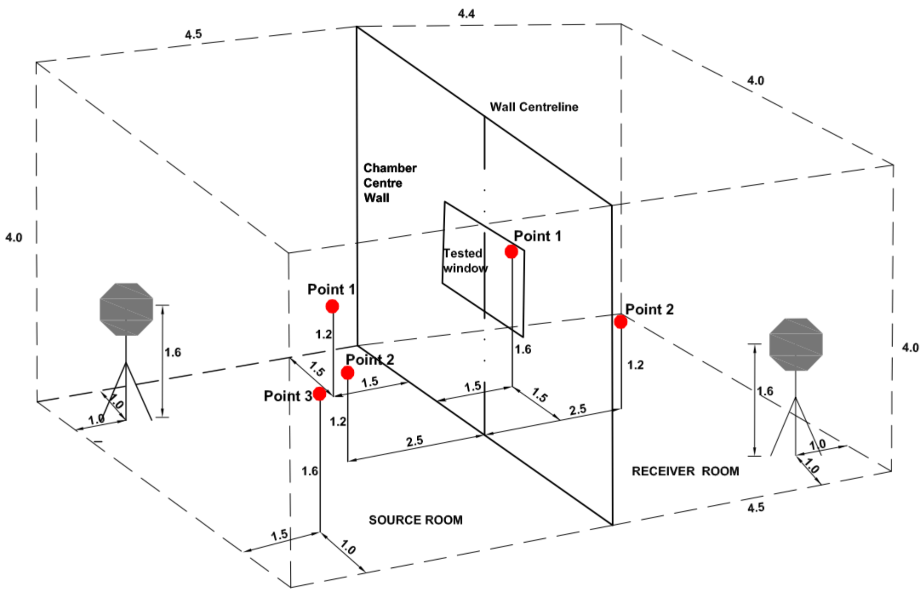


Figure 6.6 Sound source and reverberation time measurement locations (all dimensions are in meter units).

●: measurement point; ------ : approximate chamber boundaries

Figure 6.7 Reverberation time measurement setup.

6.4 Results of Full Scale Laboratory Measurements

Experimental works on plenum window were carried out to investigate the effects of window parameters and absorption materials on the acoustical performance of the device. A total of 24 different configurations with combinations of three window opening sizes ($w_i = w_o$), two gap width sizes (d) and two overlapping lengths (v), together with the cases with and without fiberglass on three sides of window frames were investigated. Every single plenum window was assigned to a side-hung window reference case.

Figure 6.8 shows the average reverberation times of all tested plenum windows cases with the corresponded reference cases. The average sound decays for plenum window with 320 mm opening sizes and those of its reference case was side-hung window with opening size of 430 mm are shown in Figure 6.8 (a). Generally the trends of the plenum window cases at this opening size are similar to that of the reference case except between frequency bands from 125 Hz to 400 Hz. Sharp dips at the 200 Hz band are observed when the overlapping and air gap width of plenum window are smaller. Clear dips at the same frequency band can also be observed when the opening size of the plenum window is changed to 600 mm. Figure 6.8 (b) shows the average sound decays of plenum window with 600 mm opening sizes and of the corresponding reference case (side-hung window with 660 mm opening). Plenum windows show higher sound decays at frequency band of 315 Hz, while the reference window gives shorter sound decay at the same frequency band. This is probably due to the multiple reflections produced by plenum window. The average reverberation times for larger opening sizes of 950 mm with the reference case is shown in Figure 6.8 (c). When the opening is larger, the larger fluctuations of reverberation times between the bands from 125 Hz to 400 Hz for different overlapping and air gap width can be seen, while the previous smaller opening sizes of plenum window typically gives the similar sound decays. From three average reverberation time graphs presented in Figure 6.8, one can be observed that the reverberation times of all plenum window cases with and without sound absorption material for the same opening sizes and gap width are similar. The difference is less than 0.2 dB.

The results of laboratory measurements of 24 configurations plenum windows are depicted in Table 6.2. Insertion losses of IL_A (equation Eq. 5.5) and IL (equation Eq. 3.3) are presented for comparison. IL_A is the difference of noise levels inside the receiver room when the side-hung window (reference cases) is changed to a plenum window, while *IL* is the difference sound levels of these two types of windows when the effects of reverberation of the receiver room is included in the estimation. In general, insertion losses $IL_{A(s)}$ are higher than the $IL_{(s)}$ except for the scenario L20. One can observe that, for the same opening size, plenum window with larger overlapping width and smaller air gap width results in higher insertion loss. In the present experimental study, the highest acoustic benefit is obtained when the opening and overlapping width of the window are larger (w_i/w_o = 950 mm; v = 700 mm), but the air gap width is smaller (145 mm). The maximum IL_A achieved is about 15 dBA while *IL* about 12.5 dBA.

As expected, the plenum window with sound absorption material provides better sound insulation compared to the plenum window without any treatment. With fiberglass lined inside the cavity, an average of 2.7 dBA and 1.9 dBA increase in term of IL_A and *IL*, respectively, are obtained. Figure 6.9 shows the relationship between IL_A of plenum window with sound absorption material and IL_A without sound absorber. The standard error is 0.8 dBA. The effect of sound absorption on *IL* is shown in Figure 6.10 with the standard errors of 0.6 dBA.

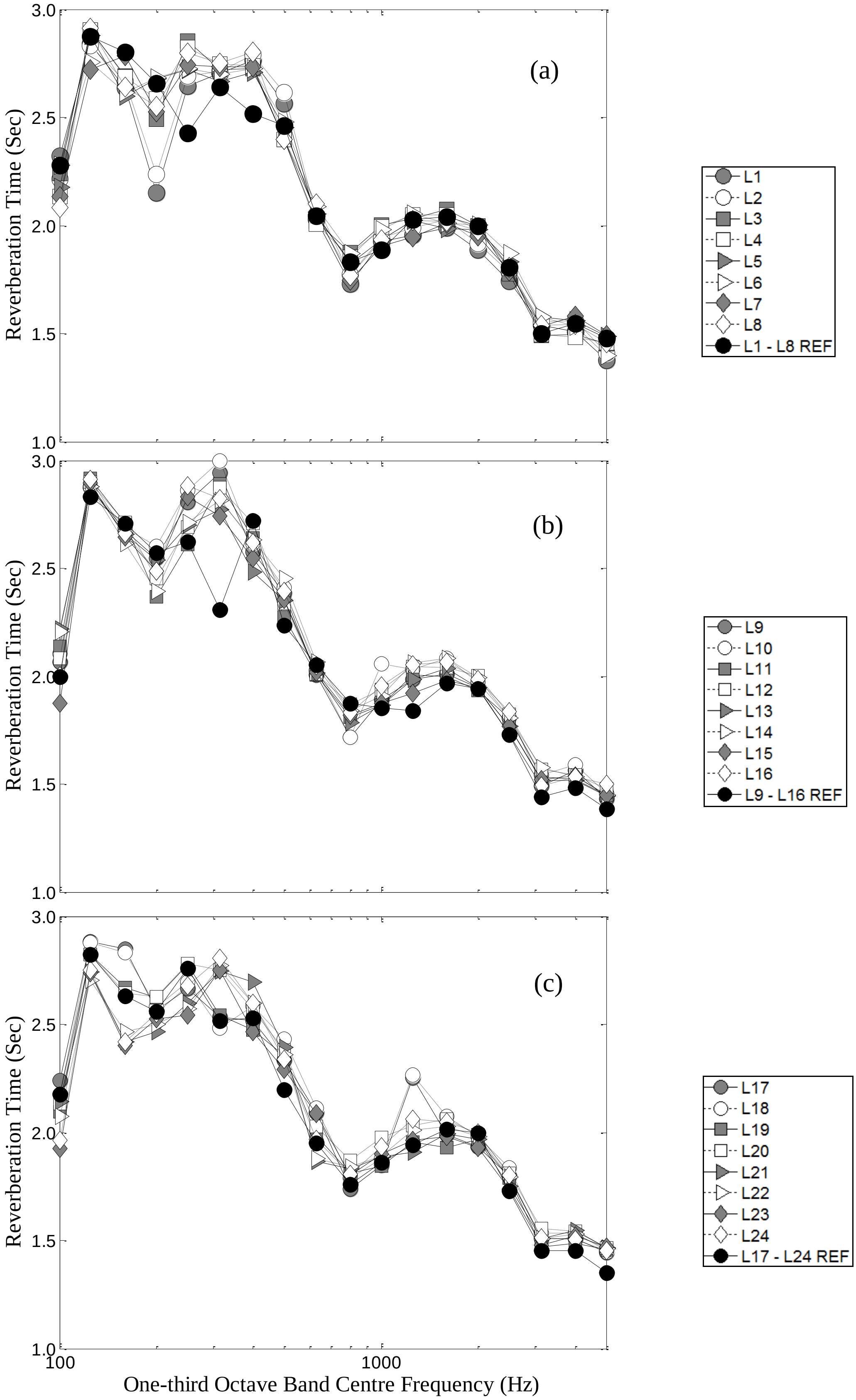


Figure 6.8 Reverberation times of plenum windows with different reference cases.

(a) Reference case is 430 mm single leaf opening side-hung window; (b) Reference case is 660 mm single leaf opening side-hung window; (c) Reference case is 1130 mm double leaves opening side-hung window.

Table 6.2 Insertion losses of 24 configurations plenum windows.

