The Hong Kong Polytechnic University

Department of Building Services Engineering

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

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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

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.

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

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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

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.

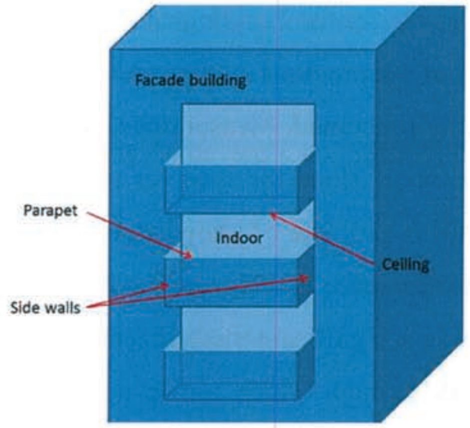

Figure 1.1 Basic components of closed balcony at façade building.

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.

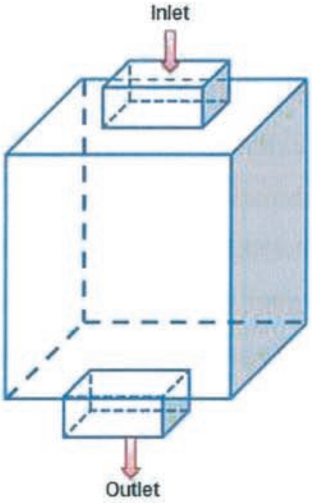

Figure 2.1 Geometry of plenum chamber.

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.

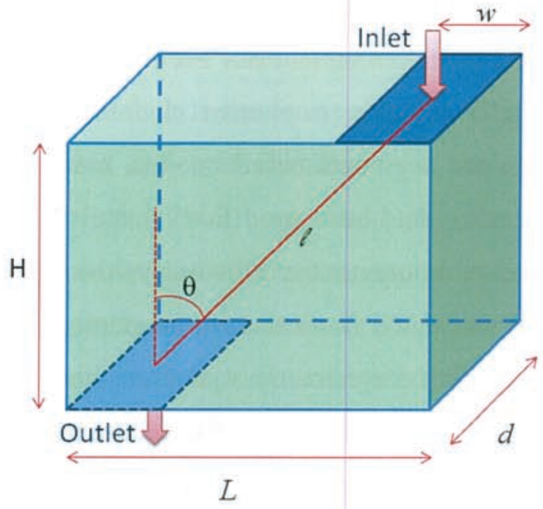

Figure 2.2 Details of plenum chamber notation.

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.

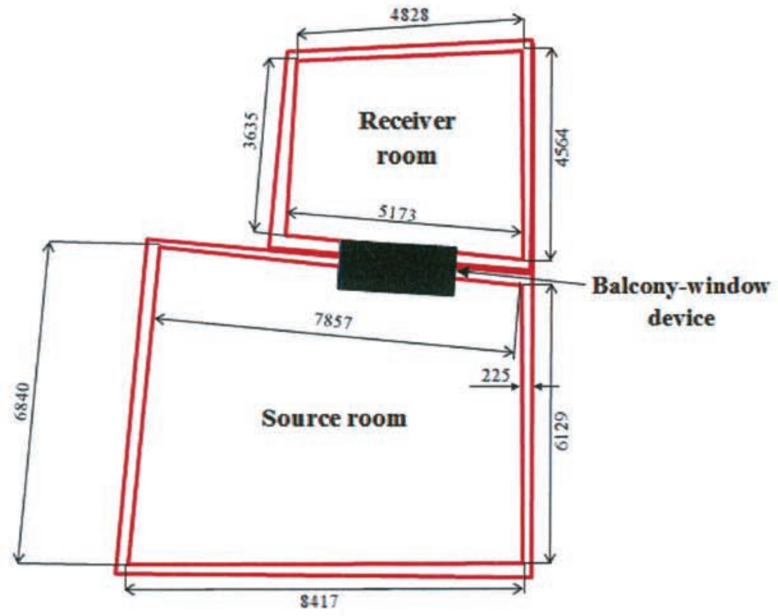

Figure 3.1 Plan of the coupled chambers (in mm).

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

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