Sound transmission across a plenum window with an active noise cancellation system

S.K.Tang[a)], Y.G.Tong[b)] and K.L.Tsui[a)]

[a)]Department of Building Services Engineering
The Hong Kong Polytechnic University
Hong Kong, China
Email : shiu-keung.tang@polyu.edu.hk

[b)]Faculty of Civil and Environmental Engineering
Universiti Tun Hussein Onn Malaysia
Parit Raja, 86400 Batu Pahat
Johore, Malaysia

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Abstract

A series of experiments was conducted in the present study in an attempt to understand how the implementation of active noise control would affect the sound transmission across a plenum window. A simple squared pressure control scheme with three error sensors equi-spaced on the vertical centerline of the indoor window opening was adopted. The secondary control loudspeakers were fixed near to the outdoor window opening. The effects of secondary control loudspeaker orientation relative to the plenum cavity and their locations on the performance of the active control were investigated. Results show that the active control system with two loudspeakers located symmetrically about the plenum cavity horizontal centerline facing directly the incoming noise gives the best performance. However, the effective frequency range is restricted to that below the first asymmetric mode cut-off frequency in the window gap direction. The active control performance is improved when the reverberation strength of the receiver chamber is reduced in general.

Primary subject classification : 51.3; Secondary subject classification : 38.2

1 INTRODUCTION

Noise pollution in the residential areas of densely populated cities has long been a problem to governments and professionals. The economic growth has led to higher demand of transportation. Noise from ground transportation has become the major source of noise pollution in these cities. Taking Hong Kong as an example, a recent survey shows that over 1/7 of the Hong Kong population is exposed to excessive traffic noise[1], but the situation is not expected to be improved in the near future even with quieter commuting machines. Similar situation is likely to have occurred in densely populated cities, such as Shanghai and Tokyo. Excessive exposure to noise has adverse effects on human health[2]. A recent WHO report illustrates that noise is the second major cause of human death in the western Europe[3] even though the EU noise directives[4] have been enforced for quite a number of years.

For convenience, people prefer to live in cities close to major transportation networks. Therefore, the outdoor environments of the living spaces are intrinsically noisy. Noise barriers and enclosures[5] to some extent can help, but they are not efficient (or even not possible) to apply in urbanized areas. Also, it has been shown by many researchers that the balconies at high-rise building façades cannot offer much acoustical protection unless sound absorption[6,7] and/or large reflectors[8] are installed. Though one can choose to close all the windows or to adopt multiple glazing windows[9] to reduce noise levels inside the living spaces, the lack of natural ventilation will also have significant adverse health impact. A device, which can offer good sound insulation and allow for natural ventilation, is therefore an ideal solution to the problem.

The results of a partially opened double glazing window of Ford and Kerry[10] have attracted the attention of researchers recently. When the double glazing window is opened and its two openings are offset, the window resembles an elongated plenum. Kang and Brocklesby[11] studied the sound insulation of such windows (hereinafter called the plenum window) with larger window openings. The effects of porous sound absorbers and micro-perforations on the sound insulation were also discussed. Tong and Tang[12] carried out scale model experiments to examine the effects of the window façade orientation relative to the sound source on the sound insulation. Tong et al.[13] presented the field measured sound insertion losses of plenum windows when real traffic on a long busy urban trunk road was the noise source. Figure 1 illustrates the configuration and dimensions of one of the plenum windows tested by Tong et al.[13] The plenum windows involved are now used in some of the public housing projects. The test results show that they can offer an additional 8 dBA sound insulation compared to a conventional side-hung casement window of an opening size just enough to meet the local statutory requirement for natural ventilation. The installation of sound absorption can further increase the sound insulation by ~1 dBA. Such small improvement should be due to the small areas for sound absorption installation.

The practical plenum windows which can be applied to a high-rise building façade are limited, especially the gap between the outer and inner layers of the glass panes has to be small (not more than 200 mm) in order not to reduce the indoor living space area significantly. Sound absorption, even the relatively transparent micro-perforated absorbers, cannot be installed onto the window because of the abovementioned gap width restriction, aesthetic reasons and daylight penetration. Active noise control technique has been implemented to ductwork[14] and to confined spaces[15]. Recently, such technique is also applied to window openings for reducing the indoor sound levels[16,17]. In principle, large sound attenuation can be achieved if the destructive interference between the primary and secondary sound fields is managed properly. Therefore, it is a potential add-on for improving the performance of plenum windows. Huang et al.[18] investigated the use of active control for improving the sound insulation performance of a plenum window using scale model experiment supplemented by numerical analysis. They restricted the incident wave to be a plane wave and thus the incident sound intensity to the plenum window outer opening was uniform. This arrangement is only true for the cases with distant noise sources. Qiu et al.[19] applied active control to a plenum window with large overlapping length and showed experimentally that the noise reduction performance could be enhanced by separating the window cavity into an upper and a lower compartment. This effectively converted the plenum window into two parallel ducts.

In this study, the sound transmission across a full scale plenum window, which was basically the same as that installed in the bedroom in the field mockup of Tong et al.[13], equipped with an active noise cancellation system is investigated experimentally inside the laboratory of the author. The performance of the active control system under various combinations of control sources and error signals is examined. The effect of the reverberation condition in the receiver room on the overall sound transmission is also studied. It is believed that the present results will provide useful information on the application of active noise cancellation in building noise control.

2 EXPERIMENTAL SETUP

The experimental study was carried out inside the building acoustic testing facility in the Department of Building Services Engineering, The Hong Kong Polytechnic University. This facility consisted of two isolated reverberation chambers originally designed for sound transmission loss measurements according to ISO140-3[20]. The plenum window in this study was installed in the middle of the brick wall separating the two chambers. The source chamber was converted into a semi-anechoic chamber by putting up 2 inches (~50 mm) thick fiberglass panels (density 32 kg/m^3) at 1 m away from its side walls, rear wall and ceiling. The floor and the separating wall remained acoustically hard. The workable size of the source chamber was 5 m by 5m by 4 m (height). The reverberation time of the source chamber was then reduced to less than 0.2 sec at frequencies above the 200 Hz one-third octave band and was about 0.5 sec within the 100 Hz one-third octave band. This condition is more realistic as it is very rare to have random sound incidence in practical situation. The reverberation of the receiver chamber could be adjusted by using fiberglass panels.

The design of the plenum window used in this study, which is shown in Fig. 1, was the same as that of the plenum window in the bedroom of Tong et al[13]. The overlapping length of this window was shorter than that of the window adopted in the experiment of Qiu et al[19]. The outer skin consisted of two conventional side hung windows separated by a fixed window of 525 mm span. The inner layer was a sliding glass pane. Throughout the experiment, the L.H.S. side hung window was kept fully opened, while the inner sliding glass pane was sealed on the L.H.S. of the plenum cavity to form an air passage with staggered openings across the plenum window. The height of the window opening was 1352 mm.

The primary sound source was a 6-inch (~150 mm) aperture loudspeaker located on the floor of the source chamber facing directly towards the centre of the plenum window outer opening. The active control in this study was implemented using the MIMO EZ-ANCII active noise controller with adaptive feedforward FXLMS algorithm. The active noise cancellation system in this study consisted of one reference signal, three error signals and three secondary control sources (10 cm aperture VISATON FR 10 HMP)[21].

