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Insertion loss of asymmetrical balconies on a building façade

S. K. Tang,[a] C. Y. Ho, and W. Y. Chan
Department of Building Services Engineering, The Hong Kong Polytechnic University, Hong Kong, China

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The acoustical insertion loss of asymmetrical balconies on high-rise buildings was studied experimentally using a 1:3 scaled down model in the present study. Four balcony forms featured by the presence of a full-height side-wall were included. A linear loudspeaker array was adopted as the sound source. The effects of source orientation and balcony elevation angle on the insertion loss and its spectral variation were examined. The position of the full-height side-wall relative to the sound source significantly affects the balcony insertion loss. It is observed that the maximum traffic noise amplification and attenuation are both ∼6 dBA. Results also suggest that the balustrade has no effect on the insertion loss spectral variation pattern, though the insertion loss magnitude could be much reduced without it in the presence of a short side-wall. This short side-wall determines the insertion loss spectral variation pattern. Significant sound amplification is found at frequencies of the odd order transverse modes, the longitudinal modes, and their coupled modes regardless of balcony form and elevation angle. It is also found that the major acoustic mode interactions are basically independent of source orientation for balconies without the short side-wall.
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I. INTRODUCTION

In a densely populated high-rise city where available land for residential purposes is limited, residential units are usually small. Balconies on building façades are very much welcomed by people as these structures can offer an extra space psychologically as well as functionally very different from the relatively confined indoor space.[1] However, residential buildings in a congested urbanized city are very often built next to main ground transportation roads for convenience. Protecting people from being exposed excessively to traffic noise has long been a challenge to acousticians and government officials.[2]

Balconies on a building façade were once regarded as a noise mitigation measure.[3] While this is true for a standalone balcony attached to a building,[4] the situation is much less obvious or even becomes questionable when balconies are applied to a high-rise building unless sufficient sound absorption can be installed within the balcony voids.[5–7] The various multiple reflections within the balcony void, including those from the balcony ceiling, the floor, and all the walls largely erase the screening effect of a balcony. The possible effect of acoustic modes on the acoustical protection of a balcony attached to the façade of a high-rise building is clearly demonstrated by Hothersall *et al*.[6] though their simulation study was done in the two-dimensional spatial domain. There are research efforts looking into the possible improvement of balcony acoustical insertion loss by using reflectors[8] and adopting special balcony void geometries.[9,10] Tang *et al*.[11] confirms the importance of various resonances and acoustic modes in shaping the spectral insertion loss of symmetrical balconies.

Owing to the limited buildable area in a congested city, residential units are packed closely together. It is very common to find asymmetrical balconies having one of their side-walls used to separate them from the balcony of an adjacent residential unit or from an adjacent bedroom of the same unit (shown later). The full height separating side-wall can add to the noise screening capacity of the balcony if the latter is in the appropriate orientation with respect to the major noise source. However, the increased reverberation within the balcony void can be counter-productive to such improvement, especially at some source orientations at which the diffractions at that full-height side-wall and the balustrade are strongly reflected by other surfaces within the balcony void. The overall acoustical performance of an asymmetrical balcony is unclear, and this forms the first major objective of this study. In addition, since the balconies are asymmetrical, the acoustic modes which are likely to be excited will be very different from those observed inside the symmetrical balconies.[11] There could be acoustic modes which do not favour sound energy build-up inside the balcony voids. The acoustic mode interactions and the ways they affect the acoustical protection of the balconies require in-depth examination. This is the second major objective of this study.

As in Tang *et al*.,[11] a 1:3 scaled down model of a balcony column was used in this study to examine in detail the acoustical insertion loss (IL) of asymmetric balconies with one of their side-walls extended to the balcony ceiling. In the foregoing analysis, the overall insertion losses of the balconies in the presence of traffic noise are first discussed using a single traffic noise weighted rating. The traffic noise insertion loss spatial variations on the model façades are then examined, and this is followed by narrow-band insertion loss analysis and a detailed investigation on the effects of various major modal interactions on IL. It is hoped that

[a]Electronic mail: shiu-keung.tang@polyu.edu.hk

the present results can inform future applications of balconies in high-rise cities.

II. SCALE MODEL EXPERIMENT

The experimental procedure of the present study followed closely that of Tang *et al*.[11] Figure 1 illustrates the experimental setup, the microphone locations, the key dimensions of the scale model, and the nomenclature adopted. All the experiments were carried out inside a semi-anechoic chamber with short reverberation times as in the previous investigations of the corresponding author.[11] The reverberation time was less than 0.2 s at frequencies between 250 and 5000 Hz and was less than 0.1 s at higher frequencies. The chamber floor was flat concrete and acoustically hard. The workable size of the testing chamber was 5 m by 4.5 m by 4 m (height). Figure 2 shows the schematics of the four asymmetric balcony forms tested in this investigation. A real practical example is also given for each balcony form. Two symmetrical balcony forms with two full-height side-walls are also included for the sake of comparison. The models were made of 20-mm-thick varnished plywood panels of negligible sound absorption. It should be noted the width of the full-height side-wall could be different from the balcony depth in practice, especially when that side-wall is used as a load-bearing building structure separating and supporting two balconies. The width of the full-height side-wall in this study was slightly longer than the balcony depth (∼14%). It is believed that such difference will not affect much the fundamental acoustics inside the balconies.

The noise source consisted of thirty 6-in. aperture loudspeakers arranged in the form of a linear array located at 3 m from the model balcony column. Its characteristics have been presented in Tang *et al*.[11] and thus are not repeated here. The sound on the surfaces supposed to be protected by the balconies was measured by 36 1/4 in. microphones (Brüel & Kjær type 4956) arranged in the form of a 6 × 6 regular rectangular array (Fig. 1). The data acquisition system consisted of a 47-channel Brüel & Kjær Type 3506 D PULSE with a sampling rate of not less than 38 000 samples per second per channel. As traffic noise is the major concern in the urbanized areas of a congested city, the working frequency of the present study was capped at below 6000 Hz,[12] which corresponds to a frequency of 18 000 Hz in data acquisition. In order to

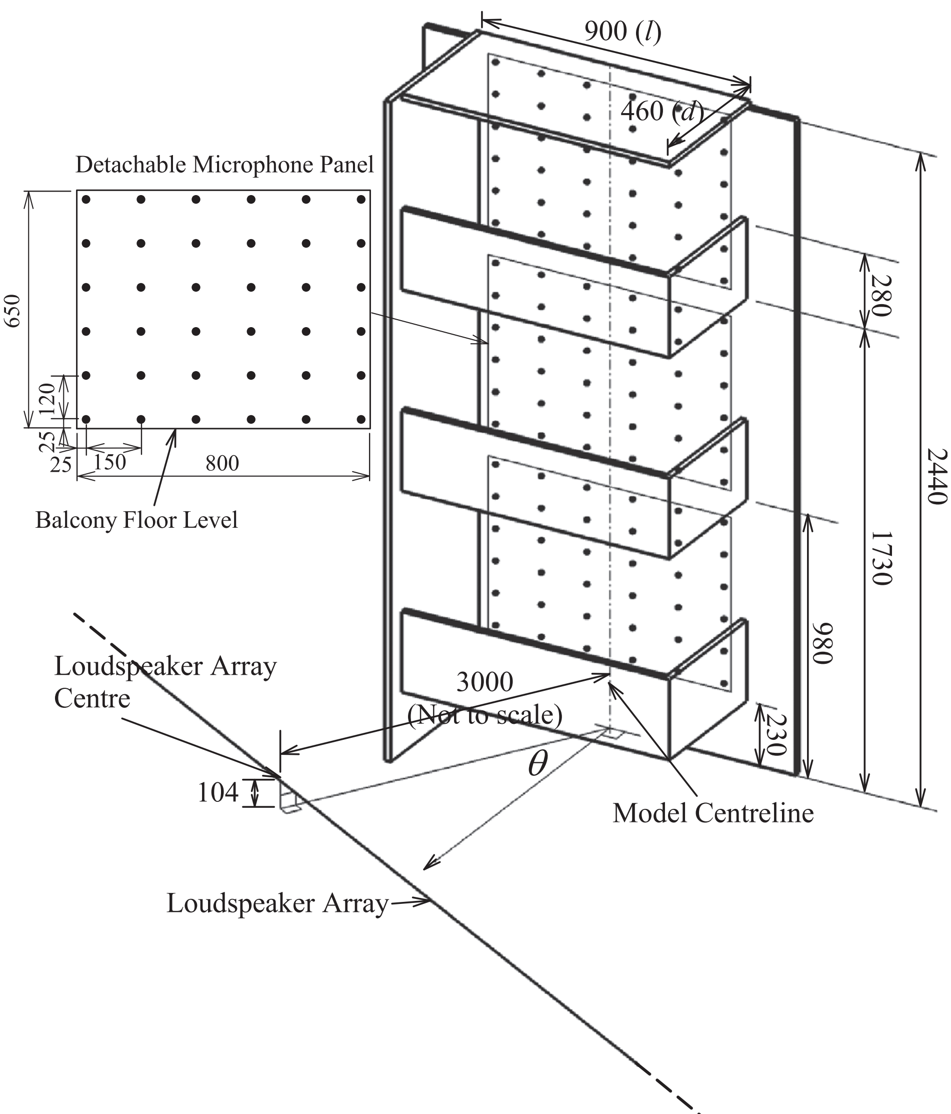


FIG. 1. Schematics of the scale model measurement setup and nomenclature.