Scenario	Side-hung window Width w	Plenum window				Laboratory measurements	
		w_o, w_i	v	d	Fibreglass	IL_A (dBA)	IL (dBA)
L1	430 (Single leaf)	320	100	145	Yes	9.8	8.5
L2					No	7.5	6.8
L3				205	Yes	13.0	9.8
L4					No	10.3	7.9
L5			700	145	Yes	14.2	9.8
L6					No	10.8	7.4
L7				205	Yes	13.2	9.9
L8					No	9.6	7.5
L9	660 (Single leaf)	600	100	145	Yes	13.0	10.6
L10					No	11.2	9.4
L11				205	Yes	11.2	10.4
L12					No	8.8	8.7
L13			700	145	Yes	14.2	11.8
L14					No	11.6	8.7
L15				205	Yes	13.5	11.6
L16					No	9.7	9.2
L17	1130 (Double leaves)	950	100	145	Yes	13.9	11.8
L18					No	11.6	10.4
L19				205	Yes	11.8	11.1
L20					No	9.4	9.7
L21			700	145	Yes	15.2	12.5
L22					No	12.7	10.8
L23				205	Yes	13.8	12.4
L24					No	11.2	10.5

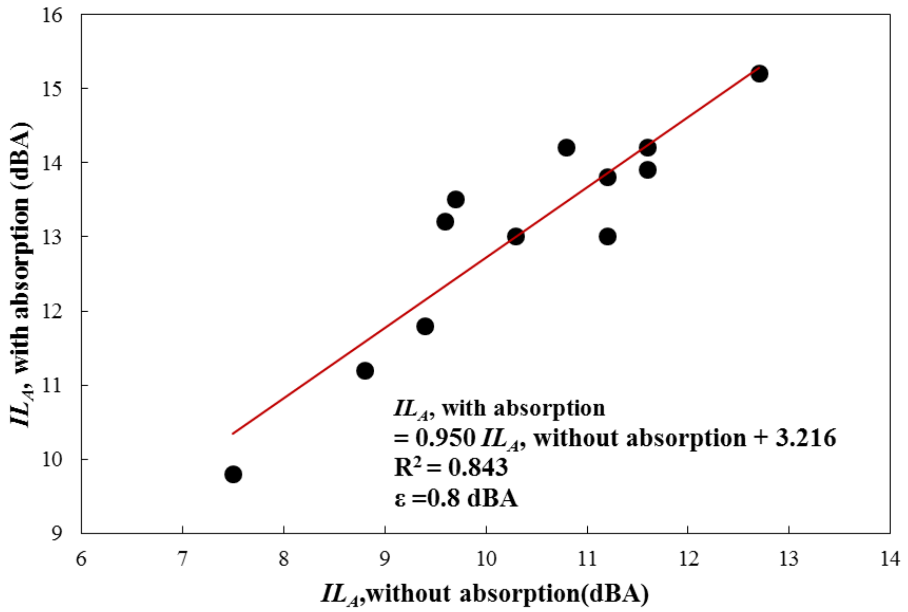


Figure 6.9 Effects of sound absorption on IL_A.

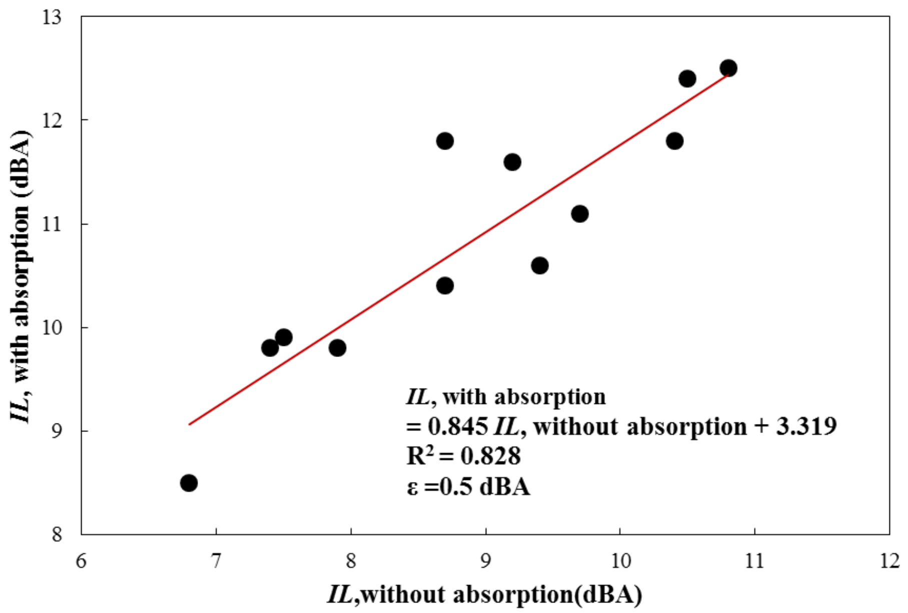


Figure 6.10 Effects of sound absorption on IL.

Figure 6.11 illustrates the change in IL_A when the air gap width (d) is varied. It can be observed that increasing the air gap width of plenum window when other parameters are kept unchanged will decrease the $IL_{A(s)}$ except for the case of small opening (w_i or w_o) and small overlapping (v). The same trend of IL_A on the effect of air gap width (d) can be noticed for the plenum windows lined with sound absorption material. The reduction of $IL_{A(s)}$ appears to decrease when the overlapping length (v) is increased. This is due to the fact that the mean propagation path for the outdoor noise to travel into the receiver room via plenum cavity become shorter when the overlapping length (v) of plenum window is reduced. For the case with small opening (w_i or w_o) and small overlapping (v), the window performance is sensitive to the change of air gap width (d) where about 3 dBA reduction can be noticed when d is reduced by 60 mm.

The effects of IL on the change of gap width are shown in Figure 6.12. When the opening sizes (w_i or w_o) of the window are small, reducing gap with (d) will result in the reduction of $IL_{(s)}$ especially for the case when the overlapping length (v) is short. The trend is similar to that of $IL_{A(s)}$ shown in Figure 6.11, but the current insertion losses are smaller than IL_A. For the cases of larger opening sizes (w_i or w_o), increase in $IL_{(s)}$ is found when the gap width is reduced from 205 mm to 145 mm only for small overlapping length. The $IL_{(s)}$ is considered constant when the gap width is reduced except for the case where the plenum window is lined with fibregalss and the opening sizes are 600 mm. the corresponding insertion loss is reduced by ~ 0.5 dBA.

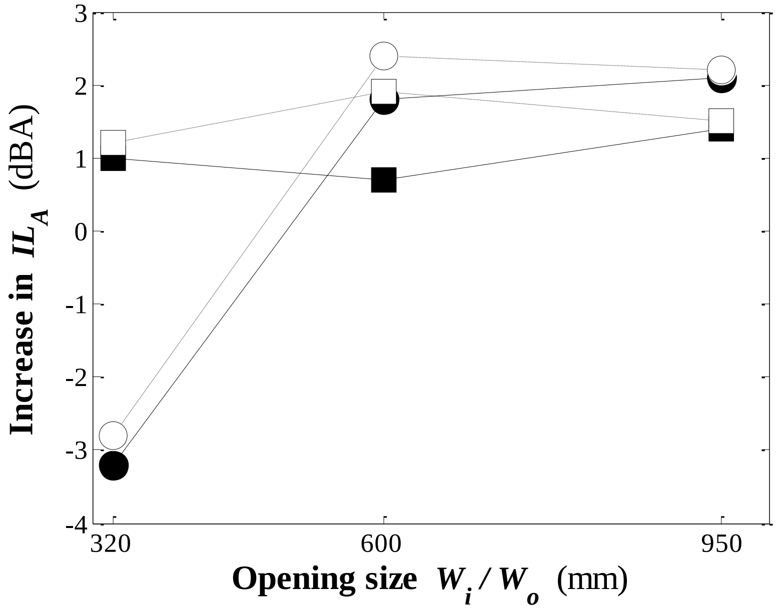


Figure 6.11 Increase in IL_A as airgap width is reduced from 205 mm to 145 mm.

● : v = 100 mm; ■ : v =700 mm; Closed symbols : with sound absorption; Opened symbols : without sound absorption.

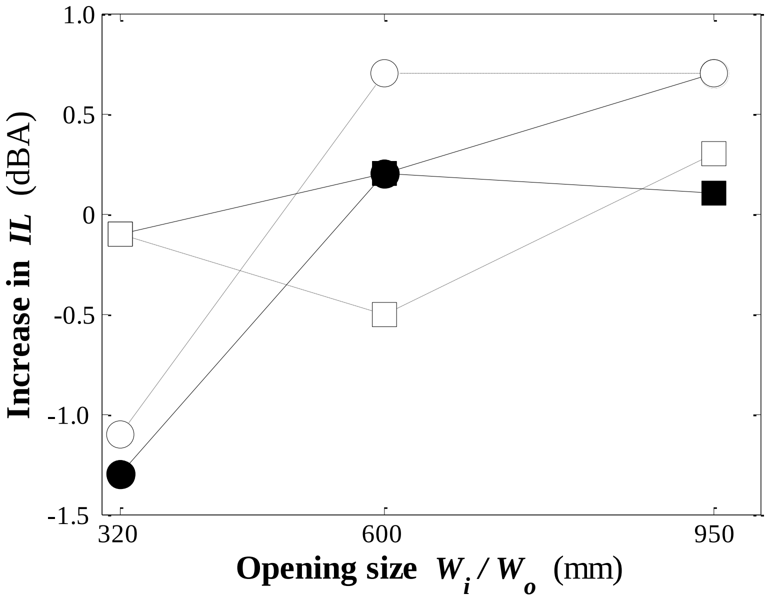


Figure 6.12 Increase in IL as airgap width is reduced from 205 mm to 145 mm.