Figure 2 illustrates the microphone locations inside the receiver room and the sub-figure shows the details of the error microphones and the secondary sources in the plenum window used in this study. The error microphones were equi-spaced along the height of the inner window opening on the vertical centerline of the inner window opening. Owing to practical reason, the error sensors were not located inside the receiver chamber. The locations for installing the secondary control sources were restricted in practice. Unlike the case of Huang et al.[18], there could only be two practical ways for secondary control source installation. The secondary sources in this study were equi-spaced either along the window mullion facing the plenum cavity or along the window panel directly facing the incoming noise near to the outer window opening. The sub-figure of Fig. 2 illustrates these two arrangements. For easy reference, the cases where the secondary sources are facing the plenum window cavity (C1, C2 and C3) and the incoming noise (F1, F2 and F3) are hereinafter referred to as ‘C’ and ‘F’ respectively. For the ‘C’ cases, the sound from the primary source is controlled within the plenum cavity, while sound interference at the plenum inlet is expected in the ‘F’ cases. There were three control configurations tested in this study. In the foregoing discussions, ‘1-ANC’ refers to the case where only the middle loudspeaker (C2/F2) was used, ‘2-ANC’ refer to the case where only the outer secondary loudspeakers (C1,C3/F1,F3) were used and ‘3-ANC’ represents the case when all the three secondary control sources were in simultaneous operation. The squared pressure control strategy was adopted[15,18]. All three error microphone signals were used simultaneously throughout this study.

It should be noted that the sources C2, F2 and the error microphone E2 were located on the nodal planes of the odd vertical (height-wise) acoustic modes and the anti-nodal planes of the even height-wise modes. The devices C1, C2, F1, F3, E1 and E3, were on the nodal and anti-nodal planes of the $2(2n\text{-}1)$th and the $4n$th order height-wise modes respectively, where n is an integer and $n \geq 1$. The effectiveness of the active control will be largely affected by these height-wise acoustic modes. This will be discussed further later. The gap-wise modes were of eigen-frequencies and were in general not important because of the then very serious modal overlapping.

The effectiveness of the active control in this study is described by the difference in the average sound pressure levels in the receiver chamber with and without the active control. These average sound pressure levels were measured by six microphones which spanned over the entire volume of the receiver chamber according to ISO140-3[20] (see Fig. 2). The reference microphone was located at 1 m away from the middle of the plenum window outer opening inside the source chamber. This is similar to that used in Kwon and Park[17]. One should note that this location may not be preferable in practice, but should be acceptable for a preliminary testing on the possibility of active noise attenuation. Microphones used in this study were the ¼" inch Brüel & Kjær Type 4935. All microphone signals were recorded simultaneously for later analysis using a Brüel & Kjær Type 3506D PULSE system. As traffic noise is the major concern in a high-rise congested city, the frequency range in the foregoing analysis starts from the 100 Hz one-third octave band[22].

3 RESULTS AND DISCUSSIONS

Tonal excitations were used in the first set of experiments. Measurements were done with and without sound absorption on the floor of the receiver chamber in an attempt to understand also the effect of receiver chamber reverberation on the active control performance. One inch (~25 mm) thick fiberglass panels of density 32 kg/m^3 were used as the sound absorber in this study. Figure 3 shows the reverberation times inside the receiver chamber in the present study. With the fiberglass in place, the reverberation strength inside the receiver chamber was reduced by approximately 50%, except at the low frequency side of the present frequency range of interest.

The plenum window itself does offer some degree of sound attenuation in the absence of the active control[12,13]. Figure 4 shows the differences between the average sound levels inside the receiver chamber and that measured at the reference location. Such level differences are large, but with a strong dip at 125 Hz. Though the first asymmetric higher mode frequency along the height of the plenum window is 125.7 Hz assuming an ambient sound speed of 340 m/s, it will be shown later that this dip is more likely to be the result of a longitudinal resonance between the two window openings. Without the sound absorbers in the receiver chamber, the sound level differences are smaller, which is expected.

Figure 5 illustrates the differences between the average sound pressure levels in the receiver chamber with and without the sound absorber when the secondary sources were arranged in the ‘C’ orientation under tonal excitation. One can observe that the performance of the active control by minimizing the sum of the squared error microphone pressures is not satisfactory. Sound amplification can be found inside the receiver chamber. In the non-anechoic receiver room, the sound field is made up of a direct and a reverberant sound field. The minimization of squared pressures at the interface between the receiver room and the plenum window can create quiet zones near to the error microphones similar to the case of Lau and Tang[15] and Joseph et al.[23], and is thus not sufficient to guarantee an overall sound energy reduction inside the receiver room. The situation can be improved with a weaker reverberant field inside the receiver room. The minimization of squared pressures at the mentioned interface will indicate global sound reduction inside an anechoic receiver room.

At excitation frequencies at or below 400 Hz, the sound absorbers in the receiver chamber in general result in a slightly better active control performance. However, there appears no definite trend at higher excitation frequencies and thus results in this part of the frequency range are not discussed. One should note that the first asymmetric eigenmode frequency across the gap width is ~970 Hz. The current secondary control loudspeakers should be unable to deal with such kind of acoustic modes as they are on the nodal planes of these modes. In general, the 2-ANC appears to be the most stable system at frequencies below 800 Hz, while the 1-ANC appears the worst with a few prominent dips at 315 Hz and 630 Hz. These dips are also observed under the 3-ANC control and are independent of the receiver room reverberation level. In fact, they can also be found under the 2-ANC control, but the corresponding dip magnitudes are relatively weak. The less effective 3-ANC is left to further investigation.

The harmonic relationship between the dip frequencies shown in Fig. 5 suggests the occurrence of resonance within the plenum window cavity under tonal excitation. The acoustic modes of the cavity and the locations of the loudspeakers (and those of the error microphones) relative to their nodal and anti-nodal planes are therefore believed to have significantly affected the active control performance. Table 2 summarizes the first 44 eigenmodes of the window cavity[24]. One can find that the eigen-frequencies of the (3,0,0), (2,0,2) and (3,0,1) plenum cavity modes are 313.8, 327.1 and 338.1 Hz respectively, while there are 5 modes having eigen-frequencies close to 630 Hz. They are all highlighted in Table 2.

In order to confirm the occurrence of modal resonance, a white noise signal was fed to the primary loudspeaker and the error microphone signals were recorded without the active control. Figure 6a illustrates the magnitudes of the transfer functions between the error microphone signals. The modal resonance around 320 Hz and at 630 Hz is obviously seen. The phase angles of these transfer functions are presented in Fig. 6b. The out-of-phase relationship between the upper and lower error microphone signals at 630 Hz suggests the resonance of vertical odd modes, which tend to be in-line with the data shown in Table 2. Similar phase relationship between the upper and the middle error microphone signals at 630 Hz should indicate the phase relationship between the (6,0,0) and the sum of all the odd modes around 630 Hz. The excitation of the even (4,0,4) mode is likely according to the results shown in Fig. 6. The situation at 320 Hz is quite similar. There is an evidence supporting the resonance of the (3,0,1) mode. However, the (2,0,2) mode alone should give a weak sound field at the upper/lower error microphone positions, such that this mode is not reliably captured.

The 1-ANC system is not expected to function well in the presence of strongly out-of-phase error signals. It is because the loudspeaker of this system is unable to create a vertical cancellation odd mode as it is located on the nodal planes of the odd modes which create strong out-of-phase signals at the error microphones E1 and E3. This happens at ~315 Hz and 630 Hz. The control loudspeaker is also located on the nodal plane of the (3,0,1) mode. The mono-loudspeaker configuration of the 1-ANC cannot handle the (2,0,2) mode as well when the upper and lower error microphones are picking up weak signals. As indicated by Fig. 6b and Table 2, the sound field inside the window cavity is dominated by vertical odd modes at frequencies around 630 Hz. Since the central/middle loudspeaker cannot produce odd cancellation modes in the vertical direction, the system may perform better if that loudspeaker is removed as the settings of the three cancellation paths in our experiment were the same. At this relatively higher frequency, a stronger receiver chamber reverberation together with the expected large degree of modal overlapping tend to equalize sound pressure across the window opening on the receiver side. This helps improve the performance of the active control. Since the vertical modes are worsening the active control performance, it is conjectured that the installation of sound absorbers on the internal perimeter surfaces of the plenum cavity[13] will enhance the performance of the active control. It is left to further investigation.

