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Full scale model investigation on the acoustical protection of a balcony-like façade device (L)

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The acoustical insertion losses produced by a balcony-like structure in front of a window are examined experimentally. The results suggest that the balcony ceiling is the most appropriate location for the installation of artificial sound absorption for the purpose of improving the broadband insertion loss, while the side walls are found to be the second best. Results also indicate that the acoustic modes of the balcony opening and the balcony cavity resonance in a direction normal to the window could have a great impact on the one-third octave band insertion losses. The maximum broadband road traffic noise insertion loss achieved is about 7 dB.
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I. INTRODUCTION

Hong Kong is a very congested city. High-rise residential buildings are erected close to ground transportation lines due to the limitation of choices. Road traffic noise has become a major source of noise pollution.[1]

Roadside noise barriers have been proposed to tackle traffic noise problems.[2] However, the noise barriers are not a total solution to the problem in the urban areas of Hong Kong due to the high-rise street canyons, the limited spaces for the barrier foundation, and other site constraints.

Balconies are façade devices that have been considered to be the alternatives for tackling traffic noise pollution. Previous examples include May,[3] Mohsen and Oldham,[4] Hossam El-Dien and Woloszyn[5] and Tang.[6] May[3] studied the use of sound absorption in reducing noise level inside the balconies of a real high-rise buildings. Because the balconies in May[3] could not be removed, the corresponding balcony insertion loss results were only indirectly estimated. Moshen and Oldham[4] investigated the effects of balcony depth on the insertion loss using a scale down model, and Hossam El-Dien and Woloszyn[5] predicted the influence of the balcony ceiling on the insertion loss using a ray tracing model. Tang[6] investigated the effects of balcony forms on the insertion loss using scale down model. Hothersall *et al*.[7] have carried out a two-dimensional numerical study on the improvement of balcony insertion loss by installing sound absorption linings inside the balconies. However, the results of May[3] and Tang[6] show that the balconies in general cannot provide satisfactory acoustical protection unless a significant amount of sound absorption has been installed into the balcony cavity.

A full scale experiment was carried out in the present study. The effects of the locations of the sound absorption materials on the acoustical insertion loss of the balcony-window configuration were tested.

II. EXPERIMENTAL SETUP

A. The testing chambers

All the experiments were carried out inside an acoustic testing facility; the facility is originally a "dual chambers" design for the ISO140-3 test. The volumes of the source and receiver rooms are 240 and 84 m^3, respectively. A 150 mm thick plastered concrete wall of surface area 10 m^2 separates the two rooms. It is where the balcony-window was installed.

The source room was converted into a semi-anechoic chamber as in Kang[8] by putting up thick fiberglass curtains at about 1 m away from the rear wall and the side walls and at similar distance below the room ceiling. The reverberation times (T_{30}) inside the source room after the installation of the fiberglass curtains were less than 0.2 s at frequency bands above 250 Hz and was ~0.5 s within the 100 Hz one-third octave band.

B. Balcony-window and measurement setup

The cross section of the balcony-window setup adopted in the present study, and the dimensions of the essential components are illustrated in Fig. 1. The dimensions of this balcony window and the cavity are typical for Hong Kong public housing buildings. The balcony was made of 120 mm thick concrete bricks. The height of the balcony front parapet was level with the window sill. A 25 mm (1 in.) thick fiberglass with density 32 kg/m^3 was installed at different internal surfaces of the balcony. Table I summarizes the different cases tested in the present study. The noise reduction classes of the fiberglass and the concrete brick surfaces were 0.45 and 0.04, respectively, as measured by an impedance tube.

Nine Brüel and Kjær type 4935 microphones randomly spaced inside the receiver room (> 1 m away from walls)

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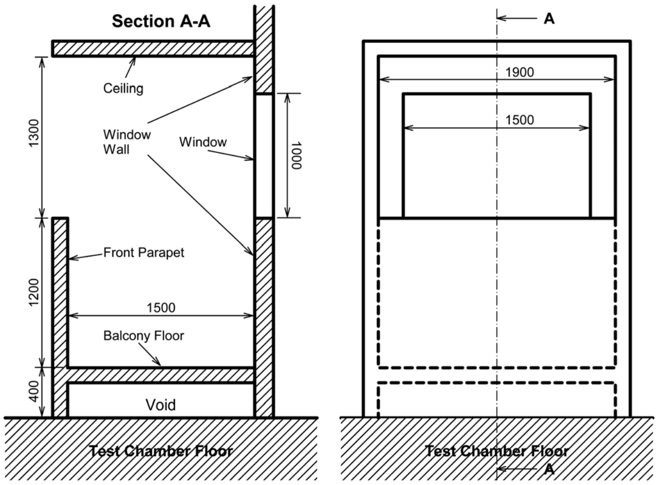