● : v = 100 mm; ■ : v =700 mm; Closed symbols : with sound absorption; Opened symbols : without sound absorption.

The total length (L) of the plenum window depends on the opening sizes (w) and overlapping length (v). Figure 6.13 shows the effects of w/L ratio on the insertion loss IL_A. Smaller gap width (d) results in higher IL_A compared to the larger d cases except at the w/L = 0.43. It is noticed that the $IL_{A(s)}$ are slightly increased when the w/L is increased from ~ 0.24 to ~ 0.32 and more rapid increment can be observed when the ratio is further increased to 0.37. However, the $IL_{A(s)}$ decreases quickly when the ratio is further increased to ~0.43. For the case of w/L = ~ 0.43, the window opening sizes and the overlapping length are small. Faster increase of insertion losses is observed for w/L> 0.43 for the smaller gap width (d) while the insertion losses keep droping for the cases of larger d. The insertion loss of the larger d then increase after w/L = ~ 0.46. An average of 2.5 dBA and ~ 3 dBA insertion loss can be obtained when sound absorption lined in the plenum window with d = 145 mm and 205 mm, respectively.

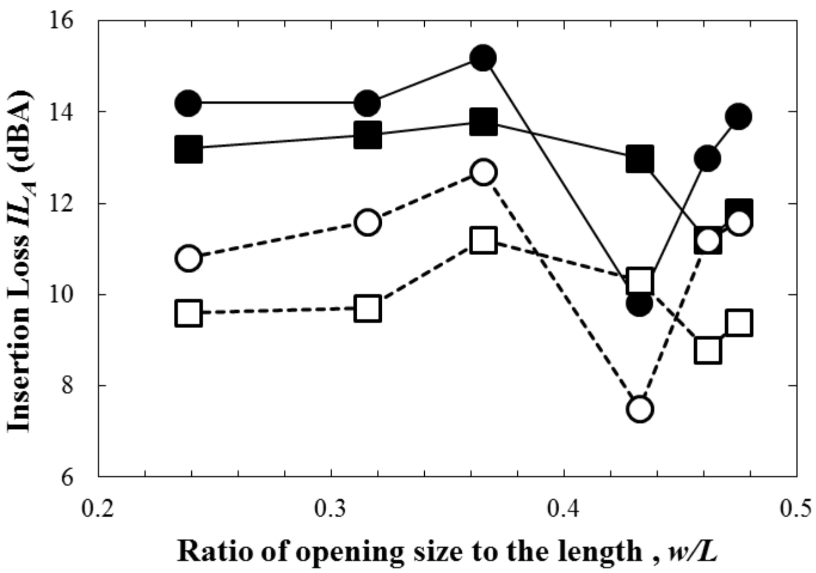


Figure 6.13 Effects of the w/L on insertion losses IL_A.

● : d = 145 mm; ■ : d =205 mm; Closed symbols : with sound absorption; Opened symbols : without sound absorption.

When the gap width (d) and overlapping length (v) are fixed, the effects of different opening sizes (w_i or w_o) on the one-third octave band noise reduction R are investigated. Figure 6.14 (a) illustrates the noise reduction for the cases with small gap width and overlapping length (d = 145 mm and v = 100 mm). The trends of frequency variation of R for three different opening sizes are clearly seen. A R dips at 200 Hz one-third octave band is observed which is probably due to the longitudinal resonance at ~ 230 Hz of the plenum total length (L) of the cases where w_i or w_o = 320 mm. Slight peaks at 125 Hz and 160 Hz one-third octave band are observed for the cases with w_i or w_o = 600 mm and 950 mm, respectively. These peaks are probably due to the longitudinal resonance which takes place at ~ 132 Hz and the corresponding harmonic resonance at ~ 172 Hz for the mentioned plenum windows. Noise reduction R generally increases with frequency except for the cases with w_i or w_o = 320 mm where the fluctuations of R across the whole frequency range are larger. At lower frequencies (less than 250 Hz), there is not much difference on R between the plenum window with and without treatment. The differences are less than 0.6 dB. At higher frequencies, the maximum R difference between windows with and without sound absorption material is ~ 4.5 dB.

Figure 6.14 (b) shows the noise reduction R when the air gap width (d) is 205 mm and overlapping length (v) 100 mm. It is observed that the magnitude of peaks and dips are reduced compared to those of the smaller d cases (Figure 6.14(a)). Figure 6.14 (c) and Figure 6.14 (d) illustrate the noise reductions R_s for plenum windows with the same overlapping length (v) of 700 mm but with different gap widths (d = 145 mm and 205 mm). At larger v, the trends of R_s are not significantly affected by the opening sizes (w_i or w_o) of the plenum window. One can observe that plenum windows with different opening sizes show the similar R_s trends. Besides, $R_s$peaks and dips can be seen at the same frequency bands.

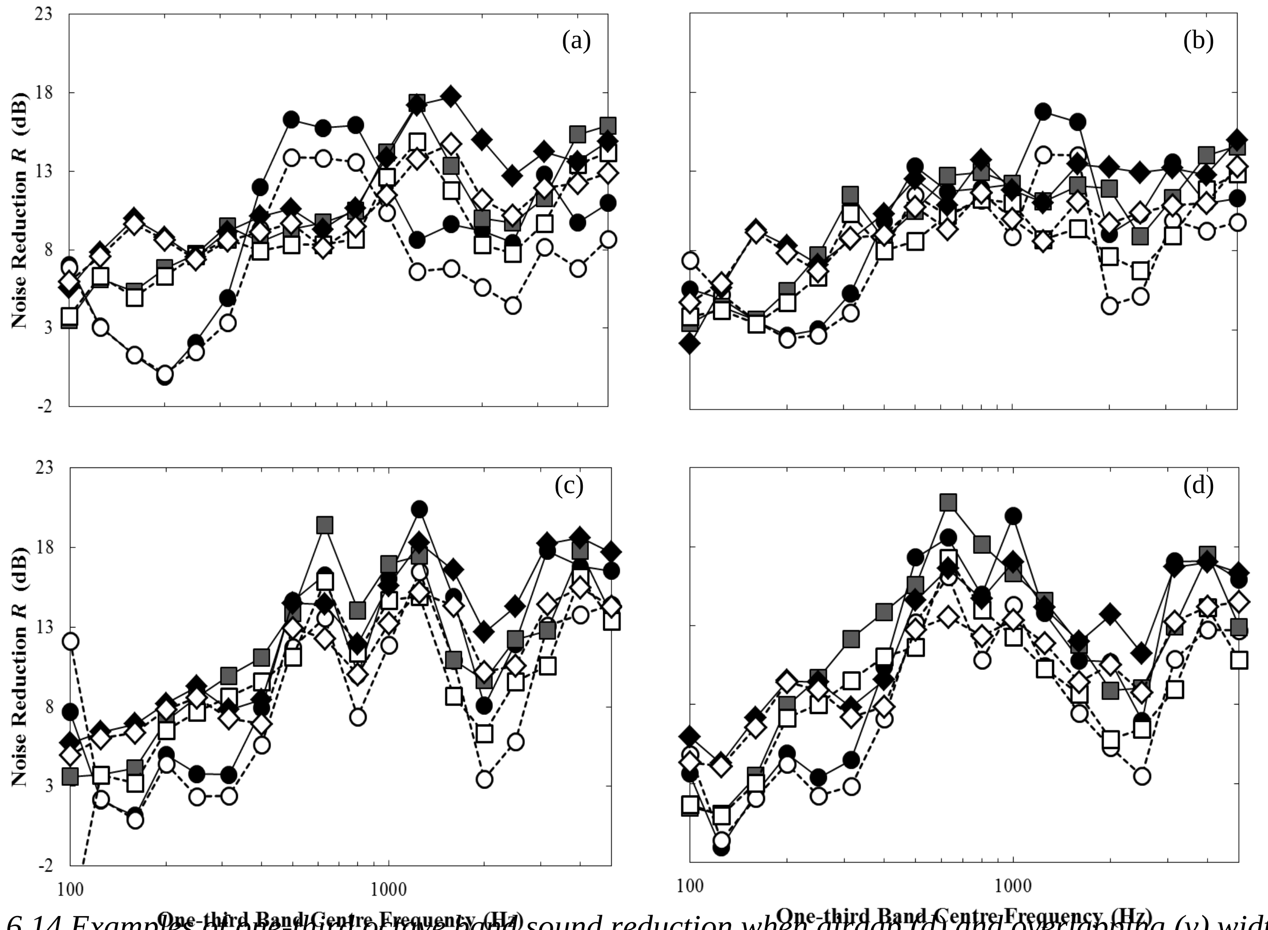


Figure 6.14 Examples of one-third octave band sound reduction when airgap (d) and overlapping (v) width are fixed.

(a) d= 145 mm, v= 100 mm; (b) d=205 mm, v= 100 mm; (c) d= 145 mm, v= 700 mm; (d) d=205 mm, v= 700 mm. ● : w_i/w_o = 320mm; ■ : w_i/w_o = 600 mm; ♦ : w_i/w_o = 950mm; Closed symbol: With sound absorption; Open symbol: Without sound absorption.