It is interesting to note that the dips in Fig. 5 at frequencies before 800 Hz are observed only at 315 Hz and 630 Hz. At very low frequency around ~125 Hz, the in-phase signals at the three error microphones (Fig. 6b) tend to indicate that the sound field along the error microphone vertical plane is relatively uniform. This suggests that the strong dip at this frequency observed in Fig. 4 is the result of a longitudinal resonance between the two window openings instead of the excitation of the odd vertical mode (0,0,1). At the frequencies of 250 Hz, 400 Hz and 500 Hz, the phase relationships between error microphones shown in Fig. 6b suggest the sound field at the error microphone region is in general dominated by even vertical modes, instead of the odd modes at 315 Hz and 630 Hz. The current ANC systems perform less satisfactorily in the latter cases as discussed above.

Figure 7 illustrates the performance of the active control when the secondary control loudspeakers were arranged in the 'F' orientation, facing the incoming sound. In general, these active control systems perform better than those with the secondary loudspeakers arranged in the 'C' orientation, especially at frequencies below 600 Hz. The worst performing system here is the 2-ANC in the presence of a very reverberation receiver chamber. The dips at 315 Hz and 630 Hz due to the modal resonance discussed above can still be found, but their magnitudes are smaller than those under the 'C' loudspeaker orientation. The reason for the dip at 200 Hz under the 2-ANC with a very reverberant receiver chamber is not known. In fact, there is also a small increase in the average noise level after the operation of the active control near to this frequency under similar receiver chamber reverberation condition as shown in Fig. 5.

In Fig. 8 are presented the typical cross spectral densities between the primary loudspeaker input signals and those of the error microphones without the active control under the two reverberation conditions of the receiver chamber in this study. It is noticed that the cross spectral densities are smaller and thus weaker sound transmission into the receiver chamber when it is more reverberant (without fiberglass panels). It can also be observed from Fig. 8a that the magnitude of the spectral density at 200 Hz associated with the lower microphone appears weak compared to those with the other two error microphones in the presence of a more reverberant receiver chamber. This situation is not found when the receiver room is less reverberant as shown in Fig. 8b. It is also found that the error microphone signals at ~200 Hz are quite in-phase (not shown here). It appears that the 2-ANC system with cancelling sources in 'F' orientation cannot effectively handle a very asymmetrical sound field at the interface between the plenum window and receiver chamber. However, it is unlikely that such a strongly reverberant receiver room will appear in practice and thus this part of the results is not further discussed. To conclude, the ‘F’ source orientation under 2-ANC appears a better choice for practical implementation as the reverberation times within normal residential units should normally be less than 0.8 sec at frequencies higher than 100 Hz.

With the same system settings, experiments were conducted with a broadband noise without strong tonalities. Figure 9 illustrates the performances of all the active control systems tested in this study when a broadband white noise was fed into the primary source loudspeaker. One-third octave band data are used as this frequency band series is the most commonly adopted one in building acoustics. It should be noted that the 3-ANC with ‘F’ oriented secondary loudspeakers could not be implemented. The reason is not known. One can observe that the ‘F’ oriented secondary loudspeakers give a better performance. The corresponding 2-ANC system gives the best performance, but the effect is mainly concentrated at frequencies less than 200 Hz. It should also be noted that the results at the 50 Hz one-third octave band may not be reliable as the small secondary loudspeakers do not perform well at this frequency[21]. Active control systems with ‘C’ oriented secondary loudspeakers do not work under broadband noise excitation. The reason is again unclear and is left to further investigation.

Results at frequencies higher than 1000 Hz are not discussed as it has been shown before that the performance trend of the active control is not straight-forward in this frequency range. The acoustic modes across the plenum window gap are believed to be the main cause of the problem. The unsatisfactory active control performance at higher frequency in Huang et al.[18] is probably due to these gap-wise modes.

Figure 10 illustrates the frequency spectrum of the additional sound attenuation achieved by implementing the active control with ‘F’ oriented secondary loudspeakers. For the 2-ANC, the additional attenuation is concentrated near to the frequencies 68 Hz, 94 Hz and ~122 Hz. The last one corresponds to the (0,0,1) plenum cavity mode. The one at 94 Hz is close the (1,0,0) mode. The peak at ~68 Hz appears to come from a resonance across the two opposite corners of the plenum window cavity (~80 Hz). The active control appears more efficient at the lower order eigenmodes in the presence of a broadband noise. This is different from the cases with tonal sound excitation. For the cases of 'C' oriented secondary loudspeakers, only the 1-ANC system can produce a significant but very narrow band of additional sound attenuation at ~100 Hz, which corresponds to the (1,0,0) mode of the plenum cavity (not shown here).

4 CONCLUSIONS

An experimental investigation was carried out in this study in an attempt to understand whether active control can be used to improve the sound transmission loss across a plenum window. Such window type has been shown in previous studies to be able to offer significant sound insulation, but can also allow for a reasonable level of natural ventilation. A simple active control system consisted of three error microphones, three secondary control loudspeakers and a MIMO active noise controller with adaptive feedforward FXLMS algorithm was used.

Owing to practical consideration, the secondary control loudspeakers were arranged in two orientations relative to the plenum window cavity. One of them was that the loudspeakers faced the cavity towards the indoor outlet of the window, and the other loudspeakers faced directly the incoming sound in the other orientation. The control strategy was to minimize the sum of the squared pressures recorded by the error microphones. Both tonal and broadband noise excitations were involved. The primary sound source was a 6-inch (~150 mm) aperture loudspeaker placed on the floor of the testing chamber. The effect of the reverberation in the receiver chamber on the active control performance was also investigated.

Under tonal excitation, the active control is in general no reliable and gives very choppy performance at frequencies higher than the first cut-off frequency of the gap-wise acoustic mode. At lower frequencies, the acoustic modes in the plenum window cavity, especially those vertical ones, are adversely affecting the active control performance. It is found that the control systems with secondary control loudspeakers facing the cavity are in general not applicable, and will lead to the deterioration of the overall plenum window sound insulation. The control system with two secondary control loudspeakers symmetrically located on the two sides of the window horizontal centerline and facing the incoming sound perform the best among all systems tested in this study.

In the presence of a broadband incoming noise, only the control system with two secondary control loudspeakers symmetrically located on the two sides of the window horizontal centerline and facing the incoming noise is useful for enhancing the performance of the plenum window. However, the improvement is restricted at the frequencies before 200 Hz, and is effective at or near to the lower order plenum window eigenmodes. It is also found that a less reverberant receiver room, in general, will result in better active control performance.

5 REFERNCES

1. Environmental Protection Department, *A Comprehensive Plan to Tackle Road Traffic Noise in Hong Kong*, HKSAR Government, Hong Kong, (2006).
2. W. Babisch, "The noise/stress concept, risk assessment and research needs", *Noise Health* **4**(16), 1 – 11, (2002).
3. WHO, *Burden of Disease from Environmental Noise. Quantification of Healthy Life Years Lost in Europe*, World Health Organization, Bonn, (2011).
4. Directive 2002/49/EC Assessment and Management of Environmental Noise (European Union, 2002).
5. K. M. Li and S. H. Tang, "The predicted barrier effects in the proximity of tall buildings", *J. Acoust. Soc. Am.*, **114**(2), 821 – 832, (2003).
6. D. N. May, "Freeway noise and high-rise balconies", *J. Acoust. Soc. Am.*, **65**(3), 699 – 704, (1979).
7. S. K. Tang, C. Y. Ho and T. Y. Tso, "Insertion losses of balconies on a building façade and the underlying wave interactions", *J. Acoust. Soc. Am.*, **136**(1), 213 – 225, (2014).
8. T. Ishizuka and K. Fujiwara, "Traffic noise reduction at balconies on a high-rise building façade", *J. Acoust. Soc. Am.*, **131**(3), 2110 – 2117, (2012).