FIG. 1. Cross section and dimensions of the present balcony-window.

were used to measure the transmitted sound level. A reference microphone was used to check any variation in the sound source spectral strength and derive the corresponding spectral corrections to the measurements if necessary. This reference microphone was located at 1.6 m height from the chamber floor and 2.5 m horizontally away from the vertical centerline of the façade device in the source room. The Brüel and Kjær 3506D PULSE system, which is capable of sampling 25 channels simultaneously at a rate of 32000 samples per second per channel, was used as the data acquisition system.

C. Sound source

The sound source in the present study was a linear array consisting of 25 6-in. aperture loudspeakers located on the chamber floor at 5 m perpendicularly away from the separating wall. The loudspeakers were capable of generating sound from the 63.5 Hz to the 20 kHz one-third octave bands with levels at least 12 dB above background noise level. Constant magnitude white noise signals were fed into the sound system throughout the experiment.

The directivity of the loudspeaker array was measured at a radius of 2 m on the vertical central plane of the balcony. The measurement angle was from 17° to 31°. The directivity variation within each one-third octave band (from 63.5 Hz to 5 kHz) was in general within 1 dB about the mean level. The source uniformity test consisted of measurements at 2 m away from the loudspeaker array at 1.2 m above the chamber floor over a horizontal span of 1.3 m. Uniformity variations within the frequency range were in general within 2 dB about the mean level.

III. RESULTS AND DISCUSSION

The broadband performance indicator used in the present study to describe the acoustical protection is the insertion loss (*IL*) defined as the average noise level reduction inside the receiver room after the installation of the balcony when the window is opened.[4] Normalized noise spectra were used in the estimation of this broadband *IL* as in Buratti.[9]

Figure 2 illustrates the one-third band insertion losses *IL* obtained in the present investigation. Data at the 50 Hz band are not presented as the corresponding insertion loss is so high that the noise levels inside the receiver room are close to the background level. At the very low frequency end, the strong impedance of the hard walled balcony cavity reflected lots of sound energy back and thus higher insertion loss can be observed with fewer amounts of sound absorption materials inside the balcony cavity in general. Such effect is quickly weakened at frequency increases.

At frequencies above the 63.5 Hz band, one can observe that there are several regions of spectral variations in the insertion loss. It can also be observed that the *IL*s at frequencies lower than the 160 Hz band are negative, probably due to the relatively strong cavity reverberation. Between the 160 and 250 Hz bands, there is a trend of increasing *IL* with increasing frequency, but the increase of the former does not show a direct correlation with the amount of sound absorption within the balcony cavity. At frequencies higher than the 250 Hz band, the *IL* increases with increasing sound absorption inside the balcony cavity, but basically fluctuates between 4 and 12 dB over the rest of the frequency spectrum provided that the balcony ceiling is treated with the sound absorption material. At frequencies higher than the 1250 Hz band, the insertion losses are in general unchanged once the balcony ceiling is treated with the absorption materials.

There are several major insertion loss peaks and dips revealed in Fig. 2. The dips at 80/100 and 2500 Hz bands are

TABLE I. Cases of the balcony window treatments and insertion losses.

	Balcony internal surface treated by absorption materials (✓)					Surface area treated (m^2)	Insertion loss (dB)		
Case	Ceiling	Window wall	Balcony side walls	Balcony floor	Front parapet		By EN1793-3	By NT-ACO 62 (low speed train)	By NT-ACO 62 (high speed train)
O0	–	No	balcony	–	–	–	–	–	–
O1	✓	✓	✓	✓	✓	18.8	7.0	7.4	8.0
O2	✓	✓	✓	✓		16.6	6.7	7.0	7.7
O3	✓	✓	✓			13.7	6.7	7.0	7.6
O4	✓		✓			10.4	6.6	7.0	7.6
O5	✓					2.9	5.9	6.1	6.9
O6						0	2.5	2.8	3.3
O7			✓			7.5	3.5	3.9	3.9