6.5 Empirical Formulation

This part will summarize the prediction of acoustical insertion losses (*IL*) of plenum windows. To the best knowledge of the author, the analytical estimation of *IL* is not available in the existing literature. The effort to establish an empirical formula for the prediction of *IL* of the plenum window will be described. It is expected the current investigation can provide a useful baseline on the recent status of acoustical prediction on this façade device.

The overall sound attenuation (hereafter referred as insertion loss) consists of three components. The first component is due to the change of opening sizes when a conventional side-hung window is replaced by the plenum window:

$$\begin{aligned}\Delta_1 &= 10\log_{10}\left(\frac{A_c}{A_o}\right)\\ &= 10\log_{10}\left(\frac{HW}{HW_o}\right),\end{aligned} \qquad \text{Eq. 6.1}$$

where A_c donates conventional side-hung window (reference case to the plenum window) open area, A_o is the area of the external window opening of plenum window, H is the height of the window, W is the opening size of the conventional side-hung window and W_o is the opening size of plenum window.

The second one is due to the change in the plenum design. Plenum window in this study can be considered as an elongated plenum chamber. Thus, the geometrical approximation by Wells (Wells, 1958) can be used as the sound attenuation of the plenum window for the present empirical prediction. The incident sound field at the inlet of the plenum in term of directivity factors (Q) also are adopted in current expression:

$$\Delta_2 = 10\log_{10}\left[A_i\left(\frac{1}{R_p} + \frac{Q\cos\theta}{4\pi d^2}\right)\right]. \qquad \text{Eq. 6.2}$$

In Sharland's estimation (Sharland, 1979), Q = 2 while Cummings (Cummings, 1978) took $Q = 4\cos\theta$ for higher frequency attenuation estimation (Cummings, 1978; Sharland, 1979). A_i is the outlet opening area of the plenum window ($A_i = HW_i$), R_p the room constant inside the plenum, d the slant distance between the centres of the two openings of the plenum. The line joining the centre of inlet to the centre of the outlet makes an angle θ with the opening normal such that:

$$\theta = \tan^{-1}\left(\frac{0.5(W_o + W_i) + L}{G}\right), \qquad \text{Eq. 6.3}$$

R_p is the 'room constant' of the plenum region which depends on the sound absorption inside of the plenum window.

$$R_p = \frac{A_p}{1 - A_p \big/ \{2[(L + W_o + W_i)G + HG + H(L + W_o + W_i)]\}}. \qquad \text{Eq. 6.4}$$

Assuming the openings are perfectly sound absorptive, the total sound absorption A_p then can be expressed as

$$\begin{aligned} A_p &= \alpha[2HG + (L + W_o + W_i)G] + (W_o + W_i)H \\ &= NRC[2HG + (L + W_o + W_i)G] + (W_o + W_i)H \end{aligned}, \qquad \text{Eq. 6.5}$$

where α is the average sound absorption coefficient of the lining. For the laboratory measurement, fibreglass is lined inside the plenum cavity of the window system. Thus, in this approach, the sound absorption coefficient α of the lining is replaced by sound absorption coefficient of fibreglass shown in Table 3.5.

The last one is the result of a change in the transmitted field. The loss due to the change in the reverberation characteristics of the receiver room when conventional side-hung window is replaced by the plenum window can be estimated by

$$\begin{aligned} \Delta_3 &= 10\log_{10}\left(\frac{A_c}{R_c} + \frac{1}{4}\right). - 10\log_{10}\left(\frac{A_v}{R_v} + \frac{1}{4}\right) \\ &= 10\log_{10}\left(\frac{HW}{R_c} + \frac{1}{4}\right). - 10\log_{10}\left(\frac{H(W_o + W_i + L)}{R_v} + \frac{1}{4}\right) \end{aligned}, \qquad \text{Eq. 6.6}$$

where R_c is the room constant in the receiver room with conventional side-hung window, A_c the transmission wall area of conventional window, A_v the transmitting wall area of plenum window design, R_c the room constant in the receiver room with the conventional window.and R_v the room constant in the receiver room with the plenum window. The room constant of the receiver room is obtained by measuring the average sound decays of the receiver room (presented in Figure 6.8) as follow:

$$R_c = \frac{A_{i,c}}{1 - A_{i,c}/S_t} \quad \text{Eq. 6.7}$$

$$A_{i,c} = \left(\frac{0.161V}{RT_c}\right) \quad \text{Eq. 6.8}$$

$$R_v = \frac{A_{i,v}}{1 - A_{i,v}/S_t} \quad \text{Eq. 6.9}$$

$$A_{i,v} = \left(\frac{0.161V}{RT_v}\right) \quad \text{Eq. 6.10}$$

where $A_{i,c}$ the sound absorption of the receiver room with the conventional window, $A_{i,v}$ the sound absorption of the receiver room with the plenum window, S_t the total surface of the receiver room, V the volume of the receiver room, RT_c the average reverberation time inside the receiver room with the conventional window and RT_v the average reverberation time inside the receiver room with the plenum window.

The insertion loss of a plenum window in each octave band with the empirical formula prediction is therefore

$$IL_{EF} = \Delta_1 + \Delta_2 + \Delta_3\,. \quad \text{Eq. 6.11}$$

Since $\triangle_2$ and $\triangle_3$ are frequency dependent, they are weighted by the normalized traffic noise spectrum (BS EN 1793-3, 1998) before the calculation of insertion loss. Table 6.3 summarizes the prediction of insertion losses IL_{EF}. The suffix "EF" represents the data from the empirical formula prediction. The first component $\triangle_1$, which is based on the change of reference conventional window to the plenum window, thus the results for same opening sizes of plenum window are same. From the table, it can be noticed that the two different directivity factors result in about 0.1 to 1 dBA difference of IL_{EF}. The estimation using $Q = 4cos\theta$ in $\triangle_2$ always give higher attenuations.

Figure 6.15 shows the relationship between the insertion losses obtained from empirical prediction and from measurements. The predictions related to plenum window with and without absorption are done separately due to the sound attenuation of plenum cavity will depend on the sound absorption. For the cases directivity factor = 2, the standard errors for the plenum window with absorption is 0.98 dBA while without absorption lined inside the window cavity 1.04 dBA. When the directivity factor is changed to $4cos\theta$, the standard errors for both cases are almost the same.

Figure 6.16 illustrates the predicted one-third octave band noise reduction of the plenum windows. In general, the fluctuations of noise reduction *R* with the frequency variation are very small compared to the measurement results. The noise reductions obtained using two different Q at w/L = 0.24 are shown in Figure 6.16 (a). There is a ~ 0.15 dB difference of *R* between the predictions obtained using these two directivity factors for the cases without absorption materials. For the cases of plenum windows with absorption, *R* increases with the increasing frequencies and also increases with increasing of gap width (*d*). *R* decreases at higher frequencies when the when w/L is increased to 0.32 and 0.37 as shown in Figure 6.16 (c) and Figure 6.16 (d), respectively. At higher frequencies, the differences of sound reduction prediction between the cases with and without absorption materials become smaller when the opening sizes of plenum window are increased. Figure 6.16 (e) illustrates the corresponding acoustical benefits at w/L = 0.43. The prediction of sound attenuation using Q =$4cos\theta$ gives about 1 dB higher *Rs* than Q = 2 over the whole frequency range of interest for the cases with *d* = 145 mm. When the opening sizes of plenum window are increased, it can be observed that the two different directivity factors give rise to two trends of *R* variation at higher frequencies for the cases in which the plenum windows are lined with absorption materials. This can be seen from the Figure 6.16 (f) and Figure 6.16 (g) when the w/L is reduced to 0.46 and 0.48, respectively.

Table 6.3 Insertion losses of empirical predictions.

Scenario	Δ_1	Δ_2		Δ_3	IL_{EF} (dBA)	
		Q =2	Q = 4cosθ		Q =2	Q = 4cosθ
L1	1.28	3.85	4.77	0.68	5.81	6.73
L2	1.28	2.51	3.17	0.70	4.49	5.15
L3	1.28	3.58	3.93	0.73	5.59	5.94
L4	1.28	2.04	2.28	0.72	4.05	4.29
L5	1.28	5.95	6.18	1.81	9.04	9.27
L6	1.28	3.77	3.91	1.84	6.89	7.03
L7	1.28	6.42	6.71	1.78	9.47	9.77
L8	1.28	3.63	3.78	1.80	6.72	6.87
L9	0.41	5.12	6.07	1.21	6.74	7.70
L10	0.41	3.84	4.53	1.28	5.53	6.22
L11	0.41	4.90	5.78	1.22	6.53	7.41
L12	0.41	3.37	3.98	1.27	5.05	5.66
L13	0.41	5.75	5.96	2.09	8.25	8.47
L14	0.41	4.16	4.31	2.15	6.73	6.88
L15	0.41	6.06	6.35	2.08	8.56	8.84
L16	0.41	4.00	4.18	2.16	6.57	6.75
L17	0.75	5.76	6.39	1.35	7.86	8.50
L18	0.75	4.58	5.05	1.40	6.73	7.21
L19	0.75	5.69	6.43	1.30	7.74	8.48
L20	0.75	4.21	4.73	1.40	6.37	6.88
L21	0.75	5.77	5.95	2.02	8.54	8.72
L22	0.75	4.49	4.62	2.04	7.28	7.42
L23	0.75	6.02	6.26	2.02	8.78	9.03
L24	0.75	4.32	4.48	2.07	7.15	7.31