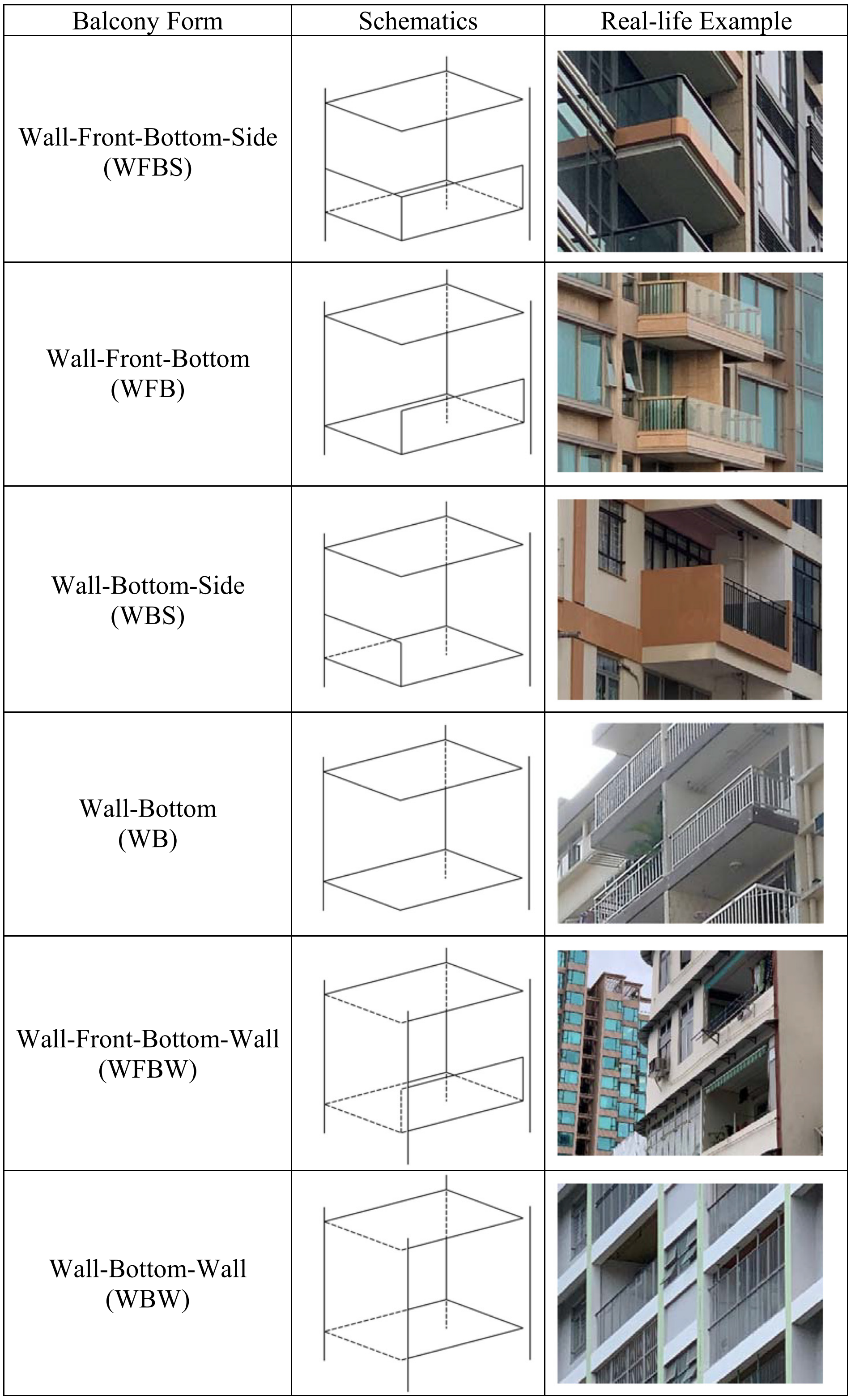


FIG. 2. (Color online) Balcony forms tested and real-life examples.

avoid confusion, the frequencies and length scales presented hereinafter are scaled back to those associated with the full-size balconies.

The azimuthal angle θ in the present study was adjusted by rotating the scaled down model about its vertical centerline in the anticlockwise direction. This angle was varied from $-90°$ to $+90°$ in intervals of $15°$ with $\theta = 0°$ represents the case in which the model façade was parallel to the noise source. For the symmetrical balcony cases, $0° \leq \theta \leq 90°$. It should be noted that for asymmetric balconies, the full-height side-wall tends to help screen sound when θ is positive, but the opposite occurs otherwise. The elevation angle of a balcony ϕ in this study is defined as the inclination angle of the direct line-of-sight from the source centre to the central point of the model building façade behind the balcony. It is equal to $9.5°$, $22.6°$, and $33.7°$ for the bottom, middle, and top balcony, respectively. It should be noted that the maximum path difference produced by the insertion of the balconies was only about 10 cm in the scale model. The effect of air absorption on the measured insertion loss should be negligible in the present study.[13] Though the maximum elevation angle for a high-rise building could be above 60°, the major modal interactions leading to significant sound amplification and reduction should readily be reflected from data at lower elevation angles. This will be discussed in detail later in Sec. III C.

III. RESULTS AND DISCUSSIONS

The insertion loss of a balcony is frequency-sensitive, but somehow it is very often necessary to present it as a A-weighted single rating in general noise control practice for simplicity as well as administrative purposes.[2] However, the numerical value of such a single rating depends strongly on the spectral characteristics of the sound source.[14,15] A normalized spectral weighting is therefore required to better describe the performance of a balcony under broadband excitation. In the foregoing discussions, the performance of the balconies will first be described in form of a single rating. One-third octave band results will be discussed, followed by narrow bandwidth analysis for a deeper understanding on the important acoustic modes and their interactions.

A. Traffic noise weighted insertion loss (IL_{TN})

As ground traffic is usually the main source of noise pollution in a congested city, the normalized traffic noise spectrum[12] is adopted to give an overall picture of the ILs of the balconies in the first place. The difference in the logarithmically averaged one-third octave band sound levels from the 36 microphones with and without a balcony is first estimated to give the one-third octave band IL spectrum. This spectrum is then weighted using the normalized traffic noise spectrum to obtain the single A-weighted rating IL_{TN} as in existing literature.[15]

1. Overall effects of elevation angle

Figure 3 shows the variations of IL_{TN} with θ for all the balcony forms tested in the present study. For the top balconies [Fig. 3(a)], the broadband overall sound insulation performance of the asymmetric balconies is very similar for $\theta \leq 0°$. The balcony ceiling, the full-height side-wall and the balcony floor appears to dominate the sound insulation process in this azimuthal angle range, resulting in sound amplification after the installation of the balconies. Under the strong sound reflection from full-height side-wall, the sound screening effects of the short side-wall and the balustrade are counterbalanced by the increased multiple reflection (reverberation) resulted from these structures. For $\theta > 0°$, the screening effect of the full-height side-wall results in sound attenuation. The IL_{TN} increases with increasing θ, which is rather expected. However, the IL_{TN}'s of the balcony WBS are considerably lower than those of the other asymmetric balconies (which are very similar). The reflection of the short side-wall of WBS in this θ range gives rise to lower sound insulation. This does not take place in

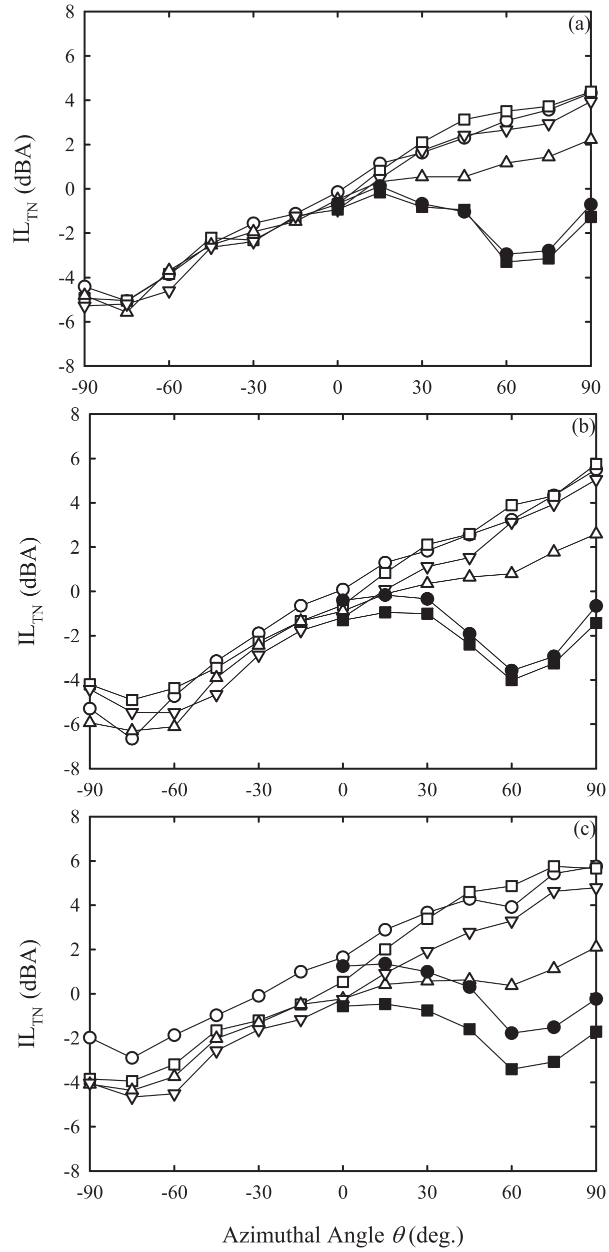


FIG. 3. Variations of IL_{TN} with azimuthal angle θ. (a) Top balconies, (b) middle balconies, (c) bottom balconies. ○: WFBS, □: WFB, △: WBS, ▽: WB, ●: WFBW, ■: WBW.

WFBS as the balustrade of WFBS screens the incident sound before it hits the short side-wall.

The IL_{TN}'s of the symmetrical top balconies are very similar and sound amplification is observed for all azimuthal angles. The strong reverberation due to the two full-height side-walls, the ceiling and the floor dominates the sound field inside the balcony voids. The balustrade has only very little effect on the sound amplification. The results show that the screening effect of the balustrade does help slightly the sound insulation, though it tends to strengthen the sound reflection inside the balcony voids. The IL_{TN}'s of these balconies are significantly lower at θ around 60° to 75°. This is the θ range in which the far-side side-wall is largely exposed to the sound source [$\sim\tan^{-1}(5/9) = 61.9°$ for this balcony dimension].