9. A. J. B. Tadeu and D. M. R. Mateus, "Sound transmission through single, double and triple glazing. Experimental evaluation", *Appl. Acoust.*, **62**(3), 307 – 325, (2001).

10. R. D. Ford and G. Kerry, "The sound insulation of partially open double glazing", *Appl. Acoust.*, **6**(1), 57 – 72, (1973).

11. J. Kang and M. W. Brocklesby, "Feasibility of applying micro-perforated absorbers in acoustic window systems", *Appl. Acoust.*, **66**(6), 669 – 689, (2005).

12. Y. G. Tong and S. K. Tang, "Plenum window insertion loss in the presence of a line source – a scale model study", *J. Acoust. Soc. Am.*, **133**(3), 1458 – 1467, (2013).

13. Y. G. Tong, S. K. Tang, J. Kang, A. Fung and M. K. L. Yeung, "Full scale field study of sound transmission across plenum windows", *Appl. Acoust.*, **89**, 244 – 253, (2015).

14. G. Canevet, "Active sound absorption in an air conditioning duct", *J. Sound Vibr.*, **58**(3), 333 – 345 (1978).

15. S. K. Lau and S. K. Tang, "Sound fields in a rectangular enclosure under active sound transmission control", *J. Acoust. Soc. Am.*, **110**(2), 925 – 938, (2001).

16. M. Nishimura, K. Ohnishi, N. Kanamori and K. Ito, "Basic study on active acoustic shelding," *Proc. INTER-NOISE* 2008, CR-ROM (2008).

17. B. Kwon and Y. Park, "Interior noise control with an active window system," *Appl. Acoust.* **74**(5), 647 – 652 (2013).

18. H. H. Huang, X. J. Qiu and J. Kang, "Active noise attenuation in ventilation windows", *J. Acoust. Soc. Am.*, **130**(1), 176 – 188, (2011).

19. X. J. Qiu, H. H. Huang and Z. B. Lin, "Progress in research on natural ventilation ANC windows," *Proc. INTER-NOISE* 2011, CR-ROM (2011).

20. *Acoustics – Measurement of sound insulation in buildings and of building elements – Part 3: Laboratory measurements of airborne sound insulation of building elements*, ISO 140-3 : 1995, International Organization for Standardization, Geneva, Switzerland, (1995).

21. VISATON, http://www.visaton.com/en/industrie/breitband/fr10hmp_4.html

22. *Road Traffic Noise Reducing Devices – Test Methods for Determining the Acoustic Performance – Part 3. Normalized Traffic Noise Spectrum*, BS ISO EN 1793-3 : 1998, International Organization for Standardization, Geneva, Switzerland, (1998).

23. P. Joseph, S. J. Elliott and P. A. Nelson, "Near field zones of quiet," *J. Sound Vib*., 172(2), 605 – 627 (1994).

24. L. E. Kinsler, A. R. Frey, A. B. Coppens and J.V. Sanders, *Fundamentals of Acoustics. 4th ed*., Wiley, New York, (2000).

Captions

Figure 1 Dimensions of the plenum window in this study (all dimensions in mm).

Figure 2 Experimental setup.

● : Microphones; ◆ : reference microphones;

○ : 'F' orientation secondary control loudspeakers;

● : 'C' orientation secondary control loudspeakers;

Figure 3 Reverberation times in the receiver chamber.

○ : without fiberglass panels; ● : with fiberglass panels.

Figure 4 One-third octave band noise level differences across the plenum window.

Legends : same as those in Fig. 3.

Figure 5 Performance of active control under tonal excitation with secondary loudspeakers in 'C' orientation.

○ : 1-ANC; □ : 2-ANC; △ : 3-ANC;

Closed symbol : with fiberglass in receiver chamber;

open symbol : no fiberglass in receiver chamber.

Figure 6 Transfer functions between error microphone signals with fiberglass panels in receiver chamber when the active control system was turned off.

(a) Magnitude of transfer functions

——— : between upper and middle error microphone signals;

—·— : between upper and lower error microphone signals;

(b) Phase differences

○ : between upper and lower error microphone signals;

□ : between upper and middle error microphone signals.

Figure 7 Performance of active control under tonal excitation with secondary loudspeakers in 'F' orientation.

Legends : same as those in Fig. 5.

Figure 8 Cross-spectral densities between primary loudspeaker input and error microphone signals without active control.

(a) Without fiberglass in receiver chamber; (b) with fiberglass in receiver chamber.

— · — : Upper error signal; – – – –: middle error signal; ——— : lower error signal.

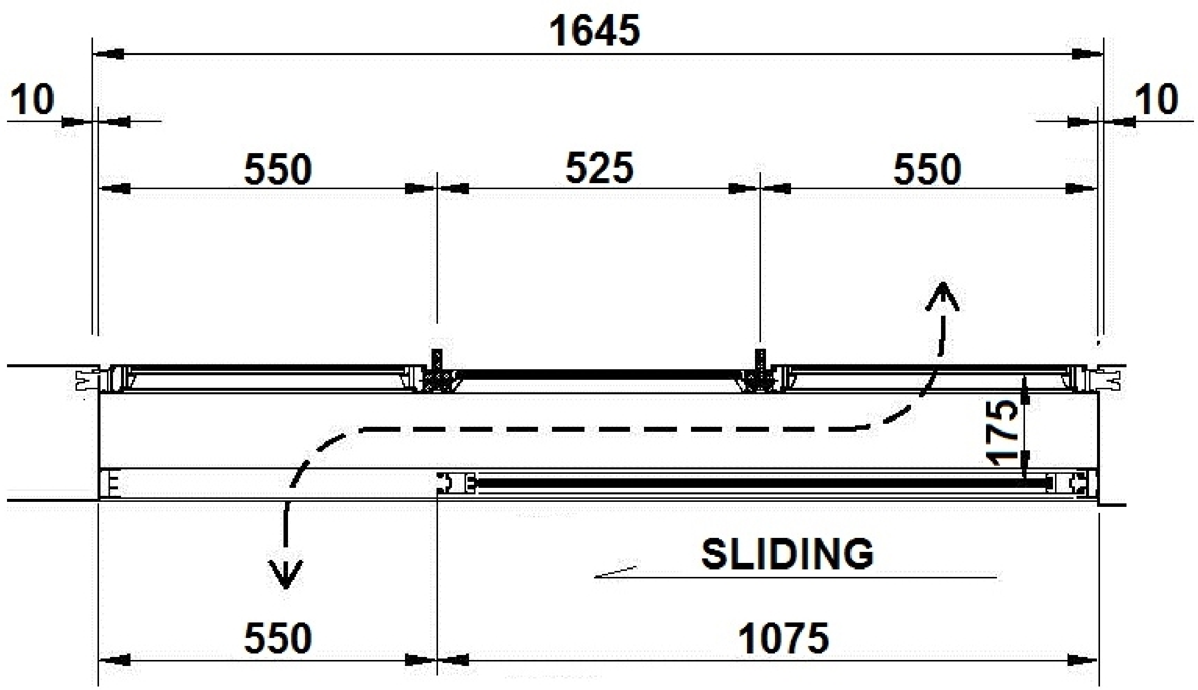
Figure 9 One-third band performances of active control systems with different secondary loudspeaker orientations under broadband noise excitation.

(a) ‘F’ orientation; (b) ‘C’ orientation.

