Effects of apartment building façade and balcony design on the reduction of exterior noise

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Abstract

The effects of building façade and balcony design on the reduction of exterior noise were investigated by measuring the noise from traffic at an apartment complex located by a road side as well as the sound field characteristics of an area surrounded by four apartment buildings. The efficiency of different balcony forms for reducing exterior noise was determined using a 1:50 scale model and a single spark source. It was found that parapets were more effective in reducing exterior noise than lintels. Based on the measurements of the parapet used for this study and the absorptive materials in the scale model, a maximum noise reduction of 23dB was obtained. Lastly, a computer simulation was conducted in order to predict the noise reduction level of lintels and parapets. The results of the simulation were compared to the results of the scale model test. Our results indicate that this method of exterior noise reduction can be useful in high-rise buildings where tall barriers cannot be built.

Keywords: Exterior noise, Facades, Balcony, Noise reduction, Scale model, Computer simulation

1. Introduction

Multi-residential buildings are the most common type of dwelling in Korea, and approximately 40% of the population lives in high rise apartment buildings. In a mega city like Seoul, many buildings are exposed to severe exterior noise due to their proximity to roads and train railways. While legal requirements and guidelines that limit exterior noise levels do exist, a recent report [18] found that six major cities in Korea exceed the legal limit and that the noise levels of high rise buildings were most severe for upper stories. This report also showed that existing sound protecting treatments, such as sound barriers, are limited in their ability to reduce exterior noise levels.

Many researchers have investigated the screening effect of balconies using either scale models or computational studies. Cheng *et al* [1] investigated the performance of the lintel using Macdonald's theoretical prediction and the image receiver theory, showing that the average predicted insertion loss provided by an absorptive top screen is 20 dB at 1 kHz and 25 dB at 2 kHz. Hotherall *et al* [2] calculated the sound pressure level relative to the free field level within balconies using a two-dimensional boundary element numerical model. Their study found that treatment of the ceiling or the rear wall of the balcony was the most efficient method of reducing noise. In addition, Hossam El-Dien and Woloszyn [3, 4] tested several different forms of balconies, and Tang [6] examined the insertion loss and noise spectrum of a rectangular balcony using a scale model.

Most previous studies mentioned above define exterior noises solely as traffic noise. Further, previous scale model tests and simulations were not conducted in an apartment complex, but rather in a single building. However, most multi-residential buildings in Korea are built as a complex consisting of 10-30 buildings, and in such an apartment complex, other noises, such as those produced from vehicles entering and exiting an underground parking lot or from a nearby outdoor market held in that area, may be produced in the surrounding area. The effectiveness of different balcony types as screening devices for these noises has not yet been investigated for an apartment complex.

In the present study, a 1:50 scale model test was carried out to investigate the noise reduction offered by the combination of various balcony treatments for a single building and an apartment complex. The treatments consist of a parapet, lintel, absorber, and balcony ceiling angle. In addition, a computer simulation was conducted to validate the scale model results. The general screening effects are expressed in terms of A-weighted sound levels [3-6].

2. Field Measurement

Field measurements were conducted to investigate traffic noise levels and acoustic characteristics of apartment complex located near a road.

2.1 Traffic noise measurement

Traffic noise was measured in apartments that were 60 m away from a six-lane road, and each of the buildings in which measurements were taken consisted of fifteen stories. There were two 4 -5 story buildings between the road and apartments, as well as an outdoor driving range across the road from the apartment complex. It was assumed that traffic noise could radiate to the apartments despite possible interference from the other buildings.

As shown in Fig. 1, traffic noise measurements were carried out in the balconies on the 1st-5th, 7th, 9th, 11th, 13th and 15th stories of buildings 107 and 108, which were exposed to the most amount of noise during the daytime (06:00~22:00) and nighttime (22:00~06:00).

Fig. 1

2.2 Traffic noise measurement results

As shown in Figs. 2 and 3, the levels of traffic noise at each building, except for the 9th floor balcony of building 107, were less than the maximum allowable exterior noise level of 65 dBA. These noise levels were lower than those reported in a recent study by Kang *et al* [18], who measured the exterior noise levels for apartment complexes in six megacities in Korea and found that the exterior noise levels often exceed 65 dBA. The reason for the difference in the exterior noise levels between the two studies is that in the current study, the apartment complex was located 60 m away from a road, whereas in the study by Kang *et al*, the complexes were located much closer to a road. Nonetheless, our measurements indicated that noise levels for the upper floors were slightly higher than the noise levels for the lower floors, which was consistent with the report by Kang *et al*.

Fig. 2

Fig. 3

2.3 Sound field characteristics of the area surround by the four buildings

Field measurements were conducted to investigate both the characteristics of the sound field in the area surrounded by the four buildings and the sound propagation from this area to the apartments. This inner area consisted of an asphalt covered parking lot and an underground parking lot entrance, which was located in the corner of buildings 106 and 108. A sound source consisting of an omni-directional speaker was located in the center of the parking lot to produce white noise and swept-sine signal. Sound signals were recorded in each balcony of buildings 106-109 using a mono omni-directional microphone (AKG 414)

2.3.1 Sound propagation characteristics

The sound pressure levels of the white noise in each balcony of buildings 106-109 were measured using a sound level meter (Bruel & Kjaer Type 2260). The results are presented in Table 1. The sound pressure level measured at a distance of 1m from the speaker was 93.5 dBA, while the sound pressure levels in most balconies were between 75 to 76 dBA. The sound pressure difference between the balconies closest and farthest away from the source was no greater than 4.1 dB; this small difference was due to sounds reflected from the hard surface of the parking lot and the facade of each building. The sound pressure levels in the balconies showed that noise produced from the area surrounded by the four apartment buildings could be propagated to the upper part of the each building without a large noise reduction.

Table 1

As shown in Fig. 4, the variation of the sound pressure levels of the white noise in the balconies with respect to the distance from the source was similar to that observed in a reverberant field. The sound pressure levels become constant at distances far away from the source, demonstrating that reflected sound dominates at these locations. This is also shown in Fig. 4, which compares the variation of the sound levels with the distance from the point source and line source in a free field.

Fig. 4

2.3.2 Sound field characteristics

The reverberation time in each balcony of buildings 106-109 was measured to investigate the sound field characteristics of the space surrounded by the four buildings. In this study, T20 was analyzed because the measurements were conducted outside. The T20 values are presented in Fig. 5 The average T20 values between 500 Hz and 1 kHz were around 3 sec, and thus, the sound generated in this space could last for a relatively long period of time. The T20 values were not highly correlated with the position of the receiver.

Fig. 5

As shown in Fig. 6, most impulse responses contained many reflected sounds that were influenced by the surrounding buildings; in some cases a flutter was observed. Sound pressure levels were affected mainly by direct sound and the first reflected sound from the parking lot surface. The first reflected sound was much higher than the second and third reflected sounds. Thus, in order to reduce the sound pressure level in each balcony, it is necessary to control the direct sound and the first reflected sound.

Fig. 6

3. Treatments for reducing exterior noise

The most common type of balcony in Korea was considered as a reference for the present study, and it is shown in Fig. 7 together with photograph of the real life example measured for this study. This type of balcony is representative of cases where the balcony consists of a solid hard side wall within the fence, which is acoustically transparent to sound propagation. The length of this type of balcony ranges from 4-8 m with a depth of 1.2 m, and is typically coupled with a living room and one or two additional rooms.

Fig. 7

Fig. 8

Six treatments, which are shown in Fig. 8, were investigated for their ability to reduce exterior noise. Each balcony has a depth of 1.2 m and length of 4.5 m. Each story of the building had a height of 3.0 m.