At lower elevation angles [Figs. 3(b) and 3(c)], the overall IL_{TN}'s of the balconies with a balustrade are in general higher than those without the balustrade. The screening effect of the balustrade becomes stronger and stronger relative to balcony void reverberation as elevation angle decreases, especially for $\theta < 0°$. The overall IL_{TN}'s of the balconies in this study, which have a balustrade and at least one full-height side-wall, tends to increase with decreasing elevation angle. The IL_{TN} of WBW does not depend much on elevation angle, showing that the reverberation within the corresponding balcony void resulted from the ceiling, floor and the two fin-like full-height side-walls is deterministic to the acoustical insertion loss. The overall IL_{TN}'s of WBS show reasonable improvement only for $\theta < 0°$, probably because of the screening effect of the short side-wall and the weaker reflection at the balcony ceiling.[9,16]

2. IL_{TN} distributions on model façade

Though the overall IL_{TN}'s of the asymmetric balconies, except WBS, are very similar at the elevation angle of 33.7° (top balconies), there are differences in the IL_{TN} distributions on the model façade behind balconies of different forms. Figure 4 shows the IL_{TN} distributions behind the top balconies. In these figures, the full-height side-wall is on the left-hand-side ordinate axis. The less reverberant balcony void of WB and WFB actually result in stronger sound insulation near to the vertical full-height side-wall than that can be achieved in WFBS, but the opposite occurs at locations closer to the balcony ceiling in the absence of the screening provided by the short side-wall. The installation of balustrade and short side-wall appears to have worsen the acoustical protection for $\theta \geq 0°$, except for the case of WBS. The situation is less problematic for $\theta < 0°$. The short side-wall tends to provide some screening effects at this azimuthal angle range.

The case of WBS appears unique in term of IL_{TN} distributions. In the absence of the balustrade, the short side-wall tends to reflect sound into the balcony void for all θ, largely reducing the acoustical protection in the middle of the balcony though the reverberation with the balcony void is also largely reduced. However, the situation is better at $\theta < 0°$ at which the short side-wall does help screen some sound from entering the balcony void. This phenomenon is observed also in the WFBS balcony. The situation at $\theta = 60°$ is actually similar to those observed within the symmetrical WFBW and WBW. The far-side short side-wall of WBS is most exposed to the incoming sound from the source, though

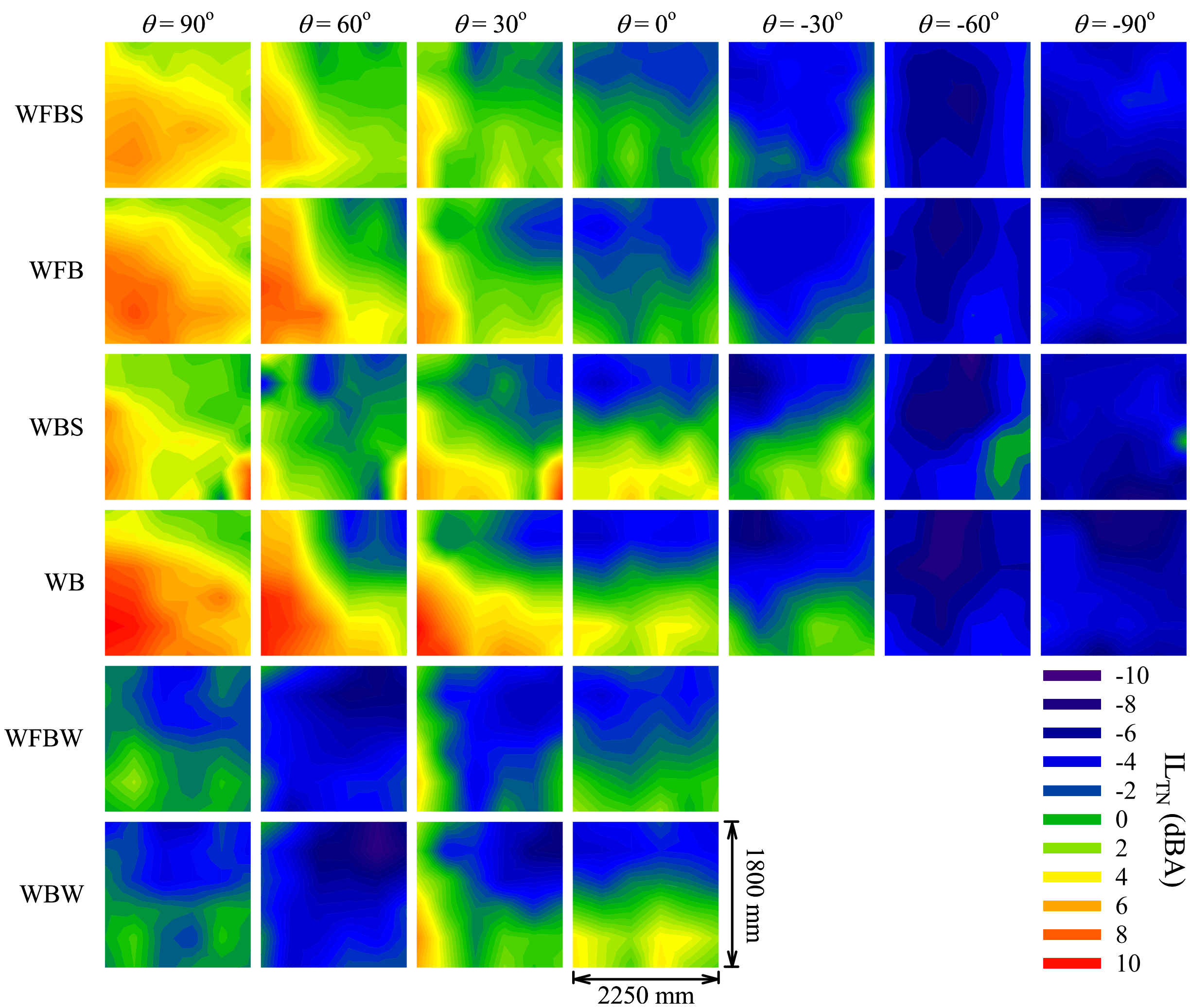


FIG. 4. (Color online) IL_{TN} distributions on model façades behind the top balconies.

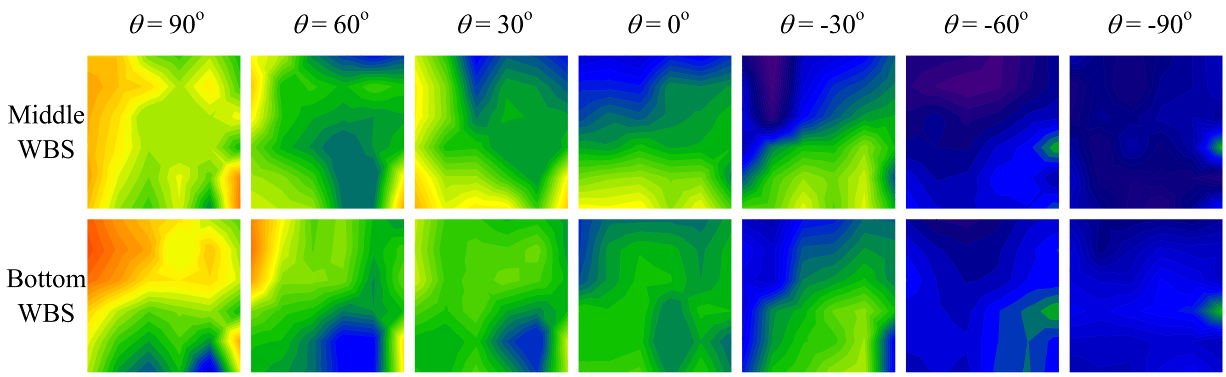


FIG. 5. (Color online) IL_{TN} distributions on model façades behind the middle and bottom WBS.

under the screening effect of the balcony floor. The relatively stronger reflection from the short side-wall results in large reduction of acoustical protection, though such effect is weaker than those occur in WFBW and WBW where a full-height side-wall is reflecting sound into the balcony void. As in existing literature (for instance, Ref. 11), modal patterns are observed for all cases, especially at $|\theta| \leq 30°$, when neither sound amplification nor attenuation is strong.

The IL_{TN} distributions on the model façades behind the asymmetrical middle and bottom balconies, except those behind WBS, are basically the same as their top balcony counterparts but with the regions of positive IL_{TN} extended towards the opposite side of the full-height side-walls and the balcony ceiling. The interference patterns remain intact. They are thus not presented. In Fig. 5 are presented the IL_{TN} distribution maps associated with the middle and bottom WBS. One can notice that for $\theta > 0°$, the acoustical protection near to the balcony ceiling is strengthened, while that near the balcony floor is weakened as elevation angle decreases. The elevation angle of the façade behind the bottom balcony is about 9°. The short side-wall at the far side tends to reflect sound within the lower part of the balcony, reducing the insertion loss there. Balcony ceiling reflection is less serious at lower elevation angle.[9,16] The insertion loss near to this region thus is improved at the same time. However, the overall acoustical protection of WBS does not vary much with balcony elevation.

It can be concluded that for asymmetrical balconies with a full-height side-wall, reasonable acoustical protection can only be achieved when that side-wall is located at the near source side. Otherwise, sound absorption is required. The WBS balcony form is not recommended. For balconies with two full-height side-walls, only limited acoustical protection can be achieved at lower elevation.