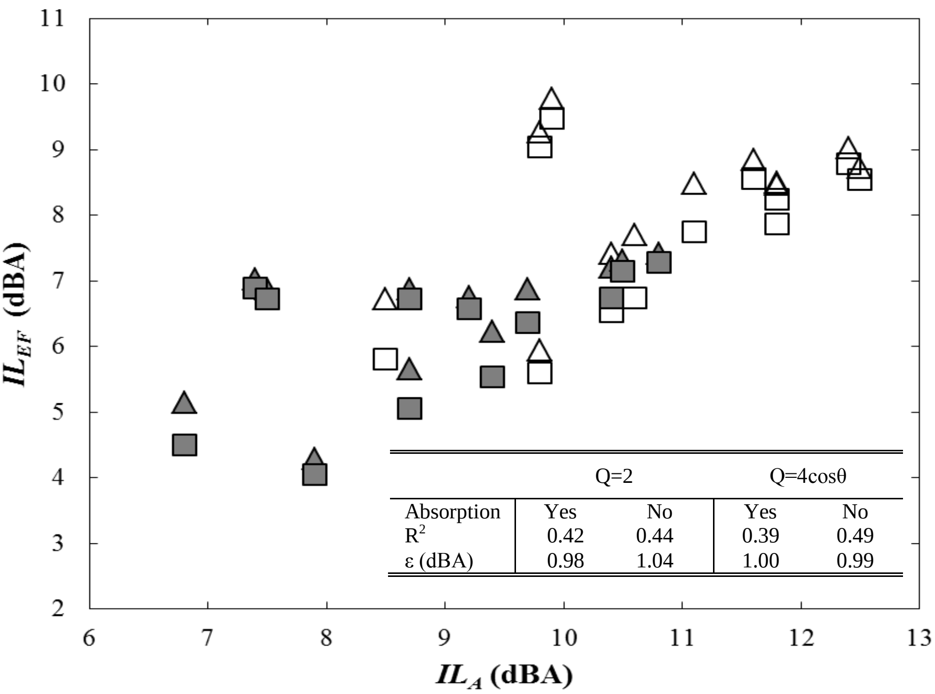


Figure 6.15 Correlation between empirical approach insertion losses with measured performances.

☐ : Q= 2; △ : Q= 4$cos\theta$; Closed symbols: Plenum windows without absorption linings; Opened symbols: Plenum windows with sound absorption linings.

6.6 Summary of Parametric Study of Plenum Window

A parametric study on the acoustical benefits of installing plenum windows has been carried out in the present investigation using two steps. The first step is to investigate how the various plenum configuration parameters will affect the acoustical benefits of this façade device. Secondly, an empirical formula has been developed and its predictions are compared with the laboratory data.

A series of full-scale laboratory works were conducted inside the two coupled but isolated chambers. A total of 24 different configurations of plenum windows with various opening sizes (*w*), gap widths (*d*) and overlapping lengths (*v*) with and without sound absorption materials lined inside the plenum cavity were tested. Two insertion losses of IL_A and IL are presented in the present study. IL_A is the difference of noise levels inside the receiver room when the conventional side-hung window is replaced to a plenum window, while IL is the difference sound levels of these two types of windows when the effects of reverberation of the receiver room is included in the calculation.

When the opening sizes of the plenum are fixed, higher insertion loss can be obtained for the window with larger overlapping (*v*) but smaller gap width (*d*). For these configurations, increasing the opening sizes will enhance the acoustical benefit of the plenum window. The maximum IL_A offers by plenum window is about 15 dBA while *IL* is about 12.5 dBA. When plenum cavity is lined with sound absorption materials, an average of 2.7 dBA and 1.9 dBA increment can be obtained in term of IL_A and *IL*, respectively. The insertion loss tends to increase with increasing window span, decrease with increasing gap width and decreasing overlapping length in general.

The empirical estimation of insertion loss proposed in the present study consists of three components. The first component is due to the change of opening sizes when conventional side-hung window is changed to plenum window. The second component of the sound attenuation is due to the change in the plenum design. In the present study, the geometrical approximation of an elongated plenum chamber is considered. Two different directivity factor of $Q = 2$ and $Q = 4cos\theta$ are adopted in the second component estimation. The last component is the transmission loss due to the change in the reverberation characteristics of the receiver room when conventional side-hung window is replaced by plenum window.

A correlation between measurement and empirical prediction is performed. When using directivity factor of 2, the standard errors for the plenum window with sound absorption lined inside the plenum cavity is 0.98 dBA. The standard error reaches to about of 1.04 dBA when there is no treatment in the plenum window system. For the directivity factor of $4cos\theta$, the standard errors for plenum window with and without sound absorption material are almost the same which is ~ 1 dBA.

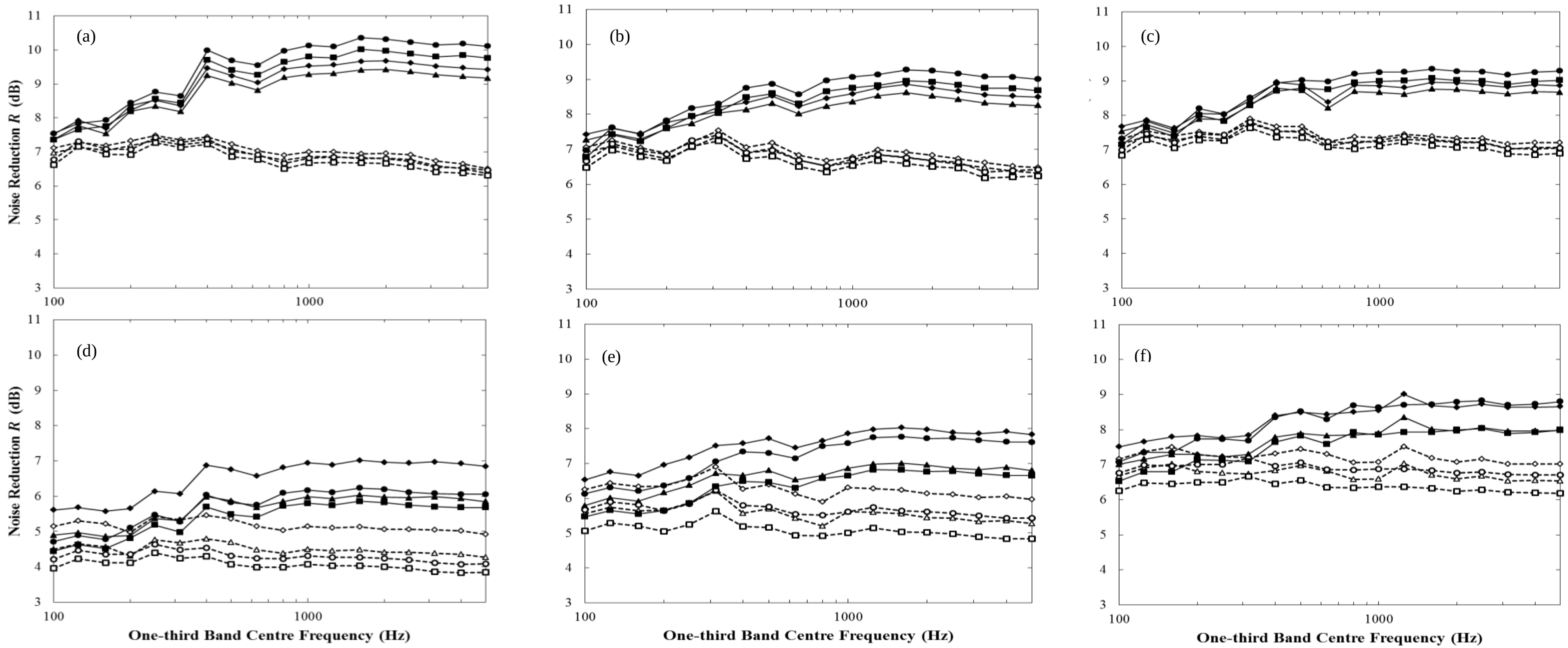


Figure 6.16 One-third octave band sound reduction of empirical prediction.

(a) *w/L* = 0.24; (b) *w/L* = 0.32; (c) *w/L* = 0.37; (d) *w/L* = 0.43; (e) *w/L* = 0.46; (f) *w/L* = 0.48. ♦: Q = 4cosθ, *d* = 145 mm; ▲: Q = 2, *d* = 145 mm; ●: Q = 4cosθ, *d* = 205 mm; ■ : Q = 2, *d* = 205 mm; Closed symbol: With sound absorption; Open symbol: Without sound absorption.

CHAPTER 7 CONCLUSION AND RECOMMENDATIONS FOR FUTURE WORK

In this thesis, the acoustical protections of façade devices including balcony-window and plenum window exposed to traffic noise were studied. The summary of the important achievements of this study are presented in this chapter. Besides, limitation and some worthwhile future works are also discussed.

7.1 Conclusions

Chapter 3 described the investigation of balcony that attached to the opened window to evaluate noise reduction obtained inside the indoor environment. The effectiveness of sound absorption materials arrangement inside the balcony cavity was also tested. Based on the full-scale laboratory measurements, façade balcony-window device which is treated at the ceiling and side walls provides the maximum sound reduction compared to the standalone opened window. About 7 dB of insertion loss can be achieved under such optimal arrangement. However, the screening effects provided by the balcony- window device itself is insufficient where only about 3 dB attenuation can be achieved when there is no treatment has been done inside the balcony cavity.