The six treatments were as follows: (a) 50 or 100 cm lintel, (b) 50 or 100 cm high parapet, (c) inclined ceiling, (d) application of the absorber to the inclined ceiling, (e) parapet plus treatment (d), and (f), application of the absorber to inner side of the parapet plus treatment (e). The effectiveness of treatment (c) was studied previously by Hossam El-Dien and Woloszyn [4] who tested the acoustic performance of three inclined angles (5, 10 and 15 °) using a computer simulation. They found that the 15 ° inclined ceiling provided the highest level of noise reduction, and thus, to decrease the power of reflection and diffuse energy components in treatment (c), an angle of 15 ° was adopted in this study.

4. Scale model and the measurements

In the present study, a scale model was used to study the noise reduction offered by different shaped balconies in high-rise apartment buildings. The choice of scale factor for the model was governed by three main requirements:

(1) A suitable size of model for housing in the laboratory.

(2) An adequate frequency range of operation.

(3) Sufficiently accurate scaling of air absorption.

A 1:50 scale factor was selected, as it satisfied these requirements for the high-rise apartment buildings. Using this ratio, the maximum dimension of a model was 96 cm. Since air absorption and transducer capabilities generally limit acoustic scale modeling to approximately 100 kHz, measurements in the 1:50 scale-model were made up to the 100 kHz octave, which was equivalent to the full-scale 2 kHz octave.

4.1 Model materials

In the present study, various materials were considered for simulating hard surfaces such as asphalt road and concrete wall. Measurements of the absorption coefficients of various materials were conducted in a 1:10 scale reverberation chamber with a tweeter speaker and a 1/8 inch microphone based on ISO 354, and they are shown in Table 2. The absorption coefficient of dense polystyrene was below 0.2 over the model frequency range. In order to select an appropriate model material, flow resistivity was also considered. An improved technique for simultaneously specifying both the optimal scale factor and the optimal modeling materials on the basis of EA (excess attenuation) has been reported by Busch and Hodgson [17]. Their results showed that dense polystyrene (3mm thick) is a good material for simulating asphalt roads and the vertical walls of apartment buildings. At a scale of 1:50, dense polystyrene also provides an effective flow resistivity of 20,000~30,000 c.g.s. Rayls/cm. Therefore, on the basis of the absorption coefficients and flow resistivity, dense polystyrene (3mm thickness) was selected as the material for constructing the scale model.

Table 2

Fig. 9

4.2 Measurement system

Line noise sources are typically used in scale model tests for simulating traffic noise. However, in the present experiment, a single spark source, which is often used to measure physical parameters of rooms, was used instead. In order to maintain an omni-directional characteristic, a small gap between each spark was required. For adequate reproducibility, a triggered source was used.

A 1/8 inch microphone (Bruel & Kjaer Type 4138) connected to measurement amplifier (Bruel & Kjaer Type 2610) was used as a receiver. As in many previous studies, such as Hammad and Gibbs [11], Mohsen and Oldham [12] and Tang [6], the A-weighted sound pressure level was calculated in every balcony. For example, impulse responses from the scale model were similar to field measurements, as is shown in the Fig. 10. Based on these results, the measurements obtained form scale model results were considered reasonable.

Fig. 10

5. Scale model results

For the present study, tests of the scale model test consisted of two parts: (a) a single building and (b) an apartment complex. For the latter test, a scale model consisting of four apartment buildings was made. Test (a) was conducted using one building of an apartment complex scale model, and simulated a single apartment building which is located close to the traffic way and the sound source was assumed to be traffic noise. In test (b), which was meant to approximate an apartment complex, the sound source was located in the center of the area surrounded by the four buildings. In both tests, the receiver was located at the rear wall of the balcony and the height of the receiver was 1.5 m above the floor of the each balcony.

5.1 Single building test

For the single building test, the sound source was located 15 m (full scale) away from the building to simulate the traffic noise. Noise reduction was defined as the reduction in sound pressure level after installation of the treatment. Fig. 11 shows the noise reduction of treatment (a) and (b) at each balcony. In both cases, the reduction of overall A-weighted sound pressure level was measured. Treatment (a), which was with lintel, made the sound attenuation performance of the balcony worse. A 100 cm long lintel provided a much lower noise reduction than the 50 cm long lintel. This was because the longer lintel generated far more reflected sounds from the ceiling, and thus functioned as an extended ceiling. As shown in Fig. 12, the effect of the longer lintel was greatly emphasized in the lower floors of the building.

Fig. 11

Fig. 12

Treatment with parapet (b) exhibited better sound attenuation performance than lintel in most floors of the building; the results of this treatment, along with floor and incidence angles, are plotted in Fig. 11. The noise reduction achieved with treatment (b) varied from -1-5.7 dB, and the parapet with a 100 cm height provided a maximum noise reduction at the 14th floor. The acoustic performance mechanism of treatment (b) in the lower, middle, and upper floors of the building is shown in Fig. 13. At the lower and upper floors of the building, the parapet blocked the paths of the most dominant sounds propagating towards the receiver and ceiling. At the lower floors of the building, the effect of the direct sound most dominant on the sound pressure level in the balcony, while on the upper floors the reflected sound from the ceiling was most dominant. Therefore, the sound pressure levels at the lower and upper floors of the building decreased with the treatment (b). However, the parapet could not block the path for the reflected sound from the ceiling at the middle floors of the building. Therefore, the sound pressure levels at the middle floors did not decrease, and in fact increased, because the reflected sounds from the ceiling could not escape from the balcony.

Fig. 13

Treatments (a) and (b) did not provide good acoustic protection, and noise reduction fluctuated depending on the floor of the building and the incidence angle. Therefore, other treatments were considered in order to obtain greater noise reduction. The combination of an inclined ceiling and absorbing material was tested with a 100 cm high parapet for reducing the multiple noise reflections inside the balcony; velour was used as the absorbing material. The absorption coefficient of 2 mm thick velour was measured in a 1:10 scale reverberation chamber, and as is shown in Table 3, was 0.67 at 1 kHz.

Table 3

The noise reduction results of treatments (c)-(f) are shown in Fig. 14 and Table 4. Treatment (c), which consisted of an inclined ceiling, did no provide positive noise reduction in the lower part (2-6 stories) of the building, and gave a maximum noise reduction level of 9.4 dB in the 11th story. The difference in acoustic performance between the lower and higher part of the building was attributed to the different angles of incidence with the sound source.

The maximum noise reduction achieved with treatment (d), which consisted of absorbing material on the inclined ceiling, was 9 dB. This treatment provided greater noise reduction compared with treatment (c) for most floors, except 2 through 10. The difference in the noise reduction levels for treatments (c) and (d) varied from -0.92-6.97 dB at 1 kHz.

Fig. 14

Table 4

In the result of the treatment (e), which consisted of a combination of parapet and treatment (d), the acoustic protection effect of the parapet was observed. The parapet as a sound barrier in the front of the balcony provided additional sound attenuation, with a maximum of 7 dB, and had far less variation between the upper and lower parts of the building than in treatment (a). Treatment (f), which consisted of absorbing materials on both the ceiling and the inner side of the parapet, provided the greatest reduction in noise. A combination of absorbing surfaces on the ceiling and parapet gave consistently high noise reduction, which had a maximum value of 23 dB for the 2nd story. The effect of an absorbing material on noise reduction can be estimated by comparing treatments (c) and (d), and treatments (e) and (f), respectively. These additional noise reductions, which were attributable to the presence of the absorbing materials, varied from 2 to 9 dB. This result was slightly higher than the additional noise reduction of the absorbing surface in Hothersall et al.'s numerical prediction [2], who found that the absorbing surface provided an additional noise reduction with a maximum of 8 dB. This was due to difference between the absorption power of the 2 mm thick velour used in the current study, which was slightly higher than that of the fibrous absorber (20,000 Nsm^{-4} flow resistivity) used by Hothersall *et al.*

In a previous study by Tang [6], various angles were used to investigate the correlation between the overall A-weighted sound attenuation of the different balcony forms and those angles. Among the angles evaluated, the elevation angle suggested by Tang (which ranged from 17-60 ˚) was almost identical to the incidence angle that was considered for this study. Tang found that the variation of the elevation angle was highly correlated with the insertion loss of the balconies and that the correlation between the elevation angle and the insertion loss can be expressed as a second order polynomial equation. Similar to Tangs study, we found that an incidence angle of less than 60 ˚ was also highly correlated with an overall A-weighted broadband noise reduction and that this correlation could also be expressed as a second polynomial equation as shown in Table 5. However, when incidence angles ranging from 17-75 ˚ were considered, the correlation between the overall A-weighted noise reduction and the incidence angle was expressed as a fourth order polynomial equation as shown in Table 6. Therefore, the formulas regarding the correlation between the elevation angle and noise reduction suggested by Tang can not be generalized at the upper floors of the building corresponding to an incidence angle greater than 60 ˚ .