B. One-third octave band ILs

Figure 6 illustrates the one-third octave band ILs behind the top balconies. One can observe that there are IL dips, which tend to indicate the excitation of acoustic modes within the balconies.[11] In fact, the spectral variation patterns

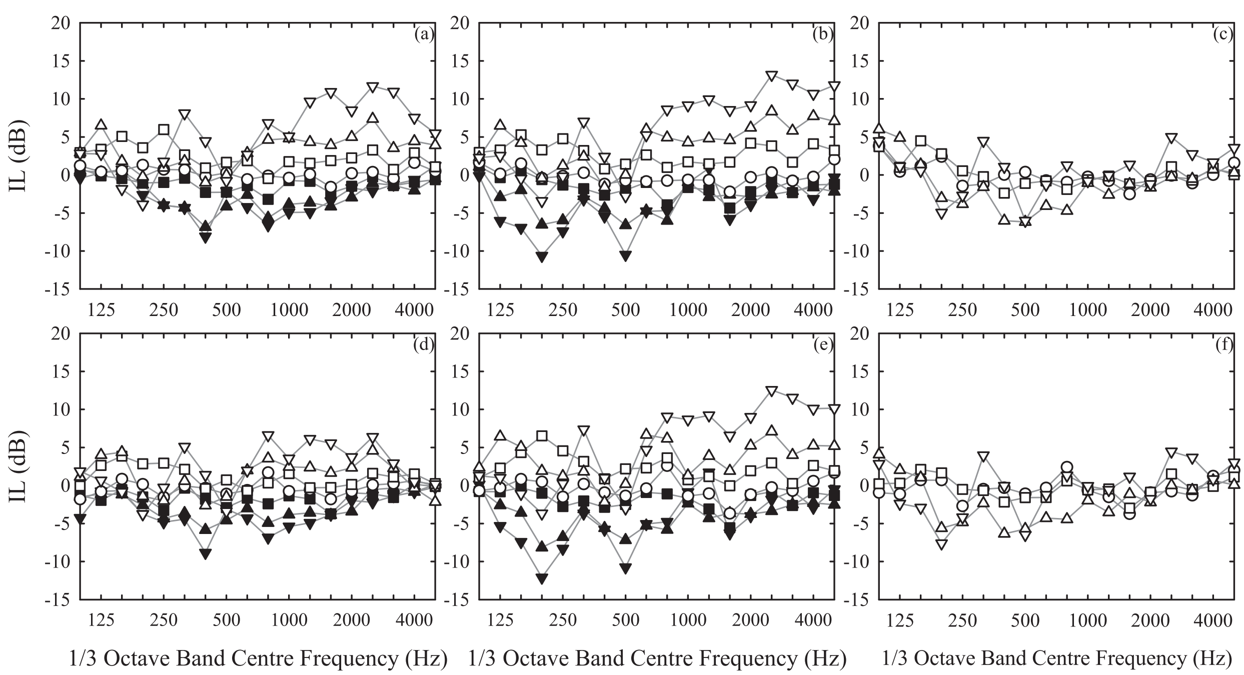


FIG. 6. One-third octave band insertion loss of top balconies at various azimuthal angles. (a) WFBS, (b) WFB, (c) WFBW, (d) WBS, (e) WB, (f) WBW. ○: $\theta = 0°$, □: $\theta = 30°$, △: $\theta = 60°$, ▽: $\theta = 90°$, ■: $\theta = -30°$, ▲: $\theta = -60°$, ▼: $\theta = -90°$.

of the corresponding ILs behind the middle and the bottom balconies, though the IL magnitudes are different, are similar. IL dips are also found within the same frequency bands, though one can find slightly blunt dips for the other balconies at $\theta < 0°$, especially for WFBS and WBS. Therefore, the corresponding data associated with middle and bottom balconies are not discussed, but are presented in the Appendix for the sake of completeness.

One can also note that the ILs are insignificant at $\theta = 0°$ within the frequency range of interest. The improved noise screening effect due to the more complicated balcony geometries has basically erased out by the then strengthened multiple reflections (reverberation) within the balcony voids when the source is parallel to the balustrade. The corresponding data are not interesting and thus are not discussed.

It is noticed that the spectral variations of IL at $\theta > 0°$ are basically the same for all the asymmetrical balconies tested. The full-height side-wall acts as a sound barrier and dominates the sound protection mechanism as θ increases toward 90°. Basically, IL increases with frequency; a typical characteristic of a sound barrier.[17] The excitation of acoustic modes within the balcony void could reduce the insertion loss of a balcony. Such information is best reflected from the IL dips at $\theta = 90°$, where the strongest barrier effect of the full-height side-wall is achieved. As observed from Figs. 6(a), 6(b), 6(d), and 6(e), there are prominent IL dips at the 200 Hz band and a relatively broader band dip between 400 and 500 Hz bands for each asymmetrical balcony case. These dips can also be found in the symmetrical balconies WFBW and WBW [Figs. 6(c) and 6(f), respectively].

For the cases with $\theta < 0°$, sound can enter the balcony void, get reflected by the full-height side-wall and ceiling, and trapped within the void. This results in sound amplification basically over the whole frequency range of the present study. The excitation of acoustic modes further reduces the sound insulation capacity of the balconies. This phenomenon is more pronounced in WFB and WB where sound enters directly into the balcony void in the absence of the short side-wall. For the balconies with a short side-wall (WFBS and WBS), strong IL dips are found within the 400 and 800 Hz one-third octave bands [Figs. 6(a) and 6(d)]. For WFB and WB, strong IL dips appear within the 200 and 500 Hz bands, and there are some minor IL dips at higher frequencies [Figs. 6(b) and 6(e)]. These frequency bands are also those within which IL dips are found for $\theta \geq 60°$. Figure 6 also illustrates that the balustrade has no significant effect on the spectral characteristics of the insertion loss.

The strong IL dips are the main concerns. In order to understand the details of the mechanisms that lead to their occurrence, a narrow-band spectral analysis on the insertion loss is carried out. Figure 7 illustrates the spectral variations of the averaged ILs of the top asymmetrical balconies at $\theta = -90°$ with a frequency resolution of 2.67 Hz. Unlike the case of Tang *et al.*[11] in which the balconies are symmetrical and without full-height side-walls, the average IL obtained on the upper half model façade behind balcony in this study

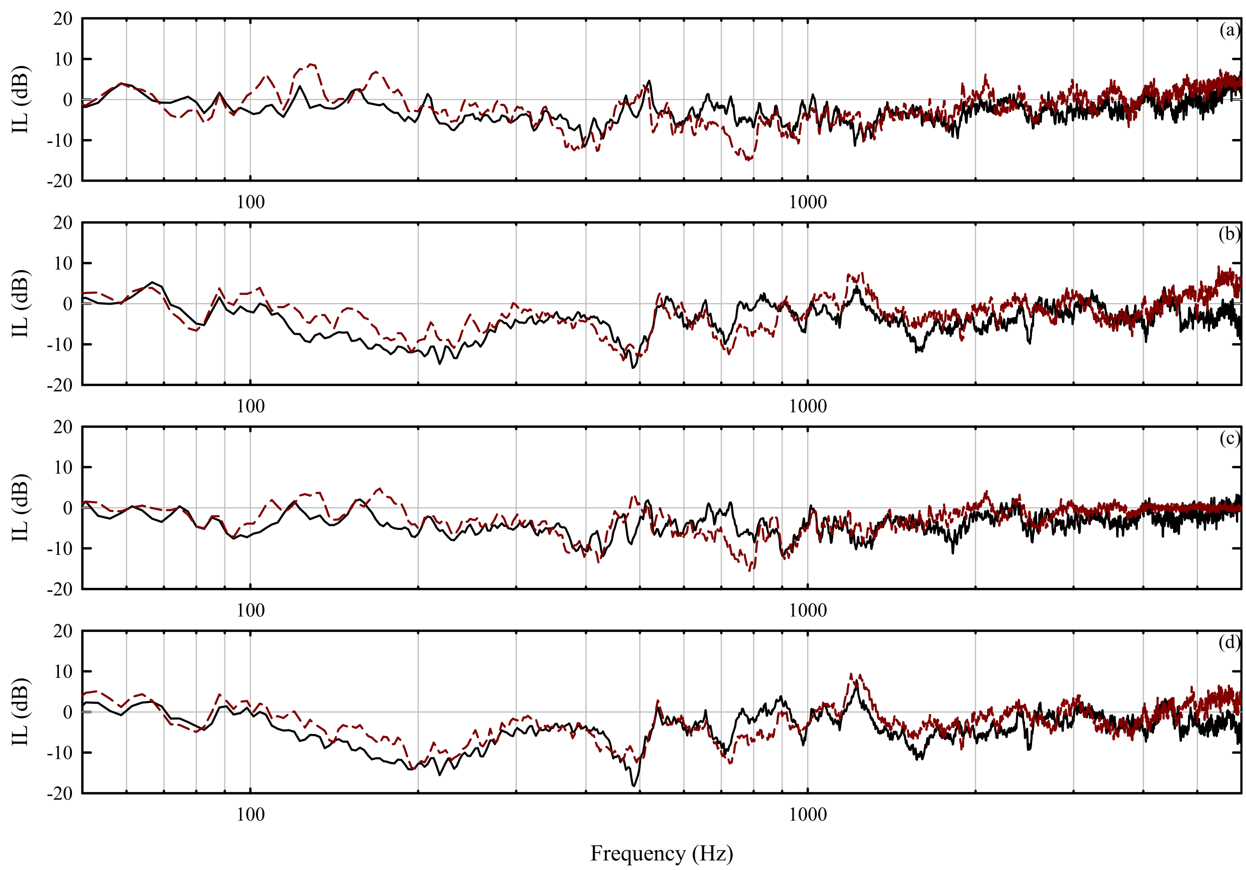


FIG. 7. (Color online) Spectral variations of averaged insertion loss of top balconies at $\theta = -90°$. (a) WFBS, (b) WFB, (c) WBS, (d) WB. —: Above balustrade edge, - - -: below balustrade edge.

is relatively similar to that obtained on the lower half façade in general, except at some frequency bands.