In chapter 4, an innovation design of window which employs the principle of plenum window was investigated. This staggered inlet and outlet opening device, called the plenum window, is evaluated for variation of sound incidence angle range from -90° to + 90° . Two types of insertion losses based on the orientation of plenum window are used to quantify the noise protection effect of the device: fixed orientation and unrestricted orientation. The window is considered in the fixed condition when the orientation of building facade is limited mostly due to view constraint. For this condition, the acoustical benefit is estimated by comparing the device with opened window at same orientation. However, for the unrestricted orientation, insertion losses offered by plenum windows are compared with an opened window at normal incident angle, $\theta = 0^{\circ}$. The performance of device at the later condition is included as the protection offered by plenum window itself and also the change of view angle of the line source. Thus, the trends of insertion losses on variation of sound incidence angles of these two cases are totally difference. Maximum acoustic benefits can be obtained when device is at position close to normal incidence angle for the fixed orientation while for the unrestricted orientation, the highest insertion loss is obtained when device is located parallel to traffic road. The results obtained in this chapter show that there is a high potential of using this plenum window at building façade to screen off the traffic noise. The maximum insertion losses achieved in both types of orientation are more than 12 dBA while the minimum acoustical benefit offered by plenum window is around 4 dBA.

The results obtained in chapter 5 illustrate the possibilities of using plenum window as façade device of the residential building in problematic high rise cities. On-site investigation of full-scale plenum window was carried out. A pair of mock-up flat units with two different systems was built next to noisy urban road in Hong Kong. One of the mock-up unit was equipped with conventional side-hung casement windows while another was installed with plenum windows. The windows were tested under different indoor conditions and room layouts to investigate how all these configurations affecting the sound transmission losses of the mock-up façades. Test unit with plenum windows offer ~ 10 dB higher noise reduction than those with conventional side-hung windows at higher frequencies. For a new unfurnished flat unit where the conventional side-hung window is replaced by the plenum window, about 7 dBA insertion loss can be obtained. From the measurement results, plenum window with sound absorption materials lined inside the plenum cavity is the most effective way to attenuate outdoor traffic noise regardless the room layout and interior condition of the flat unit.

In chapter 6, parametric study on the acoustical benefits of plenum window has been carried out. Various plenum configuration parameters included opening sizes (w), gap widths (d) and overlapping lengths (v) were tested and how these parameters affecting the noise reduction of the indoor environment are discussed. An empirical formula has then been developed and its predictions are compared with the laboratory data. The approaches used for the empirical prediction is described in details. A relationship between results obtained from the measurements and from the prediction has then been made. For the accuracy of the prediction, the results from the empirical formula show a standard errors of ~ 1 dBA compared to the measurement results.

7.2 Summary of Important Achievements

The investigation of façade devices with concern about natural ventilation is carried out because the information on its application is still insufficient. The investigation is performed using experimental and empirical approach.

The investigation of balcony-window device in the present study is different from the previous studies in term of methodologies of the measurement. This façade device is investigated using full scale model experiments and the transmitted sound pressure levels are measured inside the receiver room. The full scale laboratory experiment is carefully conducted in the present study. The acoustical benefits of balcony-window obtained from the experiments are still insufficient to mitigate serious traffic noise in urban dwellings unless it is lined with sound absorption materials.

The application of plenum window can be said as a new approach for the noise management in densely high-rise city like Hong Kong where the conventional mitigations may not be adoptable. This thesis is the first attempt to articulate a case on the applicability of plenum window at residential buildings from the theoretical and on-site angles.

An empirical formulation for the window performance prediction is developed and is validated with data of laboratory and on-site measurements. The empirical estimation of insertion loss of plenum window is useful as reference for architects and engineers in designing future urban dwellings when plenum window is adopted.

Besides, full scale on-site measurement data obtained in the present study are more realistic since the real traffic noise is used and the dimensions of the windows are the same as those uses in the residential dwellings. In addition, the sound field of the traffic noise is not easy to reproduce completely in the laboratory. The findings revealed that plenum window can provide at least 7 dBA of acoustical insertion loss compared to the conventional side-hung windows when it was attached to the residential dwelling in Hong Kong. The setting of field measurement in the present study is equivalent to the first floor of the common public housing flat. At this floor level, the flat can be considered as the worst sound insulation condition where more traffic noise can be transmitted into indoor environment. It is believed that better acoustical benefits can be offered by plenum window when this façade device is attached at higher floor of the dwelling. Besides, the concurrent in-situ test for plenum window and conventional window is carried out to compare the acoustical protection offered by these two types of windows.

In this thesis, critical parameters on the insertion losses of plenum windows subjected to a line source are investigated through scale down and full scale model measurements. Apart from the parameters of plenum window such as window opening sizes, overlapping length and air gap width, the orientation of the window relative to the traffic road is found to be great impacts on the acoustic protection of plenum window. The current study covered every 10° of sound incidence angles between 0° to 180°. Thus, it provides a useful set of new experimental data of plenum window relative to the line source. Besides, the analysis of insertion loss of plenum window that attached to the façade building in the presence of a non-parallel line source is different from the previous studies. Two types of insertion losses based on flexibility orientation of façade building to the traffic road with different references are adopted. Both types of insertion losses are not sensitive to the change in window configuration when the plenum window orientation is not in favorable propagation condition.

Nevertheless, the results of this study have significant impact at least to the Hong Kong community and have led to industrial applications. The outputs also are useful for future new development noise insulation façade device for urban dwellings. In addition, the results of this study provide a detailed picture on the acoustical benefit of plenum window in practice.

7.3 Limitation of the Study

The limitation of this study is that the performance of façade devices only evaluate on certain parameters and configurations. Since plenum window has staggered windows, the azimuthal angle of sound source is significantly influencing the sound insulation of the device. However, when window is applied on the façades of high-rise buildings, the elevation angle or the height from the noise source may also influence the acoustical protection of the device even the effects may not be as critical as the azimuth angles. Besides, the empirical formula that has been developed only limit to the plenum window with different opening sizes (w), gap width (d), overlapping (v) and the receiver room reverberation characteristic. Other parameters such as type of noise source, the distance from the noise source and angle of incidence have not been taken into account.

7.4 Recommendation for Future Work

From the evaluations discussed in chapter 3 to 6, there are potential of some works that can be done in the future to improve the current status of plenum window.

7.4.1 Window configurations and other parameters

In the present study, the performances of plenum windows are affected by the opening sizes, air gap width and overlapping length of the devices. The noise source directions also influence the protection performance of this façade device. Plenum window can be horizontally or vertically staggered. Since the conventional window that normally installed at residential building in Hong Kong is side-hung casement window, horizontally staggered plenum window was investigated and used for comparison in the present study. It is recommended that the vertically staggered window similar to the previous researchers should be carried out in the future to compare the acoustical benefits of the device with the current investigations (J. Kang & Brocklesby, 2005). Furthermore, there are still some other parameters awaiting to be explored. Other internal configurations such as include hood in front of the devices, obstacles inside the air gap, tilted the glass pane and those employed in duct silencing may also be included in the current plenum window design system to gather more information and feasibility of inventing a better façade device (J. Kang & Li, 2007; Munjal, 1987b; Yim, 2014).

7.4.2 Natural ventilation investigations

Since the main purpose of plenum window is to provide better sound insulation by allowing natural ventilation across it. Thus, the ventilation property of the device is vital. The design of acoustic ventilation façade device depends on three components which include the shape and sizes of the device that fixed on the building façade, the sound insulation of the device and lastly the aerodynamic performance of the device to provide sufficient air flow into the buildings (Chilton et al., 2012). Previous research showed that human beings living in the naturally ventilated buildings can accept higher sound level comes from outdoor compared to those living in mechanically ventilated building (Field, 2008). Larger opening sizes of the device may provide better natural air circulation, but this may reduce the effectiveness of sound insulation of the device. Linden has evaluated how the natural ventilation can be achieved by appropriate use of openings (Linden, 1999). The effects of difference types window openings on wind-driven cross-ventilation has also been investigated (Karava, Stathopoulos, & Athienitis, 2007). The relationship between opening sizes in term of acoustical and ventilation is important. In order to establish the ventilation effectiveness, the effort of how the air movement can dilute the concentration of indoor pollutants through plenum window is proposed to be made. It is also suggested to investigate the effects of indoor and outdoor temperature difference and flow turbulence across the façade devices.

When buildings are located in a densely populated high-rise environment, the study of the effectiveness of natural ventilation may not be as simple as to just evaluate the opening sizes and design of the ventilation windows. Other parameters such as wind direction, building height, building separations, building displacement and building orientation are important aspects that should be included in the investigations. Cheung and Liu (2011) studied the ventilation rate in the compact environment using computational fluid dynamics (CFD) techniques. They reported that building separation of five times the building width is the optimum setting for the natural ventilation perspective. However, suitable building arrangement can improve the natural ventilation performance even the separation between the buildings is reduced. Thus, the study of the effects of building interference in the crowded city to the natural ventilation performance is important. The study should reveal how the façade devices in the presence of neighbouring tall buildings will influence the performance of natural ventilation. The optimum setting of the device between natural ventilation and high acoustical insertion loss can then be accomplished.