Table 5

Table 6

5.2 Apartment complex test

The effect of different treatments on the reduction of noise was also investigated in an apartment complex. However, treatment (a), for which acoustic performance was low in a single building, was not considered, and for treatment (b), only the 100 cm high parapet was investigated. The exterior noises produced from the area surrounded by four buildings in the apartment complex consisted of sounds produced by vehicles entering and exiting from the underground parking lot, sounds from an outdoor market held in that area, and sounds of children in a playground. In addition to the overall A-weighted sound pressure level, acoustic performance of the treatments was calculated at 250 Hz, 500 Hz and 1 kHz, due to the varying nature of the dominant frequency ranges of these noises.

Among the four buildings studied, the balconies of two buildings (106 and 109) faced the area surrounded by four buildings. In this test, treatment (b) was installed only in building 106. Fig. 15 shows the acoustic attenuation performance of treatment (b) in an apartment complex, which provided noise reduction in most floors of building 106, except for 5th floor. The noise reduction difference of the treatment (b) between in an apartment complex and in a single building ranged from 1 to 4.5 dB. The noise reduction of treatment (b) in an apartment complex was slightly increased for the middle floors of the building, which was contrary to what was observed for the scale model for the lower and upper floors of the building, except for the 1st and 2nd story. We determined that treatment (b) was unable to provide enough acoustic performance for reducing exterior noise for either a single building or an apartment complex.

Fig. 15

The noise reduction results for treatments (c), (d), (e), and (f) are shown in Fig. 16, and the results at 1 kHz are listed in Table 7. The acoustic performance of these treatments decreased in the apartment complex compared to the single building due to the increased amount of multiple reflection sounds. The noise reduction for treatments (c), (d), (e), and (f) at 1 kHz were slightly higher than that at 250 and 500 Hz. Treatment (f) provided the greatest effect on the noise reduction, with a maximum value of approximately 10 dB at 1 kHz. The effect of the absorbing material, which was installed in treatments (d) and (f), was clearly observable at both 500 Hz and 1 kHz. The addition of the parapet to treatment (d) had a small effect on the exterior noise level, but only at 500 Hz. Treatment (f) provided the highest noise reduction at 250 Hz; however, the noise reductions of treatments (d), (e), and (f) were still very small at 250 Hz. The variations of the overall A-weighted noise reduction with the floors of the building and the incidence angle were consistent with the variation of the overall A-weighted noise reduction in a single building test result. The noise reduction at 1 kHz was almost the same as the overall A-weighted noise reduction.

Fig. 16

Table 7

6. Computer simulation

A computer simulation was conducted using RAYNOISE to validate the scale model test. Specifically, the acoustic performance of treatments (a) and (b) for a single building was investigated. The parapet and lintel were much easier to apply to the balcony in the computer simulation than other treatments. Initially, all of the surfaces in the model were defined as specular surfaces. The absorption coefficient of the surfaces was 0.07 at 1 KHz. In order to consider diffraction and absorption coefficients, the Triangular Beam Method (TBD) was used to predict the sound field. 4,000 sound rays and 1st to 10th order reflected sounds were considered.

Fig. 17

In the computer simulation, the acoustic performances of (a) the 100 cm long the lintel and (b) the 100 cm high parapet were investigated. The receiver was fixed to the 6th floor of the building and the sound source's position was changed to control the incidence angles from 10-80 ˚. The overall A-weighted noise reduction is shown in Fig. 18. There was a difference in the noise reduction of treatments (a) and (b) between the scale model test and the computer simulation; however, the variation of the noise reduction with the incidence angle in both the scale model test and the computer simulation was similar. Treatment (a) provided the highest acoustic performance at the upper floors of the building and the lowest acoustic performance at the middle floors of the building. Treatment (b) provided the highest acoustic performance at an angle of incidence of around 60◦ , and the lowest acoustic performance at 20-30◦ .. The diffraction effect of the scale model test was almost the same as that of a real sound field; however, the computer simulation was imitated in its ability to simulate this parameter. Thus, it was thought that the difference in acoustic performance for treatments (a) and (b) for the scale model and computer simulation was due to diffraction at the edges

Fig. 18

7. Conclusions

To investigate the effect of different balcony forms on the reduction of the exterior noise field measurements, scale model tests, and computer simulations were performed. The results of the field measurements in an apartment complex indicated that sound pressure level in most floors were less than the 65 dBA Korean legal limit of exterior noise, the upper floors of the building experienced a maximum level of traffic noise; however, the difference in traffic noise between each floor was not large. The reverberation time measured in each balcony of the four apartment buildings was approximately 3.0 sec, and a flutter echo was observed in a few floors due to sounds reflected by the apartment buildings. When white noise was generated in the center of the area surrounded by the four buildings in an apartment complex, the sound pressure levels in the balconies indicated that noise produced from this could propagate to the upper floors of the each building without a large reduction in noise level.

A scale model test was conducted to investigate the potential noise reduction, or acoustic performance, offered by six different balcony treatments in both a single building and apartment complex setting. In the single building test, the sound source was assumed to be traffic noise and our results indicated that a combination of absorbing surfaces on the inclined ceiling and parapet provided maximum noise reduction of 16 dB at 1 kHz. In most floors, the noise reduction level gradually increased with the installation of absorbing material and parapet. However, the acoustic performance of the treatments decreased in the apartment complex test due to the increased abundance of reflected sounds and long reverberation time. Similar to the single building test, the combination of absorbing surfaces on the inclined ceiling and parapet gave a maximum noise reduction of 10 dB at 1 kHz in the apartment complex test.

The variation of noise reduction from sounds with incidence angles ranging from 17 - 75 ° were also evaluated When the incidence angle was varied from 17-60 °, the correlation between the incidence angle and overall A-weighted broadband noise reduction was similar to the reduction obtained by Tang [6] and could be expressed as a second order polynomial equation. However, incidence angles varying from 17-75 ° were correlated with the noise reduction offered by the six treatments as a fourth order polynomial equation. Therefore, the effect of the incidence angle on the noise reduction should be considered carefully when the high-rise building greater than ten floors are built.

A computer simulation was conducted to validate the scale model test. The acoustic performance of the parapet and lintel treatments as calculated by the computer simulation had similar tendencies with the noise reduction the same treatments measured from the scale model test.