The presence of a full-height side-wall in the balconies gives rise to many possibility of acoustic mode combinations as frequency increases. The modal overlapping is very serious, such that no simple explanation can be concluded at higher frequencies. Results at frequencies higher than 2000 Hz are thus not further discussed. They are also less important as far as conventional environmental noise source is concerned.[18]

As already shown in Fig. 6, the IL performance can be grouped under the cases of "with short side-wall" and "without short side-wall." For WFB and WB, who do not have a short side-wall, a broadband reduction of IL is observed starting from 100 Hz, reaching maximum reduction at around 200 Hz before increasing back to a local peak at ∼350 Hz. The IL then drops relatively sharply between −15 dB to −20 dB at ∼500 Hz. There are also minor dips at frequencies ∼700 Hz, ∼1000 Hz, and onwards. One can also observe a minor dip at ∼80 Hz.

C. Effects of major acoustic modes

Before examining the acoustic modes responsible for the IL dips, the major fundamental acoustic modes, which are expected to be found inside the balconies, are explained in Fig. 8 and are coded for easy reference in the foregoing discussion. The first one, M1, is a longitudinal acoustic mode between the balcony ceiling and its floor. The second one M2 is that between the side-walls and the third one M3 is a kind of acoustic mode similar to that in a tube with one end closed and the other end opened.[19] M3 occurs between the full-height side-wall and the opposite side of this wall. However, the length span for building up this longitudinal mode is not certain because of end reflection. There can be acoustic modes set up between the model façade and the balustrade. However, the results in Figs. 6 and 7 tend to suggest that their effects are minor and thus these modes are not discussed in this study. The acoustic mode patterns within the balconies are combinations of M1, M2, M3, and/or their harmonics. In the rest of the discussions, Mx_n, where $x = 1$ to 3, denotes the nth order of the mode Mx with $n = 1$ represents fundamental. For easy presentation, the combination of Mx_n and a transverse mode $M1_m$ is hereinafter denoted as Mx_n*$M1_m$. The modal frequency of this combined mode is $\sqrt{f^2_{Mx_n} + f^2_{M1_m}}$.

1. Top balconies

Figure 9(a) shows the narrowband IL_{80Hz} distribution behind the top WFB (bandwidth 2.67 Hz). This frequency is near to the modal frequency of $M1_1$ (∼80 Hz) and $M1_1$*$M3_1$ (∼86 Hz). The seemingly nodal plane, which is offset from the vertical centerline of the model façade, suggests the presence of also $M3_2$. It should be noted that $M3_2$ is not likely to give vanishing sound pressure at the balcony entry because of the presence of open end reflection which tends to increase the effective length of the mode development.[19] The strong sound amplification at the sound entrance of the balcony at $\theta = -90°$ is therefore due mainly to the presence of $M1_1$, $M1_1$*$M3_1$, and $M3_2$. The relatively weaker sound amplification near to the balcony ceiling there is then

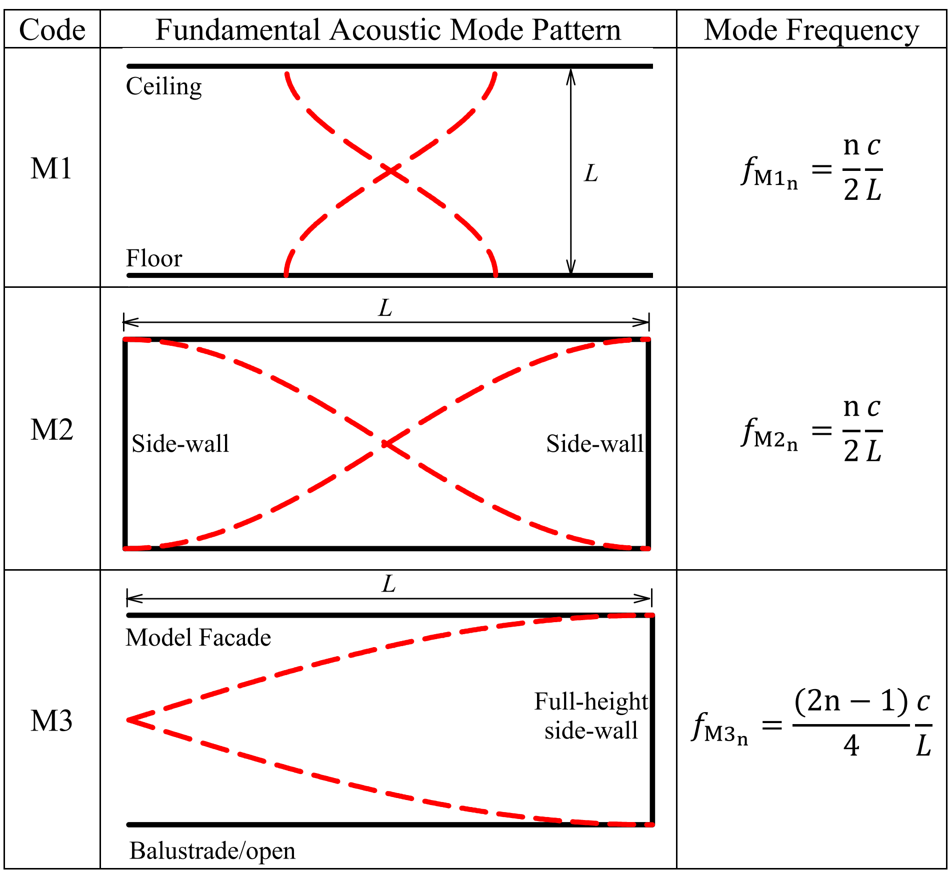


FIG. 8. (Color online) Various major acoustic mode patterns within the balcony void. - - -: Pressure magnitude variation.

obvious as $M1_1$ is an odd mode while $M3_2$ is an even one (transversely). The situation of the top WB is similar except that the modes are not so strongly forced out (not shown here).

The sound amplification near 200 Hz is very broadband and thus one-third octave band IL is use to illustrate the relatively more important modes which result in sound amplification [Fig. 9(b)]. One can find the signs for the presence of $M1_2$, $M3_2$, $M3_3$, and their combinations, though that of $M1_2$ is very brief. The fairly symmetrical IL pattern about the horizontal centerline of the measurement plane also suggests the presence of mode patterns associated with $M1_1$. However, there is no clear sign for the presence of $M1_3$. It appears that the excitation of any acoustic mode within this 200 Hz one-third octave band is detrimental to insertion loss. The weakly forced $M1_2$ is properly because of the asymmetrical acoustical excitation, which does not favour an even mode such as $M1_2$ so much.

Figure 9(c) shows the one-third octave band IL at 315 Hz. One can clear observe the presence of acoustical modes associated with $M1_2$, especially $M1_2*M3_3$, showing that this mode is the major contributor in this frequency band. There is still no clear sign for the presence of $M1_3$ related modes, though a slight indication can be found near to the full-height side-wall at location below the balustrade edge. Since the excitation comes mainly from one side of the balcony and is not even over the height of the balcony, it is not likely that any M1 mode can exist on its own without combining with one of the M3 modes. As $M1_2$ and its combinations are not favourable modes under the current setting, their excitation can only offset the screening effect of the balcony. No significant sound amplification can therefore be achieved.

There is another IL dip at ~480 Hz for the balconies WFB and WB [Figs. 7(b) and 7(d)]. The corresponding one-third octave band IL_{500Hz} distribution is presented in Fig. 9(d). The large IL dip at this frequency is due to the strong sound amplification over most of the measurement points on the model façade behind the balcony. The presence of $M1_3$ related modes is more clearly seen than before. The IL pattern suggests interactions between modes associated with $M1_3$ and M3. The nearly vanishing sound amplification near the full-height side-wall again suggests that the screening effect of the balcony is largely erased by the M3 related modes. A relatively stronger sound at the central region of the vertical full-height side-wall compared to those at the ceiling and the floor regions indicates the presence of $M1_2$ related modes.

Since modal overlapping becomes very serious as frequency increases further, the corresponding IL distributions will not provide conclusive information and thus they are not presented. However, it is expected that similar phenomena as discussed above will take place at higher frequencies. The IL dips at higher frequencies are believed to be due to the excitation of an odd M1 related mode(s). The excitation of M3 related modes continues to result in lower sound amplification on the full-height side-wall at higher frequencies (cf. Fig. 4).

It is noticed that sound amplification on the façade below the height of the balustrade is continuously higher than that above the balustrade within the frequency range from 700 to 900 Hz. It is believed that the odd M1 related modes tend to counteract the M3 related modes above the height of the balustrade, resulting in lower sound amplification. This phenomenon has briefly been observed in Fig. 9(a). Sound amplification due to mode excitation is not remarkable as frequency