Legends : same as those in Fig. 5.

Figure 10 Sound attenuation spectra of active control systems with ‘F’ secondary loudspeaker orientations under broadband noise excitation.

— · — : 1-ANC; ——— : 2-ANC.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10
10
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175
SLIDING
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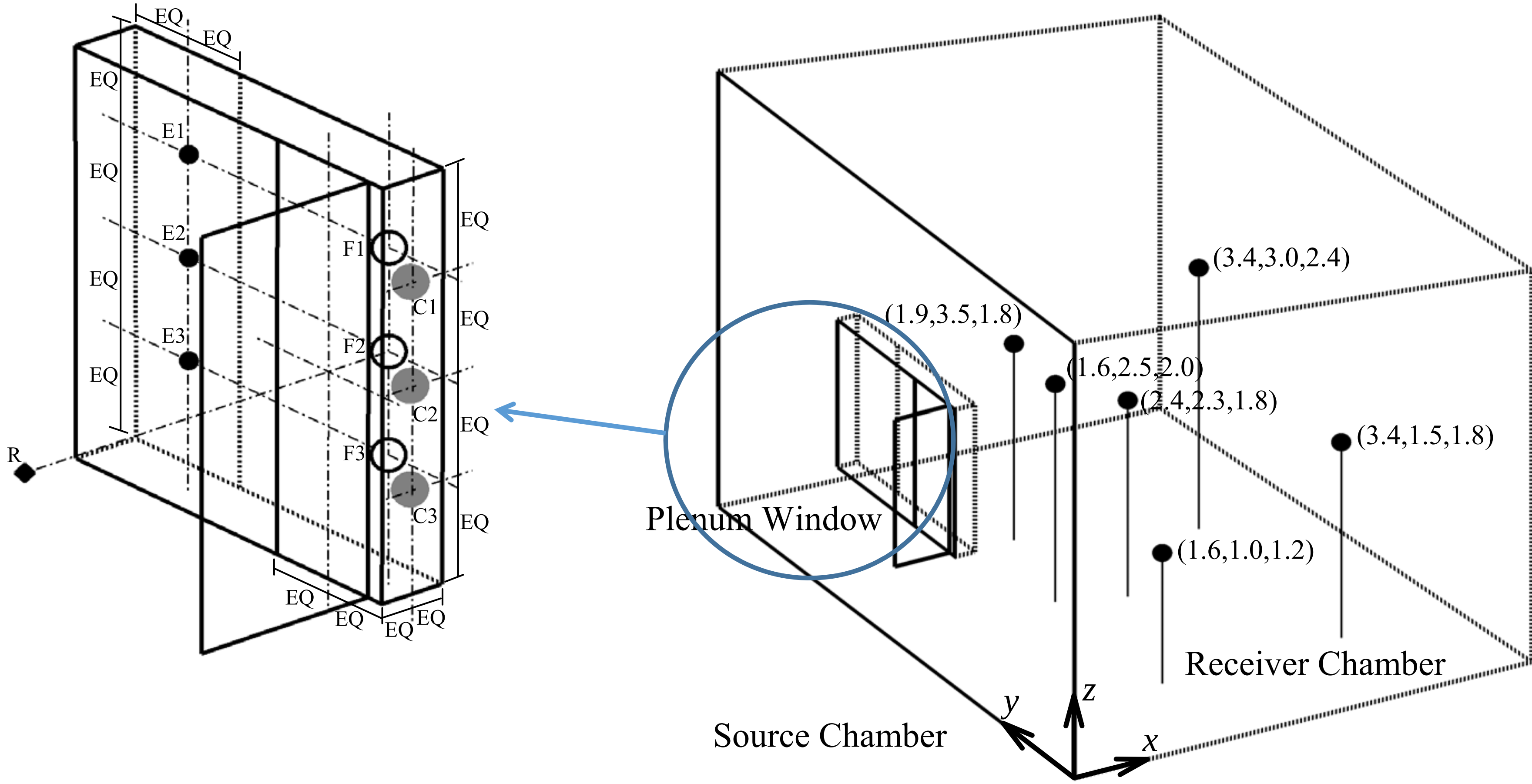
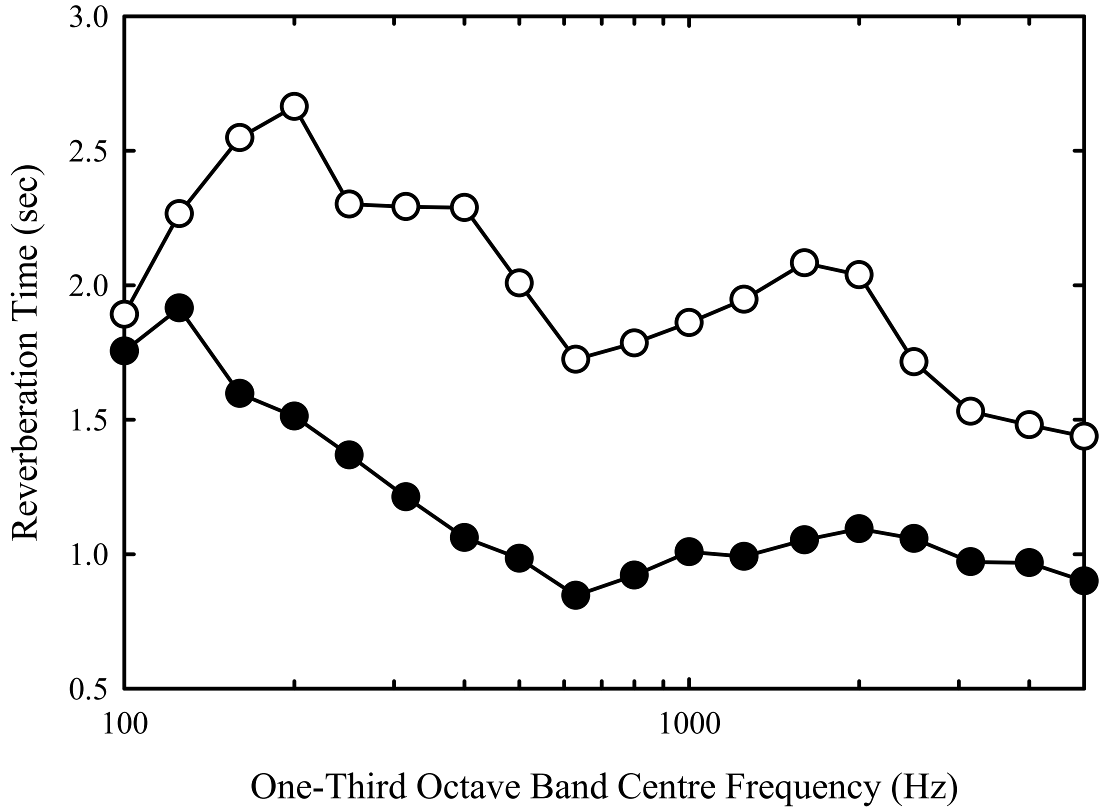
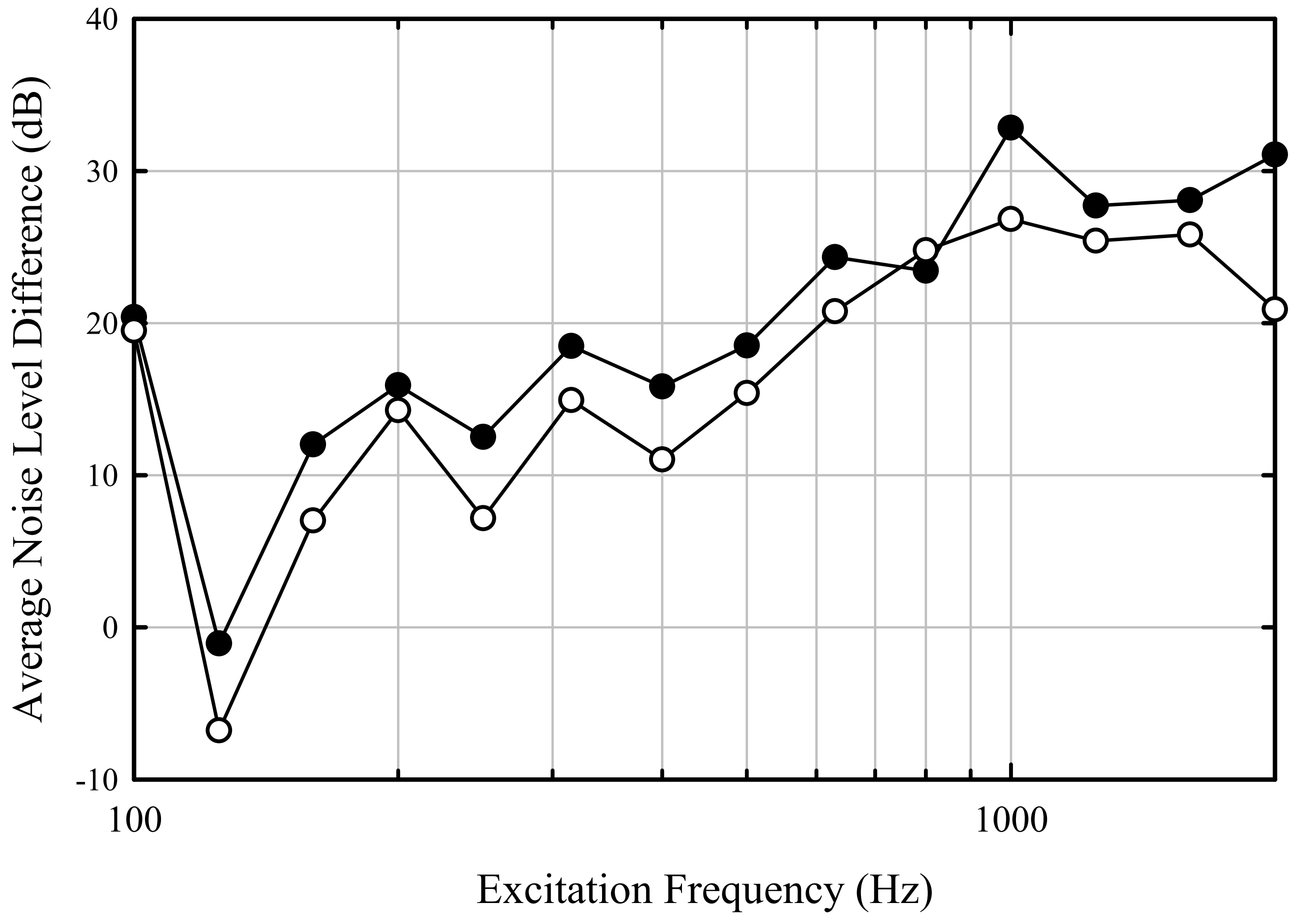
1075