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Figure Captions

[1] The apartment complex in which traffic noise was measured

[2] Traffic noise at the balconies of building 107, ○ : 15:00~17:00, □ : 18:00~20:00, △ : 20:00~22:00, ● : 22:00~24:00, ■ : 24:00~02:00

[3] Traffic noise at the balconies of building 108, ○ : 15:00~17:00, □ : 18:00~20:00, △ : 20:00~22:00, ● : 22:00~24:00, ■ : 24:00~02:00

[4] Sound pressure levels with the distance between the source and the receiver

[5] Reverberation time (T20) at each of the floors of buildings 106, 107, 108, and 109

[6] Impulse response at the 3rd floor of building 106

[7] Balcony schematic and real life example

[8] Treatments for noise reduction, (a) lintel; (b) parapet; (c) inclined ceiling; (d) inclined ceiling and an absorbing surface; (e) inclined ceiling, an absorbing surface, and a parapet; and (f) inclined ceiling, parapet and absorbing surfaces

[9] Scale model used in the study

[10] Impulse response at 3rd story of the building 106; a) field measurement, b) scale model

[11] Noise reduction of treatment (a) and (b), ● : lintel 50 cm, ○ : lintel 100 cm, ▲ : parapet 50 cm, △ : parapet 100 cm

[12] Increased reflected sounds from the lintel

[13] The effect of the parapet at various levels, a) low levels, b) middle levels, c) high levels

[14] Noise reduction provided by treatments (c)-(f), a) overall band, b) 250 Hz; c) 500 Hz; d) 1 kHz; ○ : treatment (c), △ : treatment (d), ● : treatment (e), ▲ : treatment (f)

[15] Noise reduction of treatment (b) ○ : at a single building or ● : in an apartment complex (four buildings)

[16] Noise reduction provided by treatments (c)-(f) in an apartment complex, a) overall band, b) 250 Hz; c) 500 Hz; d) 1 kHz; ○ : treatment (c), △ : treatment (d), ● : treatment (e), ▲ : treatment (f)

[17] Computer model used in this study

[18] Comparison of the acoustic performance; a) parapet, b) lintel, ● : simulation (100 cm), △ : scale model (50 cm), ■ : scale model (100 cm)

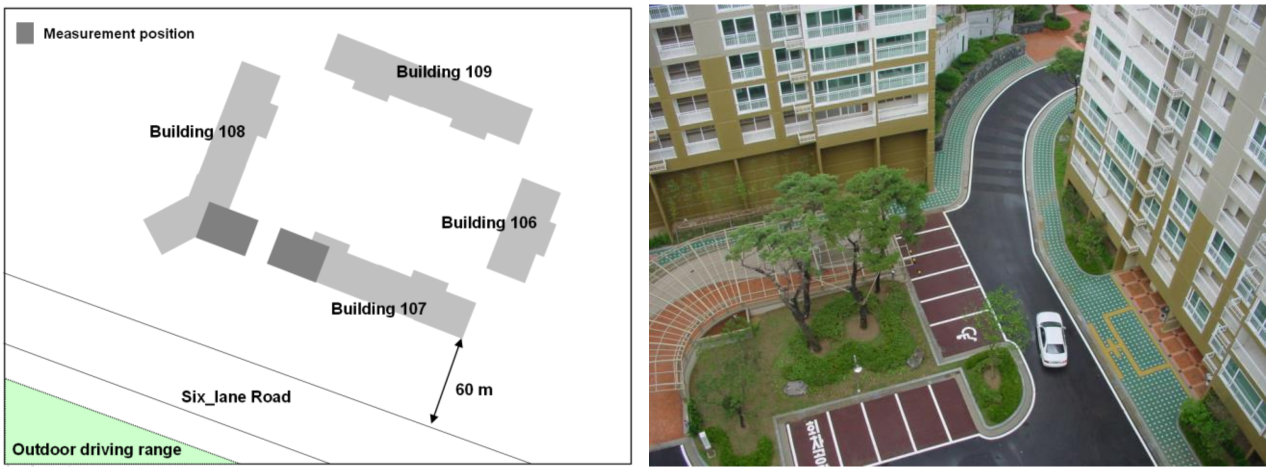

Measurement position
Building 109
Building 108
Building 106
Building 107
60 m
Six_lane Road
Outdoor driving range

Fig. 1

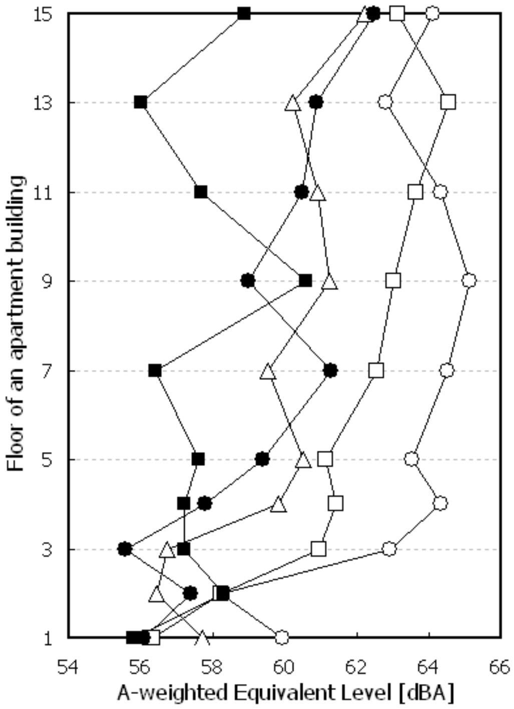

Floor of an apartment building
15
13
11
9
7
5
3
1
54
56
58
60
62
64
66
A-weighted Equivalent Level [dBA]

Fig. 2

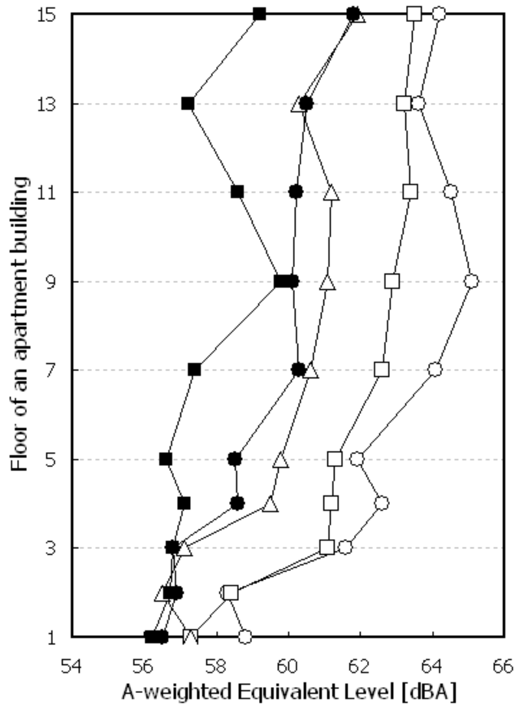

Floor of an apartment building
A-weighted Equivalent Level [dBA]
15
13
11
9
7
5
3
1
54
56
58
60
62
64
66

Fig. 3

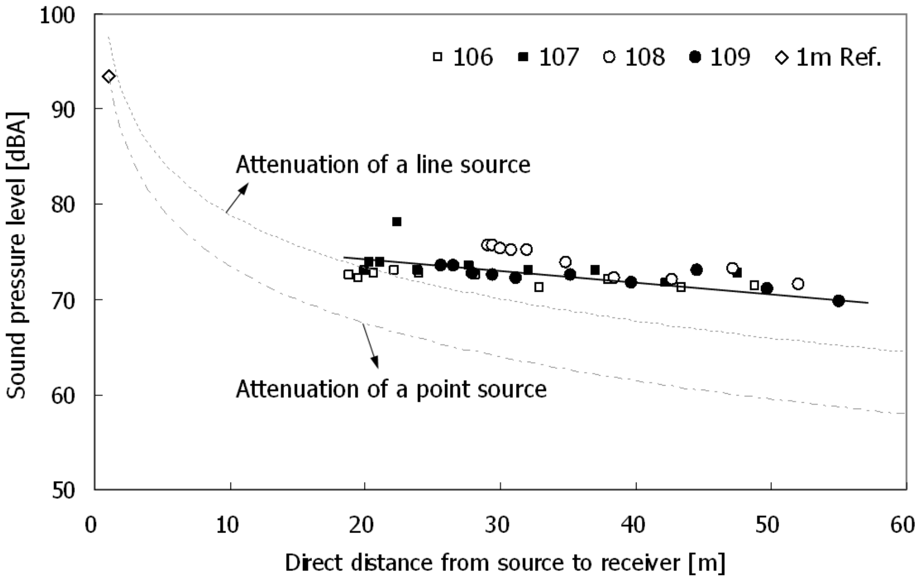

106
107
108
109
1m Ref.
Attenuation of a line source
Attenuation of a point source
Sound pressure level [dBA]
Direct distance from source to receiver [m]
100
90
80
70
60
50
0
10
20
30
40
50
60