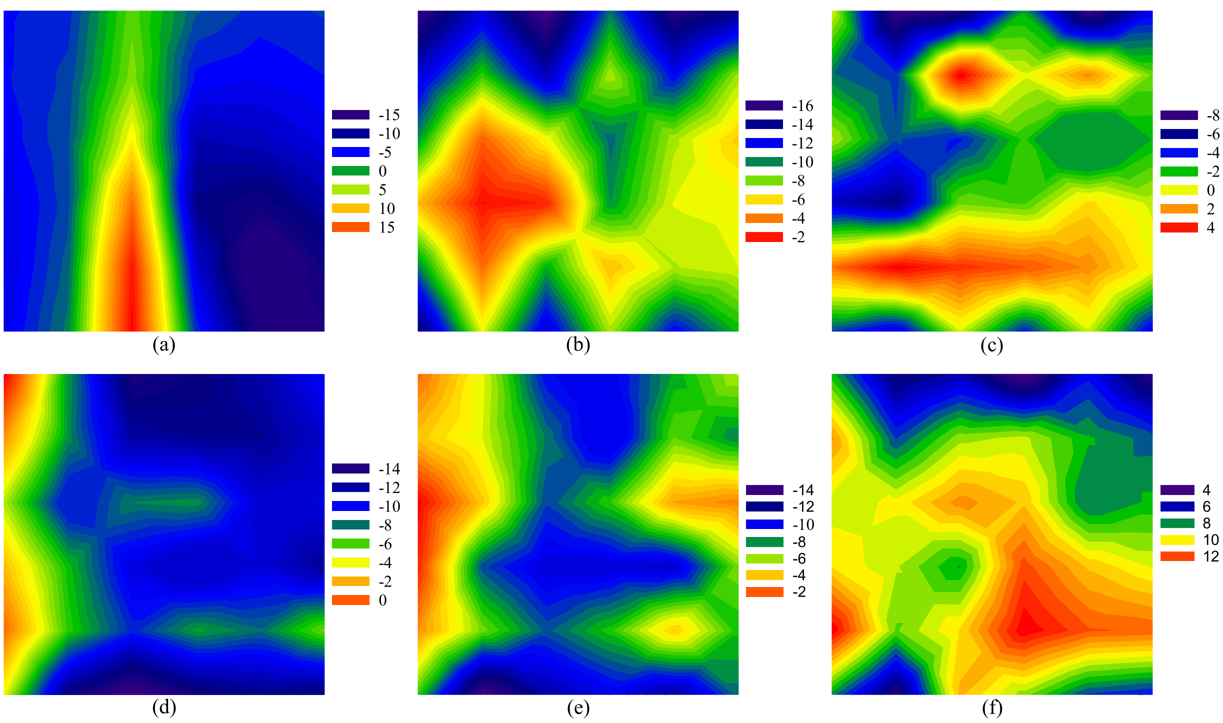


FIG. 9. (Color online) Insertion loss distribution patterns on façade behind top balcony at $\theta = -90°$ (unless otherwise specified). (a) WFB, 80 Hz, narrow bandwidth of 2.67 Hz, (b) WFB, 200 Hz one-third octave band, (c) WFB, 315 Hz one-third octave band, (d) WFB, 500 Hz one-third octave band, (e) WFBS, average between 700 and 800 Hz, (f) WFBS, 315 Hz one-third octave band, $\theta = 90°$.

increases because of the stronger screening effect of the balcony.

The short side-walls of WFBS and WBS result in less sound amplification at low frequencies as they help screen noise though they also enhance the multiple reflection within the balcony void (acoustic modes) as shown in Figs. 7(a) and 7(c). At $\theta = -90°$, the screening effect appears stronger than the latter. One should note that both M1, M2, and M3 modes could be forced out in these balconies. M3 modes are likely to exist above the short side-walls, while M2 modes should be more effectively excited at regions below the edge of the short side-walls. There could be other acoustical modes within the region bounded by the side-walls at high frequencies. Again, the configurations are more favourable to the excitation of odd M1 modes.

Taking WFBS as the example, significant sound amplification is observed when the excitation frequency reaches $\sim 388 \pm 20$ Hz. Within this narrow frequency range, one can find the modal frequencies of $M2_6$, $M1_1{*}M2_6$, $M1_3{*}M2_5$, $M1_3{*}M3_5$, $M1_5{*}M2_1$, and $M1_5{*}M3_1$ but only two even M1 related mode $M1_4{*}M2_3$ and $M1_4{*}M3_4$. The corresponding one-third octave band IL_{400Hz} distribution pattern is illustrated in Fig. 9(e). As discussed before, the excitation of M2 and M3 modes do not result in much sound amplification on the vertical full-height side-wall where the total screening effects from the balustrade and the short side-wall are strong. The sound attenuation just near to the internal surface of the short side-wall is also relatively weak because of the excitation of M2 modes. Similar to the results given in Fig. 9(d), one can observe the presence of modes associated with $M1_3$, but the presence of an even M1 related mode is not likely, or at least of secondary importance, due to the asymmetrical IL distribution about the transverse façade centreline. $M1_5$ cannot be revealed because of the spatial resolution of the measurement, but a $M3_1$ related mode is likely to be present above the balustrade. The fairly wide horizontal span of sound amplification within the central region of the balcony also suggests the co-existence of odd and even M2 related modes.

One should also note that the strong excitation of M2 modes between the side-walls could affect the effective length for M3 mode resonance. As the percentage difference between the wavelengths of $M2_n$ and $M3_n$ modes decreases as n increases, there could be a chance that the M2 and M3 related modes can be strongly excited simultaneously at some particular frequencies. The pair $M1_3{*}M2_5$ and $M1_3{*}M3_5$ in the 400 Hz one-third octave band appears to be an example. Higher spatial resolution measurements are required in the future for confirmation.

As in the cases of WFB and WB, one expects the odd M1 related modes continue to pay the key role in shaping the spectral variation of IL also in the cases of WFBS and WBS. As frequency increases, the more serious modal overlapping results in less sound amplification in general. However, one can still find relatively more significant local IL dips at frequencies near the multiple of 400 Hz in Figs. 7(a) and 7(c). Within the frequency range from 700 to 800 Hz, sound amplification is mostly found within the region between side-walls, indicating the strong excitation of M2 modes. The height of the balustrade edge above the balcony floor in this study is 280 mm (cf. Fig. 1), which corresponds to a balustrade height of 0.84 m in the full scale balcony. The sound frequency having such wavelength is 408.3 Hz. Thus, the relatively regular IL dips at frequencies near to the multiple of 400 Hz is likely to be related to the acoustic modes along the vertical height of the balustrade. This is left to further investigation.

At $\theta = 90°$, the strong screening effect of the vertical full-height side-wall dominates the IL. Figure 10 shows some examples of the corresponding IL spectral variations, and they all resemble those of the WFB and WB [Figs. 7(b) and 7(d)]. The corresponding wave interactions and the modal activities are thus believed to be similar to those discussed previously for WFB and WB at $\theta = -90°$. There is, in fact, no significant difference in the shape of the IL spectral variations of the four asymmetrical balcony forms, indicating further the dominance of the full-height side-wall in controlling IL. The corresponding results are thus not discussed. However, the results in Fig. 10 do indicate that there is a change in the spectral variation patterns of the IL associated with WFBS and WBS when θ is increased from $-90°$ to 90°. The excitation of M2 related modes are azimuthal angle sensitive.

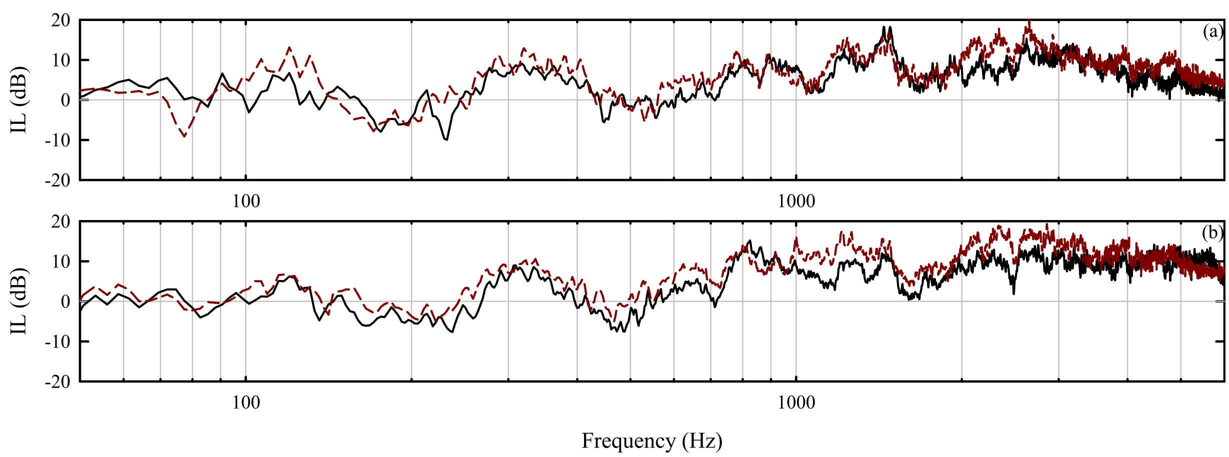


FIG. 10. (Color online) Spectral variations of averaged insertion loss of top balconies at $\theta = 90°$. (a) WFBS, (b) WB. —: Above balustrade edge, - - -: below balustrade edge.

Figure 11 illustrates the IL spectral variations of the top WFBS at $\theta = \pm 30°$ and $\pm 60°$. Sound goes directly into the balcony void at $\theta = -90°$ and the subsequent strongly forced odd M1 related modes give rise to significant sound amplification. The screening effect of the balcony floor and balustrade become stronger and stronger as the azimuthal angle is increased toward 90°. The forcing of the various acoustic modes is weakened at the same time. This phenomenon is more serious at frequencies associated with the already less strongly forced even M1 related modes. The rate of increase of IL at around 315 Hz is thus faster, leading to a more uniform IL distribution within the 315 Hz one-third octave band at $\theta = 90°$ though one can still observe the presence of $M1_2$ related modes within the region below the balustrade edge [Fig. 9(f)]. Also, the growing screening effect increases the average IL below the balustrade at a faster pace than that above the balustrade especially at frequencies higher than 1000 Hz. This is rather expected as noise screening by barriers is more effective at higher frequencies.[17] In fact, the ILs at $\theta = 0°$ are weak over the whole frequency range of interest (discussed later). The screening effect of the full-height side-wall gradually takes over and control the spectral variation of IL as θ approaches 90°.

The shift of IL spectral variation observed in Fig. 11 does not occur in WFB and WB probably because of the stronger excitation of acoustic modes within the balcony void in the absence of the short side-wall. As in WFBS and WBS, the growing screening effect as θ increases toward 0° tends to smooth out the spectral variation of IL. For $\theta > 0°$, the shape of the IL spectral variation resumes to that for $\theta < 0°$ but with higher IL magnitudes. The corresponding results are not discussed as there is no major change in the frequency characteristics of the insertion loss, and neither are the major modal interactions.

2. Middle and lower balconies

The screening effect of the balcony floors, side-walls, and balustrade will be lowered as the height level of a balcony decreases. However, there could be stronger sound going into the corresponding balconies either directly or via reflections at balcony ceiling, especially those without the short side-wall. The forcing of acoustic modes could be strengthened, but it will not necessarily result in stronger sound amplification. The spectral variations of average overall IL of the middle and lower WFBS and WB are presented in Fig. 12 as examples. In fact, the average IL at the upper half of the façade is always lower or at the most comparable to that at the lower half of the façade. Again the results of WFBS and WB resemble those of WBS and WFB respectively, and thus they are not presented.