Tang, Tong + Tsui Fig.2

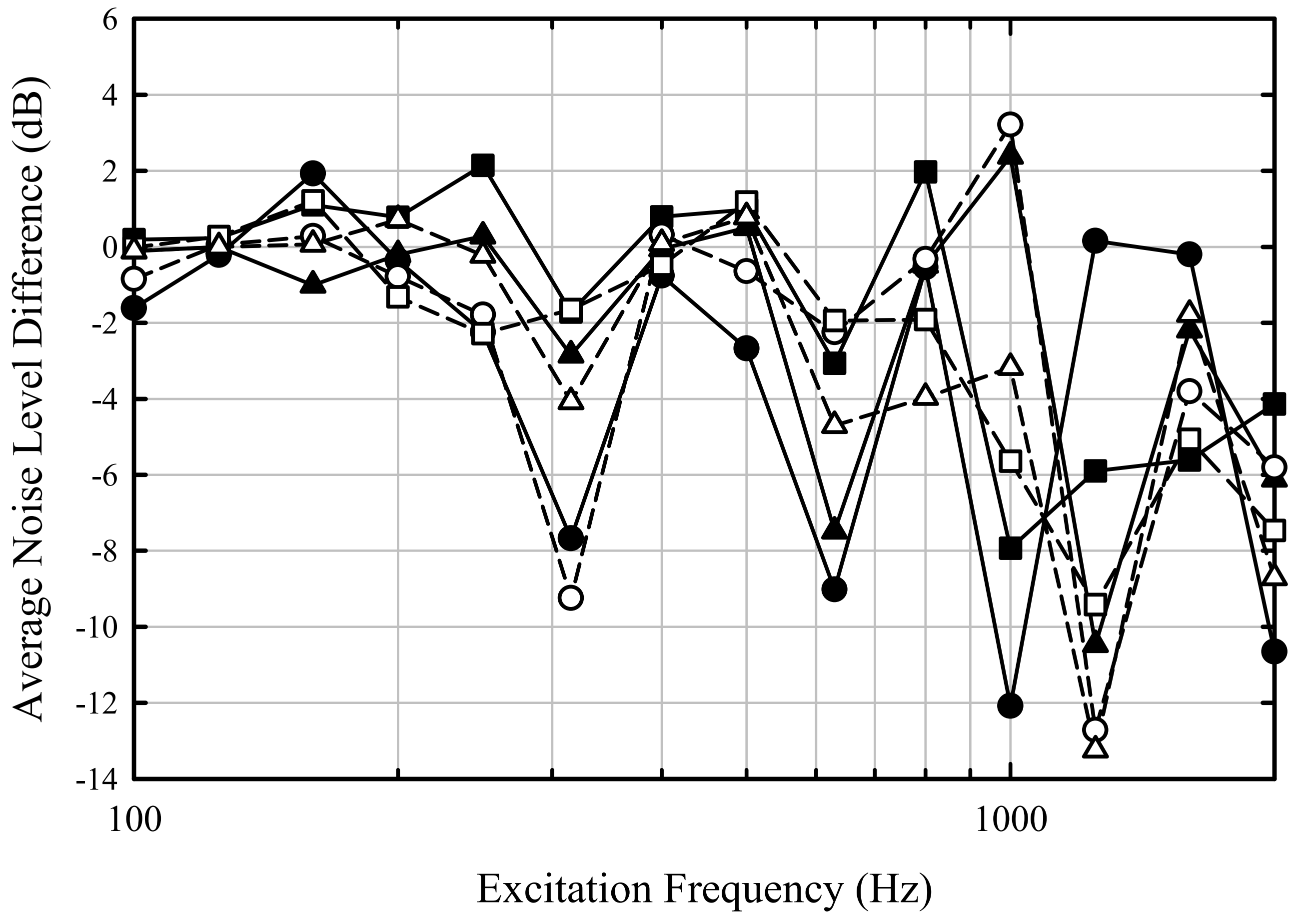



3.0
2.5
2.0
1.5
1.0
0.5
Reverberation Time (sec)
100
1000
One-Third Octave Band Centre Frequency (Hz)