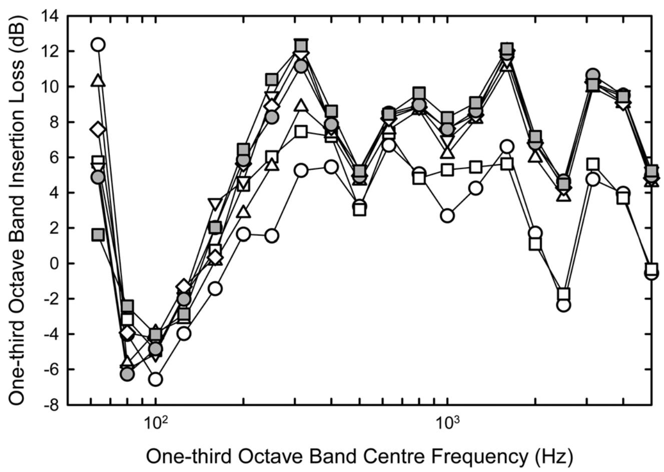

FIG. 2. One-third octave band insertion loss for test cases with window opened. ■: O1; ●: O2; ◇: O3; ▽: O4; △: O5; ○: O6; □: O7.

very significant. Because the depth of the balcony is 1.5 m, a possible resonance can take place between the parapet and the window wall and between the opened window and the balcony opening at around 100 Hz, resulting in negative *IL* even when all the balcony internal surfaces are treated with sound absorption materials. This open-end type longitudinal resonance results in strong acoustical velocity at the window opening and thus high sound intensity inside the receiver room. More effective sound absorption and stronger barrier effect of the balcony may compensate for such resonance effects at higher frequencies.

The insertion loss here depends on the sound absorption, the barrier effect of the balcony, and the resonant modes of the balcony opening as well as those of the balcony cavity. The attenuations due to sound absorption and barrier effect in principle increase with increasing frequency and thus the up-and-down fluctuations of the insertion loss shown in Fig. 2 should be the results of the resonant modes. Also one can observe that the trend of the frequency variation of *IL* does not depend much on the locations and the amount of absorption materials inside the balcony cavity, suggesting that the longitudinal resonances between the window and the balcony openings are the only important balcony resonances which have large impact on the *IL*.

Table II illustrates the modal characteristics of the balcony opening. The pressure pattern of the (N_W, N_H) mode can be represented by the expression $\cos(N_W \pi x/W)\cos(N_H \pi y/H)$, where W and H denote the width and height of the balcony opening, respectively, and x and y the coordinates. For the case of $N_W = 1$, $N_H = 0$, a relatively large low sound pressure region will be created around the central part of the opening, resulting in a higher acoustic particle velocity in the balcony opening and thus a strong sound transmission into the receiver room. The same applies to the case of $N_W = 0$, $N_H = 1$. The resonances, together with the reverberation within the cavity, explain the highly negative *IL* observed within the 100 and 125 Hz one-third octave bands. For the case of $N_W = N_H = 1$, the number of high positive and negative acoustic pressure gradient regions are the same. The lack of an overall definite acoustic velocity direction at any instant could result in less sound radiation into and across the cavity under the present oblique sound incidence (at 160 Hz band, for instance). Such phenomenon occurs whenever $N_W + N_H$ is even.

One can observe from Table II that there is a good correlation between the *IL* peaks and dips with the percentage of modes with odd ($N_W + N_H$) at the frequency bands when the modal density is low. No odd ($N_W + N_H$) mode is found at the one-third octave band where an *IL* peak is found (at 315 Hz), while no even ($N_W + N_H$) mode is observed for the large dip (at 100 Hz, for instance). The small *IL* plateau at the 250 Hz band is probably due to similar modal effect. The *IL*s at the 315 and the 400 Hz bands are very close though there are more odd ($N_W + N_H$) modes within the latter one. However, one can observe that there is no longitudinal balcony cavity mode within the 400 Hz frequency band. With sound absorption materials installed inside the balcony, the insertion loss at the 315 Hz band increases more rapidly than that at the 400 Hz band. This is probably due to the higher percentage of the odd ($N_W + N_H$) modes within the 400 Hz band, which are more suitable for sound transmission into the cavity. The weak *IL* dip at 500 Hz is believed to be the result of the longitudinal balcony mode.

When the modal density is high, the number of the modes with odd ($N_W + N_H$) is basically the same or very close to that of the modes with even ($N_W + N_H$). Modal overlapping tends to make the balcony opening resonance effect much less observable. However, the number of longitudinal balcony modes between the balcony and window openings also increases within frequency bands of higher center frequencies. One can observe the effect of such balcony cavity resonance on lowering the balcony insertion loss in the two-dimensional simulation of Hothersall *et al.*[7] for frequencies higher than 500 Hz as well.