One can notice that the IL spectral variations of the middle and lower balconies and the effect of azimuthal angle are basically similar to those of their corresponding top balcony counterparts. At $\theta = 90°$, the IL spectral variations are nearly independent of balcony height as the screening effect of the full-height side-wall dominates the insertion loss. The corresponding results are not further discussed.

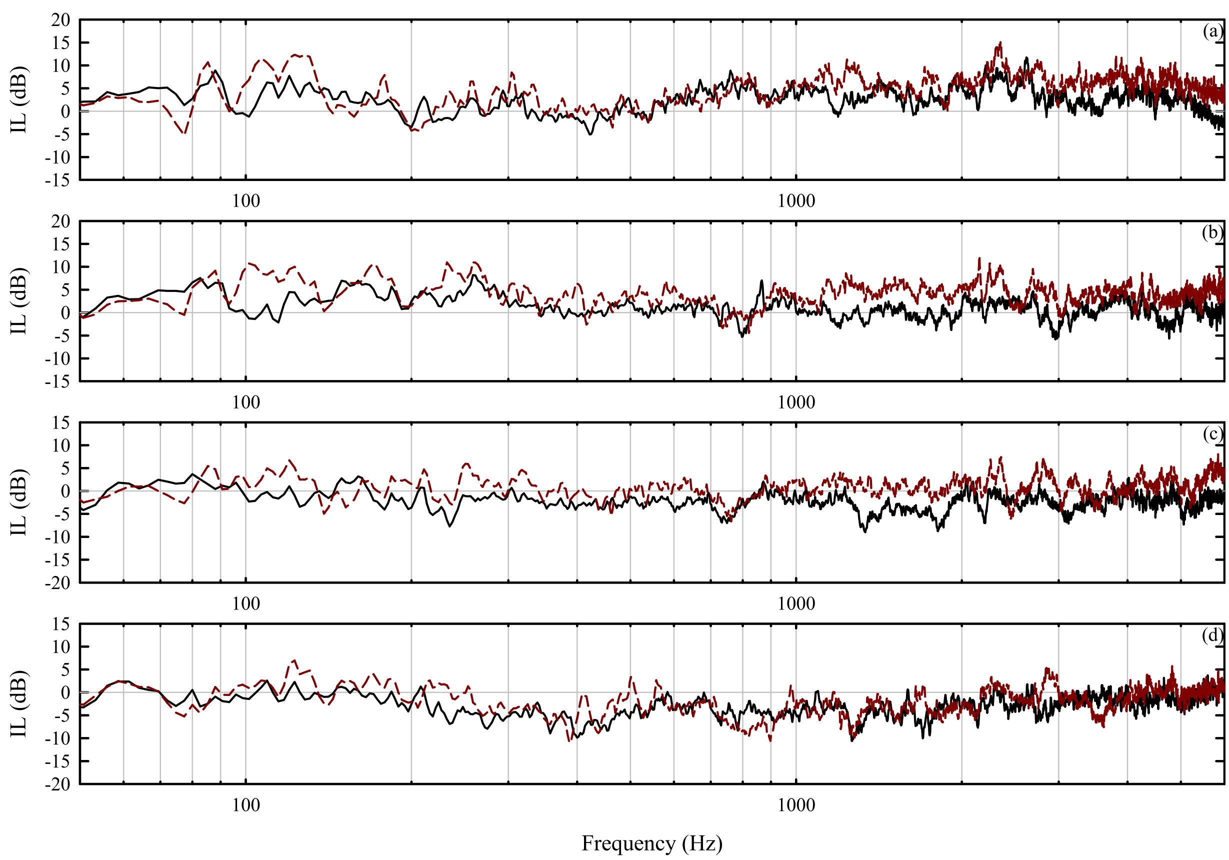


FIG. 11. (Color online) Effects of azimuthal angle on the spectral variations of averaged insertion loss of top WFBS. (a) $\theta = -60°$, (b) $\theta = -30°$, (c) $\theta = 30°$, (d) $\theta = 60°$. —: Above balustrade edge, - - -: below balustrade edge.

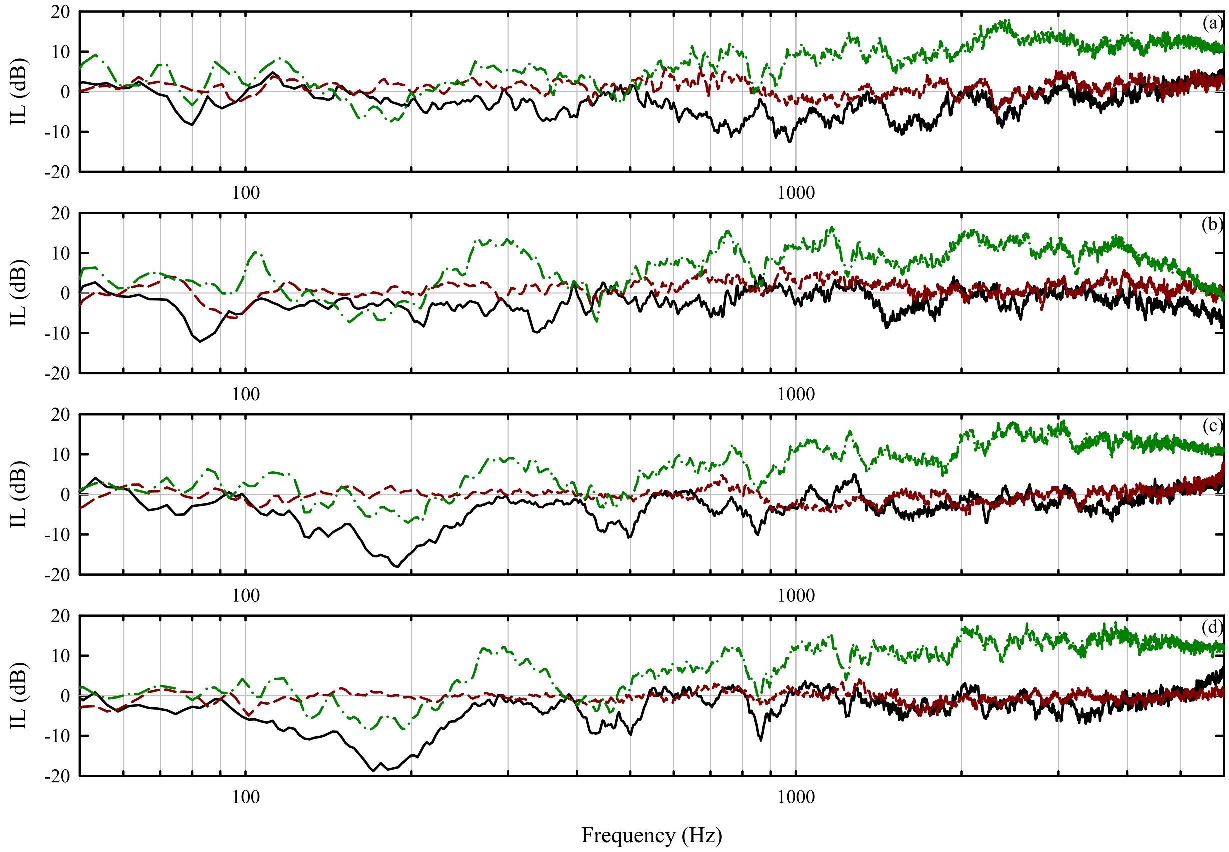


FIG. 12. (Color online) Spectral variations of averaged overall insertion loss of middle and lower balconies. (a) Middle WFBS, (b) lower WFBS, (c) middle WB, (d) lower WB. —: $\theta = -90°$; - - -: $\theta = 0°$; - · -: $\theta = 90°$.

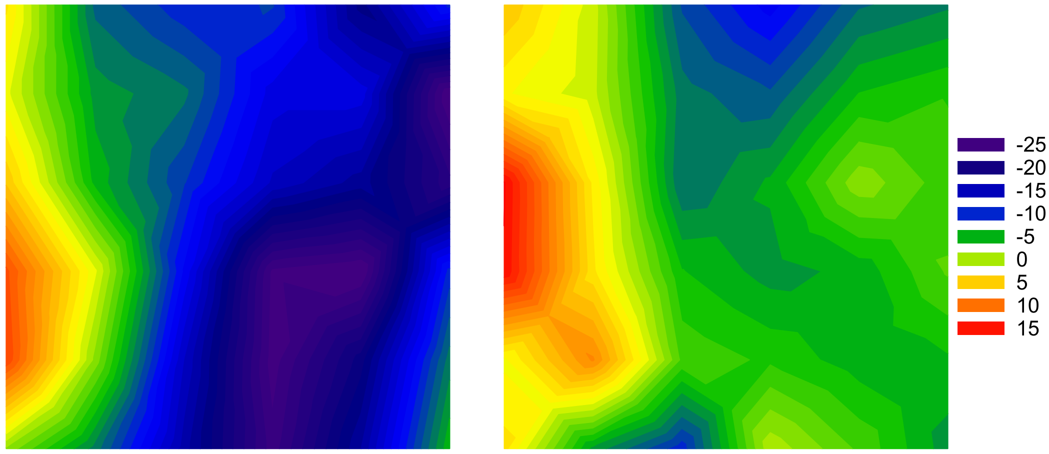
For WFBS and at $\theta = -90°$ [Fig. 12(a)], one can observe the strong IL dip at ~80 Hz in the middle and lower balconies compared to the top one. This is the $M1_1$ mode. For the middle WFBS, the dip frequencies are more or less the same at those of the top WFBS, but the magnitudes of the dips are slightly different. This observation tends to suggest that the major mechanisms of sound attenuation/amplification within the middle WFBS do not differ much from those within the top WFBS. The excitation of stronger even M1 related modes could be the reason for the dip magnitude difference. Further investigation is required for deeper understanding of such phenomenon. At $\theta = 0°$, IL is basically flat across the whole frequency range of interest and is weak. Such observation applies to all balcony forms at all height levels tested in this study.