Fig. 4

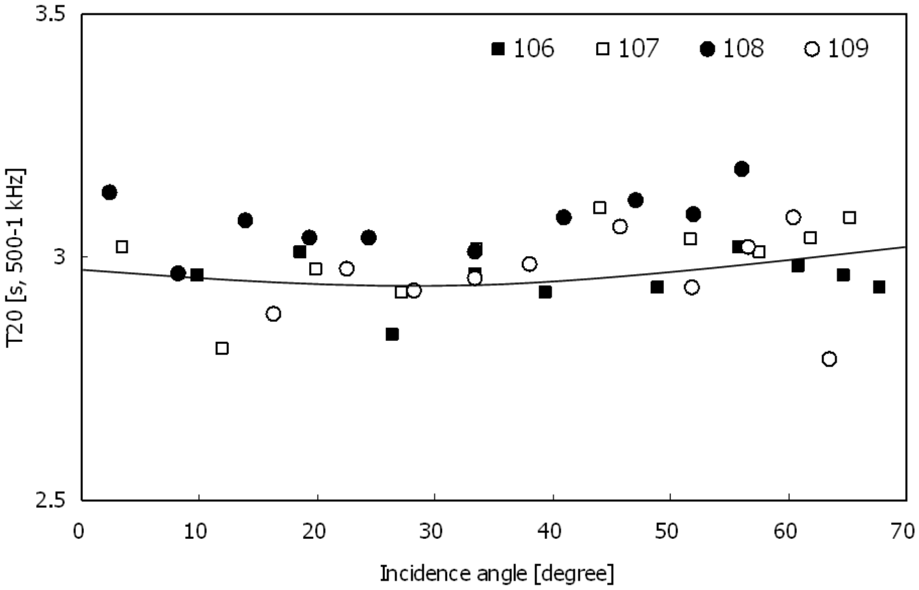


Fig. 5

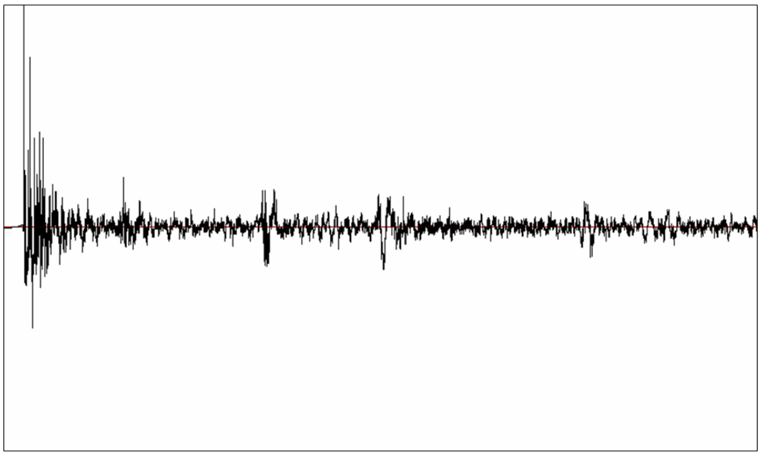


Fig. 6

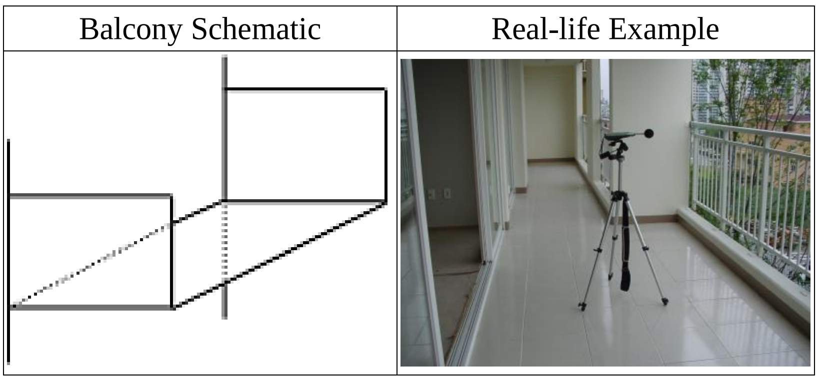


Fig. 7

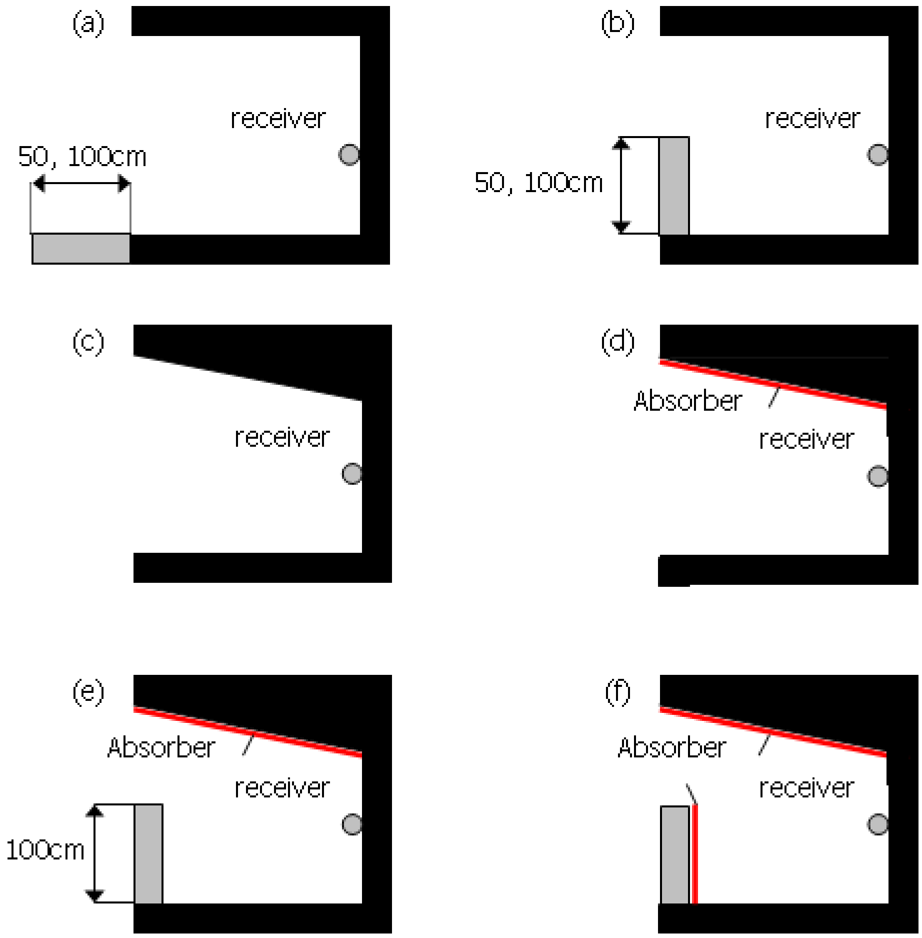

(a)
receiver
50, 100cm
(b)
receiver
50, 100cm
(c)
receiver
(d)
Absorber
receiver
(e)
Absorber
receiver
100cm
(f)
Absorber
receiver