Under similar strength of excitation, stronger resonance will occur with the acoustic modes with either N_W or N_H as zero. Because the odd balcony opening modes are more supportive to sound transmission, the larger number of such odd modes in general and especially those with either N_W or N_H is zero within the 2500 Hz band, together with the larger number of balcony longitudinal resonant modes, could have caused a large dip of *IL*. The same is believed to be true for the 5000 Hz band.

In Table I are presented the broadband *IL* of the seven cases studied. The *IL* is about 3 dB for the case without the installation of sound absorption material (O6) under the present sound incidence angle. The sound absorption materials on the balcony side walls can improve the insertion loss by about 1 dB, but that at the ceiling has resulted in a ~3 dB increase in the insertion loss. The combined actions of sound absorptions at the ceiling and on the side walls produce an *IL* of ~7 dB and further covering the other balcony internal surfaces does not basically produce any improvement of the acoustical protection. The results also suggest that the parapet, the balcony floor, and the wall under the window are not suitable for the acoustical treatment in term of noise reduction. The balcony ceiling is the most important location for acoustical treatment and the side walls are the next.

TABLE II. Modal characteristics of balcony opening.

One-third octave band center frequency (Hz)	Mode Counts							Percentage odd (N_W+N_H)	Average modal separation (Hz)
	Total[a]	Odd (N_W+N_H)	Even (N_W+N_H)	$N_H=0$, Odd N_W	$N_H=0$, Even	$N_W=0$, Odd N_H	$N_W=0$, Even N_H		
100	1 (0)	1	0	1	0	0	0	100.0	23.1
125	1 (1)	1	0	0	0	1	0	100.0	29.2
160	1 (0)	0	1	0	0	0	0	0.0	36.7
200	2 (0)	1	1	0	1	0	0	50.0	23.1
250	3 (1)	2	1	1	0	0	1	66.7	19.4
315	2 (1)	0	2	0	0	0	0	0.0	36.6
400	6 (0)	4	2	0	1	1	0	66.7	15.4
500	11 (1)	5	6	1	1	0	0	45.5	10.6
630	12 (2)	7	5	1	0	0	1	58.3	12.2
800	19 (1)	9	10	1	1	0	1	47.4	9.7
1000	36 (2)	16	20	1	2	1	1	44.4	6.4
1250	49 (3)	25	24	2	1	1	1	51.0	5.9
1600	82 (3)	43	39	2	2	2	1	52.4	4.5
2000	124 (4)	60	64	2	3	1	2	48.4	3.7
2500	200 (5)	103	97	4	3	3	2	51.5	2.9
3150	313 (7)	155	158	4	4	2	3	49.5	2.3
4000	507 (8)	252	255	4	5	4	4	49.7	1.8
5000	772 (10)	388	384	6	7	4	4	50.3	1.5

[a]Number in parentheses is the number of longitudinal resonance modes between window and balcony opening.

Consider an infinitely long sound barrier located at the same distance away from the window wall and at the same height as the balcony parapet to the window; the path differences created by such barrier at the window sill and the window center are 100 and 6 mm, respectively, while that at the window top, which is in the illumination zone, is ∼15 mm. The average insertion loss so estimated from Ref. 2 is 5.7 dB. The maximum *IL* for the present setup is between 7 and 8 dB (O1). The insertion loss of the side wall portion due to the direct line of sight obstruction in the present study is 2 dB (calculation not shown here). As the diffraction at the edges of the side walls will lower slightly the insertion loss, the ∼1.3 to ∼2 dB higher *IL* than the two dimensional prediction[2] is probably due to the effect of the side walls.

IV. CONCLUSIONS

A full scale model experimental measurement of the acoustical insertion loss of a balcony-like device for use with windows on a building façade in the presence of a line source was carried out in the present investigation.

The present results suggest that sound absorption treatment at the balcony ceiling is the most effective, while absorption on the side walls is second. There is basically no improvement in the broadband insertion loss by further addition of sound absorption once the ceiling and the side walls are acoustically treated. Under the current settings, the maximum broadband insertion loss achieved is roughly 7 dB. It is found that the side walls have resulted in 1-2 dB additional noise reduction by obstructing the direct line of sight between the noise source and the window.

The one-third octave band insertion loss results indicate the importance of the balcony opening acoustic modes in affecting the sound transmission. The results indicate that the insertion loss is high within those frequency bands containing more of those modal patterns where the number of strong positive pressure gradient regions equals that of the strong negative pressure gradient regions. The longitudinal resonances between the window and the balcony opening are likely to have high impact on the insertion losses.

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