The IL spectral variation of the lower WFBS at $\theta = -90°$ is basically flat with isolated IL dips at lower frequencies [Fig. 12(b)]. At this height level, the stronger modal excitation erases out the weakened screening effect. The dip at ~200 Hz should be related to odd M1 related modes as discussed before, while that between 333 and 343 Hz is believed to be related to $M1_3$*$M2_4$, $M1_4$*$M3_3$, and $M1_4$*$M2_2$. The corresponding IL distribution pattern shown in Fig. 13(a) indicates the presence of $M1_4$ related modes within the balcony void. The transverse asymmetrical pattern suggests further the presence of a $M1_3$ related mode. The lack of a strong sound amplification around the horizontal centreline is believed to be due mainly to the modal mismatch between the M3 and M2 related modes. The strong sound attenuation close to the full-height side-wall suggests that these modes are somewhat out-of-phase on that wall and/or weak such that their combined effect is not sufficient to counterbalance the screening effect of the short side-wall and the balcony floor.

The IL spectral variations of the middle and lower WB very much resemble those of the top WB [Figs. 12(c) and 12(d)]. For the lower WB at $\theta = -90°$, one can also observe a weak IL dip at around 347 Hz [Fig. 12(d)], which is close to the modal frequency of $M1_4$*$M3_3$. The corresponding IL distribution is given in Fig. 13(b). As a M3 mode will create a strong sound pressure level on the full-height side-wall, it is very likely that there is a $M3_3$ related mode within the balcony void. The relatively stronger sound along the second topmost and lowermost microphone rows tends to suggest the presence of a $M1_4$ related mode. The strong sound attenuation on the full-height side-wall again suggests the acoustic mode is not strongly forced out, leading to a bit less distinctive mode patterns in Fig. 13(b) in the presence of modal overlapping.

IV. CONCLUSIONS

A 1:3 scaled down model was setup to investigate the acoustical insertion loss of asymmetrical balconies on high-rise buildings in the present study. Four different commonly adopted balcony forms were tested. For practical reasons, one of the side-walls of these balconies was chosen to span



(a) (b)

FIG. 13. (Color online) Examples of Insertion loss distribution patterns on façade behind lower balconies at frequency around 340 Hz. $\theta = -90°$ and bandwidth: 2.67 Hz. (a) WFBS, 338.6 Hz, (b) WB, 346.7 Hz.

over the full height of the balconies. Effects of source orientation (in term of azimuthal angle with respect to the model façade normal axis) and the balcony elevation on the insertion loss were examined. In the present study, the source adopted was a 5 m long linear loudspeaker array consisted of 30 6-in. aperture loudspeakers and an azimuthal angle of 90° represents the case where the full-height side-wall was nearest to the source.

In general, the present results show that the traffic noise insertion losses of the balconies tend to increase with frequency and decrease as elevation angle decreases at a fixed azimuthal angle. These are rather expected. In general, for all balcony forms the traffic noise amplification is the strongest when the full-height side-wall is furthest away from the source. It decreases as the azimuthal angle increases. When the source is parallel to the model façade (azimuthal angle equals 0°), the acoustical effect of the balconies is basically not significant. Traffic noise attenuation is found after the azimuthal angle is increased beyond 0°. The screening effect of the full-height side-wall dominates the insertion loss afterwards. The highest traffic noise amplification and attenuation observed in this study are both $\sim$ 6 dBA.

It is found that the four balcony forms can be grouped into two categories. One is the "with short side-wall" group and the other "without short side-wall" group. The shapes of the insertion loss spectra within each group are similar. The balustrade basically has not much effect on the spectral variation pattern of the insertion loss, though the insertion loss magnitude is weaker for balconies without a balustrade but with a short side-wall. This balcony form is not recommended. The short side-wall actually controls the pattern of the insertion loss spectral variation.

For the balcony without a short side-wall opposite to the full-height side-wall, the screening effect is not strong such that the excited acoustic modes, especially those associated with the odd order transverse modes, the longitudinal modes, and their combinations, are effective to produce sound amplification at lower frequencies. The even order transverse modes are not effectively forced out, leading to weak sound amplification and even sound attenuation near to their frequencies in general. The insertion loss is weak and basically not so affected by frequency when the source is parallel to the model façade. As the azimuthal angle is increased further, the spectral variation pattern of the insertion loss resumes that at negative azimuthal angle, indicating that the major acoustic mode interactions as discussed above are again in place.

In the presence of a short side-wall, more acoustic modes are effectively forced out between the two side-walls, but sound amplification is found at higher frequencies when the short side-wall is nearest to the sound source because of the stronger screening effect of various balcony components. There is a shift in the spectral variation pattern of the insertion loss as azimuthal angle increases from negative to positive. This pattern resembles that of the balcony without the short side-wall eventually after the screening effect of the full-height side-wall dominates the insertion loss. For this group of balconies, the mismatch between the longitudinal modes above and below the balustrade edge tends to reduce the chance of having overall sound amplification on the model façade.

The abovementioned insertion loss patterns are basically maintained when the elevation angle is reduced. However, there is evidence that even order transverse modes are also forced out with sufficient magnitude to result in sound amplification when the balcony elevation angle is small, but the effect is not significant.

ACKNOWLEDGMENTS

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APPENDIX: ONE-THRID OCTAVE BAND INSERTION LOSSES

For the sake of easy reference and completeness, Fig. 14 illustrates the one-third octave band insertion losses of all the balconies tested in the present study.

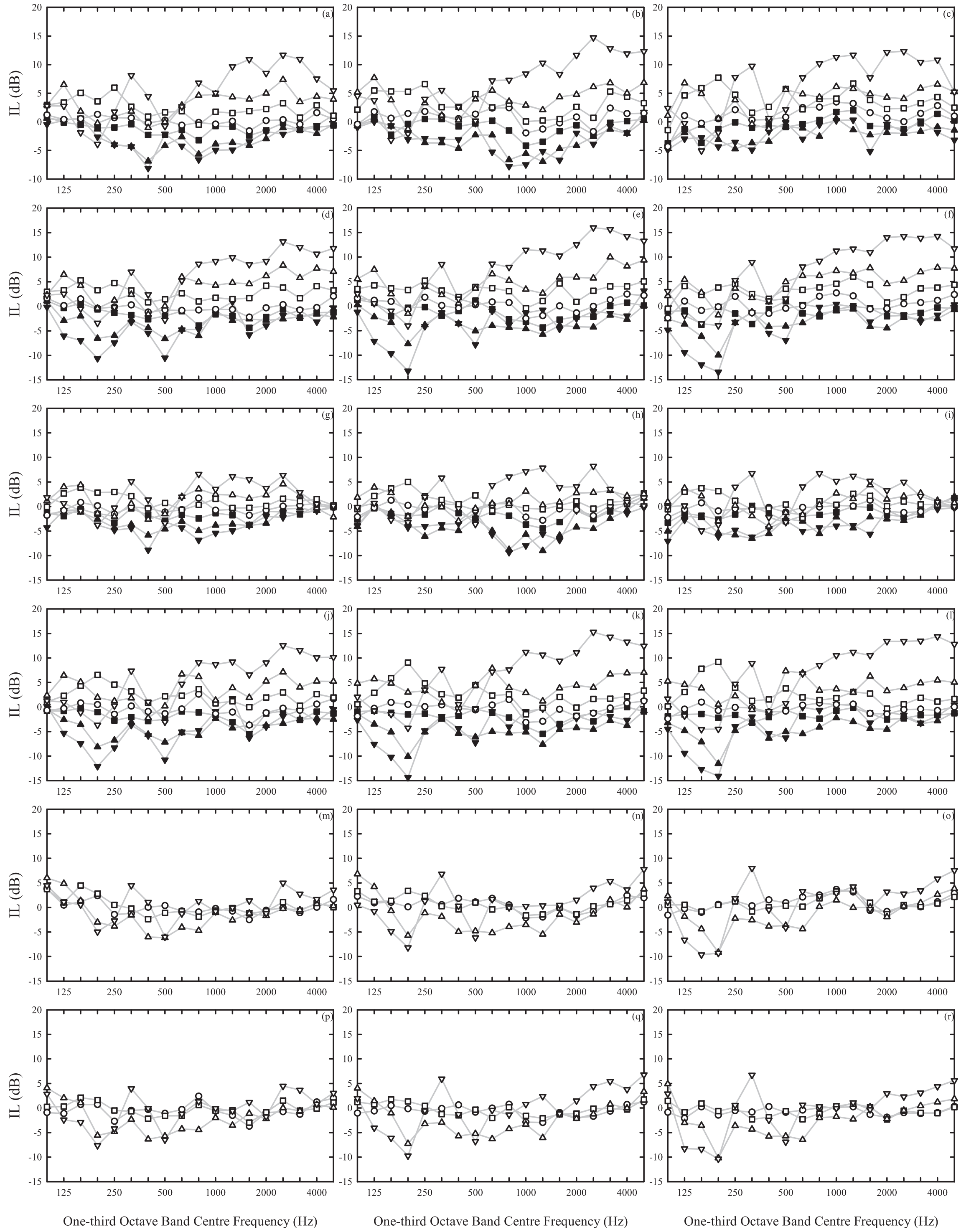

FIG. 14. One-third octave band insertion losses of all balconies tested in the present study. (a) top WFBS, (b) middle WFBS, (c) lower WFBS, (d) top WFB, (e) middle WFB, (f) lower WFB, (g) top WBS, (h) middle WBS, (i) lower WBS, (j) top WB, (k) middle WB, (l) lower WB, (m) top WFBW, (n) middle WFBW, (o) lower WFBW, (p) top WBW, (q) middle WBW, (r) lower WBW. Other legends are the same as those of Fig. 6.

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