7.4.3 Active noise control

Sound insulation using the passive noise control can improve the noise attenuations of the device, but the significant reductions of noise normally are limited to the mid and high frequencies. Unsatisfactory noise control at lower frequencies using passive approach can be overcome by introducing active noise cancellation. Although many studies have been carried out regarding active noise control in double glazing windows, the application of active control to plenum window has only been merely explored. Though active control application is difficult to implement satisfactorily in open space, the chance of its application in a semi-confined region, like the void of the plenum cavity, is highly possible. Zhang et al. (2002) has illustrated the possibility of active sound cancellation in the enclosure with an open window. They proposed the prediction of coherence of sound pressure level inside the receiver room and outside opening window theoretically and verified it by experiment.

The effort of actual implementation of the active control in the plenum window system has been made by Huang et al. (2011). The authors proposed an analytical model using modal expansion method and coupled cavities theory to estimate the sound field inside the ventilation window. Their ventilation window was designed in vertically staggered window opening form. Some assumptions have been made in their estimations for simplicity. In their analytical model, the primary sound source was set as planar sound wave with the normal incident angle and the control sources was considered point source. Besides, the air flow inside ventilation path was neglected where only external noise can be propagated into the room via ventilation path. Furthermore, the wall of the room and the frame of window were assumed to be rigid. They then applied the active noise control techniques with single and dual channel systems in their numerical simulations and scale down model experiments. For single channel system numerical simulation, 3 different locations of control sources which included top, middle and bottom part of the window cavity were investigated. Their results showed that the optimum location of secondary source was at the bottom part of the window cavity which was close to the source side opening. About 20 dB sound attenuation from 100 to about 340 Hz can be achieved by adopting this secondary source position. For dual channel system, a wider range of effective control can be achieved where the attenuation frequency range is increased to 410 Hz.

They then carried out scale model experiments for validation. There were some differences of noise reductions between their experiment and numerical results. Experiment results showed that when the sound field was well controlled, noise attenuation at observation points is almost the same as the attenuation at error sensor position was 10 dB while the numerical simulation was about 20 dB. Some idealized conditions that made by Huang et al. (2011) in developing their model are not practical. Since specific research on active noise control of staggered ventilation window is still lacking, studies of this topic should be carried out in the future to explore the feasibility of applying active noise control in this window design to improve effectiveness in practical situations.

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BIBLIOGRAPHY

renas, J. P. (2008). Potential problems with environmental sound barriers when used in mitigating surface transportation noise. *The Science of the total environment*, *405*, 173–9.

Asdrubali, F., & Buratti, C. (2005). Sound intensity investigation of the acoustics performances of high insulation ventilating windows integrated with rolling shutter boxes. *Applied Acoustics*, *66*, 1088–1101.

Asdrubali, F., & Cotana, F. (2000). Influence of filtering system on high sound insulation ventilating windows. In *INTER-NOISE and NOISE-CON Congress and Conference Preceddings* (pp. 295–302).

Babisch, W. (2008). Road traffic noise and cardiovascular risk. *Noise & health*, *10*, 27–33.

Berglund, B., & Lindvall, T. (1995). Community noise. Archives of the Centre for Sensory Research., *2*, 1–195.

Bilawchuk, S., & Fyfe, K. R. (2003). Comparison and implementation of the various numerical methods used for calculating transmission loss in silencer systems. *Applied Acoustics*, *64*, 903–916.

Bradley, J. S. (1977). A Study of Traffic Noise Attenuation Around Buildings. *Acta Acustica united with Acustica*, *38*, 247–252.

BS EN 1793-3. (1998). Road traffic noise reducing devices —Test method for determining — Part 3: Normalized traffic noise spectrum. BSI: London.

BS EN ISO 10140-2. (2009). Acoustics — Laboratory measurement of sound insulation of building elements — Part 2: Measurement of airborne sound insulation.

BS EN ISO 16283 -1. (2014). Acoustics — Field measurement of sound insulation in buildings and of building elements — Part 1: Airborne sound insulation. BSI: London.

BS EN ISO 3382-2. (2008). Acoustics — Measurement of room acoustic parameters — Part 2: Reverberation time in ordinary rooms. BSI: London.

Buildings Department HKSAR Government. (2005). Practice Note for Authorized Persons, Registered Structural Engineers and Registered Geotechnical Engineers: APP-130: Lighting and Ventilation Requirements - Performance-based Approach.

Buratti, C. (2002). Indoor noise reduction index with open window. *Applied Acoustics*, *63*, 431–451.

Buratti, C. (2006). Indoor Noise Reduction Index with an open window (Part II).

Applied Acoustics, *67*, 383–401.

Cheung, J. O. P., & Liu, C.-H. (2011). CFD simulations of natural ventilation behaviour in high-rise buildings in regular and staggered arrangements at various spacings. *Energy and Buildings*, *43*, 1149–1158.

Chilton, A., Novo, P., Mcbride, N., Lewis-nunes, A., Johnston, I., & Rene, J. (2012). Natural ventilation and acoustic comfort. In *Acoustics 2012 Nantes Conference: 11th Congrès Français d'Acoustique & 2012 IOA annual meeting*. Nantes, France.

Cotana, F. (1999). Experimental data and performance of new high sound insulation ventilating windows. In *INTER-NOISE and NOISE-CON Congress and Conference Preceddings* (Vol. 3, pp. 995–998).

Cummings, A. (1978). The attenuation of lined plenum chambers in ducts: I. Theoretical models. *Journal of Sound and Vibration*, *61*, 347–373.

Cummings, A., & Wing-King, A. M. (1979). The attenuation of lined plenum chambers in ducts, II: Measurements and comparison with theory. *Journal of Sound and Vibration*, *63*, 19–32.

Department of Transport Welsh Office. (1988). Calculation of Road Traffic Noise. London: Her Majesty's Stationery Office.

Ekici, I., & Bougdah, H. (2003). A Review of Research on Environmental Noise Barriers, *10*, 289–323.

European Environment Agency. (2011). Traffic noise: expose and anoyance, Available at <http://www.eea.europa.eu/>.

F. J. Langdon. (1976). Noise nuisance caused by road traffic in residential areas: Part I. *Journal of Sound and Vibration*, *47*, 243–246.

Field, C. D. (2008). Acoustic design criteria for naturally ventilated buildings. *The Journal of the Acoustical Society of America*, *123*, 3814.

Ford, R. D., & Kerry, G. (1972). The sound insulation of partially open double glazing.pdf. *Applied Acoustics*, *6*, 57–72.

Fujiwara, K. (1998). Noise barriers with reactive surfaces. *Applied Acoustics*, *53*, 255–272.

Garai, M., & Guidorzi, P. (2000). European methodology for testing the airborne sound insulation characteristics of noise barriers in situ: experimental verification and comparison with laboratory data. *The Journal of the Acoustical Society of America*, *108*, 1054–67.

Garcia, A. (2001). *Environmental Urban Noise* (Vol. 8). Spain: WIT Press. Retrieved from http://link.aip.org/link/?JAS/114/1199/1

Hammad, R. N. S., & Gibbs, B. M. (1983). The acoustic performance of building fa çades in hot climates: Part 2--Closed balconies. *Applied Acoustics*, *16*, 441–454.

Harris, C. M. (1979). Handbook of Noise Control. New York: McGraw-Hill.

HKSAR. (1993). Hong Kong Planning Standards and Guidelines. (E. P. Department, Ed.). Retrieved from http://www.pland.gov.hk/pland_en/tech_doc/hkpsg/full/ch9/ch9_text.htm#4. Noise

HKSAR. (2003). Guidelines on Design of Noise Barriers. (T. H. G. Environment Protection Department & Highways Department, Ed.).

HKSAR. (2006). A Comprehensive Plan to Tackle Road Traffic Noise in Hong Kong.

HKSAR. (2011). Green and Innovation Buildings, Joint Practice Note No. 1, Building Department, Land Department and Planning Department, the Government of the Hong Kong Special Administration Region, China. Retrieved from http://www.bd.gov.hk/english/documents/joint/JPN01.pdf

Hossam El Dien, H., & Woloszyn, P. (2004). Prediction of the sound field into high-rise building facades due to its balcony ceiling form. *Applied Acoustics*, *65*, 431–440.

Hossam El Dien, H., & Woloszyn, P. (2005). The acoustical influence of balcony depth and parapet form: experiments and simulations. *Applied Acoustics*, *66*, 533–551.

Hothersall, D. C., Horoshenkov, K. V, & Mercy, S. E. (1996). Numerical modelling of the sound field near a tall building with balconies near a road. *Journal of Sound and Vibration*, *198*, 507–515.

Huang, H., Qiu, X., & Kang, J. (2011). Active noise attenuation in ventilation windows. *The Journal of the Acoustical Society of America*, *130*, 176–88.

Huang, S. P., & Lai, R. P. (2012). A study on performance of ventilated soundproof windows with fans (A). *The Journal of the Acoustical Society of America*, *131*, 3320–3320.

Ih, J.-G. (1992). The reactive attenuation of rectangular plenum chamber. *Journal of Sound and Vibration*, *157*, 93–122.

Ishizuka, T., & Fujiwara, K. (2012). Traffic noise reduction at balconies on a high-rise building façade. *The Journal of the Acoustical Society of America*, *131*, 2110.