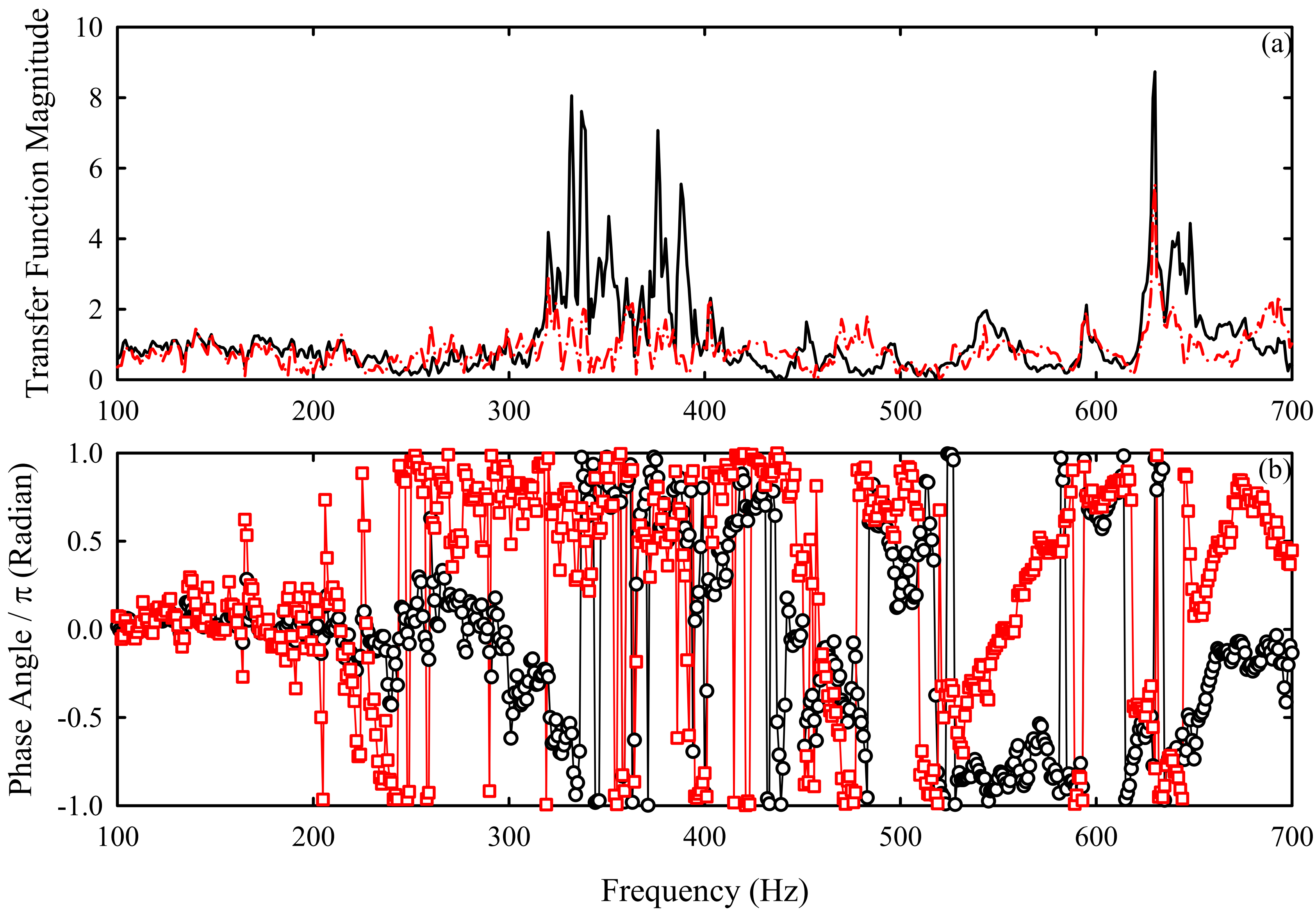
Tang, Tong + Tsui Fig.4

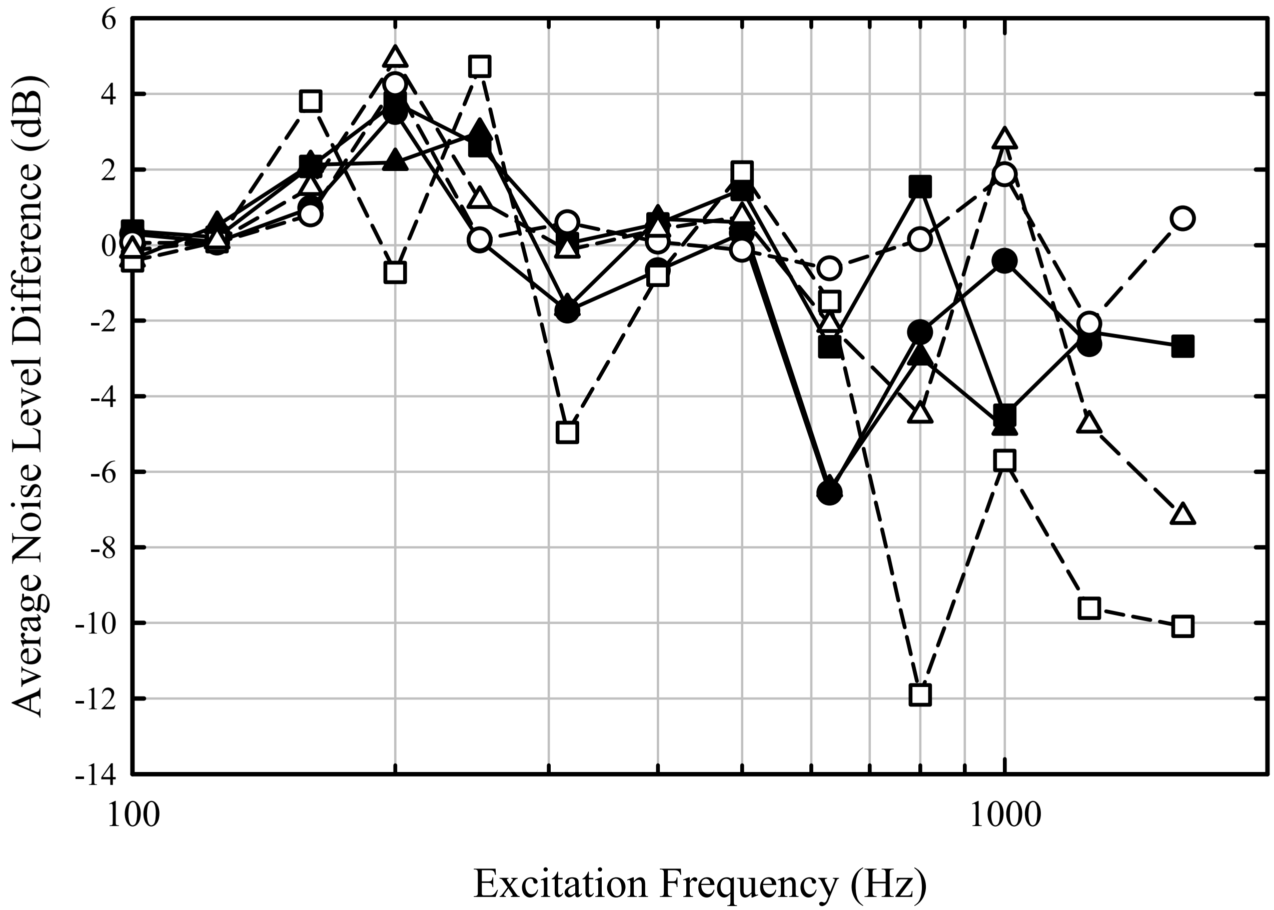


Tang, Tong + Tsui Fig.5



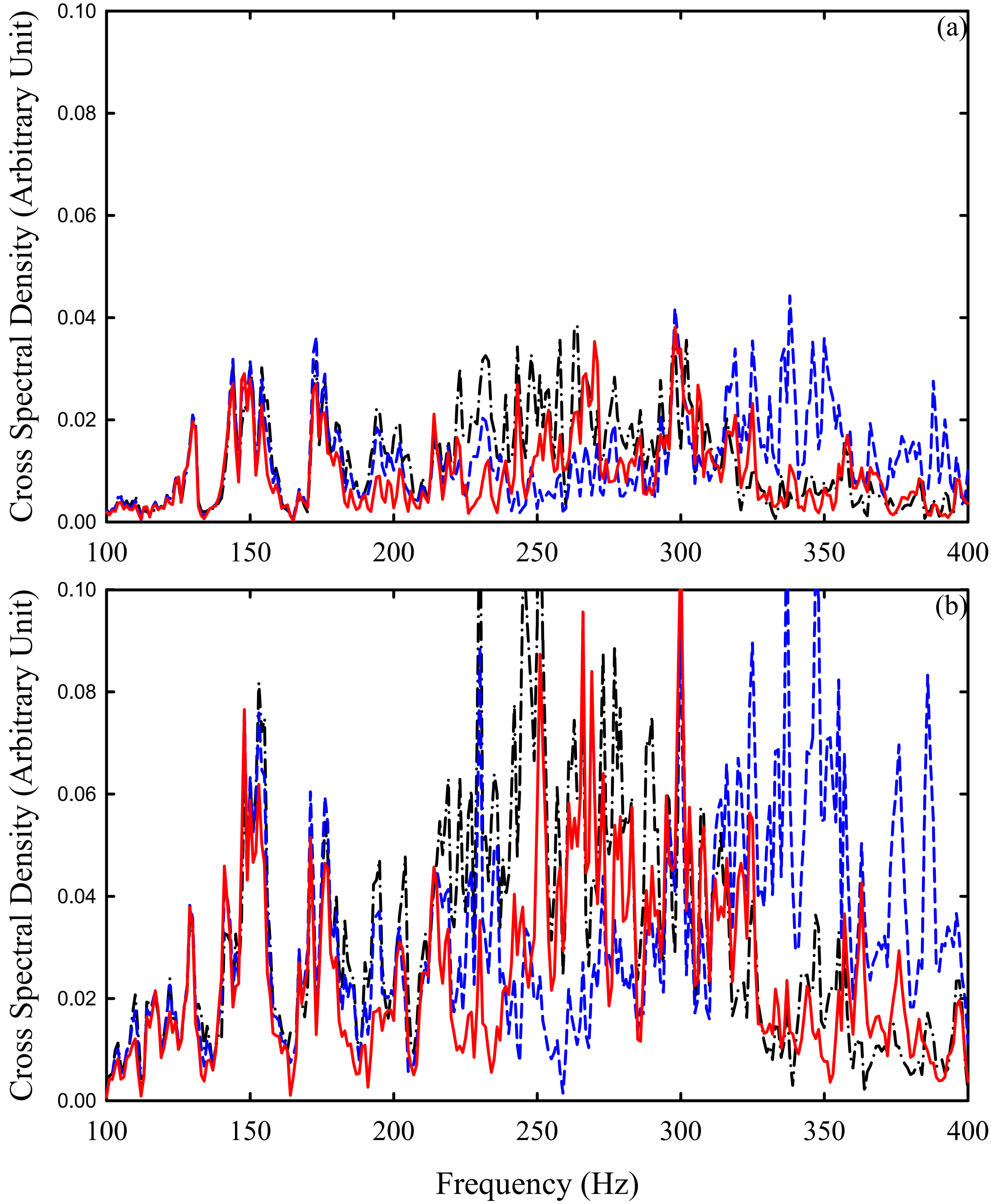
Tang, Tong + Tsui Fig.6

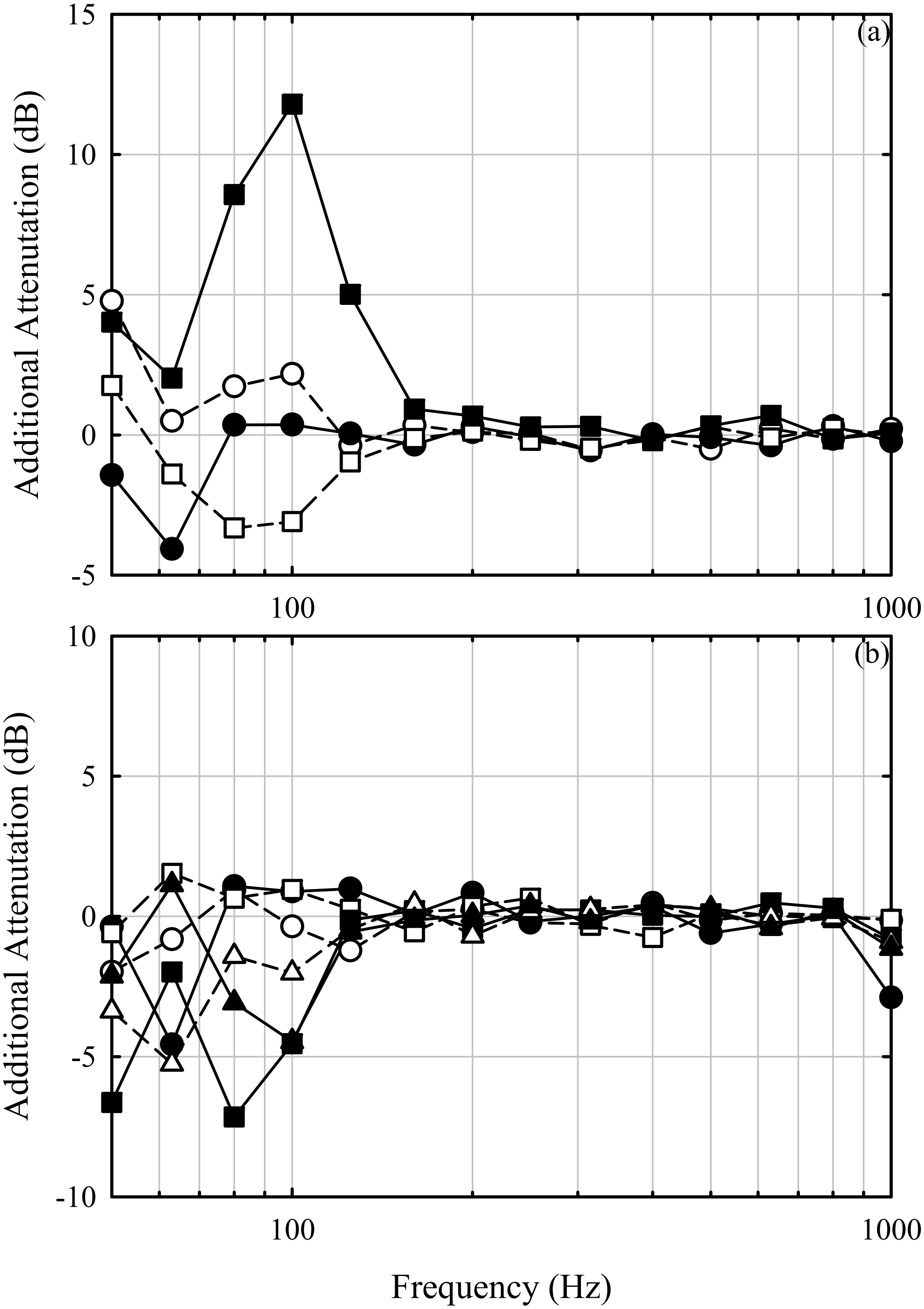




6
4
2
0
-2
-4
-6
-8
-10
-12
-14
Average Noise Level Difference (dB)
100
1000
Excitation Frequency (Hz)

Tang, Tong + Tsui Fig.8





15
10
5
0
-5
(a)
Additional Attenuation (dB)
100
1000
10
5
0
-5
-10
(b)
Additional Attenuation (dB)
100
1000
Frequency (Hz)

Tang, Tong + Tsui Fig.10