Fig. 8

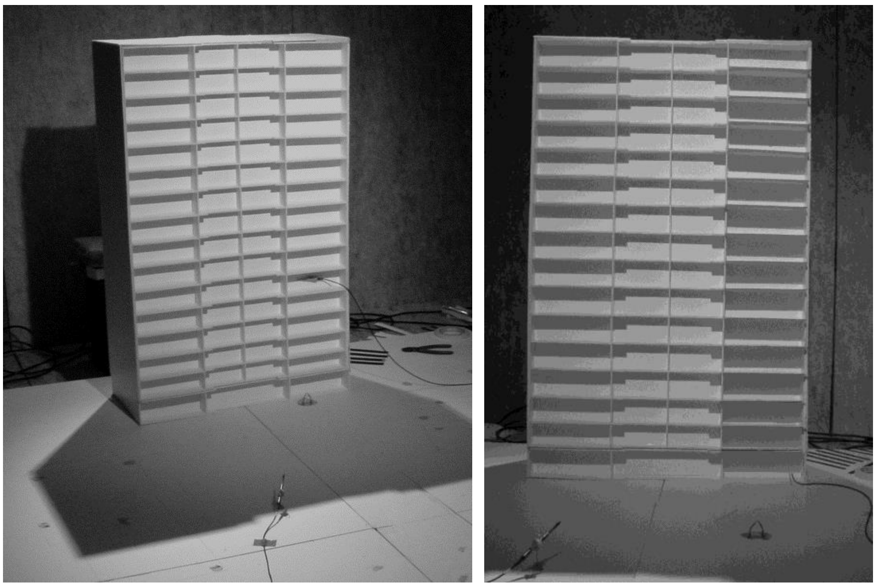


Fig. 9

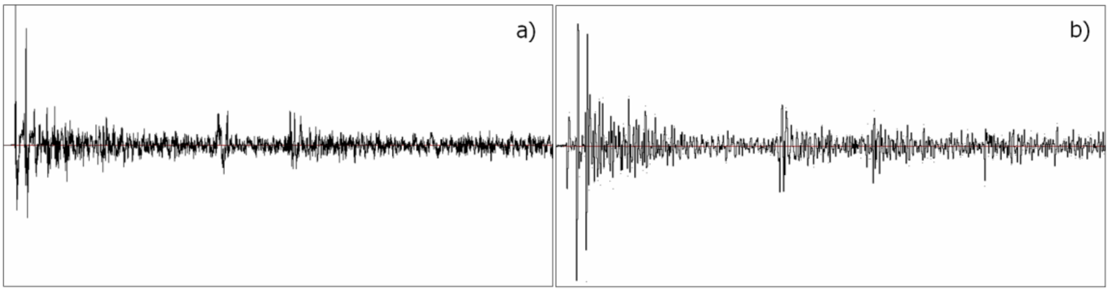

a)
b)

Fig. 10

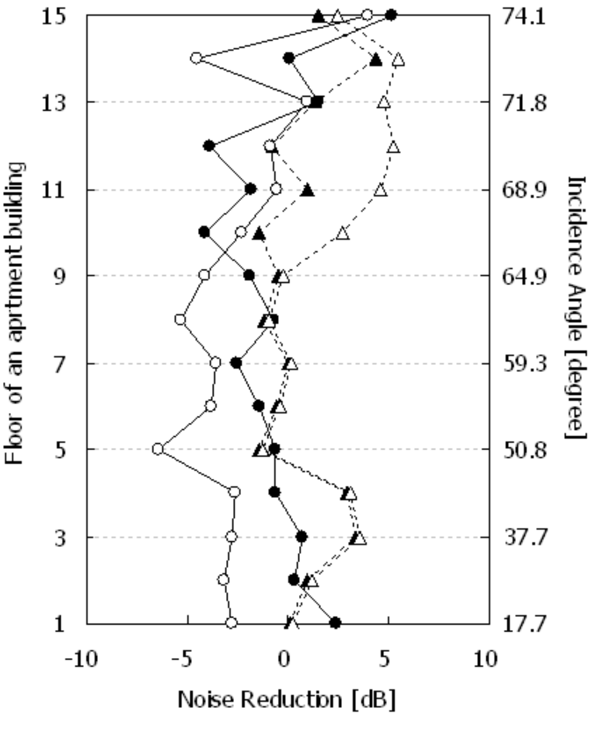

15
13
11
9
7
5
3
1
74.1
71.8
68.9
64.9
59.3
50.8
37.7
17.7
-10
-5
0
5
10
Floor of an aprtment building
Incidence Angle [degree]
Noise Reduction [dB]

Fig. 11

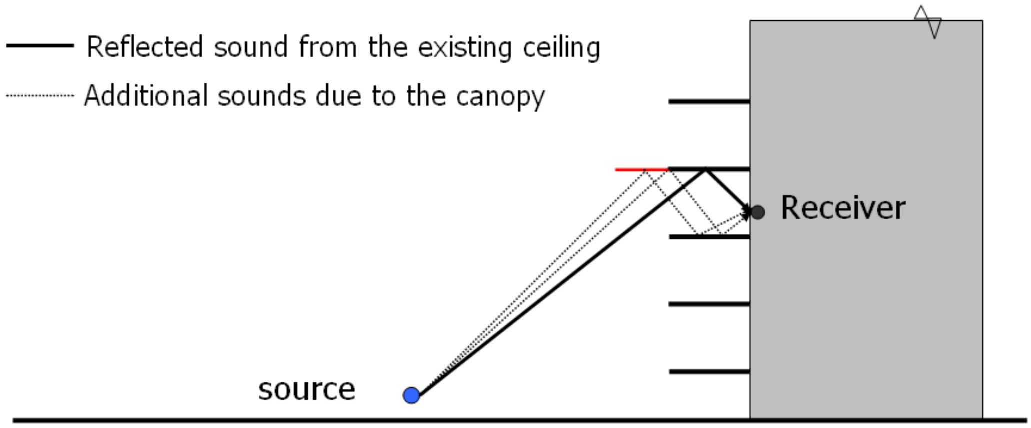

Reflected sound from the existing ceiling
Additional sounds due to the canopy
Receiver
source