Ishizuka, T., & Fujiwara, K. (2013). Full-scale tests of reflective noise-reducing devices for balconies on high-rise buildings. *The Journal of the Acoustical Society of America*, *134*, EL185–90.

Jakob, A., & Möser, M. (2003a). Active control of double-glazed windowsPart I: Feedforward control. *Applied Acoustics*, *64*, 163–182.

Jakob, A., & Möser, M. (2003b). Active control of double-glazed windows. Part II: Feedback control. *Applied Acoustics*, *64*, 183–196.

Kang, J. (2006). An acoustic window system with optimum ventilation and daylighting performance. *Noise and Vibration Worldwide*, *37*, 9–17.

Kang, J., & Brocklesby, M. V. (2005). Feasibility of applying micro-perforated absorbers in acoustic window systems. *Applied Acoustics*, *66*, 669–689.

Kang, J., & Li, Z. (2007). Numerical simulation of an acoustic window system using finite element method. *Acta acustica united with acustica*, *93*, 152–163.

Kang, J., & Li, Z. (2007). Numerical Simulation of an Acoustic Window System Using Finite Element Method. *Acta Acustica united with Acustica*, *93*, 152–163.

Karava, P., Stathopoulos, T., & Athienitis, a. (2007). Wind-induced natural ventilation analysis. *Solar Energy*, *81*, 20–30.

Kim, H.-J., & Ih, J.-G. (2006). Rayleigh–Ritz approach for predicting the acoustic performance of lined rectangular plenum chambers. *The Journal of the Acoustical Society of America*, *120*, 1859.

Kim, M., & Kim, H. (2007). Field measurements of fac - ade sound insulation in residential buildings with balcony windows. *Building*, *42*, 1026–1035.

Koussa, F., Defrance, J., Jean, P., & Blanc-benon, P. (2013). Acoustic performance of gabions noise barriers : Numerical and experimental approaches, *74*, 189–197.

Kropp, W., & Berillon, J. (2000). A theoretical model to consider the influence of absorbing surfaces inside cavity of balconies. *Acta Acustica united with Acustica*, *86*, 485–494.

Lam, K.-C., & Ma, W.-C. (2012). Road traffic noise exposure in residential complexes built at different times between 1950 and 2000 in Hong Kong. *Applied Acoustics*, *73*, 1112–1120.

Lam, Y. W., & Roberts, S. C. (1993). A simple method for accurate prediction of finite barrier insertion loss. *Journal of the Acoustical Society of America*, *93*, 1445–1452.

Lee, P. J., Kim, Y. H., Jeon, J. Y., & Song, K. D. (2007). Effects of apartment building facade and balcony design on the reduction of exterior noise. *Building and Environment*, *42*, 3517–3528.

Li, K. M., Lui, W. K., Lau, K. K., & Chan, K. S. (2003). A simple formula for evaluating the acoustic effect of balconies in protecting dwellings against road traffic noise. *Applied Acoustics*, *64*, 633–653.

Li, K., & Wong, H. (2005). A review of commonly used analytical and empirical formulae for predicting sound diffracted by a thin screen. *Applied Acoustics*, *66*, 45–76.

Li, X., & Hansen, C. (2005). Comparison of models for predicting the transmission loss of plenum chambers. *Applied Acoustics*, *66*, 810–828.

Linden, P. F. (1999). The fluid mechanics of natural ventilation, *31*, 201–238.

M Auerbach, A Bockstedteb, & Estorff, O. V. (2010). Numerical and Experimental Investigations of Noise Barriers with Helmholtz Resonators. In *Noise-Con 2010*. Baltimore, Maryland. Retrieved from http://novicos.de/system/files/files/232/Paper_NC10.pdf

May, D. N. (1979). Freeway noise and high-rise balconies. *Journal of the Acoustical Society of America*, *65*, 699–704.

Mohsen, E. A., & Oldham, D. J. (1977). Traffic noise reduction due to the screening effect of balconies on a building facade. *Applied Acoustics*, *10*, 243–257.

Munjal, M. L. (1987a). A simple numerical method for three dimensional analysis of simple expansion chamber mufflers of rectangular as well as circular cross section. *Journal of Sound and Vibration*, *116*, 71–88.

Munjal, M. L. (1987b). *Acoustics of Ducts and Mufflers*. New York: John Wiley.

Muzet, A. (2007). Environmental noise, sleep and health. *Sleep medicine reviews*, *11*, 135–42.

N. W. M. Ko. (1978). Traffic noise in a high-rise city. *Applied Acoustics*, *11*, 225–239.

Naish, D., & Tan, A. (2007). A review of residential balconies with road traffic noise. In *14th International Congress on Sound and Vibration (ICSV 14)* (pp. 0–7). Cairns.

Naish, D., & Tan, A. C. C. (2008). Residential balconies with road traffic noise: A combined source image and radiosity model. In *15th International Congress on Sound and Vibration* (pp. 864–871). Daejeon, Korea.

Naticchia, B., & Carbonari, a. (2007). Feasibility analysis of an active technology to improve acoustic comfort in buildings. *Building and Environment*, *42*, 2785–2796.

Öhrström, E. et al. (2006a). Effects of road traffic noise and the benefit of access to quietness. *Journal of Sound and Vibration*, *295*, 40–59.

Öhrström, E. et al. (2006b). Effects of road traffic noise on sleep: Studies on children and adults. *Journal of Environmental Psychology*, *26*, 116–126.

Oldham, D. J., & Mohsen, E. A. (1979). The acoustical performance of self-protecting buildings. *Journal of Sound and Vibration*, *65*, 557–581.

Omoto, A., Takashima, K., Fujiwara, K., Aoki, M., & Shimizu, Y. (1997). Active suppression of sound diffracted by a barrier: An outdoor experiment. *Journal of the Acoustical Society of America*, *102*, 1671–1679.

Ouis, D. (2001). Annoyance From Road Traffic Noise: a Review. *Journal of Environmental Psychology*, *21*, 101–120.

Robinson, D. W. (1970). *An Outline Guide to Criteria Noise for the Limitation of Urban*. *Office*. London: Ministry of Technology.

Scholes, W. E. (1970). Traffic noise criteria. *Applied Acoustics*, *3*, 1–21.

Sharland, I. (1979). *Woods practical guide to noise control*. Waterflow: Woods Acoustics.

Skånberg, A., & Öhrström, E. (2006). Sleep disturbances from road traffic noise: A comparison between laboratory and field settings. *Journal of Sound and Vibration*, *290*, 3–16.

Sørensen, M., Hvidberg, M., Andersen, Z. J., Nordsborg, R. B., Lillelund, K. G., Jakobsen, J., … Raaschou-Nielsen, O. (2011). Road traffic noise and stroke: a prospective cohort study. *European heart journal*, *32*, 737–44.

Tadeu, A. J. B., & Mateus, D. M. R. (2001). Sound transmission through single, double and triple glazing. Experimental evaluation. *Applied Acoustics*, *62*, 307–325.

Tang, S. K. (2005). Noise screening effects of balconies on a building facade. *Journal of the Acoustical Society of America*, *118*, 213–221.

Tang, S. K. (2010). Scale model study of balcony insertion losses on a building façade with non-parallel line sources. *Applied Acoustics*, *71*, 947–954.

Tang, S. K., Ho, C. Y., & Tso, T. Y. (2014). Insertion losses of balconies on a building façade and the underlying wave interactions. *The Journal of the Acoustical Society of America*, *136*, 213.

Tong, Y. G., & Tang, S. K. (2013). Plenum window insertion loss in the presence of a line source — A scale model study. *The Journal of the Acoustical Society of America*, *133*, 1458–1467.

Venkatesham, B., Tiwari, M., & Munjal, M. L. (2009). Transmission loss analysis of rectangular expansion chamber with arbitrary location of inlet/outlet by means of Green's functions. *Journal of Sound and Vibration*, *323*, 1032–1044.

Viveiros, E. (2002). Measurement of sound insulation of acoustic louvres by an impulse method. *Applied Acoustics*, *63*, 1301–1313.

Wagner, J., Cik, M., Marth, E., Santner, B. I., Gallasch, E., Lackner, A., & Raggam, R. B. (2010). Feasibility of testing three salivary stress biomarkers in relation to naturalistic traffic noise exposure. *International journal of hygiene and environmental health*, *213*, 153–5.

Watts, G. (1996). Acoustic performance of parallel traffic noise barriers. *Applied Acoustics*, *47*, 95–119.

Watts, G. R., Crombie, D. H., & Hothersall, D. C. (1994). Acoustic Performance Of New Designs Of Traffic Noise Barriers: Full Scale Tests. *Journal of Sound and Vibration*, *177*, 289–305.

Wells, R. J. (1958). Acoustical Plenum Chambers. *Noise Conrol*, *4*, 9–15.

Wong, H. K., Yung, C. N., Tang, S. K., & Tong, Y. G. (2012). On site performances of ventilation windows for public housing development. In *ACOUSTICS 2012 cum 163rd Annual Meeting of the Acoustical Society of America* (p. Paper no. 744).

Yim, J. T. H. (2014). *Acoustical insertion loss of a modified plenum window in different configurations and settings*. MEng thesis, The Hong Kong Polythecnic University.

Zhang, J., Jiang, W., & Li, N. (2002). Theoretical and experimental investigations on coherence of traffic noise transmission through an open window into a rectangular room in high-rise buildings. *Journal of the Acoustical Society of America*, *112*, 1482–1495.