Fig. 12

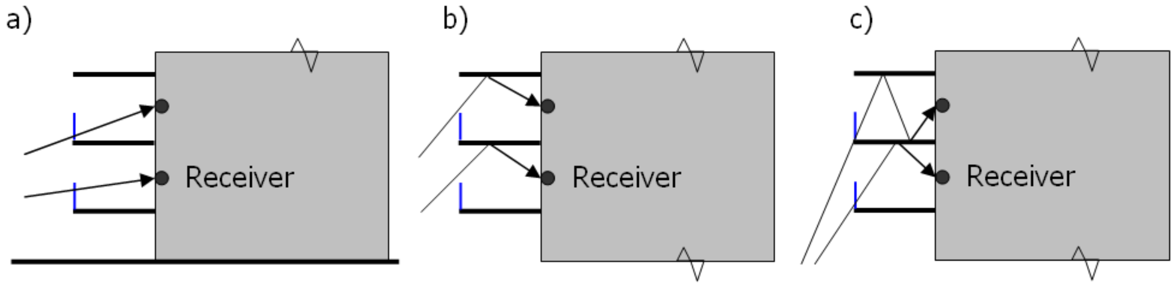

a)
Receiver
b)
Receiver
c)
Receiver

Fig. 13

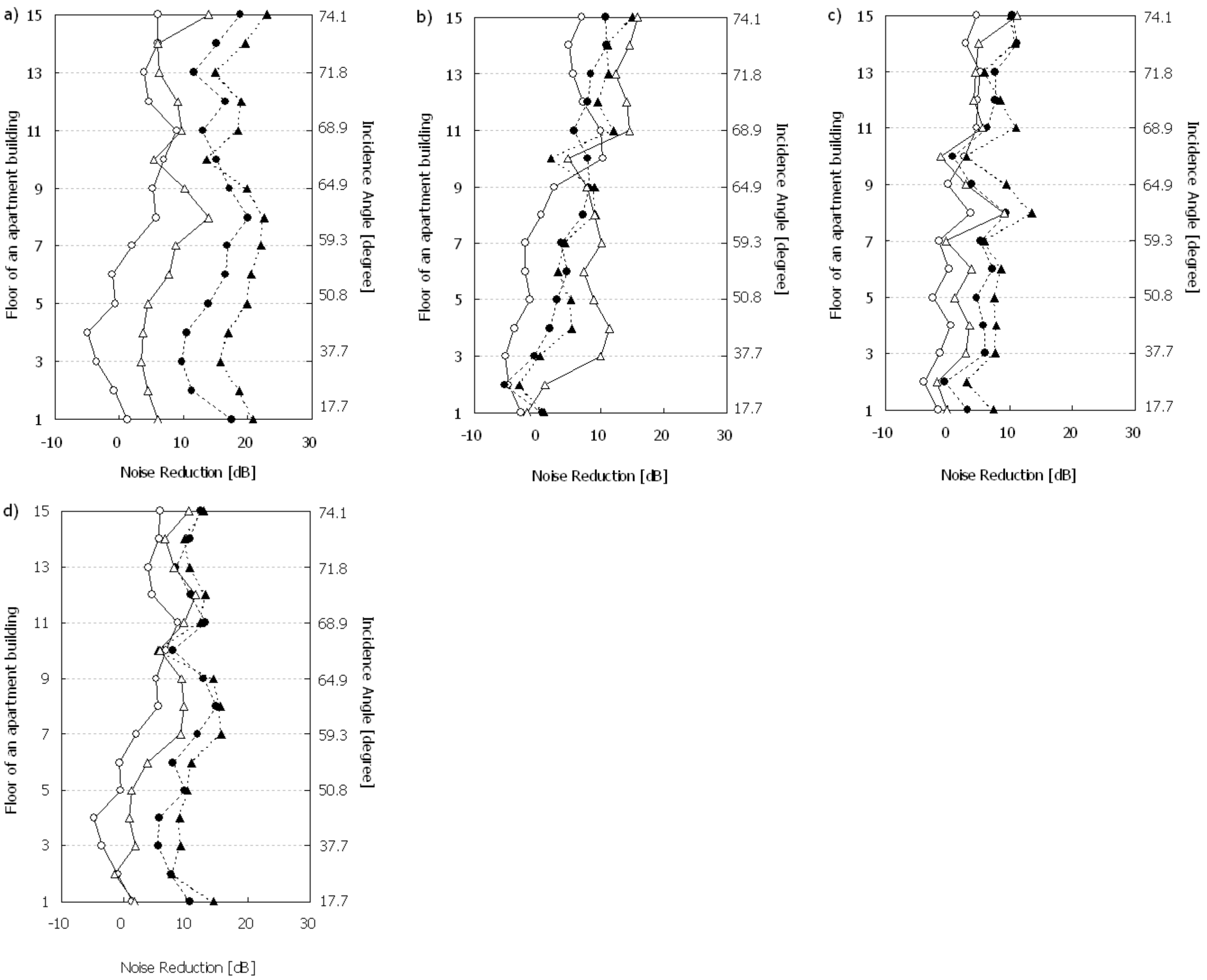

a)
b)
c)
d)
Floor of an apartment building
15
13
11
9
7
5
3
1
Incidence Angle [degree]
74.1
71.8
68.9
64.9
59.3
50.8
37.7
17.7
-10
0
10
20
30
Noise Reduction [dB]

Fig. 14

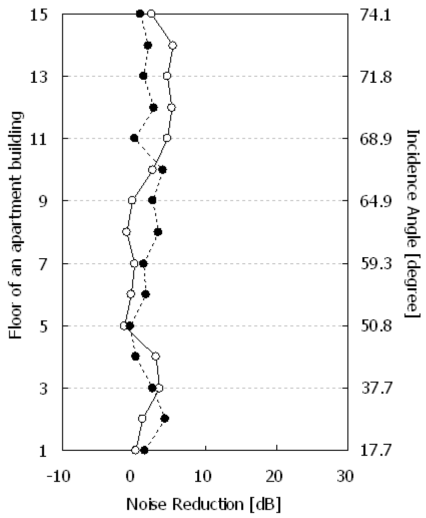

Floor of an apartment building
15
13
11
9
7
5
3
1
Incidence Angle [degree]
74.1
71.8
68.9
64.9
59.3
50.8
37.7
17.7
-10
0
10
20
30
Noise Reduction [dB]

Fig. 15

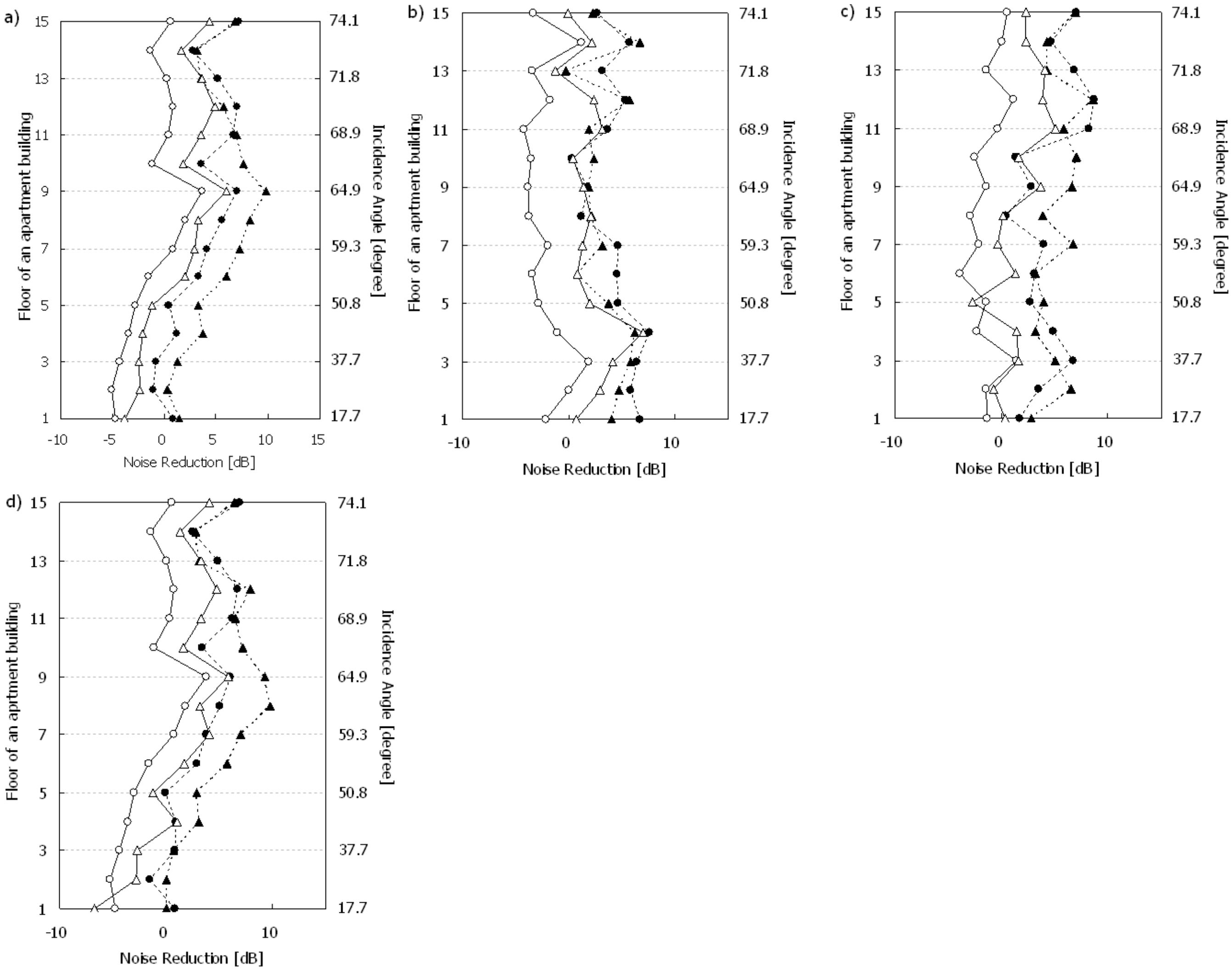

a)
b)
c)
d)
Floor of an apartment building
Floor of an aprtment building
Incidence Angle [degree]
Noise Reduction [dB]
1
3
5
7
9
11
13
15
17.7
37.7
50.8
59.3
64.9
68.9
71.8
74.1
-10
-5
0
5
10
15

Fig. 16

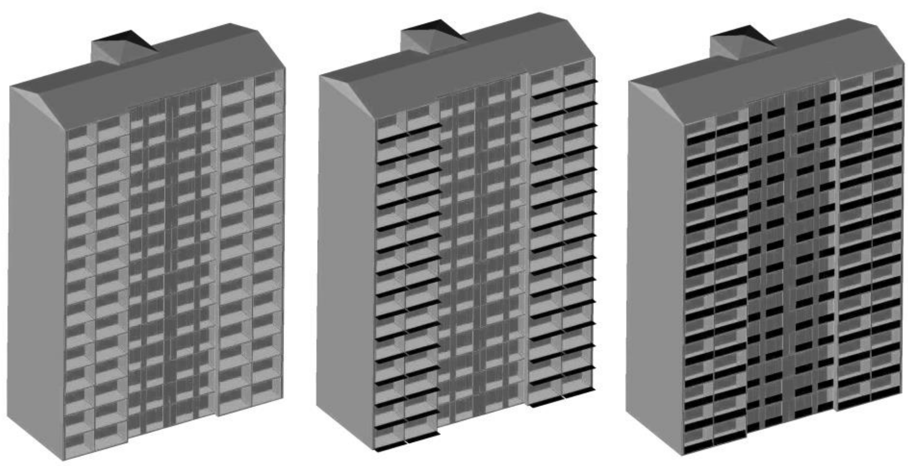
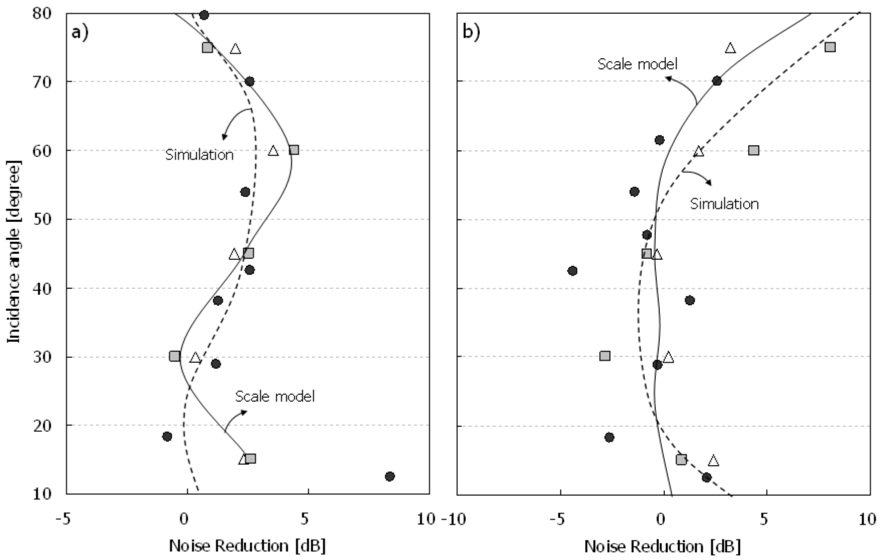


Fig. 17



a)
b)
Incidence angle [degree]
Noise Reduction [dB]
Simulation
Scale model
80
70
60
50
40
30
20
10
-5
0
5
10
-10

Fig. 18

Table Captions

[1] Sound pressure level in each balcony when noise was produced inside the apartment complex [dBA]

[2] Absorption coefficients for the candidate materials

[3] Absorption coefficient of the velour

[4] Noise reduction levels at 1 kHz provided by treatments (c)-(f) in a single building [dB]

[5] Variations of the noise reduction with incidence angles ranging from 17-60 degree

[6] Variations of the noise reduction with incidence angles ranging from 17-75 degree

[7] Noise reduction levels at 1 kHz provided by treatments (c)-(f) in an apartment complex [dB]

Table 1.

	Build. 106	Build. 107	Build. 108	Build. 109
1st	72.5	73.1	75.6	73.5
2nd	72.2	73.9	75.7	73.6
3rd	72.7	73.9	75.4	72.7
4th	73.1	73.1	75.2	72.5
5th	72.7	73.0	75.2	72.2
7th	72.6	73.5	73.9	72.6
9th	71.3	73.1	72.3	71.8
11th	72.0	73.1	72.1	73.1
13th	71.3	71.8	73.2	71.0
15th	71.4	72.7	71.5	69.7

Table 2

	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz
Dense polystyrene [3 mm]	0.01	0.03	0.07	0.17	0.14
Polystyrene [3 mm]	0.01	0.04	0.17	0.16	0.12
Polystyrene [4 mm]	0.03	0.16	0.16	0.16	0.18
Cardboard [0.5 mm]	0.04	0.12	0.30	0.21	0.17
Cardboard [1 mm]	0.06	0.14	0.18	0.17	0.11

Table 3.

125 Hz	250 Hz	500 Hz	1 kHz	2 kHz
0.08	0.15	0.44	0.67	0.71

Table 4.

Floor	Treatment (c)	Treatment (d)	Treatment (e)	Treatment (f)
1st	1.4	1.8	10.7	14.5
2nd	-0.9	-1.5	7.6	7.8
3rd	-3.5	1.9	5.6	9.2
4th	-4.8	0.9	5.7	9.1
5th	-0.5	1.3	9.8	10.4
6th	-0.6	3.8	7.9	11.0
7th	2.1	9.2	12.0	15.7
8th	5.5	9.8	14.9	15.6
9th	5.3	9.4	12.9	14.4
10th	6.8	5.9	7.9	5.5
11th	8.8	9.7	13.1	12.5
12th	4.6	11.6	10.8	13.2
13th	4.0	8.1	8.5	10.7
14th	5.8	6.6	10.6	9.8
15th	5.8	10.4	12.4	12.9

Table 5.

Balcony	Empirical formula	R^2
Treatment (c)	Noise reduction = $0.59\theta^2-4.52\ \theta+5.33$	0.80
Treatment (d)	Noise reduction = $0.43\theta^2-2.85\ \theta+8.44$	0.94
Treatment (e)	Noise reduction = $0.7\theta^2-5.18\ \theta+20.46$	0.74
Treatment (f)	Noise reduction = $0.47\theta^2-3.35\ \theta+23.3$	0.76

Table 6.

Balcony	Empirical formula	R^2
Treatment (c)	Noise reduction = $0.006\ \theta^4-0.22\theta^3+2.69\theta^2-11.25\ \theta+11.09$	0.90
Treatment (d)	Noise reduction = $0.009\ \theta^4-2.89\theta^3+2.99\theta^2-10.63\ \theta+13.84$	0.70
Treatment (e)	Noise reduction = $0.011\ \theta^4-0.36\theta^3+3.84\theta^2-14.48$	0.81
Treatment (f)	Noise reduction = $0.008\ \theta^4-0.24\theta^3+2.37\theta^2-8.4\ \theta+27.02$	0.54

Table 7.

Floor	Treatment (c)	Treatment (d)	Treatment (e)	Treatment (f)
1st	-4.8	-6.8	0.8	0.1
2nd	-5.2	-2.8	-1.5	0.1
3rd	-4.4	-2.7	0.8	0.7
4th	-3.6	1.0	0.9	3.1
5th	-3.0	-1.3	-0.1	2.9
6th	-1.6	1.7	2.9	5.8
7th	0.7	4.1	3.8	7.0
8th	1.8	3.2	5.0	9.8
9th	3.8	5.8	6.0	9.3
10th	-1.1	1.6	3.4	7.3
11th	0.3	3.2	6.3	6.6
12th	0.7	4.7	6.7	7.9
13th	0.1	3.3	4.9	3.1
14th	-1.5	1.3	2.5	2.8
15th	0.5	4.1	6.9	6.5